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Post metamorphic alteration and mineralization in a highly deformed Proterozoic terrain: the eastern Selwyn Range, Cloncurry District NW Queensland

Thesis submitted by
Geoffrey de Jong (M.Sc.)
in July 1995.

for the degree of Doctor of Philosophy
in the Key Centre in Economic Geology and Earth Sciences Department
James Cook University of North Queensland

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Geoffrey de Jong
July 31, 1995

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ABSTRACT

ABSTRACT

Structurally controlled sodic-calcic alteration and associated brecciation affected at least 200 square kilometres of the Proterozoic Cloncurry-Selwyn terrain, of the eastern Mount Isa Inlier. Shear zones separate the Cloncurry-Selwyn terrain into different lithostratigraphic domains and metamorphic grade subzones. These shear zones are interpreted as reactivated early terrain boundary faults. The alteration overprints the contact between the Maronan supergroup in the east and the Doherty Formation in the west, and is spatially associated with a major NW-SE trending lineament, the Cloncurry fault. Several east draining river sections (e.g. Maramungee Creek and Fullarton River) give a good insight into the alteration and breccia complex.

Three regional deformation phases affected the Cloncurry-Selwyn terrain, with D_2 as the main phase. The dominant foliation is S_2, developed as a penetrative N-S fabric. Overprinting younger deformations cause variations of this trend, from NW-SE to NE-SW. The peak of metamorphism coincided with D_2 and reached the sillimanite - K feldspar grade. Late-post D_2 ductile shear zones and brittle structures control the alteration and breccia complex.

Hot (400-550°C) saline (16-38 equivalent NaCl wt.%) fluids present post-peak metamorphism, based on fluid inclusion studies, have been responsible for the alteration. Rocks infiltrated by the hot saline fluids are reconstituted to albite-actinolite with destruction of primary textures and mineralogy. Albitic plagioclase (An < 8%), with magnesium rich actinolite (Mg/Mg+Fe ~ 80-90%) ± magnetite (±Ti) ± titanite are the main alteration minerals. Isothermal pressure reduction and a low X_{CO2} controlled the local occurrence of diopside. Dilatational veins commonly contain titanite and ilmenite, while some magnetites are rimmed with titanite, indicating local mobility of Ti. Main elements depleted during this fluid infiltration, have been potassium and iron. Iron liberated by mica destruction precipitated as a separate magnetite phase, and in magnetite veins.

Chlorine bearing minerals, such as scapolites, are also indicators of the presence of high salinity fluids, and support the fluid inclusion observations. Scapolite alteration is abundant in the Corella Formation of the Mary Kathleen zone, but comparatively rare in the eastern part of the Cloncurry-Selwyn terrain. Scapolites in the eastern Cloncurry-Selwyn terrain are of two distinct types, a metamorphic Ca-scapolite with approximately the same composition as the Mary Kathleen scapolite and an alteration Na-rich scapolite with a high Cl content. The latter forms selvages around oligoclase-quartz veins and occurs in strained metadolerites, located in the zones affected by the sodic-calcic alteration.

The fluids were channelized in zones of high strain, localized in reactivated faults. Unroofing resulted in a decrease in lithostatic pressure, and a relative increase in fluid pressure, evident from the abundance of veining overprinting the ductile shear zones. Two sets of veins occur, namely layer

parallel and subhorizontal vein sets. The layer parallel veins are also axial planar to the refolded folds in the shear zones. These veins consist of actinolite-tremolite centres with albite selvages. Subhorizontal veins mainly occur adjacent to the shear zones, and consist of actinolite and diopside centres overprinted by microcline selvages.

Megabrecciation is a result of increased fluid pressures caused by continuous unroofing and infiltration of new fluids, flowing up temperature. High level granite intrusions (1510-1480 Ma) are due to unroofing and (partly) sinistral strike slip movement on the Cloncurry fault. Brecciation, with similar alteration mineral assemblages, locally affects the syn to post D_3 granites, suggesting similar fluids been active for up to a maximum of 40 million years. The breccia matrix has a "pseudo-igneous" texture, with similar minerals as the altered clasts. The clast size varies from millimetre up to 10s of metres scale. Many clasts are totally altered. The clasts are subrounded due to reaction with the fluid rather than to transport. Some clasts still contain relict schist textures.

Unroofing also resulted in a telescoping effect of the alteration, with K-feldpar+quartz+hematite (300°C, 24 Eq.wt.% NaCl), and epidote+prehnite+calcite±quartz assemblages overprinting the earlier sodic-calcic alteration. Quartz and pyrite are part of a late stage (280°C, 25 Eq.wt.% NaCl, hydrothermal) alteration, controlled in fractures related to the Cloncurry fault.

A mineralized corridor east of the regional sodic-calcic alteration system is the location of the Pb-Ag±Zn and Cu-Au Maronan Prospect. This corridor is a high strain zone with various lithologies and mineralized quartz lenses. Five distinct mineralized zones occur in the Maronan Prospect, and consist of various peculiar horizons composed of magnetite, garnets, pyroxenoids and carbonates. These zones give the appearance of a Broken Hill deposit / exhalative type setting. However, overprinting relationships and elevated and flat REE patterns of garnet-rich layers, which are different to seafloor hydrothermal alteration REE patterns, suggest an epigenetic origin. Calcareous horizons and to a lesser extent the pyroxenoid layers are the main host rocks for the Pb-Ag mineralization, while Cu-Au mainly occurs in fractures and veins associated with silicified rocks. Gold shows affinities with HREE, Cu, Sb and As. Silver exhibits a strong positive correlation with Sb. Constant Pb/Cu and Au/Ag ratios in all mineralization affected rocks, and the occurrence of a high Au-Cu-As-low Ag association, might indicate two types of fluids.

CHAPTER 1

CHAPTER 1 - INTRODUCTION and REGIONAL GEOLOGY

1.1 - Introduction

Metamorphic petrology has undergone a major rejuvenation in the last decade. The idea of dynamic interactions between fluid phases and solid phases has won great favour. Earlier methods of describing the metamorphic and petrological history were based on the interpretation of mineral assemblages, with metamorphic facies as "frozen" evidence of the prevalent P-T conditions. Present day studies are focussed on ongoing processes driven by various types of gradients, such as pressure, temperature and activity gradients. Fluid flow studies, such as fluid pumping, reaction progress, heat flow and fluid pressures are studied by workers as Ferry, Dipple, Oliver, Wall and Hoisch. Integrated studies on mass transport, rate of metamorphism and metasomatism were done by Walther and Wood (1984), Bickle and McKenzie (1987), and Dipple and Ferry (1992). Their studies indicate that deep seated fluid flow is in the direction of decreasing temperatures and no large scale fluid recirculation is necessary for metasomatism.

This thesis will describe structurally controlled regional alteration, the alteration assemblages, the chemistry of the metasomatizing fluid and an associated Pb-Zn, Cu-Au deposit, located in the eastern part of the Proterozoic Mount Isa Inlier.

1.2 - Aims

The Cloncurry-Selwyn area, which is part of the Proterozoic Mount Isa Inlier, shows a remarkable protracted history of fluid-rock interaction that is reflected in regional-scale metasomatism, associated with a gigantic breccia complex which is exposed over 200 square km (De Jong and Williams 1995). This alteration system, preserves a record of fluid activity during the unroofing of the "Isan" orogenic belt. Williams & Phillips (1992) recognized that the breccia complex is composed of profoundly metasomatic rocks. Numerous subeconomic prospect and a few world-class deposits (e.g. Cannington, Ernest Henry) are spatially associated with the regional alteration and breccia complex.

This thesis will describe the different stages of alteration, and try to rationalise the interaction between the structural setting and the compositions of the fluids active during metasomatic stages. The area studied is part of this regional alteration and

breccia complex and is located northeast of the Selwyn Range east of the Williams Batholith, southeast of Cloncurry (Figure 1.1). A smaller deposit, the Maronan Prospect, is located a few kilometres east of the alteration zone. The structural setting, major rock packages and ore assemblages was studied in this prospect.

Another goal of this thesis is to try to establish if there is a distribution pattern in the various alteration stages and if this pattern can be linked to pervasive or channelized fluid flow.

The regional breccia complex in the eastern part of the Cloncurry-Selwyn terrain is defined and known by the stratigraphical implied name "Doherty Formation" (Derrick 1977, Blake 1982, Blake *et al.* 1984). However, the question is asked if the Doherty "Formation" (see section 1.4 and Chapter 2) is a genuine stratigraphical unit, or that the term "formation" is a misused term for an overprinting alteration event.

A problem related to this study is the major uncertainty of the relative timing and the correlation of the deformation events within and outside of the metasomatized zone. Related to this problem is the uncertain correlation between the deformation events of the eastern Selwyn area with the well studied, regional Mount Isa deformation history (Blake 1980, Bell 1983, Loosveld 1987-1989a-b).

1.3 - Approach

A study of the structures that are controlling the different styles of alteration is essential in understanding such a large scale alteration-breccia system. Detailed mapping of rivers (Maramungee Creek and Fullarton River) draining perpendicular to the trend of the main structural grain was undertaken in combination with regional mapping. This was done to obtain a structural framework of the zone of alteration and brecciation. The structural style in the altered and brecciated zone, which was called the Doherty Formation by Blake (1987), Derrick (1977), Blake *et al.* (1984), was compared and correlated with deformation phases in unaltered psammopelitic lithologies of the adjacent Maronan supergroup, informally named by Beardsmore *et al.* (1988) and Laing (1988).

Timing relationships of different alteration stages were established based on field data and laboratory work. Interaction between the deformation events and metasomatism was recorded and studied in detail.

Laboratory work included examining of ninety slabs which were cut and examined macroscopically for their textures and mineral assemblages. Also over five hundred thin sections were prepared, including eighty polished thin sections which were subjected to microprobe studies.

Fluid composition and entrapment temperatures of some of the main, obvious alteration styles have been constrained by fluid inclusion studies of twenty double polished thin sections.

Geochemical analyses were conducted to quantify the regional alteration. Eighty samples from the Maramungee Creek section were analysed for a suite of major and minor elements by XRF whole-rock method. The ferric oxide content from mafic samples was obtained by titration techniques. Selective mafic samples were also analysed for REE (rare earth elements) by Neutron Activation Analysis.

Thirteen diamond drill holes from the Maronan Prospect, held by Acacia (Billiton Australia) until 1994, were logged (total ~ 3500 metres). Detailed petrography was undertaken on three representative holes. Fifty samples were analysed by Neutron Activation Analysis for gold, silver and rare earth elements.

Table 1.1 defines the specific terms used in this thesis.

Table 1.1 - Definition of terms used in this thesis.

METASOMATISM	METAMORPHISM	REPLACEMENT
"Metasomatism" is defined as an allochemical recrystallization, reconstitution process, accompanied by a bulk composition change of the rock. This process is regarded as a local phenomenon in metamorphic terrains which could happen over a wide range of pressure and temperature conditions. Metasomatism usually takes place without volume change. Halogens, especially chlorine may play an important role as a transport media during metasomatism.	"Metamorphism" which is essentially an isochemical process, with facies that occur in specific pressure and temperature fields. However volatile components, such as H_2O and CO_2, are expelled during metamorphism. Metamorphic differentiation on the other hand is an allochemical process involving mass movement on a small scale, operating under specific conditions.	"Replacement" is defined as simultaneously dissolving one mineral and depositing of an other mineral in its place with the possibility of a volume change. Replacement will be used in the thesis as alteration confined to thin layers and on mineral scale. In a strict sense are replacement and alteration the same, but the extend on which this happens is much larger in the latter.

Definitions after Miyashiro (1973), Evans (1987), Henderson (1990).

The first six chapters deal with the alteration, metamorphism and structure in the Doherty Formation. Chapter seven describes the Maronan Prospect . The last chapter is a discussion with conclusions.

1.4 - Regional Geology of the Mount Isa Inlier

The Proterozoic rocks of the Mount Isa Inlier underwent multiple phase deformation and metamorphism. Blake (1987) divided the Mount Isa inlier into three main tectonic and geographical units (Figure 1.1), the "Western Fold Belt", the "Kalkadoon-Leichhardt Belt" and the "Eastern Fold Belt". Blake and Stewart (1992) subdivided the Mount Isa Inlier into the Western Area, fault bounded in the east with the Central Area by the Quilalar Fault zone in the north and the Wonomo Fault in the south. The Pilgrim Fault zone separates the Eastern Fold Belt from the Central Fold Belt (Figure 1.2). Including the "Mary Kathleen zone" "in the Central Fold Belt" is the difference with Blake (1987).

The Western Fold Belt is subdivided, on the basis of faults and stratigraphy, into four subunits; these are from west to east the "Lawn Hill Platform", "Leichhardt River Fault Trough", the "Ewen Block" and the Myally Shelf". Basement is defined as rocks that were deformed and metamorphosed before 1875 Ma, such as the Yaringa Metamorphics and the May Down Gneiss (Blake 1987), which forms part of the Barramundi Orogeny. The Ewen Block consists of the Ewen Granite and metasedimentary rocks, defined as cover sequence 1 by Blake (1987), while the other subunits consist of cover sequence 1 and 2 (Figure 1.3). Derrick (1982) and Glikson *et al.* (1976) described the Western Fold Belt as an ensialic or continental margin rift structure, which was formed at 1800-1650 Ma, as a north-south trending basin, which Derrick called the Leichhardt River Fault Trough. This rift system now forms a central uplift in the Mount Gordon Arch, which divides the Leichhardt River Trough into two sub-basins, with the Lawn Hill Platform in the west (Figure 1.2).

The central belt contains the Kalkadoon-Leichhardt Belt and the Mary Kathleen zone (Blake and Stewart 1992), and is bounded in the west by the Quilalar Fault zone which separates this belt from the Leichhardt River Fault Trough and the Myally Shelf. To the east, the Kalkadoon-Leichhardt Belt is separated from the Mary Kathleen zone by the highly deformed Wonga Belt (Derrick 1981). The Kalkadoon-Leichhardt Belt consists mostly of basement and cover sequences 1 and 2 (Blake 1987). Derrick *et al.* (1977) divided the belt into the Kalkadoon-Leichhardt Block

and the Blockade Block. The common rock type of the former consists of gneissic metasediments with recrystallised porphyritic metavolcanites cut by the Kalkadoon Granite. The Blockade Block is bounded in the east by the Wonga Belt/Fault. The main rock types are metarhyolite, dacite and metagabbro-dolerite. Blake and Stewart (1992) regarded the Mary Kathleen zone as being structurally part of the Kalkadoon-Leichardt Belt. The Mary Kathleen zone is highly deformed and consists predominantly of plastically deformed banded calc-silicate rocks of cover sequence 2 (Corella Formation) and the foliated Wonga Batholith (Figure 1.3).

Figure 1.1 - Tectonic zones in the Mount Isa Inlier. The subdivision is made on the basis of stratigraphical, tectonic and geographical features. Figure is after Blake and Stewart (1992).

The Eastern Fold Belt was subdivided by Blake (1987), from west to east into the Quamby-Malbon zone and the Cloncurry-Selwyn zone. The Quamby-Malbon zone consists mostly of greenschist facies quartzites and conglomerates belonging to cover sequence 2 and 3 (Figure 1.3). Amphibolite facies rocks of the Cloncurry-Selwyn zone, are separated by the Mount Dore Fault from the greenschist facies Quamby-Malbon zone. The Cloncurry-Selwyn zone consists of strongly deformed metasediments, which Blake (1987) assigned to cover sequence 2, overprinted by large scale sodium (± calcium and magnesium) metasomatism and brecciation. Most major plutons, such as those of the Williams batholith, which forms the central part of the Cloncurry-Selwyn zone, postdate the main deformation.

1.4.1 - Regional Stratigraphy and Lithology

Figure 1.3 gives an overview of the stratigraphy on the Mount Isa Inlier. Basement rocks are considered to be the Yaringa Metamorphics, the Plum Mountain Gneiss and Kurbayia Migmatite in the southern part of the Kalkadoon-Leichhardt Belt In the Western Fold Belt (Blake 1987). The Double Crossing Metamorphics are considered to be the oldest exposed rocks in the Eastern Fold Belt, in the south of the Quamby-Malbon zone.

The Double Crossing Metamorphics in the Eastern Fold Belt consist of quartzo-feldspatic metasediments, with migmatitic gneisses and minor felsic and mafic rocks. Quartz-tourmaline rocks and hematite-rich strata occur in this package. This possible basement is more deformed and metamorphosed than the concordant and partly faulted contact with the Answer Slate and Staveley Formation of cover sequence 2. Bultitude and Wyborn (1982) considered the Double Crossing Metamorphics to be similar to the Argylla formation. In the Eastern Fold Belt, the Argylla Formation forms the base of cover sequence 2.

The Ballara Quartzite in the Kalkadoon Leichhardt Belt and the Malbon Group in the Eastern Fold Belt forms the base of the Mary Kathleen Group, which forms the upper part of cover sequence 2 in those two belts. These formations and the Soldiers Cap Group will be described in Chapter 2.

Cover sequence 3, 1680-1670 Ma, Blake (1987), was considered to be only extensively exposed in the Western Fold Belt and the Kalkadoon-Leichardt Belt. Page (1993) dated the Soldiers Cap Group in the Eastern Fold Belt as 1677 ± 9 Ma, based

on zircon U-Pb data, and considered this unit to be part of the cover sequence 3, which has the same age as the Mount Isa Group in the Western Fold Belt. The overlaying McNamara Group consists of a more dolomitic stromatolitic base, with a psammitic top. Cover sequence 3 in the Western Fold Belt are intruded by different pulses of granite namely, the Weberra Granite - 1698 Ma, the Sybella Batholith - 1671 Ma and the Sybella Microgranite - 1670 Ma (Wyborn *et al.* 1988).

Figure 1.2 - Proterozoic blocks of the Mount Isa Inlier bound and cut by major north-south trending fault zones. These fault zones underwent a complex history of dominantly transcurrent and transpressionial movements.

Some controversy exists on the nature of cover sequence 3 in the Eastern Fold Belt. Earlier work of Blake *et al.* (1984), Blake (1987) and Derrick *et al.* (1977) indicated an almost total absence of cover sequence 3, though Wyborn *et al.* (1988) considered part of the Mount Albert Group as cover sequence 3. Laing (1991) considered the Maronan supergroup and the Cloncurry terrain as an allochthonous fragment of the Diamantina Orogen, thrusted onto the Mount Isa Inlier, with the Corella Formation as the detachment zone. Laing (1991) based his conjecture on the distinctly different geochemical, sedimentary and lithological features of the Mount Isa Inlier and the Cloncurry terrain.

1.4.2 - Regional Structural Framework

Earlier work on the Mount Isa Inlier was mostly concentrated on the Western Fold Belt (Glikson *et al.* 1976, Blake *et al.* 1984, Bell 1983, Page and Bell 1986, Valenta 1989). The Central Area was studied by Reinhardt and Rubenach (1989), Holcombe *et al.* (1991), Pearson *et al.* (1992) and Oliver *et al.* (1992). Only few studies have been conducted on the Eastern Fold Belt, Loosveld (1989a-b, 1992), Laing (1991), Beardsmore *et al.* (1988) and Williams and Phillips (1992) and Phillips *et al.* (1994), but recent discoveries of large deposits in the Cloncurry - Selwyn zone, such as Cannington, Ernest Henry and Osborne, will bring about changes in this situation.

Not much is known of the early deformation phase that affected the basement of the Mount Isa inlier termed the Barramundi Orogeny (1870 - 1890 Ma) (Etheridge *et al.* 1987, Page 1988, Page and Williams 1988, Wyborn 1988). Blake and Page (1988) ascribed the tectonism, with complex folding and metamorphism, partial melting and formation of migmatite of the Kurbayia Migmatite in the Kalkadoon-Leichhardt Fold Belt to the Barramundi Orogeny. The occurrence of gneissic textures, myrmekites and leucosomes, indicates upper amphibolite facies metamorphism with pressures of probably 4 kbar which can be correlated with the high grade metamorphic Yaringa Metamorphics of the Western Fold Belt. Page (1988) dated the Barramundi Orogeny on the basis of U-Pb zircon studies and recognized two elements that are typical for this tectonism; first regional deformation and metamorphism of the basement, supra-crustals, and secondly accompanying orogenic magmas with crystallization of I-type, potassium rich felsic intrusions. The Barramundi Orogeny affected approximately a third of the Australian continent (Page and Williams 1988). Wyborn (1988) and Wyborn and Page (1988) considered that the magmatism was due to underplating

caused by small scale convection cells in the upper asthenosphere creating Proterozoic basins as a result of mantle upwelling.

Figure 1.3 - Schematic stratigraphic correlation diagram of the major tectonic, stratigraphic and intrusive events in the Mount Isa Inlier. Geochronological data from Page (1983), Page and Bell (1986), Page (1988) and Wyborn and Page (1983), Page (1993).

1.4.2.1 - Early Deformation Phases of the Isan Orogeny - D_1 Extension

The period of 1850 - 1780 Ma, between the Barramundi Orogeny and the Isan Orogeny was characterized by rifting with cycles of basin development and deposition of the cover sequences. The first rifting stage that followed the Barramundi Orogeny was described by Derrick (1982) and Glikson *et al.* (1976) as

the Leichhardt River Fault Trough which was formed over a period of 150 Ma as a major extension zone overlaying a region of thermal mantle upwelling. The trough was up to 600 km long and 65 km wide, developed as a half graben. A zone of central uplift is evident (Mount Gordon Arch). On the basis of sedimentological and paleogeographical variations (thinning of the cover sequence formations in the centre of the trough), basin subsidence took place up to the deposition of the Myally Subgroup, which was then covered by the Quilalar Formation. Derrick (1982) also mentioned significant thickness variations in the cover sequence from north to south across east-west faults, which were interpreted as growth faults. Glikson *et al.* (1976) proposed, also on the thickness variations, that the east-west faulting took place before deposition of the Myally Subgroup. Bell (1983) argued against the east-west faults being growth faults and favour an origin as listric faults in a décollement zone giving a imbricate geometry within a thrust duplex, formed during the Isan Orogeny. Etheridge (1986) and Lister (1991) questioned Bell's "ramp synclines" and "roof thrust" hypotheses and offered the idea that north-south trending structures are transpressional (D_3) wrench fault systems containing east-west orientated "flower structures".

Brittle extensional features, occurring in the Kalkadoon-Leichhardt Belt, were recognized by Williams and Etheridge (1987). Low angle normal southwest dipping faults are part of early detachment zones, and caused regional extension in the Duchess Belt (Figure 1.3). These low angle faults were active prior to the Isan Orogeny, and were described as rotational normal faults which make a small angle with the bedding. Roll-over anticlines and ramp synclines were described from adjacent areas. Extension of between 67-81% were been estimated from fault block separation. Breccia lenses inferred to by formed by collapse in to dilations of the brittle fault are strained by the early ductile deformation of the Isan Orogeny. These extension faults affect the Mitakoodi Quartzite of the Malbon Group which is separated from the underlaying Argylla Formation by a low-angle detachment fault that truncates the Argylla Formation and along which a basic sill intruded. These extension features affect a granite dated at 1740 Ma (Page 1983) and ceased to be active before deposition of the Mount Isa Group 1670±18 Ma.

The Mount Isa Inlier underwent three main ductile deformation events, following the early brittle extensional deformation, which affected the whole of the inlier, ascribed to the Isan Orogeny, between 1620 and 1480 Ma (Table 1.2). Holcombe *et al.* (1991) considered the tectonic-magmatic activity associated with subhorizontal shearing in

the Mary Kathleen Fold Belt to part of D_1. Holcombe *et al.* (1991) interpreted the strong biotite-amphibole mineral lineation, which has a subhorizontal to vertical orientation, to be folded D_1 stretching lineations. The stretching lineations were formed in a mid crustal extensional décollement surface at 7 to 10km depth. A high thermal gradient is inferred to have caused strain softening at such shallow depths. Early extension in D_1 was also acknowledged by Loosveld and Schreurs (1987), but seemed to have occurred after a thrusting event in the Blockade Block in the Mary Kathleen Fold Belt.

Table 1.2 - General geochronology of the tectonic events in the Mount Isa Inlier. Note in this thesis the suffix 1, 2, 3, 4 added to D indicates respectively the deformation / tectonic events while the suffix 0, 1, 2, 3 added to S indicates respectively bedding / primary layering, firsts, second and third developed (recognised) cleavage. The symbols L_1^0, L_2^0, L_2^1, L_3^2 indicate a lineation defined by the intersection of respectively the bedding and the firsts developed cleavage, the second cleavage, the first and second cleavage, and the second and third cleavage.

TIMING Ma	DEFORMATION		TECTONIC FABRIC and ORIENTATION	COMMENT
	post	D_4	Large scale flexures with NEE axial planes	
		$D_{3\text{-brittle}}$	Conjugate NNW-ENE faults and fractures, metasomatism	
1510-1480	D_2	$D_{3\text{-ductile}}$	NW-NE trending folds with shearing	Reinhardt (1992)
	D_2	$D_{2b\text{-shearing}}$	Highly strained retrograde fabric, parallel to S_2	
1545		$D_{2a\text{-compression}}$	S_2 penetrative cleavage, NW-ENE trending folds, metasomatism	Winsor (1983) Valenta (1989)
1620	D_1	$D_{1\text{-compression}}$	S_1 cleavage, N-S thrusting with E-W folds	Bell (1983) Loosveld (1988)
1670-1740		$D_{1b\text{-extension}}$	E-W low angle faults with southward movement	Holcombe *et al.*(1991)
1777±7		$D_{1a\text{-extension}}$	E-W to NW-SE low angle faults	Williams & Etheridge (1987)
1780-1850	Rifting LRFT		N-S trough bounded in the east by the Quilalar Fault	Derrick (1982) Glikson *et al.* (1976)
1890-1870	Barramundi Orogeny		Complex folding with migmatites	Page & Williams (1988) Wyborn & Page (1988)

ISAN OROGNY

Loosveld (1989a and b) described a compressional phase postdating an extensional phase (approximately 41% extension based on dolerite intrusions). Loosveld suggested two possible ages for the extensional event in the northern part of the Cloncurry-Selwyn zone. First he noted that the extension has been synchronous with the early deposit of the Mitakoodi Quartzite, which correlate with the 1780 Ma extension event in the lower Malbon Group. This is based on the observations that the Mitakoodi Quartzite is not affected by the dolerite intrusions and associated high-angle faults. Secondly if the Mitakoodi Quartzite had behaved in a more ductile

manner, then the extension event could also be younger and that the Mary Kathleen Group that was deposited during the second extensional event. Orientation of the mineral lineations indicate a NW-SE direction of shear.

Much controversy still exists on the early nature of the Isan Orogeny. Low angle high strain zones (the shear zones make a low angle with the bedding) were recognized by workers as Bell, Loosveld and Passchier. Repetition of the stratigraphy and bedding parallel shear zones are a result of thrusting and extensional faulting. Only a combination of the knowledge of the above criteria and metamorphic isograds prior to the faulting will demonstrate either thrusting or extension.

1.4.2.2 - D_1 Compressional Phase

The D_1 contraction phase happened at about 1620 Ma (Page and Bell 1986). Bell (1983) and Valenta (1989) recognized tight east-west D_1 synclines with the development of a slatey cleavage, but without associated anticlines in the Mount Isa Group of the Western Fold Belt. Bell ascribed this to early north-south fold thrust duplex-formation and the development of late D_1 E-W faults (Valenta 1989, Winsor 1983).

S_1 is developed as a penetrative fabric in the Wonga Granite (Central Fold Belt, Passchier 1991, Reinhardt 1992). Reinhardt (1992) recognized thrusting in the Mary Kathleen Fold Belt, with D_1 represented by a flat-lying north-south foliation. Loosveld (1989a) described tight to isoclinal upright folds, east of the Pilgrim Fault, attributed to the D_1 compression with an E-W to NNW trend in the Soldiers Cap Group. S_1 is axial planer and contains a south to southeast plunging mineral lineation. S_1 is in places bedding parallel and developed in discrete zones (Loosveld 1989b, Reinhardt 1992). Mesoscopic folds are only found in the northern part of the Eastern Fold Belt and in eastern part of the Cloncurry-Selwyn terrain (Chapter 3).

From above it can be deduced that the geometry of D_1 is poorly constrained in the Cloncurry-Selwyn terrain. Beardsmore *et al.* (1988) deduced D_1 on the basis of fold interference patterns formed by D_2 and on downward-facing D_2 structures and interpreted D_1 thrusting and recumbent folding.

Compression in the later phase of the D_1, resulted in NW direction thrusting. Loosveld (1989b) argued that the Cloncurry Fault in the Cloncurry-Selwyn zone is a thrust fault and that the NNW verging folds are parasitic D_1 folds on the limbs of large scale nappe structures The nappe structures were results of NW-directed simple shear, while the upright folds are due to a coaxial N-S shortening.

1.4.2.3 - Peak Deformation Phase in the Mount Isa Inlier - D_2

The main tectonic orientation in the Mount Isa Inlier is a well developed north-south fabric. This fabric was produced by east-west shortening (D_2) which occurred at about 1548 Ma (Page and Bell 1986, based on D_2 structures in the Sybella Granite). Large scale open to tight upright to slightly inclined folds with a north-south cleavage were produced during this stage Local anisotropy caused deflection in this trend.

D_2 fold hinges in the Western Fold Belt preserved relict D_1 folding. D_1 quartz inclusion trails are also observed in cordierite porphyroblasts (Rubenach 1992). The foliation is developed as a slaty cleavage in the lower grade rocks of the Mount Isa Group (Page and Bell 1986, Winsor 1985).

D_2 styles and orientations are more diverse in the Eastern Fold Belt than in the rest of the Mount Isa Inlier. Loosveld (1989) noted that D_2 styles and structures are different to those in the other fold belts and recognized S_2 as a steeply dipping crenulation cleavages with NNW-SSE and NNE-SSW strikes and steep plunging L_2^2 mineral lineations. The Williams Batholith (crystallization age of the granite is 1480±28 to 1500 Ma, Page 1993) intrude into the D_2 structures, which constrain the upper time limit of D_2. SHRIMP age dating on zircons, gives ages in the order of 1584±17 Ma (Page 1994).

Metamorphism reached its peak during D_2 (Jaques *et al.* 1982, Reinhardt 1992). Loosveld (1989) observed weakly deformed sillimanite fibres overgrowing the muscovite S_1 foliation, with cross cutting fibres in the D_2 fold hinges and argued peak metamorphism to be syn- to post-D_2. Jaques *et al.* (1982), divided the Cloncurry-Selwyn Range into three metamorphic zones with lower grade metamorphism in the west and amphibolite grade metamorphism in the east.

1.4.2.4 - Post D_2 Deformation Phases in the Mount Isa Inlier

Post D_2 transpressional strike-slip faulting development at the brittle-ductile transition (Lister 1991, Page and Bell 1986). Etheridge and Thomas (1986) discovered that these faults had substantial influence on the structures in the Western Fault Belt. Wrench faulting caused transpression during D_3 / D_4, resulting in refolding of earlier structures, normal, reverse and strike slip faulting. Local pop-out structures causes deflection of the northerly trending D_2 fold axes to northwesterly and northeasterly orientations.

Two major sets of strike-slip faults exists in the Mount Isa inlier: a northeast dextral set and a northwest striking sinistral conjugate set. These fault orientations suggests a continuing east-west compression with a north-south extensional component (Stewart 1990).

Post D_2 east-west faults are located in areas between major transcurrent faults which have opposite sense of movement. These east-west faults have mainly normal fault movement and are consistent with the north-south extension.

1.4.3 - Alteration in the Mount Isa Inlier

Alteration is widespread in the Mount Isa Inlier. A long history of alteration events has been documented in the Haslingden Group of the Western Fold Belt, and especially the Eastern Creek Volcanics adjacent to the Mount Isa Fault (Rubenach 1992, Huang and Rubenach 1994). Early pre- to syn-D_1 alteration of metabasalt involved addition of Mg and loss of Ca and Na producing chlorite-quartz schists. Quartzitic rocks and psammites in high strain zones of the Eastern Creek Volcanics exhibit gains in Na and Ca, and a strong losses in K and Mg, during syn- to late-D_2 alteration, resulting in massive tremolite and oligoclase-tremolite pods (Huang and Rubenach 1994). Muscovite-biotite schist, adjacent to metadolerites and in boudin necks between metadolerites, are reconstituted to cordierite - quartz ± anthophyllite rocks. Preserved L_2 lineations, indicate that the schist was metasomatized post D_2.

Lesley (1987) recognized four alteration stages affecting the metabasalts in the Eastern Creek Volcanics, with the onset of the first alteration approximately 200 Ma after deposition of the Mount Isa Group, hence ± D_3. This type 1- alteration consists of albite-actinolite ± chlorite. The overprinting alterations are: type 2- which consists

of epidote and titanite and type 3- of calcite and magnetite; while type 4- only occurs in late retrograde shear zones in amphibolite grade metabasalts which are altered dominantly to albite-chlorite-rutile rocks. Copper and uranium are leached during the alteration. Hannan *et al.* (1993) attributed the regional chloritization of the metabasalt of the Eastern Creek Volcanics due to focussing of hydrothermal fluids in post D_2 shear zones, conform to the stratigraphy. Hannan *et al.* (1993) also recognized that several components, e.g. K, Rb, Ba and Cu were removed from these shear zones, forming adjacent biotite schist and Cu enrichment of the wall rocks.

The central part of the Mount Isa Inlier and especially the Corella Formation in the Mary Kathleen Fold Belt exhibit large scale scapolitization of calc-silicate rocks (Oliver *et al.* 1990a-b, 1992, 1993, Oliver and Wall 1987). Oliver and his co-workers demonstrated that metasomatism and related fluid flow could be correlated to particular structural styles and deformation intensity. Earlier work of Oliver, demontrated that rocks deformed in a ductile fashion show evidence of low fluid/rock ratios, indicating negligible fluid infiltration. This contrasted with episodic brittle behaviour elsewhere associated with high fluid/rock ratios. The timing of the fluid pathways (and scapolitization) is still controversial. Scapolitization was first interpreted to occur syn to late D_2 in and adjacent to competent metadolerite bodies. Later work of Oliver *et al.* (1994) suggest, based on isotopic studies, that the scapolitization occurred during D_1 extension, and is controlled by D_1 shear zones.

Alteration affected all kinds of lithologies (metasedimentary and igneous) in the Eastern Fold Belt. The rocks that are affected by alteration are reconstituted to high variance mineral assemblages, composed of albitic plagioclase ± amphibole ± clinopyroxene ± scapolite ± iron oxides (Blake *et al.* 1983, Donchak *et al.* 1983, Williams and Phillips 1992, Phillips *et al.* 1994, De Jong and Williams 1995). The alteration shows a protracted thermal history, beginning late-post D_2 and stayed active to at least D_3. Iron mobility throughout the alteration event is the cause for the enigmatic term "red rock". Different hues of red are dependent on the grain size and abundance of hematite in the rock. The occurrence of hematite is a function of the T-fO_2 conditions, and occur generally in the later D_3 event (Williams 1994a-b). Fluids related to the metasomatism are in general hypersaline and are in the order of 30~40 weight % NaCl (Chapter 6).

1.4.4 - Mount Isa Inlier as a Metallogenic Province

The Mount Isa Inlier is a major producer of lead, zinc, silver, copper and also gold. Uranium and REE have been mined at Mary Kathleen, but mining activity stopped in 1982. Mining has been a major activity since the discovery of copper and gold at Cloncurry in the last century. Major mines in the Western Fold Belt are the Mount Isa -, Hilton - (just north of Mount Isa), Lady Loretta and Century mines, which are shale hosted Pb-Zn-Ag deposits (Figure 1.4). The Mount Isa and Hilton mines are hosted in the Mount Isa Group, while Lady Loretta is hosted in the McNamara Group. Another major Pb-Zn-Ag deposit is Dugald River, located in the Eastern Fold Belt, and hosted in the Mary Kathleen Group. This might be taken to suggest there were at least two episodes of this type of ore forming; respectively ~1670 Ma and ~1720 Ma for the Western and Eastern deposits. However, a lively debate is still ongoing for the last fifteen years if those stratiform shale hosted Pb-Zn-Ag deposits are not replacement.

Subeconomic stratiform iron-rich Pb-Zn deposits, such as Pegmont, Fairmile, Dingo, Maramungee and Maronan, occur in the Maronan supergroup, in the Eastern Fold Belt (Figure 1.4, Stanton and Vaughan 1979, Vaughan and Stanton 1989, Williams and Heinemann 1993). A striking feature in the Mount Isa Inlier is the linear geographical occurrence of the deposits (Figure 1.4). Another striking feature is the lack of Pb-Zn in Cu-Au deposits. New discoveries of concealed deposits in the Eastern Fold Belt, were all made in the last ten years: Osborne (Cu-Au, 36 million tonnes @ 2% Cu, 1 g/t Au), Cannington (Pb-Ag, 47 million tonnes @ average 10.7% Pb, 4.6% Zn, 470 g/t Ag) and Ernest Henry (Cu-Au, 132 million tonnes @ 1.2% Cu, 0.6% Au). Geophysical methods, and especially aeromagnetic anomalies, played an important role in the discovery of these concealed deposits. Geochemical exploration formed the basis for the discovery of Tick Hill (470 000 tonnes @ 27 g/t Au). The discovery of Cannington, being possibly the biggest Ag resource in the world, has changed the outlook on exploration for the Cloncurry terrain.

Other minor commodities mined as by-products in the Mount Isa Inlier are: cobalt, tungsten, mica, beryl, manganese, cadmium and bismuth. Considerable amounts of calcite and silica have been mined for the use as flux in the smelters of the Mount Isa mine.

Figure 1.4 - Major metalliferous deposits in the Mount Isa Inlier, with detail from the Cloncurry terrain in the Eastern Fold Belt.

1.5 - Introduction to the studied area

The studied area is located in the eastern part of the Cloncurry-Selwyn terrain (Figure 1.4). Eight smaller areas were mapped in detail (Figure 1.5), in conjungtion with the Cloncurry-mapping project of James Cook University. Regional mapping was undertaken at 1:25000, while specific river sections were mapped at a more detailed scale. In the following chapters references will be made to these specific

areas and locations. This section outlines the main lithologies and structures in the different subareas.

The Cloncurry-Selwyn terrain (Figure 1.5)

A brief overview will be given of the eastern part of the Cloncurry-Selwyn terrain (Figure 1.5). The main lithologies are upper amphibolite facies calc-silicate and psammopelitic metasediments, intruded by different (pre to post peak deformation and metamorphism) felsic and mafic igneous rocks. Multiple deformation occurred with D_2 as the main phase (synchronous with peak metamorphism) which caused north-south upright close to tight folds (Chapter 3). Major brittle and ductile high strain zones seperate several structural domains (Chapter 3). Although the main structural grain is north-south, the main fabric orientation in these domains deviate from this general trend. A major northwest trending lineament, the Cloncurry fault (10-30 metres high and 2-5 metres thick), is prominent on aerial photographs and satellite imagery and manifests itself as a silicified stockwork breccia. Locally gneissic rocks are observed in the fault. A large batholith, the Williams Batholith, which consists of unfoliated hornblende two feldspar granite (Mount Angelay granite), bounds the studied area in the west. Fracture patterns in the granites are approximately parallel to the Cloncurry fault and orientations of post D_2 deformations.

Maronan-Fairmile area (Figure 3.3)

This area is part of the northern extension of domain (iii) in the Glen Idol-Fairmile region. It consists predominantly of interbedded psammopelitic schists and amphibolites. Overprinting deformation events (D_3 over D_2) cause a complex interference pattern. The northern part contains a major D_2 north to north-east plunging antiform (Turpentine antiform). The Maronan Prospect is located just north of this antiform. This prospect will be described in Chapter 7.

Figure 1.5 - Geology of the eastern Cloncurry-Selwyn terrain. Map after BMR: 1:100000 "Geology of the Duchess-Urandangi Region" (1983), and the JCU 1:25000 Cloncurry Mapping Project (1990 to 1993). The areas mapped in detail are: A- Maronan-Fairmile area; B- Glen Idol - Fairmile; C- The Fullarton River Area; D- Fullarton River gorge; E- Mallee Gap area; F- Spring Creek area; G- Boorama Waterhole area and H- Maramungee Creek.

GEOLOGY MAP
EASTERN SELWYN RANGE

Glen Idol -Fairmile area (Figure 1.6)

The Glen Idol - Fairmile region is separated into three structural and lithological domains by zones of high strain, trending approximately north-south (Figure 1.6). Four deformation events have been recognized, with the last two events overprinting all previous deforations.

i) The western domain (west of Glen Idol) consists of competent laminated calc-silicate rocks and psammopelitic schists interlayered with amphibolites and metadolerites of the Doherty Formation (see Chapter 2). This domain is bounded in the west by the Mount Angelay granite and the Cloncurry Fault. The main fabric is S_2 which strikes about 340° and makes a small angle with the Cloncurry Fault. The Cloncurry Fault is a locus for post D_2 breccias and alkali metasomatism.

ii) The central domain forms a wedge shape, and is bounded by strain zones that join northwest of Fairmile near Willy's Bore. The dominant lithology is a coarse retrograde muscovite ± sillimanite, biotite, quartz, feldspar gneiss with partial melts (leucogneiss), typical of the "Fullarton River Group", and is the structurally deeper component of the Maronan supergroup (Beardmore *et al.* 1988, see Chapter 2 and 7). The main trend of S_2 is 320° - 330° and there are numerous concordant pegmatites.

iii) The eastern domain (which contains the Fairmile Prospect) is composed of the rocks belonging to "Soldiers Cap Group", the structurally higher part of the Maronan supergroup (see Chapter 7 and 2). It comprises interbedded pelites and psammites with quartzites and amphibolites. Some quartzite horizons grade into quartz - magnetite ± garnet ± apatite rich horizons. The main trend of the foliation in this domain is north-south.

The three structural and lithological domains are separated by zones of steep easterly dipping strained and retrograde fine grained muscovite schist, with a penetrative cleavage. These high strain zones reflect post D_2 faulting, which juxtaposed the stratigraphically deeper Fullarton River Group as a wedge-shaped window between the Doherty Formation and the Soldiers Cap Group. The different orientations of S_2 in the eastern domain compared to the central and western domains are partly due to this faulting and later overprinting deformation events (Chapter 3).

Figure 1.6 - Geology of the Glen Idol - Fairmile region. Three major lithological and structural domains are present. Domain (i) west of Glen Idol contains mainly the competent calc-silicate and brecciated rocks. Domain (ii) consists of coarse muscovite-quartz gneiss with concordant pegmatites. Domain (iii) consists of high strained psammopelitic metasediments with amphibolites. Map after JCU Cloncurry Mapping program 1993.

The Fullarton River Area and Fullarton River gorge (Figures 1.7 and 1.8)

The Fullarton River area is part of domain (i) in the Glen Idol-Fairmile region. It contains a kilometre scale moderately northwest plunging D_2 antiform (Figure 1.7), with relict gneiss and "altered" schist (see Chapter 2) in the core. Numerous steep faults and fractures are developed parallel to the axial plane and are the locus for large scale brecciation. Brittle faults are concentrated in the nose of the antiform, and localising large scale megabreccias, which are well exposed in the Fullarton River gorge (Figure 1.8). The lithologies varies from "pristine" unaltered psammopelitics, calc-silicates, marbles to regional alteration-affected metasediments. Breccia clast

diameters vary dramatically, from centimetres up to tens of metres. These clasts rest in an albite-clinopyroxene±actinolite matrix. Numerous small diapiric fine grained leucogranite intrusions outcrops in the core of the antiform.

Mallee Gap, Spring Creek and Boorama Waterhole areas (Figures 1.9-10-11)

The central part of the studied area includes the Mallee Gap area (part of domain (i) of the Glen Idol-Fairmile region) and two smaller areas in the south, Spring Creek and the Boorama Waterhole. Mallee Gap is a hundred metre 50° inclined waterfall, which exposes granitic and unaltered and altered metasedimentary rocks. Sinistral movements caused small scale thrusting east and west of the Cloncurry fault. Strongly deformed metasedimentary rocks and foliated granites are dominant in the east and north, while unfoliated granite intrusions and breccias occur in the west and south. Metasediments east of the Cloncurry fault are folded by a tight northwest-plunging D_2 synform, while west of the Cloncurry fault there is a tight south plunging D_2 antiform. Brittle open space veins, varies in width from centimetres upto tens of metres scale, which make a small angle with the Cloncurry fault, are filled with quartz and K-feldspar.

The Spring Creek area (Figure 1.10) is located 1.5km SE of the Mallee Gap area. This area contains a high strain zone which separates coarse muscovite-quartz±biotite gneiss with foliated granites in the east from calc-silicate, weakly foliated granites, metadolerites and breccias in the west. Fracture patterns related to this high strain zone indicate dextral movement (Figure 1.10). The breccias form a trend parallel to the shear contact, and cause albitization of the granites. The felsic and mafic intrusions form a large net-veined complex.

The Boorama Waterhole area located south of Spring Creek consists predominantly of intrusive rocks (Figure 1.11). Extensive granites and metadolerites are intruded in calc-silicate rocks are foliated and folded by the D_2 deformation. This results in a tightly folded southeast plunging antiform and synform. On regional scale and outcrop scale, the granite and metadolerite from a complex deformed net-veined system. Fractures and brittle-ductile strain zones make an approximately 40° angle with the Cloncurry fault and were apparently formed by late sinistral movement.

Figure 1.7 - Geology of the Fullarton River area.

GEOLOGY of the FULLARTON RIVER area

Maramungee Creek section (Figure 1.12)

A number of east-draining river systems, provide a good three-dimensional insight in the geology. The Maramungee Creek section in the southern part of the studied area, exposes ductily deformed rocks, located in high strain zones. The rock units are predominantly calc-silicates, with foliated felsic and mafic intrusions (Enclosure B: "Geology of the Maramungee Creek"). Reconstituted rocks, which reflect the regional metasomatism, are controlled by late D_2 structures. These shear zones, which are the loci for the sodic-calcic metasomatism, are up to 100 metres thick and are overprinted by breccias. The breccias are heterogeneously deformed in places. These metasomatic breccias are characteristic of the regional alteration event, and overprint retrograde muscovite schist, indicating that the alteration itself is retrograde.

Figure 1.8 - Geology of the Fullarton River gorge section.

Figure 1.9 - Geology of the Mallee Gap area.

472000 mE
473000 mE
474000 mE
475000 mE
476000 mE
477000 mE
478000 mE
7649000 mN
7648000 mN
7647000 mN
7646000 mN
7645000 mN
7644000 mN
7643000 mN
7642000 mN
7641000 mN
7640000 mN
7639000 mN
Mallee Gap
Three Sisters
CLONCURRY FAULT
D2
N
LEGEND
Cover, alluvium
Psammitic schist interbedded with pelitic layers and amphibolite
Coarse muscovite biotite quartz feldspar schist
Laminated and massive calc-silicate
Carbonate pods, interbedded with Kfs layers
Strongly foliated amphibolite / metadolerite
Coarse weakly foliated basic igneous rock (gabbro)
Coarse unfoliated quartz containing basic rock (diorite)
Mt Angelay granite, hornblende, quartz two feldspars, with miarolitic cavities
Unfoliated granite, with zoned plagioclase crystals
Weakly to unfoliated fine grained leucogranite
Strongly foliated, mylonitic granite
White fine grained altered, albitized granite
Altered schist, biotite quartz sillimanite schist ± corundum overprinted by albite
Open space veins with red Kfs, hematite, quartz/chalcedony infill ± sulphides
Breccias, consisting of altered granites, schists, metadolerites and calc-silicate rocks
Granitic / pegmatitic vein
White buck quartz vein
*G
Goethite vein
Fault, inferred
Shear-, high strain zone
Thrust
Antiform
Synform
S1
S2
S3
Lineation / fold axis

Figure 1.10 - Geology of the Spring Creek area.

Figure 1.11 - Geology of the Boorama Waterhole area.

Figure 1.12 - Geology of the Marramungee Creek section, showing the relationships between the metasomatic rock units. Abbreviations after Ketrz (1983), with Me Scp, meionite scapolite; Ma Scp, marialite scapolite; And, andesine; Cc, calcite. The Cloncurry Fault is about 1 km west of this map.

CHAPTER 2

CHAPTER 2 - STRATIGRAPHY and LITHOLOGY of the Eastern Cloncurry - Selwyn terrain

2.1 - Introduction

Rock types encountered in the eastern Cloncurry-Selwyn terrain are the metasediments of "rift cover" sequences 2 and 3 (Blake 1987). The "rift cover" metasediments are divided into two stratigraphic groups, the Mary Kathleen Group (1790 - 1720 Ma) at the base, overlain by metasedimentary rocks informally named the Maronan supergroup (Beardsmore *et al.* 1988, 1677±9 Ma based on SHRIMP zircon dating, Page 1993).

The Malbon Group lies beneath the Mary Kathleen Group. The former comprises two formations, the Marraba Volcanics and the conformably overlaying Mitakoodi Quartzite. The former consists of interlayered metabasalts (and/or meta-andesites) with fine- to coarse- grained psammopelitic metasediments. The latter formation mainly consists of fine grained feldspathic and psammitic metasediments with minor scapolite-bearing calc-silicate rocks (Blake *et al.* 1984).

The upper part of the Mary Kathleen Group is well studied in the Central Fold Belt and the Quamby-Malbon zone (Derrick *et al.* 1977, Wilson 1983, Reinhardt 1992, Blake *et al.* 1984, Oliver *et al.* 1991). The Corella Formation is the most extensively exposed unit in those areas. Its rock types range from psammopelitic, quartzitic metasediments to marble, but are predominantly layered calc-silicates. The calc-silicate bearing rocks were divided into rocks containing various mineral assemblages consisting of various combinations of biotite, calcite, quartz, microcline, amphibole, scapolite, clinopyroxene, magnetite, titanite and minor garnets, plagioclase and muscovite (Oliver *et al.* 1990, 1992). Numerous dolerites intruded the Mary Kathleen Group prior to the onset of the Isan Orogeny. The Doherty Formation is seen by various workers as the Corella Formation equivalent in the Cloncurry-Selwyn terrain (see next section 2.2).

The Maronan supergroup is believed to have been thrust over the Mary Kathleen Group during the D_1 compression phase (Loosveld 1989b, Laing 1990) and comprises quartzites, psammopelitic metasediments interlayered with metabasic and metafelsic volcanic rocks. The Maronan supergroup was divided by Beardsmore *et al.* (1988) into two units, at the base, the Fullarton River Group conformably overlain by the Soldiers Cap Group.

The Fullarton River Group was further subdivided into the Gandry Dam Gneiss, the Glen Idol Schist and the New Hope Arkose formations. These consist broadly of massive to poorly thick-bedded coarse quartzofeldspathic psammites, biotite-rich psammopelites and pelites. Higher metamorphic grade rocks (sillimanite-K-feldspar) at the base of the Fullarton River Group are composed of granitic gneisses, quartzofeldspathic segregations and are intruded by swarms of pegmatite sills.

The Soldiers Cap Group consists of lower amphibolite facies metamorphic rocks (sillimanite-muscovite and andalusite-staurolite grade). The Soldiers Cap Group was also subdivided into three formations: Llewellyn Creek Formation (oldest), Mount Norna Quartzite and the upper Toole Creek Volcanics (youngest). Discrete interbedded psammopelite units, interpreted to have been derived from turbidites (Beardsmore *et al.* 1988), form the base of the Soldiers Cap Group. Towards the top, the rocks become more feldspathic intercalated with graphitic slates and minor marble (see Chapters 3 and 7).

2.2 - The "Doherty Formation" as a tectono-stratigraphic unit

The "Doherty Formation" (1720±7 Ma U-Pb zircon dating, Page 1993), in the Cloncurry-Selwyn terrain, is seen by various workers as the Corella Formation (Blake 1982, Wilson 1983, Oliver *et al.* 1990, Williams and Phillips 1992). Blake *et al.* (1984) described the Doherty Formation as predominantly thin-bedded calc-silicate granofels with massive chaotic, oligomictic and polymictic calc-silicate breccias. The breccias where thought to be possibly of sedimentary and/or tectonic origin (Glikson 1972). Williams and Phillips (1992) were the first to recognize that the breccias of the Doherty Formation were probably formed due to a large scale fluid overpressured alteration system. They reported that large volumes of rocks were affected by a "telescoped" hydrothermal system and that the Doherty Formation consists of strongly altered products of precursor rocks similar to the Corella Formation, as in the Mary Kathleen Fold Belt, and to metasediments of the Maronan supergroup. Williams and Phillips (1992) also observed that the affected area of the so called "Doherty Formation" formed a zone of brecciated and reconstituted rocks, strongly spatial associated with a major northwest-southeast trending lineament, the Cloncurry Fault. By a "telescoped" hydrothermal system, Williams and Phillips (1992) suggested that the system cooled down due to unroofing, causing

overprinting of younger and cooler alteration assemblages on the earlier older and hotter alteration assemblages (Chapter 5).

The recognition that the "Doherty Formation" is not a stratigraphic unit (senso stricto, Figure 2.1) explains much of the controversial observations previous workers reported on this unit. Although the term "formation" is not correctly used in a chronostratigraphical sense, in this study, the term "Doherty Formation" will still be used for the brecciated and alteration affected rocks, but also for the unaltered calc-silicate (Corella type) rocks. The area that is affected by this type of regional-scale brecciation and alteration is in the order of hundreds square kilometres.

Figure 2.1 - Schematic tectono-stratigraphical column for the eastern Cloncurry-Selwyn terrain. Note the diachronous nature of the Doherty Formation. FRG is Fullarton River Group, SCP is Soldiers Cap Group. Stratigraphic nomenclator after Blake *et al.* (1984) and Beardsmore *et al.* (1988). The Maramungee suite intruded pre to syn D_2, while the Williams Batholith intruded mainly syn to post D_3 (see section 2.4).

2.3 - Lithology and Distribution
2.3.1 - Rock types in areas of inferred low Fluid/Rock ratio

Areas of low fluid/rock ratios are inferred on the basis of a paucity of veining, breccias and absence of obvious alteration. These domains host the "pristine" precursor rock units of the reconstituted rocks. The rock units in those domains are laminated, strongly deformed, folded, and are characterized by low-mineral variance assemblages (Table 2.1, see also Table 5.1). Two types of banded calc-silicate units can be distinguished (CS_I-A and CS_I-B) on the basis of their mineral composition. The stratigraphic relationship between those calc-silicate units is somewhat enigmatic, due to the overprinting alteration and the spatial distribution. However, the calc-silicate unit CS_I-A lies structurally deeper in the sequence (Enclosure B), based on the main orientation of the foliation in the terrain.

Table 2.1 Approximate mineral abundances in some of the rock types and veins of the Doherty Formation.

Rock/Sample		Plagioclase				Amphibole			Scapolite												
	Qtz	And	Ol	Ab	Kfs	Hbl	Act	Di	Ma	Miz	Bt	Ms	Ep	Czo	Ttn	Cal	Ap	Chl	Mag	Hem	Sulp
PRISTINE CALC-SILICATE (CSI-A)																					
DP#44618	+		+			+		tr		++			+		tr	tr	tr		tr		
DP#44627	+	+			++	+						+			tr	tr	+	tr	+		
DP#44628	+	+			+	+					+	tr			tr	tr	tr	+	+		
DP#44629	+	+			+	++					+	tr			tr	tr	tr	tr	+		
DP#44631	+		+	+	+	+							tr	tr					tr	tr	
PRISTINE CALC-SILICATE (CSI-B)																					
DP#4634	+	++		tr	tr			++					tr		tr	tr	tr			tr	
DP#46311	+	+		tr			tr	+					tr		tr	+	tr	tr			
LESS ALTERED CALC-SILICATE (CSm-A)																					
DP#44623	tr			+++	+		+					tr				tr		tr	tr		
DP#44624			+	+	++		++								tr			tr	tr	tr	
DP#44652			+	++	+		+										tr		+	+	
DP#44654					+++		+	+			+		tr		tr		tr		tr	tr	
DP#44657	+	+			++		++	+			+		tr	tr	tr		tr		tr	tr	
ALTERED (?) CALC-SILICATE (CSm-B)																					
DP#44637	+			+	++					tr	++					tr	tr		tr		
DP#44651	+			+	+++		++			++					tr	+	tr	tr	+		
ALTERED CALC-SILICATE (MSZ) (CSh-A)																					
DP#44585	tr		+	++			++	tr			tr		tr		tr	tr			+		
DP#44586	+	+	++		+		++	++			+	tr	tr		tr	tr		tr	tr		
DP#44638			++	+			++	+			+				tr	tr			tr	tr	
DP#44639	tr			+++	+		+	tr			++	tr	tr			tr	tr		+		
DP#44590	tr		+	++			++	+							tr				tr		
PRISTINE METADOLERITE																					
DP#44593	tr		tr		tr	++		++				tr	tr		+	tr			+		
DP#44597	tr		+++			++		+							+	tr	tr				tr
DP#46334	tr			+++		+		+					+	tr	tr	tr	tr	tr	tr		
DP#46335	tr		+			++		+							tr	tr	tr	tr	+		
DP#46316			+++			+	+								tr	tr	tr	tr	tr		
DP#44615		+	+		++	+++		+											tr		tr
DP#44643	tr		++				+++				tr	tr				tr	tr	tr	+		
METADOLERITE (± SCAPOLITIZED)																					
DP#44592		+	++		+	++++			+				tr		tr				tr		
DP#44599			++			++		+	+++				tr						tr		
DP%46305				tr	tr	++		+	+++							tr	tr	tr			
DP#44675			+			++		tr	++				+	tr			tr		tr		
DP#44679						++		tr	+++							tr			tr		
DP#44625	tr	tr			+++		+++			++			+		tr	tr	tr		tr		
ALTERED METADOLERITE																					
DP#46332	tr		++				++	+				+	+	tr		tr	tr	+	tr		
DP#46315	tr		+++		tr	++									tr	+	tr		tr	tr	
46316 (Bx)	tr			++			++									+	tr		+		tr
DP#44646	tr			+		++	tr	tr					+	+		+	tr	+	+	+	
DP#44647	+	+	++			+++		++				tr				tr			tr	tr	
DP#44676	tr		++					++		tr			tr		tr	tr				+	
DP#44677																					
DP#44678			+		++	+		+++					tr		tr				tr		
VEIN at margin Metadolerite																					
DP#44598		++++			tr	++		tr	+			tr	tr	tr		tr			tr		
DP#44616		+++				+			+			+				tr					
VEIN in Altered Calc-silicate																					
DP#44636			++	++			+	+	++				+			tr			tr	+	

Note: Bx=breccia, Qtz=quartz, And=andesine, Ol=oligoclase, Ab=albite, Kfs=K-feldspar, Hbl=hornblende, Act=actinolite, Di=diopside, Ma=marialite, Miz=mizzonite, Bt=biotie, Ms=muscovite, Ep=epidote, Czo=clinozoisite, Ttn=titanite, Mag=magnetite, Cal=calcite, Chl=chlorite, Hem=hematite, Ap=apatite, Sulp=sulphides. Approximate mineral abundance: tr= < 5, 5-15=+, 15-30=++, 30-60=+++, 60-100=++++, MSZ= Maramungee Shear Zone. CSI-A refer to text.

"Pristine" Calc-Silicate Units

CS_I-A - This unit is well exposed in the western part of the Maramungee Creek section and comprises centimetre-scale bands, locally strongly deformed, with pegmatite veinlets (Figure 2.2A). These bands consists of greyish microcline-biotite-rich bands, alternating with green, coarse (0.5 to 1mm length crystals) hornblende bands and reddish feldspar (± quartz) only bands. Internally the bands are foliated due to alignment of metamorphic brown (pleochroic) biotite (overprinted by chlorite), dark green hornblende (X_{Mg} defined as Mg/Mg+Fe is ~ 0.7, Figure 2.2B), which is replaced by epidote (with an average Ps, pistacite, of 28, $100Fe^{3+}/(Al+Fe^{3+}-2)$), titanite and recrystallized quartz and microcline. Metamorphic feldspars consist of microcline (with hatch twinning) and K-feldspar (Carlsbad twinning) with myrmekite intergrowths and perthitic exsolution textures. Myrmekite textures occur frequently in the strain shadows of K-feldspar porphyroblasts. Andesine plagioclase (~40% An) is more dusted with hematite, and exhibits dynamic and static recrystallization textures. Accessory minerals are zircon, rutile, apatite calcite (with traces of Fe and Mg) and magnetite (containing 10 wt.% Ti and up to 34 wt.% Ti in exsolution lamellae, see Chapter 5). Meionitic scapolite with an equivalent anorthite percentage (Eq.An) of about 50 occurs in some layers (see also section 5.5.4). These layers are possibly metamorphosed evaporitic beds. These metamorphic scapolite crystals are deformed and slightly elongated, parallel to the main foliation (Figure 2.2C). The quartz crystals are deformed to ribbons with a strong crystallographic c-axis orientation due to intense deformation.

The pegmatite bands consist of coarse-grained microcline and quartz. The bands are half a centimetre thick with pinch and swell structures. The quartz is recrystallized, while some of the K-feldspars exhibit myrmekitiec and perthite textures. Occasionally these pegmatites cross-cut the calc-silicate banding, but are generally parallel to the banding and folded by the main D_2 deformation event (Figures 2.2A).

This laminated calc-silicate unit is locally interlayered with narrow (< 1m) beds of more micaceous schist. These narrow beds exhibit a domainal foliation and are composed of dark brown pleochroic biotite with quartz and plagioclase lithons, with traces of K-feldspar, magnetite, apatite and hornblende.

CS_I-B - Another type of banded and deformed calc-silicate rock dominates in the northern part of the studied area (Boorama Waterhole-, Mallee Gap- and Fullarton River domains). This calc-silicate unit is more fine grained, and in general also

redder, than CS_{I-A} (Figure 2.2D). The bands are also thinner than CS_{I-A} (and a few millimetres up to half a centimetre in width). There are also no pegmatites. The prograde metamorphic mineral assemblage contains green diopsidic clinopyroxene (Kd ~ 0.95, Kd=Ca/(Fe+Mg)), plagioclase (20-30 An%), traces of quartz, titanite, apatite and calcite. Secondary minerals overprinting this assemblage include epidote, traces of albite, microcline and hematite. The hematite is partitioned into the feldspars, giving them a macroscopic brick red colour (Figure 2.2E).

A pronounced red hematite alteration affects the more brittle deformed area in the north (Chapter 3), that have been altered under high fluid/rock conditions. Hematization only occurs in areas of high fluid/rock ratios in the Maramungee Creek section. Almost no hematite alteration is observed in the Boorama Waterhole area. Hematization becomes more pronounced in the Fullarton River area. This hematization, associated with red colouring, is one of the later effects of the ongoing alteration process. In this case hematite becomes stable relative to magnetite, due to unroofing which caused a decrease in temperature (and possibly minor fO_2 increase, Chapter 5).

*Pristine Psammopelitic Metasediments (**PS_I-PL_I**)*

High grade schists and gneisses of the Fullarton River Group (Beardsmore *et al.* 1988) form the base of the Maronan supergroup. Numerous pegmatite sills intruded this gneiss (Spring Creek area). Locally domains in the Doherty Formation contain pristine siliclastic metasediments. As mentioned previously, the pristine calc-silicate unit, CS_I-A, is interlayered with narrow biotite-quartz-feldspar schist. A large zone of this unaltered siliclastic metasediments occurs, interbedded with amphibolites, in the Mallee Gap area (Figure 1.9). Quartzite and quartzofeldspathic beds look similar to the ones observed in the Soldiers Cap Group in the Maronan-Fairmile area (Chapter 3 and 7) and could possibly be refractory domains.

Figure 2.2 - Rock types in areas of low fluid/rock ratio. **A**- "Pristine" calc-silicate unit, CS_I-A, deformed with pegmatite veinlets (location M157/dp#44665-6). **B**- Microphotograph of unit CS_I-A, sample DP#44628, aligned hornblende and biotite with feldspar and quartz. Field of view 0.9mm. **C**- Sample DP#44618, deformed metamorphic calcic scapolite. Field of view 0.9mm. **D**- "Pristine" calc-silicate unit, CS_I-B. Fine, folded, compositional banding, with hematite overprint (location 32.7). **E**- Microphotograph of unit CS_I-B, sample DP#46304, diopsidic pyroxene, with plagioclase and quartz overprinted by hematite. Field of view 2.6mm.

N.B. In this thesis following objects were used as size indicators on photographs: geology hammer - 40cm; bank hammer - 50cm; black pen with red tip - 20cm; compass - 10cm; photocap - 5cm; 1 dollar Australian coin - 2.3cm; 2 dollar Australian coin - 2cm; 5 cent possum Australian coin - 1.9cm.

A
pegmatite
CS$_I$-A

B
Bt
Mag
Hbl

C
Hbl
Ttn
Ca-Scp

D
CS$_I$-B

E
Hem dusted
Ab
Ttn
Di

*Marble Pods (**MB$_l$**)*

Marble units (± scapolite) are a distinct rock package in the Corella Formation (Blake *et al.* 1984). These marble units are locally outcropping in the Doherty Formation, east and west of the Cloncurry Fault. Marble pods are clustered in groups and form relatively unaltered large breccia clasts, up to tens of metres in size (Figure 1.8, Rose 1993). These pods are laminated, with calcite rich- and silicate bands, in which the calcite bands accommodated stress, by means of crystal plastic deformation (Hobbs *et al.* 1976). The silicate bands vary in thickness from centimetre up to decimetre scale and behaved competently, to produce boudinage and pinch and swell structures. This is in contrast to the calcite bands which deformed in a more ductile fashion. The overall incompetent behaviour of these marble pods, compared with surrounding calc-silicates, results in a paucity of veining and fractures.

2.3.2 - Rock types in inferred moderate zones of Fluid/Rock ratio

Areas where rocks have been altered by moderate fluid/rock ratios are those that contain sufficient veining, with selvages causing pervasive alteration adjacent to veins, but lack major breccia occurrences. These type of rocks occur at margins of high strain zones (these high strain zones acted as fluid conduits, Chapter 4 and 5), or as relict / refractory enclaves in high fluid/rock ratio zones. Three types of moderately altered calc-silicate rocks can be distinguished (mineral assemblages are tabulated in Table 5.1). These are best observed in areas such as the Maramungee Creek section and at the Boorama Waterhole (Figure 1.12, Figure 2.3 and Figure 5.1).

Moderately Altered Calc-Silicate Rocks

CS$_m$-A - The precursor of this rock unit was probably the "pristine calc-silicate" type CS$_l$-A; however, recognizable relicts of pegmatites are only locally observed. This unit consists of wispy irregular banding on millimetre to centimetre scale (Figure 2.3A and B). Actinolitic hornblende (X_{Mg} ~ 0.82), clinopyroxene (Kd ~ 0.7) and epidote (Ps ranges from 33-37) with some oligoclase-andesine plagioclase (~ 24 An%, see Appendix C) magnetite and traces of titanite and calcite are dominant in greenish grey bands. Slightly reddish bands consist of albitic plagioclase, quartz and K-feldspar with relict traces of metamorphic (chloritized) biotite (Mg/Fe ~ 0.25) and calcite. Feldspars are dusted with submicroscopic hematite. White-grey bands are more wispy in character and more fine grained than the others (Figure 2.3C). This type of band is more microcline rich with a granoblastic mineral texture. Near zones

of high fluid/rock ratio, these wispy white bands consist dominantly of granoblastic albite (5-10 An%).

Subhorizontal veining occurs regular in this rock unit and consists of mono-mineralic clinopyroxene (diopside, Kd ~ 0.87, Appendix C) or actinolite (X_{Mg} ~ 0.76) and traces of oligoclase (~ 15 An%). These diopside-dominant veins have microcline selvages (Figure 4.10, Figure 2.3D). This in contrast to veining in more intensely altered areas, where the dominant vein infill is actinolite (X_{Mg} ~ 0.81). These veins have albite (~ 5-10 An%) selvages. However, albite-quartz ± magnetite also occur as steep axial-planar type veins (see Chapter 4) in the less altered areas of this rock unit (see Figure 4.10).

CS_m-B - Inside areas of totally reconstituted rock, there are layered calc-silicate rock units which are rock buffered. Two types of weakly altered rocks have been observed: CS_m-B_i, which consists of thin units (< 30 cm) of fine grained biotite-muscovite-feldspar±quartz schist, overprinted by albite-actinolite and some microcline, and CS_m-B_{ii}, which comprise of a ten to twenty metre thick grey coloured unit of foliated fine grained biotite-microcline-plagioclase-scapolite (Eq.An ~ 40) schist (see also section 5.5.4). The latter looks similar to the thin micaceous beds (except for the presence of scapolite). On microscopic scale this micaceous calc-silicate unit shows a mineral compositional banding, with laminations rich in metamorphic scapolite (Eq. An ~ 41), and secondary microcline (Figure 2.3E). Aligned actinolite (X_{Mg} ~ 0.82) with traces of calcite is concentrated on the boundaries between those laminations. Brown pleochroic biotite and amphiboles define the foliation. The calcic scapolite is anhedral and deformed. Metamorphic microcline and adjacent plagioclase show myrmekite intergrowth. Accessory minerals are apatite, quartz, titanite, rutile, magnetite and euhedral tourmaline. Rock units in the more altered zones behave in a more competent fashion, which is indicated by boudinage (mullion type) and veining. The veinlets consist of oligoclase (~ 16 An%) and quartz with sodic scapolite (Eq.An ~ 20) selvages (Figure 2.3F).

Figure 2.3 - Rock types in moderately fluid/rock ratio zones. **A**- Wispy compositional banding, CS_m-A, cut by altered early pegmatite vein (location M145/DP#44656). **B**- Microphotograph of CS_m-A, sample DP#44654, band of coexisting actinolite and (metamorphic?) microcline, and a more albite-rich band. Field of view 0.9mm. **C**- Same unit, sample DP#44658, granoblastic microcline and albite-rich band. Field of view 0.9mm. **D**- Microphotograph of subhorizontal veins, sample DP#44657, with hematite dusted microcline selvages. Field of view 2.6mm. **E**- Microphotograph of CS_m-B, sample DP#44651, bands with metamorphic scapolite and secondary (?) microcline. Field of view 2.6mm. **F**- Oligoclase vein with marialite selvages, sample DP#44636, in unit CS_m-B. Field of view 0.9mm.

A
CS_m-A
B
Mc
Act
Ab
C
Act
Mc
Ab
D
Mc
Cpx-vein
E
Mc
Ca-Scp
F
Na-Scp
Plg-vein

CS_m-C - Several thin dark green bands (25 to 30 cm thick, Figure 4.1) were observed in the reconstituted high fluid/rock ratio high strain zone of the Maramungee Creek section, and preserved some of their primary mineral composition. Relict metamorphic minerals are strained scapolite (Eq.An ~ 40, Appendix C), chloritized brown-green ragged biotite, K-feldspar and andesine (33-36 An%). Actinolitic-hornblende (X_{Mg} ~ 0.75, Appendix C) partly defines the foliation, but also grows interstitially; and makes up approximately 40% of the rock (Figure 2.4A and B). Interstitial pure magnetite (< 1 wt.% Ti) is aligned in the dominant foliation. Other secondary minerals are microcline and epidote which is abundant and overprints the amphiboles. Accessory minerals are titanite, apatite and calcite.

Moderately Altered Siliclastic Metasediments

Quartzofeldspathic gneissic rocks of the Fullarton River Group are sheared and retrograded to muscovite-biotite-feldspar-quartz schist (**PL_m-A**), located at the Doherty Formation and the Maronan supergroup contact. Closer to the contact, the strain intensified causing isoclinal folding and transposition. Pink coloured, 2 to 5 millimetre thick en échelon aligned, sericitized oligoclase veins, with selvages consisting of coarse albite and traces of chloritized biotite laths, cross-cut the schist. Muscovite disappears in the strained transposed schist, while the laminae develops to a mineral compositional banding. Brown biotite laminations are overprinted by corundum and euhedral tourmaline, and are separated form quartz ± apatite laminations by a K-feldspar and albite corona ("altered corundum bearing schist", Figure 2.4C, the significance of corundum-bearing assemblages are discussed in section 5.2.1 "Biotite breakdown"). There are traces of relict metamorphic plagioclase (20-38 An%, Appendix C). These "altered corundum bearing schists" are observed only at the contact between the altered rocks of the Doherty Formation and the siliclastic metasediments of presumably Maronan supergroup age. This altered schist unit occurs as unbrecciated outcrops, and also as large breccia clasts (up to tens of metres). These relatively "unaltered" breccia clasts are overprinted by subhorizontal actinolite (X_{Mg} ~ 0.75) veins with a hematite dusted albite (2-14 An%) selvage.

Psammite and pelite units, siliclastic metasediments in the Mallee Gap area, occur at the contact with the more altered and brecciated rocks of the Doherty Formation. The pelitic unit (**PL_m-Ai**), looks very similar to the "altered corundum bearing schist", with transposed highly deformed biotite-oligoclase-corundum stringers, microcline-corona and quartz-laminations. However, corundum is not as abundant in

the biotite rich bands and that there are still relicts of sillimanite. The sillimanite occurs as fibrous grains in elongated deformed, possibly relict metamorphic andalusite porphyroblasts (see Chapter 3). Accessory minerals are monazite, tourmaline, magnetite and (metamorphic ?) ilmenite. The biotite (Mg/Fe ~ 0.7-0.9) is chlorine bearing (0.3 to 0.4 wt.% Cl, Appendix C). In places the biotite is retrogressed to chlorite, and the schist is overprinted by net-veining with amphibole centres and hematite albititic plagioclase dusted rims.

Laminated / banded psammite units, at Mallee Gap, consist of quartz-albite-biotite and euhedral magnetite and elongated titanium bearing magnetite (10 wt.% Ti); which is overprinted by centimetre size andalusite porphyroblasts (**PS_m**). The albite in the matrix was probably produced by alteration of metamorphic feldspars (K-feldspar and plagioclase) prior to the andalusite growth. The andalusite is restricted to replacement veins parallel to the foliation, but locally cross-cutting. The andalusite grains have a millimetre thick K-feldspar rim, with muscovite in the strain shadows. Albite veins overprint this unit (Figure 2.4D, see also Chapter 5).

2.3.3 - Rock types in inferred high Fluid/Rock ratio zones

Areas of high fluid/rock ratio are located in "narrow" (some hundred metres width) shear zones, or in variable size breccia complexes. Extensive veining cross-cuts these deformed zones and complexes (however, veins, certainly open-space infill veins are an indication of precipitation, and does not necessary have to means large amounts of fluid flow). The lithologies of both the breccias and the rocks in the deformed zones are characterized by a high variance mineral assemblage (albite-actinolite±diopside, see Table 5.1, which reflects post D_2 retrograde metamorphic conditions, Chapter 3). The eastern part of the Maramungee Creek section exposes the contact between the (unaltered) Maronan supergroup and the metasomatic rocks of the Doherty Formation. The dominant characteristics of the "early" metasomatism are alkali exchange, with structurally controlled and host rock composition depending potassium depletion and sodium addition (see Chapters 4 and 5).

Altered Laminated Calc-Silicate Rocks

CS_h-A - Deformed granofelsic calc-silicate rocks are located in major syn to late D_2 shear zones, which exhibit a variety of fold styles, with refolding of pre-existing folds, compositional banding and are cross-cut by "axial planar" type veinlets (see Chapter 4, Figure 4.10F, Enclosure C). Three types of layering are dominant and are

macroscopically easily recognized from their colour: i) light to dark green- ii) white reddish layers, and iii) greyish. Microscopically the contacts between the bands are gradual.

i) The green bands vary most in thickness, from millimetre up to half a centimetre and contain actinolite ($X_{Mg} \sim 0.83$) overprinting relict (metamorphic ?) diopsidic clinopyroxene and microcline (Figure 2.4E). The actinolite crystals are aligned parallel to the layering and are 0.2 to 0.5mm in grain size. Some are poikiloblastic with subrounded quartz inclusions. The amphiboles are generally undeformed and show weak to absent undulose extinction. This is in contrast to the strained relict overprinted clinopyroxene. These green amphibole rich bands show pinch and swell structures.

ii) White reddish laminae are only 1 to 3mm thick and exhibit complex alteration and overprinting relationships. Large poikiloblastic K-feldspar (and plagioclase) grains, locally make up the whole layer, overprinting albite (2-18 An%, Appendix C) and quartz (Figure 2.4F). These large feldspar grains are formed due to some sort of exaggerated grain growth caused by layer parallel fluid buffering. These large grains are strained with undulose extinction, interlobate grain boundaries and subgrains. The K-feldspar grains are dusted with submicroscopic hematite, sericite and calcite. The large K-feldspar grains also overprint relict clinopyroxene (Kd ~ 0.87).

iii) The third type of lamination consists of undeformed granoblastic oligoclase-albite (~10 An%, with 120° triple points) which were formed coevally with interstitial actinolite. The strain free albites are dust free and have partly replaced the margins of the large K-feldspar grains of laminations (ii). These albite grains are 0.1 to 0.3mm in size. Traces of relict brown green intergranular biotite are present.

Accessory minerals are apatite, zircon, euhedral titanite and magnetite (8 to 10 wt.% Ti), with a late epidote overprint. This unit is possible the more altered version of rock units CS_m-A, CS_m-B and CS_m-C. The laminae (i) and/or (ii) vary in thickness and occurrence can be totally absent. This variety is frequently observed in the Fullarton River area.

CS_h-B - This banded unit occurs sporadically in unbrecciated outcrops and forms large clasts in breccia complexes at the tectonic contact between the Maronan supergroup and the Doherty Formation (Enclosure B). This unit also occurs at the Boorama Waterhole locality and in the breccia complex of the Fullarton River

section. The compositional banding is very regular (few millimetres). Grass green bands consists of granoblastic clinopyroxene (diopside) overprinting an earlier albite-actinolite rock (Figure 2.5A). Albite grains are in some cases hematite dusted (Fullarton River section), but elsewhere occur hematite free (Maramungee Creek section). White to reddish bands with albite and intergranular actinolite are finer grained than actinolite free bands. Accessory minerals are anhedral apatite, epidote (Ps is 26) and euhedral titanite. Anhedral magnetite is more frequent in the actinolite-albite bands. The precursor of this type of rock unit was probably CS_l-B and/or MB_l.

CS_h-C - Another type of banded high mineral variance assemblage rock unit is located in narrow high strain zones in the vicinity of intrusive mafic bodies (Boorama Waterhole, Figure 1.11). These are probably deformed pervasive zones of veining, in which the precursor rock is totally reconstituted. This rock unit consists of white pinkish coloured and dark green to black bands. The light coloured laminations consists of large dusted albitic plagioclase grains, with localized recrystallization of dust free albite. Some albite shows twinning with "chess board" textures, due to recrystallization under continuous deformation (Figure 2.5B). The mafic bands consist of clear, weakly deformed aligned actinolite laths overgrowing the albite. The actinolite is in places overprinted by green chlorite with anomalous brown interference colours. Euhedral magnetite and traces of allanite are concentrated in the chloritic areas. Anhedral titanite grains are aligned parallel to the foliation. Locally relict, possibly feldspar porphyroblasts, are altered to albite with small stubby actinolite crystals. The foliation is defined by actinolite and albite, and locally wraps around these relict porphyroblasts.

PL_h - The alteration did not succeed in totally destroying the fabric in some metre scale clasts . This makes it possible to recognize relict textures of rock unit PL_m-A, the "altered schist" (see Figure 4.8E-F). These clasts were strongly deformed prior to brecciation and are almost mylonitic. Almost all micas are destroyed, with magnetite and titanite stringers replacing the relict "mica foliation fabric".

Figure 2.4 - Rock types in moderately fluid/rock ratio zones. **A-** Microphotograph of mafic sill, sample DP#44625, with actinolitic-hornblende and metamorphic scapolite, CS_m-C. Field of view 0.9mm. **B-** As (A), with crossed polars. **C-** Altered corundum bearing schist, sample DP#44604, PL_l-A, with biotite-corundum clusters, feldspar corona and quartz laminations. Field of view 0.9mm. **D-** Altered psammite, PS_m, with quartz-biotite±albite bands. Overprinted by andalusite with K-feldspar rims, cut by albite veins. Location MG1/DP#46329. **E-** Microphotograph of sample DP#44586, actinolite overprinting clinopyroxene (or coeval?). Field of view 0.9mm. **F-** Sample DP#44682, large poikiloblastic K-feldspar. Field of view 2.6mm.

A
Act
Ca-Scp
B
Act
Ca-Scp
C
Crd
Bt
Ab
Qtz
D
And
Kfs
Ab
E
Di
Act
F
Act
Kfs
Di

Relicts of chloritized biotites are locally present. Relict feldspar porphyroblasts are sericitized and elongated. Numerous neo-formed grains of albitic plagioclase with subgrains and granoblastic textures overprint the mylonitic foliation. Chloritized actinolite is locally present in the foliation. Accessory minerals are euhedral apatite and traces of calcite.

Brecciated Rocks

Breccias forms one of the major rock types in the Doherty Formation (see section 4.4). These breccias were formed in almost all stages of the metasomatic history of this terrain, from the early ductile-brittle metasomatic event (narrow breccia zones), to the later megabreccia complex overprinting parts of the Williams Batholith. Jig - saw fracturing and crackle / net veining are some of the evidence that the breccias were formed by fluid hydro-fracturing. Clast size varies from millimetre scale up to tens of metres. Smaller clasts are totally reconstituted to albite, actinolite or clinopyroxene, in contrast to larger clasts, which preserve precursor rock mineralogy and fabrics. Six types of breccias have been discriminated, based on the clast and matrix mineralogy and fabric, structural setting and general morphology (see Chapter 4). However, at this stage they are described in two groups discriminated by their brittle-ductile versus brittle structural setting.

Bx-A - Brecciation related to a brittle-ductile environment is located in shear zones (vein-jog breccias). These are narrow breccia zones, discordant to subparallel to the main foliation (Figure 2.5C, see Figures 4.10H-I-J). The petrology of the breccias in the shear zones is relatively monotonous, compared with the host rocks. The main matrix minerals are tremolitic actinolite (X_{Mg} ~ 0.80-0.85, see Appendix C) with some albite-oligoclase (~ 6-8 An%), and an actinolite/albite ratio in the matrix varying from 0.7-0.9. Matrix amphibole grains are up to 2mm long, and roughly aligned with the external layering. Clasts are in places elongated and ductiley deformed, consisting solely of albitic plagioclase. Larger clasts are hematite dusted, and relict host rock fabrics are locally preserved. However, smaller clasts comprise granoblastic dust-free albite crystals. Traces of apatite are only observed in the clasts. Large rare euhedral titanite grains are concentrated in the matrix. Hematite dusted coarse albite, with traces of calcite, occurs at the margins of these narrow breccia zones.

Bx-B - This type of chaotic megabreccia is more widespread in the northern part of the studied area, and easier to recognize in vegetation overgrown outcrops, because of the variable matrix supported clast size and resistance to weathering. Clasts vary from less than a centimetre to tens of metres across. Larger clasts appear not to have

moved far from their prebrecciation position. Their composition depends, of course, on the host rock. Previously deformed metasomatic rocks and granites are generally altered to albite rich clasts while clasts of mafic rocks are altered to diopside clinopyroxene and/or actinolite. Occurrences of prebrecciation and metasomatized folded and foliated clasts indicate this megabrecciation happened post peak deformation and metamorphism (Figure 2.5D).

As in the above breccia unit Bx-A, macroscopically sharp clast-matrix contacts are microscopically vague. These pinkish-green coloured matrix is generally not foliated and has a "pseudo-igneous" texture (Figure 2.5E), similar to a very coarse unfoliated gabbro or diorite, and the matrix consists of various ratios of subhedral laths of albite, and subhedral to euhedral stubby crystals of clinopyroxene and/or actinolite. The ratio between the mafic and felsic matrix minerals varies considerably, from an almost pure mafic matrix to a felsic matrix (Figure 2.5F). Small subrounded cavities are occasionally observed, with inward growing albite and a centre of calcite ($Cal_{93.6}Mgs_{3.1}Rhs_{0.6}Sid_{2.6}$), overgrown by acicular iron rich actinolite ($X_{Mg} \sim 0.62$-0.73), with rims of more tremolitic amphibole ($X_{Mg} \sim 0.92$, Appendix C). The matrix of the Mount Philip Breccia, near the Pilgrim Fault (Blake *et al.* 1982) is very similar to the breccias observed in this study. The breccia matrix consists of stubby tremolite in a albite groundmass with small cavities. Blake *et al.* (1982) interpreted these textures as a result of a high-level felsic or mafic intrusion, with crystallization from a melt. However, these breccias are most likely formed due to high fluid pressures (Chapter 4 and 5). This breccia unit, at the Fullarton River Gorge, is locally cut by prehnite-calcite rich veins.

2.4 - Intrusive Phases

The Cloncurry-Selwyn terrain is dominated by a large (mostly) unfoliated and unmetamorphosed granite complex, the Williams Batholith, with an outcrop area of approximately 2100 square kilometres (Wyborn *et al.* 1988). However, smaller foliated, and locally altered, granitic bodies (dykes and sills) occur in the adjacent metasedimentary rocks of the Corella / Doherty Formation and Maronan supergroup.

Figure 2.5 - Highly altered and brecciated rocks. **A-** Less hematite altered CSh-B, sample DP#44654, from Maramungee Creek section. Early actinolite overprinted by diopside. Field of view 0.9mm. **B-** New growth and subgrains formed during deformation, causing "chess" board texture, CS_h-C, sample DP#46320. Field of view 0.9mm. Breccias in the Doherty Formation. **C-** Vein jog type breccia, in the high strain zone at Maramungee Creek. Field of view 70cm. **D-** Totally reconstituted and brecciated altered schist (PL_h), with feldspars replaced by albite, micas altered to albite, magnetite and titanite. Field of view 35cm, location 40.2/DP#46308) **E-** Pseudo-igneous matrix texture. Location 47.2. **F-** Albite dominated matrix, with clasts altered to albite (schist precursor) and clinopyroxene (metadolerite precursor). Note the numerous cavities, possibly formed due to devolatization (Fullarton River gorge).

A
Di
Act
B
chess-board
Plg
Chl
C
Vjb
D
relict foliation
clast
E
clast
F
relict foliation

Both concordant and discordant intrusions with the main fabric occur in the eastern Cloncurry-Selwyn terrain. This relationship has some implications on the depth of emplacement. Higher in the crust rocks react in a more brittle fashion to an implied stress field, causing fractures and discordant intrusions (Philpotts 1990). At depth, fracturing is less abundant, due to the higher confining pressure, and the ability of rocks to behave in a ductile fashion. Compositional banding and foliations, in a ductile environment, are planes of weakness; hence, if there is an excess fluid / magma pressure, fracturing will exploit such planes (perpendicular to the direction of minimum principal stress, Pollard 1973).

2.4.1 - Felsic Intrusive Rocks

Maramungee Suite Granites (intruded pre to syn D_2)

The early trondhjemitic granite suites, are characterized by a low K/Na ratio (Williams 1992), and are D_2 folded sill like bodies (Figure 2.6A). These bodies occur in all sizes, from metres upto hundreds of metres thickness. The majority of the small scale granite sills are emplaced in the least (CS_l-A) to moderately (CS_m-A) altered calc-silicate rocks of the Doherty Formation, while larger scale bodies are emplaced in the stratigraphically lower part of the Maronan supergroup. Age dating on the Maramungee granite, and granitic gneiss near Boorama tank, using the U-Pb SHRIMP technique, resulted in ages of 1530-1545 Ma (R. Page and S. Sun pers. com. 1996). Volumetrically this granite suite makes up as much as 10% of the outcrops in those rock units.

Thin pink granite sheets are intruded parallel to banding of the surrounding calc-silicate rocks. These granites have a porphyritic and mylonitic textures and are tightly to isoclinally folded by D_2. This indicates that these granite sheets intruded prior to D_2 and were possibly emplaced syn D_1. It is possible that the mylonitic fabric developed due to the D_1 compressional thrusting (Chapter 3). These mylonitic, porphyritic granite sheets consist of quartz ribbons with a strong crystallographic orientation, which bend around rigid K-feldspar and plagioclase porphyroclasts. Traces of magnetite (with ilmenite exsolutions) and rutile are present. Symmetrical pressure shadows are commonly developed around the rigid porphyroblasts, filled with fine grained dynamically recrystallized quartz (Figure 2.6B), plagioclase and microcline and traces of chloritized biotite "fish".

Thick white granite sills are in general only weakly foliated and do not have the strong mylonitic fabric of the thin pink granite sheets (except the ones located in post

D_2 high strain zones). These sills are open to tight folded by D_2 (Enclosure B) and were probably emplaced early to syn D_2. They consist of plagioclase, K-feldspar with myrmekite intergrowths, occasionally perthitic microcline, quartz and traces of biotite and hornblende. Graphic textures of (intergrown quartz and feldspar) indicate that crystallization occurred close to the eutectic point of the melt.

Felsic porphyries (which are possibly similar to the trondhjemites) occur in the southern part of the Eastern Cloncurry-Selwyn terrain. Quartz porphyries have been dated at 1720 ± 7 Ma (Page 1983), and consist mainly of quartz and plagioclase, with traces of amphibole. Only a few small, metre scale, possibly similar porphyry outcrops were observed in the Maramungee Creek section (Enclosure B).

Williams Batholith Suite (intruded syn to post D_3)

The unfoliated Williams Batholith is a series of granite plutons, which intruded after the main "Isan Orogeny" at about 1510 to 1480 Ma (Page 1993). The Squirrel Hills granite, at the western margin of the studied area, has the largest volume. Smaller plutons with roughly elongated shapes occur in the northern part of the studied area, respectively east and west of the Cloncurry Fault, the Saxby granite and the Mount Angelay granite (Figures 1.7, 1.9, 1.10 and 1.11). These plutons are spatially and temporally associated with the extensive brecciation and alteration of the country rock (Figure 1.8). In places the granites are veined, brecciated and overprinted by albite, and later K-feldspar and/or hematite alteration.

The Squirrel Hills and Mount Angelay granites intruded into predominantly calc-silicate country rock, while the main body of the Saxby granite intruded the Maronan supergroup. The occurrence of local miarolitic cavities and grain size difference between the margins and the centre indicate that some of the granites intruded at shallow (possibly between 1 to 3km depth) crustal levels. However, Mitchell (1993) reported narrow (metre width) contact aureoles with a higher abundance of andalusite ± sillimanite and local hornfels cordierite bearing around parts of the Saxby granite. This could indicate that the granite was emplaced rapidly, or that

Figure 2.6 - Felsic rocks from the eastern Cloncurry-Selwyn terrain. **A**- Tightly folded trondhjemitic, porphyritic granite sheet (Maramungee Creek, Field of view 4m). **B**- Microphotograph of the porphyritic granite, sample DP#44619. Field of view 0.8mm. **C**- Miarolitic cavities in fine grained leuco Saxby granite (Fullarton river area). **D**- Reconstituted, albitized granite, DP#4615 (Mallee Gap area). Net-veined complex at the Boorama Waterhole. **E**- Close-up of strongly deformed granite veins. **F**- Felsic net-vein intrusion into metadolerite, both are foliated. However, in the Spring Creek area unfoliated metadolerite intruded into foliated granite (Figure 1.10).

A

B

C
cavity

D
Hem
Act
Ab

E

F

the temperatures of the country rock was close to that of the granite at the time of emplacement, which contradicts with the "high" crustal intrusion. New observations in the granites indicate a complex intrusion history, with emplacement at 5 kbar (G. Mark, pers. com. 1995). The whole suite is characterized by high levels of Na, F, P, U and Th, which makes them high heat producing granites (Wyborn *et al.* 1988).

Heterogeneities within the Mount Angelay granite and also the Saxby granite are due to fractional crystallization (Mitchell 1993). The main Mount Angelay Granite in the Mallee Gap area is a pink-green coarse grained hornblende, two feldspar granite, with microcline and perthite, plagioclase and quartz as the main constituents. Accessory minerals are biotite, magnetite, titanite and fluorite. There are a few miarolitic cavities filled with chlorite. The mineral assemblages, and the abundance of hornblende suggest that the Mount Angelay granite is an I-type granite. A granite body at the margin of the main Mount Angelay body consists of a white, coarser grained two feldspar granite with less hornblende (Figure 1.9). This granite contains zoned plagioclase, K-feldspar with myrmekite, quartz and traces of titanite ± hornblende.

The southern plutons of the Saxby granite crop out in the Fullarton River area as numerous small-scale fine grained, non to weakly foliated leucogranite bodies, with local miarolitic cavities (Figure 2.6C). Larger scale intrusive bodies are coarse grained and contains quartz, plagioclase, microcline with traces of magnetite, titanite, zircon and hornblende.

Altered granites

In the previous section it was mentioned that brecciation and associated alteration overprinted margins of the Williams Batholith. Some of the early trondhjemitic granites are totally reconstituted to albite rocks with the fabric, in most cases, totally destroyed (Williams and Phillips 1992). Reconstitution of parts of the Mount Angelay and Saxby granites is generally associated with the younger brecciation and veining event. These altered granites occur adjacent to, and are cut by the Cloncurry Fault. Macroscopically they are white, containing very fine grained albite, with occasional relicts of igneous feldspars (K-feldspar and plagioclase) and traces of titanite, actinolite, magnetite and calcite (Figure 2.6D). In places these granites are fractured with K-feldspar and hematite infill.

2.4.2 - Mafic Intrusive Rocks

Mafic bodies such as metadolerites and metabasalts make up of about 10% of the rock volume in the investigated area. Amphibolites interlayered with metasediments have a strong foliation and undergone the same deformation history as the country rocks. The Doherty Formation contains concordant mafic sills exposed in the southern part of the studied area. These sills vary in size, from 1-100m wide and 100-1000m long.

Large mafic-felsic net-veined complexes occur in the central part of the studied area, the Boorama Waterhole and Spring Creek (hundred of metre scale, Figure 1.10) areas. These complexes consist of two main intrusive phases of mafic and felsic composition (Figure 2.6E). Net-veined complexes occur at the contact between mafic and felsic intrusions and are a result of magma or melt mingling, at a relatively high crustal level. Blake (1981) interpreted the intrusion of the granitic-dolerite net-veined complex at the Boorama Waterhole as mafic rocks being younger or of similar age than the felsic rocks. Subrounded mafic inclusions in a felsic matrix, at the contacts, were interpreted as due to intrusion into felsic granitic magma (Figure 2.6F).

"Pristine" metadolerites

Metadolerites, in the Doherty Formation, intruded in two stages, based on their field relationships, deformation and metamorphism. Earlier stage metadolerites intruded prior to the main D_2 deformation and are affected by the dominant sodium (calcium) alteration phase. These earlier metadolerites consist of > 80%, medium to coarse grained green hornblende ($X_{Mg} \sim 0.62$, with traces of chlorine, 0.2 to 0.5 wt.%, Appendix C), with albitic to oligoclase plagioclase (Figure 2.7A). In the centre of large metadolerite bodies, diopsidic clinopyroxene (Kd ~ 0.89) is replaced with rims of green pleochroic hornblende, coexisting with oligoclase (Table 2.2, E3 of Ellis and Wyborn 1984). Plagioclase exhibits a poikiloblastic texture with quartz inclusions. Both euhedral and anhedral titanite is present. Segregation with titanite rich bands are observed in narrow metadolerite dykes which are intensely foliated located in high strain zones. Locally, magnetite is overgrown by anhedral titanite. The second stage of unmetamorphosed dolerite intruded on east-west, kilometre scale length, fractures (E4 type of Ellis and Wyborn 1984).

Table 2.2 - Summary of description of metadolerites of the eastern Cloncurry-Selwyn terrain after Ellis and Wyborn (1984).

Type	Description	Possible equivalent
E2	Large dyke, 12km by 15m, subparallel to the main foliation. Metamorphosed to amphibolite facies grade, with local relict ophitic texture. Composed of hornblende (overprinting actinolite), plagioclase, titanomagnetite, locally replaced by titanite, diopside, quartz and minor biotite, epidote and scapolite. Metasomatized to scapolite and biotite.	Altered metadolerite
E3	Irregular dykes, sills and plugs (1738±4 Ma, Page 1983, Lunch Creek Gabbro, Mary Kathleen Group). Relict igneous clinopyroxene and plagioclase, weakly affected by regional metamorphism. Other major constituents are quartz, hornblende, cummingtonite, actinolite, titanite and magnetite.	Pristine metadolerite
E4	Cross-cutting all regional structures and are unmetamorphosed (cut the Williams Batholith). Fine grained groundmass of plagioclase, pyroxene and magnetite. Lakeview Dolerite dated at 116±12 Ma (Page 1983).	E-W trending dolerite

Altered metadolerite

Superimposing a stress field on large metadolerite bodies, would cause those bodies to act in a rigid and competent fashion (Oliver *et al.* 1987, 1990), resulting in microfracturing and veining. Crackle / net-veining occur at the margins of the metadolerite bodies. These veins consist of large fractured andesine (~ 30-35 An%) crystals with clusters of hornblende (X_{Mg} ~ 45, Figure 2.7B). The fractures are filled with sodium rich scapolite (~ 30 Eq. An, Figure 2.7C). Smaller metadolerite bodies are totally reconstituted to actinolite and/or scapolite ± diopside (Figure 2.7D, type E2 of Ellis and Wyborn 1984, see also sections 5.5.4 and 5.5.4.2). Oliver and Wall (1987) noted that scapolite alteration of metadolerites resulted in a 20% volume loss. Granoblastic chlorine bearing scapolite (~ 20 Eq.An) can make up to 40% of the altered metadolerite and is an indication that the fluids that affecting the rocks were hypersaline (Oliver *et al.* 1990). Veining parallel to the foliation occurs in the central part of the metadolerite bodies. These veins consists of albite centres with recrystallized coarse hornblende selvages. Apart form being scapolitized, metadolerite bodies are locally also overprinted by later stages of epidote- and hematite dusted K-feldspar-alteration (Chapter 5).

Large foliated metadolerite clasts in the Fullarton River gorge were crackle veined prior the megabrecciation (Figure 2.7E, Figure 4.16, see Chapter 4). These veins overprint the metadolerite clasts and consist of albite with epidote-albite selvages. Late stage megabrecciation caused shattering of the clasts, resulting in angular fragments. The infill matrix consists of albite, iron-magnesium bearing calcite and clusters of acicular actinolite/tremolite (Figure 2.7E and F).

2.4.2.1 - Geochemistry of the metadolerites

Metadolerites from the Doherty Formation in the Maramungee Creek section, were analysed by X-ray fluorescence and NAA methods (Appendix D). The objective was to determine their tectomagmatic environment and to establish the behaviour of the elements, by comparing "pristine" and "altered" metadolerites.

Most of the "pristine" metadolerite rocks contain less than 52.5 wt.% SiO_2, and are therefore of basaltic (and tholeiitic) composition. This is in contrast to altered metadolerites which have high silica content (Appendix D). The iron content is high (ranging from ~ 5-15 wt.% Fe_2O_3t), with $Fe^{3+}/Fe^{2+}>1$. Commonly used elements for characterizing the different magma types and tectomagmatic environments are Ti, Zr, Y, and Nb (Meschede 1986). This because the ratios and concentrations of these elements are highly variable between different magma types. These elements are commonly acting in an immobile fashion. It is therefor argued that discrimination diagrams based on analyses of modern-day basalts can be used for ancient metabasalts. The Maramungee Creek metadolerites exhibit little variation in the Zr/Nb ratio (~11). Y/Nb ratios are also fairly constant (~2-3). Correlations are found for other incompatible trace element pairs, such as a weak negative correlation between Ti and Cr and a positive correlation of Ti and Zr with a Ti/Zr ratio of approximately ~ 95 (Figure 2.8). Constant element ratios indicate that these elements behaved in a coherent fashion, and that the metadolerites are possibly related to a common source. The distribution coefficients for example of Nb and Zr are both very low in mineral phases in equilibrium with a (tholeiitic) magma and the Zr/Nb ratio therefore will remain constant during fractionation.

Elements that are strongly concentrated in the liquid phase during partial melting or fractional crystallization are called incompatible (but many of these are mobile during alteration). They are called incompatible because these elements cannot substitute into the crystal structure of early-crystallized minerals, due to a high ionic charge and/or large ionic-radius (Meschede 1986). Generally, elements such as K, Rb, Cs, Sr, Ba and U, are strongly mobile. Relatively immobile elements are the

Figure 2.7 - Photographs of metadolerite textures. **A**- Microphotograph of "pristine" metadolerite (sample DP#44597). Relict diopside replaced by hornblende, with oligoclase and titanite with magnetite rims. Field of view 0.8mm. **B**- Sample DP#44598. Sheared andesine-hornblende-scapolite veins at margins of sheared metadolerite. **C**- Microphotograph of the vein. Sodic scapolite in fractured andesine. Field of view 0.9mm. **D**- Altered metadolerite with granoblastic sodic scapolite, actinolite ± diopside and albite (sample DP#44675, Field of view 0.9mm.). The above samples are from the Maramungee Creek section. **E**- Late stage brecciation in the Fullarton River section. Rounded pre brecciation veined metadolerite clasts in albite and acicular actinolite matrix with Fe-Mg calcite overprint. **F**- Microphotograph of the acicular actinolite with albite and calcite (sample DP#46316, Field of view 0.35mm).

A
Hbl
Di
B
Hbl
Na-Scp
An
C
An
Na-Scp
D
Na-Scp
Act
E
F
Act
Cal

incompatible rare earth elements (REE) and high field strength elements (HFSE), such as Ti, V, Nb, Zr, Hf, Th and Y. Geochemically immobile, incompatible and compatible elements are the basis for discrimination diagrams. Empirical diagrams, based on analyses from basaltic rock suites from specific plate-tectonic environments, have been constructed by workers such as Floyd and Winchester (1978), Winchester and Floyd (1976, 1977), Pearce and Cann (1973), Pearce *et al.* (1977) and Meschede (1986). Plate-tectonic environments are broadly divided into four subgroups 1) diverging plate margins, which result in eruption of mid-ocean ridge basalts (MORB), 2) converging plate margins with intrusions of volcanic-arc basalts, 3) within plate oceanic crust environment, with ocean island basalts and 4) within plate continental crust environment intruded by continental basalts (Pearce and Cann 1973). Differentiation of the "parent" magma is generally divided into three general groups, the tholeiitic, calc-alkaline and alkaline series.

The immobility of incompatible elements has first to be demonstrated before being able to use the discrimination diagrams. In order to establish immobility, HFSE are plotted in inter-variation diagrams (Figures 2.8 and 2.9). These diagrams illustrate, in most cases, a tight inter-relationship between the "pristine" metadolerites, while the "altered" metadolerites a more scattering exhibit. Strong intra-correlations, with minimal scattering, for both the "pristine" and "altered" metadolerites, are observed in combinations of Nb-Zr-Y plots. Ti and V are also relatively immobile, however mobility is apperent in the "altered" metadolerites.

The unaltered metadolerites are tightly clustered in a Nb-Zr-Y discrimination plot (Figure 2.10). Except for some of the "altered" metadolerites (and sample M5, DP#44588), the analyses are plotted in field B, a MORB "plume" setting. Also a Zr/Nb ratio smaller than chondritite (i.e. less than Zr/Nb=16) is typical for a plume type MORB or WPT setting. Y/Nb ratio larger than 1.0 are characteristic for a tholeiitic MORB setting, which reconfirms the plate-tectonic setting of the mafics in the Maramungee Creek section (Ellis and Wyborn (1984) classified the mafic intrusions of the eastern part of the Cloncurry-Selwyn terrain as continental tholeiites suite emplaced in an intracontinental rifting setting). In general, a "plume" type MORB setting is geochemical characterized by enrichment in incompatible elements (e.g., Rb, Nb, Th, K and light REE, Meschede 1986). This fits well with the distribution of the rare earth elements in "pristine" metadolerites, which have normalized chondrite topologies with elevated light REE values (Chapter 5).

Figure 2.8 - Inter-element biplots between Ti-Y-Zr-V HFSE, from 9 metadolerite bodies from the Maramungee Creek. Strong positive correlation exist between Zr-Y, for both the "pristine" and "altered" metadolerites, slightly less for Y-TiO_2, V-TiO_2 and V-Y. A strong positive correlation only exists for the "pristine" metadolerites in the TiO_2-Zr and Zr-V biplots, while the "altered" metadolerites are scattered. Sample M5 is DP#44588.

In short, metadolerites in the Maramungee Creek section, are of high iron tholeiitic composition and are possibly metamorphosed metabasalts intruded in a continental setting, based on discrimination diagrams using immobile and incompatible elements, such as Nb, Zr and Y. All metadolerites are possibly derived from the same source. Post metamorphic alteration stages effected the metadolerites, causing K depletion and Na enrichment (subsequent potassium alteration causes local K increase, Chapter 5), and mobility of almost all elements.

Figure 2.9 - Inter-elements biplots between the Nb-Zr-Y-V-Ti HFSE. Zr-Nb exhibits a good positive correlation, while Y-Nb exhibits a clustering. Biplots from Nb versus TiO_2 and V, illustrates a strong positive correlation for the "pristine" metadolerites, but a slight scattering for the "altered" metadolerites. Sample M5 is DP#44588.

2.5 - Summary

Lithologies encountered in the eastern Cloncurry-Selwyn terrain are amphibolite facies grade metasediments, including psammite, pelites, calc-silicates, carbonates, together with mafic and felsic intrusive phases .

The gneisses and schists of the Maronan supergroup, overlie (structurally, and stratigraphically) the metamorphosed calc-silicate, equivalent to Corella type, Doherty Formation rocks.

The "Doherty Formation" (Blake 1984) consists of rocks that are diachronous and affected by a regional-scale alteration and brecciation event, over an area of approximately hundred square kilometres (JCU Cloncurry Mapping Project 1990-1994). This alteration affected all rock units and caused high variance mineral assemblages (see also Chapter 5).

Figure 2.10 - Zr-Y-Nb relationships for the mafic suites in the Maramungee Creek section. Diagram after Meschede (1986). Tholeiitic mafics bodies plot in a continental within plate or mid ocean ridge plume type setting. Sample M5 is DP#44588. The use and interpretation of discrimination diagrams constructed from modern volcanic rocks, postulating a Proterozoic tectonic setting, must be done with caution. To eliminate spurious results a suite of samples must be used instead of a single samples. Samples analysed: "pristine" metadolerites N=16, "altered" metadolerites N=6.

The inhomogenities of alteration and brecciation in calc-silicate rocks are related to areas of low-, moderate-, or high fluid/rock ratios. Areas of low fluid/rock ratios contain the "pristine" rock units, which consists of hornblende, biotite, quartz,

feldspar, diopside and scapolite-bearing assemblages, marbles and biotite, quartz, feldspar schist and psammites.

Rocks unaffected by alteration which occur within the zones of moderately fluid/rock ratios, have similar compositions as rocks in the low fluid/rock ratio areas. Rocks affected by alteration in the moderately fluid/rock ratio areas, are overprinted by microcline ± diopside ± actinolite (and locally albite).

Areas of high fluid/rock ratio are of two types: 1) shear zones containing reconstituted rocks, consisting of actinolite and albite and 2) brittle megabreccia complexes, with generally matrix-supported altered clasts and pseudo-igneous textured matrix. The brecciation also affect the earlier alteration.

Different stages of felsic intrusions occur in the eastern part of the Cloncurry-Selwyn terrain. Early intruded granites (pre to syn D_2) include mylonitic porphyritic granite sheets and sills, of trondhjemitic composition (Maramungee suite). The late dominant felsic intrusion phase (syn to post D_3) contains a hornblende two feldspar granite (I-type) of the Williams Batholith. Local occurrences of miarolitic cavities and grain size differences between margin and centre, indicate that some of the granites intruded high in the crust.

Mafic intrusions contains "pristine" metadolerites consisting of hornblende, diopside, oligoclase, magnetite and titanite, while "altered" metadolerites are overprinted by scapolite and albite ± actinolite, and later by microcline and epidote. Metadolerites in the Doherty Formation are derived from rocks intruded in a continental within plate or "plume" mantle MORB setting. This is based on discrimination diagrams using the immobile and incompatible Nb-Zr-Y and partly immobile Ti and V elements.

Metadolerite sills are dominant in the southern part of the studied area, indicating emplacement in a ductile, deeper crustal level. Further north, mafic and felsic rocks intrude in a net-veined type complex.

CHAPTER 3

CHAPTER 3 - STRUCTURAL SETTING and METAMORPHISM

3.1 - Introduction

The eastern Cloncurry-Selwyn terrain has undergone several deformation events and associated metamorphism. The general characteristic of the main regional deformation phase is a pervasive north-south trending S_2 (Loosveld 1989a and b, Beardsmore *et al.* 1988, Oliver *et al.* 1990, Reinhardt and Rubenach 1989). Prograde regional metamorphism in the Cloncurry-Selwyn terrain reached the upper amphibolite facies (sillimanite - K-feldspar). According to Jaques *et al.* (1982), this took place during D_1 deformation, which is equal to the D_2 in this thesis. Other workers also suggested that peak metamorphism in the Mount Isa Inlier happened during D_2 (Beardsmore *et al.* 1987, Reinhardt and Rubenach 1987).

This chapter will try to explain the regional structural setting, and the relationships with the metamorphic events. A structural setting of the studied area and associated maps are already briefly discussed in Chapter 1 and are tabulated in Table 3.1. The first part of this chapter deals with the regional structures (section 3.2), while the second part describes the structures in the Maronan supergroup (section 3.3). The third part covers the deformation phases in the Doherty Formation (section 3.4). The fourth part (section 3.5) describes the metamorphic events and the relationship with deformation.

3.2 - Regional Structural Setting

Multiple deformation phases affected the eastern part of the Cloncurry-Selwyn terrain. This is manifested in overprinting relationships such as refolded folds, crenulations, rotation of lineations and development of high strain zones, in which the latter caused juxtaposition of rocks with different metamorphic grades (Figure 3.1). The regional deformation phase, D_2 is an upright N-S to NW-SE trending "tight" to "close" asymmetrical west-verging fold style and is pervasive throughout the region. The original orientation of D_1 is obscured by D_2. D_2 tight folding causes reorientation of the S_1 fabric approximately parallel to S_2 (see section 1.4.2.2). Refolded folds are observed at all scales, from regional to microscopical (Figure 3.2). Overprinting relationships are commonly observed between S_1-S_2 fabrics, causing crenulations in the metasedimentary schistose rocks and tight folding of

mylonitic granite sheets. Regional D_3 interference patterns are observed in the Maronan-Fairmile area (Enclosure A: Geology map Maronan-Fairmile area).

High strain zones occur in the limb regions of regional D_2 folds (Figure 3.3), which was also noted by Loosveld and Schreurs (1987). Stratigraphical repetition and a persistent concordant orientation of the foliation over large areas in combination with foliation parallel faults are characteristic for thrust terrains (Elliot and Johnson 1971, Ramberg 1977, Butler 1982, Loosveld and Schreurs 1987). Enclaves of andalusite-bearing lower amphibolite grade mica schist in sillimanite-bearing schist and amphibolite grade calc-silicate rocks (Figure 1.9), located at approximately six kilometres to the west of the main psammopelitic / calc-silicate contact, would suggest a large scale recumbent nappe folding or a large anticline. However, large thin thrust sheets cannot be moved by a subhorizontal σ_1 stress direction only, this because of the high stresses necessary to overcome the friction at the base of such a thrust nappe (Ramberg 1977). However, high fluid pressures along the base of a thrust sheet can reduce the frictional effects caused by gravity.

Table 3.1 - Geological evolution of the eastern Cloncurry-Selwyn terrain, north Australia.

Phase	Age Ma	Structural Events	Geological Events
early D_1 (D_{e1-3})	1777-1670	Extension with E-W low angle faults.	Concordant trondhjemitic granite intrusions. Onset of the Cloncurry Fault?
late D_1 (D_{c1}	1620	Compression, resulting in thrust-nappe structures, with partly overturned stratigraphy and moderately dipping S_1 axial-plane cleavage.	Prograde metamorphism, reaching lower amphibolite facies grade. Possibly concordant pegmatite and mafic intrusions, with some albite veining.
D_2 (D_{c2})	1580±17	Main homogeneous ductile deformation event with upright to slightly inclined S_2 axial-planes. Moderately north and south plunging l_2^1.	Peak metamorphism, reaching upper amphibolite grade (intrusion of the Maramungee suite 1530-1545 Ma*). Expulsion of metamorphic fluids.
early post D_2	?	Reactivated D_1 faults? Non-coaxial ductile shearing in D_2 limb regions with possible sinistral movement and $\gamma > 10$. Causing refolded folds, sheath folds and juxtaposing rocks of different metamorphic grade.	Introduction of hot saline fluids causes channelized sodic-calcic alteration, with a retrogressive mineral assemblage (oligoclase and Act).
late post D_2	?	Tabular brittle-ductile shear zones with dextral movement, reactivating earlier ductile shear zones	Numerous axial-planer and subhorizontal type extensional veins. With dilational breccia jogs and Ab and Act as the stable mineral phases. Onset of unroofing, causing an increase in fluid pressure, resulting in megabrecciation.
D_3 (D_{c3+})	1510-1480	Locally developed NE-SW trending folds, with steep plunging fold axis, in the micaceous rocks. S_3 developed as a spaced cleavage in calc-silicate rocks.	Onset of discordant large scale granite intrusions and pegmatite dykes (Williams Batholith*). Ongoing brittle deformation, with mega-brecciation and partly affecting the granites. Cpx and Cal becoming more stable.
post D_3	?	Brittle sinistral movement on the Cloncurry fault with Riedel fractures affecting the granites.	Continuous unroofing, resulting in a change in mineral stability, with silica and Kfs as the stable mineral phases.
D_4	?	Brittle E-W fracturing, causing regional scale deflections in earlier fabrics.	Intrusions of non metamorphosed E-W trending dolerite dykes.

N.B. Ab is albite; Act is actinolite; Cpx is clinopyroxene; Cal is calcite. Deformation phases in parenthesis after Loosveld (1989a). Geochronological data after Page and Bell (1986), Pearson (1992), Page (1994). * Pers. com R. Page and S. Sun 1996.

Figure 3.1 - Schematic sections drawn across the eastern part of the Cloncurry-Selwyn terrain, from profile lines in Figure 3.7. Vertical scale is exaggerated. Foliations drawn are bedding parallel to S_1. Note in profile 1 the reverse younging direction (arrows) and the "jump" in metamorphic grade. The same metamorphic discontinuity is apparent in profile 2; in which gneissic sillimanite-K-feldspar amphibolite grade rocks are juxtaposed by andalusite amphibolite grade mica schist rocks. Post D_2 shear zones causes sillimanite grade synform to be thrusted in lower grade rocks. Profile 3 coincides with the Maramungee Creek section, for a detailed profile section see Enclosure B: "Geology of the Maramungee Creek". Black triangles are breccia zones; Sil is sillimanite; And is andalusite; Kfs is K-feldspar; CCYF is the Cloncurry fault.

Many high-grade metamorphic terrains are cross-cut by retrogressive shear zones. Large chemical changes of bulk composition of the shear zone rocks compared to the unsheared host rocks, could imply large amounts of fluid infiltration (Ferry 1984, Kerrich 1986). Enrichment in potassium and silica (alkali metasomatism with silicification) is a common alteration characteristic in shear zones (Newton 1990, Selverstone *et al.* 1991). This is manifested by the presence of a dominant muscovite mineral phase, such as in the post D_2 shear zones in the Maronan supergroup. In near surface regimes, shear zones commonly occur in multiple en échelon arrays and anastomose. The width of the shear zones can roughly be correlated to the metamorphic grade. With depth and under greenschist metamorphic conditions these zones widen to hundred of metres to a few kilometres (Korstgård *et al.* 1984). In granulite grade facies rocks, shear zones could widen up to 15-30 kilometres. The shear zones in the eastern part of the Cloncurry-Selwyn terrain are only up to few hundred metres wide. This observation in combination with the mineral assemblages implies greenschist metamorphic grade. These shear zones would have been formed at depths less than 10 kilometres (i.e. at pressures lower than those of the regional metamorphism).

Figure 3.2 - Minor structural elements, based on outcrop sketches and photographs. Showing overprinting relationships between different deformation phases in calc-silicate, metadolerite and mica schist. **A**- Location M144/DP#44655, Maramungee Creek. Isoclinally folded bedding in moderately altered calc-silicate overprinted by D_2 causing dissolution in the S_2 foliation. **B**- Location M93, Maramungee Creek. Bedding in "pristine" calc-silicate is isoclinally folded by D_1, S_1 refolded by D_2 and dissolution of the bedding in the S_2 foliation. Post D_2 shearing in the limb region. **C**- Location 44.3B/DP#46319, Fullarton River gorge. Tight D_1 folded banded calc-silicate, with moderately dipping S_1, overprinted by a spaced S_2 cleavage in the Fullarton River gorge. **D**- Location M35, Maramungee Creek. Banding in "pristine" calc-silicate with melanocratic and leucocratic bands (hornblende and feldspar rich) is isoclinally folded by D_1 and overprinted by D_2. **E**- Location 26.19, south of Fairmile. Mica schist rock in the Fairmile area with two well-developed lineations; a shallow plunging L_2^1 and a steep plunging L_3^1. **F**- Location M57/DP#44610, Maramungee Creek. Enclave of muscovite-biotite-quartz schist in brecciated and altered rocks. S_1 parallel to bedding, refolded by D_2. **G**- Location 7.8, Turpentine antiform. Mica schist from the Maronan-Fairmile area showing S_2 parallel to S_1 overprinted by D_3. **H**- North of location 48.4, Spring Creek. Fabric development in the waning stage of a high strain zone in the Spring Creek area. Development of extensional crenulation cleavage (ecc) causes dragging of the mylonitic fabric into the shear bands, which forms at a low angle (35°) to the dominant foliation. **I**- Location M103, Maramungee Creek. Minor shear zone developed syn albite veining in metadolerite, associated with chlorite rich shear bands. Assuming simple shear, and an angle of $\theta' = 17°$ gives a shear strain of about $\gamma = 2.96$. **J**- Location M148/DP#44658, Maramungee Creek. Sigmoidal tensional gashes filled with actinolite formed during progressive brittle-ductile dextral shearing in moderately altered calc-silicate. Overprinting albite veins exploit the zone of weakness.

A
S1 Axial Plane
070/49
S0
070/42
350°
N
S1
S2
064/62
2 cm
B
NE
SW
060/66
S2
dissolution
late post
D2
shear zone
S0
S1
D2
D2
C
W
E
S0
274/40
S1
S2
254/65
S2
S2
S0
5 cm
S1
269/45
F
NW
SE
S2
S2
S1
S0
S2
S0
S1
5 cm
D
2cm
S2
fracture
S0
S1
039/76
fracture
S2
E
346/80
L1 3
S3
064/69
L1 2
130/25
S2
027/77
S1
050/57
1cm
G
S2
S1 244/62
S3
S1
1 cm
S3
293/78
S2
243/70
H
358/80
S
037/84
ecc
1cm
I
C
239/75
Ab
S
073/83
Chl
S2
2cm
J
less altered
calc-silicate banding
080/71
tension
gash
046/69
albite
vein
Act
5 cm

The major regional (post D_2) shear zones manifest themselves in the field as domains with a dominant muscovite fabric, especially in the Maronan supergroup. With ongoing mylonitization this would result in parallelism of the C-and S-fabrics, recording a high finite strain which can be seen as a strong planer fabric (Figures 3.2, 3.4A). Towards the late stage of a mylonitic deformation, a new set of shear bands develops, making a small angle (theoretically about 30°) with the dominant mylonitic fabric (Marcoux *et al.* 1987). This fabric is known as the extensional crenulation cleavage (ecc, Figure 3.2). Extensional crenulation cleavage bands were only sporadically observed in Spring Creek area and make a 37° angle with the major shear fabric.

Mapping located shear zones in D_2 limb regions, exploiting the S_1 fabric and affecting the S_2 foliation. From these observations it can be deduce that the earliest these shear zones were active, is during the late stage of the main D_2, but before the D_3 deformation phase. Mica schists behaved relative incompetently compared to calc-silicate rocks. Any post-D_2 stress superimposed on the terrain would therefore result in simple shear and flexural flow parallel to the XY plane which approximately coincide with the D_2 axial planes in the micaceous rocks (Williams 1976, Ghosh 1982). The relatively competent calc-silicate rocks would not act in this manner, but would be (micro) fractured. This could explain the dominance of breccia occurrences in the structurally deeper calc-silicate rocks.

The occurrence of brecciation is widespread and covers an area of hundred square kilometres. Brecciation shows a strong spatial association with the Cloncurry fault and is concentrated in the calc-silicate dominated zone (Figure 3.1 and Figures 3.5 and 3.6). The nature of the Cloncurry fault and its role in brecciation are described in detail in section 3.4.1. Megabrecciation is more strongly developed in the northern part of the studied area (Fullarton River section, Figure 1.8) compared to the southern part (Maramungee Creek section, Figure 1.12). Regional scale sodic-calcic alteration is associated with this brecciation. Albite and actinolite (± diopside ± magnetite) form the main mineral constituents in the matrix of the breccias and of the alteration (see Chapter 2 and 5). These constituents are a retrograde greenschist facies mineral assemblage compared with the peak amphibolite metamorphism, but indicate that alteration and brecciation occurred under quit high temperature condition. Late to post D_2 tabular shear zones in the Maramungee Creek section, indicate that the ductile shearing deformation not only affected the micaceous rocks, but also the calc-silicates (Maramungee Creek shear zone, Enclosure C).

3.3 - Deformation phases and styles in the Maronan supergroup

Three main structural domains can be distinguished south of the Maronan Prospect: i) the Turpentine antiform area, ii) a domain including the zone of high strain (reactivated early thrust) and west of the this zone iii) the Percy Bore synform area (Figures 3.3, Enclosure A). A deformation scheme for the Maronan supergroup is tabulated in table 3.2.

Turpentine Antiform : this domain consists of a large two kilometre wavelength D_2 antiform with numerous parasitic folds on the limbs. The antiform plunges north with minor fold axes rotating from 356/15 to 004/80. The S_2 axial plane orientation is ~110/85, while S_1 orientations cluster near 095/85 and 280/85. Shearing occurs on fold limbs in the eastern part of the domain and tightens the form surface trends. S_2 is more strongly developed in the south and is refolded by D_3. The D_3 axial plane trends NE-SW with a steep fold axes plunging ~135/85.

High strain zone : narrows down from 500 metres wide in the northern part of the Maronan-Fairmile area to 200 metres north of Fairmile. It trends NNE in the north and rotates to SSE southwards. No stretching lineations were observed. This zone shows retrograde mineral assemblages, and is distinguished by slaty cleavage. This high strain zone, with a general N-S strike (Figure 3.4B), runs through the Maronan-Fairmile area has been postulated to be an early thrust (Beardsmore *et al.* 1988, Loosveld 1989a-b). The outcrops in the high strain zone are scarce and consist of phyllite, graphitic slates, calcareous rocks, amphibolites, quartz-pyroxene-amphibole ± garnet rock and a leached unit consisting of white feldspathic material (metavolcanite ?) with blue tourmaline (schorl) overprint.

Percy Bore area : lies in a D_2 synform with an average S_2 orientation of 080/85 and a S_1 of 260/85 with fold axes plunging ~000/20. There are numerous layer-parallel quartz-tourmaline bearing veins together with quartz lenses in the nose of the synform. The overall vergence is to the west. Shear zones associated with brittle features occur in the eastern part of this area. The shear zones are parallel to the main trend of the foliation (Figure 3.4C). Locally downward-facing D_2 structures in psammitic beds, of the Soldiers Cap group (Figure 3.4D), suggest the above mylonites were formed during D_{1c} compressional phase described by Loosveld (1989a and b).

In the psammopelitic rocks of the Maronan supergroup, D_3 is developed on a broad scale, causing regional interference patterns (see section 1.5 and Enclosure A). The D_3 fold style is reclined and tight on map scale, but on hand specimen scale box folds is also common. The S_3 axial-plane trend NE-SW to NNE-SSW and dips steeply east to subvertical (Figure 3.3). The L_3^1 lineation plunges steeply to subvertical to the north, and can easily be distinguished from the L_2^1 by its more "straight" character, compared to the "wavy" nature of L_2^1 due to D_3.

Table 3.2 - Deformation scheme of the Maronan supergroup in the Maronan-Fairmile area, and mineral assemblages of the psammopelitic rocks.

EVENT	DESCRIPTION	ORIENTATION	METAMORPHISM mineral growth	INTRUSION
pre syn D_1	Low angle thrusting with E-W folds .	N-S movement		
D_1	Isoclinal folding of bedding; development of S1.	Reorientated S_1 foliation average 285/70, 080/70	1st prograde phase, amphibolite facies And, Alm, Qtz, fsp, Pl, Bt, Ms.	Pegmatite(1)
D_2	Main deformation phase, asymmetrical tight upright folding, crenulation of S_1, L_2^1 lineation.	S_2 average 090/ 85, 270/80, L_2^1 355/20 to 000/ 75	2nd prograde phase, upper amphibolite facies, andalusite replaced by Sil. Enclave with new growth of St, Alm, Kfs.	Amphibolite, metadolerite, pegmatite(2)
late post D_2	Sodic metasomatism and layer parallel shearing, causing dilation with quartz lenses.	exploit S_2	Retrograde phase, andalusite replaced by Ms, Grt, Qtz.	White buck quartz veins, with occasionally sulphides.
D_3	On regional scale S_2 overprinted by open to tight D_3 folds, on hand specimen scale box-folding, development of L_3^2 crenulation lineations, faulting.	S_3 average 330/ 85, L_3^2 vertical north plunging, faults with a NE and NW direction.	No new growth observed.	
D_4	Open folds, and faulting.	E-W axial plane and fault orientation.	No new growth observed.	Pegmatite(3), dolerite

NB. Mineral abbreviations: Qtz=quartz, And=andalusite, Sil=sillimanite, Alm=almandine, Grt=garnet, St=staurolite, fsp=feldspar, Pl=plagioclase, Kfs=K-feldspar, Bt=biotite, Ms=muscovite.

3.3.1 - Local brittle features in the Maronan-Fairmile area

Two steeply dipping fault orientations cross cut the general foliation trend. A fault set trending NW-SE and its conjugate set striking NE-SW; all faults are steeply dipping (Figure 3.3, Enclosure A). Faults of this conjugate set show no vertical movement but have minor lateral displacement with sinistral movement. Fault breccias are occasionally observed NE of Fairmile. The breccias contain angular clasts, of psammite and muscovite schist. The clasts are matrix supported and vary in size from millimetre scale up to centimetre scale. The matrix consists of fine grained quartz, sericite and traces of staurolite. A third fault orientation trend E-W (few faults shown on Figure 1.6). E-W faults lack lateral displacement, but show minor vertical displacement with blocks moving north and downward. East draining creeks exploit these faults.

Figure 3.3 - Geology map of the Maronan-Fairmile area. A zone of high strain separated a D_2 synform in the west from a D_2 antiform (Turpentine antiform) in the east. The high strain zone is also the boundary of the sillimanite isograd.

SIMPLIFIED GEOLOGY MAP OF THE MARONAN-FAIRMILE AREA

Figure 3.3 - Geology map of the Maronan - Fairmile area

Silicification occurred late in D_2, probably related to late D_2 shearing, with crackle veining and open-space quartz infill (Daylight Bore, Percy Bore, Maronan Prospect, Figures 3.4E-F). Quartzite-psammite units at the Percy Bore locality are altered to sugary albite rocks with layer-parallel fractures filled with quartz, arsenopyrite, pyrite and chalcopyrite. At Daylight Bore, quartz overprints and destroys the fabric in net-veins, which in part brecciate the rocks, creating open spaces and produce a "jig saw" type breccia (Figures 3.4F). Clasts consist of albite in a quartz matrix. This also happened on a smaller scale at Wild Cat. Blue quartzites in the centre of the Turpentine antiform, contain veins with of millimetre scale quartz-albite centres and coarse recrystallized rims of albite and quartz. This veining was formed during D_2 ductile phase and is a normal phenomenon in the cores of D_2 folds in this area.

Regional principal stress orientations, during D_2, indicate an east-west $\sigma 1$ direction. This is also apparent from the foliation poles in the equal area stereoplots of Figure 3.3 and rose diagrams in Figure 3.6.

3.4 - Deformation phases and styles in the Doherty Formation

The previous section 3.3 dealt with the deformation styles in the psammopelitic rocks of the Maronan supergroup. This section will concentrate on the deformation event in the calc-silicate rocks of the Doherty Formation.

D_1 early compressional deformation phase (1620 Ma)

Some structural styles of D_1 can still be observed, despite the fact that the original orientation of S_1 is overprinted by D_2. These features include a strong mylonitic fabric in trondhjemitic granite sheets which are refolded by D_2, located at Maramungee Creek (Figure 2.7A-B).

The strong parallelism between the S_1 and S_2 fabric (see stereoplots on map figures in Chapter 1 and rose diagrams in Figures 3.6-3.7), would imply a coaxial orientation for D_1 and D_2. Hinge zones are domains of relative low stress, and are ideal sites in preserving earlier fabrics. In some cases, both bedding and S_1 fabrics are still preserved. From observations in those domains it becomes apparent that D_1 and D_2 are not coaxial and that the original orientation of S_1 was moderately inclined relative to S_2 (Figure 3.2C).

Concordant trondhjemitic granite sheets probably intruded in the early stages of the D_1 deformation phase (see Chapter 2). These sheets are mylonitized prior to and/or syn the D_2 folding; however, the relationship with D_1 is enigmatic. An extrusive, D_2 metamorphosed, felsic porphyry in the Doherty Formation (west of the Maramungee granite) has been dated at 1720±7 Ma (Page 1983), while U-Pb SHRIMP dating on the Maramungee granite give ages in the order of 1545 Ma (R. Page and S. Sun pers. com. 1996). This metavolcanic is intruded by early granites; this intrusive activity is interpreted as the D_1 extensional phase (Holcombe *et al.* 1991, Oliver *et al.* 1991).

Fluids, possibly expelled during the prograde D_1 metamorphic phases are trapped in early extensional veins. This is apparent from isoclinally folded albite veins in concordant mafic sheeted dykes, in the Maramungee Creek section (Figure 2.4A). These metadolerite dykes were probably emplaced prior to the D_1 compressional phase. Larger mafic bodies with no obvious extensive ductile overprinting relationships were emplaced late to post D_1, but before D_2 (see Chapter 2).

D_2 main penetrative deformation phase

The main regional D_2 deformation event caused considerable northeast-southwest shortening with upright to slightly inclined tight to close asymmetrical folding. A penetrative S_2 axial-plane foliation is developed in the micaceous metasediments of the Maronan supergroup. In the more competent rocks of Doherty Formation S_2 is developed as a spaced cleavage.

Although the D_2 axial-plane orientation differs by about 20°-30° (from N-S to 330°-340°, see stereoplots Figures 1.7, 1.10, 1.11 and 3.3) between the micaceous Maronan supergroup and the calc-silicate dominant Doherty Formation, the two fold trends are considered to have been formed by the same deformation phase. This because of the similar D_2 fold style, general regional vergence to the west and similar deformation stages that affected the areas. Furthermore, no overprinting relationships have been observed between these two orientations.

Figure 3.4 - Photographs from outcrops and rock-slabs from the Maronan-Fairmile area. **A**- Post D_2 dextral shearing, with rotation of the S_2 foliation into the high strain zone (east of Turpentine antiform, location 13.8). **B**- Highly deformed and retrograde amphibolite; part of the reactivated high strain zone during D_2. Overprinted by E-W D_4 folds (location 22.10). **C**- Post D_2 high strain zone with dextral movement and boudinaged quartz veins (Daylight Bore). **D**- Refraction of S_2 cleavage in feldspathic bedding, indicating overturned bedding (Percy Bore). **E**- Albitized rock, deformed causing dilations filled with quartz and sulphides (Percy Bore). **F**- Silicification overprinting albitized rocks at Daylight Bore.

A
S2 dragging
B
S2
S4
C
boudinaged
Qtz
post D2 shearing
S1
S2
D
E
Qtz
Ab
F
10 cm
Qtz

The overall geometry of the D_2 folds is fairly consistent. Coaxial homogeneous shortening caused gently north and/or south plunging first order regional scale folds. However, non-coaxial homogeneous deformation produced outcrop-scale asymmetrical second order folds which are non-cylindrical.

The interlimb angle of D_2 folds (α, angle formed by the tangents at the inflection points of a fold), varies considerably, from 20° up to about 80° (Figure 3.5). First order folds have interlimb angles of approximately 40° to 55° and aspect ratios (amplitude of the fold divided by the span/wavelength) close to unity. Outcrop and hand specimen scale D_2 folds, have tangent interlimb angle and aspect ratios well below unity. These fold geometries change dramatically toward limb regions and in zones of high strain, with a decrease of the interlimb angle and an increase in the aspect ratio.

The intersection lineation L_2^1 formed by the overprinting of S_1 by S_2 foliations, is subparallel to the D_2 fold axis, and on a regional scale plunges moderately to the northwest and/or southeast. Doubly plunging folds occur locally in high strain zones, as a consequence of attenuation of the D_2 folds (section 4.2.1).

Figure 3.5 - Plot of the interlimb angle (α) versus the aspect ratio (amplitude/span) of folds in the eastern Cloncurry-Selwyn terrain. Folds in high strain zones are attenuated D_2 folds. Note the large spread in α and aspect ratio. The boundary between D_2 and attenuated D_2 folds occur at a longitudinal strain (e) of 70% shortening.

Mineral lineations occur only sporadically in the calc-silicate rocks of the Doherty Formation but occur frequently in the psammopelitic rocks of the Maronan supergroup (see section 3.3). These lineations lie in the XY plane, in subvertical direction, and are aligned biotite, muscovite and/or andalusite. Lack of lineations in the "pristine" calc-silicate rocks (quartz, feldspars, scapolite and hornblende), is possibly due to lack of grain shape anisotropy in the constituent minerals.

Post D_2 shearing (in calc-silicate rocks)

Progressive ductile deformation is inhomogeneously distributed through the rock, and concentrated in D_2 limb regions. This resulted in a post D_2 non-coaxial simple shear of the D_2 fold limbs (Figure 3.1 and 3.2B). This deformation type has been described for the more micaceous rocks in a previous section (section 3.3). Such shear zones in the Doherty Formation, are the earliest manifestations of focussing of a high fluid activity which resulted in extensive sodic-calcic alteration as in the Maramungee shear zone (section 4.2.2).

A strong planar fabric defined by a compositional banding, composed of oligoclase-albite and actinolite (± magnetite and titanite), forms the shear planes in this type of retrograde shear zone. The strong (compositional) banding causes the shear zones to act in a tabular fashion, with domains that have different lateral displacements. This banding has been formed by attenuation of D_2 folds. The net, early, movement in these zones is developed horizontally based on the orientation of sheath folds, refolded folds and weakly developed horizontal stretching lineations. These movements were probably sinistral, with shear strain (γ) larger than ten (see section 4.2.1).

At some point in time the movement on the shear zone became dextral and of a more brittle-ductile nature. Numerous veins, tension gashes and dilational jogs, characterised by generally similar mineral assemblages, were formed during this stage (see section 4.3 and Figure 3.2). The fact that the rocks exploit brittle deformation argues that unroofing of the terrain must have occurred, with lowering temperature.

The Maramungee Creek section (section 4.3) gives a good three dimensional insight into the relationships of the ductile and brittle-ductile structural elements of these post D_2 shear zones. This is because of the absence of and/or weak development of the overprinting younger deformation events.

Relationship between post D_2 shear zones and D_3

The occurrence of highly strained and reconstituted calc-silicate rocks which are brecciated during the major megabrecciation phase and the observation of a weak developed fracture cleavage in the breccia matrix (section 4.4.2, Figure 4.15), suggest that shearing happened pre-D_3.

D_3 late ductile-brittle deformation phase

The D_3 deformation phase is strongly partitioned in to zones of ductile- and brittle-ductile deformation. D_3 is also more prominent in the northern part of the studied area. D_3 is only weakly developed in the calc-silicate rocks of the Doherty Formation, and is observed as a widely spaced fracture cleavage. The orientation of S_3 is similar in the Doherty Formation and Maronan supergroup. However, D_3 only causes some minor deflection of the regional D_2 north plunging antiform in the Fullarton River region. Evidence for D_3 appears to be totally absent in the Maramungee Creek section. Minor D_3 activity is evident from the occurrences of thin pegmatite dykes and tension gashes with S_3 orientation.

D_3 is the onset for major igneous activity, causing emplacement of large discordant I-type granite intrusion (Williams Batholith suite, Chapter 2, section 2.4). The occurrence of a weak fracture fabric in combination with the discordant character, can provide a timing constrain on the emplacement of the Williams Batholith granite. Fracture patterns in the granites are approximately parallel to the Cloncurry fault and to the D_4 orientation. Miarolitic cavities (Figure 2.7E), grain size differences between the margins and centre of the granites, indicate that the emplacement was shallow.

Continuous unroofing resulted in a decrease in confining pressure, causing a relative increase in fluid pressure which resulted in mega-brecciation that affected both the granites and highly strained rocks in the post D_2 shear zone (see sections 4.3.1 and 4.4.2).

Post D_3 deformation

Transpressional movement on the Cloncurry fault resulted in brittle fractures that make a small angle (10°-30°) with the Cloncurry fault, Riedel fractures (Tchalenko 1970, Sibson 1989, Figures 3.6 and 3.7). Riedel fractures affecting the syn-D_3 granites (Williams Batholith suite) provide relative timing evidence for the strike

slip activity of the Cloncurry fault. The fractures contain red, hematite dusted, K-feldspar and quartz (Figure 3.8A), and indicating that fluids were still active during this deformation phase. Minor thrusts are related to this strike slip movement in the Mallee Gap area (Figure 1.9).

Figure 3.6 - A- Lineament map of the eastern Cloncurry-Selwyn terrain, compiled from aerial photographs and TM satellite imagery. Zones A-D are based on geology boundaries and lineament orientations. Zone A is predominantly the breccia and alteration complex of the Doherty Formation. Zone B is the psammopelitic metasediments of the Soldiers Cap Group. Zone C is the quartz-muscovite gneissic rocks of the Fullarton River Group. Zone D is predominantly the Squirrel Hills granite and Zone E is predominantly the Saxby granite. (see also Figure 1.5). **B-** Contour plot of the same area. Contours represent lineament density per four square kilometres. Note the apparent (weak) coincidence of the fracture density and the breccia-alteration complex in zone A.

D_4 brittle deformation

The latest regional recognized deformation phase is the D_4. This is a brittle E-W to ENE-WSW trending fracture pattern, and in places off setting the K-feldspar bearing Riedel fractures. Occasionally unmetamorphosed dolerite and pegmatite dykes are

intruded along these fractures. On a regional scale D_4 is responsible for the large open to gentle flexures in the form surface of the post D_2 strain zones and minor deflections of the S_2 and S_3 fabrics. However, the brittle E-W fractures and gentle flexures could be unrelated and representing different deformation stages.

Lineament analysis based on aerial photographs and satellite imageries

Lineaments observed from aerial photographs and satellite imageries (Figures 3.6 and 3.7), are from various deformation stages and structural styles. Imageries show that the calc-silicate rocks only have one pronounced NW-SE lineament direction. This contrasts with observations in the micaceous rocks of the Maronan supergroup, which have prominent N-S and NW-SE directions (Figures 3.6 and 3.7). The lineaments observed in the calc-silicate and micaceous rocks could partly be of D_2 origin, based on the same orientation of S_2 plotted in the streoplots of Figures 1.7, 1.10, 1.11 and 3.3.

Other reasons that for the presence of these different lineament orientations are: 1) firstly, it is possible that the axial-plane orientation of the older D_1 could have been variable. This requires a deformation phase between D_1 and D_2, which is not apparent in the terrain. 2) Secondly, they could represent major differences in the exposure of various structural deformation events. 3) A third explanation is that the rheological properties of calc-silicates differ from micaceous rocks and that they behaved differently under the same stress field. 4) Finally, post D_2 north-south trending ductile shear zones would have affected the main foliation (apparent from the occurrences of C-S and ecc-S fabric relationships in the micaceous rocks).

3.4.1 - The evolution of the Cloncurry fault

The Cloncurry fault is a major lineament on aerial photographs and satellite images, and extends a few hundreds of kilometres in a NW-SE direction. In the field, the Cloncurry fault manifests itself as a prominent discontinuous topographic feature composed of 10-30 metres high and 2-5 metres thick wall of silicified stockwork breccia (Figure 3.8B-C-D). The earlier ductile character of the fault is obscured by this younger silicified stockwork breccia. Relicts of an intense ductile fabric are still preserved in some locations (Fullarton River section). These mylonitic gneissic rocks, are composed of strained quartz and feldspar lenses, with pulled-apart peak metamorphic sillimanite, and biotite fish. These kinematic indicators suggest an early ductile sinistral and east over west thrust movement (Figure 3.8E-F).

Figure 3.7 - **A**- Overview of the geology of the eastern Cloncurry-Selwyn terrain. Boxes indicating locations of two well-exposed river sections. **B**- Rose diagrams of photolinear trends. Compiled from 1:25000 scale aerial photographs and Landsat TM imagery, see also Figure 3.6. The rose diagram in zone A-B-C represents lineaments of fractures and S_2 fabrics and fold trends. Rose diagrams of zone D and E would mainly represent fracture lineaments. Note the apparent spatial association between the breccia-alteration zone (zone A) and the Cloncurry fault. Arrows indicate profile lines of Figure 3.1.

Figure 3.8 - Photographs related to the Cloncurry fault. **A**- K-feldspar vein with quartz infill, cross-cutting a granite at the Boorama Waterhole location. **B**- The Cloncurry fault in the field. **C**- Sample DP#46330, Mallee area. Slab of rebrecciated Cloncurry fault, with chalcedony, comb-quartz and traces of pyrite. **D**- Episodical fault and fluid activities cause multiple silicification and brecciation in the younger stages of the fault history. **E**- Relict of an earlier ductile episode in the Cloncurry fault history. Strongly mylonitic and quartz-feldspar-biotite-sillimanite gneissic rock. **F**- Sample DP#46321, Fullarton River gorge. Microphotograph of the gneiss. Sil is sillimanite, Qtz is quartz, Bt is biotite, Fsp is feldspar. The rhombohedral shape of the quartz-feldspar lenses (E) and biotite fish (F) are kinematic indicators of a ductile east over west movement.

A
B
C
Py
D
2cm
E
Fsp
Bt
Qtz
F
Ms
Qtz
Sil
Bt
0.01mm

The overprinting of D_2 peak metamorphism also indicates that the fault was already present prior to the D_2 peak metamorphism and possibly also prior to the D_2 deformation phase and was probably formed during the D_1 deformation phase. This would fit well with Loosveld's (1989a and b) observations.

Loosveld (1989a) and Blake & Stewart (1992) refer to the Cloncurry fault as the Cloncurry Overthrust. Loosveld (1989) identified (D_{c1}) fold nappe structures in Soldiers Cap Group rocks, north of the studied area and suggested that the fault is a major thrust on the overturned limb of these nappes.

The Cloncurry fault lies close to the granite contacts and in places transgresses foliated albitized granites and ductile structures in the Doherty Formation (Figure 3.1). Clustered groups of marble units occur very sporadically in the Doherty Formation and can be used as a marker unit. These marble units occur on both sides (east and west) of the Cloncurry fault and are occasionally brecciated by movement on the fault in the Boorama Waterhole area (Figure 1.11).

The relationship with post D_2 ductile shear zones in psammopelitic rocks of the Maronan supergroup are somewhat problematic. The brittle character of the fault conflicts with the ductile nature of the post D_2 shear zones. The overall direction of the ductile shear zones and the Cloncurry fault is striking and reflects a similar orientation of their stress fields. The earlier history of the Cloncurry fault was possibly also ductile (see above), however, the juxtaposition of the present day ductile and brittle structures indicate than unroofing of the terrain occurred more rapidly in the vicinity of the Cloncurry fault and major granite intrusions. Or the post D_2 shearing resulted in an uplift of the stratigraphically deeper Doherty Formation.

A damaged zone approximately 2 kilometres wide adjacent to the Cloncurry fault is apparent from a high lineaments density (Figure 3.6). Late brittle features associated with the Cloncurry Fault are formed during a sinistral movement. These fractures were dominantly trending 130°-140° and are interpreted as R_1-Riedel shear fractures (Sibson 1989, Tchalenko 1970). Veins trending W to WNW were observed by Verran (1992). These fractures overprint the granite. This left lateral movement is also apparent from displacement of an albitized granite by several hundred metres (Figure 1.9). Some Riedel- and W to WNW trending dilational fractures are filled with brick red, hematite dusted K-feldspar, and is reactivated and infilled with milky comb-textured quartz. Brittle reactivation of the Cloncurry fault resulted in a

multiphase silicified brecciated stockwork, with chalcedony and minor sulphides as one of the last infill stages (Figure 3.8D and A).

3.5 - Metamorphism Related to deformation

The peak regional metamorphic grade reached the amphibolite facies, based on the mineral assemblage sillimanite (replacing andalusite), K-feldspar (± staurolite) in the psammopelitic rocks of the Maronan supergroup and hornblende, anorthite, biotite, quartz in the "pristine" calc-silicate rocks of the Doherty Formation. S_1 is defined by the metamorphic minerals, biotite, quartz, andalusite and feldspars, which forms a fine spaced and/or domainal cleavage in the schists of the Maronan supergroup. These minerals are stable at a low amphibolite facies grade (Winkler 1976, Philpotts 1990). S_1 is developed as thin laminated bands in calc-silicate rocks and possibly reflects modified bedding in the (Corella equivalent) Doherty Formation.

Figure 3.9 - Histogram of pressures obtained from Al_{total} in hornblende, in "pristine" calc-silicate rocks. Pressures show a relative large scatter, possibly due to resetting. A pronounced peak at 3.0-3.5 kbar possibly reflects the peak metamorphic depth of about 12-15 km.

Pressures obtained from the aluminium content in hornblende in "pristine" calc-silicate rocks are in the order of 3.5-4.5 kbar (Figure 3.9), while averages are tabulated in Table 3.3. Depths corresponding to these pressures are in the order of 12-15 kilometres. These pressures are obtained using experimental derived equations from Hollister *et al.* (1987), Hammarstrom and Zen (1986), Johnson and Rutherford

(1989) and Schmidt (1992). Essentially the Al-in-hornblende geobarometer is calibrated for a hornblende + biotite + plagioclase + K-feldspar + quartz + titanite + Fe-Ti-oxide assemblage for a natural tonalite rock. However, the peak metamorphic mineral assemblage from the "pristine" calc-silicates is similar to the calibration assemblage, and could be used for Al-in-hornblende pressure estimates (Hammarstrom and Zen 1986).

Table 3.3 - Pressures obtained from aluminium in hornblende, from "pristine" calc-silicate rocks of the eastern Cloncurry-Selwyn terrain.

Sample		average	(average) PRESSURE - kbar							
DP#	Total	Al-total	A	StDev	B	StDev	C	StDev	D	StDev
44618	5	1.23	2.20	0.83	2.29	0.74	1.74	0.63	2.86	0.70
44627	8	1.44	3.38	0.45	3.34	0.40	2.63	0.34	3.86	0.38
44628	10	1.36	2.90	1.19	2.92	1.06	2.28	0.90	3.46	1.00
44629	2	1.58	4.15	0.16	4.03	0.14	3.22	0.12	4.51	0.13
44631	5	1.57	4.07	0.39	3.95	0.35	3.16	0.30	4.44	0.33

Pressures obtained after A- Hollister *et al.* (1987), B- Hammarstrom and Zen (1986), C- Johnson and Rutherford (1989) and D- Schmidt (1992). StDev = standard deviation.

The deviation from the average of 4 kbar and large standard deviation in samples DP#44618 and DP#44628, is possibly due to the deviation in their mineral assemblage. Sample DP#44618 contains meionite, while DP#44628 is schisteous with a large portion of biotite.

Pressure estimates for the D_1 metamorphism, are in the order of 4 kbar, based on D_1 mineral assemblage in psammopelitic rocks (Mueller and Saxena 1977). This assemblage includes andalusite, quartz, biotite, almandine, plagioclase, K-feldspar and muscovite. Pressures calculated for the D_2 metamorphic event is of the same order, and indicate that prograde metamorphism is controlled by the temperature. The replacement temperature of andalusite by sillimanite during the D_2 prograde metamorphic event by the above pressure, would be approximately 600°C (Mueller and Saxena 1977). The occurrence of overprinting actinolite, albite and epidote in the Doherty Formation, indicates greenschist facies retrograde metamorphic conditions (Chapter 5). Pressures during this retrogression (alteration stage) can be estimated from a sillimanite bearing psammopelitic rock (Mallee Gap location), in which biotite breaks down to corundum, magnetite and titanite, and subsequently gets overprinted by andalusite with K-feldspar rims (Figure 2.4C-D). Both sillimanite and andalusite are present in the rocks (few metres apart), but fabric data shows that the sillimanite predates the andalusite and biotite break down. Fisher (1970) describes similar textures; segregations consisting of andalusite-biotite-quartz cores surrounded by a quartz-K-feldspar mantle in sillimanite-biotite-feldspar gneiss near Västervik, Sweden. He suggested a pressure of 3 kbar and 500°C, based on the coexisting of sillimanite and andalusite and biotite-feldspar crystallisation

temperatures. The metamorphic mineral growth in relation to the deformation phases is tabulated in Table 3.4.

Table 3.4 - Common metamorphic and alteration minerals versus deformation stages from the eastern Cloncurry-Selwyn terrain.

Metamorphic / Alteration Minerals	Stable Assemblages	Lower Amphibolite Grade D_1		Upper Amphibolite Grade D_2	Greenschist Grade post D_2
Psammopelitic rocks*					
Quartz	1, 2, 3a, 3b, 4a, 4b	----------	--------	----------	----------
Andalusite	1	----------			------
Almandine	1, 3a, 3b	----------		----------	
Plagioclase	1, 3a, 3b	----------		----------	
Biotite	1, 2, 3a, 3b, 4b	----------	--------	----------	----------
Muscovite	2, 3b, 4b		--------	----------	----------
Staurolite	3a			---------?	
Sillimanite	3b			----------	
K-feldspar	3a, 3b, 4b			----------	----------
Calc-silicate rocks*					
Hornblende	3a, 3b			----------	
Diopside	3b, 4a			?---------?----------	----------
Magnetite+Ti	3a, 3b			----------	
Titanite	3b			----------	
Meionite	3a			----------?	
Alteration rocks*					
Actinolite	4a, 4b				----------
Albite	4a, 4b				----------
Magnetite	4a, 4b				----------
Epidote	5				----------
Marialite	4a, 4b				----------

N.B. (*) Generalised mineral assemblages of the rocks. Numbers indicate stable mineral assemblages.

3.5.1 - Metamorphic isograds in the Maronan supergroup

Prograde regional metamorphism in the Cloncurry-Selwyn zone reached the upper amphibolite facies (sillimanite - K-feldspar). Work conducted in the Mount Isa Inlier suggested that peak metamorphism occurred during D_2 (Beardsmore *et al.* 1987, Reinhardt and Rubenach 1987).

The regional metamorphic grade increases from lower to upper amphibolite facies, and towards the south and west in the Maronan-Fairmile area. Two types of prograde metamorphism are recognized and can be correlated to deformation events, followed by retrogression. The first prograde metamorphism took place during D_1, while the second prograde metamorphism took place late syn D_2 deformation. Retrogression took place between the D_2 and D_3 deformation phase (Table 3.2).

The first prograde metamorphic stage is a regional event throughout the Maronan-Fairmile area. The mineral assemblage in pelites contains andalusite, garnet, muscovite and biotite, which is associated with lower temperature amphibolite facies. Andalusite porphyroblasts only grow in particular layers, which must have had a favourable composition. No evidence for graded bedding was seen from porphyroblast size variations. The porphyroblasts grew up to ten centimetres long and are flattened by later deformations (Figure 3.10A). Garnets nucleated late in D_1 and are generally poikiloblastic. In same cases S_1 quartz inclusion trails are present (Figure 3.10B).

The second prograde metamorphic event took place late syn D_2. This is reflected in a sillimanite-in isograd, parallel to the high strain zone, indicating activity of the shear zone post D_2. Schists in the southern part of this area become coarser and more gneissic. Numerous veins are evidence for anatectic melting, and indicate high temperatures and P_{fluid}. Andalusite porphyroblasts are replaced by sillimanite, which locally grow aligned to the muscovite mineral lineation, but is general random (Figure 3.10C). Sillimanite replacing andalusite occurs as small fibrous grains, whereas discrete grains up to 15 centimetres long occur at the Percy Bore locality. Rare euhedral staurolite was observed east of Daylight Bore (Figure 3.10D).

The S_2 foliation bends around the andalusite blast and garnets. A second generation of garnets nucleated early syn D_2 overgrowing the S_2 fabric and with occasional pressure shadows (Figure 3.10D). These D_2 almandine garnets vary in size from millimetre up to centimetre scale and occur throughout the area, but are frequently observed on the limbs of the D_2 folds and associated high strain zones.

Retrogression is well marked in the Turpentine antiform area where andalusite porphyroblast are replaced by muscovite, biotite and a third generation of garnet (Figure 3.10E). These late garnets, are relatively inclusion free, compared with the earlier garnets (Figure 3.10F). No new mineral growth was observed in the D_3 ductile folds. The conditions estimated from the assemblages for D_1 metamorphism, are in the range of 4-5 kbar and 450-500°C. The second phase must have reached temperatures between 550-650°C (Jaques *et al.* 1982, see also Appendix H).

A petrographic grid (Figure 3.11) was calculated with the computer program "THERMOCALC" (Powell and Holland 1988). The petrographic grid illustrates the stability fields of some metamorphic minerals.

3.5.2 - Metamorphism in the Doherty Formation

Peak metamorphic mineral assemblages in "pristine" calc-silicates, in zones of low fluid-rock ratios, are typical for amphibolite grade metamorphism (similar mineral assemblages are described by Liou *et al.* 1974, Maruyama *et al.* 1983). These metamorphic minerals, e.g. hornblende, anorthite, K-feldspar, biotite, Ti-magnetite, quartz and titanite, define the relict banding parallel to the S_2 foliation (see section 2.3.1).

The presence of metamorphic scapolite, meionite, in certain layers in the "pristine" calc-silicates, can give some constrains on the temperature and X_{CO_2} activity during the D_2 peak metamorphic event, if the pressure of formation is know. Natural meionite has a wide stability field in T-X_{CO_2} space at 4 kbar, with a X_{CO_2} at approximately 0.4 (Ellis 1978, Moecher and Essene 1990). The fact that titanite is stable relative to rutile narrows the range of temperature to a minimum of 500°C, for the above X_{CO_2} -pressure conditions. Meionite appears to be stable at temperatures above 800°C, based on calculations with the computer program "THERMOCALC" (Powell and Holland 1988). Liou *et al.* (1974) modelled the temperature transition between actinolite and hornblende at about 550°C.

Figure 3.10 - Metamorphic minerals versus deformation. **A**- Andalusite porphyroblasts, aligned and plunging north (Turpentine antiform). Partly retrograded to quartz, muscovite, garnet ± biotite. **B**- Garnet with quartz inclusions in quartz-biotite schist (Sample DP#46339, east Daylight Bore). The quartz inclusions interpreted as S_1, are curved creating a helicitic structure. **C**- Late to syn D_2 sillimanite porphyroblasts (east of Percy Bore), randomly orientated, in placed aligned to the D_2 muscovite mineral lineation (not shown). **D**- Sample DP#46338, east of Daylight Bore. Euhedral staurolite in garnet, quartz biotite schist. Note the slight wrapping of the S_2 foliation around the early-syn D_2 poikiloblastic staurolite and garnets. Note the uniformity of garnet crystal size. The location is possibly fault bounded in the sillimanite zone. Staurolite stable in a medium to high pressure terrain are generally Zn-rich, Deer *et al.* (1992). **E**- Sample DP#46339. Large porphyroblasts, probably andalusite, is totally replaced by coarse muscovite, fibrous sillimanite and inclusion free garnets. **F**- Sample DP#46337, east of Percy Bore. Late inclusion free garnet (and tourmaline) overgrowing the S_2 foliation.

A
And
B
C
Sil
D
Grt
E
Ms
Sil
Grt
Bt
F
Tur
Grt

Figure 3.11 - Illustration showing reaction curves for some common metamorphic minerals. Shaded areas showing the stability fields of some minerals in the Cloncurry terrain, during the D_1 and D_2 deformation and metamorphic events.

3.6 - Summary

The Cloncurry-Selwyn terrain is part of the eastern Proterozoic Mount Isa Inlier. This terrain has undergone several major ductile and brittle regional deformation events, and associated metamorphic phases.

The orientation and nature of the earlier ductile deformation phase(s) are somewhat speculative due to the strong overprint of the pervasive D_2 deformation phase and post D_2 retrograde sodic-calcic alteration. However, D_1 appears to have been a flat lying event. The D_2 deformation is manifested as an upright tight N-S to NW-SE trending fold style verging to the west. The eastern part of the Cloncurry-Selwyn terrain is transected by major north-south trending ductile retrograde, greenschist facies shear zones and a brittle lineament, the Cloncurry fault. The ductile shear zones are concentrated in limbs of F_2 folds and were active post D_2. However, these shear zones are believed to be initiated as basement structures, formed prior to or syn

D_1. They also bound rock units of different metamorphic grade, indicating there was a dip-slip component to the movement (or major strike-slip of a tilted block).

Regional brecciation overprints the earlier ductile and brittle-ductile shear zones. This is evident from the occurrence of altered clasts containing earlier high strained fabrics and veins controlled by fold structures. The brecciation is spatially associated with the Cloncurry fault and high level granite intrusions. Weak D_3 fabrics and partly brecciated granites are evidence for the synchronous nature of the brecciation with the D_3, and granite emplacement.

Early metamorphic grade reached the lower amphibolite facies grade with pressures approximately 4-5 kbar and temperature in the order of 450°-500°C. Metamorphic minerals related to this event are aligned in S_1 and consist of andalusite-biotite-almandine-quartz-feldspar-muscovite, in the Maronan supergroup. Metamorphism reached its peak, upper amphibolite facies grade, during D_2 with sillimanite overprinting andalusite. Pressures remained relative constant, based on Al-hornblende geobarometry in hornblende-biotite-quartz-plagioclase-K-feldspar-magnetite(+Ti)-titanite±meionite±diopside calc-silicate rocks of the Doherty Formation. However the occurrence of euhedral staurolite in the Maronan supergroup indicates a slight pressure increase. Greenschist facies grade retrograde metamorphic mineral assemblages (sodic-calcic alteration) are concentrated in post D_2 shear zones, in calc-silicate rocks of the Doherty Formation and consist of actinolite-albite-magnetite-titanite±diopside.

CHAPTER 4

CHAPTER 4 - STRUCTURAL CONTROL on METASOMATISM

4.1 - Introduction

The brittle-ductile high strain zone close at the contact between the Doherty Formation and the Maronan supergroup in the Maramungee Creek section (Figure 1.12, Enclosure B), is an example of a shear zone in which reactive fluids were focussed after the D_2 deformation event. The fluid activity is apparent from the change in bulk mineral assemblages in the shear zone compared with surrounding rocks, and the occurrence of numerous vein sets and dilational breccia jogs.

4.2 - Structural elements in the post D_2 ductile Maramungee shear zone

Outcrop maps of the Maramungee shear zone are presented in Figure 4.1 and Enclosure C. The shear zone is located approximately one kilometre to the west of the Doherty Formation - Maronan supergroup contact. Internal structures in shear zones can reveal the mechanisms controlling their evolution. For example, ductile and brittle structural elements are both observed within the shear zone (Figure 4.2). It is apparent from ductile folds, that the Maramungee shear zone was formed in a ductile regime during its early stages. This is based on overprinting relationships, such as brittle fractures and veins cross-cutting the early ductile folds.

The shear zone has a main orientation subparallel to the S_2 foliation, with a NW-SW direction. The exposed shear zone varies from 80 to 100 metres in width and can be traced for several hundreds of metres along strike. Given the location and trend of the zone, it is likely that it is part of a larger zone of displacement separating profoundly sodic-calcic altered rocks from less reconstituted calc-silicate rocks in the west and schist in the east. Dragging of foliation on the western contact indicated sinistral displacement (Enclosure B).

The rocks within the shear zone show a dramatic change in mineralogy, especially an increase in the abundance of albitic plagioclase and actinolite (± titanite ± magnetite). These minerals reflect a greenschist metamorphic grade facies (rock unit CS_h-A, see sections 2.3.2 and 2.3.3). Permeability contrasts between the layers in the shear zone are indicated by the present of moderately altered layer parallel lithologies that contain relict minerals reflecting peak metamorphic grade. These include thin mafic mineral-rich sills, in the centre of the shear zone, containing

deformed mizzonite scapolite (CS_m-C). A biotite, K-feldspar, mizzonite scapolite fine grained calc-silicate rock unit (CS_m-B) outcrops at the eastern margin, within the high strain / shear zone. Exposure east of the shear zone is poor and precludes establishing the extent of the shear zone. These outcrops consist of laminated and brecciated rocks, composed of albite with actinolite and clinopyroxene (CS_h-B).

Figure 4.1 - Sketch of part of the Maramungee Shear zone (see also Enclosure C, and Figure 4.3), illustrating strong layering, with partitioned shearing and intensity in deformation. The bedding and S_1 are post-D_2 deformed and reorientated (sub) parallel to D_2.

Kinematic indicators in the Maramungee shear zone during ductile and brittle-ductile movement.

1) vein-jog dilation
2) asymmetry of trails growing around clasts
3) layer-parallel vein
4) axial-planer veins
5) metre scale shear zones cutting folds
6) shearing of metre scale folds
7) transposed folds with aspect ratio >7
8) refolded, disharmonic and sheath folds
9) shearing of cross-cutting pegmatite
10) boudinage with fish-mouth
11) tension gashes
12) sigmoidal tension gashes

Figure 4.2 - Structural elements formed during the ductile and brittle-ductile post D_2, but pre D_3, deformation stages in high strain zones, in the eastern Cloncurry-Selwyn terrain.

4.2.1 - Ductile deformation characteristics of the Maramungee shear zone

Detailed structural investigation has revealed that the early history of the shear zone involved profound ductile deformation, which resulted in a macroscopic well-defined layering (Figure 4.1, Enclosure C). Such a well-defined layering can also be derived from primary sedimentation, such as a tuff and other volcanic bedding, or from an igneous origin, and possibly also by metasomatic segregations. It is often difficult to distinguish primary and secondary layering in strongly deformed layered rocks, especially if the rocks are profoundly altered.

Mylonitic layering development

Continuation of deformation caused in the late stages of the D_2 attenuation of outcrop scale D_2 folds. The mechanism by which this occurred was probably a combination of flexural slip and flexural flow (Figure 4.3). Narrowing of the interlimb angles and an increase in the aspect ratios of the folds reflect this progress in strain (see Figure 3.7). Longitudinal shortening of folds perpendicular to the S_2 in the XZ plane, indicate that a minimum strain (e) of -70% occurred in the shear zone. At the margin of the shear zone folds are clustered at about 40% shortening.

Recognising bedding becomes progressively difficult with continuous deformation. This is not only due to the increase in strain, but mainly to the fact that the rocks become more altered and are overprinted by layer parallel veins containing the same mineral constituents. The thin dominantly albitic and/or actinolitic rich layers (CS_h-A) probably reflect the modified bedding (section 2.3.3).

Form surface closures

Vertical extension attributed to continuous post D_2 attenuation of D_2 folds, produced highly non-cylindrical folds with doubly plunging fold axis. This is reflected in closure of form surface traces of foliations. The interpretation of these closures has to be approached with some caution. Close examination of these structures indicated three types of closures. Each occurring in the Maramungee shear zone, and each of them formed by a different mechanism in a ductile regime (Figure 4.4).

i) The first type of closure, occurring in the Maramungee shear zone, was already partly mentioned above. Most folds in nature are *non-cylindrical* and homogeneous progressive deformation causes a flow of material (vorticity vector) parallel to the mineral lineation (in this case L_2). The mechanism by which this flow type occurs, is close to "pure shear". Material will flow from a high stress region to low stress regions. This type of closure is shown in Figure 4.1 (synform with north plunging fold axis), Figure 4.4A and Figure 4.5A.

ii) The second type of form surface closure that occurred in high strain zones, and in the Maramungee shear zone, is the result of progressive deformation affecting *refolded folds* (Figure 4.4B and Figure 4.5B and C). These refolded structures are strong evidence for the post D_2 timing of the shear zone (Figure 4.1, Enclosure C). Non coaxial simple shear causes deflections in the axial plane of the fold. Rotation of the axial plane towards the shear plane would only occur if the rheological properties of the fold did not differ from the surrounding rocks. Difference in competency between the layers could result in, depending on the P/T conditions, fracturing or shearing of the less competent rocks.

iii) The third type of form surface closures in the Maramungee shear zone differs from previous types, in that the closures of the foliations occur in the YZ plane (Figure 4.4C and Figure 4.5D). These structures are believed to represent true *sheath folds*, such as are commonly found in many shear zones (Henderson 1984, Coward 1984). Studies have shown that the fold axis direction is approximately parallel to the maximum principal direction of the bulk strain ellipsoid. Experimental work by

Cobbold and Quinquis (1980) showed that local inhomogeneities in the rheological properties of the layers caused them to become "unstable" during deformation. This results in rotation of linear elements towards the extension direction (Hansen 1971). The dominance of subhorizontal NW plunging fold axes in the Maramungee shear zone indicates that the ductile shearing was dominantly strike slip with a subhorizontal NW direction movement (Enclosures B and C). Cobbold and Quinquis (1980) also pointed out that high shear strains, $\gamma > 10$, are needed to form sheath folds. With such large γ values, all earlier planar elements will be rotated into sub-parallelism with the shear plane, and earlier lineations such as fold hinges, provided they are not parallel with the shear plane, will also be rotated towards the shear direction. By using this value and a minimum width of 80 metres for the shear zone, a minimum displacement of just less than one kilometre can be calculated.

Figure 4.3 - Formation of layered / banded mylonite by progressive deformation of D_2 folds during the post D_2 deformation stage. The schematic diagram illustrates the changes that occur from zones outside (1) the shear zone, to the margin (2) and within the shear zone (3). Photographs (A-C) show that with increasing deformation bedding becomes more difficult to recognize.

Figure 4.4 - Schematic diagram for the formation of form surface closures. **A**- Progressive deformation affecting non-cylindrical folds causes rotation of the fold hinge resulting in cone shaped folds (Ramsay 1980, Ridley and Casey 1989). **B**- Progressive non-coaxial deformation resulting in refolding of earlier folds. Continuous deformation causes tightening of the "fold head" and eventually shearing in the neck. **C**- Sheath fold developed due to progressive non-coaxial deformation in ductile shear zone (Cobbold and Quinquis 1979). **D**- Type 1 dome-and-basin interference pattern caused by superimposed fold generations (Hobbs *et al.* 1976).

Rotation of fold hinges of non-cylindrical folds, and the occurrence of sheath folds, indicates that flow of material occurred in both the X and Y directions, but with a large material flow component in the X direction.

iv) Form surface closure can also be formed by overprinting deformation phases (Figure 4.4D). Interference patterns of two folding phases, with tangent axial planes, can create "dome and basin" type structures (Hobbs *et al.* 1976). On outcrop scale a strong cleavage perpendicular to the long axis of the form surface ellipsoid would be expected. This type of form surface closure is not observed in the eastern part of the Cloncurry-Selwyn terrain, in which the earlier deformation phases are almost coaxial.

Other ductile structural elements

Disharmonic folding is commonly observed in the high strain zones of the tabular developed Maramungee shear zone (Enclosure C, Figure 4.5E, Figure 4.2). These structures are diagnostic of folding styles developed in layers which contain rheological irregularities (Hansen 1971). These fold styles, in the Maramungee shear zone, are usually observed near form surface closures.

Irregularities such as rigid objects, commonly referred to as augen or porphyroclasts, show a strong resistance against material flow in shear zones. Recrystallized foliations are asymmetrically distributed around these rigid objects and are referred to as "tails" or "pressure shadows". The geometries of this asymmetry are useful in determining the shear sense (Simpson and Schmid 1983). These types of structures can occur at all scales, from microscopic up to regional; and shear sense directions are interpreted in the same way. Microscopic and hand specimen scale rigid objects with tails, are divided into sigma-σ and delta-δ types, depending on the amount of material that is available to recrystallize in the tail. Sigma (σ) type porphyroclasts have "enough" material available to recrystallize and are the only types rarely observed in the Maramungee shear zone (Figure 4.2). They indicate a ductile sinistral movement (Figure 4.5F).

Sinistral displacement causes dragging of the layers on the west side of the shear zone. This resulted in reclined folding with steep, subvertical, plunging fold axes (Enclosure B).

4.2.2 - Relationships between alteration and ductile deformation

The "early" post D_2 ductile shearing deformation phase in the Doherty Formation coincides with the onset of the sodic-calcic alteration event. Mylonitized rocks composed of albite and actinolite are also the oldest altered rocks found in clasts in the Doherty Formation breccia complex in the Fullarton River gorge (Figure 4.6).

Figure 4.5 - Photographs of different types of form surface closures and other ductile elements. **A**- Small scale attenuated D_2 fold at Mallee Gap, viewed on the XZ plane. **B**- Refolded D_1 fold due to shearing in the Maramungee Creek shear zone. **C**- Continuous shearing result in tightening of the "fold head"; the closure is only partially visible. **D**- Sheath fold in the Maramungee Creek shear zone viewed parallel to the XY plane. **E**- Disharmonic folding. This fold is interpreted as the connection, neck, between the shear layering and the sheath fold. **F**- Sigma (σ) type pressure shadows on rigid clasts indicating sinistral sense of shear.

A
B
C
D
E
10cm
F
σ tail

Figure 4.6 - Outcrop sketch of part of a larger rebrecciated clasts in the megabreccia complex in the Fullarton River gorge (location 44.1/DP#46318). A highly strained rock showing complex foliation patterns, defined by thin laminations composed of albite and actinolite (see also Figure 2.5E), is overprinted by a subsequent albite actinolite phase, with concentration of actinolite in the shear planes. This rock was rebrecciated and is part of a larger clasts.

The progression in fold style revealed, by increasing in the aspect ratio and narrowing of the interlimb angle towards the Maramungee shear zone, suggest that the rocks in the shear zone were the same as the less deformed rocks on its western margin. The dominant mineral constituents across the shear zone show that the shear zone is a metasomatised fault zone, with a major change in bulk composition. A hot and saline fluid (see Chapter 6) was focussed and channelized into the shear zone, causing the alteration. The relationship between the change in fold style attitude and sodium over potassium ratios across the shear zone is illustrated in Figure 4.7.

Schist fabric at the Maronan supergroup - Doherty Formation contact

The psammopelitic rocks of Maronan supergroup are highly strained at the tectonic contact with the Doherty Formation. The psammopelitic metasediments alters from a retrograde quartz-biotite-muscovite schist into a biotite-quartz schist which corundum - albite ± K-feldspar ± tourmaline alteration (Williams 1994). The

intensity in strain manifests itself by transposition of bedding and smearing of earlier fabrics and crenulations (Figure 4.8). Eventually the altered schist is overprinted by the main breccia complex. This overprinting of D_2 crenulations and brecciation provides a timing for the onset of the alteration in this rock unit, which is coeval with the main ductile shearing and fluid channelling in the Maramungee shear zone.

Figure 4.7 - Schematic diagram illustrating the increase in fold attenuation and sodium content towards the centre of the Maramungee shear zone. Locations are approximate.

Figure 4.8 - **A**- Transposed bedding and S_1 foliations in sheared retrograde quartz-muscovite schist at the Maronan supergroup Doherty Formation contact. **B**- Intensified transposition, with isoclinal biotite foliation (dark bands) with corundum, albite and quartz. Overprinted by actinolite vein with hematite dusted (red) albite selvages (see Figure 2.4K). **C**- Contact between an enclave of Maronan supergroup schist (right) and Doherty Formation breccia complex (left) with high strained altered schist in the centre. **D**- Breccia with clasts of altered schist in an albite, actinolite, clinopyroxene matrix, overprinted by calcite. Photographs A-D are from the Maramungee Creek section. **E** - Altered schist (same as B), with relict bedding (location L1.6/DP#46323). **F**- More intensified fabric in altered schist, with albite (white) and laminations of magnetite and titanite (black), location 39.1/DP#46303. Photographs E-F are from the Fullarton river gorge.

A
S_0 transposed
B
Act
Ab
Hem dusted
Bt
C
breccia
schist
D
pseudo-
igneous texture
relict schist
E
S_0
F
Mag
Ab
1 cm

4.3 - Brittle-ductile deformation in late post D_2 high strain zones

Mylonite zones commonly exhibit a period of "steady state" ductile deformation followed by a late brittle stage. This change in deformation process may be attributed to a decline in metamorphic conditions such as uplift, causing rocks to behave in a more brittle fashion. If fluids are present in the shear zone, such an uplift will cause a reduction in lithostatic pressure and subsequently causing an increase in the fluid pressure. The Maramungee shear zone exhibits such a history, which is manifested in the later stages by brittle-ductile veining and dilational jogs that overprint the early ductile mylonitic fabric (Figure 4.1, Enclosure C and Figure 4.9).

The veining can be subdivided on the basis of orientation, composition and the mechanism of formation. There is a strong spatial association between the density of veining and the ductile high strain zones. In areas of megabrecciation, such as in the Fullarton River gorge, ductile shear zones are obscured and the relationship of veining overprinting ductile high strain zones is only apparent from clasts containing high strained fabric overprinted by veining (Figure 4.6).

Late post D_2 (high temperature) veins occur throughout the area (Table 4.1, Enclosure B and C), but are more concentrated in high strain zones (high F/R ratios) and adjacent areas (moderate F/R ratios) and at margins of large metadolerite bodies. Contoured poles to vein distribution in stereoplots indicate two distinct point maximas (Enclosure B). A set parallel to the D_2 axial plane (V_1 and V_2) and a subhorizontal set (V_3). The former has to be subdivided into axial-planer veins (V_1) and layer-parallel veins (V_2), based on the forming mechanisms and type.

Vein orientations in the Maramungee Creek section, show that the mechanism by which these three vein sets formed was related to their structural setting, resulting in their spatial separation. The subhorizontal set (V_3) is mainly observed adjacent to high strain zones were the fold axes are steep or subhorizontally plunging. Axial planar veins (V_1) are only present in the shear zone, while layer parallel veins (V_2) occur in both structural domains. The most visually spectacular vein set is the axial-planar type, V_1.

Axial-planar veins (V_1)

These veins formed in a domain which had previously undergone high non-coaxial compressional stresses. The veins are open-space extension fractures predominantly

filled with actinolite and traces of albitic plagioclase, quartz and diopside in the strongly banded and disharmonic folded altered calc-silicate rocks. They occur in the Maramungee shear zone and altered ± corundum bearing schist to the east. Vein selvages are composed of albite and are hematite dusted in the altered calc-silicates but not in the altered schist (Figure 4.10). Oligoclase is the dominant infill mineral in axial-planar veins in retrograde schist at the Maronan-Doherty Formation contact. Oligoclase and traces of quartz are also the dominant infill minerals in veins at the margin of the Maramungee shear zone, in rock unit CS_m-B (mizzonite bearing). The selvages are however more interesting in that they are composed of sodium rich scapolite (marialite).

Figure 4.9 - Schematic diagram showing the structural styles of shear zone-related alteration features as present in the Maramungee Creek section.

Table 4.1 - Summary of commonly observed veins in the Cloncurry-Selwyn terrain. Apart from veins that cross-cut a breccia host rock, the veins were emplaced post early D_2 shearing and pre D_3.

Vein type	Host rock	Structural setting	Centre	Selvage/Rim
V_1 Axial planar	Altered calc-silicate	Fold hinges in sz	Act» Ab-Mag± Qtz	Ab (Hem dstd)-tr Mc
	Moderately altered cs	Fold hinge margin sz	Ab±Qtz	Ma Scp
	Altered schist ± Crn	Fold hinges in sz	Act	Ab (not dstd)
	Retrograde schist	Tectonic contact	Ab±Qtz	Rexx coarse Ab
V_2 Layer parallel (rp & ex)	Altered calc-silicate	Shear zones	Act-Ab» Qtz-Mag-Cpx	Ab (± Hem dstd)
	Moderately altered cs	Adjacent to sz	Tr/Act-Ab-Mc» Qtz-Mag	Ab±Mc (Hem dstd)
	Altered schist	Reactive parallel S_2	Act» Ab	Ab (not dstd)
	Metadolerite	Reactive ± parallel S_2	Ab±Qtz	Rexx Hbl
V_{2b}	Altered calc-silicate	High strain zone	Ab±Act±Qtz±Mag	Absent
V_3 Subhorizontal	Moderately altered cs	Perpendicular fold axis	Act-Cpx	Mc (Hem dstd)±Ab
	Altered schist	Perpendicular fold axis	Act	Ab (±Hem dstd)
	Altered calc-silicate	Margin sz	Mag	Absent (Ab)
V_{JB} Vein jog bx	Altered calc-silicate	Shear zones	Act» Ab-Ttn and Ab clasts	Ab (±Hem dstd)
Tension gash		High strain zones		
TG_1	Altered calc-silicate	Sigmoidal	Qtz-Ttn	Absent
TG_2	Altered calc-silicate	Sigmoidal	Act±Cpx±Qtz±Ab	Ab±Mc (Hem dstd)
TG_{3b}	Altered calc-silicate	Straight	Kfs-Qtz-Hem	Absent
Crackle veins	Metadolerite	High strain zones at margins metadolerite	Ca-plg±Hbl±Ma Scp	Absent
	Altered schist	Hinge zones	Ab (Hem dstd)	Ab (Hem dstd)
syn post D_3 veins	Megabreccia complex	V_{2b} type	Qtz-Ab±Ttn	Cpx-Act
	Megabreccia complex	Subhorizontal	Qtz-Ttn±Cpx	Ab-Qtz
	Megabreccia complex	Tension gash (TG_{3a})	Cpx-Ttn±Act	Mc (Hem dstd)
	Altered granite	Subparallel S_3	Hem±Mag	Hem
	Altered granite + cs	Replacement style	Ab±Qtz	Absent
	Breccia	NW-SE trend	Ep-Prh±Ab±Qtz±Cal±Ttn	Ab-Mc

Abbreviations: Act-actinolite; Tr-tremolite; Hbl-hornblende; Cpx-clinopyroxene; Ab-albite; Mc-microcline; Kfs-K-feldspar; Ca-plg-Andesine; Qtz-quartz; Ma-marialite; Scp-scapolite; Mag-magnetite; Hem-hematite; Ttn-titanite; Ep-epidote; Prh-prehnite; Cal-calcite; Crn-corundum; Rexx-Recrystallized; cs-calc-silicate; sz-shear zone; bx-breccia; dstd-dusted; (rp & ex)-replacement and extensional.

V_1 veins are regularly spaced (Figure 4.9 and 4.10, Enclosure C), subparallel to the shear and banding fabric and most importantly located in folding domains within the high strain zone. The thickness of the veins varies from 1-20 mm and they are up to 3 m long. Actinolite is relatively concentrated in the most dilated part of the veins. The actinolite crystals are aligned parallel to the vein wall but with strong orientation differences of the crystal c-axes (Figure 4.11), which show two main directions of crystal growth. These are a vertical lineation plunging down dip of the vein wall and a more variable subhorizontal direction parallel to the strike of the vein wall. This suggests that there was still some compressional stress during the vein dilation. This apparent contradiction needs further explanation.

This type of extensional veins exploits fold axial planes. Folding by flexural slip mechanism in competent rocks, such as calc-silicates causes microfracturing parallel to the axial plane in fold hinges (Hobbs *et al.* 1976). Axial plane foliations are usually structures developed parallel to the XY-plane of the strain ellipsoid and perpendicular to the direction of maximum shortening (Williams 1976). This suggests that no shearing should occur on the XY-plane. However, Ghosh (1982) pointed out that during the "progressive deformation strain "and the "finite strain" an intermediate stage of rotational deformation occurred which correspond to some shearing, resulting in rotation of material planes toward the XY-plane. The final maximum angle between the two planes is small (about 2°). Field observation can therefore not distinguish between the theoretical XY-plane and the foliation (Gosh 1982). If irregularities in the foliation plane exist, shearing along such planes would create dilations. These dilations would have low fluid pressures and fluids would migrate instantaneously to those sites, causing actinolite to precipitate. The existing shear component will cause the alignment of the actinolite blades parallel to the vein wall, but cannot explain the two main c-axis directions observed in the veins at Maramungee Creek.

Figure 4.10 - **A**- Axial planar veins in altered calc-silicate rocks in the Maramungee shear zone. **B**- Breccia clast containing altered schist with fold controlled axial planar veins, located in the Fullarton River gorge. **C**- Reactivated V_2 type vein in metadolerite, in Maramungee Creek. **D**- Layer parallel vein (V_2) cut by subhorizontal vein (V_3). Layer parallel vein is in this case probably a replacement vein, west of the Maramungee shear zone. **E**- Layer parallel vein in strongly altered schist, cut by en échelon subhorizontal veins, located in the Fullarton River gorge. Note the actinolite concentration at the intersections. **F**- Layer parallel extensional vein in altered calc-silicate in the Maramungee shear zone. **G**- Vein type V_{2b}. Albite veins making a small angle with the main shear fabric in altered schist in the Fullarton River. **H**- Vein jog breccia (V_{JB}) cross cutting the shear fabric at a small angle (Maramungee Creek shear zone). Note the alignment of the clasts and the albite selvages. **I**- Relationship between the layer parallel replacement vein (V_2) and the vein jog breccia (V_{JB}). Note the narrowing of the replacement V_2 away from the vein jog breccia. Fluids from the vein jog breccia infiltrated into specific horizons. **J**- Deformed albite clasts in vein jog breccia (Maramungee Creek shear zone). **K**- Subhorizontal veins in hinge region with steep plunging fold axis (west of the Maramungee Creek shear zone). **L**- Subhorizontal veins in boudinaged limb regions of upright folds with subhorizontal fold axis (east of the Maramungee Creek shear zone).

A
V1
Act
Ab
10cm
B
altered schist
Ab
V1
10cm
C
metadolerite
Ab
V2
Hbl
D
CSm-B
V2
Mc
Act/Cpx
V3
E
altered schist
V1
V3
mafic dyke
F

G
H
1cm
I
METRIC 1 2 3
V_{jb}
V_2
J
K
steep lineation
V_3
L
V_3
20cm
horizontal lineation

An alternative mechanism that could have operated in conjunction with the above is that fluid flow across the shear zone was progressively arrested by fine grained granoblastic albite deposition during the ductile shearing stage. Bands of albite within the mylonitic layering formed low permeability seals and fluids were restricted to layer parallel flow zones. Compartments within the shear zone would have different fluid pressures because they were not hydraulically connected, this due to the impermeable seals. Compartments in the shear zone that are favourable domains in fluid focussing, would eventually have high fluid pressures. Such as folding structures in which fluids are focussed in the hinge zones (Etheridge *et al.* 1983, Valenta 1989). Episodical stress cycling in fault zones has been demonstrated by Sibson (1991, 1994) and Wood (1994). These studies pointed out, that fracture formation and fluid flow towards these fractures is dependent on the mean stress variations ($\bar{\sigma}$). By lowering the mean stress, by means of uplift, unroofing, stress cycling or combination of these three, fluids will flow from high to low fluid pressure compartments. In the case of the axial-planar veins in the Maramungee shear zone the high fluid pressure domains are the folding zones. Reduction of the mean stress caused flexural slip axial plane fractures to dilate, forming axial-planar veins. The moment fluid migrates into the fractures the mean stress would have increased, causing some alignment of the actinolite crystals.

Figure 4.11 - C-axis orientation of actinolite crystals in axial planar vein in the Maramungee shear zone. The alignment of crystals infers some stress during formation.

Layer parallel veins (V_2 and V_{2b}) and Vein jog breccias (V_{JB})

These veins are described together because of the cogenetic mechanism by which they formed.

Layer parallel veins (V_2) are divided into extensional and replacement veins and occur in a variety of rock units with vein compositions depending on the host rock. For instance, V_2 veins, up to 2cm wide, in metadolerite bodies have albite centres and coarse grained recrystallized hornblende selvages. Some V_2 veins in the metadolerites show evidence of reactivation, which is attributed to episodic fluid pumping (Figure 4.10C). Layer parallel veins in moderately and/or extremely altered calc-silicate and schists, are composed of actinolite centres with albite selvages. Traces of diopside also occur in veins in the calc-silicate rocks. These veins are narrow up to 5 mm (Figure 4.10D-F). Actinolite crystals are aligned with the vein walls, though in the moderately altered calc-silicates they are less aligned. V_2 veins appear to be open-space veins in the metadolerites and altered schists, with infill crystals larger than the host rocks. Both open-space and replacement style V_2 veins occur in the calc-silicate rocks (compare Figure 4.10D with 4.10F). The formation of the extensional veins can be explained by the same mechanism as the axial-planar veins. The formation mechanisms of the layer parallel replacement veins are enigmatic. These veins have irregular width and selvages, and can sometimes be traced for over ten metres.

Vein type V_{2b} are narrow fractures that is only observed in the high strain zones, such as the Maramungee shear zone (Figure 4.10G, Enclosure C). The dominant infill mineral is albite, with traces of quartz and rare actinolite. Selvages are generally absent but are present locally. This vein type includes two sets of fractures, namely one that makes an angle (~30°) with the mylonitic fabric, and another that trends north-south and intersect the fabric at a high angle (see stereoplots and rose diagram on Enclosure C). The regular spacing and zonal distribution in high strain zones (Enclosure C, Figure 4.1) suggest that these fractures are controlled by a brittle ductile movement of the shear zone. The most common fracture set is the north-south trending one. The orientation of the fractures relative to the mylonitic fabric suggest a dextral sense of shear (Tchalenko 1970).

Vein jog breccias (V_{JB}) are narrow planar bodies in shear zones with a length:width ratio > 20. The width ranges from centimetre up to metre scale. Angles between the vein jog breccias and the shear fabric are generally small (10°-15°). However, breccia splays can make angles up to 35° (Figure 2.6A, Figure 4.1 and Enclosure C, Figure 4.10). Actinolite is the dominant matrix material, with traces of albite and titanite. Some larger clasts show internal laminations parallel to the surrounding fabric indicating that they had a metasedimentary precursor. Smaller clasts are

totally altered to albite with destruction of the fabric. Although the contacts are sharp between the matrix and the clasts macroscopically, they are gradational microscopically. Narrow selvages composed of albite occur at the margins of the vein jog breccias. Tips of vein jog breccias locally propagate into layer parallel veins (SE part of Enclosure C). Layer parallel veins more commonly splay of the margins of the vein jog breccias (Figure 4.10I).

The orientation of the vein jog breccia planes relative to the shear fabric implies dextral shear movement as with the V_{2b} veins. Larger vein jog breccias have prolate clasts aligned (Figure 4.12, Figure 2.6B) parallel to the actinolite matrix. This strong shape fabric indicates that ductile deformation was still present during this stage. A more oblate clast shape would have been expected had the fluids percolated through the rocks utilising only the plane of weakness parallel to the foliation. The oblate clasts would also have formed if the vein jogs had been formed by dilation due to strike slip deformation; a pressure drop in the dilation would cause splintering of the vein wall. This might have occurred in a minor way, but it is more likely that the brittle-ductile shearing caused a planar zone of fracturing (shear parallel veins of Valenta 1989). This fracturing formed an anastomosing pattern in a juvenile "dilational" zone, creating equidimensional clasts which subsequently were deformed in a ductile fashion. This scenario can be demonstrated indirectly from a strain (R_f/ϕ') analysis of the clasts.

The initial step in the strain analysis is estimation of the original shape of the clasts. To obtain the original form, the ellipticity ($R=(1+e_1)/(1+e_2)$ where e_1 and e_2 are the long and short axes of the ellipsoid, based on the long and short axis of the clasts, and the angle (ϕ') between the shear direction and the long axis are measured in the principle planes. By plotting these values against each other on a R_f/ϕ' diagram, the minimum and maximum final strain, in a particular principle plane, can be obtained (Figure 4.13). The fluctuation (F) which is the degree of spread around the shear direction can also be measured. The final (measured) strain ellipsoid is a function of the initial- and superimposed strain ellipsoid. If the fluctuation is less than 90°, the initial- and superimposed strain ellipsoids can be calculated respectively from the following formulas $R_{i\text{-}max}=(R_{f\text{-}max}/R_{f\text{-}min})^{0.5}$ and $R_s=(R_{f\text{-}max} \times R_{f\text{-}min})^{0.5}$ (Ramsay & Huber 1983).

The strain ellipsoids, inferred from these axial ratios of these clasts, has X/Z ratios that are generally less 5 which represents a moderate degree of strain. As previously

noted, the deformation is heterogeneous, being strongly concentrated in shear domains, and is also variable developed within the vein jog breccia. For example, within different shear domains, X/Z ranges from 1.5 to over 10 in different vein jog breccias. The maximum superimposed strain in the principal directions are approximately 2:1.6:1, while the initial form shape of the clasts in the X:Y:Z directions are 1.01 : 1.03 : 1. This implies an equidimensional shape of the clasts before deformation. This must have been due to anastomosing fracturing and veining prior to the deformation.

Figure 4.12 - Form shape of the albite clasts in the vein jog breccias in the Maramungee shear zone, illustrated perpendicular to the principle planes. Note the prolate form of the clasts. Actinolite grain orientation in the matrix (not shown) is parallel to the long axis of the clasts.

The vein jog breccias are classified with the brittle-ductile veining event and not with the main brecciation process (section 3.4) because of the following reasons: 1) They exhibit the same mineral assemblages as the veins, namely actinolite and albite. 2) They have albite selvages, in the same manner as the veins. 3) They have an intimate spatial and timing relationships with the veins that were formed in high strain zones.

Figure 4.13 - Strain measurements of clasts in the vein jog breccias, using the Rf/ϕ' method. Measurements are taken in principle planes. The XY plane is parallel to the foliation. A-C are R_f/ϕ' plots, while in D a Flinn-diagram is illustrated. **A-** Form ellipsoid measured in XY plotted against the angle ϕ'. **B-** Form ellipsoid measured in XZ plotted against the angle ϕ'. **C-** Form ellipsoid measured in YZ plotted against the angle ϕ'. **D-** Flinn-diagram, with the average clast shape plotted in the apparent constriction or prolate field. Abbreviations: R=ellipsoid, f=final, i=initial, F=fluctuation, ϕ'=orientation of the long axis of the deformed ellipsoid with the maximum principle stress, s=standard deviation, G=geometric mean, H=harmonic mean, A= arithmetic, min=minimum, max=maximum. The geometric, harmonic and arithmetic calculated means, assist in the superimposed strain (R_{strain}) calculation.

Subhorizontal veins (V_3)

Another set of veins related to the "late" post D_2 brittle-ductile event forms a subhorizontal set (V_3). This type of vein set is concentrated at the margins and outside of the main high strain (and high F/R ratio) zones. The rocks cross-cut by this V_3 vein set are less altered then those within the shear zones, but there are still sufficient veins present to classify these areas as moderately F/R ratio domains. The veins are generally composed of actinolite, with diopside centres and microcline hematite dusted selvages. The veins are about half a centimetre width with irregular "Christmas tree" or "telegraph pole " selvages (Figure 4.10, see "tension gash"

section). The veins are developed in en échelon arrays up to a metre long and as "simple" large planar structures, depending on the structural setting. These veins cross-cut the layer parallel replacement veins (Figure 4.10D).

Two types of structural setting control the presences and characteristics of the subhorizontal veins (Figure 4.14). These are discriminated on the basis of the orientation of the fold plunge (subhorizontal or steep). In the field the relationship between the fold axis and the subhorizontal veins proves to be a useful tool in identifying the structural setting of small outcrops and megabreccia clasts (Table 4.2).

Figure 4.14 - Mechanism of subhorizontal vein formation. **A-** Veins formed in limb regions of upright folds, attributed to horizontal compression producing mullions and boudinage. **B-** Inclined folds with steep plunging fold axis are a result of shearing (or dragging). This causes torsion in the hinge region with development of en échelon fractures. **C-** Stress directions during crack propagation perpendicular to σ_3. The direction of the crack extension makes a small angle with σ_1, causing the en échelon character.

Subhorizontal veins perpendicular to the foliation within steeply plunging folds (Figure 4.10E, K) are slightly sigmoidal, and are orientated with an en échelon array geometry (Enclosure B). Steeply plunging fold axes occur west of the Maramungee shear zone, due to dragging of the layers. Torsion in the hinge zones of these inclined folds, created subhorizontal fractures (c.f. Olson and Pollard 1991). Veins can form (see section 4.3.2) when fluid pressure (P_f) have reached lithostatic pressure. However, veins can also form in a dilational crack where the fluid pressure

is instantaneously lowered, and fluids can than migrate inwards on the P_f gradient. The actinolite and diopside infill in the en échelon subhorizontal veins are randomly orientated. There was then no induced stress superimposed during the vein formation. So after sealing by new growth of fine grained granoblastic albite fluid was expelled from the shear zone towards the margins. The en échelon subhorizontal fractures, that was formed due to dragging coevally with the ductile shearing became "sinks" for the expelled fluid. The following P_f conditions are required to maintain the fractures to stay open (Etheridge 1983, Etheridge *et al.* 1984, Valenta 1987, Sibson 1989): i) P_f must approach lithostatic pressures, and ii) P_f must be larger than the combined tensile strength and the vertical principle stress in the rock.

The second type of subhorizontal veins is developed in limb regions with fold axes parallel to the extensional fractures (hence subhorizontal plunge). The fractures are formed by boudinage attributed by ongoing deformation. Boudinage structures are common in zones of large-scale penetrative deformation and are produced by extension of a more component layer within a more ductile host. Relict bedding within the Maramungee shear zone locally exhibits "fish mouth" boudins with extension parallel to the strike slip shear direction. This means that post-boudinage plastic deformation occurred. Mullions and extension fracture boudinage occur at the margin of the shear zone on the long limb of folds (Figure 4.10L, Figure 4.14). These extensional fractures are filled with actinolite and contain albite selvages. The fractures are planar and regularly spaced at centimetre scale and up to a few metres long and wide.

Vertical extension at the margin of the Maramungee shear zone caused mm-scale subhorizontal fractures to be filled with magnetite overprinting reconstituted rocks. These veins form the sink for iron expelled from the shear zone (section 3.3.1.2).

Tension gashes (TG) and crackle veins

Other types of veins that formed during the brittle-ductile "late" post D_2 include tension gashes and crackle veins. The geometry of tension gashes and the relationship with the orientation of the principle compressive stress has been studied by Durney & Ramsay (1973) and Ramsay (1980). Two styles of geometrical tension gashes are observed in high strain zones in the study area, namely slightly sigmoidal (TG_1, TG_2) and straight (TG_{3b}) shapes.

TG_1 tension gashes are composed of quartz and titanite (Figure 4.15A and Figure 5.1). These veins are evidence that Ti can be mobile under certain physicochemical conditions (high temperature and salinity, Chapter 5). Hence, titanite is also a product of the sodic-calcic alteration in the reconstituted rocks. These veins have only been observed in the western part of the Maramungee Creek section. The dilations are located on a parasitic limb verging to the east and are cross-cut by an albitized granite dyke (P.J. Williams pers. com. 1994). A possible mechanism for formation, based on their location and orientation relative to a minor antiform, is flexural slip on the limbs which caused the dilation. The timing of this vein set is enigmatic. The host rock is an altered CS_h-A overprinted by the V_{2b} veins, which also overprint the quartz, titanite (TG_1) tension gashes. The quartz exhibits undeulose extinction and numerous healed fractures with fluid inclusions. These dilations occurred after the main ductile shearing and alteration phase but before the main brittle-ductile phase, indicating a minor or local intervening deformation stage.

TG_2 tension gashes are composed of actinolite with infill of quartz and albite in the most dilated fractures. The selvages of these veins are composed of hematite free albite in the altered calc-silicate rocks (CS_h-A), while in moderately altered calc-silicates they consist of hematite dusted microcline (Figure 4.1 and Figure 4.15B); this is probably due temperature controlled, see Chapter 5 and 8. A dextral strike slip movement is obtained, based on the orientation of these tension gashes relative to the foliation. This agrees with the direction of movement, developed from the V_{2b} and V_{JB} vein sets described previously, and which probably formed coevally.

The "straight" tension gashes (TG_{3b}) are orientated subparallel to S_3, perpendicular to the foliation and clearly overprint the main sodic-calcic brittle-ductile alteration event (Figure 4.1). They are therefore formed in a late fracturing event. The constituents of these straight tension gashes are distinct from those previously described and represent a lower temperature (280°C) stable assemblage (Chapter 6), composed of K-feldspar, hematite and quartz (Figure 6.1). These veins may be coeval with the K-feldspar-quartz-filled Riedel fractures formed during post D_3 sinistral shearing on the Cloncurry fault.

Figure 4.15 - **A**- Sketch of quartz-titanite tension gashes, TG_1 (see also Figure 5.1C), hosted by altered calc-silicate rocks, located on a the limb of a parasitic antiform at the western part of the Maramungee Creek section. The tension gashes cross-cut by an albitized granite dyke and V_{2b} type veins. **B**- Sketch of tension gashes caused by layer parallel shearing, and are composed of actinolite, quartz and albite, with "telegraph pole" hematite dusted microcline selvages (Maramungee Creek section). **C**- Crackle / net veining in altered corundum bearing schist in the breccia clasts at Mallee Gap. The dominant vein set perpendicular to the foliation is probably a V_1 type and the layer parallel veins V_2. This is possibly a hinge zone structural setting. **D**- Crackle veining at the margin of a metadolerite body in the Maramungee Creek section. Abbreviations, Ab - Albite; Act - Actinolite; Ttn - titanite; Qtz - quartz.

Crackle veins were only observed in metadolerites and in brecciated altered schist. Crackle veining in clasts of altered corundum bearing schist, occurred prior to the megabrecciation stage. The veins are orientated in an orthogonal crackle vein system, in which one set is orientated perpendicular to the foliation while the conjugate set is parallel. The vein set perpendicular to the foliation is dominant and more consistently developed. Layer-parallel veins are discontinuous and interconnect with the dominant set (Figure 4.15C). The veins are composed of actinolite in more dilated fractures with hematite dusted microcline selvages. Transposed bedding, S_2 crenulations and L_2^1 parallel to the dominant vein set suggests it is likely that this crackle veining is located in a (re)brecciated hinge zone, with the dominant vein set forming axial planar veins (V_1) and the conjugate layer parallel set as V_2 type veins (see Table 4.1).

Sheared crackle veining, composed of andesine and hornblende overprinted by marialitic scapolite, also occurs at the margins of large metadolerite bodies and (Figure 2.10C, Figure 4.15D). Stress induced on this type of rigid body has been studied by Oliver *et al.* (1990a-b) who pointed out that intense alteration is localised at the margins of metadolerites due to increased permeabilities. This was induced by relatively high differential stresses, which caused extension in both horizontal and vertical directions approximately within the foliation plane, and reflects ductility contrasts between the metadolerite bodies and the calc-silicates.

4.3.1 - Discussion on veining and alteration

Veins are fossils channelways in which a fluid phase passed through rocks. Veins can be divided into two end members: 1) open space fractures in which fluids can pass rapidly, 2) or as an intra-rock connecting "diffusive" (slow) pathway. Both of those endmember vein types are observed in this study; except for the layer parallel veins, the veins are open space fractures. Layer parallel replacement veins and the frequent occurrence of selvages are the evidence that the second endmember (intra-rock fluid movement) also took place. These selvages and replacement veins are the actual alteration features. The degree of alteration, especially in the case of selvages, is therefore dependent on the vein density (high fluid/rock ratio). The geometry of the selvages along the extensional veins depends on two main types of control, namely structural (Table 4.2) and chemical. Structural controls on selvage geometries are:

1) The orientation of the vein relative to the host rock fabric. Veins that are parallel to, or make a small angle with the host rock fabric have more irregular and narrow developed selvages. This is due to an anisotropy in permeability along and perpendicular to the host rock fabric, attributed to alignment of platey minerals such as amphiboles and micas. It will be easier for a fluid to flow along than across the foliation. Veins that make high angles with the host rock fabric have well-developed selvages. These selvages look like "telegraph poles" or "Christmas trees" and selectively replace certain layers.

2) The anisotropy of the host rock also plays a role in the geometry of the selvages. In isotropic rocks, such as unfoliated granites or metadolerites, selvages around veins will be irregular and can be pervasive. The spacing of the fabric in isotropic rocks, such as foliation in metasediments or layering and banding in mylonitic rocks (Maramungee shear zone), is an other factor that dictates the geometry of the selvages. Where there is a fine spaced foliation or differential layering, fluids will selectively replace certain layers. The fine spacing, however, gives the selvage a "Christmas tree" appearance. Selective replacement of a more widely spaced, or banded host fabric will develop a more "telegraph pole"-like selvages.

The chemical factor is the main controlling factor in replacement. The chemical control is a combination of factors, namely 1) the composition of the host rock, 2) the physicochemical conditions of the fluid (temperature, salinity, composition), 3) the amount of fluid/rock interaction. The fact that all rock types (schist, marble, calc-silicates, metadolerites, granites) in the eastern part of the Cloncurry-Selwyn terrain that have been infiltrated by the fluids during the post D_2 early shearing and late post D_2 brittle-ductile deformation events, are altered, indicates that the fluids are responsible in altering the rocks. Focussing of the fluids in particular structures is therefore of importance in causing reconstitution of the rocks in those structures.

Table 4.2 - Diagnostic features of veins in relation to orientation and selvage development.

Vein Type	Rock fabric	Lineation	Selvage	Type	Comment	Christmas versus Telegraph pole
V_1 - Axial planar	perpendicular	parallel	good	Christmas tree	Hinge zones	
V_2 - Layer parallel	parallel	parallel	poor	Irregular	Replacement + extension	
V_3 - Subhorizontal	perpendicular	parallel	good	Telegraph pole	Boudinage on limbs	
V_3 - Subhorizontal	perpendicular	perpendicular	good	Telegraph pole	Hinge zones, en échelon	

N.B. "good" means that the vein selvage is well developed with a large selvage-length/vein-width ratio. "poor" means that the vein selvage is not strongly developed with a small selvage-length/vein-width ratio. The selvage-length/vein-width ration is relatively larger for the telegraph pole (B) then for the Christmas tree (A).

4.3.2 - Mechanisms of vein formation

The minerals in extensional veins indicate post D_2 greenschist facies conditions during vein formation (Chapter 5). The fact the vein mineral composition reflects high temperatures, is an indication that high temperature fluids *were* present during fracture formation and that infill occurred simultaneously. Extensional veins indicate that the fluid pressure, P_f, must have been close to the lithostatic pressure, P_l (Etheridge *et al.* 1984). An increase in pore fluids pressures (relative to lithostatic pressures) will decrease the effective normal stress, σ_{eff}, (Etheridge *et al.* 1986),

$$\sigma_{eff} = \sigma_n - P_f$$

were σ_n is the normal stress acting on a surface. The change in of the rock rheology will change the effective principle stresses,

$$\sigma_1' = (\sigma_1 - P_f) > \sigma_2' = (\sigma_2 - P_f) > \sigma_3' = (\sigma_3 - P_f)$$

If the fluid pressure increases, due to unroofing, than the effective stress will move to the left in a Mohrs diagram intersecting the failure envelope. If this happens in a compressional field, shear failure will occur, however if the effective stress difference is low, tensional failure could occur. Extensional fracturing occurs if the pore pressure is higher than the minimum principle stress plus the tensional strength of the rock,

$$P_f \geq \sigma_3 + T'$$

where σ_3 is the minimum principle stress and T' is the tensile strength, including planar elements such as cleavage and bedding (Valenta 1989). These criteria allow for dilatancy subparallel to the maximum compressional stress (e.g. V_1 and V_2 type veins).

4.4 - Brittle deformation and regional brecciation

Previous sections dealt with the ductile and brittle-ductile deformation affecting the eastern part of the Cloncurry-Selwyn terrain. This section describes the brittle phase. The timing of this brittle phase has been deduced from observations of deformation stages present in clasts prior to brecciation (Figure 4.6 and Figure 4.16). The onset of this main regional brecciation event occurred after "late post D_2". Fractures and breccia dykes perpendicular to and subparallel to the S_3 cleavage that overprint the megabreccia coupled with the occurrence of brecciated granites in the Doherty Formation, indicate the synchronous nature of the main brecciation stage with the D_3 deformation and granite emplacement. Riedel fractures filled with K-feldspar are

not affected by regional megabrecciation indicating that the regional brecciation ceased activity prior to post D_3 sinistral movement on the Cloncurry fault.

The regional brecciation is concentrated in zone A (Figure 3.6B). In the southern part of the eastern Cloncurry-Selwyn terrain the megabreccia clasts are located in two broad zones, one at the contact with the Squirrel Hills granite, which runs parallel to the Cloncurry fault, and the other at the highly strained tectonic contact between the Doherty Formation and the Maronan supergroup. These zones join north of the Boorama Waterhole area, where there is evidence for extensive high level granite intrusions (Figure 3.6). D_2 structures host this brecciation on a more local scale. This is apparent in the Fullarton River area, were megabreccias occur in limb regions and the "nose" of a northwest plunging D_2 antiform (Figure 1.7 and 1.8).

This regional brecciation process occurred at a relatively high crustal level, accompanied by geothermal activity. This is supported by the occurrence of high level granites that are affected by the brecciation (Figure 1.9) and by the presence of high temperature minerals, such as actinolite and diopside in the breccia matrix (Table 4.3). Cavities in the matrix are interpreted to be a result of devolatization coeval with the brecciation process and are filled with inward growing albite crystals and calcite (Figure 2.6H). The similarity of the mineral assemblage in the breccia matrix (albite, actinolite and diopside) and the alteration minerals formed during early and late post D_2 (albite and actinolite), is striking. This similarity can be interpreted as separated fluids with matching composition being active, but it is more likely that a single fluid controls the alteration and brecciation mineral composition and assemblages.

Extensional veins that overprint the breccia complex, were formed at different temperatures and variable X_{CO_2}, which is reflected in their compositions (Table 4.1). High temperature and low X_{CO_2} activity veins have compositions quite similar to the veins formed during the brittle-ductile late post D_2 stage (quartz, albite, titanite, actinolite, diopside). The second type of vein reflects lower temperatures and higher X_{CO_2} activity and are composed of epidote, prehnite, calcite, quartz with traces of titanite and albite (Chapter 5).

4.4.1 - Classification of the breccias

The classification of breccias used in this study is based on features including the process through which the different breccia types were formed, the general

characteristics of the form and shape of the breccia body, the shape, dimensions and composition of the clasts, and the texture and composition of the matrix (Table 4.4). "Megabreccias and milled breccias" are the most commonly observed type of breccias in the Doherty Formation and are well exposed in the Fullarton River gorge (Figure 1.8, Figure 2.6D and Figure 4.16).

Table 4.3 - Alteration minerals formed during the ductile and brittle regional alteration stages (stages will be described in Chapter 5).

	DUCTILE			BRITTLE			
Alteration	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7
Minerals / veins		V_{1-3}, V_{jb}	TG_{1-3}		syn post D_3 veins	TG_{3B}	
Oligoclase	----------	----					
Albite	---	----------	----------	----------	----------	---	
K-Feldspar		----------				----------	-----
Marialite		----------					
Actinolite	----------	----------	----------	----------			
Diopside		----------	----------	----------	----		
Magnetite		----------	----------	----------	-------		
Hematite		----------				----------	----------
Titanite		----------	----------	----------			
Epidote			--------	----------	----------		
Allanite					----------		
Prehnite					----------		
Apatite		----------	----------	----------			
Calcite				----------	----------		----------
Quartz	----------	----------	----------	----------	----------	----------	----------
Sulphides							----------
CONTROLS	Shear zones, extensional veins < 4 kbar, 450°-550°C			Fluid pressure, unroofing, tensile failure < 2 kbar, < 300°C			

The term *megabreccia* is used because of the large clasts size, locally up to tens of metres in diameter, though they are more typically less than ten metres. The brecciation affected all rock types and relict deformed fabrics in the clasts provide the timing relationships. Macroscopic contacts between the matrix and clasts are sharp, but are gradational microscopically. Larger clasts are angular and unaltered, while small clasts are altered and subrounded. The matrix is generally massive and in places exhibits a pseudo-igneous texture. Weak foliations / fracturing subparallel to S_3 and S_2 also occur in the Fullarton River gorge (Figure 1.8).

The *milled breccias* have subrounded to rounded clast, varying in size up to 50cm and are matrix supported. The clasts are partly to totally altered to albite or actinolite / diopside. The term "milled" is used because of the rounded character of the clasts, though significant transport of clasts is not believed to have occurred. Mixed precursor clast types are only observed in areas were the brecciation overprinted lithological contacts. Abrasion is attributed by chemical reactions of the clasts with the matrix.

Breccia dykes are vertical planar dilational structures that overprint the megabreccias and milled breccias. The matrix has a pseudo-igneous texture with no fabric and is composed of albite, and anhedral to euhedral diopside and actinolite. Clasts in the breccia dykes are not frequently observed. The clasts in these breccia dykes are matrix supported and altered, generally to albite. Occasionally the breccia dykes branches out at the tip (Enclosure C), with an increase in the proportion actinolite / diopside infill at the tips. Absence of fractures at the tip is more common. This is a typical characteristic phenomenon of hydraulic fractures caused by a viscous fluid at high crustal level (Pollard 1973).

Table 4.4 - Classification of breccias in the eastern Cloncurry-Selwyn terrain.

Type	Characteristics	Clasts	Matrix	Tectonic setting	Process
Vein jog breccia	Narrow and planar with albite selvages. Related to brittle-ductile event	Deformed, altered, prolate subrounded albite clasts, < 10cm	Aligned Act and Ab.	Dilations in brittle-ductile late post D_2 high strain zones	Hydraulic Tectonic
Net vein / crackle breccia	Anisotropy and tensile strength of host rock dependent. High vein density	Altered clasts, shape dependent on host rocks; rectangular in schist, rhombohedral in metadolerites	Vein infill, in schist and in some cases metadolerites, aligned Act infill. In the latter commonly albitic to andesine plagioclase. In granites cracks with Ab	In hinge zones of anisotropic rocks; at margins of shear zones and lithology contacts with contrasting competency Granite roof	Hydraulic Tectonic
Mega-breccia	Regional occurrence, affecting all rock types: unaltered and altered schist, calc-silicate, marble, metadolerites and granites	Large, up to tens of metres in diameter, angular and "unaltered". Predominantly matrix supported	Fine grained Ab and Act ± Di ± Cal, weakly foliated with pseudo-igneous texture.	Strained and sheared tectonic contacts; accommodated in D_2 structures; roof pendent of high level granites	Tectonic Hydraulic
Milled breccia	Zones 20-100m wide	Subrounded to rounded clasts (< 50cm); matrix supported; locally polymixed	Weakly foliated and unfoliated; Ab, Act and Di; Ab/(Act+Di) is host rock dependent	Bound by high strain zones; at lithological contacts	Tectonic Hydraulic Chemical
Breccia dykes	Narrow planar; sharp boundaries with narrow to absent reaction rims; cross -cut the megabreccias	Angular to subrounded; matrix supported; altered clasts	Non to weakly foliated composed of Ab, Act, Di ± Cal, with pseudo-igneous texture	NNW-SSE	Hydraulic Tectonic
Fault breccia	Cloncurry fault related; silicification	Rebrecciated	Silica / chalcedony, Hem, Kfs, traces of Ab	High crustal level; low temperature	Tectonic Hydraulic

Abbreviations: Ab - Albite; Kfs - K-feldspar; Act - Actinolite; Di - Diopside; Cal - Calcite; Hem - Hematite

The abundant carbonate content in the megabreccia matrix, relative to clasts assemblages formed during the post D_2 ductile and brittle-ductile stages, points to a fluid phase that became relatively enriched in CO_2 (Chapter 5). Cooling and/or pressure reduction, due to possibly unroofing, of an aqueous-CO_2 solution can lead to separation into an aqueous-rich fluid and a CO_2-rich vapour. This may result in vesiculation and boiling, and hence precipitation of carbonates in the vugs.

Figure 4.16 - Traverse maps of part of the rock platform in the Fullarton River gorge showing different styles and overprinting relationships in the megabreccia complex. Second phase sodic-calcic alteration forms megabreccia in rocks that had previously undergone similar alteration in a more ductile environment. Abbreviations, Ab - albite; Act - actinolite; Amp - amphibole; Cpx - clinopyroxene.

Outcrop sketches from
rock platforms in the
FULLARTON RIVER GORGE

Line 1

Line 2

Line 3

LEGEND

- Altered schist
- Calc-silicate rocks
- Metadolerite
- Breccia dykes
- Cpx-Amp clasts / pods
- Albite clasts / pods
- Fractured zone
- Veins / fractures
- Veins with selvage

0 metres 5

4.4.2 - Mechanism of brecciation

The formation process of breccias that formed the Doherty Formation, was a result of interaction between the lithostatic pressure and the fluid pressure. The lithostatic pressure is depth dependent and reflected in the style of faulting and brecciation processes, e.g. from ductile mylonitic regimes to a brittle-ductile, brittle pseudotachylite, cataclasite and fault gauge breccia regimes. Breccias are always formed by a brittle process, associated with dilation. However the onset of dilations can occur in a ductile regime, as with the vein jog breccias.

The orientations and locations of the breccia zones indicate tensile failure was accommodated on post D_2 structures. Breccia dykes perpendicular to S_3 and subparallel to S_2 formed by extension perpendicular to the σ_3 of the D_3 strain ellipse. The vein mechanism analogy can be used in the brecciation process. Periodic seismic pumping (Sibson 1994, Wood 1994) along basement faults, such as the Cloncurry fault and major shear zones, could have generated the increased fluid pressures and accompanying stress relaxation required for tensile failure to occur.

The spatial association of the breccia occurrences with high level granite intrusions, suggest a magmatic component in the breccia formation. Pseudo-igneous textures of the matrix and mega clasts floating in the matrix, can be generated as a consequence of evolution of an intrusive complex (Blake *et al.* 1982, Laznicka 1989). The pseudo-igneous texture of the matrix was explained by Blake *et al.* (1982), as recrystallized partial melt derived from calc-silicate rocks. However, a hot viscous fluid injected and focussed at rock contacts (Figure 4.17), would give a melt intrusion appearance.

4.5 - Summary

Unroofing produced a regional brecciation and alteration complex in the eastern part of the Cloncurry-Selwyn terrain. This Proterozoic terrain has undergone several major ductile and brittle regional deformation events, with peak metamorphism reaching the upper amphibolite facies, during the D_2 deformation phase.

The eastern part of the Cloncurry-Selwyn terrain is transected by major north-south trending ductile retrograde, greenschist facies shear zones and a brittle lineament, the Cloncurry fault. The ductile shear zones are concentrated in limbs of F_2 folds and are

active post D_2. These tabular shear zones in the predominantly calc-silicate rocks of the Doherty Formation are the locus for sodic-calcic alteration during the "early post D_2" sinistral ductile shearing event. Fluids active during this ductile shearing produced high mineral variance assemblages in the shear zone. Increased fluid pressure, due to unroofing resulted in brittle-ductile structures, such as veining and dilational jogs that overprint the earlier ductile features. Vein orientations are related to different structural styles and forming mechanisms, but are concentrated in and adjacent to the early post D_2 ductile shear zones. The composition of the vein infill (actinolite, albite, diopside, titanite) reflects the retrograde host rock assemblages, but are still indicating relatively high temperatures.

Uplift, possibly synchronous with the emplacement of granite intrusions during D_3, resulted in a reduction of the lithostatic pressure and increased fluid pressure. This resulted in the onset of regional brecciation by lowering of the effective differential stress which caused tensional failure.

Continued unroofing resulted in a telescoping effect with juxtaposing and/or overprinting of the earlier sodic-calcic alteration mineral assemblage with a later and shallower K-feldspar, quartz, chalcedony mineral alteration phases and an epidote, prehnite, calcite alteration phase. These phases are partly structurally controlled in Riedel extensional fractures attributed to post D_3 sinistral movement of the Cloncurry fault.

Figure 4.17 - Photograph of fluid injection at the lithology contact, between a granite and laminated calc-silicate rock. Located in the Fullarton River gorge.

CHAPTER 5

CHAPTER 5 - SODIUM-CALCIUM METASOMATISM AND ALTERATION PARAGENESIS IN THE CLONCURRY-SELWYN terrain

5.1 - Introduction

Shear zones and associated breccia complexes (see Chapter 4), control the post D_2 sodic-calcic alteration in the eastern part of the Cloncurry-Selwyn terrain. This alteration is a result of fluid infiltration that caused retrograde greenschist grade alteration to overprint amphibolite grade rocks, and form a high variance mineral assemblage. Altered rocks consist mainly of albitic plagioclase with actinolite and/or diopside, associated with minor magnetite and titanite. All rock types in the Doherty Formation, and to a lesser extent the syn to post D_3 felsic intrusive phases, are affected by this type of alteration.

Absolute dating of the duration of this sodic-calcic alteration event has not been done. However relative timing, in relation to the major deformation events in the Mount Isa Inlier establish the "approximate" age as between 1580 and 1480 Ma (Page 1994).

This chapter describes the effects of the alteration on the calc-silicate rock types. The geological setting dictates the degree of albitization / alteration. This albitization is defined as in situ (calc-alkali) metasomatism, attributed by infiltration of hot saline fluids in country rocks adjacent to shear zones. Shear zones are the conduits for fluid channelling and locations of major mass transfer (Chapter 4). A high degree of albitization is located in shear zones and breccia complexes, while infiltration of alteration fluids away from the shear zones caused a less intense albitization. This is evident from petrographic observations and geochemistry.

The first part (section 5.2) of this chapter deals with the chemistry and physicochemical conditions of the alteration mineral assemblages. The second part (section 5.3) observes the bulk chemical changes by means of whole rock analyses. The third part (section 5.4) deals with the alteration in the metadolerite rocks and associated rare earth element (REE) behaviour. Part four (section 5.5) touches on some chlorine bearing minerals and the implications on the composition of the equilibrium fluid.

5.2 - Alteration stages and mineral paragenesis

Based on the overprinting relationships in combination with the mineral paragenesis (Table 5.1), seven stages of alteration are recognized. These stages are summerized as followed.

Stage 1: Na-Ca(±Mg±Al) alteration related to shear zones
Post D_2 ductile shear zones in calc-silicate rocks in the Doherty Formation consist of oligoclase-actinolite(±diopside) mineral assemblages. Focussing of saline fluids (see Chapter 6) in these ductile post D_2 shear zones (see Chapter 4), resulted in the high mineral variance assemblage. Transposed schist with quartz lenses and biotite-corundum lenses with albite rims occur at the Maronan supergroup - Doherty Formation.

Stage 2: Na-Ca(±Mg±Fe±Ti±?K) alteration related to veining and breccia dykes
Axial planar, layer parallel and subhorizontal veins cross-cut the post D_2 shear zones (see Chapter 4). The central part of these veins consists mainly of actinolite, albite, diopside and quartz (± magnetite). Selvages of these veins consist in the shear zone of albite and marialite. These actinolite-diopside high temperature veins further away from the shear zones (main fluid conduits), contain hematite-dusted microcline (with "cross-hatch" twinning) selvages.

Stage 3: Na-Ca-Si-Ti(±Fe±P±Mg) alteration related to veining
Shear related tension gashes filled with mainly quartz-titanite and traces of apatite and actinolite. These veins overprint stage 1 (see Chapter 4).

Stage 4: Ca-Mg-Na(±Fe±Ti±CO_2) alteration related to megabrecciation
This is the main brecciation stage, which contains diopside, actinolite, albite, magnetite, titanite in the matrix. Vughs filled with calcite. The breccia matrix has a "pseudo-igneous" texture, due to euhedral diopside and actinolite.

Stage 5: Ca-Fe-Mg-Na(±CO_2) alteration related to veins and vughs
Epidote, prehnite, calcite veins cross-cut the breccia of stage 5. Irregular fractures are filled with acicular tremolite needles.

Table 5.1 - Stable mineral assemblage of the different alteration stages in the eastern part of the Cloncurry-Selwyn terrain. Temperature estimates are from fluid inclusion data (Chapter 6) and phase stability diagrams. Pressure estimates are based on Al in hornblendes (Chapter 3) and phase stability diagrams.

Table 5.1 - Stable mineral assemblages of the various alteration stages in the Eastern Cloncurry-Selwyn terrain.

Stage	Mineral Occurrence	Host Rock type	Control /Setting	P / T	Type-Location
STAGE 1	Oligoclase, actinolite ± diopside.	Laminated calc-silicate, retrograde schist and trondhjomite granite dykes.	Post D_2 high strain zones and lithology contacts. Focussing of NaCl rich fluids in shear zones.	3-4.5 kbar 450-550°C	MC-sz
STAGE 2a	Actinolite, albite ± magnetite ± titanite ± marialite (± diopside).	Metasomatic rocks from stage I.	Post D_2, layer parallel shearing in strain zones, creating veins parallel to the layers;.	2.5-3 kbar 500°C	MC-sz, MG-area, FR-gorge
STAGE 2b	Actinolite (± diopside) veins with rims of albite ± magnetite.	Metasomatic rocks from stage I altered schist ± corundum ± tourmaline.	Post D_2 axial plane veins, with alignment of the vein minerals. Telescoping effect controls microcline.		MC-sz, MG-area, FR-gorge
STAGE 2c	Actinolite / tremolite ± diopside veins with rims of hematite dusted microcline.	Moderately altered calc-silicate rocks.	Subhorizontal veins and dragging of foliation adjacent to shear zones.		MC-sz
STAGE 2d	Albite clasts in actinolite / tremolite matrix ± magnetite ± apatite, with hematite dusted albite rim. Actinolite concentrated in dilations.	Metasomatic rocks from stage 1, metadolerites and altered granites.	Breccia dykes. Dilational jogs due to shearing. Relative sharp boundaries with narrow selvages.	P_{fluid} ↑	MC-sz, Boorama W
STAGE 3a	Albite, quartz, titanite, magnetite ± actinolite ± diopside ± apatite.	Metasomatic rocks from stage 1, stage 2 and altered schist.	Post D_2 fluid focusing in reactivated D_1 strain zones; contains D_2 folded and crenulated clasts.	P_{fluid} ↑ and/or $P_{lithostatic}$ ↓ due to unroofing	MC-sz, MG-area, FR-gorge
STAGE 3b	Quartz ± titanite ± diopside ± albite.	Altered calc-silicate rocks.	Tension gashes due to post D_2 shearing.	450°C	MC
	BRITTLE	DUCTILE	TRANSITION		
STAGE 4	Diopside, actinolite, albite ± magnetite ± epidote ± allanite ± calcite, no selvage ± chlorite.	Breccias of stage 3a.	NW-SE trending breccia dykes due to sinistral strike slip movement of the Cloncurry fault.		FR-gorge
STAGE 5	Epidote in veins ± prehnite ± quartz ± albite ± chlorite ± talc.	Altered calc-silicate rocks and metadolerite.	Oxygen activity increase and CO_2 decrease. NW-SE trend.	T< 400°C P< 2 kbar	MC-sz, FR-gorge
STAGE 5b	Tremolite needles, Mg-calcite.	Overprinting the breccia matrix.	Veins and vugs.	Decreasing P-T	FR-gorge
STAGE 6	K-feldspar ± hematite ± quartz.	Calc-silicate, granites and metasomatic rocks from stage 1.	R_1-riedel shear veins due to sinistral movement of the Cloncurry fault; affecting the Williams granite, creating post D_3 tension gashes.	300°C	Boorama W, MG-area, MC-sz
STAGE 7	Quartz, sulphides.	Cloncurry fault.	Cloncurry fault; reactivated D_1 fault (?).	300-350°C	CCY-fault, MP

N.B. Abbreviations of type-section locations are given in the "sample list" appendix.

Stage 6: Si-K-Fe alteration related to Riedel fractures
Fractures on a NW-SE trend (R_1-Riedel veins) are filled with red, hematite dusted K-feldspar and quartz. The fractures vary in size, from microscopic to metres scale. The K-feldspars are pericline twinned.

Stage 7: Si-Fe-S alteration related to veins and fractures
Quartz veins on a NNW-SSE trend, locally containing sulphides.

The overprinting alteration stages are both, structurally and physicochemically controlled. Structurally controlled alteration in relation to various overprinting ductile-brittle veining events is described in Chapter 4. Telescoped alteration is found adjacent to the early ductile, sodic-calcic altered, shear zones, and occasionally in the shear zones and brittle-ductile breccia matrix. The common overprinting alteration minerals (stage 5-7), such as, microcline / K-feldspar, epidote, calcite ± prehnite, are stable at lower temperatures than the earlier albite-actinolite/diopside alteration stage (stage 1-4). The scale at which the alteration occurs varies. Chapter 4 illustrated that the early alteration affected tens of metres wide shear zones, but also occur as narrow selvages around veins.

5.2.1 - Stability and chemistry of the alteration minerals

Representative minerals of the various alteration stages were analysed by microprobe. This is to understand the relationships and reactions between the overprinting alteration stages and the chemical changes associated with these reactions. Compositional variations in the mineral chemistry of feldspars, amphiboles, clinopyroxenes, titanites, iron-oxides, epidotes, carbonates, prehnites and chlorites, are described below.

The feldspar series
Albitic plagioclase is the earliest recognized major alteration mineral (stage 1). Plagioclase analysed has an anorthite content ranging from 0-38 An%. Andesine is found solely in the pristine calc-silicate rocks (CS_l-A), and occasionally in crackle veins at the margins of large metadolerite bodies (see Chapter 2, Figures 5.1 and 5.2).

Alteration plagioclase in the "moderately altered" calc-silicates (CS_m) consists of granoblastic plagioclase coexisting with (possibly) relict metamorphic K-feldspar,

and (? alteration) microcline. Strongly deformed "altered" calc-silicates, exhibit layer parallel grain size variations, which is possibly vein controlled (type V_2, stage 2). Internally the albite crystals are granoblastic with weakly developed deformation lamella. The larger albite crystals are occasionally poikiloblastic, with quartz and (early) plagioclase inclusions, and could be as thick as the layer. Subgrains developed at the margins of the large crystals, at the contact between the fine and coarse grained albitic layers. Hematite and calcite (stage 6 and 4) selectively overprint the larger crystals. This is in contrast to smaller "clean" granoblastic albite crystals. This variation could reflect recrystallization after post D_2 layer parallel shearing, in which the finer grained layers are more strained and subsequently recrystallized. Albitic plagioclase in the pseudo-igneous breccia matrix (stage 4) composes of almost pure albite. There are two distinct albite textures, a "chess-board" texture which gets overprinted by more granoblastic albite (with albite twinning, Figure 5.2). This texture is possibly a result of deformation before the recrystallization of granoblastic albite.

Figure 5.1 - Histogram of anorthite percentage in plagioclase. Note that the late stage breccia matrix related plagioclases are more albitic than the earlier oligoclase alteration plagioclase. "n" is the amount of samples / rocks analysed.

The observation that the overprinting plagioclase of the breccia matrix is more albitic than the early oligoclase located in shear zones, fits well with the experimental data of Liou *et al.* (1974). They demonstrated (for a closed system) that at the amphibolite-greenschist transition the anorthite percentage in plagioclase decreases (from oligoclase to a more albite composition, Figure 5.1).

Alkali feldspars

Two crystallographic types of K-feldspar are observed in the altered rocks, namely microcline crystals with "cross-hatch" twinning and orthoclase with occasionally pericline twinning. Microcline occurs adjacent to major fluid conduits, such as albite-actinolite containing shear zones and as selvages of actinolite-diopside veins, whereas orthoclase with pericline twinning occurs in specific veins and layers (Figure 5.2, stage 6). The latter type is also more often reddish in appearance (due to hematite dusting), and can easily be mistaken for hematite dusted albite. The origin of the granoblastic microcline in the "moderately altered" calc-silicate, coexisting with the granoblastic albite (Figure 5.2B), is still enigmatic. These microclines could be of metamorphic origin.

Relationship between sodic and potassic alteration

Alkali feldspar solvus curves discussed by Parsons (1978), illustrates that end-member feldspars, e.g. albite and K-feldspar, are stable at approximately similar temperatures (Figure 5.3). Whitney and Stormer (1977) studied the effects of temperature on the structural state of microcline and the partitioning of albite between microcline and plagioclase solid-solutions. Their findings indicated that the more disordered microclines are not stable at temperatures above 500°C, and that most natural feldspars with this disordered state precipitated from a hydrothermal solution. This could mean that the microcline observed in the alteration matrix formed below these temperatures, and precipitated from a solution. Experimental and theoretical work by Orville (1963) and Carten (1986) on the K/K+Na alkali ion exchange between fluid and feldspars demonstrated that varying salinities and pressure have minimal effect on the distribution. From Orville's (1963) experimental distribution curves, it becomes clear that the fluid in equilibrium with albite must have had a K/K+Na < 0.2, while a fluid composition with a K/K+Na > 0.2 would precipitate K-feldspar at similar temperatures (Figure 5.3).

Figure 5.2 - Microphotographs of feldspar alteration textures. A- Sample DP#44658. Microcline with "cross-hatch" twinning coexisting with albite (?). **B**- Sample DP#44672. Grain size differences of albitic plagioclase crystals, parallel to the layering, and are possibly veins (stage 2). **C**- Sample DP#44680. Contact between large albite crystals and granoblastic fine grained albite crystals. Note the forming of subgrains at the margin of the large crystal. **D**- Sample DP#446322. "Altered" schist with relict feldspar crystals and magnetite stringers. The albite crystals are recrystallized to a fine grained and granoblastic texture (stage 1). Magnetite veinlets (stage 2) cross-cut the strongly foliated rock. **E**- Sample DP#46315. Breccia matrix with two types of albite textures. Granoblastic albite with albite twinning (stage 4) overprints earlier "chess-board" albite. **F**- Sample DP#46307. Vein controlled alteration overprinting style; microcline vein cross (stage 6) cutting albite in pseudo-igneous breccia matrix (stage 4).

A
Mc
Ab
B
Di
Ab
Ab
C
Act
Ab
D
Mag
Ab
relict Plg
E
Ab
chess-board
F
Mc
Ab

Fluids in the major fluid conduits, such as shear zones and open-space veins, were possible higher than similar compositional fluids infiltrated in the selvages around these fluid conduits. This could explain the early microcline, which should not be in equilibrium with the albite-actinolite alteration.

However, at one location in the Mallee Gap area, the transposed biotite-corundum-bearing schist with relict sillimanite nests, albite veins overprint andalusite veins with K-feldspar reaction rims (Chapter 2, Figure 2.4D).

Figure 5.3 - A- Fluid composition versus alkali distribution curves after Orville (1963). This diagram illustrates that with a fixed fluid composition, cooling of the fluid would first precipitate albitic plagioclase followed by K-feldspar. **B-** Alkali feldspar solvus after Parsons (1978).

Amphibole series

Amphiboles (Figures 5.4) are another common mineral group that is characteristic for the regional sodic-calcic alteration. With evolving alteration, the amphiboles become progressively more Mg and Si rich, while Al and Fe are decreasing. The continuous lowering of the Fe/Mg ratio is possibly linked to the coeval crystallization of iron-oxide phases such as, in the earlier stages magnetite and later hematite.

Metamorphic dark green pleochroic magnesio-hornblende amphiboles occur in the "pristine" calc-silicate rocks and in metadolerites. The latter contain up to 1.6 wt.% TiO_2. High strain zones with high fluid/rock ratios contain green pleochroic actinolite (stage 1) interstitial to the granoblastic albite (Figure 5.5). Coeval intergrowth of actinolite with clinopyroxene, locally occur in the coarser albitic plagioclase layers (see plagioclase section above). Colourless to pale-green

actinolites occur as euhedral crystals in the overprinting breccia albite-actinolite/diopside matrix (stage 4). The pale green colour of the actinolites coincides with increasing MgO content (stage 5). Some of these late stage actinolites are zoned with slightly darker rims having elevated Na content, reflecting a more complex crystallization pattern. Al and Fe decrease with increasing alteration, similar to the ones observed in the calc-silicates.

Figure 5.4 - Compositional variation diagram, based on Leake (1978) amphibole classification. Amphiboles in the reconstituted "altered" calc-silicates, breccias and partly the "moderately altered" calc-silicates are of magnesium rich actinolite. Some "moderately altered" and "pristine" rocks have a more actinolitic-hornblende, to hornblende. Some late acicular amphiboles overprinting the pseudo-igneous breccia matrix are tremolites. "n" is amount of rocks analysed. For calculation of Fe^{2+}, see Appendix C.

Figure 5.5 - Microphotographs of amphibole and clinopyroxene textures. **A**- Sample DP#44652, Maramungee Creek. Granoblastic "clean" albite with interstitial actinolite occurs in "altered" calc-silicate rock. **B**- Sample DP#46336, Boorama Waterhole. Sample taken from a breccia dyke in granite. Clinopyroxene and actinolite are coeval (?), or clinopyroxene is replacing actinolite. Note the concentration of magnetite (black spots) in the clinopyroxene. **C**- Sample DP#46312, Fullarton River Gorge. Pseudo-igneous breccia matrix. Relict actinolite occur in euhedral diopside cores. Calcite overprints diopside. **D**- Sample DP#46312, Fullarton River Gorge. Pseudo-igneous breccia matrix. Euhedral diopside and actinolite occur coevally. Acicular tremolitic-actinolite occur in fractures. Note that diopside is less stable than the zoned actinolite. **E**- Sample DP#46309, Fullarton River Gorge. Pseudo-igneous breccia matrix. Clinopyroxene overprinted by acicular amphibole. **F**- Sample DP#44607, Maramungee Creek. Pseudo-igneous breccia matrix. Euhedral diopside is growing into a cavity, with quartz infill.

A
Act
Ab
B
Cpx
Amp
Ab
Ttn
C
Cpx
Act
D
Di
Ab
Act
Tr
E
Cpx
Amp
F
Ttn
Di
Qtz

The breccia matrix of the alteration stage 5 (Table 5.1), contains mostly diopside. Amphiboles and clinopyroxenes coexist in the breccia matrix. However, actinolite inclusions, locally, occur in cores of clinopyroxene, which could indicate that actinolite was replaced by clinopyroxene (Figure 5.5B). Also was noted fine grained acicular tremolitic actinolite (stage 5) that replaces the euhedral diopside and in part also the euhedral actinolite crystals (stage 4). These millimetre scale sized pale green to translucent needles occur in fractures, but also as unorientated needles overprinting albite, large euhedral actinolite and diopside (Figure 5.5).

Clinopyroxenes

All clinopyroxenes analysed, disregarding the rock type, are diopside with a narrow compositional variation (Figure 5.6). Diopside of the "altered" calc-silicates and breccias have slightly higher atomic iron and sodium content than in the rest of the analysed rock types (Appendix C). The sodium values are not high enough to classify the clinopyroxenes as "aegirine", such as the ones reported by Mazumdar (1995) from the Brumby Prospect 30km south of the Maramungee Creek. These high sodium clinopyroxenes were crystallized during the late stage brecciation process near the Cloncurry fault, and indicate reducing conditions (Fe^{2+} in clinopyroxene becoming relatively more stable than Fe^{3+} in amphibole).

Most of the clinopyroxene analysed in this study, are from the reconstituted calc-silicate rocks and the pseudo-igneous breccia matrix. The narrow compositional variation suggests that the clinopyroxene (with the exception of possibly metamorphic diopside in the "less altered" metadolerites) formed during a single stage. Overprinting relationships argue against a single diopside stage (see Figure 5.5B, C, D, E). Diopside occurs in the following regimes.

(i) Anhedral clinopyroxene in the "altered" calc-silicate rocks occur in the coarser albitic plagioclase layers (?veins) and usually interlocked with actinolite (stages 1 and 2). Good evidence for actinolite overprinting diopside, or visa versa, has not been observed in these layers. This could suggest for a metamorphic origin of the diopside.

(ii) Regional mapping identified "pristine" diopside bearing calc-silicates (CS_I-B) in the Mallee Gap and Boorama Waterhole areas (see Chapter 2).

(iii) Diopside coexisting with actinolite occurs in subhorizontal extensional veins (Chapter 4, V_3), adjacent to high strain zones (stage 2).

(iv) Three generations of clinopyroxene occurs in the pseudo-igneous breccia matrix (stage 4). From the amphibole section (see previous section) it becomes clear that euhedral clinopyroxene partly overprints an early actinolite; is coeval with the main actinolite in the matrix; and eventually gets overprinted by a more tremolitic actinolite (Figure 5.5).

Figure 5.6 - **A**- Compositional diagram of clinopyroxenes from the eastern Cloncurry-Selwyn terrain. Analyses are from all clinopyroxene bearing rock types such as reconstituted schist, calc-silicates, metadolerites, granites, and unaltered equivalents (Appendix C). Eighty analyses from twenty-one rocks. **B**- Atomic Na versus atomic Al. Pyroxenes plot above the 1:1 (Jadeite component) line, and possibly contain a $NaFe^{3+}$ component.

Stability of and relationship between amphiboles and clinopyroxene

Coexisting actinolite and diopside indicate that the physical conditions, such as P-T-CO_2, were close to the amphibole dehydration curve. The Fe-Mg partition coefficient between coexisting amphibole and clinopyroxene (Figure 5.7) is calculated as follows:

$$KD^{Fe-Mg}_{Amp-Cpx} = \left(\frac{Fe}{Fe+Mg}\right)_{Amp} \Big/ \left(\frac{Fe}{Fe+Mg}\right)_{Cpx} \qquad (5.1)$$

with values for the "altered" calc-silicates and pseudo-igneous breccia matrix close to unity. Amphiboles in the "altered" metadolerites contain more Fe than coexisting diopside. A K_D value close to unity indicates that the Fe-Mg was evenly distributed between these two minerals. The exchange reactions for Fe and Mg among the silicates can be written by the following ideal reaction:

$$Ca_2Fe_5Si_8O_{22}(OH)_2 + 5CaMgSi_2O_6 \leftrightarrow Ca_2Mg_5Si_8O_{22}(OH)_2 + 5CaFeSi_2O_6$$

ferroactinolite *diopside tremolite* *hedenbergite*

The distribution coefficient can therefore be used as a good indication of whether the phases are in equilibrium.

Figure 5.7 - Fe-Mg distribution between coexisting amphiboles and clinopyroxenes. $K_D \sim 1$ suggest equilibrium between amphibole and clinopyroxene.

It is possible to reconstruct a P-T-(CO_2) path for the alteration fluid that is responsible the regional megabrecciation process, causing a pseudo-igneous texture. Experiments by Liou *et al.* (1974) on the compositional variation of amphiboles as a function of temperature, illustrate that Al decreases with decreasing temperatures. The amphibole compositional variation curve versus temperature (Liou *et al.* 1974), indicates that actinolite is stable below 5 wt.% Al_2O_3 and 480°C at 2 kbar. The amount of Al_2O_3 is < 3 wt.% in the investigated actinolites (see Appendix C), and would therefore indicate that these alteration actinolites possibly formed at temperatures lower than 500°C. The dehydration curve is the boundary between actinolite and diopside in a P-T diagram. Actinolite overprinted by clinopyroxene initially formed in the amphibole field. There are two possible explanations for the clinopyroxene overprint: i) an isobaric temperature rise could shift the stability of the minerals into the clinopyroxene field, ii) a second method to shift from the amphibole field to the clinopyroxene field is by a, relatively larger, isothermal pressure drop. The coeval and coexisting clinopyroxene and amphibole, indicates narrow physical P/T conditions, supported by textural observations and distribution coefficient close to unity values. The isobaric dehydration-(decarbonation) reaction between actinolite and diopside can be written as follows:

$$\underset{\textit{actinolite}}{Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2} + \underset{\textit{calcite}}{3CaCO_3} + \underset{\textit{quartz}}{2\,SiO_2} \leftrightarrow \underset{\textit{diopside}}{5Ca(Mg,Fe)Si_2O_6} + 3CO_2 + H_2O$$

From this reaction it becomes clear that diopside formation depends on the activity of quartz, calcite and CO_2. The reaction constant for this reaction can be written as follows:

$$K = \frac{a_{Di}^{5} \cdot a_{CO_2}^{3} \cdot aH_2O}{aAct \cdot a_{Cal}^{3} \cdot a_{Qtz}^{2}} \qquad (5.2)$$

The CO_2 activity is limited ($X_{CO_2} < 0.10$, Figure 5.8). The abundant occurrence of rutile and calcite in the regional breccia complex supports the low CO_2 activity.

Figure 5.8 - T-CO_2 phase diagram at 2.5 kbar. With decreasing temperature and X_{CO_2}, the stability of the minerals moves towards invariant point I. Continued lowering of the temperature causes movement of stability of the minerals towards invariant point II. Calculated using Thermocalc (Powell and Holland 1985).

Titanite

Titanite varies from dominantly subhedral to anhedral in the ductile sodic-calcic alteration (stages 1-2) to subhedral-euhedral rhombohedral grains in the pseudo-igneous breccia matrix (stage 4, Figure 5.9). It is less dominant in the pseudo-igneous matrix of the breccias.

Figure 5.9 - Microphotographs of titanite. **A**- Sample DP#46336, Boorama Waterhole. Pseudo-igneous breccia matrix containing euhedral titanite, and is coexisting with clinopyroxene, actinolite and albitic plagioclase. **B**- Sample DP#44608, Maramungee Creek. Pseudo-igneous breccia matrix. Titanite crystal with core that contains magnetite. **C**- Sample DP#46310, Fullarton River gorge. Fractured clinopyroxene with magnetite infill and titanite reaction rims. **D**- Sample DP#44659, Maramungee Creek. Altered calc-silicate rock, that contains titanite that nucleated on magnetite. **E**- Sample DP#44663, Maramungee Creek. Backscatter photograph showing the "breakdown" of titanite to rutile, calcite and quartz. **F**- Sample DP#46315, Fullarton River gorge. Backscatter photograph of euhedral titanite with magnetite core (not shown) breaks down to rutile, calcite and quartz.

A
Ttn
Cpx
Act
Ab
B
Mag
C
Cpx
Ttn
Mag
D
Mag
Ttn
Act
Cpx
E
1μm
Ttn
Ru
Cal
F
10μm
Ttn
Cal

Titanite commonly nucleates on magnetite and form rims around the magnetite. These titanite (reaction) rims are thicker were magnetite is in contact with actinolite or clinopyroxene, and possibly formed by the following reaction:

$$Ca_2(Mg,Fe)Si_4O_{12} + Fe_2TiO_4 + {}^1/_2O_2 \leftrightarrow CaTiSiO_5 + Fe_3O_4 + CaMgSiO_6 + SiO_2$$

Large, centimetre scale anhedral titanite crystals occur with quartz (and actinolite) in tension-gash veins (stage 3), in the western part of the Maramungee Creek. This suggests that Ti acted in a mobile fashion. However, from whole-rock analyses (see section 5.3) it appears that titanium acted in an immobile fashion. It appears that titanium was locally redistributed and probably lost from the metamorphic amphiboles, biotites and Ti-magnetite. Titanite eventually breaks down to calcite and rutile by the following reaction (Figure 5.9E-F):

$$\underset{rutile}{TiO_2} + \underset{calcite}{CaCO_3} + \underset{quartz}{SiO_2} \leftrightarrow \underset{titanite}{CaTiSiO_5} + CO_2$$

Iron-oxide phases

The Doherty Formation is geophysically characterized by a high magnetization (Blake *et al.* 1984), caused by the abundance of *magnetite*. Iron depletion occurs during the early sodic-calcic alteration stage, based on whole rock analyses. Williams (1994) pointed out that this Fe loss was in part caused by biotite destruction in retrograde schist and albitization of metadolerites. Reintroduced of iron occur in the later alteration stages, with iron partly incorporated in recrystallized actinolite and epidote, but also as a separate iron-oxide phase. Early subhedral to euhedral metamorphic magnetite contain ilmenite rich lamella. Magnetite formed during different alteration stages. Euhedral magnetite overgrew "stage 1" phases (Table 5.1). The main euhedral magnetite precipitation occurred during "stage 2", though some anhedral magnetite formed at margins of V_1 axial-planar veins (Figure 4.10A). Continuous post D_2 deformation caused the secondary actinolite and clinopyroxene to fracture, and form subhorizontal veins (V_3, Figure 4.10D). Anhedral magnetite precipitates in these fractures and veins. In the overprinting brecciation stage, magnetite forms euhedral crystals. This "stage 4" magnetite generally occurs as clusters and in albite rich breccia matrix. The magnetite clusters are possibly relict clinopyroxenes (Figure 5.5B). The following reactions for end-members could go as follow:

hedenbergite + (CO_2 containing) fluid + O_2 ↔ magnetite (Fe bearing) calcite + quartz or
hedenbergite + (CO_2-NaCl) fluid + albite ↔ magnetite + (Fe) calcite + quartz + oligoclase or

$$3Fe^{2+} + 3CaFeSi_2O_6 + 2H_2O - 2Fe_2O_3 + 2H_2 + 3Ca^{2+} + 6SiO_2$$

However, CO_2 abundance must have been low (see amphibole versus clinopyroxene and titanite section). The TiO_2 content in magnetite of the reconstituted metasedimentary rocks is about 5-10 wt.%. Magnetite in the breccias is almost Ti-free (Figure 5.10).

Figure 5.10 - Plot of the amount of TiO_2 versus Fe-oxide (total).

Another iron-oxide mineral commonly found with this regional alteration and brecciation complex is *hematite*. Hematite grains form submicroscopic inclusions in albitic plagioclase and microcline and causes a macroscopic red colouring of stage 2 and 3 feldspars. Hematite dusted feldspars are more abundant in the Mallee Gap and Fullarton River areas, compared to the Maramungee Creek area. This discolouring of the feldspars occurs in selvages of the various vein sets. Stage 6 hematite is vein controlled and crystallizes as large macroscopic crystals in post D_3 tension and Riedel fractures together with K-feldspar and quartz.

Stability of iron-oxides

The solubility of iron and the precipitation of magnetite and/or hematite depends on the physicochemical conditions, such as the pH of the alteration fluid, temperature, pressure and oxygen fugacity (Chou and Eugster 1977). High temperature (>400°C) saline fluids are able to carry large amount of iron at low pH (McPhail 1993, Hemley *et al.* 1992). Experiments conducted by Zeng *et al.* (1989), revealed that the solubility of magnetite-hematite in NaCl hydrothermal solutions dependent entirely on the pH, and not on the salinity, especially at low pH and low temperatures (<300°C). From these studies it is clear that with decreasing temperature, iron becomes less soluble. A pressure increase will also decrease the solubility of iron (Hemley *et al.* 1992). The reactive (hot 450°C and saline 30-40 Eq.wt.% NaCl, see

Chapter 6) fluid passing through the different unaltered rock types, liberated the iron from these rocks and put Fe in the solution (c.f. Chou and Eugster 1977). The fluid therefore altered the rocks (to albite) and re-precipitates part of the Fe from the solution into the altered calc-silicate rocks and breccias. The iron precipitated in the form as magnetite in the pseudo-igneous matrix breccias and to a lesser extent in the altered (calc-silicate) rocks. The occurrence of iron-oxides in the breccias indicates that the pressure was not the controlling factor. Both magnetite and hematite occur in the brittle-ductile alteration stages. This suggests that precipitation of iron-oxides occurred close to the magnetite-hematite fO_2 boundary and mainly controlled by the temperature. Fluids further away from the vein channel would be cooler (if host rocks are cool) and precipitate hematite (and microcline). Pure magnetite veins occur locally in the high F:R ratio zones of the Maramungee Creek section and at the Doherty Formation - Maronan supergroup metasomatic front (Williams 1994).

Biotite breakdown

The formation of magnetite, at the expense of biotite in the highly strained retrograde schist, at the Doherty Formation - Maronan supergroup contact, can be written as follows (see also Figures 2.4C and 4.8F):

$$KFe_3AlSi_3O_{10}(OH)_2 + Na^+ + {}^1/_2O_2 \leftrightarrow NaAlSi_3O_8 + Fe_3O_4 + K^+ + H_2O$$

The annite component in biotite reacts with a saline fluid to produce magnetite and albite. Relict biotites from these "altered" retrograde schists contain between 1.7 and 3.9 wt.% TiO_2, which is higher than Ti in biotites from the calc-silicate rocks. Titanite accommodated the liberated Ti, produced by the biotite breakdown. However, biotite breakdown in a more complicated fashion than described in the above situation. The occurrence of corundum with the biotite and the rim of albite separating the corundum from quartz (corundum and quartz forms an unstable assemblage) also suggests the following (ionic) reactions:

$$2KFe_3AlSi_3O_{10}(OH)_2 + H_2O + O_2 \leftrightarrow Al_2O_3 + 6HSiO_4^{2-} + 6Fe^{2+} + 2e$$

$$2Na^+ + Al_2O_3 + 8HSiO_4^{2-} \leftrightarrow 2NaAlSi_3O_8 + 2SiO_2 + 5{}^1/_2O_2 + 7e$$

Relict biotite composition in the "altered" calc-silicates, are similar to the biotites of the "pristine" calc-silicates. This is another indication that the "pristine" calc-silicates are probably the precursors of the "altered" calc-silicates (Figure 5.11).

Ca-Si±Fe±Mg±CO_2-H_2O system, epidote, calcite, prehnite (±talc)

The occurrence of rutile, calcite, quartz, epidote and prehnite in the breccia complex reflects low T and low CO_2 conditions (Hunt and Kerrick 1977). Continuous unroofing during the later alteration stages caused a reduction in P/T conditions and

an increase in oxygen fugacity. This becomes apparent from the breakdown of titanite, the overprinting of epidote and calcite of actinolite and clinopyroxene, the cross-cutting prehnite-calcite veins (and hematite-K-feldspar-quartz assemblages).

Figure 5.11 - Composition of relict metamorphic biotites.

- *Epidote*, Ps value [100Fe/(Fe+Al)] varies around the mode of ~30 to 34 (Appendix C). Epidotes formed at two stages: i) overprinting the albite-actinolite-clinopyroxene assemblages (stage 4), and ii) in open space veins (stage 5, Figure 5.12). Epidotes with Ps ~ 30 are typical for greenschist facies conditions (Maruyama *et al.* 1983), although compositions can vary isothermally due to variations in fO_2 (Liou 1973). With decreasing temperature and increasing fO_2, epidotes (and prehnites) increase in Fe^{3+} content coupled to a decrease in aluminium (Liou *et al.* 1983). The epidotes not related to the veins could have formed by two types of reactions:

a) $3An + Ttn + H_2O \leftrightarrow 2Zo + Rt + Qtz$

b) $3An + Cal + H_2O \leftrightarrow 2Zo + CO_2$

In which -An- and -Zo- would respectively be the anorthite component in albitic plagioclase and the zoisite component in epidote.

Another epidote-group mineral, which locally overprints the regional alteration, is the rare earth element, La-Ce, bearing mineral *allanite*. Allanites are euhedral in shape (Figure 5.12) and have epidote rims.

- *Prehnite* occurs as subhedral to euhedral crystals in veins (Figure 5.12) cross-cutting the megabreccias, with epidote alteration. Calculated phase diagrams (Parry *et al.* 1988) for epidote-prehnite-chlorite, illustrate that with decreasing temperature and pressure (from 350°C and ~3 kbar to 150°C and ~0.5 kbar), the prehnite stability field increases dramatically. The relationship between epidote and prehnite can be written by the following simplified reaction:

$$\text{Ps 32 epidote} + H_2O \leftrightarrow \text{prehnite} + \text{hematite}$$

Experimental work conducted by Liou *et al.* (1983) revealed a more complicated reaction path, with the formation of grandite garnet [$Ca_3(Fe,Al)_2Si_3O_{12}$] at lower fO_2. The fact that garnets are not observed as part of the alteration assemblage suggests a maximum $\log fO_2$ of about -22 and temperatures < 350°C (Fig. 2 from Liou *et al.* 1983, at 2 kbar).

- *Calcite* commonly overprints actinolite and clinopyroxene is in the northern part of the study area, especially in the megabreccia complex of the Fullarton River gorge. Calcite contains, in most cases, traces of Fe, Mg and Mn, though, no systematic variation has been detected. Calcite not only overprints the alteration amphiboles and clinopyroxene (Figure 5.12), but is also found in vugs in the pseudo-igneous breccia matrix (see Chapter 2). Cross-cutting calcite-prehnite±epidote veins overprint the breccia complex. Calcite also formed by titanite breakdown (see above).

- *Chlorite,* formed during the later stages of the regional alteration (Figure 5.12). Chlorites are Fe- and Al-rich (~21 wt.%) and poor in silica (~25 wt.%, Figure 5.13) in the "pristine" calc-silicates. Mg-rich chlorite replaces actinolite and clinopyroxene from the pseudo-igneous breccia matrix.

- Fine grained *talc* locally replaced the albite-actinolite-diopside assemblage in the pseudo-igneous breccia matrix. The formation of talc during hydrothermal alteration is an indication of an increase in H_2O and silica activity. Lower temperature and higher aH_2O favour the formation of talc over tremolite.

5.3 - Whole rock analyses of sodic-calcic alteration

The degree of alteration (albitization) can broadly be characterized according to location with respect to the metasomatized shear- and brecciation zones. Sodic-calcic alteration is strongest in the shear- and brecciation zones. Adjacent to those zones, sodic-calcic alteration will be of a medium degree albitization. Further away from the major fluid conduits, the degree of alteration is lowest. These "zones" have been defined by textural and petrographic characteristics and coincide with the "altered", moderately altered" and "pristine" calc-silicate rock classification. Fluid focussing in local faults, veins and small scale fold structures in the "pristine" and "moderately altered" calc-silicate rocks, resulted in altered rocks on a local scale.

Whole rock analyses were only undertaken on rocks from the Maramungee Creek section. Sampling was conducted across the regional northwest-southeast D_2 structural trend and mainly from the sodic-calcic alteration and brecciation stage. Based on structural observations, and the relationship of the structural setting in which unaltered and altered specimens were sampled, the precursor rocks of the altered samples can with a certain degree of reliability be obtained. Whole rock samples were analysed for major and trace elements by X-ray fluorescence on fused- and compressed powder discs.

5.3.1 - Geochemical characteristics of the "unaltered" rocks

Metasedimentary rocks that are less affected by the sodic alteration are the psammopelites at the metasomatic front at the eastern part of the Maramungee Creek section and the "pristine" calc-silicates in the western part. Elements that are characteristic for these metasediments can establish the geochemical variability in precursor rocks of the alteration affected rocks.

Figure 5.12 - Textural relationships of epidote, allanite, prehnite, calcite and chlorite. **A**- Sample DP#44650, Maramungee Creek section. Epidote vein is cross-cutting and overprinting actinolite and albite. **B**- Sample DP#46416, Fullarton River gorge. Diopside, actinolite, hematite dusted albite and magnetite banding, overprinted by epidote and chlorite. **C**- Sample DP#44657, Maramungee Creek section. Subhedral to euhedral allanite, overprinting coarse hematite dusted microcline. **D**- Sample DP#46417, Mallee Gap location. Calcite-prehnite vein is cross-cutting altered metadolerite. **E**- Sample DP#46415, Fullarton River gorge. Clinopyroxene overprinted by calcite. **F**- Sample DP#46311, Fullarton River gorge. Relict clinopyroxene overprinted by pale green pleochroic chlorite.

A
Ep
Act
B
Cpx
Chl
Hem dusted
Mc
Ep
C
Ab
Mc
Aln
D
Prh
Cal
E
Cal
Cpx
F
Ep
Chl
Cpx
Mag

Figure 5.13 - Compostional diagram of chlorites.

Knowing the geochemical influence of the detrital components in the metasedimentary rocks would give some indication if element mobility in the alteration affected rocks are truly due to the alteration or that the apparent element behaviour is reflecting the effects of the detrital input. Detrital input that might affect the psammopelite rocks could be zircons, which would give a scatter in an Al versus Zr diagram, detrital feldspars, quartz, clays, and carbonates in the calc-silicate rocks.

Various elements are plotted against Al_2O_3 on inter-element plots (Figures 5.14, 5.15. 5.16). Based on gain/loss diagrams (Figure 5.17), Al_2O_3 appears to be acting in an immobile fashion. The "biotite breakdown" reaction (section 5.2.1) indicate liberation of Al_2O_3. The liberated Al_2O_3 remains immobile in the phase corundum, and will react with sodium bearing fluids into albite. However, Al-bearing minerals precipitating in veins does indicate that some Al might have been removed from the "biotite breakdown" reaction site (or that the vein-fluid composition was originally Al-bearing).

A possible positive correlation exists between Al versus Ti and K (Figure 5.14) in the "less" and "moderately affected" schists. These trends are due to the original illite (clay) content. Some scattering of Zr versus Al might indicate the input of detrital zircons.

Good correlations exist between Al, Ti, Cr, Sc, and V in the "pristine" and "moderately altered" calc-silcate rocks. V and Sc exhibit more scattering in the "altered" calc-silicate rocks (Figures 5.15 and 5.16). The positive trend and constant ratios between Al versus Ti and Ti versus Cr might indicate a clay precursor for those elements. Al versus Zr exhibits a strong negative correlation in the "pristine" and "moderately altered" calc-silicate rocks. This indicates that Zr was probably incorporated in detrital clay (illite). Al versus K (not shown, c.f. Figure 5.18A and C) does not show any correlation in the "pristine" and "moderately altered" calc-silicate rocks, which might indicate that detrital K-feldspar was present.

Figure 5.14 - Inter-element plots from schists at the Maronan supergroup - Doherty Formation contact. The scarcity of data available is reflected in the amount of analyses done. However, the samples analysed were collected from a well exposed site (see also section 4.2.2).

5.3.2 - Geochemical characteristics of the alteration affected rocks

Alteration studies must take in account that the volume of the affected rock might change during the alteration process. Increase in rock volume can give a dilution effect on particular elements in the rock, appearing to be depleted. Field observations indicate that any large volume increase in the inferred high fluid/rock ratio zone of the Maramungee Creek shear zone can be excluded (section 4.2.2, Figure 4.7). Although some volume increase did occur, evident by the occurrence of structurally controlled dilation veins and vein jog breccias (section 4.3). Megabreccias, close to the Doherty Formation - Maronan supergroup contact are also evidence for volume increase during the late stages of the alteration. The inferred moderately fluid/rock ratio zone, adjacent to the shear- and breccia zones, only exhibit small volume changes.

The fact that the "less-" and "moderately altered" schists plot on the same trend in the inter-element diagrams, suggest that the "less alteration affected" schists are the precursor rocks of the "moderately altered" schist. Relative gain/loss diagrams (Figure 5.17) illustrate dramatic chemical changes in the schist at the metasomatic front. From these diagrams it becomes apparent that all elements acted in a mobile fashion during the alteration. However, elements such as Al, Sc and Sr are acting in a less mobile fashion. Elements as Y and Ti are acting in an immobile fashion between samples of less and more altered schists. Comparison between the schist and schist in breccia clasts indicate a strong increase in these elements. Elements gained are Na, Mg and Ca, while K and Fe are lost. This was also demonstrated by Williams (1994) for this area.

It appears that the original sediments of the "pristine", "moderately altered" and "altered" calc-silicates were quite similar, based on the "tight" positive trends between Al, Ti, Cr, Sc, and V in the calc-silicate rocks. From these trends it is possible to suggest that the alteration affected calc-silicates were derived from a similar protolith as the "pristine" calc-silicates. Comparison of the geochemistry of the "pristine" calc-silicates with "moderately altered" and "altered" calc-silicates would give same information on the elements involved in the alteration. On the basis of the gain/loss diagrams and inter-element plots (Figure 5.17) it becomes obvious that Na and K acted in a mobile fashion and in an opposite manner. "Moderately altered" calc-silicates are less Na enriched than the "altered" calc-silicates (Figure 5.18). Fe exhibits a negative correlation with Na, but not as pronounced as K. The

increase in Ca and Mg in the "altered" calc-silicates is due to an increase in actinolite and diopside.

The alteration, albitization, that affected the schist is of the same type (sodic-calcic alteration) that affected the calc-silicate rocks. This is apparent from the fact that most major elements gained and lost are similar for both rock types. This is a gain in Na, Ca and Mg and a loss in K and Fe. Elements that behaved in a relative immobile fashion are Al, Cr and Sc, while Ti and V acted in both a mobile and immobile fashion (scale depended). Zr acts in a mobile fashion in the "altered" calc-silicates, but is relative immobile in the "pristine" and "moderately altered" calc-silicates.

Figure 5.15 - Inter-element plots from calc-silicate rocks in the Doherty Formation. Al versus Ti, Zr, Cr, Sc and V in the "pristine" and "moderately altered" calc-silicates exhibit good correlations. No well developed correlation exists between Al and Zr (and V) in the "altered" calc-silicates.

5.3.3 - Breccia geochemistry

There are two types of breccias, "vein jog breccias" and breccias with a "pseudo-igneous matrix". The "vein jog breccias" are older than the "pseudo-igneous matrix" breccias (see Chapter 4). The two breccia types have distinct geochemistry.

The vein jog breccias occur in, and are related to, the "altered" calc-silicate rocks in the Maramungee Creek shear zone (see Chapter 4). The geochemistry between the two is quite similar (Figure 5.17, gain/loss diagrams). However, the vein jog breccias are more enriched in Ca, Mg and Fe, due to the increase in actinolite and magnetite in the matrix. Negative correlations between Sc, V versus Al, are striking differences with the calc-silicate rocks.

Figure 5.16 - Inter-element plots from calc-silicate plots. Symbols are similar as Figure 5.15. "Pristine" and "moderately altered" calc-silicates exhibit well-defined correlations between the elements. V and Sc exhibit some scattering in the "altered" calc-silicates.

Analyses were tried to done only on the matrixes of the "pseudo-igneous matrix" breccias. Altered calc-silicates, schists and metadolerites are the host rocks for these breccias. The geochemistry of this matrix appears to evolved from the vein jog breccias (Figure 5.19). The "pseudo-igneous matrix" breccias have lower Na, but higher Mg and Ca content than the vein jog breccias. The relationship between the various elements and Al is not as "tight" as in the "vein jog breccias". A possible reason for this phenomenon is, that it is an affect of the original host rock.

Figure 5.17 - Gain/loss diagrams for less altered and altered rocks in the Doherty Formation.

Vanadium is much lower in the "vein jog breccias" (< 100ppm), compared to the moderate V content in the calc-silicate rocks (60-110ppm) and the high V content in the "pseudo-igneous matrix" breccias (> 110ppm). It appears that with an increasing degree of alteration V becomes increasingly mobile. The V increase is possibly related to the increase in diopside, which could incorporate trivalent vanadium (Bernau and Franz 1987).

5.4 - Rare Earth Element mobility and alteration in metadolerites

It is believed that rare earth elements (REE), and also HFSE (Ti, Zr, Hf, V, Y, Nb), are acting immobile during metamorphism and possibly also during alteration (Rogers *et al.* 1984). However, mobility of REE during "early" sea floor alteration

has been demonstrated by Salvi and Williams-Jones (1990). REE behaviour is studied at two metadolerite localities in the Maramungee Creek section. At these localities, light rare earth elements (LREE, La to Sm) and some HFSE revealed extreme mobility.

To establish the relationship between the REE behaviour and the alteration at those two metadolerite localities, the alteration affecting the metadolerites will first be described in terms of whole-rock component changes.

Figure 5.18 - Inter-element plots from calc-silicate rocks in the Doherty formation, illustrating the alteration. **A**- Progressive increase in Na, from "pristine" to "altered" calc-silicates. **B**- Weak developed negative trend, between Fe and Al. **C**- There is a strong linear negative correlation between K and Na. Increase alteration, Na enrichment, formed at the expense of K depletion. **D**- Iron loss occurs with an increasing in the sodic alteration.

Alteration of the metadolerites

Geochemical data and petrographical descriptions of the metadolerites are presented in Chapter 2. From these data, and in combination with overprinting deformation phases, it was established that the metadolerites were intruded during the same period and from a magma source with similar composition.

Figure 5.19 - Geochemistry from the "vein jog breccias" and "pseudo-igneous matrix breccias" from the Doherty Formation. The "pseudo-igneous matrix breccias" have lower Al content than the "vein jog breccias", and this is possibly due to dilution.

At the metadolerite "location 1", samples were collected from the centre to the margin of the igneous body (perpendicular to the D_2 structural foliation). The reason behind this type of sampling technique was, that the centre of this large metadolerite body would be less affected by fluid infiltration and alteration, compared to the margins, which exhibit a higher vein density and sheared, strained contacts with the

surrounding country rocks. Samples collected from the metadolerite body at "location 2" were collected in a two by two metre area with obvious colour differences, presumably reflecting the alteration.

Metadolerites that were less affected by the sodic-calcic alteration contain more iron (see also iron-oxide section), and is expressed in the molar $100xFe_t/(Fe_t+Mg)$ ratio (X_{Fe}). The differentiation index (DI defined as the sum of weight % of normative quartz + orthoclase + albite + nepheline, average DI for basalt = 35) can also be used as an alteration index for the metadolerites. Less affected metadolerites have X_{Fe} > 35 and differentiation index ~30-40. Unaltered metadolerites exhibit a narrow spread in Al and Na, but with variable Fe/Mg ratios (Figure 5.20). Molar Na/Al ratios versus molar Fe/Fe+Mg, indicate that alteration affected dolerites is Fe depleted and Na enriched. Williams (1994) reported major loss of iron in metadolerites, related to sodic alteration. The degree of alteration in metadolerites can indirectly be related to the total iron loss. Altered metadolerites are highly differentiated, with DI ranging from 35 to 72. This is due to an increase in silica and sodium.

The occurrence of different stages, types of alteration that are overprinting each other in the metadolerites, complicate the interpretation of the geochemical data. The main sodic (± calcic) alteration resulted in new growth of albite and sodic scapolite (marialite), associated with andesine veining (samples DP#44599 and DP#44616). K-feldspar overprints the metadolerite body at the margins, indicated by a mass increase in potassium in samples DP#44647 and DP#44646, and a lower Na/Na+Ca+K ratio versus DI (see also Figure 5.20). Elements that acted in a relative immobile fashion are Al, Ga, Zn, Cr and V (Figure 5.21).

REE mobility in metadolerites

Rare earth elements (REE) and high field strength elements (HFSE) may all behave in a mobile fashion during the sodic-calcic alteration in the Doherty Formation. Pristine or less altered metadolerites, with a main hornblende-plagioclase ± diopside mineral composition, provides a starting point for the alteration process. The final REE concentrations in the rock, will be controlled by several factors, such as: 1) the original concentration of REE in the rock, 2) the concentration of REE in the interacting solution, 3) the interaction, or partitioned behaviour of REE in a particular alteration type (Graff 1977). LREE (atomic numbers 57-62) have larger ionic radii than HREE (atomic numbers 63-71); the latter are compatible with Zr and Y. REE phases in the Doherty Formation were identified by semiquantitative EDS analysis (see Appendix C). Two major REE phases have been identified, monazite

[(Ca,Ce,Th)PO_4] in breccias of schist host rocks and allanite [$(Ca,Ce)_2(Fe,Al)_3(Si_3O_{12})OH$] in breccias of calc-silicate and metadolerite host rocks. Monazite formed euhedral crystals, while epidote form rims around the allanite. However, REE, especially LREE, can also be incorporated in titanite (Bernau and Franz 1987).

Figure 5.20 - Fe/Fe+Mg and differentiation index (DI) plots from metadolerites in the Maramungee Creek. Unaltered metadolerite (plots -A- and -B-) have relatively constant Al and Na, however, the F/Fe+Mg ration varies. The more altered samples have higher DI and Na, but lower Fe (and Ti).

Figure 5.21 - Gain/loss diagrams between "less" and "altered" metadolerites at two localities in the Maramungee Creek. **A**- Comparison between samples from the margin and centre of the metadolerite at location 1. The altered sample is enriched in K and a REE. **B**- Sample comparison at location 2. Both samples are altered with DI of respectively 36 and 62. (-c- is iron recalculated after titration).

REE are generally presented on a logarithmic plot normalized to the REE abundance of a chondrite (Figure 5.22). LREE enrichment is about 15 to 300 times relative to the chondrite normalized values, in the sodic-calcic affected metadolerites at the two studied localities. The standard deviations (Figure 5.22) for samples in a suite are low, reinforcing that the samples were sampled from a single suite. HREE are 10 to 60 times enriched. A first order interpretation of the REE patterns and Nb content, suggest that the metadolerites involved are related to a differentiated alkali dolerite system (Le Roex 1987). This misleading similarity is solely a reflection of the REE abundance in the alteration fluids and not from the original rock type. A possible explanation for the similarity between the "alteration" and "magma evolving" REE trend could be that at the time the alteration fluids entered the system various stages of fractionated magmas was being emplaced synchronously. This might have occurred in the later stages of the alteration history, with alkali dolerite intrusions being affected by the alteration. However, no field evidence supports an igneous activity related to alteration focussed in the early ductile-brittle regimes.

Metadolerites with relative high molar X_{Fe} ratios (ranging from 35 to 50) appear less affected by alteration and have flat REE patterns and normalized LREE/HREE ratios between 1 and 2. Ratios of La/Th are in the order of 3.6 to 4.5 (Table 5.2). Ratios of Th/Yb behave opposite to the Th/Yb (0.9 to 1.5). These ratios are typical for

dolerites (McLennan *et al.* 1980). V/Yb and Al_2O_3/Yb ratios decreases dramatically with increasing alteration., Yb however, remains constant

Alteration affected metadolerites have low X_{Fe} ratios (generally < 35). These metadolerites are enriched in REE, particular LREE. Most of the REE patterns have a distinct "hump" at Ce and a distinct negative La anomaly. The $(La/Ce)_N$ ratios are very constant, meaning similar chemical behaviour of Ce and La. The enrichment of $(LREE/HREE)_N$ is in the order of 1.1-4.4. This can be accounted by the presence of secondary diopside. McDonough and Frey (1989), Graugh (1989) suggest that clinopyroxene is a dominant host for HREE and Zr. Analyses low in CaO/Yb are enriched in LREE and tend to have high $(La/Yb)_N$ ratios.

The Eu/Eu* ratios are all below unity, illustrated by negative Eu anomalies of the REE trends on Figure 5.22 (Eu* is the interpolated Eu value between Sm and Gd if there was no anomaly). This could mean two things. i) Eu fractionated in plagioclase during crystallization, or ii) Eu was carried in the alteration fluid and incompatible. A negative Eu anomaly could indicate oxidizing and relative cool conditions (Parr 1992, Palacios *et al.* 1986). However, FeO/Fe_2O_3 versus differentiation index (DI, Figure 5.20) illustrates that with increasing DI, the FeO/Fe_2O_3 increases, indicating reducing conditions.

Figure 5.22 - REE patterns normalized to chondrite, with molar X_{Fe} and DI (xx/xx) in brackets from metadolerites in the eastern Cloncurry-Selwyn terrain. **A**- Metadolerites with X_{Fe} ratios mainly > 35 (indicating less iron loss, hence moderate interaction between reactive alteration fluids and metadolerites), have relatively flat patterns. The two odd samples (DP#44675 and 44679) are strongly scapolitized. Standard deviations are La=1, Ce=1, Nd=1, Sm=0.5, Eu=0.4, Gd=0.6, Tb=0.3, Ho=0.3, Yb=0.5, Lu=0.19. **B**- Metadolerites with X_{Fe} mainly < 35 exhibit elevated LREE patterns. Standard deviations are La=3, Ce=6, Nd=3, Sm=1.3, Eu=0.7, Gd=1.2, Tb=0.5, Ho=0.6, Yb=1.0, Lu=0.39.

Table 5.2 - Summary of REE and other element ratios in the different degrees of alteration in metadolerite rocks of the Maramungee Creek section.

Sample DP#	Eu/Eu*	X_{Fe}	FeO/Fe_2O_3	$(LREE/HREE)_N$	$(La/Yb)_N$	$(La/Ce)_N$	Th/Yb	La/Th	V/Yb	Al_2O_3/Yb	CaO/Yb	log10(Ti/Eu)
Less alteration affected (samples of location 1)												
44597	0.42	38	0.07	2.0	3.7	1.3	1.5	3.7	174	8.4	5.7	4.2
44669	0.68	34	0.27	1.6	3.1	1.2	1.3	3.8	144	8.2	5.4	4.0
44599	0.54	47	0.65	1.5	2.5	1.1	0.9	4.5	125	6.0	4.4	4.2
44647	0.45	39	0.11	1.7	3.2	1.4	1.3	3.6	170	5.5	5.1	4.4
More alteration affected (mainly samples of location 2)												
44646	0.48	37	0.31	2.6	6.5	1.8	0.9	10.5	70	3.0	1.6	3.9
44675	0.77	36	0.51	1.1	3.6	1.2	1.2	4.5	177	8.2	2.4	3.8
44679	0.51	21	0.04	2.0	3.6	1.1	2.3	2.4	71	11.2	6.1	3.9
44676	0.44	21	0.21	3.5	6.0	0.7	2.3	3.8	41	4.9	3.5	3.6
44677	0.46	24	0.11	3.0	5.3	0.8	1.8	4.5	96	5.6	3.2	4.0
44678	0.44	31	0.04	4.4	7.0	0.7	2.5	4.1	31	3.8	3.0	3.7

N.B. X_{Fe} is molar fraction of total Fe/Fe+Mg; $(xx/xx)_N$ is element ratio normalized to chondrite.

In summary it can be said that the altered metadolerites gained in Si and Na, lost in Fe, while K is first lost during the sodic alteration and than gained in the potassic alteration. Metadolerites "less affected by alteration" have $X_{Fe} > 35$, while metadolerites "more affected by alteration" have $X_{Fe} < 35$. The "more alteration affected" metadolerites exhibit elevated normalized REE patterns, especially in LREE, compared to the REE patterns of the "less alteration affected" metadolerites. HFSE appears to have been mobile in the metadolerites in contrast to the calc-silicates. Overprinting alteration, such as potassium and silica complicate the interpretation of the geochemical data from the metadolerites.

5.5 - Chlorine distribution in some minerals

Chlorine, together with fluorine, is part of the halogen group and plays an important role in metamorphic, hydrothermal and metasomatic fluids. Chlorine can form metal complexes in halide rich fluids which are potential metal transport media (Munoz and Swenson 1981, Mora and Valley 1989, Heinrich *et al.* 1989).

Chlorine is a minor trace constituent in apatites, micas, scapolites and amphiboles. Partitioning of chlorine in micas and scapolites are potential indicators of fluid compositions in equilibrium with these minerals. The distribution of Cl is sensitive to pressure and temperature and the pH of fluid (Zhu and Sverjensky 1991). Decreasing pressure and pH and increased temperature will for example favour Cl partitioning into annite with respect to fluid.

Chlorine was routinely analysed, by microprobe technics, in apatite, scapolite, amphiboles of "altered" metadolerites, and biotites (of the Maronan Prospect). Chlorine content in, weight %, can vary in these minerals from 6 to 19 percent.

5.5.1 - Chlorine in apatite

Apatite is the most abundant phosphate mineral in the crust, occurring in a wide variety of geological environments, and stable over the entire range of metamorphic conditions. Apatites (in this study) are clear, subhedral to euhedral, and occur as a trace constituent in the "altered corundum bearing" schist and "altered" calc-silicate rocks. Apatite in the corundum schist is concentrated in the quartz-feldspar layers and sporadically distributed in the biotite-corundum-tourmaline bands. In the "altered" calc-silicate rocks apatite is more sparsely and randomly distributed throughout the rock, with both euhedral and anhedral crystal forms. This in contrast to certain calcareous layers in the Maronan Prospect (see Chapter 7), which contains up to 30 modal precent of elongated (deformed ?) apatite (DP#46359).

The halogen content of apatite is an indicator of halogen / hydroxyl exchange between the fluid and mineral on the hydroxyl site (Roegge *et al.* 1974). At constant fluid composition and temperature, the chlorine over hydroxyl ratio (K_{Ap}) in apatite is proportional to the chlorine activity in the fluid and hence to the chlorine concentration in the fluid (Korzhinskiy 1981, Yardley 1985).

The variation in K_{Ap} was calculated at 3 kbar and 450° for the altered corundum schist (Table 5.3, after Korzhinskiy 1981). The fugacity obtained by this method is in the order of $\log(fH_2O/fHCl) \sim 4.7$. These uniform log fugacities might indicate that the system was overprinted by a single (aqueous) fluid (fluid-buffered).

Table 5.3 - Chlorine content in apatites and estimated fluid compositions based on Korzhinskiy (1981).

Sample	wt.% Cl	X_{-Cl}	X_{-OH}	$X_{-Cl/OH}$	$\log(fHCl/fH_2O)$
"Altered" corundum bearing schist (450°C)					
DP#44606\6\1	0.45	0.07	0.93	0.07	-4.71
DP#44606\6\2	0.40	0.06	0.94	0.06	-4.77
DP#44606\5\1	0.42	0.06	0.94	0.06	-4.75
DP#44606\5\2	0.43	0.06	0.94	0.07	-4.75
DP#44606\5\3	0.42	0.06	0.94	0.06	-4.67

N.B. Chlorine content obtained by EDS microprobe analyses. OH calculated assuming ideal mixing of Cl-OH and Cl+OH=2, assuming no F.

Korzhinskiy (1981) equations are: (19) $\log K_T^{Cl/OH} = 0.00267 \bullet T - 6.00$, (20) $K_P^{Cl/OH} = 0.0855 \bullet P - 3.38$. T in kelvin, P in kbar.

5.5.2 - Chlorine in biotites

Relict metamorphic brown-green pleochroic biotites in "altered" corundum bearing schist at Mallee Gap is chlorine-bearing. Other chlorine bearing biotites occur in the Maronan Prospect. These secondary biotites are green pleochroic and related to the mineralization.

Chlorine exchange on the hydroxyl site depends on the dimensions of the hydroxyl site and on the octahedral cation site occupancy (Speer 1985, Munoz 1985). The association of Mg increase coupled to a chlorine decrease in biotite, is experimentally illustrated by Munoz (1985). This is called the "Cl-Mg avoidance" rule. This rule is also applicable to the studied chlorine-bearing biotites. The Mg/Fe ratio of the metamorphic biotites range from 0.77 to 0.94, while chlorine varies from 0.51-0.37 wt.%. The green pleochroic alteration biotites in the Maronan Prospect exhibit chlorine values ranging of 0.30-3.91 wt.% and Mg/Fe ratios from 1.09-0.06. Barium containing biotites of the Maronan Prospect have the highest observed chlorine content. This was also described by Tracy (1991) in Ba-Cl rich biotites from the Sterling Hill skarn, New Jersey.

5.5.3 - Chlorine in amphiboles

Chlorine bearing amphiboles occur in "pristine" metadolerite megabreccia clasts and in crackle veins at the margin of metadolerites.

The chloramphiboles in the relict "pristine" metadolerites megabreccia clasts exhibit a larger compositional variation, but still belong to the magnesio-hastingsite-edenite hornblende group, while the edenitic hornblendes amphiboles in the crackle veins exhibit a narrower compositional range (see Appendix C). There are a few striking features in the analyses. Firstly the relatively high K_2O (1.6 wt.%), which is unusual for calcium amphiboles (Sharma 1981). Apart from the high K_2O, the amphiboles show a considerable replacement of Mg by Fe, with lower $Mg/(Mg+Fe^{2+})$ (~ 0.55) ratios in the amphiboles of the crackle vein, compared with the "pristine" metadolerite amphiboles (~ 0.70). These studied amphiboles are similar to chlorine bearing amphiboles of Oliver *et al.* (1992) from the Mary Kathleen Fold Belt. Oliver *et al.* (1992) explain the large scatter in chlorine content as a reflection of variable temperature and/or chlorinity in the coexisting fluid. They also found that the chlor-hastingsitic amphiboles are stable at high-Fe content and high a_{HCl}.

5.5.4 - Scapolite occurrence in the Eastern Fold Belt

Scapolite was first described from the Eastern Fold Belt by Edwards and Baker (1959) who postulated that the scapolitization in the Mary Kathleen region reflects large-scale metasomatic introduction of volatiles, sodium and chlorine. Detailed

petrographic work by Ramsay and Davidson (1970) revealed that the (meionitic) scapolite in metasediments, in the Mary Kathleen region, formed by isochemical metamorphism and that the original Cl content of the rock was the primary control on the scapolite composition. They concluded that the marialitic scapolite in metadolerites and metavolcanics in the Mary Kathleen region are metasomatic and due to infiltration of volatile-rich pore-fluids derived from the adjacent sediments. Oliver *et al.* (1992) observed variable volatile activities between adjacent layers in the unaltered scapolite bearing calc-silicate metasediments of the Mary Kathleen Fold Belt. Layers containing NaCl-rich scapolites possibly formed by exchange with high a_{NaCl} fluid. However, large variations in the Cl-content in scapolite reflect large variations in the a_{NaCl} of the fluids.

In the eastern part of the Cloncurry-Selwyn terrain, scapolite was reported by Williams and Heinemann (1993) and Rose (1993). Williams and Heinemann (1993) observed a meionitic type of scapolite in drill core from the Maramungee skarn deposit. The scapolite crystallized in the retrograde phase of the skarn formation, in graphite bearing metasediments.

Deformed peak metamorphic mizzonite - meionite scapolite occurs locally in the "pristine" calc-silicate rocks where it coexists with poikiloblastic hornblende, quartz, oligoclase and minor diopsidic clinopyroxene. Mizzonitic scapolite also occurs in ~30 cm thick relict basic dykes located at the margin of the Maramungee Creek shear zone. These foliated dykes contain actinolite, microcline, biotite, quartz and albite, with traces of tourmaline, titanite, calcite, apatite and magnetite.

Granoblastic, equidimensional and relatively unstrained marialitic scapolite locally overprint the mafic bodies in the Doherty Formation (stage 2). Scapolitization at the margins of strained metadolerites, is a result of fluid infiltration with a high chlorine activity (Oliver *et al.* 1992, Ellis 1978, Orville 1975). The scapolitized metadolerites consist of oligoclase, hornblende and marialite.

5.5.4.1 - Chlorine partitioning in scapolite

Scapolite forms a solid solution between the end members marialite [$Na_4(AlSi_3O_8)_3Cl$], meionite [$Ca_4(Al_2Si_2O_8)_3CO_3$ / SO_4] and mizzonite [$NaCa_3Al_5Si_7O_{24}CO_3$]. The crystal structure of scapolite is very similar to that of the feldspars (Sherriff *et al.* 1987). Marialite and meionite can respectively be seen as

$3Na(AlSi_3O_8)$ + NaCl and as $3Ca(Al_2Si_2O_8)$ + $CaCO_3$ / $CaSO_4$. Scapolite solid solutions are potential sensors for fluid compositions and chlorine activities in the fluid (Orville 1975, Ellis 1978). The scapolites in this study do not contain SO_4^{2-}. Apart from the scapolites that occur as selvages of albite veins in the altered calc-silicates, the composition of the scapolites falls between the marialite - mizzonite, meionite joins (Figure 5.23). The scapolites in the "altered" calc-silicates and "metabasalt" (DP#44625) fall exactly on the marialite - mizzonite join, indicating that marialite forms a solid solution with mizzonite and therefor that mizzonite can incorporate an amount of chlorine on its hydroxyl site which was not observed by Orville (1975) or Evans (1969). Vanko and Bishop (1982) reported marialitic scapolite with EqAn [= 100x(Al-3)/3] 12-37 and X_{Cl} 0.72-0.96. These are similar to the most chlorine rich scapolites in this study.

Figure 5.23 - Composition of coexisting scapolite and plagioclase. Thick lines are solid solutions between marialite and mizzonite or meionite. Plagioclase compositions plot on the horizontal axes. Solid tielines represent coexisting plagioclase and scapolite; dashed lines are pairs not in equilibrium. Cl in scapolite decreases with in creasing EqAn (=100x(Al-3)/3).

Coexisting plagioclase and scapolite compositions are fixed at equilibrium in simple systems (Goldsmith and Newton 1977, Ekström 1972), and is temperature dependent. Scapolite coexists with anorthitic plagioclases in the "pristine" calc-silicate rocks, but is in disequilibrium with local overprinting albite. Scapolite in veins at metadolerites margins formed in microfractures and is in disequilibrium

with the andesine plagioclase. This textural type of incipient scapolite was also observed by Vanko and Bishop (1982) in albitized gabbros from the Humboldt Lopolith, N.W. Nevada. Replacement of plagioclase by scapolite appears to be strongly dependent on the composition of the fluid. The final composition of the scapolite is a function of the composition of the original plagioclase and the scapolitizing fluid.

5.5.4.2 - Fluid composition in equilibrium with scapolite

Experimental work by Ellis (1978), Goldsmith and Newton (1977), Vanko and Bishop (1982) and Orville (1975) showed that Cl-rich scapolites form in equilibrium with NaCl rich fluids. Compositions of the fluid in equilibrium with the scapolite and plagioclase can be estimated on the basis of Ellis (1978) exchange reaction (at 750°C and 4 kbar):

$$NaCl_{scapolite} + (CaCO_3)_{calcite} \leftrightarrow (CaCO_3)_{scapolite} + NaCl_{fluid}$$

Although alteration temperatures (350°-450°C) in the studied area did not reached such high temperatures (750°C), fluid compositions were calculated (based on Ellis 1978 and Mora and Valley 1989), and are tabulated in Table 5.4. This was done to compare the fluid composition trend based on this method, with fluid inclusion studies (see Chapter 6).

The fluid compositions obtained from fluid inclusion studies (see Chapter 6) appears to coincide with the calculated fluid composition in equilibrium with the marialite. The occurrence of a uniform EqAn for the metasomatic marialitic scapolites compositions, indicates that scapolitization was probably a single event.

5.6 - Summary

Alteration or metasomatism is the process involving a change in bulk chemical composition. The alteration that affected the eastern Cloncurry-Selwyn terrain can broadly be divided into an early ductile-brittle related sodic-calcic alteration and late stage brittle overprinting sodic-calcic-magnesium alteration stage.

Table 5.4 - Estimated fluid salinities based on coexisting scapolite and plagioclase

Sample	EqAn	Cl / (Cl+CO_3)	X-Ab*	ln Kd**	X-fluid-NaCl
Pristine" Calc-silicate					
DP#44618/2/5	51.85	0.35	65.72	-0.608	0.26
Metabasalt					
DP#44625\2\1	40.70	0.32	64.16	-0.934	0.16
DP#44625\2\1	39.12	0.38	66.01	-0.993	0.20
DP#44625\2\3	37.02	0.25	65.09	-1.081	0.10
Strained Metadolerite					
DP#46305\1\1	22.48	0.73	98.41	-2.016	0.34
Vein at margin Metadolerite					
DP#44598\1\1	26.90	0.68	69.92	-1.652	0.38
DP#44598\1\2	28.10	0.65	65.81	-1.570	0.37
DP#44598\1\3	32.09	0.60	67.97	-1.324	0.37
DP#44598\1\4	30.24	0.61	68.48	-1.432	0.35
DP#44598\1\5	27.88	0.69	68.05	-1.586	0.42
Vein in "Altered" Calc-silicate					
DP#44636\5	19.34	0.84	90.45	-2.326	0.50
DP#44636\6	20.85	0.80	91.27	-2.168	0.44
DP#44636\7	23.46	0.80	90.45	-1.926	0.55

N.B. n.a. = not analysed. St deviations in parentheses. * composition of plagioclase; ** calculation from equation 3 (Mora and Valley 1989); X-fluid-NaCl calculated from equation 2 (Mora and Valley 1989); X-calcite-$CaCO_3$ in equation 2 assumed as unity.

There are seven main stages of alteration. The early alteration stages are quite similar in mineral assemblages. During the later stages epidote-calcite-prehnite-talc became more stable, while K-feldspar-quartz-hematite±sulphides are stable in last stages. The alteration stages are: 1) Oligoclase-actinolite alteration related to post D_2 ductile shear zones. 2) Albite-actinolite-diopside-magnetite alteration related to veins. 3) Tension gashes veins with quartz-titanite-actinolite-diopside. 4) Regional brecciation with diopside-actinolite-albite-magnetite±epidote alteration. 5) Vugs and fractures filled with tremolite-epidote-Mg calcite-prehnite-talc. 6) R_1-riedel shear veins filled with quartz-K feldspar-hematite. 7) Quartz-sulphide alteration related to NNW-SSE fractures.

Elements that acted in a relative immobile fashion in the calc-silicate rocks, were Ti and Al. However, titanite-quartz veins and titanite nucleating on magnetite indicate some mobility of Ti. Elements that were lost are Si, K and Fe, while Na, Ca and Mg were gained. Fe was lost due to biotite breakdown in the schists and lost from hornblende in the metadolerites.

Alteration of metabasic rocks caused scapolitization and a strong depletion in iron. Elements gained were Si, Al and Na, while Fe, Mn and P were lost. Mg, Ca and K were both gained and lost. Strongly altered metadolerites also exhibit distorted REE geochemistry. Light rare earth elements are 15 to 300 times enriched relative to the chondrite normalized values. Heavy rare earth elements exhibit less enrichment.

A progressive increase in magnesium activity is reflected in the progressive development of tremolite, talc and Mg-calcite. An extremely low CO_2 activity is

deduced from mineral phase relationships. The stability of the various mineral assemblages was therefore only strongly temperature and pressure controlled. A sudden pressure drop, such as during brecciation, would have caused diopside to be stable, while a subsequent temperature decrease would have favoured actinolite. Epidote, calcite and prehnite would become stable with the temperature decrease and low XCO_2.

Chlorine bearing minerals formed both during peak metamorphism and during the peak regional alteration. Metamorphic chlorine bearing minerals include magnesio-hornblende amphiboles in metadolerites and meionitic scapolites in calc-silicate rocks. Marialitic scapolite, apatite and green pleochroic biotites crystallized during alteration. Apatite may contain fluorine, but have not been analysed for that element. The green biotites are barium bearing and are related to the mineralisation at the Maronan Prospect (see Chapter 7).

The occurrence of marialite replacing plagioclase in strained metadolerites and as selvages of albite veins are an indication of high chlorine activity. Calculated fluid compositions in equilibrium with scapolites indicate that the metamorphic scapolites (meionites) formed at lower fluid salinities than the alteration scapolites (marialites).

CHAPTER 6

CHAPTER 6 - FLUID INCLUSION STUDIES

6.1 - Introduction

Most geological phenomena take place in the presence of a fluid phase. A direct evidence of the nature of these fluids attending these processes include droplets of fluids, that is fluid inclusions (FI), trapped within crystals of minerals (Roedder 1979, Roedder and Bodnar 1980).

The fluid phase is of prime importance in many situations. Obvious examples are hydrothermal ore deposits where sulphides are concentrated in the ore veins. Although mass transport will be less spectacular in metamorphism than in ore deposits, it is an essential process affecting large volumes of rocks. Pore fluids are also a major factor in controlling reaction kinetics and allow metamorphic reactions to go to completion. The fluid phase also takes part in many mineral reactions and therefore its composition controls the mineral assemblage of the rock (Parry *et al.* 1988, Holm *et al.* 1989, Lespinasse and Cathelineau 1990, Philippot and Selverstone 1991).

Fluids can be studied from their effects on rocks, but a more direct approach is to study fluid inclusions. Fluid inclusions (as mentioned above) are small (generally microscopic) volumes of fluid trapped during crystallization (or recrystallization) of a crystal from a fluid. Fluid inclusion studies are now an essential routine practice in most alteration studies (Ho 1988, Perring *et al.* 1988, Hemley and Hunt 1992, Hemley *et al.* 1992, Li and Naldrett 1993).

Fluid inclusions show a variety of compositions, which reflect the characteristics of the environment of their formation. A fluid inclusion commonly contains an aqueous phase and / or vapour / gas phase and / or a solid(s) (daughter mineral(s) e.g. salts, oxides, sulphides). Aqueous solutions generally contain chlorides which are associated with the salts. Several fluid inclusion generations within a crystal may record the fluid evolution.

This chapter describes and discusses the observations made of the fluid inclusions in different styles of alteration in the Cloncurry terrain. The entrapment temperature of the fluid inclusions is constrained, the composition(s) of the fluid(s) obtained by the freezing method, and a discussion is provided of the implications of the obtained

results for the evolving alteration system. Abbreviations used are tabulated in Table 6.1.

Table 6.1 - Abbreviations for fluid inclusion studies.

	DESCRIPTION		DESCRIPTION
FI	fluid inclusion(s)	L	liquid phase
T_{eut}	eutectic, first melting temperature	V	vapour phase
T_m	melting temperature	S	solid phase (see in what text context)
T_{fm}	final melting temperature	P	primary fluid inclusion
T_t	entrapment temperature	S	secondary fluid inclusion
T_h	homogenization temperature	PS	pseudosecondary fluid inclusion
T_{h-v}	homogenization temperature of the vapour phase	wt.%	weight percent (salinity measurement)
T_{h-s}	homogenization temperature of the solid phase	Eq.wt.%	equivalent weight percent
		F	degree of fill

Note- Temperatures are all given in degrees Celsius (°C). Abbreviation -S- will be obvious in text context.

6.2 - Setting of fluid Inclusion samples

Modelling of fluid movement is essential to understand the behaviour of the fluids in regional alteration systems. Recent studies (Ferry 1988, Powell and Phillips 1991, Dipple and Ferry 1992) showed that fluid migration is an effect of thermal gradients and the buffering capacity of the "passing" rocks. Studies of fluid inclusions can provide useful information about the thermal history of a regional alteration system. In the case of large scale metasomatism as in the Cloncurry terrain, fluids were obviously in disequilibrium with the rocks. A large volume of mono- and bimineralic metasomatic rocks was achieved by mass transfer in the upper part of the crust (Chapter 5). The mobility of the various elements (e.g. Na, Ca, Mg, Si, Fe) depends on the composition and temperature of the fluid (Vidale and Hewitt 1973, Zeng and Wang 1987, Spencer *et al.* 1990) and of the solubility of the metasomatic minerals.

Studies of fluid inclusions of alteration-related veins in the Doherty Formation and of the Cloncurry Fault indicate a complex fluid composition in the $CaCl_2$-KCl-NaCl-H_2O ($\pm$ $FeCl_2$ $\pm MgCl_2$) system (see coming sections). Seven stages of alteration (see Chapter 4) are recognized, but three main distinct stages are investigated in more detail. These are the main sodic-calcic (albite-actinolite$\pm$clinopyroxene) alteration which is overprinted by a K-feldspar stage with subsequent silica overprint. Fluid inclusions were also studied in quartz in the retrograde schists, which occur adjacent to the alteration front, at the contact between the Doherty Formation and the Maronan Supergroup (Figure 1.12, Enclosure B, Figure 4.8C).

6.2.1 - Samples from the "Sodic-calcic stage"

Five samples were taken of quartz-albite veins and matrix quartz from the Maramungee Creek section. Together with sample DP#46303, which comes from Boorama Water Hole (Figure 1.11). These veins are layer parallel- and / or axial planar type veins (Chapter 4). Samples DP#44614 (Figure 6.1A) and DP#44674 are from the intensely metasomatized zone and within certain inclusions in matrix quartz. These samples consist of diffuse laminations of green pleochroic diopside, in parts replacing and coexisting with actinolite (Chapter 5), with traces of quartz and laminae of albitic plagioclase (± hematite dusting) and quartz. Titanite is randomly distributed throughout the samples and is coeval with plagioclase. Accessory minerals are magnetite, apatite and late rutile. Some layers are overprinted by coarse poikilitic oligoclase, which in its turn is replaced by sericite (± calcite).

The veins from the sodic-calcic alteration stage (samples DP#44591, DP#44620 and DP#44664) are open space quartz and albite infill veins with ± albite selvages. Sample DP#44591 shows a complex history (Chapter 4) of opening, infill and shearing. The sample taken from this vein consists of central clear coarse quartz, with a (titano) magnetite-rich rim and an inner selvage of coarse (hematite) dusted albite with traces of a later epidote overprint and an outer selvage of finer grained albite (Figure 6.1B). Sample DP#44620 is from a deformed early tension gash cut by an axial planar type aplite vein in reconstituted (hematite dusted) albite, clinopyroxene actinolite rocks. Sample DP#44620 consists of coarse milky quartz with large crystals of titanite and traces of green pleochroic clinopyroxene and albite (Figure 6.1C and Figure 4.15A). Sample DP#44664 was taken from an open space quartz-albite vein, which was been reopened and filled with comb quartz and hematite laths. The fluid inclusion-data from this sample were obtained from the quartz-albite vein stage.

The Boorama Waterhole sample DP#46303 was taken from an open space quartz-albite vein on a ± 160° trend in a foliated two feldspar granite. The vein consists of a quartz core and inner selvage of "early" albite and a "late" outer selvage of more reddish microcline.

6.2.2 - Samples from the "K-feldspar stage"

Samples from this stage are taken from veins related to the late stage of the post D_2 shearing event (Figures 3.8A, 4.1) that was part of the main sodic-calcic alteration stage (DP#44630 and DP#44640 from the Maramungee Creek section). The relationship between the sodic-calcic and K-feldspar fluid stage is best observed in the Maramungee shear zone (Chapter 4 and 5). High variance mineral assemblage rocks (most altered calc-silicate rocks) consisting of albite, actinolite ± clinopyroxene and magnetite are highly deformed and sheared with tension gashes. These tension gashes are filled with clear quartz, pinkish coloured K-feldspar and hematite (Figure 6.1D and Figure 4.1). A sample was also studied from the Spring Creek area from a quartz - K-feldspar bearing vein on the 130° trend (DP#46412). This sample also contains abundant specular hematite (locally weathered to limonite).

Sample DP#44630 was collected from a quartz - phlogopite vein with a rim of microcline in the "pristine calc-silicate" unit from the Maramungee Creek section. The vein is vertically orientated and parallel to the axial plane of a synform difined by a foliated porphyritic granite. The tight folded granite sheet is ± 7.5 metres thick and consists of quartz, plagioclase, microcline and traces of biotite (Chapter 2). The core of the synform consists of "pristine calc-silicate" with microcline, quartz, green pleochroic hornblende and traces of titanite and Ti-bearing magnetite. Retrograde minerals such as chlorite, epidote, sericite and calcite are also present.

Figure 6.1 - Rock slabs and outcrop photographs, from samples taken for fluid inclusion studies. **A**- Sample DP#44614, reconstituted rock consisting of laminations of (white) oligoclase, albite ± quartz and (grey) laminations of diopside and actinolite, cut by an actinolite vein. **B**- Sample DP#44591, reactivated axial planer type vein with albite rims (white) and quartz centre (light grey); see text. **C**- Sample DP#44620, quartz (white), albite (pinkish), titanite (brown) and diopside (dark green) vein. **D**- Sample DP#44640, tension gashes filed with quartz, K-feldspar and hematite. **E**- Stockwork type breccia filed with comb-quartz (white) in the Cloncurry fault (location 28.3). Pen size 15 cm. All photographs, except -E- are taken from the Maramungee Creek section.

A
METRIC

B
METRIC

C
Ab
Qtz
Ttn

D
Hem
Kfs
Qtz

E

6.2.3 - Samples from the "Comb - quartz stage"

Samples from comb-quartz alteration fluid stage are from the higher crustal level, epithermal style quartz stockwork breccia (samples DP#46410, DP#46411 and DP#46413), the Cloncurry Fault (Figure 6.1E and Chapter 3). Fluid inclusion data obtained from sample DP#46410 are from an open space clear banded quartz vein in a rebrecciated milky white quartz vein with hematite (locally weathered to limonite). The same style of refracturing applies to sample DP#46411 which is a milky white quartz vein with open space stringers of clear secondary quartz. Sample DP#46413 is an open space quartz vein with comb quartz with discrete growth zoning. The base of the comb quartz is cloudy due to numerous small (< 5 μm) fluid inclusions while the end of the quartz crystal prism is clear. Sample DP#44668, however, is from a rebrecciated quartz vein in a granite sheet in the Maramungee Creek section which has the same stockwork breccia style as the Cloncurry Fault.

6.2.4 - Samples from the "Retrograde schist stage"

A zone of high strain with retrograde schist occurs at the contact between the Doherty Formation (metasomatized zone) and the Maronan supergroup (psammopelitic rocks). This zone consists of two types of schist: 1) a muscovite ± biotite, quartz and two-feldspar schist, located closer to the unaltered Maronan supergroup, and 2) a chlorine biotite, corundum ± tourmaline, two feldspar and quartz schist which occurs towards the more reconstituted zone (Chapter 4 and 5). Fluid inclusions studied from these retrograde schist samples (DP#44604 and DP#44642) are from matrix quartz.

6.3 - Description of fluid inclusions

Fluid inclusions have to be discriminated on the basis of what phases are present, liquid (L) and / or vapour (V) and / or solid(s) (S) and on whether the fluid inclusions are primary, secondary or pseudosecondary (Figure 6.2) (Roedder 1979, Roedder and Bodnar 1980, Roedder 1984, Shepherd *et al.* 1985).

During cooling after entrapment of a homogeneous fluid within a growing crystal, at the entrapment temperature T_t and at a certain pressure, the original homogeneous fluid phase will undergo phase changes. The fluid will, in general, separate into a fluid phase and a vapour phase. In some cases the included fluids become very

concentrated brines and supersaturated on cooling, resulting in precipitation of one or more crystalline daughter minerals.

Primary fluid inclusions (P), are those inclusions which were formed and trapped during the initial growth of the host crystal (Roedder 1976). Data obtained from this type of inclusion reflect the physicochemical conditions of the fluid that was in equilibrium with that particular crystal. The habits of those inclusions are generally rounded to subrounded and they occur isolated or in clusters. In general, primary fluid inclusions can only be unambiguously identified in euhedral crystals showing growth zones. In the absence of growth phenomena, relatively large isolated inclusions are therefore considered to be primary.

Figure 6.2 - Sketches of fluid inclusions in quartz at room temperature. **A**- Primary subrounded fluid inclusions of the K-feldspar stage (sample DP#44640 / M118), L-V with occasionally a halite cube. Secondary fluid inclusions are orientated in fluid inclusion planes and are small (generally L-V only). Note that the primary (?) fluid inclusions close to the secondary fluid inclusion planes are more angular (possibly reflecting negative crystal shapes). **B**- Cluster of primary L-V±S fluid inclusions of the comb-quartz stage (sample DP#46413 / 21/336). Note that the larger irregular shaped fluid inclusions contain halite cubes. **C**- Pseudosecondary fluid inclusions containing L-V and in one case L only phases (sample DP#44604 / M51. Uncorrected homogenization and freezing temperatures is in degrees °C, the abbreviations are listed in Table 6.1.

Inclusions orientated in planes (fluid inclusion planes) which do not cross cut the crystal grain boundaries are defined as pseudosecondary fluid inclusions (PS). It is assumed that these pseudosecondary fluid inclusions were trapped in fractures during the crystal growth, indicating that healing of these fractures took place before the termination of that crystal growth. This means that the pseudosecondary fluid inclusions also reflect the fluid composition in which the crystal grew and healed (Roedder 1976, Shepherd *et al.* 1988). Pseudosecondary fluid inclusions were found to be more common than primary inclusions in this study.

Secondary fluid inclusions (S) are formed after the initial growth of the host crystal and are orientated in healed fractures seen as fluid inclusion planes that cross cut the crystal grain boundary. These fractures are formed due to a post crystal growth deformation phase (could be much later than the crystallization) and therefore, in general, would not reflect the fluid composition in which the original host crystal was formed. Crack-seal fluid inclusion planes are dilations orientated parallel to σ_3 of the post crystal growth deformation stress field and perpendicular to the tensional direction. Secondary fluid inclusions can yield information on overprinting fluid compositions, but also on migrated and retrapped primary fluid during vein recrystallization, and on the post host crystal growth stress field (Cox and Etheridge 1983 and 1989, Etheridge *et al.* 1984).

6.3.1 - Morphology of Primary and Pseudosecondary Fluid Inclusions

Quantitative observations of fluid inclusions were only obtained from primary and pseudosecondary fluid inclusions. The studied inclusions are small in (5 to 15 μm, occasionally up to 40 μm in diameter). Most are subrounded, spherical to rectangular. Volumes, however, show a large variation (3 to 10000 μm^3) and were calculated, derived from to the principle equation of Bodnar (1983):

$$V = \frac{M}{D} \qquad (6.1)$$

where the total volume (V) of a fluid inclusion is equal to the total mass (M) of the inclusion phases divided by the total density (D) of the inclusion phases (Figure 6.3). Fluid inclusions of the sodic-calcic stage and some from the K-feldspar stage are relatively large in volume compared to those of the comb-quartz and retrograde schist stages. The two latter populations are relatively uniform with over 65 precent of the inclusions within the range of 10 to 90 μm^3. The same percentage accounts for fluid inclusions of the sodic-calcic stage, in the volume range 200 to 500 μm^3 with an average of approximately 250 μm^3.

Figure 6.3 - Plot of primary and pseudosecondary fluid inclusion volumes from the different fluid stages, plotted on $\log_{10}$ scale. Volumes are calculated according the method of Bodnar (1983). In general, two populations of fluid inclusion volumes are apparent; "large" fluid inclusions more than 200 μm^3 in size and a population of fluid inclusions of about 40 to 90 μm^3. In this case the sodic-calcic stage and to a lesser extent also the K-feldspar stage contains the larger fluid inclusions, while the other samples have smaller size fluid inclusions contain. Sample CM31.1B = DP#46412, sample M118 = DP#44640.

The fluid inclusion volumes of the K-feldspar stage show a bimodal distribution (Figure 6.3): a set of volumes in the order of 3000 μm^3 and a set of fluid inclusion volumes in the order of 40 μm^3. The larger fluid inclusions are from veins related to the 130° trend (Chapter 4), while the smaller inclusions are measured in K-feldspar filled tension gashes in the Maramungee shear zone (sample DP#44640). However, the smaller fluid inclusions of sample DP#46412 are a result of necking-down (Figure 6.4).

Necking-down is a process in which large fluid inclusion will, in time, break down into smaller and more stable fluid inclusions. Caution should be taken if data of this type of fluid inclusion are used. By breaking down from large to smaller fluid inclusions, the phase ratios might not stay constant in the newly inclusions. This phase ratio irregularity will introduce errors into the interpretation of homogenization temperatures. If however, the phase ratios are constant in a group of fluid inclusions, than the effect of necking down was no effect on the interpretation of the data (Shepherd *et al.* 1985).

Figure 6.4 - Microphotography of fluid inclusions from the K-feldspar stage (sample DP#46412). Base of the photograph ± 1.5 mm. **A**- Sample DP#46412. Necking-down of pseudosecondary L-V only fluid inclusions. Note that the degree of fill is relatively constant. **B**- Same sample, similar magnification. Size of the fluid inclusions is approximately the same as in -A-, but note the larger vapour phase, hence lower degree of fill.

A method to quantify the phase ratio in fluid inclusions is to calculate the degree of fill (F, see Appendix F). Fill characterize the different phases in the fluid inclusions and can give a first order approximation if the fluid system was liquid or vapour dominated. This can give some indications if boiling of the fluid occurred. The degree of fill is defined as the volume of the liquid phase relative to the total volume of the fluid inclusion:

$$F = \frac{V_L}{(V_L + V_V \pm V_S)} \tag{6.2}$$

with V_L, V_V and V_S as the volumes of respectively the liquid, vapour and solid phases. The degree of fill for the different fluid stages is determined at room temperature, and is plotted in Figure 6.5. Fluid inclusions containing liquid (L) only (F=1) were disregarded because these were probably formed by necking-down. Overall, the degree of fill of primary and/or pseudosecondary inclusions, is quite uniform in all fluid stages. The maximum spread of 0.2 fill units is present in the K-feldspar stage. The lower degree of fill (F=0.8 average) in the sodic-calcic stage is from fluid inclusions in matrix quartz from samples DP#44614 and DP#44674. The degree of fill in the comb-quartz is relatively high (average of F=0.9), while the fill in the retrograde schist stage is very uniform with an average of F=0.9. The overall uniformity of high fill reflects the fact that the fluid phases in the different fluid stages are liquid dominated.

Figure 6.5 - Plot of degree of fill (F) against the different types of fluid stages. Fill of fluid inclusions are defined as the volumes of L/(L+V±S), while volumes are calculated according to the method of Bodnar (1983). The sodic-calcic stage contains mostly L-V-S, while the remaining stages (in most cases) L-V phases contain. The cluster of lower fill (± F=0.8) in the sodic-calcic stage are fluid inclusions from matrix quartz in samples DP#44614 and DP#44674. The degree of fill in the K-feldspar stage shows a large scatter, due to necking-down. The fill in the comb-quartz stage is relatively high, containing more liquid. There is a weak positive trend between the fluid stages and the degree of fill; a higher degree of fill in the later overprinting (cooler higher crustal level) fluid stages. The retrograde schist stage shows a more stable fluid inclusion fill.

The phases that are present in the fluid inclusions at room temperature (20° to 25°C) are liquid (L), vapour (V) and solids (S). On the basis of the type of phases present, degree of fill and volumetric size of fluid inclusions a generalized division can be made, which will divide the fluid inclusion into three categories.

Type 1, these are fluid inclusions containing three phases (L-V-S, Figure 6.7). They are generally sub-angular to subrounded primary pseudosecondary fluid inclusions of the sodic-calcic stage and to a much lesser extent of the K-feldspar and comb-quartz stage. Most of these L-V-S fluid inclusions are larger than 200 μm^3. In almost all cases is the solid phase larger in volume than the vapour phase (Figure 6.6). The cubic daughter mineral is identified as halite, based on optical properties and microprobe technics (section 6.3.1.1). Fluid inclusions containing halite daughter minerals, indicate salinities in the order of 23 to 26 weight precent NaCl (wt.% NaCl) for a NaCl-H_2O system (Hall *et al.* 1988).

Type 2, inclusions are subrounded and contain only L-V phases (Figure 6.7). These are observed in all samples and fluid stages but dominate in the comb-quartz and K-feldspar and retrograde schist stages. Volumes range from 3 to 5000 μm^3 and the phase ratio stays quite constant (see above).

Figure 6.6 - Solid volume-vapour volume plot of type 1 inclusions. The solids are perfect cubes, and are identified as halite. Note that the retrograde schist stage does not contain any solids. The solid volumes are in most cases larger than the coexisting vapour phase. Most L-V-S phase fluid inclusions are from the sodic-calcic fluid stage and to a lesser extent from the K-feldspar and comb-quartz stage. There is a separation between the volume size of the coexisting L-V-S phases and the fluid stages. The K-feldspar stage contains the largest coexisting V-S phases, compared with the comb-quartz stage.

Type 3, is monophase, liquid only fluid inclusions (Figure 6.7). Their shape is irregular if the fluid inclusion is large (40 μm in length) and isolated, or rounded, occasionally dark coloured and small (5 μm in length). They are probably formed due to necking-down from type 2 inclusions. In this work, only the L-V and L-V-S phase fluid inclusions are studied.

Figure 6.7 - Microphotographs of fluid inclusions at room temperature, base of photographs approximately 1 mm. Type 1, 2, 3 are described in the text above, and indicate respectively L-V-S, L-V, and L phase fluid inclusions. **A**- Sample DP#44664. Angular primary L-V-S phase fluid inclusions. Note the relatively large halite cube, compared with the vapour phase. **B**- Sample DP#44664. Primary L-V-S and L-V phase fluid inclusions. Note the angularity of the large fluid inclusions, some with facet lines visible due to negative crystal habitues. **C**- Sample DP#44591. Pseudosecondary L-V-S- and L-V fluid inclusions. **D**- Sample DP#44591. Primary L-V-S and L-V phase fluid inclusions. **E**- Sample DP#44591. Pseudosecondary L-V±S phase fluid inclusions cut by secondary L-V phase fluid inclusions. Photographs A-E are all from the sodic-calcic fluid stage. **F**- Sample DP#44604. Primary L-V phase fluid inclusions from the retrograde schist stage. Note the lower V/L ratio (large vapour bubble). **G** and **H**- Liquid (L) phase fluid inclusions. **G**- Sample DP#44614. Relatively large irregular and angular habitues. **H**- Sample DP#44620. Small rounded to subrounded L phase fluid inclusions.

A
Type 1
V
S
B
Type 2
Type 1
C
Type 2
Type 1
D
Type 2
Fl-plane
Type 1
E
Type 2
Type 1
Fl-plane
Fl-plane
F
Type 2

Figure 6.8 - Microphotographs (SEM) of solid phases in opened fluid inclusions. **A** and **B** is from the sodic-calcic stage (DP#44620). **C** is from the K-feldspar stage (DP#44640). **D** is from the comb-quartz stage (DP#44668). The scale bar is 1 µm.

6.3.1.1 - Microprobe analyses of daughter minerals in opened fluid inclusions

Identification of daughter minerals commonly depends on the optical properties of the mineral such as crystal shape, refractive index and birefringence. More sophisticated technics include extraction of individual minerals with analyses by X-ray diffraction, or the Raman spectroscopy and/or microprobe techniques.

Some daughter minerals were analysed by microprobe to verify the type of salt-water systems in the fluid inclusions, obtained by the freezing point depression. Inclusions were mechanically opened at room temperatures by fracturing the samples (for method see, Anthony *et al.* 1984, Kwak and Abeysinghe 1987, Li and Naldrett 1993). Only freshly broken surfaces were examined.

The success of the analysis depends on the size and orientation of the daughter mineral in the freshly opened fluid inclusion. Representative secondary electron imagery microphotographs of the solid phases in cavities of the fluid inclusions are shown in Figure 6.8. Although the radiation intensity from the daughter mineral is less than the surrounding quartz host, it is still possibly to obtain and recognize distinct element peaks. These raw peak intensities of the daughter minerals are consistent on reproducible daughter minerals. A characteristic Si peak of the host quartz is always presents in the spectra, because the x-rays will penetrate the daughter minerals into the cavity of the inclusion (Figure 6.9).

Halite occurs in all samples and fluid stages. Sylvite was also identified in samples from the sodic-calcic and comb-quartz stage (Sample DP#44591). However, K can also substitute for Na in some chloride salts (Quan *et al.* 1987, Cloke and Kesler 1979) of the comb-quartz stage (Figure 6.9) . Non-salt minerals were identified in the sodic-calcic stage, such as albite (?) and Ca-Mg-carbonate, possibly dolomite (Figure 6.10). The Ca-Mg-carbonates could also be identified by optical means as tiny minerals with high birefringence. These were rarely observed in the sodic-calcic stage, but no CO_2-bearing fluid inclusions were found. Iron oxide was occasionally identified in samples DP#44591 and DP#44664 from the sodic-calcic stage and occurred as reddish ragged minerals when optically observed (in sample DP#44664). Calcium was not found as a single Ca-chloride salt, but rather as a complex solid solution of a Na-Ca chloride and Fe-Ca chloride salt. In the sodic-calcic stage (sample DP#44664) there are possibly also $CaSO_4.nH_2O$ salts present (Figure 6.10).

The occurrence of albite in one of the opened fluid inclusion is a rather unusual finding. The probed albite mineral did not contain any a good crystal structure and had a ragged appearance. It could possibly be a chip of albite that "fell" into the cavity while opening the inclusion. However, Philippot and Selverstone (1991) reported inclusions with albite daughter minerals in eclogitic veins of the Western Alps.

Figure 6.9 - Some representative energy dispersive spectrum of solid phases in opened fluid inclusions. **A**- Sample DP#44640, Na chloride. **B**- Sample DP#44640, Na chloride. **C**- Sample DP#44668, K chloride. **D**- Sample DP#44591, Fe oxide. More complex spectra: **E**- Sample DP#44620, Na-Ca chloride. **F**- Sample DP#44668, Na-K chloride. **G**- Sample DP#44591, Fe-Ca chloride. **H**- Sample DP#44664, Fe-Ca chloride, or Ca chloride and Fe oxide in albite background.

6.3.2 - Freezing behaviours and fluid compositions

Freezing (melting) temperatures of aqueous inclusions are controlled by the composition of the fluid. The addition of salt to pure water affects the freezing point of an aqueous system and will depresses it proportionally to the type and amount of salt added. Therefore, by obtaining the initial (first) melting temperature, which corresponds to the eutectic (T_{eut}) temperature, the type of salt(s) in the system (a "salt-water system") can be determined (Table 6.2). Melting of frozen inclusions start at this eutectic point where ice+hydroxy-salt(s) react to hydroxy-

salt(s)+solution or ice+solution. For a NaCl-H_2O system the eutectic temperature is (±) -21.2 °C containing (±) 23 weight percent NaCl (Hall *et al.* 1988). For inclusions containing less than 23 wt.% NaCl, progressive melting of ice dilutes the solution and raises the melting temperature until all the ice is molten.

Figure 6.10 - Some complex energy dispersive spectra of chlorine and silicate-minerals in fluid inclusions. **A**- and **B**- Sample DP#44664, cluster of small minerals causing a complex spectrum. **C**- Sample DP#44664, albite. **D**- Sample DP#44591, Ca-Mg carbonate (dolomite).

The final melting temperature (T_{fm}) is a function of the salinity. If salts other than NaCl are present, they would have a similar effect on the melting point of the solution. Although fluid inclusions contain several components e.g. H-O-Na-K-Ca-Mg-Fe-Zn-Cl-S-C, they are often represented in the simplified NaCl-H_2O system (± Ca and K) and salinities are therefore normally expressed as *equivalent wt.% NaCl.*

Table 6.2 - Temperatures and compositions of some salt(s)-water systems at their eutectic points.

System	Eutectic temperature °C	Eutectic composition	Reference
H_2O-NaCl	-21.2	23.2% NaCl	Hall *et al.* 1988
H_2O-NaCl-KCl	-22.9	20.2% NaCl 5.8% KCl	Hall *et al.* 1988
H_2O-$MgCl_2$	-34.0	21.0% $MgCl_2$	Spencer *et al.* 1990
H_2O-NaCl-$MgCl_2$	-35.2	6.1% NaCl 19.1% $MgCl_2$	Spencer *et al.* 1990
H_2O-$CaCl_2$	-49.8	30.2% $CaCl_2$	Linke 1965
H_2O-NaCl-$CaCl_2$	-51.6	2.9% NaCl 29.6% $CaCl_2$	Spencer *et al.* 1990
$CaCl_2$-$MgCl_2$-H_2O	-52.2	28.0% $CaCl_2$ 4.8% $MgCl_2$	Spencer *et al.* 1990
$CaCl_2$-KCl-NaCl-H_2O	-55.0	44.8% $CaCl_2$ 3.2% KCl 0.6% NaCl	Yanatieva 1946

Experimentally derived eutectic point, temperatures can vary by an order of 1 °C.

6.3.2.1 - Results of freezing behaviours of studied fluid inclusions

An important tool in fluid inclusion studies is the heating / freezing stage. This is a sample chamber mounted on an ordinary microscope and allows observation of fluid inclusions while heating or cooling (Figure 6.11). The working range for the Reynold stage used is -200°C to +600°C.

Figure 6.11 - Schematic diagram of the Reynold stage. Oxygen free N_2 gas pressurises the liquid N_2 vessel. To freeze the sample, liquid N_2 flows over the sample. To heat the sample, oxygen free N_2 is heated by heating elements before the gas flows over the sample. The temperature in the Reynold stage is measured by a thermocouple.

On freezing fluid inclusions, temperatures are rapidly lowered to approximately -200°C. Metastable phase behaviour is commonly observed the first time the fluid inclusions are cooled. Only after sequential reduction of the temperatures to -200°C and reheating to around 0°C, do phase changes occur. These involve the transformation of the liquid phase (solution) to solid (ice). Motion (Brown motion ?) of the vapour bubble ceases, while the surface of the bubble becomes more ragged and the volume of the bubble (normally) decreases slightly. In some cases the vapour bubble disappears totally (or is possibly obscured by the newly formed ice crystals) and reappears on heating. This is due to the formation of ice crystals which grow from the liquid phase at the expense of the space for the vapour bubble. These newly formed ice crystals are usually very small. By keeping the fluid inclusion just above the expected eutectic temperature it is possible to grow larger ice crystals. That make phase changes easier to observe. In samples DP#44591 and DP#44664 (of the sodic-calcic stage) some "large" ± 20 μm in diameter fluid inclusions, show peculiar behaviour during freezing. The vapour bubble expands by approximately 1.5 times in diameter on freezing (< -100°C in DP#44591 and ~0°C in DP#44664). The reason for these phenomena could be that fluid inclusions are iso-volumetric. Fluid inclusions are assumed to represent constant-volume (and constant-mass) systems.

On freezing the volume stays constant, but the density will increase. Keeping in mind equation (6.1), the volume of the liquid phase will decrease, increasing the space for the vapour bubble which is able to expand.

In some L-V-S (at room temperature) phase fluid inclusions (samples DP#44664, DP#46412) the solid (halite cube) is crushed by the formation of the newly formed ice crystals during freezing. After freezing and re-equilibrating these fluid inclusions to room temperature, rectangular fragments of the halite cubes are observed.

Another diagnostic feature observed during freezing procedures is a distinct colour change. Numerous inclusions (in all samples except DP#44642 and DP#44604 of the retrograde schist stage), become dark brown on freezing. This browning and low freezing depression point (see next paragraph) is characteristic of a $CaCl_2$-NaCl-H_2O "salt-water" system (Davis *et al.* 1990). Other fluid inclusions stay colourless on reaching the low freezing depression point, implying a $CaCl_2$-NaCl-H_2O-KCl system (Shepherd *et al.* 1985).

6.3.2.2 - Observed freezing temperatures

Eutectic (or first) melting temperatures (T_{eut}) are notoriously difficult to observe (Shepherd *et al.* 1985). Nevertheless, first melting points were observed at temperatures ranging from -35 to -70°C (Figure 6.12A). Overall the first melting point shows a gauss like distribution, with a slight skew to lower first melting temperatures. The model is in the order of -45 to -50°C, close to the ternary $CaCl_2$-NaCl-H_2O (T_{eut} is -51.6°C, Table 6.2 and Table 6.3). For the sodic-calcic and comb-quartz stages the observed eutectic points fits well with the $CaCl_2$-NaCl-H_2O eutectic point. However, the K-feldspar stage is skewed to lower temperatures (Figure 6.12A), which could be an indication of an increased proportion of KCl present. The T_{eut} for the $CaCl_2$-NaCl-KCl-H_2O salt-water system is -55.0°C (Table 6.2). Another possibility for the lower observed initial melting temperatures than the predicted T_{eut} for the $CaCl_2$-NaCl-H_2O system is the metastable melting behaviour of $CaCl_2$-hydrate. The hydrate is probably $CaCl_2.4H_2O$, which reacts (melts) at lower metastable eutectic temperatures, between -60° and -75°C (Davis *et al.* 1990).

The low initial melting and brown colour are, as mentioned earlier, characteristic for fluids containing $CaCl_2$. The reason for the brown colouring is still enigmatic, but could be due to the formation of antarcticite ($CaCl_2.6H_2O$). At the ternary eutectic of

± -52°C, antarcticite starts to melt and followed by either ice or hydrohalite ($NaCl.2H_2O$, Table 6.3). Fourteen different equilibrium melting sequences are possible in a $CaCl_2$-NaCl-H_2O system (Schiffries 1990). Most inclusions of the $CaCl_2$-NaCl-H_2O system mentioned in the literature and those in this study have common melting sequences of type A, B and C as labelled in Figure 6.13 (Vanko *et al.* 1988, Li and Naldrett 1993). Fluid inclusions at room temperature contain the L-V phases for fields A, B, E and F in Figure 6.13. The remaining fields contain L-V-S (halite) phases at room temperature. The hydrate daughter crystals in the fluid inclusions formed during the freezing procedures are commonly difficult to identify by of optical microscopy because of their small size and resemblance to ice crystals. These salt hydrate crystals can be identified indirectly by comparing the melting behaviours with predicted melting temperatures based on the S-M-W solution model of Spencer *et al.* (1990), and on the phases present at room temperature.

Figure 6.12 - Histogram of the freezing behaviour of the different alteration styles. **A**- First melting of a component, a phase change, in the fluid inclusions; which coincides with the eutectic point of the particular fluid system. **B**- The melting of a salt (hydrohalite, antarcticite or ice). **C**- Final melting of the fluid system. The alteration styles "sodic-calcic", "K-feldspar" and "comb-quartz" stages are all consistent with a fluid composition in the $CaCl_2$-NaCl-H_2O (± KCl ± $MgCl_2$) system. The "retrograde schist" stage consists of L-V fluid inclusions only and does not show the distinct brown colouring on freezing. Sample DP#44604 only has two phase changes (figure -A- and -C-); an eutectic temperature of about -35° to -40°C and a final melt of -10° to -15°C, which could indicate the system NaCl-H_2O ± $FeCl_2$ ± $MgCl_2$. The "retrograde schist" stage data in figure -B- are from sample DP#44642 only and could represent the NaCl-H_2O ± KCl system.

On increasing the temperature through the ternary eutectic, a frozen inclusion would contain at T_{eut} ice, hydrohalite, antarcticite and some liquid (melt solution). Further heating of the fluid inclusion causes an increase in liquid and the fluid composition

will follow the boundary between ice (A) and hydrohalite (B) or antarcticite (E). However hydrohalite does not crystallize in fluid inclusions which minimal contains 24.4 wt.% $CaCl_2$ (Davis *et al.* 1990). This fits well with the observed salinities in fluid inclusions of the K-feldspar and comb-quartz stage where low NaCl (< 2 wt.% NaCl) fluid compositions plot in field F of Figure 6.13 (compare Figure 6.13 and 6.12). Melting temperatures of the salt-hydrates are plotted in Figure 6.12B. The observed melting temperatures (Figure 6.12B) for the sodic-calcic stage possibly reflect a combination of antarcticite and ice. The brown colouring at those temperatures starts to disappear and the frozen solids appear to be coarser and become fewer in number (Table 6.3).

Equilbrium melting sequence from the eutectic point to liquid homogenization

A- $I+HH+AA \rightarrow I+HH+AA+L_E \rightarrow I+HH+L \rightarrow I+L \rightarrow L$

B- $I+HH+AA \rightarrow I+HH+AA+L_E \rightarrow I+HH+L \rightarrow HH+L \rightarrow L$

C- $I+HH+AA \rightarrow I+HH+AA+L_E \rightarrow I+HH+L \rightarrow HH+L \rightarrow H+HH+L \rightarrow H+L \rightarrow L$

D- $I+HH+AA \rightarrow I+HH+AA+L_E \rightarrow HH+AA+L \rightarrow HH+L \rightarrow H+HH+L \rightarrow H+L \rightarrow L$

E- $I+HH+AA \rightarrow I+HH+AA+L_E \rightarrow HH+AA+L \rightarrow HH+L \rightarrow L$

F- $I+HH+AA \rightarrow I+HH+AA+L_E \rightarrow I+AA+L \rightarrow I+L \rightarrow L$

G- $I+HH+AA \rightarrow I+HH+AA+L_E \rightarrow HH+AA+L \rightarrow HH+AA+H+L_{P1} \rightarrow H+HH+L \rightarrow H+L \rightarrow L$

H- $I+HH+AA \rightarrow I+HH+AA+L_E \rightarrow HH+AA+L \rightarrow H+HH+AA+L_{P1} \rightarrow H+AA+L \rightarrow H+L \rightarrow L$

Figure 6.13 - Modified ternary $CaCl_2$-NaCl-H_2O phase diagram after Schiffries (1990). The melting sequences for each region (labelled A to H) are unique. Fluid inclusion melting behaviour in this study follows the sequence of regions A, B or C, depending on their fluid composition and phases present at room temperature. Abbreviations used are: I=ice, HH=hydrohalite, AA=antarcticite, H=halite, L=liquid, L_E=eutectic liquid and L_{P1}=peritectic liquid (equilibrium melt forms at approximately -22°C).

Table 6.3 - Summary of observed melting behaviours of halite bearing aqueous solution in the system $NaCl-CaCl_2-H_2O$, with observed temperatures (°C) and interpretation.

Observed Melting Behaviour	Observed Temperatures	Interpretation
Dark blackish browning, glassy and occasionally decrease or sudden collapse of vapour bubble.	-75 to -54	Melting of metastable $CaCl_2$-hydrate.
Coarser granular appearance than above, more brown than black.	-65 to -44	Eutectic melting and recrystallizing ice.
Inclusions become lighter, rim of melt visible, still granular, fewer grains but coarser, still brown.	-45 to -20	Melting of $CaCl_2$-hydrate grains and occasionally hydrohalite and H_2O-ice.
Brown colour disappears, still coarse, granular.	-45 to -30	All hydrohalite melted.
Colourless inclusions, with fewer larger subrounded cubes starting to melt, more liquid, bubble movement.	-50 to -10	Final melting of ice. (Low melting T due to meta-stability of ice)
Occasionally sudden movement of bubble, due to melting of clear lath like crystals with similar refractive index to liquid.	-10 to +10	Possibly final melting of metastable $CaCl_2$-hydrate, or hydrohalite; only observed occasionally.

Figure 6.14 - Plot of final melting temperatures versus the fluid inclusion volume. There appears to be a very weak correlation between the volume and the final melting temperature. The smaller the inclusions, the lower the final melting temperature. Ice melts in some small size comb-quartz stage fluid inclusions as low as -50°C.

Final melting temperatures vary with the size of the inclusions and the $CaCl_2$ concentration. Small fluid inclusions of the comb-quartz stage show final melting temperatures as low as -50°C (Figure 6.12C and 6.11) falling in region F of Figure 6.13 with $CaCl_2/NaCl$ ratios of approximately 0.9. Davis *et al.* (1990) observed that final melting temperatures of ice, in the presence of hydrohalite, can vary by up to 15°C in fluid inclusions of different sizes but of the same bulk $CaCl_2-NaCl-H_2O$ composition. In general, the final melting temperatures show a bimodal distribution.

A peak at around -30° to -35°C and a very pronounced culmination at -15° to -20°C. In a few (L-V inclusions at room temperature, DP#46412) cases from the K-feldspar stage, final melting occurred at temperatures in the vicinity of 0°C, mostly around +10°C. Around those temperatures, rapid nucleation of lath like crystals with slight positive relief occurred, followed by rapid melting; and are interpreted as final melting of metastable antarcticite in a $CaCl_2$-H_2O system (Schiffries 1990). Another option for this phenomenon is (Vanko *et al.* 1988) that these regrown lath (bladed) crystals are hydrohalite accompanied by growth of halite, which could occur at temperatures close to 0°C (assumed to be metastable). Halite was not observed in these particular fluid inclusions so metastable antarcticite is therefore the preferred interpretation.

6.3.2.3 - Modelled fluid composition and obtained salinity

The above observations and statements were all than based on modelling in the $CaCl_2$-NaCl-H_2O salt-water system, suggested by a low T_{eut} and brown colouration during freezing procedures. However, the brown colouration that occurs after freezing could also be produced in a NaCl-$CaCl_2$-$MgCl_2$-H_2O system (Shepherd *et al.* 1985). It was also mentioned earlier that fluid inclusions with low T_{eut} (-60°C) which stayed colourless during freezing could contain KCl, implying a KCl-$CaCl_2$-NaCl±$MgCl_2$-H_2O system. These colourless (on freezing) fluid inclusions with low T_{eut} were modelled in the ternary $CaCl_2$-NaCl-H_2O system.

The retrograde schist stage inclusions show different melting behaviours. Fluid inclusions in sample DP#44642 (L-V at room temperature) show only one distinct melting point at approximately -21.5°C. The phase that melts has a relief of $n_{fluid} < n_{salt} << n_{quartz}$, and is interpreted to be a salt-hydrate. These fluid inclusions has been modelled in a NaCl-KCl-H_2O system (Hall *et al.* 1988), but could also be modelled in the simplified NaCl-H_2O system. These salt-water systems do not change colour during freezing (Shepherd *et al.* 1985). Sample DP#44604 however, contains fluid inclusions with much lower initial melting temperatures, around T_{eut} of -35° to -40°C and a final melt of -10° to -15°C, which could be modelled in the system NaCl-H_2O ±$FeCl_2$±$MgCl_2$ (Spencer *et al.* 1990).

In some of the fluid inclusions from comb-quartz (samples DP#46410 and DP#46411) only two phase changes were observed, namely the T_{eut} (around -50°C) and a low final melt (-30° to -50°C). These observations came from small inclusions

(see previous section 6.3.2.2), which become brown during freezing. Salinities for these fluid inclusions were modelled for fluid compositions in the $CaCl_2$-H_2O system (Linke 1965).

Salinities calculated on the basis of freezing temperatures (and halite dissolution temperatures) are plotted in Figure 6.21 and tabulated in Table 6.4. The salinities are generally the highest in the sodic-calcic stage, ranging from approximately 25-to 40 Eq. wt.% NaCl, with an average of 30 Eq.wt.% NaCl. This relatively high salinity is also apparent from the fact that most of the fluid inclusions of the sodic-calcic stage contain halite daughter crystals. However, the overprinting K-feldspar and comb-quartz stages, both show salinities (in most cases) just below the NaCl saturation curve at room temperature. The average salinities obtained by freezing method are respectively 24.2 and 24.6 Eq.wt.% NaCl, for the K-feldspar and comb-quartz stage (Table 6.4).

Table 6.4 - Salinities obtained by microthermometry and expressed as equivalent weight % NaCl (Eq.wt.% NaCl).

	Mean Salinity Eq.wt.% NaCl	stdev
Sodic-calcic stage		
DP#44664 (n=13)	31.41	2.32
DP#44674 (n=8)	35.84	0.85
DP#44614 (n=6)	33.38	5.13
DP#44591 (n=20)	30.14	2.20
DP#46303 (n=18)	25.96	1.82
DP#44620	23.10	
average	29.97	2.46
K-feldspar stage		
DP#44630 (n=12)	23.77	2.94
DP#44640 (n=20)	22.17	6.19
DP#46412 (n=23)	26.68	4.38
average	24.20	4.50
Comb-quartz stage		
DP#46411 (n=25)	27.17	3.06
DP#46410 (n=27)	22.93	2.02
DP#46413 (n=25)	25.36	3.75
DP#44668 (n=30)	22.87	1.58
average	24.58	2.60
Retrograde schist stage		
DP#44604 (n=33)	20.54	1.78
DP#44642 (n=17)	22.49	0.26
average	21.51	1.02

Note: Stdev = standard deviation; n is the number of heating or freezing runs.

The salinities obtained in the retrograde schist stage show a very narrow range (low standard deviation number) and are under saturated with respect to halite (L-V phase fluid inclusions only). The average salinities are 21.5 Eq.wt.% NaCl (Table 6.4). These salinities are relatively high compared to a (ordinary) metamorphic fluid derived from a schist (~10 Eq.wt.% NaCl, Roedder 1984). However, metamorphism of evaporate beds, which was not observed, could have increased the salinity. These observed salinities possibly reflect mixing between D_2 derived metamorphic fluids and overprinting sodic-calcic fluids.

6.3.2.4 - Fluid composition based on the "phase volume method"

Compositions of fluids estimated on the basis of the volumes of the phases present in fluid inclusions has been proven to be useful by Ramboz (1979), for a porphyry copper deposit, and by Brown (1983) and Witt (1988), for mineralized granites in north Queensland. They calculated the dimensions of all the phases present and applied known densities and the compositions for saturated fluids of salt-water systems. Ramboz (1979) estimated errors in fluid compositions up to 50 percent, by using this method, but argued that this method is still useful for trend indications.

Only L-V-S phase fluid inclusions were used in this study to calculate the fluid composition based on the phase-volume method (calculation method is described in Appendix F). These particular inclusions are assumed to be saturated with halite. The fluid inclusions of the different fluid stages have been calculated for both the NaCl-$CaCl_2$-H_2O and NaCl-$CaCl_2$-KCl-H_2O salt-water systems (Table 6.5 and 6.6). Microprobe and optical analyses suggest that most of the daughter salts are halite. The specific gravity of halite (2.17 g/cm^3) was therefore used for calculating the weight percent of the solid phase in the fluid inclusions. The bulk composition for the liquid weight percent used are from Table 6.2.

Table 6.5 - Composition of fluid inclusions calculated for the NaCl-$CaCl_2$-H_2O and NaCl-$CaCl_2$-KCl-H_2O systems (see Appendix F), based on the "phase-volume method" (Bodnar 1983, Witt 1988).

	NaCl-$CaCl_2$-H_2O system						NaCl-$CaCl_2$-KCl-H_2O							
	NaCl		$CaCl_2$		H_2O		NaCl		$CaCl_2$		KCl		H_2O	
	wt%	stdev	wt%	stdev	wt%	stdev	wt%	stdev	wt%	stdev	wt%	stdev	wt%	stdev
Sodic-calcic stage														
DP#44664 n=10	18.57	7.60	24.82	2.32	56.60	5.28	17.43	7.65	37.24	3.45	2.68	0.25	42.66	3.95
DP#44674 n=4	30.60	2.93	21.16	0.89	48.24	2.03	29.53	2.95	31.78	1.33	2.28	0.10	36.41	1.52
DP#44614 n=2	27.44	5.63	22.12	1.72	50.44	3.91	26.35	5.67	33.22	2.56	2.39	0.18	38.05	2.93
DP#44591 n=13	16.12	6.74	25.57	2.05	58.31	4.69	14.97	6.77	38.35	3.05	2.76	0.22	43.93	3.50
DP#46303 n=2	21.00	9.61	24.08	2.93	54.92	6.68	19.87	9.66	36.14	4.36	2.60	0.31	41.40	4.99
average	22.75	6.50	23.55	1.98	53.70	4.52	21.63	6.54	35.35	2.95	2.54	0.21	40.49	3.38
K-feldspar stage														
DP#44630 n=2	13.73	4.94	26.30	1.51	59.97	3.43	12.56	4.96	39.43	2.24	2.83	0.16	45.17	2.56
DP#46412 n=5	12.41	5.05	26.70	1.54	60.89	3.51	11.24	5.07	40.03	2.29	2.88	0.16	45.85	2.62
average	13.07	5.00	26.50	1.52	60.43	3.47	11.90	5.01	39.73	2.26	2.85	0.16	45.51	2.59
Comb-quartz stage														
DP#46410 n=3	14.86	7.08	25.95	2.16	59.18	4.92	13.70	7.10	38.92	3.20	2.80	0.23	44.58	3.67
DP#46413 n=5	19.00	6.90	24.69	2.10	56.31	4.80	16.03	7.26	37.87	3.27	2.72	0.24	43.38	3.75
average	16.93	6.99	25.32	2.13	57.75	4.86	14.87	7.18	38.39	3.24	2.76	0.23	43.98	3.71

Note: n is number of fluid inclusions with solids on which phase-volume method is used. Stdev is standard deviation.

Calculated equivalent salinities obtained by the phase-volume method are very much subject to the components present in the salt-water system and to the bulk composition of the saturated fluid. The more components present and higher Eq.wt.% NaCl for the saturated bulk composition, the higher the estimated Eq.wt.% salinities would be, based on the phase-volume method. The salinities in Table 6.5 are therefor overestimated.

Equivalent salinities estimated by the phase-volume method are 1.5- to 1.8 times larger for the $NaCl-CaCl_2-H_2O$ system, compared with the salinities obtained by microthermometry method, and 1.9- to 2.3 times for the $NaCl-CaCl_2-KCl-H_2O$ system. The salinities are approximately 46, 40 and 42 Eq.wt.% NaCl for respectively the sodic-calcic, K-feldspar and comb-quartz stage in the $NaCl-CaCl_2-H_2O$ system, and 60, 55 and 56 Eq.wt.% NaCl in the $NaCl-CaCl_2-KCl-H_2O$ system. Salinities obtained by the microthermometry would therefore be considered to be a minimum estimate, while the salinities obtained by the phase-volume method, in the $NaCl-CaCl_2-KCl-H_2O$ are the maximums. One reason for this "overestimation" of the salinities based on the phase-volume method is the inaccuracy of the volume estimates of the phases (solid and vapour bubble) in the fluid inclusions.

Figure 6.15 - Fluid compositions estimated from freezing temperatures in the $NaCl-CaCl_2-H_2O$ system (method of Shepherd *et al.* 1979). Fluid inclusions from the K-feldspar and comb-quartz stage are L-V (at room temperature) phase only; though some L-V-S phase fluid inclusions are present and could indicate an overlap with the sodic-calcic stage.

Cation ratios of Ca/Na (and K/Na, Table 6.6) indicate that the Ca/Na molar cation ratios for the $NaCl-CaCl_2-H_2O$ system fit reasonably with ratios determined for natural fluid inclusions (for that salt-water system), 0.26 to 0.66 (Vanko *et al.* 1988). Ca/Na ratios in the $NaCl-CaCl_2-H_2O$ system for the comb-quartz stage (Ca/Na = 0.83) are only slightly higher than those obtained by Vanko *et al.* (1988). The K-feldspar stage Ca/Na ratio, however, is about twice the value (Ca/Na = 1.20). The concentration of $CaCl_2$ is probably overestimated due to the fact that other soluble

salts such as $FeCl_2$ and $MgCl_2$ are not taken into consideration (Witt 1988). An other possibility for the high concentration is perhaps a result from leaching of calcium during the albitization of plagioclase (or K-feldspathization, Carten 1986, Witt 1988).

However, modelling of salinities for the $NaCl$-$CaCl_2$-H_2O system based on freezing temperature render $CaCl_2/NaCl$ ratios of 0.5 to 0.9 for the sodic-calcic, 0.6 to 0.9 for the K-feldspar and 0.9 for the comb-quartz stage (Figure 6.15). Except for the comb-quartz stage, these numbers are compatible with the average ratios obtained by the phase-volume method, being 0.5, 0.65 and 0.6 for respectively the sodic-calcic, K-feldspar and comb-quartz stages. If the result is remodelled in the quaternary system $NaCl$-$CaCl_2$-KCl-H_2O, and the KCl concentrations are combined with the NaCl on a wt.% equivalent basis, the $CaCl_2/NaCl$ ratios based on the phase-volume method are approximately 0.25 higher than those ratios modelled in the ternary $NaCl$-$CaCl_2$-H_2O system.

Table 6.6 - Cation ratios (molar quantities) for the salt-water systems given in Table 6.5

	Ca/Na*	K/Na**	Ca/Na**
Sodic-calcic stage			
DP#44664 (n=10)	0.72	0.13	1.41
DP#44674 (n=4)	0.30	0.06	0.56
DP#44614 (n=2)	0.38	0.07	0.70
DP#44591 (n=13)	0.89	0.16	1.77
DP#46303 (n=2)	0.60	0.11	1.14
average	0.52	0.09	0.99
K-feldspar stage			
DP#44630 (n=2)	1.12	0.20	2.27
DP#46412 (n=5)	1.29	0.23	2.64
average	1.20	0.22	2.44
Comb-quartz stage			
DP#46410 (n=3)	1.00	0.18	2.01
DP#46413 (n=5)	0.70	0.15	1.60
average	0.83	0.16	1.78

Note: * ratio from $NaCl$-$CaCl_2$-H_2O, ** ratio from $NaCl$-$CaCl_2$-KCl-H_2O systems

If the halite bearing fluid inclusions are modelled in the $NaCl$-$CaCl_2$-KCl-H_2O system, it is possible to obtain the K/Na ratio (Table 6.6). The K/Na molar cation ratio averages 0.09, 0.22 and 0.16 respectively in the sodic-calcic, K-feldspar and comb-quartz stage inclusions. The K/Na ratio of a fluid in equilibrium with two alkali feldspars was experimentally obtained by Orville (1963) (Chapter 4). In a closed system, the K/Na ratio in a fluid is temperature dependent. The activity ratio (concentrations) would be larger at higher temperatures compared to the fluid in equilibrium with the same assemblage at lower temperatures. This means that a fluid migrating from a high- to a low temperature environment would cause potassium metasomatism (Orville 1963, Wintsch 1973, Giggenbach 1984, Carten 1986).

A fluid with a K/Na ratio of 0.09 can only be in equilibrium with albitic plagioclase in sodic-calcic stage (at P = 2 kbar). The fluid K/Na ratio of the K-feldspar stage (K/Na = 0.22), would only be in equilibrium with K-feldspar at temperatures below 500°C (at 2 kbar), which is in agreement with corrected homogenization temperatures obtained from fluid inclusions (see next section). The comb-quartz stage, however, has an average K/Na ratio of 0.16, which would be in equilibrium with an albitic plagioclase (trace amounts of albite is present in the Cloncurry fault comb-quartz and also in the post D_2 white buck quartz lenses of the Maronan supergroup; determined by XRD method, D. Aswin pers. com. 1994). This type of alteration assemblage was observed by Foley (1993) at Daylight bore in the Cloncurry terrain (Chapter 3 and Chapter 7).

6.3.3 - Heating experiments on fluid inclusions

Heating of fluid inclusions (on the Reynold stage) can cause four different types of phase change in L-V-S and L-V inclusions present depending on the phases present, the degree of fill (F) and the bulk composition density (Pichavant *et al.* 1982, Figure 6.16).

(i) High density L-V-S and high degree of fill fluid inclusions. The vapour bubble will decrease in size before the solid phase disappear (homogenization to liquid) when it reaches the liquid - vapour curve (in a phase diagram for that particular fluid system).
(ii) Moderate density L-V-S and high degree of fill fluid inclusions. The solid phase disappears before the vapour with homogenization to liquid.
(iii) L-V-S inclusions with densities between (i) and (ii) in which the vapour and solid disappear simultaneously and homogenize to a liquid.
(iv) L-V inclusions with a low degree of fill will homogenize to a vapour phase, while a high fill fluid inclusion homogenize to a liquid (the former is only ones observed after repeated heating cycles; possibly leakage occurred).

If the inclusion was formed from a homogeneous fluid (normally assumed) then the homogenization temperature (T_h) provides a minimum estimate of the entrapment (and formation) temperature (T_t). The actual conditions of formation lie on a constant density line (isochore in a P-T diagram), starting at the point of homogenization (at phase changes of scenario (iii), Figure 6.16). The isochore is a

constant volume section through a liquid or vapour plane, and approximates to a straight line.

Since the entrapment temperature must lie somewhere on the isochore line an independent geobarometer should be applied to obtain the T_t. If the entrapment pressure (the lithostatic pressure of the formation) and the density (isochore) of the fluid is known, the isochore can be used for P-T estimates to obtain the correct T_t, or visa versa, hereby assuming a lithostatic fluid gradient. In general are the densities not known, but the composition of the fluid (expressed as Eq.wt.% NaCl) can be estimated from microthermometry (or phase-volume technics). Potter (1977) presented a series of pressure correction diagrams for salinities up to 25 Eq.wt.% NaCl and pressures up to 2 kbar. It is evident from these correction diagrams that the temperature corrections are less sensitive to the composition of the fluid than to the entrapment pressure.

Figure 6.16 - Distorted schematic P-T projection of phase equilibrium in salt-H_2O system (after Pichavant *et al.* 1982, Knight and Bodnar 1989). Three paths are showing that cause L-V-S fluid inclusions to homogenize to liquid (points 2, 3 and 4). Point 1 is T_{h-v} for inclusion (i) following path 1-2-7; Point 2 is T_{h-s} for inclusion (i) following path 1-2-7; Point 7 is the inclusion (i) at P_t and T_t for the path 1-2-7. Point 3 is the T_h of both solid and vapour for a fluid inclusion (iii) path from room temperature to 3. Point 3 is also (for this sketch) the T_{h-s} for inclusion (ii) following path room temperature-3-4. Point 4 for is T_{h-v} for inclusion (ii) following path room temperature-3-4 and than up the isochore. The L-V-S curve is the salt-H_2O solubility curve. The isopleth is the constant composition curve. The critical curve would be constructed from the different point 5 points on different isopleths. Point 5 is the location on a isopleth at which a fluid exhibits critical behaviour and separates the bubble-point curve (left of 5) from the dew-point curve (right of 5). Point 6 is the intersection between the dew-point curve and the solubility curve.

Experimental work of Zhang and Frantz (1987) on synthetic fluid inclusions in the system NaCl-KCl-$CaCl_2$-H_2O render in a ten-parameter polynomial regression, which permits to calculate the density as a function of temperature, pressure and fluid composition (equation 12 of Zhang and Frantz, 1987). By substituting the corrected homogenization temperatures, based on Potter (1977), into Zhang and

Frantz's (1987) equation 12, it is possible to compare the used pressure correction in Potter (1977) with pressures obtained by equation 12. The pressures obtained by Zhang and Frantz (1987) method are: 3 kbar, 2 kbar and 1.5 kbar for respectively the sodic-calcic, K-feldspar and comb-quartz stage (see also Chapter 3). These pressures are close to the once used for the Potter (1977) correction. The calculations where done in the NaCl-H_2O system, but the admixing effects of KCl, $CaCl_2$ and $FeCl_2$ should lower the pressure (Quan *et al.* 1987). Although these fluid pressures are low, and could easily have been below lithostatic pressures, it is believed that the fluids followed a lithostatic fluid pressure gradient path. This is based on zones with inferred high fluid/rock ratios, evident by the abundance of high temperature vein systems (section 4.3) and breccias formed by hydro-fracturing.

6.3.3.1 - Observed heating behaviour in studied fluid inclusions

With one exception the fluid inclusions homogenize to liquid. In L-V inclusions the vapour bubble decreases in size and disappears and the inclusions homogenize to a liquid. In over ninety percent of the L-V-S phase inclusions, the vapour bubble decreases in size and disappears before the solid phase (halite) melts, and the inclusion homogenizes to a liquid. On heating, the cubic solid first becomes subrounded and finally rounded before it melts. On cooling back to room temperature, most vapour bubbles reappear between 25° and 80° below the T_{h-v}. The solid phase however, does not reappear on return to room temperature, except in two cases (DP#44664 FI #7 and DP#44591 FI #18, see Appendix F) which happen to be the highest salinity inclusions in these samples (38 and 32 Eq.wt.% NaCl).

Entrapment temperatures (Figure 6.17) have been established by the Potter (1977) method. T_{h-s} was used (final and / or entrapment) for most of the cases of L-V-S phase type of inclusions while the T_{h-v} was taken as the corrected homogenization temperature for the L-V phase type of inclusions.

The (corrected 25 Eq.wt.% NaCl and 2 kbar) final homogenization temperatures are the highest for the sodic-calcic stage ranging from about 320° to 490°C (Figure 6.17). These show a bimodal distribution with peaks at 355°C and 455°C. The higher T_h determinations are from the inclusions in the matrix quartz of samples DP#44614 and DP#44674, while the lower temperature ones are from inclusions in quartz-albite veins. Corrected final T_h for the K-feldspar stage (corrected for 20 Eq.wt.% NaCl and 1.5 kbar) range from 180° to 330°C with a pronounced peak at

295°C and a distribution skewed to lower temperatures. Estimated T_h form the comb-quartz stage (corrected for 25 Eq.wt.% NaCl and 1.5 kbar) overlap partly with the K-feldspar stage, with a weak developed bimodal distribution which has a large peak near 270°C and a smaller peak at 185°C. The temperatures of the retrograde schist stage (corrected for 20 Eq.wt.% NaCl and 2 kbar) overlap with the lower distribution of the sodic-calcic stage with a peak at 375°C. As mentioned previously, Potter's (1977) correction diagrams are only valid up to 2 kbar. However, Potter's (1977) pressure correction is approximately a linear function between the correction temperature and the pressure, ~50°C per ~0.5 kbar. Corrected entrapment temperatures for the "retrograde schist" and sodic-calcic stages would than be respectively ~150°C and ~100°C higher (this should be kept in mind when corrected homogenizaton temperatures are quoted in this chapter! However, using Potter's correction diagrams outside the intended range, must be used with caution!)

Figure 6.17 - Entrapment temperatures of fluid inclusions in quartz from overprinting styles of alteration estimated applying pressure and salinity factors from Potter (1977). **A**- Pressure and salinity conditions are: sodic-calcic stage - 2 kbar, 25 Eq.wt.% NaCl; K-feldspar stage - 1.5 kbar, 20 Eq.wt.% NaCl; comb-quartz stage - 1.5 kbar, 25 Eq.wt.% NaCl; and retrograde schist stage - 2 kbar, 20 Eq.wt.% NaCl. The sodic-calcic stage shows a complex bimodal distribution, with peaks at 355° and 455°C. The homogenization temperatures of the comb-quartz and K-feldspar stage are approximately 100 degrees lower and are in the order of 280°C. **B**- Corrected homogenization temperatures based on extrapolated temperature/pressure corrections (see text). Conditions for the K-feldspar and comb-quartz stage are the same as in -A-, pressure correction conditions for the sodic-calcic and retrograde schist stage is done for respectively 3 kbar and 3.5 kbar. The large range in T_h is possibly a function of post-entrapment modification, such as necking-down (Figure 6.4), or overprinting deformation / stress which could cause leakage and lower decrepitation temperatures.

6.3.3.2 - Dissolution of halite (T_{h-s}) versus the vapour homogenization (T_{h-v})

As mentioned previously, T_{h-v} in most L-V-S inclusions from the different alteration stages occurs at lower temperatures than the final dissolution (T_{h-s}) of halite (Figure 6.18). This type of homogenization behaviour is an indication that fluid boiling did not occur during entrapment of the inclusion. Ramboz *et al.* (1982) explained this type of behaviour as heterogeneous entrapment of a saturated fluid with solids, or due to supersaturation and/or entrapment of refractory daughter minerals. Refractory daughter minerals, are generally considered to be non salts or solids that have not (yet) dissolve at the decrepitation temperature. These where not observed in this study. If heterogeneous entrapment occurred, then a common criterion for recognizing this phenomenon in fluid inclusion studies is the occurrence of two groups of fluid inclusions in the same sample and at the same location in that sample. One type should homogenize to liquid while the other must homogenize to vapour (Ramboz *et al.* 1982).

The L-V-S phase inclusions of the sodic-calcic stage homogenize on an almost vertical trend in a T_{h-s} versus T_{h-v} plot, parallel to T_{h-s} (Figure 6.18). This behaviour can be explained as non-boiling of a "super" saturated brine (Witt 1988). Other possibilities are:

Figure 6.18 - Plot of uncorrected vapour homogenization temperature against the uncorrected halite dissolution temperature. In almost all cases is the halite dissolution temperature higher than the vapour homogenization temperature. Points that fall on, or is close to the line $T_{h-v} = T_{h-s}$ represents inclusions that were trapped during, or close to boiling; these are the later (higher crustal level) K-feldspar stage and to a lesser extent the comb-quartz stage. Note that there are more sodic-calcic data points, indicating more L-V-S type of fluid inclusions compared with the overprinting fluid stages. The deviation of the sodic-calcic data points from the theoretical boiling line represents a "halite trend" meaning that the solutions became oversaturated on cooling and precipitated halite.

- Heterogenous trapping of solid salts in a constant density saturated brine (T_{h-v} is constant), would cause an artificially high T_{h-s} such that the actual entrapment, T_t, would be at the lower end of the vertical trend at corrected T_{h-s} of 350°C.
- The high corrected T_{h-s} (± 450°C) represents the actual T_t, and the vertical trend is caused by precipitation of halite in a cooling fluid, to the lower part of about 350°C. This is called the "halite trend" by Cloke & Kesler (1979) and Quan *et al.* (1987).

The latter explanation is preferred, due to the fact that the sodic-calcic stage displays a complex bimodal (T_h) distribution, and from the fact that the overprinting K-feldspar and comb-quartz stages are in general characterized by similar fluid compositions. The densities are quite consistent for the inclusions of the different stages (S.G. 0.95 to 1.20 g/cm^3, Figure 6.19). Another argument that favours the "halite trend" is the fact that most L-V-S inclusions are from the sodic-calcic stage and that solids were only occasionally solids where observed in the K-feldspar and comb-quartz inclusions. Also are the halite dissolution temperatures of the overprinting stages at the lower part of the vertical trend of the sodic-calcic stage and close to the line of equal $T_{h-s} = T_{h-v}$. This means that boiling could have occurred during the K-feldspar stage and to a lesser extent in the comb-quartz stage (indicating a decrease in lithostatic pressure). This is supported by the large spread in the degree of fill for the K-feldspar stage (Figure 6.5).

Figure 6.19 - Plot of fluid inclusion densities at homogenization temperature against the fluid inclusion volumes. Densities and volumes are calculated according Bodnar (1983); densities calculated according Zhang and Frantz (1987) are S.G. 0.05 to 0.10 g/cm^3 heavier. The sodic-calcic and K-feldspar stage show a relatively large spread in density while the latter also displays a large volume variation. The comb-quartz stage contains small, relatively high density fluid inclusions while the retrograde schist displays uniform density and volume. High density fluid inclusions occur in both very large or very small volume size fluid inclusions.

Although the densities of the fluid inclusions from the different alteration stages are similar, the overprinting K-feldspar and comb-quartz stage inclusions have slightly higher fluid densities (Figure 6.19). This can be explained by the "halite trend" as the overprinting fluid stages are residual fluids derived from the sodic-calcic stage and are therefore more concentrated (higher density). Halite is less soluble than KCl and / or $CaCl_2$ and precipitate earlier in a cooling salt saturated fluid (Shepherd *et al.* 1985). This is the reason why there are more halite-bearing inclusions in the sodic-calcic stage compared with the overprinting stages. This is also reflected in the cation ratios; Table 6.6 show cooler overprinting fluids contained higher K/Na and Ca/Na ratios (Figure 6.20).

Figure 6.20 - K/Na and Ca/Na molal ratios vs. the final homogenization temperatures. Temperatures are from microthermometry, while the cation ratios are obtained by the phase-volume method (Table 6.6). A well-defined negative correlation exists between the cation ratios and an increase in temperature, which agrees with the "halite trend" (Cloke and Kesler 1979). This means that the overprinting fluids became more enriched in Ca and K relative to Na, causing NaCl to become undersaturated in the fluid of the overprinting stages.

Plotting the salinities from microthermometry against the corrected vapour homogenization temperature (Figure 6.21), provides an indication of the fluid history. Although Figure 6.21 is based on a pure NaCl-H_2O system, this type of diagram can still provide useful information on boiling, mixing and salinity variations.

Figure 6.21 - Corrected vapour homogenization temperature against the Eq.wt.% NaCl salinity of the different alteration styles. Data points that fall to the right of the "halite saturation curve" all have, halite daughter minerals (at about 25 Eq.wt.% NaCl). The sodic-calcic stage has the highest observed salinities. The inclusions of the sodic-calcic stage are in overall halite saturated and fall on top or in the halite saturation field. Some of the fluid inclusions follow trend 1, indicating mixing with cooler and less saline fluids (overprinted by the K-feldspar and comb-quartz stage), or just cooling and precipitation of halite until the fluid became undersaturated with halite. The fluid inclusions of the sodic-calcic -, K-feldspar -, and to a lesser extent the retrograde schist stages, follow trend 2; isothermal mixing with fluids of contrasting salinity (due to the "halite trend", boiling, necking or possibly misinterpretation of primary fluid inclusions). The later comb-quartz stage follows trend 3, which could be interpreted as boiling with some cooling; which explain some of the low T_h for this alteration stage (Figure 6.17). However, homogenization only goes to liquid, while homogenization to vapour was not observed.

6.4 - Interpretation of the physicochemical conditions based on fluid inclusions

Microthermometry of the fluid inclusion data allows a reconstruction of the T (-P) evolution of the alteration fluids. Temperatures and fluid composition obtained by microthermometry on fluid inclusions indicate a telescoping temperature effect on a NaCl-$CaCl_2$-KCl(±$MgCl_2$±$FeCl_2$)-H2O salt-water system. Interpreted entrapment temperatures suggest that the fluids responsible for first sodic-calcic stage were hot 450°C (~550°C) and saturated with respect to halite. Eventually the temperature dropped to ~275°C and the composition of the fluid changed. The K/Na and Ca/Na ratios increased with decreasing temperature (overprinting K-feldspar and comb-quartz stage) fitting well with the "halite trend" and ionic reactions of (Carten 1986). A heating of a Na-Ca-K-H-O fluid in contact with binary plagioclase would cause albitization; while a further temperature decrease would exchange the potassium in

the fluid with the sodium in the host rock, causing potassium alteration (Hemley *et al.* 1980, Giggenbach 1984, Carten 1986).

6.5 - Summary of fluid inclusion data

Fluid inclusion data indicate a complex fluid chemistry and thermal history. The following statements summarize the findings of this study.

-Chemistry of fluids present during sodic-calcic, K-feldspar and comb-quartz stage alteration, are complex $NaCl$-$CaCl_2$-KCl-H_2O±$FeCl_2$±Mg-Ca-(CO_3 ?) solutions.

-The main alteration fluid stage, the sodic-calcic stage, was hot; in the order of 350° to 450°C (+100°C if pressure correction is applied according to Potter 1977 method) and saturated with respect to halite (average of 30 Eq.wt.% NaCl). This stage was overprinted by the K-feldspar stage, which had a temperature of 295°C(±50°) and 24 Eq.wt.% NaCl. Subsequently the previous stages were overprinted by a comb-quartz stage whose fluids had a temperature of 275°C(±65°) and 25 Eq.wt.% NaCl.

-Cation ratios, K/Na and Ca/Na increased linearly with decreasing temperature, corresponding well to the theoretical ionic reactions of Hemley *et al.* (1980) and the experimentally obtained "halite trend". It is also consistent with downward flowing fluids to precipitate albite, while rising fluids will precipitate K-feldspar (Giggenbach 1984).

-Boiling did not occur during the early sodic-calcic stage. Boiling might have occurred in the K-feldspar and comb-quartz stage (large spread in degrees of fill and $T_{h-s} \sim T_{h-v}$).

-Retrograde schist crystallized in association with a (different) comparatively low salinity fluid lacking $CaCl_2$. Entrapment temperatures are in the order of ~350°C (+150°C).

CHAPTER 7

CHAPTER 7 - ALTERATION RELATED TO MINERALIZATION
The Maronan Prospect as a case study

7.1 - Introduction

Alteration zones are generally developed around hydrothermal mineral deposits due to the action of fluids derived from magmas, heated connate or metamorphic waters (Cox *et al.* 1987, Hemley *et al.* 1992). This happens if the fluid is in disequilibrium with the rocks. Fluids can be channelized in structural features such as faults, veins and/or hinge zones, but fluids can also "infiltrate" specific metamorphic or metasedimentary layers (Cox *et al.* 1986, Hutchinson *et al.* 1980).

Numerous prospects occur at the eastern margin of the Williams Batholith, hosted in the Maronan supergroup sequence (Figure 7.1). The close spatial association between the deposits and the regional sodic-calcic alteration / breccia complex, and similarities between several alteration stages, reflect a relationship between the two. This part of the Mount Isa Inlier is anomalous in copper, lead, zinc with gold and silver. Most of the mineral occurrences are subeconomic and have been described as sediment hosted lead-zinc-silver deposits associated with iron-rich stratiform layers and major faults; for example Fairmile, Pegmont, Dingo, Maramungee and Maronan (Laing 1991, Cannington is an economic deposit). The regional alteration and brecciation was described in previous chapters. This chapter deals with the case study of the Maronan Prospect, and describes the mineralization and alteration.

The Maronan Prospect is covered by alluvial sediments and is hosted in the Maronan supergroup, north-northeast of the Turpentine antiform. The prospect was discovered during follow up exploration on an aeromagnetic anomaly, in the Soldiers Cap Tenement, EMP 6982, held by Billiton Australia (now Acacia). The prospect is located along strike of post to late D_2 high strain zones on the east side of the Turpentine antiform (Figure 3.3). Drilling commenced in 1988 and terminated in 1994, though, a joint venture established that year with MPI (Mining Project Investors Pty Ltd) should lead to further work. Sixteen diamond drill holes (MND 1 - MND 16) were drilled on a grid with an average 100 by 250 metres spacing. The prospect is elevated in Pb, Ag, Cu and Au. The mineralization partly occurs as discrete zones, e.g. Pb-Ag, Cu-Au, Pb or Zn. Geochemical analyses were undertaken by Billiton to establish a better drilling strategy and to find broad scale pathfinders that could lead to the mineralized zones. Most holes were assayed (by Billiton) on

metre intervals, while MND 7 was analysed (by Billiton) for major and certain minor elements by the XRF method (X-Ray Fluorescence). During the current study, NAA (Neutron Activation Analyses) and thin sections were prepared from specific intervals. Three holes, MND 10, 11 and 12 were structurally logged using orientated core, while others (MND 1 to MND 13) were logged for lithology and structural vergence.

Figure 7.1 - Regional map of the eastern part of the Cloncurry terrain. Many of the deposits occur close to faults and high strain zones. The Levuka Trend (LT) is shown on satellite imagery.

7.2 - Geology and Structural Setting of the Maronan Prospect

Two prominent tectonic fabrics, S_1 and S_2 (see Chapter 3), are developed in the Maronan Prospect (Figure 7.2), both foliations dip steeply west. An indication of a parasitic D_2 antiform, verging to the east, was logged in MND 11 (Figure 7.3).

Figure 7.2 - Stereoplots of structural data from orientated drill holes MND 10-11-12. Bedding (not shown, n=146) coincide with S_1 and S_2. L_2^1 rotate, on a great circle, from shallow south- to steep north-plunging.

The zone of mineralization is located on a sheared limb in a parasitic D_2 synform (Figure 7.4), named the Maronan "syncline" (Laing 1990). S_1 is intensely folded by D_2 in drill holes MND 5 and 6. High strain zones have a mylonitic appearance and consist mainly of muscovite. The shear zones in drill cores are manifested as strongly foliated muscovite schists (with traces of relict garnet ± biotite ± quartz ± feldspar) and strongly deformed calcareous, Fe-Mn-silicate and iron-rich layers. Lithology and competency contrasts and D_2 limb regions control the location of the high strain zones in a similar fashion to that observed in the regional alteration complex. Shear zones are inclined, exploiting S_2 and separate the Maronan Prospect into hanging wall and footwall packages. In the shear zone, silicification overprints the strong muscovite foliation (see section 7.3.2.2). Ironstones (composed of magnetite, garnet and locally hematite) occur in the hanging wall, while the footwall contains strained calcareous units and Fe-Mn silicate layers. Laing (1990) interpreted this zone of high strain as the axial plane of the Maronan "syncline".

Figure 7.3 - Plan projection of the Maronan Prospect geology at 100 m depth RL.

However, Morrison (1990) interpreted this zone as an antiform. Shallow plunging L_2^1 crenulation lineations steepen in the high strain zone, indicating that the movement of the shear zone was not purely strike-slip, but also had a dip-slip component (Figure 7.2). However, this steepening of the lineation could also be an affect of a D_3 event (or late post D_2 shearing). Dextral shearing, based on field observations, such as dragging of surface trends on the east side of the Turpentine antiform, is responsible for a dilation zone filled with quartz ± sulphides and gold mineralization, elsewhere in the area.

Figure 7.4 - Schematic interpreted block diagram based on structural data obtained from drill cores (see Appendix G). Quartz and sulphides occur as dilational fill, in reactivated post-D_2 shear zone. The shear zone is located on the east limb of the Maronan synform and has a halo of silicification (shaded). East of the shear zone carbonate and Fe-Mn-silicate mineral layers are dominant and exhibit strong ductile deformation. Metadolerite occurs in MND 8 and MND 13.

Breccias locally occur adjacent to zones of high strain (Figure 7.3). Breccias occur in the dilated and silicified zone and adjacent to and in calcareous layers (Figure 7.5). Absence of mylonitic clasts indicate that brecciation was synchronous with shearing. Ductile strain was accommodated in the calcareous units, while the surrounding rocks exhibit more brittle deformation.

A NE-SW fault is interpreted on the basis of ground magnetic data and interpolation of the drill holes. This is possibly a normal fault, with the northern block displaced downward, causing offset on limbs of a north plunging synform. Fault striae logged in MND 10 are subhorizontal with east-west strike, but this could be related to minor subhorizontal thrusting.

CROSS SECTION THROUGH **MND 12 - MND 2**

Figure 7.5 - Schematic profile through drill holes MND 12 and MND 2. Note the silicification of the limb of a parasitic synform and brecciation in the footwall. Mineralization is concentrated in the silicified unit and in the Fe-Mn silicate interfingering calcareous units (see Appendix G).

7.3 - Lithologies of the Maronan Prospect

Lithologies encountered in the Maronan drill cores are quite different to the outcropping rocks further south, with the exception of the psammopelites, iron-rich horizons (possibly similar to the ones at the Fairmile Prospect, Figure 7.1), and locally developed carbonates in the "high strain zone" west of the Turpentine antiform (Enclosure A, Figure 3.3).

7.3.1 - Petrography of the Maronan Prospect

Host rocks consist of microcline-rich psammopelitic schist, quartzites with almandine garnets and local mafic and pegmatitic rocks.

Psammopelitic schist predominate in the hanging wall sequence and is composed of mica (biotite ± muscovite), quartz, garnet, plagioclase (An~20%) and K-feldspar. *Quartzite* with disseminated almandine, traces of biotite, muscovite and in places spessartine-rich layers is abundant in the footwall of the Maronan Prospect.

Different generations of micas formed during prograde metamorphism, retrogression and alteration. Prograde micas include red-brown pleochroic biotite (Mg/Mg+Fe ~ 0.2) and muscovite. Muscovite, biotite and elongated quartz define the main foliation. Fine grained retrograde sericite replaces feldspar. Euhedral garnets are zoned with poikiloblastic cores containing quartz inclusions, whereas the rims are free of inclusions (Figure 3.10). Compositional zoning is also present with cores of $Alm_{53}Sps_{30}Grs_{14}Prp_{2}Adr_{1}$ and $Alm_{60}Sps_{19}$ $Grs_{18}Prp_{3}$ rims (see Appendix C). This compositional variation, might indicate a change P/T conditions and fluid activity during nucleation.

Both, concordant and discordant *amphibolite* bodies occur in the Maronan Prospect. Concordant amphibolite occurs locally adjacent to iron-rich units in the hanging wall, and are up to 10 metres thick. Amphibolites are generally chloritized, but relicts of patchy blue-green amphiboles are still present. Interstitial amphibole coexists with idioblastic quartz and feldspars in a less altered sample (DP#46408). Anhedral garnet overgrows the quartz-feldspar groundmass, with abundant interstitial magnetite. Small laths of brown biotite replace the amphibole and define the foliation. An ophitic texture is locally preserved in altered amphibolite (DP#46409). Plagioclase laths are altered to fine grained quartz and sericite.

Figure 7.6 - Schematic lithological column of the Maronan Prospect, illustrating the five mineralized zones (based on drill-log compilation).

Amphiboles are chloritized with hematite dusting and hematite laths. A thick unit (±160m) of discordant amphibolite was logged in drill holes MND 8 and MND 13. This is in contrast to concordant amphibolites observed in outcrop (Enclosure A). The discordant amphibolite unit is well foliated parallel to S_2 and was possibly emplaced pre-D_2.

Figure 7.7 - Representative column of "zone 2" from MND 4. The thin lines represent minerals that are sporadically observed in drill core.

7.3.1.1 - Peculiar stratiform lithologies

Five mineralized "zones" containing "peculiar" stratabound lithologies occur in the Maronan Prospect (Figure 7.6). These zones are ~25-50m thick, and seem to be concordant with the psammopelitic metasediments. The upper (structural) three zones (zones 1-3) make up the main body of the Maronan Prospect. The two deepest zones are only observed in drill hole MND 11, and lie approximately 150m below the lower "zone 3" of the main Maronan Prospect body (Figure 7.6). "Zone 1" is located in the hanging wall of the prospect, while "zone 2" occurs just below the fault zone in the footwall. "Zone 3" is located approximately 50m below "zone 2". "Zone 1" is mainly composed of iron-rich, Fe-Mn silicate horizons and minor amphibolite. "Zone 2" contains Fe-Mn silicate horizons, while "zone 3" is mainly composed of interfingering-lensing calcareous and Fe-Mn horizons.

The "peculiar" stratabound lithologies (Figure 7.7, see Appendix G) are: i) Fe-Mn silicate mineral rich layers, ii) silicified rocks, iii) iron-oxide rich horizons and iv) mineralized carbonate horizons. These "peculiar" horizons are possibly a product of different alteration stages (Table 7.1. Physio-chemical conditions are discussed in Chapter 8.). Recognition that these horizons are alteration phenomena, are based on textural (and geochemical, see sections 7.4 and 7.5) criteria, such as:

- Symmetrical appearance, e.g. massive in the centre and laminated at the margins (Figure 7.7).
- Consistent occurrence of a distinct garnet±biotite±magnetite layer at the top and base of the Fe-Mn, iron-rich and calcareous horizons (Figure 7.7).
- Local observations of cross-cutting relationships (< 5°) of these horizons with the main foliation (Figure 7.8A+B).
- Overprinting relationships, mainly between the dominant mineral constituent of the various "peculiar" horizons. These also provides relative timing between the "peculiar" horizons (alteration stages, Figure 7.8C+D).
- Rhythmic (zoned) monomineralic laminations, dominantly garnet, magnetite or carbonates (Figure 7.8E).

Figure 7.8 - Photographs illustrating criteria for alteration. **A**- Sample DP#46395. Garnet-biotite-pyroxenoid layer (stage 1), with sericite selvage, cross-cut with a low angle (< 5°), quartzitic ± biotite ± garnet host rock; also cut by yellow carbonate vein (siderite?). **B**- Sample DP#46393. Discordant garnet replacement vein (stage 1) is cross-cutting the psammopelitic host rock. **C**- Sample DP#46396. Boudinaged quartz lenses(stage 2) infilled by carbonate (stage 4) and galena (stage 5). Field of view 3.3cm. **D**- Sample DP#46397. Boudinaged and fractured magnetite-quartz lenses (stage 3) infilled and replaced by carbonate (stage 4), with traces of pyrite (stage 5). Field of view 3.1cm. **E**- Sample DP#46374. Laminated garnet-biotite-magnetite-carbonate rock (stages 1-3-4). **F**- Sample DP#46391. Pyroxmangite and magnetite. This texture is interpreted as magnetite overgrowing the pyroxmangite. Field of view 0.9mm.

A
Grt
Sd
B
Grt
Grt
C
Qtz
Gn
Cal
Cal
Qtz
D
Mag
Py
Cal
E
Grt
Bt
Mag
1 cm
F
Pxm
Mag

However, a rock package containing ironstones, amphibolites and interfingering-lensing, calcareous and Fe-Mn silicate horizons, and the (sub)concordant appearance could also be interpreted as a metasedimentary exhalative sequence (c.f. Parr 1992). A symmetrical appearance, textural and/or mineralogical, is interpreted by workers such as Einaudi *et al.* (1981) as a "reaction skarn". Metamorphism with retrograde metasomatism, involving hydrothermal circulation of fluids and sulphide precipitation, can result in a zonal / symmetrical pattern. Skarns (Pb-Zn) commonly contain this zonal patterns, with massive sulphide replacing carbonate rocks. Manganese-rich minerals, such as johannsenite, bustamite and knebelite (the latter two are also present in the Maronan Prospect, see below), are found in these skarns (c.f. Shimazaki and Bunno 1978, Einaudi *et al.* 1981, Abrecht 1985). An established skarn deposit, with a skarn sequence from garnet to pyroxene to bustamite to marble is described at Altyn-Toykan by Smirnov and Gorzhevsky (1977), and seems similar to some alteration stages, and sequence, in the Maronan Prospect (see below), and might indicate that the Maronan Prospect is a skarn.

7.3.2 - Description of the alteration stages / "peculiar" horizons

There are six alteration stages recognized in the Maronan Prospect (Table 7.1). These stages are from old to young:

Stage 1: Fe-Mn±K±Ba±Cl silicate mineral alteration
Stage 2: Silicification
Stage 3: Iron-oxide (mainly magnetite) alteration
Stage 4: Calcite±apatite±quartz alteration
Stage 5: Sulphide±quartz mineralization
Stage 6: Carbonate / tourmaline / quartz / albite late veining stage.

The textural relationships between the stages are not clear-cut, especially overprinting relationships between stages 1-3-4 (see Figures 7.8). Some of the textures could be interpreted as iron-oxide (stage 3) being early (Figure 7.8F).

7.3.2.1 - Stage 1: Fe-Mn±K silicate mineral alteration

Fe-Mn silicate (pyroxenoids, garnets, Mn-rich olivines and amphiboles) horizons are up to 6 metres thick, and interfinger lens with carbonate units (MND 10 to MND 7, Figure 7.3 and 7.5). These horizons occur in all zones, and are locally numerous as

small layers in and adjacent to iron-rich horizons, composed of pyroxenoids, garnets, green pleochroic Cl-bearing biotite with secondary magnetite and carbonates.

Table 7.1 - Provisional mineral paragenesis and alteration stages of the Maronan Prospect.

	D_2	Post D_2					
Minerals	Metamorphism	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
		Fe-Mn±K±Ba±Cl	Si	Fe	Ca-P±Si	Fe-Cu-Gn-S	Si-B-Na-Ca±S
Quartz	----------		----------	----------	----------	----------	----------
Plagioclase	----------						----------
K-feldspar	----------						----------
Muscovite	----------						------sericite------
Biotite	----------	------high Cl------	----------		----------		----------
Almandine	----------						
Zircon	----------						
Rutile	----------						
Spessartine		----------		----------	----------		
Bustamite		----------					
Knebelite		----------					
Pyroxmangite		----------	----				
Dannemorite		----------		----------			
Apatite		--------		----------	----------		
Titanite		----------		----------			
Magnetite		----	----------	----------			
Hematite				----------			----------
Chlorite				----------			----------
Pyrosmalite							----------
Calcite					----------	------	---- ----------
Rhodochrosite						------	----
Siderite						----	----
Pyrite						----------	----------
Chalcopyrite						----------	----------
Pyrrhotite						----------	
Arsenopyrite						----------	
Galena						----------	----------
Sphalerite						----------	----------
Chalcocite							-----
Covellite							-----
Digenite							-----
Bornite							
Tourmaline							----------
Monazite					----------	----------	----------
Baryte						----------	----------
Cassiterite						? - - - ? - - - ? - - -	? - - - ? - - - ? - - -
Pitchblende						? - - - ? - - - ? - - -	? - - - ? - - - ? - - -
Silver Ag						?------?------?-----	
Gold Au						?------?------?-----	? - - - ? - - - ? - - -

The pyroxenoids are bustamite and pyroxmangite (Appendix C) fall in the $CaMgSi_2O_6$-$CaFeSi_2O_6$-$CaMnSi_2O_6$ system (Figure 7.9). Natural *bustamite* has a large compositional range with calcium exchanging for Mn, Fe and/or Mg (Abrecht and Peters 1980, Shimazaki and Bunno 1978). Pyroxenoids together with other manganese rich minerals (e.g. spessartine, rhodochrosite) are typical minerals of skarn deposits, and could result from metasomatism. Bustamites from the Maronan Prospect are extremely iron-rich and close to the low Ca endmember [$Fe_1(Mn_{0.8}Ca_{0.2})Si_2O_6$]. Strictly speaking they are *ferrobustamite* (Fe/(Fe+Mn > 0.5, Mason 1975). Fractured bustamite coexisting with intergranular green pleochroic biotite and pink spessartine is infilled by galena (Figure 7.10A), and traces of pyrite and chalcopyrite, with silver values up to 637 ppm. Pyroxmangite has less calcium [$Fe_{0.98}(Mn_{0.85}Mg_{0.03}Ca_{0.09})Si_2O_6$] and overprints bustamite

Spessartine ($Sps_{62.3}Alm_{32.6}Grs_{4.9}Prp_{0.2}$) replacement veins (overprinting the psammopelitic host rocks, RV, see Table 7.2, overprinted by chlorite-muscovite-quartz, stage 6) are buckled and subparallel to parallel to the main foliation (Figure 7.8A-B-E). Garnets vary in shape, from euhedral to anhedral to almost "single grain layer". Carbonate and/or magnetite or sulphides concentrate in the hinge zones of microfolds. Similar looking, garnet-rich rocks observed at the Broken Hill Pb-Zn-Ag deposit (interpreted as a metamorphosed sulphide deposit, Spry and Wonder 1989) forms a "garnet envelope" around the ore-bodies. These quartz-bearing garnetite and garnetite rocks are massive or layered and exhibit a granoblastic texture (similar to the ones at the Maronan Prospect). This garnet-rich envelope, described at Broken Hill, is either discordant to the prograde metamorphic foliation, of concordant to a retrograde metamorphic foliation (Spry and Wonder 1989). Garnet compositions from the garnet-rich rocks at Broken Hill are quite similar, but have more Mg and less Mn then those in the peculiar horizons at Maronan, but the garnets in the psammopelitic host rocks are more Fe-rich (Figure 7.9).

There are different theories on the origin of the garnet-rich rocks at Broken Hill: i) sediments formed at hydrothermal vents on the ocean floor (Hackett and Bischoff 1973), ii) metamorphosed manganiferous chamositic beds (Stanton 1976), or iii) a Mn-gel formed at the sediment-seawater interface reacting with biogenic silica (Huebner *et al.* 1986). Epigenetic theories for the garnet formation are: i) Mn-Ca rich fluids expelled from Mn-Ca-bearing orebodies during prograde metamorphism reacting with Al-rich wall-rocks (Hodgson 1975), ii) Mn-fluids introduced in pelitic sediments before metamorphism (Billington 1976), iii) a metasomatic Mn-Ca replacement during retrograde metamorphism overprinting Al-rich wall-rocks evident by zonation in garnets and "garnet-trains" in garnet-rich rocks (Tracey 1982). This is also observed at the Maronan Prospect (Figure 7.11A).

Figure 7.10 - Photographs of Fe-Mn silicate minerals. **A**- Sample DP#46363. Bustamite-garnet-biotite laminations with galena infill. **B**- Sample DP#46390. Pyroxmangite vein cross-cutting bustamite. Field of view 0.9mm. **C**- Sample DP#46369. Lamination of coexisting biotite and garnet, and zone of garnet-magnetite. Field of view 0.9mm. **D**- Sample DP#46369. Euhedral spessartine garnets with inclusions of green biotite. Field of view 0.9mm. **E**- Sample DP#46399. Pyroxenoid rock cross-cut by quartz-biotite vein with garnet, irregular Christmas tree like, selvages, overprinted by radial dannemorite nests. Field of view 5.3cm.

A
Grt
Bt
Bst
B
Pxm
Bst
C
Grt
Bt
D
Grt
Bt
E
Grt
Pxm
Bt
Dan

Knebelite or fayalitic olivine, occurs as strain free high birefringence grains with narrow rims of pyrosmalite (Figure 7.11B), partly overgrown by pyroxmangite and bustamite. Olivines at the Maronan Prospect have a relatively high MnO content, up to 20 wt.%, but consist largely of fayalite (Fe_2SiO_4) and negligible amount of fosterite (Mg_2SiO_4, see Appendix C, the manganese variety is called tephroite, Mn_2SiO_4). The average composition of the olivine is $Fa_{70}Te_{29}Fo_1$ and is more accurately referred to as Fe-knebelite. Coexisting spessartine-rich garnet and knebelite indicate a low X_{CO2} fluid (Abrecht 1989). Fe-knebelite are also reported from metasomatized limestones as an early product during mineralization in the Bluebell mine, British Columbia (Mossman and Pawson, 1976).

Pyrosmalite [$(Fe,Mn, Mg)_8Si_6O_{15}(OH,Cl)_{10}$], forms rims around knebelites (Figure 7.11B), due to infiltration of a hydrous (+ Cl bearing) fluid. Pyrosmalite (Fe/Fe+Mn ~ 0.92) has also been identified in the Pegmont lead-zinc deposit. Currently defined Fe/Fe+Mn ratios varies from 0.15 to 0.59 (Vaughan 1986). The pyrosmalite [$(Fe_{4.8}Mn_{3.1}Mg_{0.1})Si_6O_{15}(OH,Cl)_{10}$] in the Maronan Prospect has a Fe/Fe+Mn ratio of 0.57 and trace of Cl (< 0.9 wt.%, see Appendix C). The Mn-rich member of the series is referred to as *friedelite* (Abrecht 1989). Friedelite nucleating at knebelite grain boundaries, suggests the following reaction: $4(Fe,Mn,Mg)_2SiO_4 + 2SiO_2 + 3H_2O + 2HCl \leftrightarrow (Fe,Mn,Mg)_8Si_6O_{15}(OH_8,Cl_2)$.

7.3.2.2 - Stage 2: Silicification

A silicified zone (up to 50 metres thick, located in a high strain zone between "zones" 1 and 2) consists of white buck quartz infill. Good evidence for silicification overprinting stage 1 has not been observed. However, local brecciation of stage 1 infilled with quartz and biotite (Figure 7.11C) is the only evidence that the Fe-Mn±K alteration is (possibly) older than the silicification. Also, silicification overprinted by stage 3 (iron), indicating that this stage is at least older than stage 3 (see below). A silicified halo occurs at the margin of the white buck quartz, overprinting the metamorphic foliation (Figure 7.11D). Traces of relict metamorphic micas are present with ragged grain boundaries, sericite and calcite dusted feldspars. D_2 crenulated schist inclusions in the buck quartz sustain the view that shearing and dilation occurred post D_2. The buck quartz grains are up to 3mm long and only slightly strained. This in contrast to the fractured bustamite of stage 1, suggesting that bustamite formed before the buck quartz. However, quartz grain boundaries are sutured with subgrains and interstitial calcite. Chalcopyrite and pyrite ± arsenopyrite

infill (Figure 7.11E) are the primary sulphides and were precipitated along with minor calcite during stage 5 (see below). Elevated gold values (up to 2350 ppb, see Appendix D) occur in association with sulphides.

7.3.2.3 - Stage 3: Iron-oxide alteration

Iron-rich horizons occur in all the five zones and are 1-8 metres thick (Figure 7.6 and 7.7). They are bound by garnets, with traces of Fe-Mn silicate rich laminations at top and base. Magnetite (with possible ilmenite lamella) is the common iron-oxide phase in the central part of massive iron-rich horizons. Magnetite grains are variable in shape, euhedral to anhedral and fractured and overprint the pyroxenoid minerals of stage 1 (Figure 7.8F and 7.12A). Margins of iron-oxide horizons are laminated and diverse in mineral composition, with garnets, pyroxenoids and dannemorite (Figure 7.8E). Dannemorite belongs to the cummingtonite-grunerite-dannemorite-tirodite series (see Appendix C), which is poor in Al and Ca (Leake 1978). Such amphiboles are commonly found in metamorphic Mn-rich formations (Stout 1970), but are also observed in metamorphic iron-formations coexisting with manganese carbonates (Deer *et al.* 1992). It also occurs in Pb-Zn skarns described by Einaudi *et al.* (1981), with the above described Fe-Mn minerals, along structural and lithological contacts. However, in the Maronan Prospect, it occurs as bladed, unstrained, twinned laths in radial clusters (Figure 7.10E and 7.12B) and overprints the pyroxenoids. This suggest that no major deformation affected these amphiboles, and that they grew post-D_2 (? even D_3). The dannemorite contains 14.5-16.5 mole % Mn, with a Mg/Mg+Fe ratio between 0.05-0.07 (see Appendix C).

The (upper) iron-rich horizon in "zone 1" is hematite-rich, ~5m thick and has a strong foliation. This hematite horizon becomes along strike, towards the north, magnetite-rich. A hematite-rich horizon also occurs in MND 11 (zone 4). This horizon contains chloritized biotite with a Mg/Fe ratio of 0.2. Garnet ($Sps_{60}Alm_{11}Grs_{14}Prp_2Adr_{12}Ti_1$) and carbonate (77% rhodochrosite) are more manganese rich in the hematite-horizon than in the magnetite-horizons (81% siderite).

Figure 7.11 - Photographs of stages 1 and 2. **A**- Sample DP#46398. There are two generations of garnet growth. Garnet vein cross-cutting massive garnet layer. Drill core diameter is 5cm. **B**- Sample DP#46388. Knebelite grains with pyrosmalite rim and pyrite infill. **C**- Sample DP#46372. Pyroxenoid unit is fractured and brecciated, with quartz (?stage 2) and biotite infill. Field of view 5.8cm. **D**- Sample DP#46404. Silicification and strained quartz veining, with relict biotite foliation. Sulphides selectively replacing relict foliation. **E**- Sample DP#46403. Infill of arsenopyrite and pyrite in quartz vein. Field of view 3cm.

A
B
Knb
Py
C
Grt
Pxm
Bt
Qtz
Bst
D
Py
Qtz
DOLLAR
E
Qtz
Py
Apy

A possible reason for this association is that manganese can occur in various oxidation states (Mn^{2+}, Mn^{3+}, Mn^{4+}, Mn^{7+}), while iron only occurs in two oxidation states (Fe^{2+}, Fe^{3+}). The increase in Mn/Fe reflects an increase in fO_2 (Spry and Wonder 1989). Barium bearing K-feldspar is present in this horizon (Ba/K+Ca+Na ² 4%, see Appendix C).

Magnetite-quartz±microcline rocks of the central part of upper zone 2 contain stringers of magnetite and metamorphic almandine ($Alm_{88}Prp_9Grs_2Sps_1$). Magnetite is poikiloblastic with quartz inclusions. Foliation is defined by elongated quartz and stringers of euhedrical magnetite (Figure 7.12C). Quartz crystals vary in size, with smaller grains pinned by magnetite. Magnetite grains are locally replaced by late hematite laths (martitization, Figure 7.11D) in iron horizons of "zones 2 and 3". These horizons are overprinted by stage 5-6 calcite, siderite, rhodochrosite.

The iron-oxide phase (stage 3) is overprinted by sulphides, e.g. chalcopyrite (stage 5, which forms rims around magnetite, Figure 7.12E), minor sphalerite, pyrite, arsenopyrite and traces of carbonates and apatite. Fractured magnetite nucleated earlier than adjacent strain free pyrite (sample DP#46362, Figures 7.14A).

7.3.2.4 - Stage 4: Calcite±apatite±quartz alteration

Calcareous / marble horizons (individual horizons are 3-8 metres thick) are dominant in zone 3. Figures 7.8C+D and 7.13B illustrates the relationships with earlier stages. Calcareous horizons consist of large weakly strained calcite crystals with polygonal, idioblastic recrystallized quartz and pleochroic brown biotite (green biotite also occur as narrow selvages around calcite veins, see section 7.3.2.6). Calcite ($Cal_{90}Rds_{10}$) is the main constituent of the peculiar carbonate horizons. However, carbonates overprinting the iron-horizons of stage 3 are more Mn-rich, with a substantial amount of Mg ($Rds_{75}Cc_{16}Mgs_8$). Mn-carbonates ($Rds_{65}Cal_{35}$) also overprint Fe-Mn silicate minerals (stage 1) and locally replaced the calcite horizons. Coexisting biotite has numerous halos (monazite inclusions, confirned by micro probe analyses). Apatite is present up to 30 modal % concentrated in bands or clusters (Figure 7.13C). Intergranular chalcopyrite and pyrite are concentrated at the margins of these calcareous horizons.

7.3.2.5 - Stage 5: Sulphide±quartz mineralization

Four stages of ore paragenesis, based on textural overprinting relationships, are established for the Maronan Prospect and are as follows, with (A) as oldest and (D) as the youngest:

A) Magnetite (±Ti, stage 3, oxide stage)
B) Pyrite- Chalcopyrite ± Pyrrhotite ± Arsenopyrite ± Au
C) Galena - Sphalerite ± Chalcocite ± Pyrrhotite ± Ag
D) Covellite - Digenite - Bornite

Sulphide minerals are infill products in dilations. A spatial relationship exists between the type of sulphides and the (host rock) lithology. Lead and zinc sulphides are dominant in the calcareous units (Figure 7.8C), while iron-copper sulphides mainly occur in the silicified and iron-rich lithologies (Figure 7.11D+E). This is a reflection of the changes in the chemistry of the mineralizing fluid, (such as pH, sulphur activity and solubility of the metal-chlorine complex. A discussion on the metal complexes in solution is given in Chapter 8.), that occurred when these fluids infiltrated respectively carbonates or quartz-rich rocks. Base-metal complexes will precipitate as base-metal sulphides, if the mineralizing fluid infiltrates carbonate rocks, providing there is a sulphide source, causing an increase in the pH (see also Chapter 8). Lead-chlorine and other metal complexes are soluble at low pH values. Fluid infiltrating quartzites or silicified rocks, would remain more acid, keeping the base-metal chloride complexes in solution. Solubilities of lead and zinc is higher at lower temperatures than that of iron and copper (Hemley *et al.* 1992). A mineralizing fluid at higher temperatures would therefore be more undersaturated in Pb-Zn, than in Fe-Cu

The first sulphide assemblage in the paragenetic sequence is *pyrite* with *chalcopyrite*. Chalcopyrite and pyrite exhibit a simple intergrowth relationship (sample DP#46347), but chalcopyrite also occurs as en échelon veins in pyrite (sample DP#46357).

Arsenopyrite forms typical spear like idiomorphic minerals (samples DP#46379 and DP#46384). Arsenopyrite is concentrated in the calcareous units (of zone 3) and in the iron-rich horizons of zone 1.

Figure 7.12 - Photographs related to stage 3. **A**- Sample DP#46394. Pyroxmangite layer is fractures and veined with magnetite and galena infill. Field of view 6.3cm. **B**- Sample DP#46389. Radial cluster of twinned dannemorite crystals, coexisting with garnets, at margins of magnetite horizons. Field of view 0.9mm. **C**- Sample DP#46368. Magnetite growing interstitially in quartz-microcline rock, parallel to the foliation, coeval with biotite. Field of view 0.9mm. **D**- Sample DP#46344. Magnetite with hematite laths (martitization), with sphalerite filled in fractures. Field of view 2.5mm. **E**- Sample DP#46375. Euhedral magnetite crystals with rim of chalcopyrite. Field of view 2.5mm.

A
Grt
Gn
Pxm
Mag
B
Dan
Grt
Mag
0.2 mm
C
Mag
Bt
D
Sp
Hem
Mag
E
Mag
Ccp
0.5 mm

Pyrrhotite infills in a breccia "dyke" (<1m) in the lower part of the calcareous rocks in "zone 3". It contains a few rounded clasts of relict carbonates, but more quartz-rich clasts, embedded in a pyrrhotite massive matrix. Pyrrhotite also appears to coexist pyrite (Figure 7.13D).

Galena and sphalerite, occur in cavities with chalcopyrite rims (Figure 7.13E). Locally, galena and digenite nucleate on the boundaries between pyrite and chalcopyrite (Figures 7.14F). Galena occurs in microveins cross-cutting both pyrite (Figure 7.14A+B) and chalcopyrite in the calcareous units (sample DP#46347). Galena also precipitated in fractured bustamite (Figure 7.10C), and in post D_2 veins. Galena and chalcopyrite are not only infill products in open spaces, but also replace peak metamorphic micas (Figure 7.14C).

Sphalerite occurs as discrete veins and as an intergranular phase in iron-rich horizons. On microscopic scale, sphalerite coexists with chalcocite, and forms "graphic" exsolutions in pyrite and chalcopyrite (Figure 7.14D). However, orientated exsolution blebs of chalcopyrite are found in sphalerite, possibly due to segregation while cooling (Figure 7.14E).

Secondary (? supergene) sulphide minerals are: *digenite*, which occurs as fracture infill in the pyrite (sample DP#46350), *bornite*, which replaces pyrite in vein-like stringers (sample DP#46341), and *covellite* that replaces both pyrite and bornite in fractures parallel to the schistosity (Figure 7.14A). Covellite is more abundant with bornite than with pyrite. Microfractures are filled with *galena*. Chalcocite (?) is replacing both the bornite and covellite (Figure 7.14A).

7.3.2.6 - Stage 6: Tourmaline / quartz late veining stage

This stage is related to subhorizontal open-space veins (EV2), which cut the steeper veins (EV1, Figure 7.15 and Figure 7.16A). This EV2 type of vein forms a broad outer halo (Figure 7.6) around the more silicified zone. There are three types of subhorizontal EV2 veins (EV2-a, EV2-b, EV2-c, see below and Table 7.2). The EV2-a types are tourmaline-quartz±pyrite±chalcopyrite veins. There are two types of tourmaline veins. One vein set with pure white albite selvages, and another with macroscopically red selvages, due to hematite dusted microcline (Figures 7.17B+C). The microcline replaces the albite. The grain size varies in the selvage, due to

numerous new quartz subgrains. The tourmaline crystals are zoned with Al-rich cores and Na-rich (±S) rims.

Other types of subhorizontal veins are monomineralic, filled with anhedral quartz (EV2-b, stage 6) or carbonate (EV2-c, stage ?4-6) only. The anhedral weakly deformed quartz grains contain sutured grain boundaries. Fractures perpendicular to the vein wall is filled with Fe-rich carbonate. The selvages are narrow (compared with the vein width) and consists of green chloritized biotite and intergranular carbonate. Vein growth in the carbonate veins occurs in two stages. The inner zone has elongated crystals with an anhedral carbonate outer zone (possibly stage 4). The selvages consist of green pleochroic biotite (Figure 7.16D).

The unstrained tourmaline and quartz subhorizontal veins (EV2-a-b), and possibly also the unstrained quartz layer parallel veins (EV1-b, see below) are truly stage 6 only.

Other veins and vein orientations

Vein orientations of the Maronan Prospect show a bimodal distribution (Figure 7.2), with a set subparallel, and a set perpendicular to the foliation (subhorizontal). The veins subparallel to the foliation are from different alteration stages: i) replacement veins (spessartine-rich, stage 1) and ii) infill veins (stage 6, Table 7.2). Open-space infill veins are spatially related to the shear zone, with higher vein concentrations in the hanging wall (Figure 7.6 and 7.15). These consist of quartz with Fe-Cu-sulphides, while the selvages are diffuse and consist of muscovite. The subhorizontal veins offset the open-space foliation parallel veins, indicating that they are younger, and consist of quartz, tourmaline with or without Fe-Cu-Pb-sulphides. Brittle subhorizontal (thrust) faults are related to these subhorizontal veins. These veins could still be part of alteration stage 5, based on the mineral constituents.

Figure 7.13 - Photographs of overprinting relationships continued. **A**- Sample DP#46362. Fractured magnetite, with infill of quartz and weakly deformed pyrite. Field of view 1.0mm. **B**- Sample DP#46364. Garnet vein with biotite selvages (stage 1) is cut by calcite vein (?stage 4, with sericite selvages). Field of view 3.5cm. **C**- Sample DP#46355. Apatite rich band in calcareous unit. Field of view 2.6mm. **D**- Sample DP#46350. Fractured pyrite and pyrrhotite, with chalcopyrite and digenite infill. Field of view 2.6mm. **E**- Sample DP#46347. Galena infilling in fracture, with chalcopyrite rim (and traces of sphalerite). Field of view 0.9mm. **F**- Sample DP#46347. Galena nucleated at the grain boundaries between coeval pyrite and chalcopyrite. Field of view 2.5mm.

A
Py
Ap
Mag
B
Cal
Grt
Bt
C
D
Py
Dg
Po
Ccp
E
Gn
Ccp
Sp
F
Py
Gn
Ccp
Gn

Table 7.2 - Tabulated description of veining stages in the Maronan Prospect.

Type	Orientation		Mineral assemblage	Description
RV stage 1	Bedding/layer-parallel	centre: selvage:	Sps ± grn Bt, overprinted by Mag ± tr Cal Overprinting stage 6: Ms, Chl, Qtz	Strongly folded, sheet folds (?), locally cross-cut foliation
EV1-a stage 5-6	Layer-parallel	centre: selvage:	strained Qtz, Mc, Sd ± Gn ± Ccp Qtz, brw Bt, Mc ± Hem ± Sd	Planar veins, locally boudinaged, with strained crystals and narrow developed selvage, in hinge and high strain zones
EV1-b stage 5-6	Foliation parallel	centre: selvage:	unstrained Qtz, Ccp, Py, Bt ± Bst sulp, Rds ± Sd ± Ttn	Planar veins, weakly deformed, concentrated in D_2 limb regions
EV2-a stage 5-6	Subhorizontal	centre: selvage:	Qtz, Tur, fsp, Py, Ccp ± Gn ± Sp Ab → Mc ± Hem ± Ms ± Cal	Mineralized subhorizontal veins, cutting EV1 veins, concentrated in the hanging wall; Christmas selvage
EV2-b stage 6	Subhorizontal	centre: selvage:	Qtz with tr of Cal grn chloritized Bt, tr Cal	Unmineralized, as an outer halo around the mineralized zone; Christmas selvage
EV2-c stage 4-6	Subhorizontal	centre: selvage:	carbonate (Cal, Rds, Sd) grn Bt	Relative narrow to absent selvage

NB. Abbreviations: Qtz=quartz, Bt=biotite, Ms=muscovite, Chl=Chlorite, Tur=tourmaline, Ttn=titanite, Grt=garnet, Sps=spessartine, Cal=calcite, Rds=rhodochrosite, Sd=siderite, sulp=sulphides, Py=pyrite, Ccp=chalcopyrite, Po=pyrrhotite, Gn=galena, Sp=sphalerite, Bst=bustamite, fsp=feldspar, brw=brown, grn=green. RV=replacement vein, EV=extentional/open-space vein.

Open-space veins (EV) are generally mineralized and consist of quartz and or carbonates (ranging from pure siderite to $Sd_{80}Cc_9Mgs_6Rds_5$ solid solutions) ± pyrrhotite ± pyrite ± chalcopyrite ± galena and sphalerite. These veins are generally 0.10 up to 10 millimetres wide, with selvages of 0.3-3 centimetres, consisting of microcline ± sericite ± chlorite. Selvages are selectively developed parallel to the foliation in the more micaceous layers. Selvages with traces of Fe-Cu-sulphides occur locally in veins cross-cutting carbonate rocks.

There are two generations of layer-parallel (steep) veins. An early generation (EV1-a) of boudinaged veins contains strained quartz and traces of coarse microcline, with selvages of quartz, brown-green pleochroic biotite and hematite dusted microcline. Galena or chalcopyrite (stage 5?, or remobilized stage 5) are precipitated in the boudin necks, with traces of siderite (stage 6).

The later generation of steep veins (EV1-b) consists of weakly strained large quartz grains, with chalcopyrite and pyrite as the dominant sulphides (stage 5). At the margins of the sulphides there are rims of carbonates. Two types of carbonates are present (stage 6). Small, rhombohedral siderite crystals overgrowing large anhedral carbonate (rhodochrosite ?, Figure 7.14F), with traces of titanite.

7.4 - Whole rock geochemistry

Whole rock geochemistry of the Maronan Prospect has been conducted on MND 7 drill core by Billiton. Half core samples were analysed by AAS (Atomic Absorption Spectrometry) for base metals, gold and Mn, and by XRF analyses for major components (except Ti and P) and a suite of minor elements (see Appendix D).

Representative homogenized samples of approximately 5 metres interval were analysed, taken into account lithology boundaries. MND 7 was selected for this study because it contains several, non overlapping, distinct zones of mineralization (Figure 7.18). Specific samples of drill holes MND 10, 11 and 12, were analysed by NAA (Appendix D).

7.4.1 - Alteration geochemistry

Elements that are believed to be enriched during the various alteration stages are: Fe-Mn-Ca-K (stage 1), Si (stage 2), Fe (stage 3) and Ca-P (stage 4). Stages 1 and 4 contain elements that are also typical for "ordinary" sedimentary rocks, such as psammopelites and carbonates. The original components in the sediments will influence the geochemical characteristics of the metasedimentary and/or altered rocks. Therefore, an immobile-element reference frame has to be established to determine if the above elements are truly enriched (Figure 7.17), or if there is a detrital influence on the geochemistry. Pelites (derived from shales) usually contain various proportions of a detrital mineral fraction, that can provide information on the provenance.

Positive correlations between Al_2O_3 and K_2O and the narrow spread in Al_2O_3:K_2O ratio reflects the original clay (illite) content in the rocks, now present in biotite and possibly K-feldspar. A constant molar Al_2O_3:K_2O ratio (~3:1) in the various rock units (except the ironstones and metadolerites), indicates that the provenance of these elements in these rocks was similar. A ratio closer to ~1.2:1 would indicate that K-feldspar was dominant in the rocks and possibly was also present as a detrital phase. This ~3:1 ratio indicates that K-feldspar was not present as a detrital component, and that the ratio is mainly controlled by phyllosilicates.

Figure 7.14 - Photographs of overprinting relationships continued. **A**- Sample DP#46341. Fractured pyrite with covellite infill. Finer fractures are filled with galena. Covellite is overprinted by bornite (? and chalcocite). Field of view 2.5mm. **B**- Sample DP#46379. Fractured pyrite with galena infill. Field of view 1.0mm. **C**- Sample DP#46378. Chalcopyrite and galena infill mica foliation planes, indicating mineralization occurred post peak metamorphism. Field of view 2.5mm. **D**- Sample DP#46358. "Graphic" textures in pyrite, filled with chalcocite and sphalerite (?tetrahedrite). Field of view 2.5mm. **E**- Sample DP#46365. Chalcopyrite exsolution blebs in sphalerite. Field of view 1.0mm. **F**- Sample DP#46351. Quartz-sulphide-carbonate vein. Pyrite with rhodochrosite rim and siderite crystals. Field of view 2.6mm.

A
Bn
Py
Cv
Cc
Gn
B
Py
Gn
C
Gn
Ccp
Gn
D
Sp
Cc
Py
Bn
E
Ccp
Po
Ccp
Sp
F
Py
Rds
Sd

Figure 7.15 - Cartoon illustrating interpretation made of formation, timing and spatial distribution of the different type of veins.

Calcareous units are evenly distributed on this constant Al_2O_3:K_2O ratio line, meaning that they had variable amounts of a similar component in their precursor. If the calcareous units were derived from pure carbonates, than they would plot close to the origin (some do). Variation plots of Al versus Ti or Cr would give additional information on the presence or absence of detrital K-feldspar, however, the latter two elements are not analysed.

The Al_2O_3:K_2O was used, by Beeson *et al.* (1989), to interpret the depositional environment of stratiform lead-zinc deposits in the Proterozoic Mount Isa - McArthur River district. Beeson *et al.* (1989) divided the Al:K ratio into three categories, namely high aluminium (1:3), intermediate and high potassium (1:1.5). High potassium reflects the deeper, central part of a basin, while higher concentrations in aluminium and sodium occur towards the margin. Samples from the Maronan Prospect have an Al_2O_3:K_2O ratio of ~3:1 reflecting deposited at basin margins (based on Beeson *et al.* 1989 model). Rubidium and barium are coherent with potassium, illustrated by constant K:Rb and K:Ba ratios. K:Rb ratios for the Maronan Prospect are ~1:177, indicating high Rb levels. Which is unusual and reflects, in general, tuff beds (Beeson *et al.* 1989). K:Ba ratios would not be constant if barium was deposited synsedimentary in the form as baryte in an evaporitic, coastal plain type environment. Constant ratios of these elements (K-Rb-Ba) have to be interpreted with caution. These elements form part of the LIL, large ion lithophile, group elements and are highly mobile during alteration. A fluid buffered system, that carries these elements would also have a constant ratio.

The protoliths of the psammopelitic rocks probably also contained some smectites. This is evident from the weak positive correlation between Al_2O_3 versus MgO (Figure 7.17). The calcareous units plot at the lower end of psammopelitic trend.

A weak negative correlation between Al_2O_3 and Zr in the metasediments, partly in the calcareous units and silicified samples, suggests a presence of detrital zircon. This correlation could indicate Zr being incorporated in the (precursor) clay fraction. Detrital zircon, if present, would usually cause a scatter of the data points. Although there is still much scatter in the data points, the silicified rocks, calcareous units, and doubtful in the amphibolites and iron-rich rocks, exhibit a weak positive trend between Al_2O_3 versus Zr. This coherent behaviour between Zr and Al_2O_3 is probably a reflection of the alteration. The trend towards the origin is due to dilution by silica and possibly mass increase.

Figure 7.16 - Photographs of overprinting relationships continued. **A**- Sample DP#46364. Layer parallel garnet vein with biotite selvage cut by subhorizontal calcite vein. **B**- Sample DP#46414. Quartzitic schist cut by tourmaline±quartz-calcite vein with hematite dusted microcline selvage. **C**- Sample DP#46400. Psammopelitic rock, cross-cut by tourmaline vein with white albite selvages. Field of view 12cm. **D**- Sample DP#46392. Two stage calcite veins (note faint clear rim), with green biotite selvage. Subsidiary calcite vein cross-cut garnets. Field of view 5.0mm.

The calcareous units plot at the lower end of the psammopelitic trend in the (Al_2O_3 versus K_2O-MgO and K_2O versus Rb, not well with Ba) interelement diagrams. If these trends represent clay-type protoliths, than it is likely that the calcareous units are diluted with quartz-pelite mixtures, or that they represent metamorphosed carbonate sediments, with some detrital phyllosilicates. Barium is enriched in certain calcareous samples (possibly some baryte), and there appears to be a separate Ba-K_2O trend in the calcareous units.

Silica exhibits a strong negative correlation with aluminium in the psammopelitic rocks (Figure 7.17), derived from quartz-pelite mixtures. The silicified samples plot on the same Al_2O_3 versus SiO_2 trend as the psammopelites. This can be interpreted as silica overprinting the psammopelites.

7.4.2 - Base metals distribution

Drill hole section MND 7 (Figure 7.18 and Figure 7.6) illustrates the correlation between lithology and mineralization. These profiles indicate that some correlation exists among the various elements and between the lithology (Cu-Au-As in silicified and brecciated rocks, Pb-Zn-Ag in calcareous units). There appears to be a constant Pb/Cu ratio (Figure 7.19A) in the various lithologies of MND 7, suggesting i) a metal-carrying fluid infiltrated all the rocks, and ii) that the metal-carrying fluid had a constant Pb/Cu ratio. If the mineralization was syngenetic, one would expect variable Pb/Cu ratios in the different rock units. Close inspection of the Au-Cu and Ag-Pb-Zn peaks in Figure 7.18 indicates some offset of these peaks, possibly a result of fractionation, while the interelement plots do not exhibit tight trends. The Cu-mineralization is not well represented in MND 7 (Figure 7.19), and might well plot off the Pb/Cu trend (which indicate fractionation of the base metals). High Pb values plot of the trend, indicating that fractionation might have occurred.

Pb correlated well with Ag. The correlation between CaO and Pb+Zn is better defined than iron versus Pb+Zn, especially in the siliceous rocks and calcareous units (which is almost vertical, Figure 7.19). This means that Pb and Zn behaves independent of iron. Trends of Fe and Ca versus the base-metals confirm the textural observations of an early iron phase (magnetite) overprinted by Fe-sulphides (pyrite, chalcopyrite). The positive trend between Ca and base-metals in the siliceous samples implies an associated Ca phase (late carbonate alteration).

Iron-rich horizon
Amphibolite
Psammopelites
Calcareous units
Siliceous horizon
A
B
C
D
E
F
K2O wt.%
MgO wt.%
Zr ppm
SiO2 wt.%
Rb ppm
Ba ppm
Al2O3 wt.%
K2O wt.%

Figure 7.17 - Interelement plots of whole rock analyses from MND 7. **A**- Positive correlation between Al_2O_3 and K_2O, with an Al_2O_3:K_2O ratio of ~1:2.8. **B**- Correlation between Al_2O_3 and MgO. **C**- Zr versus Al_2O_3. Weak negative correlation in the psammopelites. Positive correlation in the silicified rocks. **D**- Silica versus aluminium. The silicified rocks fall on the same Si-Al trend as the psammopelite. **E**- Positive correlation between K_2O and Rb, indicating coherent behaviour. **F**- The relationship between Ba and K is less pronounced than between Rb versus K.

Base-metal element versus Zn+Cu and Pb+Zn plots, illustrate better correlations than if plotted among themselves (not shown). This suggests a zoned pattern (lithology controlled) or two populations. Ag also exhibit better correlations with Pb+Cu and Pb+Zn (not shown). This suggests two separate Ag associations, phases (in galena and as ? native silver, see Appendix C).

7.4.3- Gold and Silver distribution

The distributions of gold and silver are related to specific lithological units (Figure 7.5, Figure 7.18). Silver is concentrated in the "peculiar" Fe-Mn silicate units (stage 1), calcareous units (stage 4) and cross-cutting galena bearing veins (stage 5-6). A positive correlation exists between silver and antimony (Figure 7.20).

Microprobe techniques failed in identifying the gold phase. However, anomalous gold mineralization is mainly analysed in three different lithologies (Figure 7.18+7.20 and Appendix D). First, anomalous gold is observed in garnet-rich rocks (Fe-Mn silicate unit, stage 1). Secondly, gold occurrence is related to open-space quartz veins and the silicified horizon with pyrite and chalcopyrite as the main sulphide phases (Figure 7.5+7.18, stages 5 and 6?). Thirdly, gold is related to quartz-tourmaline ± pyrite ± chalcopyrite veins (stage 6, see Appendix D).

Gold behaves in a similar fashion as silver and antimony, in the calcareous units and Fe-Mn silicate units (Figure 7.20, and also to copper, c.f. Figure 7.18). The clustering of "high" gold values and the positive correlation between Ag and Sb with the "lower" gold values, suggest that gold fractionation has occurred. The samples containing "high" gold values are (mainly) veined and brecciated (see Appendix D).

In summary it can be said that:

i) Silver is related to Sb, Pb, with galena in stage 5 veins (developed in calcareous units and Fe-Mn silicate units).
ii) Gold fractionated out of the fluid.
iii)The "low" gold phase is associated with Ag, Pb and Sb, mainly in the calcareous and Fe-Mn silicate units.
iv)The "high" gold phase is associated with low Ag, As and Cu.

Figure 7.18 - Gold, silver and base metals of MND 7 plotted against depth and lithology. Note the positive copper-gold correlation and the affinity of lead, zinc and silver. Pyroxenoid alteration (stage 1) is weak developed in MND 7.

Figure 7.19 - Interelement variation plots, based on whole rock analyses of MND 7. There appears to be only good positive correlations between Pb versus Cu and Ag (figures A and B). Interelement plots, based on total Pb+Zn versus Fe_2O_3 and CaO (figures C and D). Interelement variation plots, based on total Zn+Cu and Pb+Zn versus Pb and Cu (figures E and F).

Figure 7.20 - Au-Ag-element plots, based on NAA from samples from drill holes MND 10, 11 and 12. Positive correlation between Ag and Sb (**A**). **B**- and **C**- show positive relationships between gold and antimony and silver in the calcareous units and Fe-Mn silicate units. Gold is possibly fractionated, high Au with low Ag, and low Au with Ag-Sb.

7.5 - Rare Earth Element behaviour in the Maronan Prospect

Rare earth elements (REE) can behave in an immobile fashion in geological processes, e.g. metamorphism (Winchester and Floyd 1977, 1978, Rogers *et al.* 1984, Pearce and Cann 1973). However, REE are quite mobile in chlorine and fluorine bearing fluids (Hellingwerf 1987, Kwak and Abeshinghe 1987, Hellman *et al.* 1979). REE studies can help in understanding the geochemical conditions of hydrothermal systems and ore-forming fluids. REE characteristics are reflections of temperature, oxygen fugacity (fO_2) and the pH of the fluid (Parr 1992, Palacios *et al.* 1986, Salvi and Williams-Jones 1990, Oreskes and Einaudi 1990).

The stabilities of Eu^{2+} and Eu^{3+} ions (also Ce^{2+} and Ce^{4+}) are strongly dependent on the T, fO_2 and pH conditions and the fractionation into minerals. For example heavy rare earth elements (HREE) are strongly partitioned into garnets, while feldspars easily incorporate europium (Grauch 1989). Eu^{2+} is dominant in reducing environments at temperatures > 250°C, while Eu^{3+} reflects more oxidizing cooler conditions (Parr 1992). This could mean that a positive or negative europium peak in chondrite-normalized REE profiles respectively reflect a hot reducing or cooler

oxidizing hydrothermal- or ore-forming fluid. However, a hot oxidizing fluid would probably also exhibit a positive Eu anomaly.

Typical REE bearing minerals in the Maronan Prospect are monazite, allanite (see Appendix), and possibly also apatite. However, REE can also be incorporated in other silicate and carbonate minerals (see above and below).

7.5.1 - Rare Earth Element results

REE in the Maronan Prospect have been normalized to chondrites and PAAS (Post-Archaean Average Australian Sedimentary rocks, Evensen *et al.* 1978 and McLennan *et al.* 1980, Figure 7.21 and 7.22). REE profiles are divided on the basis of the main lithologies or dominant mineral constituent. These are: psammopelitic-quartzitic schists, pyroxenoid-rich samples (stage 1), calcareous units (stage 4), garnet-magnetite samples (stage 3), barren quartz (stage 6) and Cu-Fe sulphide-rich samples (stage 5-6). The main features of the chondrite-normalized REE profiles are:

i) All samples exhibit similar enrichment relative to the primitive chondrite, although there is a variety of fractionation trends depending of the lithology.
ii) Most samples show enrichment in LREE over HREE.
iii) Large positive-, moderate negative- and flat Eu anomalies occur, dependent on the mineral constituents.
iv) A weak positive correlation exists between the europium anomaly and LREE to HREE fractionation, but varies internally depending on the lithology (Figure 7.21).
v) Normalized PAAS profiles are flat, but with large to moderate positive Eu anomalies for most samples and rock types.

Psammopelites (host rock)

The metasedimentary rocks (and quartzitic ± garnet schist) of the Maronan Prospect provide a comparative data base for the "peculiar" lithologies. Psammopelites are characterized by LREE enriched chondrite-normalized profiles with negative Eu anomalies (Figure 7.21A). Overprinting carbonate alteration possibly causes some variations in the Eu anomaly (see below). Carbonate-rich samples appears to have large Eu anomalies, and overprinting would obscure the original negative Eu anomaly of the unaltered quartzitic schist. In the case of sample DP#46377 the disappearance of the Eu anomaly is probably due to a cross cutting galena veinlet

(with minor carbonates). Normalized PAAS profiles are close to unity, and suggest a "normal" metasediment precursor.

Figure 7.21 - Chondrite-normalized REE patterns for the different lithologies. The dashed lines in (**B**), (**C**) and (**D**) are samples rich in magnetite (> 19% iron). Samples with circles are also pyrrhotite bearing.

Calcareous and pyroxenoid rich samples

The chondrite-normalized REE profiles of these lithologies indicate strong enrichment in Eu (up to 300x the chondrite value, Figure 7.21C-D). Eu anomalies are more pronounced in the calcareous unit (Eu/Eu* ~ 4.1, Eu* is the interpolated Eu value between Sm and Gd if there was no anomaly) than in the pyroxenoid rich samples (Eu/Eu* ~ 2.8). Pyroxenoid rocks also show strong positive Eu anomalies,

which increases with increasing LREE-enrichment (similar to the psammopelites, Figure 7.23). Calcareous units and pyroxenoid samples that have lower Eu anomalies and flatter profiles, contain magnetite. The strong Eu fractionation can not be explained by feldspars (practically absent in those lithologies), but is possibly related to the carbonate / apatite alteration. Normalized PAAS plots, show that both lithology types are close to unity but with Eu enrichment. This could mean that there is no real REE enrichment, except for the Eu. However, based on the geochemistry (see above), the shale component is highly diluted, indicating that REE are enriched. An alternative explanation is that the data reflect an original REE distribution.

Figure 7.22 - PAAS normalized REE patterns for the different lithologies. Profiles close to unity could indicate syn-sedimentary REE distribution.

Figure 7.23 - Eu/Eu* versus La/Yb plot for the Maronan Prospect. There appears to be two trends: 1) LREE-enrichment with high Eu/Eu* and 2) less LREE-enrichment with low Eu/Eu* (the psammopelites). This might indicate a possible influence of the clay/detrital component on the REE distribution.

Garnet-magnetite rich samples

These samples contain 19-30 wt.% Fe, and are taken from the margins of iron-rich horizons. The light to heavy REE fractionation is less pronounced than in the above-described lithologies (flat profiles), indicating a higher degree of partitioning of HREE. Garnet can preferably incorporates HREE than LREE (Grauch 1989). The Eu anomaly is weakly negative, but samples overprinted by carbonate alteration have zero to slightly positive Eu anomalies (Figure 7.21E, see Appendix D). However, the profiles illustrate also enrichment of LREE relative to the chondrite. Normalized PAAS plots, display enrichment in the middle REE range (Sm, Eu, Gd).

There is a weak negative correlation between the fractionation and the Eu anomaly (Figure 7.23). These less LREE-enriched samples inherited the REE pattern of the (quartzitic) host rocks (c.f. psammopelitic REE profiles, see below).

Quartz veins and Cu-Fe sulphide rich samples

Barren quartz vein profiles are moderately enriched relative to chondrites and flat with no apparent Eu anomaly (Figure 7.21B). Tourmaline bearing veins are more enriched than the others. REE enrichment relative to the chondrite is small (< x10).

Copper-iron sulphide veins exhibit more interesting profiles. Sulphide samples with carbonate alteration have large positive Eu anomalies. This in contrast to silicified quartz rocks, with minor sulphides, that lack carbonate alteration. These patterns suggest multiple fluids (? 3 types).

7.5.2 - REE discussion

Although garnet-magnetite rich layers occur in contact with iron- and pyroxenoid-rich units, their normalized-chondrite REE patterns are quite different. This is in contrast to the similar patterns in the calcareous units and the pyroxenoid rich units. Those units were never observed in physically attached to each other in drill core (but logging indicated lateral and uphole lensing and/or interfingering, Figures 7.3 and 7.5). This variation in REE patterns originates from either: (1) a pre-metamorphic, syn-sedimentary REE distribution during precipitation of the sediments, (2) differential mobilization of REE during episodes of prograde and retrograde metamorphism, (3) selective REE partitioning in specific rock units which acted as fluid conduits for the ore-bearing, hydrothermal fluids.

(1) Close to unity normalized PAAS profiles are likely to reflect synsedimentary or shale like REE distributions, assuming immobile behaviour of REE. La/Th and Th/Sc ratios can also reflect syn-sedimentary characteristics. These ratios are constant in PAAS, respectively 2.8 and 1.0 (McLellan *et al.* 1980). The Th/Sc ratios at the Maronan Prospect lie close to unity (Figure 7.24); La/Th ratios (Figure 7.24) show a much larger spread. The calcareous units (stage 4 alteration) plot off this trend. If the pyroxenoid-rich units indicate some sort of Fe-Mn rich sediment that formed under reducing conditions, and laterally interfingered with more carbonate sediments, than the La/Th should be similar, which is not the case. Also an iron-rich sediment, of some sort, which would then be the precursor of the garnet-magnetite rich samples would have to have similar REE distribution and similar patterns, which is also not the case. Some remnant sedimentary-, and/or early hydrothermal-, and/or seafloor alteration signature would be present if the garnet-magnetite rich layers are metamorphosed early alteration affected sediments. Modern hydrothermal fluids have LREE-enriched patterns, with distinct Eu anomalies. Metalliferous Fe-Mn sediments precipitated on the seafloor and interacting with seawater, would have seawater signatures, with flat profiles and negative Eu and Ce anomalies (Lottermoser 1989, Klein and Beukes 1992, Parr 1992). The garnet-magnetite profiles are quite different to modern hydrothermal signatures and lack any negative

Ce anomaly, as in seawater. This suggests that the REE signature in the garnet-magnetite layers at the Maronan Prospect was formed after deposition, possibly reflecting a metasomatic origin, or at least metamorphism. Normalized chondrite-REE patterns from the Broken Hill mineralization are similar to the ones from the Maronan Prospect and are interpreted as a signature of an "exhalative setting" (Parr 1992, Lottermoser 1989). If the REE patterns reflect sedimentary conditions, than iron-rich samples would be products of oxidizing conditions with large negative Eu anomalies (zero to positive Eu anomalies with PAAS indicate Eu mobility). This is not the case for the garnet-magnetite samples and certainly not for the magnetite bearing calcareous unit and pyroxenoid samples (dashed lines, Figure 7.21).

Figure 7.24 - Plots of (**A**) La versus Th and (**B**) Th versus Sc. La/Th shows a wide spread around 2.8, while Th/Sc is more confined around 1. These ratios are upper continental crust values (McLennan 1989).

(2) If REE mobility occurred during metamorphism than rocks of similar mineralogy and metamorphic textures would have similar REE signatures. In the case of garnet-magnetite rich samples this is partly true. A garnet rich rock, would under normal metamorphic conditions preferentially incorporate HREE into its garnet crystal lattice. Garnet-magnetite samples of the Maronan Prospect have relatively flat profiles, but with no extreme HREE enrichment. This could mean that LREE were mobilized and partly incorporated into the garnet crystals. It is more likely that other minor phases, such as monazite and apatite control the REE distribution. Normalized

PAAS profiles for the garnet-magnetite samples (Figure 7.22) do not show LREE enrichment. The work of Parr (1992) and Lottermoser (1989) on garnet rich horizons lead to the suggestion that LREE enrichment is due to an intergranular amorphous garnet-like gel. They rejected the option that this pattern could be a post metamorphic hydrothermal REE signature on the bases of variable Eu anomalies. The flat garnet-magnetite profiles, imply that garnet influenced the REE pattern. This would only occur during garnet crystallization, implying that this profile was formed during metamorphism or alteration (depending on when garnet crystallized during alteration at Maronan.

(3) Eu anomalies are dependent on the host mineral constituents. Positive Eu anomalies are occur in calcareous units, pyroxenoid units (both containing galena) and Cu-Fe-rich samples. This coincidence of a positive Eu peak with samples containing sulphides is striking. Cu-Fe mineralized samples with rhodochrosite and siderite alteration are more enriched in Eu (large positive Eu anomaly). Cu-Fe sulphide bearing samples from the silicified units exhibit only moderate to zero Eu anomalies.

On the basis of the above observations and arguments, it seems that positive and/or zero Eu anomalies are associated with sulphide mineralization and/or carbonate alteration. This correlation of REE concentration with mineralization supports an epigenetic mineralization model, caused by infiltration of a REE-carrying fluid. The magnitude of the Eu anomaly is controlled by the mineralogy. Calcareous units (pH controlled) and pyroxenoid rich units acted as reducing fluid path ways, causing an ore-fluid to precipitate base-metals.

Garnet-magnetite rich layers are not metamorphosed Fe-Mn metalliferous sediments or sediments being influence by early hydrothermal activity. This is apparent from garnet-magnetite REE patterns that are quite different to the signatures of seawater and hydrothermal fluids. Also the flat nature of the garnet-magnetite REE patterns, imply that garnet crystallization influenced the REE distribution, which occurred post sedimentation.

7.5.3 - Gold and silver versus REE abundance

Under acidic conditions and high temperatures, gold occurs in solution as either a chloride complex or as $AuHS^{\circ}$, depending on the abundance of sulphur (Heinrich *et al.* 1989).

Gold and silver values of the Maronan Prospect are plotted against the Eu anomaly and fractionation (Figure 7.25). Silver is concentrated in the calcareous units and pyroxenoid-rich samples (coexisting with galena) and shows a weak positive correlation with increasing La/Yb (Figure 7.20D). The narrow range of Eu/Eu* (~4), indicates a constrained fO_2. Gold on the other hand shows weak association with discrete REE fractionation. "High" Au values are clustered around an Eu anomaly of 1-2, compared with "low" Au values, which exhibit a large Eu/Eu* range (0.5-7). "High" Au samples also have slightly lower fractionation factors, indicating relative slight enrichment in HREE and flatter profiles.

Figure 7.25 - Gold and silver versus Eu/Eu* anomaly and La/Yb. "High" Au is taken at >150 ppb. **A**- "Low" Au exhibits a large spread with Eu/Eu*, and implies an independence of the fO_2; but it occurs with fractionated REE (**C**). High gold values relate to zero Eu anomalies in association with HREE enrichment. **B**- and **D**- Silver exhibits an increase with La/Yb.

7.6 - Fluid inclusion observations

Fluid inclusions have only been observed in quartz of the silicified unit and rarely in quartz in the calcareous units. Most inclusions are small, < 10μm, rounded and with an estimated degree of fill of about F ~ 0.9 to 0.95. Liquid-vapour-solid fluid inclusions are slightly bigger, about 10 to 20μm.

Chlorine bearing green secondary biotite indicates that the fluid present during stages 1 and 5 was chlorine bearing. Salt containing fluid inclusions confirm this. These solids only occurred sporadically in some fluid inclusions of sample DP#46343 and are optically identified as chloride daughter minerals. Transparent cubes of halite (NaCl), subrounded cubes of sylvite (KCl) and elongated, slightly green in colour, possibly, iron-chloride ($FeCl_2$) salts.

A complex fluid, containing the above salts, would at least have a salinity ~47 Eq.wt.% NaCl (Shepherd *et al.* 1985, Hall *et al.* 1988). Temperatures are about 400°C, based on knebelite and carbonate stabilities. Fluid inclusion studies in nearby deposits, indicate salinities between 35~87 Eq.wt.% NaCl (Switzer 1987, Laing 1991). Estimated temperatures and salinities in other ironstone associated deposits, such as Eloise, Osborne and Starra, differ to the Maronan Prospect. Salinities and temperatures at Osborne and Eloise are quite high, ~60 Eq.wt.% NaCl and >500°C (pers. comm. N. Adshead and T. Baker 1995).

7.7 - Summary

The Maronan Prospect is located in a post D_2 high strain zone. Post D_2 deformation caused steepening of the originally shallow north plunging L_2^1 crenulation lineation. Continuous deformation resulted in shearing on a parasitic D_2 steeply (70°) west dipping fold limb, which was the locus for infiltration of a moderate temperature (± 400°C), saline (~47 Eq.wt.% NaCl) ore-carrying fluid.

The Maronan Prospect is a "skarn" type deposit with six alteration stages. The first stage is a Fe-Mn±K type alteration with typical skarn-type minerals, e.g. bustamite, pyroxmangite, knebelite, dannemorite and spessartine. The second stage is related to post D_2 shearing with quartz-veining and silicification. The third stage was again an Fe(±Mn) event, with mainly magnetite and minor dannemorite and spessartine. This is overprinted by a carbonate alteration (stage 4). Stage 5 is the sulphide

mineralization event. Subhorizontal veins (tourmaline), which forms a halo around the main alteration and mineralization zone, are part of stage 6.

Chondrite-normalized REE patterns for the various (unaltered and altered) rock units, except quartz veins, are quite similar in light to heavy REE ratios (same slope). Pronounced Eu anomalies occur with carbonate alteration and sulphide mineralization. Carbonate alteration is also responsible for increased Eu anomalies in garnet-magnetite and metasedimentary rocks. Comparison with PAAS suggests that the fluid was not strongly enriched in REE. Garnet-magnetite samples exhibit flat REE profiles (increased HREE). This implies that the REE fractionated into the garnet during crystallization and not during sedimentation, and supports the proposed origin by skarn-type alteration.

Two types of mineralization are present (Pb-Ag±Zn and Cu±Fe-Au). The former was mainly precipitated in pyroxenoid units and calcareous units. Copper-iron sulphides mainly infill fractures in the silicification zone with rhodochrosite and siderite alteration, but also overprint the iron-oxide (magnetite) units (± pyrrhotite). Galena and secondary (supergene) sulphide minerals infill microfractures in pyrite and chalcopyrite. Possible multiple-fluids caused the alteration and mineralization. This is implied from constant a Pb/Cu and Au/Ag ratios in the different rock (alteration) types, while some fractionation in base-metals and anomalous Pb and Au occur in others.

Gold rich samples display affinities with HREE. High gold values are associated with Cu, As and lower Ag. Lower (but still anomalous) gold values are associated with Ag, Pb and Sb. Gold rich samples are also associated with tourmaline veins. Gold together with silver, only occurs in Fe-Mn silicate samples. Silver is associated with galena and antimony, mainly in the calcareous- and pyroxenoid units.

CHAPTER 8

CHAPTER 8 - DISCUSSION AND CONCLUSIONS

8.1 - Geological history - a tectonic model

Previous chapters document the evolution of a post D_2 regional sodic-calcic telescoped alteration system in the eastern part of the Cloncurry-Selwyn terrain. Fundamental characteristics relevant to the evolution of this system involve:

1) The terrain is a linear feature, with a north-south trend.
2) Major lineaments, brittle and ductile faults lie parallel to the north-south trend.
3) There is extreme strata and crustal shortening (due to two coaxial deformation phases) normal to the belt.
4) Metamorphic patterns are (sub)parallel to the fold belt.
5) There are distinctive zones of sedimentary rocks parallel to the fold belt.
6) Evaporite and carbonate sediments mainly occur in the west, while psammopelite and amphibolite sequences mainly occur in the east.

The above features suggest that the eastern Cloncurry-Selwyn terrain is a mountain belt formed marginal to a continent, where an intracontinental Proterozoic "basin" underthrusted a (?Archaean) continental margin. Underplating of (Archaean) crust caused by small-scale mantle convection resulted in early Proterozoic sedimentary basins, proposed by Etheridge *et al.* (1987) and Wyborn (1988). These basins resulted from extension of pre-existing Archaean continental crust, and contain three sequences, rifting, thermal subsidence and deposition of coarse clastics. Ophiolites, sutures and paired metamorphic belts are absent in the Mount Isa Inlier, suggesting that the geotectonic setting was essential "ensialic" (continental setting). However, to cause an ensialic (intracontinental) orogeny, gravitational instability (lithospheric delamination) is not possibly unless the asthenosphere temperature exceed the lithosphere temperature by 700°C (Ellis 1992, Zhao and Cooper 1992). Ellis (1992) demonstrated that an additional driving force, a distant subduction, is needed to cause a thermal subsidence followed by delamination of the crust.

A sequence of events by which an initial underplating of an intracontinental basin converts a margin to a mountain belt is schematically illustrated in Figure 8.1(A-D). Underplating caused local extension and basin formation. At the "consuming" edge / margin, compression causes a local "uplift" with basin-inward wedges, bound by growth faults. Basalts intruded along these growth faults and deposited together with

clastic sediments (possibly similar to island-arc settings). These basalts were possibly derived from melt from the descending plate, and are geochemically similar to seafloor tholeiites. Entrapped seawater saturated metasediments were possibly dragged downwards. Devolatization of these sediments may have contributed to the chlorine in the fluid. An asymmetrical intercontinental basin, with step-faults in the west, has existed behind the "uplift" at the consuming margin. This basin would have been the locus for deposition of coarse clastic sediments, interlayered with volcanics overlain by carbonates and evaporites (?now the Corella Formation). Bimodal (felsic and mafic) volcanics intruded along the step-faults.

Continuous compression would have caused the formation of an embryonic orogenic belt (Barramundi orogeny 1870±20 Ma), which was cross-cut by low angle thrust faults. High-temperature deformation and metamorphism began to affect the lower sedimentary pile, while an increase in sediment flux occurred towards the continental graben. The axis of this newly formed orogenic belt expanded towards the west (Isan orogeny 1620-1480 Ma) and eventually rose above sea-level (Beardsmore *et al.* 1988, Loosveld 1989a). A major reverse fault nucleated at depth and propagated toward the surface, causing local deep seated (mantle) material to be thrusted upwards (Loosveld 1989b, Holcombe *et al.* 1991). Mafic dykes would have intruded along these steeper faults (possibly during a time of stress relaxation, hence a period of temperature reduction, between D_1 and D_2. Mafic material have a tendency to melt at lower temperatures than felsic material). The graben deepened, partly due to a renewed compression phase (?D_2), and partly due to progressive sediment influxes. The thickening of the sediment pile would have resulted in higher metamorphic grades, with devolatization of the sediments. Meteoric and connate waters possibly descended along major fault structures (post D_2). Deepening of the basin would have resulted in upwelling of the asthenosphere, generating a higher heat flux. This heat flow could have caused circulating fluid movement, which could have been responsible for the descending fluid flow, but also resulted in onset of granite intrusions. Regional alteration of the infiltrated rocks is the effect of these fluids (sections 8.2 and 8.2.1).

The overall compressional stress field shifted from the normal to the orogenic belt. This resulted in strike-slip movement of the major faults and thinned the sedimentary sequence in the graben even more, causing I-type granite intrusions (post D_2 to syn D_3, section 8.1.2).

Figure 8.1 - Schematic sequence of sections illustrating a model for the evolution of a mountain belt development by underthrusting. Figure A illustrates the Barramundi Orogeny, while B, C and D illustrates a possible scenario for the Isan Orogeny. Vertical scale exaggerated.

8.1.1 - Structural modelling of granite emplacement

Granites were emplaced during different deformation stages (section 2.4, Figure 8.2) as is evident from the presence or absence of foliation(s), respectively the Maramungee suite (pre-syn D_2) and Williams Batholith suite (syn-post D_3). Extensional or strike-slip faults are necessary for large volumes of magma to reach the surface (Philpotts 1990). The type of stress regime also would have affected the magma composition. Basaltic magmas generally erupt in extensional regimes, while in compressional regimes magmas undergo extensive fractional crystallization and

felsic compositions dominate (Windley 1984, Philpotts 1990). Magmatism occurs more frequently at convergent and divergent plate boundaries, than at transform faults / boundaries. *Local* extensional regimes within these geological settings are the focus for the magmatic activities. "Pull-apart" basins are the locus for volcanism and magma emplacement in transform-fault systems (Windley 1984). Pull-apart basins are small features relative to the extent of the transform fault which along they occur (Figure 8.2, Mann *et al.* 1983).

Figure 8.2 - Wrench-fault model with "pull-apart basin", illustrating possible controls on granite emplacement. The Saxby Granite, Wimberu Granite and Yellow Waterhole Granite, are dated at respectively 1520±10, 1508±8 and 1492±11 Ma (Page 1994). **A**- Schematic geology of the eastern Cloncurry-Selwyn terrain, which illustrates the relationship between granites and faults. **B**- Cartoon of faults and depression area. **C**- Riedel shear model, adapted from Tchalenko (1970). R_1 low-angle fractures, synthetic R shears, R_2 antithetical high-angle fractures, Y "mature" fractures parallel to the main shear, X folds and domino faults sub-normal to the shear, P is P-shears. Most fractures observed are orientated between T and R_1 (see Figure 3.7).

Pull-apart basins are generally described for sedimentary rocks overlaying a basement that has been subjected to strike slip faulting (Tchalenko 1970, Mann *et al.* 1983). Deep strike-slip faulting could cause subsurface pull-apart action and provide

space for magma emplacement in the crust. This type of tectonics could have caused thinning of the crust with upflow of voluminous granites, in the eastern Cloncurry-Selwyn terrain. Williams and Phillips (1992) demonstrated that the chemical signature of the trondhjemitic granitoid suite (Maramungee suite), show a depletion in Y and HREE. These type of granitoids could be present in a subduction type of tectonic setting described above (Zhao and Cooper 1992). Part of the Williams Batholith suite (dated 1480-1510 Ma), especially some parts of the Squirrel Hill and Mount Angelay granites, appear to have been intruded in a subsurface "pull-apart" type setting (Figure 8.1D and Figure 8.2). Other parts of this granite complex (Mount Angelay Granite) intruded at 3-5 kbar (G. Mark pers. com. 1995). These granites are bound by steep subparallel faults, namely the Mount Dore Fault and Cloncurry Fault, and are approximately 40 km apart. Late stage post-D_2 movement on the Cloncurry Fault is sinistral (see Chapter 3). The Mount Dore Fault, and (?or) Starra Shear developed during D_{1b} extension, and has an overall sinistral post-D_2 movement at the Selwyn Mine (Davidson 1992). Left lateral movement on this fault system created wrenching, which resulted in subsidiary faults, such as the Big Mick Fault (?P shear) and Straight Eight Fault (synthetic R_1 shear ?). This left lateral wrenching caused additional thinning of the crust (beside deepening of the overlaying basin due to sediment input). The occurrence of Riedel fractures (mainly R_1) in these granites indicates that continuous sinistral fault movement occurred during (or slightly after) emplacement (and consolidation). These granites created a renewed heat pulse.

The Yellow Waterhole Granite (south of the Squirrel Hills Granite, Figure 8.2) has an unusual east-west orientation. Movement on the major strike-slip faults causes dilation in the R_2 fault plane, along which the granite intruded. This granite is unfoliated and zircon dated at 1492±11 Ma (Page 1994).

8.1.2 - Fluid flow

Understanding of the controls on alteration systems has increased dramatically in the last two decades (e.g. Etheridge 1983, Etheridge and Wall 1983, Ferry 1988, Oliver *et al.* 1990, Dipple and Ferry 1992), assisted by microstructural theoretical and experimental work (e.g. Bell and Etheridge 1973, Windsor 1983, Etheridge *et al.* 1984, Walther and Wood 1984, Bell and Cuff 1989, Valenta 1989). A divergence in handling this problem has evolved: i) one method is the geochemical and/or petrographical approach. Rock or fluid buffering depends heavily on the

permeability and porosity of the rock, diffusion between solute in the alteration fluid and the interacting minerals, and on the concentration of the fluid and mineral abundances. Method ii) considers the mechanical controls of fluid flow, which in this case depend entirely on the deviatoric stress field, hydraulic head, fluid pressure and tensile strength of the rock matrix (Brown 1987, Sibson 1989, Ridley 1993). This process is generally dealt in chapter 4, section 4.3.

Episodic stress cycling attributed to fluid fault-valve pumping (e.g. axial planer veins, section 4.3, Sibson 1986, 1994), is a generally accepted and common phenomena in hydrothermal systems (note the various brecciation stages in the Cloncurry fault, Figures 3.8D and 6.1E). Crack-seal textures, growth bands and various generations of fluid inclusion trails in hydrothermal veins (section 6.2) are the physical evidence of episodic fluid flow (Rumble 1989). A critical factor in maintaining fluid flow in deformed rocks is the competition between the processes of sustaining high permeability pathways and those that close the pathways.

Fluids present in the rocks, formed by expulsion during metamorphism, or by infiltration of an external source, such as meteoric, connate or igneous fluids, will move perpendicular on iso-gradient planes (for example chemical potential, pressure, temperature and hydraulic head gradients, Fyfe *et al.* 1978, Wood and Walther 1986, Yardley 1986, Bickle and McKenzie 1987). The movement of fluids through the rocks will be either by a chemical-diffusion and/or a mechanical-fluid pathway mechanism. The rate of fluid flow in rocks will be considerably slower than by, for example, diffusion mechanism than by movement through open fractures and veins. Fluid movement through rocks of medium to high metamorphic grades does not go through fractures, but is more of an interconnective grain boundary fluid transport, driven by deformation. Many processes, for example alteration, in rocks involve an interaction between the infiltrating fluid phase and the host rocks. The absence or presence of a fluid phase controls the rate at which deformation occurs. Fluids are capable in enhancing and promoting strain-softening, dislocation creep, solution-precipitation processes and micro-fracturing (Etheridge *et al.* 1984, Cox and Etheridge 1989, Handy 1990).

Diffusional processes occur generally in zones affected by large shear strain and play an important role in the dissolution and solution transfer (see section 4.3.1). This however, does not have to create a chemical change across a shear and/or mylonite zone, provided that the solution is in equilibrium with the host rock (Bell and Cuff

1989); this is however, very rare. In most cases significant mass transfer will occur in shear zones by solute diffusion in static or migrating fluid media (Cox and Etheridge 1989, Bell and Hayward 1991). This is apparent at the Maramungee shear zone and metasomatic front in the east, where there is a notable decrease in biotite abundance (breakdown of biotite), at the expense of albite and magnetite.

Dilatancy, on the other hand, can occur with high pressure and temperature deformation, provided that the pore fluid pressure is close to the lithostatic pressure. This is argued by Etheridge *et al.* (1984), based on the occurrence of extensional veins filled with minerals that reflect the P/T conditions of the host rock. That this dilation also formed under high P/T conditions is confirmed by experimental work undertaken by Fischer and Paterson (1989). Their work showed, that the Carrara marble, Solnhofen limestone and Gosford sandstone exhibit enhanced permeability attributed by microfracturing when deformed under a confining pressure of 3 kbar, 500°C and a fluid pressure about 2.8 kbar. The high temperature subhorizontal V_3 veins, were probably formed under such circumstances (section 4.3).

Modern conceptional models for large scale fluid movement, separate a circulating fluid flow regime in the upper crustal level, from a dominantly upward flow regime below a certain depth, generally deeper than 3-8 kilometres (Walther and Wood 1984, Yardley 1986, Ridley 1993). High confining pressures below this 3-8 km depth should generally close the pores. In the presence of a fluid phase, this will result in an increase in fluid pressure causing it to approach the lithostatic pressure (which could cause brecciation, see sections 4.4 and 4.4.2). On a large scale, fluids will therefore only flow with an upward component towards the earth surface. However, Byerlee (1993) reported penetration of meteoric water to a depth of at least 20 km, indicating that the pore fluid must have been at least at hydrostatic pressures throughout that part of the crust.

Shear zones provide the evidence that fluid flow is focussed in deeper crustal levels (Sibson 1990-1994, Olson and Grant 1991). Ridley (1993) argued that focussing of upward fluid flow in channelways can be attributed to lateral gradients in fluid pressure. These channelways would have had higher permeabilities and lower fluid pressures than the surrounding rocks for this lateral focussing to occur (there is a higher abundancy of veining in the Maramungee shear zone, than adjacent to the shear zone). Permeability is a significant factor in fluid flow. Rock permeability varies considerably; for example the permeability of unfractured metamorphic and

igneous rocks is about 10^{-18} m^2, while in salts it might be lower than 10^{-20} m^2, and could be as high as 10^{-9} m^2 for karst limestone (Philpotts 1990). Ferry (1988) observed that the permeability in altered calc-silicate rocks in Maine, is mainly lithologically controlled. Ferry pointed out that fluid:rock (F/R) ratio varied between individual layers, but was consistent along the individual layers (evident from the layer parallel veins V_2, section 4.3).

8.1.3 - Regional fluid flow model

Field evidence indicates that albitization (with actinolite - magnetite - titanite ± diopside) occurred in late-syn to post D_2 shear zones (Figure 8.3). Calc-silicates and syn D_2 granites (Maramungee suite, see Chapter 2) occur together in the "footwall" (structural lower part of the shear zone), and are altered to microcline-rich rocks (see Chapter 2 and 5). The albitization mineral assemblages indicate high temperatures, confirmed by fluid inclusion studies (± 550°C, Chapter 6). The ductile nature of the shear zone indicates depths well below 10 km (? lithostatic pressures ~ 2-3 kbar, based on SG ~2.7). Giggenbach (1984) demonstrated theoretically that if the physical conditions of a fluid in equilibrium with albite and K-feldspar changed, than the fluid would either precipitate albite or K-feldspar, depending on whether the fluid was heating up or cooling down. This would in general mean an ascending or descending fluid flow. However, local "curved" isotherms could lead to warming of an ascending fluid. The origin of the alteration fluid (meteoric, connate, metamorphic, juvenile) is still enigmatic. Observations of overprinting alteration stages indicate that the widespread albitization occurred before K-feldspathization.

An ascending fluid (exotic, metamorphic or magmatic) with a specific fluid composition, in first instance formed albite (and leached potassium). Fluid compositions necessary to create the albitization, or at least to be in equilibrium with albite, have K/(K+Na) ratios ≤ 0.25 (Orville 1963). A fluid in equilibrium with K-feldspar and albite at ± 400°C would have K/(K+Na) ~ 0.14 (Dipple and Ferry 1992). Dipple and Ferry (1992) demonstrated that metasomatism in amphibolite facies ductile faults did not require an exotic fluid, but is the consequence of metamorphic fluid flow through rocks along temperature gradients under near-equilibrium conditions (fluid with the two feldspars). Their studies indicated that most of the metasomatism is the result of fluid flow in the direction of decreasing temperatures, causing precipitation of potassium minerals (K-feldspar, mica).

Fluid composition of the early albitization stage in the eastern Cloncurry-Selwyn terrain is approximately K/Na ~ 0.1, K/(K+Na) ~ 0.09, based on the "phase volume method" of salt bearing fluid inclusions (Chapter 6). This accords with the work of Giggenbach (1984) and Orville (1963), illustrating albite being stable. For a fluid with that composition to attain equilibrium with both feldspars it has to deposit 80~90% of its sodium (extrapolated from Giggenbach's 1984, Fig. 4, and using ionic ratios for the activities). The overprinting K-feldspathization stage has a fluid composition, based on fluid inclusion studies, of K/Na ~ 0.2, K/(K+Na) ~ 0.17, and temperatures < 300°C. A fluid in equilibrium with feldspars, at 300°C, would have a K/(K+Na) ratio of approximately 0.08 (Dipple and Ferry 1992). This indicates that the above K-feldspathization fluid (K/(K+Na) ~ 0.17) would have to deposit 60% of its potassium and dissolve 10% of sodium in albite to retain equilibrium with both feldspars (Giggenbach 1984), and that a high F:R is not necessary to cause the alteration.

The observations from the fluid inclusion studies only confirm the theoretical work, but do not imply any direction of fluid flow. The change in fluid composition depends on the host rock compoition, and temperature-, pressure gradients. A fluid that flowed along a temperature and/or pressure gradient and maintained chemical equilibrium would therefore have to produce alteration. Theoretical work undertaken by Ferry and Dipple (1991) revealed that, in general, fluid will flow up temperature associated with prograde metamorphism, but this does not necessary require a downward flow direction. Lateral temperature gradients can be fundamental driving forces for prograde fluid flow up temperature. Retrograde metamorphism is typically associated with flow in the direction of decreasing fluid pressure (and temperature).

Two alteration scenarios with implications for the type of "starting" fluid can explain the first occurrence of albitization:

i) A deep seated hot fluid with the right composition, K/(K+Na) < 0.25, was in first instance out of equilibrium with K-feldspar and leached potassium and deposited sodium. Subsequently the fluid would have equilibrated with the two feldspars. The fluid was pumped down the temperature gradient, due to seismic activity. For these cooling down, upward flowing, fluids to maintain equilibrium with the infiltrated rocks, these fluids have to precipitate K-feldspar.

ii) A more realistic scenario, with fewer assumptions, would be as follows. Post D_2 fault structures formed conduits for downward-travelling cool meteoric and/or connate waters up the temperature gradient. Onset of syn-D_3 granite (Williams Batholith suite, see section 2.4.1) emplacement could enhance this downward flow of cool fluid, but this is not necessary to explain the alteration. The initial brines would have a high Na/K ratio. A study on fluid samples taken from boreholes, showed that fresh water near-surface exponentially increases in salinity with depth, as a result of incongruent dissolution (Deming 1994). This is one possibility for the elevated salinities in the fluids. It is more likely that evaporite beds in the Corella Formation was the source of the chlorine content, however, CO_2 fluids were not encountered (which might indicate that halite beds were more abundant in the eastern than western part of the Cloncurry terrain). The fluid would at some point have become saturated with respect to a mixture of chloride minerals. Increased temperature will preferentially dissolve K (and Mg, Ca) phases (e.g. K-feldspar), and precipitate sodium phases (e.g. albite, Hanor 1994). From this point scenario (i) will develop, with the exception that the "starting" fluid is now more constrained.

Figures 8.3 - Schematic cross-sections illustrating the progression of fluid circulation and episodic alteration in and around the Cloncurry fault and Williams Batholith. **A-** Schematic representation of the formation of the Cloncurry fault zone by continuous shearing on D_2 fold limbs. Channelized hot saline fluids in the shear zone caused albite-actinolite-magnetite-titanite±diopside alteration. Fluid circulation and ductile shearing were enhanced by the intrusion of granitoid bodies at depth. K-feldspar, quartz and hematite precipitated at higher crustal levels and at the margins of the shear zone. **B-** Continual unroofing, episodic granitoid emplacement and fluid circulation resulted in a series of fluid overpressuring and brecciation/alteration events which were temporally and spatially closely associated to the emplacement of granitoids and the Cloncurry fault zone. Episodic alteration during uplift allowed telescoping, resulting in the Cloncurry fault zone to be overprinted by each progressively more shallow (and lower temperature) alteration.

Early syn- (Maramungee suite) and late- to post-D_3 (Williams Batholith suite) granite emplacement (see section 8.1.1) compensated isostatically for the unroofing and thinning of the crust. Thinning of the crust also resulted in reduction of lithostatic pressures, causing the upward fluid flow along decreasing pressure gradients. Reduction in lithostatic pressure would have caused a decrease in confining pressure, which would result in a relative increase in fluid pressure, and resulted in hydraulic fracturing with vein formation. Some of these granite intrusions occurred high in the crust, as evident from the presence of miarolitic cavities. Isotherms around these granites would have been dense, and resulted in not only in downward (unsaturated) fluid flow, but also with large lateral fluid flow directions towards higher temperatures. This lateral flow would have resulted in precipitation of albite in a larger volume of rock. Overprinting granite intrusions (Mitchell 1993, G. Mark pers. com. 1995) created a new isotherm pattern that kept attracting new fluids. The continued introduction of laterally flowing fluid and older upward flowing fluid maintained high pore pressures in the alteration zone, which resulted in brecciation. The albitization would have also caused low permeability seals between the fault (alteration) zone and country rock, with seal-bounded high pressure fluid compartments (Byerlee 1993). Seismic activity of the large crustal fault zone would have caused Riedel fractures and ruptures of the high fluid pressure compartments, with fluid flowing up these fractures precipitating K-feldspar and a quartz stockworks in the apices of these structures.

8.2 - Arguments for syngenetic versus epigenetic mineralization

Close examination of the Maronan Prospect revealed the presence of epigenetic mineralization, with overprinting and cross-cutting sulphides and iron-oxides (Chapter 7). It is therefore essential to establish the timing of the mineralization which has implications for exploration strategies. If the mineralization is syngenetic (i.e. deposited during stage(s) A or B, Figure 8.1), then only specific stratigraphic horizons have to be targeted. If, however, the mineralization is epigenetic and precipitated in stage D of Figure 8.1, then exploration has to be directed towards structural and/or lithological controlled fluid flow conduits.

Features that might suggest the Maronan Prospect (and other deposits) in the eastern part of the Cloncurry-Selwyn terrain to be syngenetic, are:

1) Base-metal dominant deposits occur on a linear north-south trend, parallel to the regional fold-belt, hosted in the same stratigraphic package (Figure 7.1, Stanton and Vaughan 1979, Vaughan and Stanton 1986, Beardsmore *et al.* 1988, Loosveld 1989a). These deposits are hosted in interbedded psammopelite-amphibolite rocks of the Maronan supergroup (located geographically on the "local rise", Figure 8.1A).

2) The Maronan supergroup, has a different chemical signature to the rest of the Mount Isa Inlier (higher bulk Fe and Mn, Laing 1991). Laing (1991) interpreted the Maronan supergroup as a volcanosedimentary sequence, deposited in an ensialic rift setting. The close stratigraphic and deformation-style resemblance to rocks from the Broken Hill / Olary Block and the Georgetown Inlier lead to the conjecture that these rocks belong to the same sequence. Laing (1991) therefore proposed that the Maronan supergroup is part of a separate orogeny (Diamantina) which was rafted on to the Mount Isa Inlier. These blocks, especially Broken-Hill, are anomalous in base-metals. The Broken Hill Pb-Zn-Ag deposit lies in Early to Middle Proterozoic rocks of the Willyama Supergroup, and is believed to be metamorphosed. The Potosi Gneiss at Broken Hill is dated at about 1690±5 Ma (Page and Laing 1992), which is quite different to the Maronan supergroup (dated at less than 1677±9 Ma and metamorphosed at about 1580 Ma).

3) Broken Hill-type deposits are hosted in Mid-Proterozoic rocks characterized by stratabound Pb-Zn-Ag-sulphide orebodies. This mineralization type is associated with a chemically unusual rock package, interpreted as metamorphosed exhalites, deposited in a rift-related environment (Morganti 1981). The exhalites include manganiferous, ferruginous, siliceous and calcareous rocks (with minor barian and boron-rich rocks), and are interfingered and interbedded along strike with the sulphide orebodies. This description appears similar to the Maronan Prospect.

4) Minerals such as grunerite-cummingtonite amphiboles, which occur in the Maronan Prospect, are typical of intermediate grade (350°-550°C) metamorphosed ironstones (Maynard 1983, Klein and Beukes 1992). Higher grade (> 550°C) metamorphosed ironstones are defined by the appearance of iron-pyroxenes (ferrohypersthene and hedenbergite; also the pyroxenoids are typical "skarn" type minerals). The main occurrence of sedimentary ironstones (BIFs) is of typical Archaean age (with Western Australian BIFs < 2500 Ma), which is much older than the sedimentary rocks of the Maronan supergroup.

From the above observations it appears that there are some arguments for syngenetic mineralization. However, arguments against this are:

1) The stratigraphic horizon, which hosts the mineralization, is also a high strain zone, in which an epigenetic mineralizing fluid could have been focussed, and caused the overprinting sulphide mineralization (see point 3 below).

2) Textural features, such as overprinting relationships and the occurrence of undeformed Fe-Mn silicates (dannemorite laths), rules out pre-metamorphic mineralization (Chapter 7).

3) The sulphide mineralization overprints and infills the Fe-Mn silicate rocks (Figures 7.8C and 7.10A), and also occurs in cross-cutting veins, which indicate that mineralization occurred late.

4) PAAS normalized REE patterns of magnetite±garnet layers in the Maronan Prospect are close to unity (Figure 7.28), relatively flat and lack pronounced Eu anomalies, which is quite different to Archaean BIFs. Archaean patterns are below unity, inclined, depleted in LREE, especially Ce, and with a pronounced Eu peak (Klein and Beukes 1992). These Archaean patterns are interpreted as a signature of seawater and hydrothermal mixtures. The difference between the magnetite-garnet-, and the Archaean BIF-REE profiles, might indicate that the Maronan Prospect profiles are not influenced by an early sea-floor alteration.

8.2.1 - Fluid movement modelling in the Maronan Prospect

One possible mechanism for a metal resource is by focussing of large amounts of fluid through a large volume (km^3) of country rock (Etheridge *et al.* 1983, Fyfe 1987, Oliver et al. 1990). This fluid flow focussing into particular structures depends strongly on the predominating stress field, the related permeability and porosity of the country rock and the gradients in the hydraulic head (Ridley 1993). Transport of matter, on the other hand, due to pressure solution or ionic diffusion along mica fabrics, requires only a low fluid/rock ratio (Bell and Cuff 1989, but have possibly no real potential for ore genesis).

The type of conduits (brittle or ductile) that would focus the fluid flow depends on the lithostatic pressure (e.g. depth) and temperature. Deep seated fluid conduits control the fluid flow in ductile shear zones. Higher in the crust, the fluid pathways are open-space faults and veins (Ramsay 1980, Passchier 1987, Sibson 1989).

According to Wood and Walther (1986) fluid flow circulation would not occur at depths greater than about 3-8 km (however, occurrences of plutons can cause fluid circulation). At this depth, fluid pressures are close to lithostatic and this would imply that the fluid was *close to* the boiling point. This means there only will be upward directed fluid flow (Ridley 1993). This is a brittle-ductile transition zone, with temperatures ranging between 300° to 350°C (but will be higher in regimes with active magma emplacement), which is lower than at the Maronan Prospect. This is defines as the "mesothermal" zone (Peters 1993). This is also the zone in which fissured oreshoots formed, composed of quartz-pods ± Au in a connected vein system. Apart from the lower temperatures, the above model fits the Maronan Prospect, because Cu-Au mineralization occurs with the silicification in both brittle and ductile features, and there is no evidence for boiling (based on high liquid fill values, see section 7.6).

The silicified zone in the Maronan Prospect is recognized as a shear zone, on the basis of highly strained relict foliations, indicating that the silicification zone started as a ductile feature. This zone subsequently acted in a more competent fashion than the adjacent unaltered rocks. Other types of shear zones, in the Maronan Prospect, are the narrow zones of muscovite-only schist.

Fluids are channelized to areas of low stress. Fluid would therefore have focussed at tips of rigid bodies, open-space veins and dilations in strike-slip and dip-slip fault systems (Oliver *et al.* 1987, 1990). Studies of metamorphic terrains have demonstrated that fluid flow can be channelized into specific, individual, rock units (Ferry 1983, 1988). These are possibly the "peculiar" units in the Maronan Prospect.

The main stress (D_2) orientation in the Maronan Prospect is an east-west compression with a vertical σ_3 (Appendix H), resulting in subhorizontal and layer-parallel veins. Deviation in the stress field caused shearing with dilation and volume increase, creating localized sites of low fluid pressure. Fluid would have been focussed into these sites, with lower pressure and temperatures, resulting in a decrease in quartz solubility and precipitation of quartz. Fluid reactions with the country rock caused silicification and resulted in an impermeable barrier leading to further slight deviations in the stress field. σ_1 became moderately inclined with a NE-SW orientation (see Appendix H, Figure A4) associated with subhorizontal thrust faults, which are the loci for barren quartz veins (Figure 8.4).

Figure 8.4 - Model of fluid flow through the Maronan Prospect. An intense ductile deformed folding zone ($R_{strain\ ellipse} > 5$) caused by shearing on fold limbs. Limb zones become shear zones. Fluid focuses into the shear zone and into specific rock units. Silicification of the shear zone enhance competence contrast causing deviation in the stress field and subhorizontal thrust faulting. See also Figure 7.5.

8.2.2 - Mineral stability and ore fluid chemistry of the Maronan Prospect

Skarn mineralogy

Although the fluid compositions and trapping conditions are not well constrained in the Maronan Prospect, a few remarks can still be made on the basis of mineral- and ore-paragenesis (Table 7.1). Iron-pyroxenes in ironstones are stable at higher temperatures (> 550°C). Amphiboles, such as grunerite-cummingtonite, in metamorphosed ironstones are stable at temperature ranges from 350°-550°C (Maynard 1983, Klein and Beukes 1992). The presence of Fe-Mn silicate skarn related minerals as knebelite, bustamite, spessartine and dannemorite indicate a low carbon-dioxide activity, about $X_{CO_2} \sim 0.013$ (Peters 1973). The overprinting carbonate phase, especially siderite, implies an increase in the CO_2 activity at later stages in the Maronan Prospect, while the presence of magnetite and hematite in the

iron-oxide rich horizons indicate conditions of near the magnetite-hematite buffer. The oxygen fugacity is buffered by the reaction,

$$4Fe_3O_4 + O_2 \rightarrow 6Fe_2O_3 \qquad (8a)$$

The assemblages magnetite-pyrrhotite and pyrite-pyrrhotite±magnetite, and the absence of pyrite-hematite pairs, narrows the oxygen- and sulphur-fugacity to the invariant triple point in an fO_2-fS_2 diagram .

Other volatiles that are involved in the relative stability of skarn minerals are water and carbon-dioxide, generally expressed as mole fractions (when in a dominant H_2O-CO_2 fluid). Non volatile compositional variables (aqueous species) are expressed as activities. Variations in fO_2, fS_2, X_{CO_2}, and temperature are, as mentioned above, critical in the stability of minerals.

However, identifying a single variable as the controlling factor for stability of a particular mineral composition or assemblage is difficult (and possibly not realistic), as illustrated by the following example. Consider the relative iron content of a coexisting garnet and pyroxenoid:

$$Ca_3Fe_2Si_3O_{12} \text{ (in spessartine)} + H_2SiO_4 + 2H^+ \leftrightarrow 2CaFeSi_2O_6 \text{ (in pyroxenoid)} + Ca^{2+}(aq) + {}^1/_2O_2 + 3H_2O \qquad (8b)$$

The equation expresses the composition of garnet and pyroxenoid in terms of the activities of aqueous silica and calcium ion, pH and fO_2. The compositions of the garnet and pyroxenoid can be controlled by any combination of the above variables.

The pH is considered as one of the "main" variable. Thus, high-iron pyroxenoids (e.g. those in reaction Zn-skarns) can precipitated from "acid" solutions. However, the pH of high temperature hydrothermal solutions (iron-pyroxenes stable at > 550°C) does not vary greatly.

A low calcium activity would favour the formation of the pyroxene (in the pyroxenoid). Gradients in the calcium activity could be the cause of mineral zoning; hence, pyroxmangite and bustamite.

To express the iron content in garnet - pyroxene (in pyroxenoid) compositions as an unique function of oxygen fugacity (and temperature), an additional solid phase must be present. For example in the following reaction:

$$Ca_3Fe_2Si_3O_{12} + 12SiO_2 \leftrightarrow 2CaFeSi_2O_6 + CaSiO_3 + {}^1/_2O_2 \qquad (8c)$$

The relative amounts of hedenbergite in pyroxene (X_{Hd}) and andradite in garnet (X_{Ad}) are only functions of fO_2 and temperature. However, the mineral wollastonite was not observed in the Maronan Prospect. The iron must therefor be controlled by an other reaction; possibly by:

$$3FeSi_2O_6 \text{ (in pyroxmangite)} \leftrightarrow Fe_3O_4 \text{ (in magnetite)} + 6SiO_2 + O_2 \qquad (8d)$$

This reaction confirms petrographic observations (see Figure 7.8F). Where these minerals occur together, it cannot be concluded that there was a unique fO_2 and temperature environment of overall skarn formation. A mineral assemblages may represent the crossing of T-fO_2-XCO_2 equilibria, but there is no evidence that the skarn represent buffered T-fO_2-XCO_2 conditions. Using the mineral equilibrium concepts, however, one can conclude that: (i) pyroxmangite formed at more reducing conditions than the magnetite, and (ii) the replacement of a pyroxenoid±magnetite assemblage by a garnet-quartz±pyroxenoid assemblage does not necessarily require a change in fluid composition, but does require a change in the T-fO_2 environment of the skarn formation. The last point is of particular importance, because it illustrates that even in the case of bulk compositional changes do take place between an early and a later, cross-cutting event, the replacement of the early assemblage by the later assemblage may ultimately be caused by changes in temperature and/or volatile concentration.

Sulphide mineralogy

Solubilities of base-metal sulphides have been studied extensively over the last two decades (Hemley *et al.* 1992). The general results of experimental and theoretical studies indicate that:

1) Solubility products of base-metal sulphides increase with increasing temperature. This in contrast to oxygen and sulphur fugacities of mineral buffers, which increases exponentially with temperature (Eugster and Wones 1962). Experimental work undertaken by Hemley *et al.* (1992) on the solubility of iron-copper-zinc-lead sulphides in chloride solutions, in the presence of a K-feldspar - muscovite - quartz buffering assemblage, demonstrated that the metal solubility of lead and zinc decreases more dramatically for the same amount of temperature drop than that of copper and iron. This contradicts with the observations that galena (± sphalerite) nucleates on pyrite and chalcopyrite, indicating that other factors might play a role.

2) Chloride complexing increases in importance as temperature rises, particular above 250°C. If metals were transported as a chloride complex, than the precipitation of base metals is pH dependent by the following reaction(s):

$$MCl_2 + H_2S \rightarrow MS + 2HCl \qquad (8e\text{-}1)$$

$$HCl + CaCO_3 \rightarrow CO_2 + Ca^{2+} + OH^- + Cl^- \qquad (8e\text{-}2)$$

With -M- as Pb^{2+}, Zn^{2+} or Fe^{2+} ions. An increase in pH would cause precipitation of base metals. The occurrence of chalcopyrite blebs in sphalerite can be explained by a fO_2 decrease and a pH increase according to reaction:

$$4Cl + ZnS + FeS \text{ (in sphalerite)} + 4H^+ + O_2 \rightarrow 4CuFeS_2 + 4ZnCl^+ + H_2O \qquad (8f)$$

3) pH, is a further factor controlling the solubility of base metal sulphides. Sulphide ion concentration decreases at constant pH and total sulphide with increasing temperature (Figure 8.5). The increase in pH is caused by sulphide-bearing fluids interacting with magnetite. Magnetite is replaced by hematite (see 7.3.2.3), mainly in the presence of a Fe-Cu sulphide phase. The alteration from magnetite to hematite consumes oxygen ($4Fe_3O_4 + O_2 \rightarrow 6Fe_2O_3$), causing sulphide-bearing fluids to become more reduced. The oxygen that is used in the above reaction comes from:

$$Fe_3O_4 + SO_4^{2-} + 12H^+ \rightarrow 3FeS_2 + 6H_2O + 11O_2 \qquad (8g)$$

A decrease in pH would cause pyrite to precipitate. Chalcopyrite, on the other hand, will precipitate with an increase in pH, controlled by the following reaction:

$$4CuCl + 4FeS_2 + 2H_2O \leftrightarrow 4CuFeS_2 + 4Cl^- + 4H^+ + O_2 \qquad (8h\text{-}1)$$

Ironstones, hence magnetite, are important because of the above reactions, and the brittle manner in which it deforms (pyrite and chalcopyrite can than precipitates in fractured magnetite). Chalcopyrite nucleating on magnetite is controlled by the following reaction:

$$3CuCl + Fe_3O_4 + 6H_2S + {}^3/_2H_2O \leftrightarrow 3CuFeS_2 + 3Cl^- + 3H^+ + {}^3/_4O_2 \qquad (8h\text{-}2)$$

These factors all cause rapid increases in the solubilities of base metal sulphides with temperature in concentrated NaCl solution. In general, the deposition of base-metal sulphides can be adequately explained by decrease in temperature of such solutions, increase in pH due to wallrock alteration reactions, and/or dilution of the metal-carrying hydrothermal solution by less-saline ground-, meteoric waters.

Gold precipitation

Gold appears in two stages (section 7.4.3), associated with (i) Cu and with (ii) Pb. This would suggest that gold was transported in two types of complexes.

(i) Gold associated with chalcopyrite was probably transported as an $AuCl_2^-$ complex. Gold precipitation would be caused by temperature and/or pH increase or decrease in either a_{Cl^-} or fO_2:

$$4AuCl_2^- + 2H_2O \rightarrow 4Au + 4H^+ + 8Cl^- + O_2 \quad (8i)$$

(ii) If precipitation of base metals occurs in a moderately saline fluid (with a pH increase, due to minor circulation of metamorphic fluids), then this could leave gold as a bisulphide complex in the remaining solution (Heinrich *et al.* 1989, Hemely and Hunt 1992, Hedenquist *et al.* 1994). The stability of this gold complex depends partly on the concentration of reduced sulphur in the solution, illustrated by the following reaction:

$$Au(HS)_2^- + 2H_2O + 4H^+ \rightarrow Au + H_2S + O_2 \quad (8j)$$

If the remaining fluid with the gold-bisulphide complex reaches an area of low hydrostatic pressure, then volatilises (e.g. O_2) can escape the fluid (boiling), causing the gold to precipitate. Likely structures that this process could happen are open-space veins, brittle faults and related breccia zones. The fS_2 in the fluid increased, evident from the occurrence of, late stage (?supergene), secondary sulphide minerals as covellite, chalcocite and bornite. This increase in sulphur activity only happened on a local scale. These locally acidic fluids were formed due to a local drop in fluid pressure, caused by micro-fractures (Figures 7.15A-B), and were in disequilibrium with the pyrite and chalcopyrite, causing overprinting of the secondary sulphide minerals.

8.2.3 - Regional alteration versus "Maronan" alteration

The Proterozoic sediment hosted Pb-Zn-Ag deposits in the eastern Cloncurry-Selwyn terrain, are spatially and temporally (see below) associated with the regional (Doherty Formation) alteration. However, the Maronan Prospect is hosted by siliciclastic metasediments. Both alteration styles happened post D_2, and are related to shear zones on F_2 limbs (this is particularly true for the early stages 1-3 of the Doherty Formation), or in D_3 faults and fractures controlled by F_2 folds. Another similarity between the two alteration systems is that they both overprint metasediments of the Maronan supergroup. The alteration of the "Doherty Formation" is mainly developed in the rocks of the Corella Formation, while the alteration related to the mineralization is entirely within the Maronan supergroup.

The regional sodic-calcic alteration that affects large areas of the eastern Cloncurry-Selwyn terrain is different to the mineralization alteration at the Maronan Prospect.

Some alteration stages in the two systems are comparable, especially the later ones (carbonate and sulphide alteration, Table 8.1). Evidence that the two systems might be related is based on structural timing relationships and characteristics.

Figure 8.5 - Stability diagram after Huston and Large (1989). With increasing pH and decreasing temperature, sulphide will eventually precipitate. The fluid path passes through the pyrite zone towards the pyrrhotite and chalcopyrite zone. Log(fO_2) - pH diagram at 300°C, showing the evolution of the Maronan Prospect hydrothermal fluid. Arrow illustrates the possible evolution path.

1) The early sodic-calcic alteration in the Doherty Formation is related to post D_2 shear zones (Enclosure C, Figure 4.6), which is also the case in the Maronan Prospect (Figures 3.3 and 7.3).
2) The post D_2 shear zones, are in both systems located in limb-regions (c.f. Figure 3.1 with Figures 7.4 and 7.5).
3) The earlier alteration in the ductile shear zones is in both systems overprinted by veins and fractures. The vein-set in both systems show a bimodal distribution (Enclosure B and Figure 7.2) with layer-parallel veins cross-cut by subhorizontal veins (c.f. Figure 4.10 and Figure 7.16A).

Other evidence that might support the coeval nature of the two alteration systems is as follows:

4) Most fluid inclusions in quartz of the Maronan Prospect are free of daughter salts. This is partly true for the comb-quartz alteration stage that has a salinity between 23-27 Eq.wt.% NaCl (Chapter 6, salinities with approximately 25 Eq.wt.% NaCl in a NaCl-H_2O system contain salts).
5) REE patterns in altered metadolerites of the Doherty Formation are different to the patterns in the Maronan Prospect. The normalized REE patterns related to the sodic-calcic alteration have distinct Ce anomalies and negative Eu peaks. Normalized REE patterns of the magnetite±garnet alteration horizons closely resemble those in the altered metadolerites. However, the Ce anomaly is absent and the slope is flatter (less LREE enriched). Fluids that have caused the main sodic-calcic alteration in the Doherty Formation and fluids related to the mineralization at the Maronan Prospect were not similar, but could still have been related, based on these REE patterns.

A model for the relationship of the two alteration systems has to involve and explanation of why one is barren and the other is mineralized. Experimental work undertaken by Hemley *et al.* (1992) and McPhail (1993) demonstrated that solubilities of iron and base metals increase with increasing temperatures in a chloride solution, and decreased with increasing pressure. Post D_2 fluid activity (leaching of elements and causing alteration) mainly affected the Corella Formation. Base-metals and iron are present as similar type of chloride complexes in the fluid at temperatures > 400°C, based on similar behaviour regarding P/T change (Hemley *et al.* 1992). The alteration fluid possibly leached metals from the Corella / Doherty Formation and carried the metals in a metal-chloride complex. These fluids eventually have to escape the high fluid pressure area through fractures, faults and permeable lithologies.

A lithostatic pressure reduction, but with "constant" temperature (adiabatic conditions, e.g. the breccia stage in the regional alteration, evident by amphibole overprinted by clinopyroxene, Chapter 5) would have an inverted effect on the precipitation of metals (Hemley and Hunt 1992). If the effect of pressure reduction is significant, and the temperature remains constant, then metal-complexes stay in solution longer and can be transported over long distances (away from the source of leaching). This lithostatic pressure reduction, due to unroofing in the Doherty Formation, could be the reason for the lack of mineralization.

Table 8.1 - Comparison between the regional sodic-calcic alteration of the Doherty Formation and the alteration related to the mineralization at the Maronan Prospect. Arrows indicate possible similar fluid conditions.

8.3 - Conclusions

Prograde metamorphism of the Cloncurry-Selwyn terrain, which is part of the Proterozoic Eastern Fold Belt of the Mount Isa Inlier, reached amphibolite grade facies early in D_2, and was subsequently affected by regional scale telescoped sodic-calcic, iron-sodic-calcic, potassic-iron-silica and silica-sulphide alteration.

Rocks present are psammites, pelites and/or calc-silicate, with mafic and felsic intrusive phases. The psammopelitic gneisses and schist of the Maronan supergroup, overlie the calc-silicates of the Doherty Formation (possibly equivalent to the Corella Formation). The "Doherty Formation", is composed of rocks that are diachronous and have been affected by the regional-scale sodic-calcic alteration and brecciation. The Doherty Formation (alteration area) covers an area of approximately hundreds square kilometres. This alteration affected all rock units and caused a high variance mineral assemblage.

Orientation and nature of the earlier ductile deformation phase(s) are speculative, due to the strong overprint of the pervasive D_2 and the post D_2 sodic-calcic

alteration. D_1 appears to have developed flat lying structures. Regional D_2 deformation is associated with an upright tight N-S to NW-SE trending fold style, verging to the west. The eastern part of the Cloncurry-Selwyn terrain is transected by major north-south trending ductile retrograde, greenschist facies shear zones and a brittle lineament, the Cloncurry fault. Post D_2 ductile shear zones occur in D_2 fold limb regions. Some shear zones were possibly initiated prior to, or syn D_1. These shear zones also juxtapose rocks of different metamorphic grade, indicating a dip slip component.

Different phases of felsic and mafic intrusives occur in the eastern part of the Cloncurry-Selwyn terrain. Felsic granites (trondhjemitic) form early mylonitic porphyritic granite sheets and sills (Maramungee suite), were deformed along with calc-silicate rocks. The Williams Batholith is a major I-type two feldspar-hornblende granite intrusive complex, and intruded syn to post D_3 (Williams Batholith suite). Miarolitic cavities and grain size differences between margin and centre, indicate that some granites (of the Williams Batholith suite) intruded high in the crustal level, while others were emplaced at 12-15km (3-5 kbar, G. Mark pers. com. 1995).

Iron-rich tholeiitic metadolerites are possibly derived from metamorphosed metabasalts. Metadolerite sills are dominant in the southern part of the studied area, indicating emplacement in a ductile, deeper crustal level. Mafic and felsic intrusions in the northern part of the studied area form a net-veined complex, and are in places affected by post D_2 deformation.

Various degrees of alteration and brecciation reflect areas of low-, moderate-, or high fluid/rock ratios. Areas of high fluid/rock ratio consist of two types: 1) narrow ductile shear zones, overprinted by 2) breccias. There are two types of breccias, i) breccia dykes containing deformed clasts and cross-cutting the ductile shear zones and ii) breccias with undeformed clasts in a "pseudo-igneous" matrix. The breccia clasts are matrix supported. Relict fabrics are still visible in larger clasts, compared to totally altered smaller clasts. The "pseudo-igneous" matrix is formed by stubby diopside and/or actinolite and albitic plagioclase.

The shear zones in the predominantly calc-silicate rocks of the Doherty Formation were the locus for sodic-calcic fluid focussing during the "early post D_2" sinistral ductile shearing event. Fluids active during this ductile shearing produced high variance mineral assemblages in the shear zone.

A relative increase in fluid pressure, due to a decrease in confining pressure and unroofing resulted in brittle-ductile structures, such as veining and dilational jogs, overprinting the earlier ductile shear zones. Vein orientations reflect different structural styles and forming mechanisms. The veins occur in, and adjacent to the early post D_2 ductile shear zones. The composition of the vein infill (actinolite, albite, diopside, titanite) reflects the retrograde host rock assemblages, but still indicating quite high temperatures (± 400°C).

Unroofing, which caused thinning of the crust, resulted in an isostatic compensation by high level granite intrusions, emplaced during the D_3 deformation (Williams Batholith suite). Thinning also caused reduction of the lithostatic pressure and relative increased the fluid pressure. This resulted in the onset of regional brecciation by reduction of the effective differential stress, causing tensional failure to occur. Brecciation is spatially associated with the Cloncurry fault and the high level granite intrusions. Weak D_3 fabrics and partly brecciated granites (Williams Batholith suite) are evidence for the synchronous nature of the brecciation with the D_3 deformation phase and granite emplacement.

Continuous unroofing resulted in a telescoping effect with juxtaposing and/or overprinting of the earlier sodic-calcic alteration mineral assemblage with a later and shallower K-feldspar-quartz-chalcedony alteration phase and an epidote-prehnite-calcite alteration phase. These phases are (partly) structurally controlled by Riedel extensional fractures attributed by post D_3 sinistral movement of the Cloncurry fault.

Fluid inclusion data indicate a complex fluid chemistry and thermal history. The fluids active during the different stages of alteration (sodic-calcic, K-feldspar and comb-quartz stage), were a complex $NaCl$-$CaCl_2$-KCl-H_2O±$FeCl_2$±Mg-Ca-(CO_2 ?) salt-water system.

The main sodic-calcic alteration fluid was hot, about 450-550°C and saturated with respect to halite, averaging 30 Eq.wt.% NaCl. Mineral assemblages infer very low X_{CO_2} in the main sodic-calcic alteration fluid. K-feldspar stage, with temperatures of ± 295°C and 24 Eq.wt.% NaCl salinity, overprinted the sodic-calcic stage. A silica, comb-quartz stage that had a temperature of ± 275°C and 25 Eq.wt.% NaCl salinity, subsequently overprinted the previous stages.

Pb-Zn-Ag and/or Cu-Au prospects occur on an N-S linear trend east of the regional sodic-calcic alteration zone. The Maronan Pb-Ag and Cu-Au prospect is located on this post D_2 high strain zone. Structures and specific "zones" channellized and focused the mineralizing fluid. Five mineralized zones contain several, foliation parallel, "peculiar" rock horizons composed of pyroxenoids, silica, ironstones and carbonates.

The origin of Fe-Mn silicate rich units and the relationship with the calcareous units is somewhat enigmatic. The laterally interfingering and/or lensing between those units, overprinting the host rocks, and the constituents such as bustamite, pyroxmangite, knebelite and dannemorite could be interpreted as a "skarn-type" replacement. Chondrite-normalized REE patterns for these units are similar.

Chondrite-normalized REE patterns for all the different (unaltered and altered) rock units at Maronan (except quartz veins), are quite similar in light to heavy REE ratios (same slope). Sulphide mineralization and secondary carbonate alteration produced pronounced Eu anomalies (300 times chondrite, $Eu^*/Sm \sim 2.9$) in the calcareous and pyroxenoid units, and zero anomalies in garnet-magnetite and metasedimentary rocks. The fluid was not strongly enriched in REE, based on Post Australian Archaean Sediments (PAAS). REE patterns of magnetite-garnet units are flatter, indicating post-sedimentary HREE enrichment.

Copper-iron sulphides precipitated mainly in fractures and veins in the silicification zone, with rhodochrosite and siderite alteration, but also overprint the iron-oxide (magnetite) units (± pyrrhotite). Galena, tetrahedrite, and other secondary sulphide minerals overprint the pyrite and chalcopyrite in microfractures. Carbonates and pyroxenoid units host the Pb and Ag, but is mainly concentrated in the carbonates. Silver correlates with antimony (tetrahedrite?). Gold rich samples show affinity with HREE, and association with tourmaline veining. Gold correlates positively with Cu, Sb and As. Gold and silver occur together in Fe-Mn silicate rich samples.

Constant Pb/Cu, Au/Ag and K_2O/Rb and Ba ratios in all observed rock types suggest a single-pass fluid flow for the alteration and mineralization. However, the high Au-Cu-As-low Ag association, might indicate a separate event, suggests that two different fluids could have been involved.

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APPENDIX A

Sample Description List A1
Table - sample list A2

SAMPLE DESCRIPTION LIST

Condensed sample descriptions are tabulated in the Sample List. Major mineral constituents are given in abbreviations following Kretz (1983). Samples are ordered by geographical location. Exact sample sites are given in the "Sample Location Maps".

Sample numbering starting with "M" only (e.g. M31, not MG1 or MPI1 or MND10/123.1) are from Maramungee Creek. The "M"'s are occasionally omitted from text and/or figures and/or tables, due to space problems. Samples from Maramungee Creek can be recognized quickly, because the lack of a "decimal" point in their numbering.

Maronan Prospect samples are numbered in the thesis in the following manner, e.g. MND10/123.1, or as 10/123.1, in which MND stands for the Maronan Prospect and "10" is the drill hole (1 to 15) and "123.1" is the depth in metres.

Departmental numbers "DP#" are geochemical samples, specific thin-sections, fluid inclusion samples and specific photographed samples, used in this thesis. The geographical sample numbering is cross-linked with the DP numbers in the sample list. The DP# are 44585-44682 (Maramungee Creek samples) and 46301-46415 (remaining samples).

Other abbreviations used are:

CS	Calc-silicate
Ma	Marialite
Me	Meionite
Miz	Mizzonite
N	Normal thin-section
P	Polished thin-section
M	Microprobe analyses performed
S	Rock slab cut
F	Fluid inclusion analysis performed
X	XRF whole rock analyses performed
A	Neutron activation analyses performed
a→b	Mineral "a" is replaced or altered to mineral "b"
S_X	Foliation generation "x"
D_X	Deformation stage "x"

DP	Sample	Description	N	P	M	S	F	X	A	Location
44585	M1	Vein jog breccia with granoblastic dusted Ab, in altered CS	x	x	x			x		MC-sz
44683	M2	Amp-Cpx vein with dusted Kfs-Ab selvage in altered CS	x	x				x		MC-sz
44586	M3	Altered CS, layered Ab-Act, with Kfs overprint	x	x	x	x		x		MC-sz
44587	M4	Breccia (VjB), Ab±Act±Ttn						x		MC-sz
44588	M5	Foliated metadolerite dyke, with Hbl-Ttn-Plg	x					x		MC
44589	M6B	Subrounded Ab breccia clasts in Act matrix, vein jog breccia	x					x		MC-sz
44590	M7	Elongated breccia clasts with granoblastic Ab (Vjb)	x	x	x	x		x		MC-sz
44591	M8	Qzt-Mag-Ab vein in Mic-Qtz-Phl moderately altered rock	x			x	x	x		MC
44592	M9	Metadolerite dyke, foliated, with scapolite alteration	x	x				x		MC
44593	M10	Metadolerite, coarse grained, weakly foliated, no scapolite	x	x				x		MC
44594	M14	Metadolerite dyke, no scapolite, with sericitic feldspars	x	x				x		MC
44595	M19	Quartzite, biotite schist	x					x		MC-east
44596	M20	Breccia pseudo-igneous texture, altered schist clasts with relict banding	x	x		x		x		MC-east
44597	M22	Metadolerite, weakly foliated, Cpx with rims of Amp	x	x				x	x	MC
44598	M23	Andesine-Ma scapolite crackle vein in metadolerite with chlorine bearing Hbl	x	x	x			x		MC
44599	M24	Metadolerite with Ma-Scp, foliated, margin dolerite body	x	x				x	x	MC
44600	M28	Qtz-vein with Chl selvages in moderately altered CS	x	x	x					MC
44601	M29	Pristine CS, Bt-Hbl-Qtz-Plg-Mic-Ttn-Ap-Mag±Ilm, Qtz-rich	x	x				x		MC
44602	M34	Pristine CS, Hbl-Bt-Qtz-Fsp-Ttn-Mag±Ilm	x	x	x			x		MC
44603	M50	Breccia, Cpx-Act matrix and dusted albite clasts, pseudo-igneous texture	x					x		MC-east
44604	M51A	Bt-Qtz schist, overprinted by Crn-Ab±Mic±Tur, transposed	x				x			MC-east
44605	M51B	Breccia, pseudo-igneous texture, Cpx-Act-Ab-Qtz rock	x					x		MC-east
44606	M53	Biot-Qtz schist, overprinted by Crn-Ab, cut by Act vein with Ab dusted rim	x	x	x	x				MC-east
44607	M55A	Breccia pseudo-igneous texture, Act-Cpx-Ab, replaced by Ttn-Ab and Ep	x					x		MC-east
44608	M55B	Breccia, pseudo igneous texture, Ru-Mag with rims of Ttn, trace Cal	x					x		MC-east
44609	M56	Bt-Qtz transposed schist, overprinted by Crn-Ab±Mic	x					x		MC-east
44610	M57	Bt-Qtz schist, transposed, overprinted by Crn-Ab±Mic and eventually by Tur	x					x		MC-east
44611	M58	Breccia, pseudo igneous texture, Act-Cpx-Ab-Ttn-Mag-Qtz	x					x		MC-east
44612	M60A	Altered CS, coexisting, coeval Cpx-Act, Alb, Ttn, overprinted by large Kfs	x	x				x		MC-east
44613	M60B	Altered CS, as above	x					x		MC-east
44614	M61	Altered CS, Cpx-Act-Ab-trace Qtz-Ttn overprinted by trace Cal	x	x	x	x	x	x		MC-east
44615	M62	Metadolerite margin, Amp-Cpx-Plg (albitic), overprinted by Kfs	x							MC
44616	M63	Crackle vein , at margin metadolerite, composed of andesine with Ma-Scp	x					x		MC
44618	M64	Pristine CS, Hbl-Mic-Plg-Qtz±Me-Scp	x	x	x			x		MC
44619	M66	Granite / aplite, mylonitic texture, symmetrical pressure shadows	x							MC
44620	M69B	Quartz-titanite vein, in tension gashes	x				x			MC-west
44621	M70	Altered CS, Cpx-Act-Ab overprinted by dusted Fsp-Ttn and Cal	x					x		MC-west
44622	M74	Pristine CS, Hbl-Fsp-trace Ru, with leucosome/pegmatite veins	x	x				x		MC-west
44623	M76	Altered CS, in breccia zone in moderately altered CS	x					x		MC
44624	M77	Moderately altered CS, progressively overprinted by Ab	x	x	x			x		MC
44625	M78	Metabasalt/Metadolerite dyke, Act-Ab-An-Mic-Miz-Scp-trace Ttn-Mag	x	x	x			x		MC-sz
44626	M79	Moderately altered CS, Hbl-Qtz-Plg-Mic, overprinted by Mic and trace Chl		x				x		MC
44627	M81	Pristine CS, Hbl-Mic-Bt-Qtz-Mag±Ilm, overprinted by Ttn, Ep, Chl	x	x	x			x		MC
44628	M82	Pristine CS, Bt-Hbl-Qtz-Fsp-Ttn-Ap-Mag-Ilm,foliated, S2	x	x	x					MC
44629	M83	Pristine CS, Hbl-Mic-Qtz-Plg-myrmekite	x	x	x			x		MC
44630	M86	Quartz vein with traces of phlogopite					x			MC
44631	M88	Pristine CS, Qtz-Bt-Hbl-Fsp-Ttn, leucosome/pegmatite vein	x	x	x			x		MC
44632	M89	Chloritized Bt-Qtz-Fsp schist, trace Ttn-Ap-Mag-Ilm, anastomosing foliation	x					x		MC
44633	M90	Metadolerite dyke, foliated, with Qtz-Ab-Plg vein	x					x		MC
44634	M97	Pristine CS, Hbl-Fsp	x			x		x		MC
44635	M99	Metadolerite, sheared bands, with Ma-Scp	x	x				x		MC-west
44636	M113	Altered CS, relict Bt-Plg-Mic replaced by Ab-Act cut by Ab-Qtz-Ma-Scp vein	x	x	x	x		x		MC-sz
44637	M115	Moderately altered CS, relict Bt-Mic-Miz-Scp, overprinted by Act	x	x				x		MC-sz
44638	M116	Vein jog breccia contact with altered calc-silicate	x	x	x	x		x		MC-sz
44639	M117	Axial-planer vein, Act centre with dusted Ab ±Mic selvage	x			x		x		MC-sz
44640	M118	Tension gash filled w/ Ksp-Qtz-Hem	x				x			MC-sz
44641	M119	Moderately altered CS, Qtz-Plg-Mic±Bt, overprinted by Act±Cpx±Ttn	x					x		MC
44642	M120A	Ms-Bt-Qtz-Fsp retograde schist	x				x	x		MC-east
44643	M121	Amphibolite dyke, Amp-trace Bt-Fsp-Mag	x	x				x		MC-east
44644	M130	Breccia pseudo-igneous texture, Cpx-Ttn-Act-Ab	x					x		MC-east
44645	M131	Breccia pseudo-igneous texture, Act-Cpx-Ttn with Mag overgrowing Ab	x	x		x		x		MC-east
44646	M134F	Altered metadolerite, banded, Amp-Cpx-Plg, overprinted by Hem dusted Kfs	x					x	x	MC-east
44647	M134G	Metadolerite, Amp-Cpx-Plg-trace Py-Ttn-Ap, overprinted by dusted Kfs	x	x				x	x	MC-east
44648	M135	Breccia, pseudo-igneous texture						x		MC-east
44649	M135B	Breccia, pseudo-igneous texture, Cpx-Act-Ttn-Ab-Mag, Kfs, trace Cal	x					x		MC-east
44650	M136	Metadolerite, foliated, Hbl-Cpx-Kfs-Plg, no Ttn	x					x		MC-east
44651	M140	Moderately altered CS, Bt-Miz-Scp-Mic-Qzt, schisteous,-> Act-Ab-Ttn-Mag	x	x	x			x		MC-sz
44652	M141	Altered CS, Ab-Act±Kfs, with Tr-vein and Hem dusted Ksf selvages	x	x	x	x		x		MC-sz
44653	M143	Moderately altered CS, Mic-rich rock, as next sample	x					x		MC
44654	M143B	Moderately altered CS, banded, Hbl-Mic-Plg-Qtz-Bt->Act-Ab->Hem dusting	x	x	x			x		MC
44655	M144	Moderately altered CS, cut by Ab-Act vein	x							MC
44656	M145	Breccia (Vjb?), Act-Ab-Mag-Ttn-trace Ap, oveprinted by Mic	x	x				x		MC
44657	M147	Moderately altered CS, cut by subhorizontal Act-Cpx vein and Mic selvages	x	x	x			x		MC
44658	M148	Moderately altered CS, layered, Ab-Act, Mic-Act, Mag-Ttn-Ap laminations		x						MC
44659	M149	Altered CS/ breccia, Cpx-Ab-Qtz-Ttn-Mag±Kfs	x							MC
44660	M149B	Breccia (Vjb?), Ab-Act breaks down to Bt+Chl, Ttn-Mag	x	x				x		MC
44661	M150	Granite, graphic texture, weakly foliated, trace Hbl	x							MC
44662	M151	Moderately altered CS, Mic-Bt-Plg-Qtz-trace Ap oveprinted by Act-Mag-Ttn	x	x				x		MC
44663	M152E	As above, less Mt, more Mic, laminated, relict S0?	x	x	x	x				MC
44664	M155A	Qtz vein with Hem lats and trace of Ab	x		x		x			MC-west
44665	M157A	Pristine CS, foliated, Hbl-Mic-Qtz-Ttn-Mag, cut by leocosome/pegmatite vein	x	x	x			x		MC-west
44666	M157B	Pristine CS, Hbl-Mic-Plg-Qtz-Mag-Ttn, folded by D2	x	x	x			x		MC-west
44667	M163B	Metadolerite, at margin of tension gash	x	x				x		MC-west
44668	M164	Quartz vein in granite					x			MC-west

DP	Sample	Description	N	P	M	S	F	X	A	Location
44669	M166	As above	x					x	x	MC
44670	M167	As above, cross-cut by pegmatite dyke	x					x	x	MC
44671	M168	Altered CS, laminated, Cpx-Ab-Ttn-Mag, oveprinted by dusted Kfs and Cal	x					x		MC
44672	M169	Altered CS with a strong compositional and grain size banding	x	x	x			x		MC-sz
44673	M170	Altered, laminated CS, Ab-Cpx, overprinted by Hem dusted Kfs-trace Cal	x					x		MC
44674	M171	Altered CS, laminated, overgrown by coarse poikiloblastic Ab crystals	x	x	x		x	x		MC
44675	M172	Metadolerite, with Ma-Scp alteration	x	x				x	x	MC
44676	M172B	Metadolerite, with Hem dusting, no scapolite	x					x	x	MC
44677	M172C	Metadolerite						x	x	MC
44678	M172D	Metadolerite, Cpx-dusted Fsp, no scapolite	x	x				x	x	MC
44679	M172E	Metadolerite, Hbl-Cpx-Plg-Ma-Scp	x	x					x	MC
44680	M173	Altered CS/breccia/metadolerite?, Ab-Amp-Mag-Ttn, oveprinted by Cal	x							MC
44681	M174A	Altered CS clasts, Ab-Act-Ttn-Mag, replaced by Hem dusted Kfs	x	x	x					MC
44682	M176	Granite / aplite dyke, Qtz-Plg-Mic		x						MC-sz
46301	30.2	Bt-Qtz transposed schist overprint by Crn-Ab±Mic, Bt replaced by Chl	x							FR-gorge
46302	30.4	Carbonate, Cal(±Mg±Fe)-Mic-Chl-trace Ap, weathered sulphides?	x							FR-gorge
46303	39.1B	Open space quartz-albite vein, with some Hem staining				x				FR-gorge
46304	39.3A	CS, folded, Cpx-Hem dusted Ab-trace Mic-Ap-Ttn-Mag	x	x		x				FR-gorge
46305	39.3B	Metadolerite, sheared, with Ma-scapolite, Ab-Hbl-trace Mic-Cpx	x	x	x					FR-gorge
46306	40.1B	CS, Ab-Act, overprinted by Act and Hem dusted Mic, trace Mag	x	x	x	x				FR-gorge
46307	40.1C	CS clasts and matrix, Act-Ab-trace Mic-allenite-Chl-Ep-Mag	x	x	x					FR-gorge
46308	40.2	CS, open folded, Cpx-dusted Ab-Ttn-Mag-trace Act-Ep	x	x	x	x				FR-gorge
46309	41.1B	Breccia, margin metadolerite, Ab-Cpx replaced by Act, trace Ep	x			x				FR-gorge
46310	41.1C	CS, margin metadolerite, laminated, Cpx-Ab-Ep-trace Scp	x			x				FR-gorge
46311	41.1D	CS, laminated, Ab-Ttn-Act-Cpx-Chl-Ap, oveprinted by Cal		x	x					FR-gorge
46312	41.2	Breccia, relict Cpx -> Act, Ab-trace Mic, Qtz-Tit-> Mag+Ru	x	x	x					FR-gorge
46313	41.2B	CS / metadolerite, Cpx-Ab-Cal, cross-cut by Ep-Ab-Prh vein		x	x					FR-gorge
46314	41.2C	Breccia, with cavities, Cpx clusters->Act, Ab-Cal(+Mg), Chl-talk	x	x	x	x				FR-gorge
46315	41.2F2	Breccia, matrix, Ab-trace Mic, Cal(+Mg+Fe), Mag+Ti, Ttn->Ru	x	x	x					FR-gorge
46316	41.2G1	Crackle Breccia, Ab-Act-Cal(+Mg+Fe), Mag-Ttn->Ru-Qtz-Chl	x	x	x	x				FR-gorge
46317	42.1	Milled breccia, Ab-trace Mic-Act-Cpx-Cal-Qtz-Ttn->Ru	x	x	x					FR-gorge
46318	44.1	CS, deformed, Ab-Act laminations, Act overprint	x			x				FR-gorge
46319	44.3	CS, banded, Cpx-Ap-Hem, Ab(?), Mag-Ttn, Act->Cpx, Ep alteration	x			x				FR-gorge
46415	44.4D	CS, more Cal overprint, less Cpx, more Act-Ab, Mag-Ttn	x			x				FR-gorge
46320	49.1	Breccia, laminated/flow?, Act-Hem Ab, Chl-Ep, Ttn, Mag, allunite, Ru	x			x				FR-gorge
46416	50.1	CS, Cpx-Act-Chl-Ab dusted-Ep/allenitet-Mag-Ttn	x							FR-gorge
46321	55.4	CCY fault, brittle-ductile, Bt-Ms-Qtz-Plg-Kfs-Sil	x			x				FR-gorge
46322	L1.3	Totally altered schist, texture preserved, Bt -> Mag	x			x				FR-gorge
46323	L1.6	Breccia/CS laminated, Ab-Mic coeval, Cpx-Act, Ttn, Cal, Mag, Chl		x	x	x				FR-gorge
46324	L3.4	Breccia matrix?, almost pure Ab, trace Mic, Mag , pure Cal breccia		x	x					FR-gorge
46325	L4.2	Breccia dyke, Cal-Cpx-Ab-Ttn-Ep-talc-allenite	x	x	x	x				FR-gorge
46326	L4.3	Breccia dyke, Act-Ab-Cal, trace Ttn, no Cpx		x	x	x				FR-gorge
46417	23.2	Altered metadolerite, Hbl->Ep+Cal±Chl, Fsp, Qtz, Ttn-> Ru+Qtz+Cal	x							Mallee Gap
46327	23.4A	Granite, Qtz-Fsp-Hbl, trace Ttn, Chl in mariolitic cavity, edge breccia	x							Mallee Gap
46328	23.5*	Sillimanite-Kfs-Bt-Qtz transposed schist, overprinted by Crn-Ab, Tur	x	x	x	x				Mallee Gap
46329	MG1	Andalusite-Mic-Ab-Bt±Ms vein, in Qtz-Fsp-Bt psammite	x	x	x	x				Mallee Gap
46328B	23.5	Albitized granite, Ab-Qtz, relict Kfs, trace Cal, Chl, Mag	x							Mallee Gap
46330	25.15	Quartzite, foliated, Qtz,Bt, in places albitized, solution transfer	x							MG-area
46331	25.16A	Albitized psammite, trace Mic, brecciated with Hem veins +Mic	x			x				MG-area
46332	27.11	Altered metadolerite, sericitic, Cpx-Act, Ab-Mic, Ep-talc, Ttn		x	x					MG-area
46415	28.11	Kfs dyke, Hmt dusted Mic, Qtz, Hmt	x							MG-area
46333	33.13B	Assimilation, granite intruded dolerite, Hbl relict->Bt, Qtz, Plg, Mic	x			x				Boorama W
46334	34.9B	Amphibolite, foliated, Hbl-Plg-Qtz-Ttn-Mag, trace Cxp		x	x					Boorama W
46335	34.9C	Amphibolite foliated, as above		x	x	x				Boorama W
46336	35.2	Brecciated zone in granite, anorthitic Plg, Act, Mag, Ttn, trace Cpx	x			x				Boorama W
46337	3.10	Bt-Qtz-Ms-garnet±Tur schist, S1 anastomosing	x							PB-east
46338	9.6A	Bt-Ms-Qtz-Fsp-garnet-staurolite schist with And->Ms	x							DB-east
46339	9.9D	Bt-Ms-Qtz-garnet-Sil-And schist And->Ms, S1	x							DB-east
46340	10/138.8	Qtz-Mic-Plg-Bt schist cut by garnet-Tur-Qtz vein with Ms selvages		x	x					10/138.8
46341	10/261.45	Quartz vein with garnet and overprinted by carbonate		x	x				x	10/261.45
46342	10/270.65	Qtz-Mag rock, margin Qtz vein, Mag stringers overprinting Qtz		x					x	10/270.65
46343	10/277.5	Quartz vein, overprinted interstitial by carbonate, as above		x			x		x	10/277.5
46344	10/309.85	Qtz-Mag rock, base of Qtz vein as above, Mag in places poikiloblastic		x					x	10/309.85
46345	10/312.65	Bt-Ms-Qtz±garnett schist, sheared S2 main, Qtz vein with Bt rim		x						10/312.65
46346	10/316.3	Pegmatite vein, Mic, Qtz, Bt, trace Ms, trace Py-Po		x					x	10/316.3
46347	10/325.25	Sulphide-Qtz-Ap vein at margin of calcareous gneiss		x	x				x	10/325.25
46348	10/326.3	Folded calcareous gneiss, garnet overprinted by red brown Bt, Py		x	x				x	10/326.3
46349	10/328.05	Calcareous gneiss, as above, Gn, strained Qtz, trace Ms		x					x	10/328.05
46350	10/339.4	Qtz-Kfs-Oligoclase-Bt±Ms schist with Py-Qtz vein and Bt-carbonate rims		x	x				x	10/339.4
46351	10/349.8	Quartzite with Py vein with rhodochrosite+siderite rim, trace Ccp		x					x	10/349.8
46352	10/352.49	Quartzite, as above, Qtz, sericitic Fsp, Bt, Ms, Chl defining S1		x					x	10/352.49
46353	10/356.5	Calcareous gneiss with clear garnet, strained Qtz, Ap, intergranular Ccp-Py		x					x	10/356.5
46354	10/361.8	Bt-Qtz-garnet-Fsp schist with sulphide vein rimmed by carbonate		x					x	10/361.8
46355	10/363.9	Calcareous gneiss, trace Qtz, Ap, garnett, Ccp-Py-Mag		x					x	10/363.9
46356	10/365.4	Quartz-carbonate rock with Mag and sulphide, Ccp replacement		x					x	10/365.4
46357	10/368.95	Qtz-carbonated-sulphide rock, Ccp with siderite rim, trace Ab, brown Bt		x	x				x	10/368.95
46358	10/379.7	Carbonate-Atz rock, foliated, Ccp-Py-Gn, trace Ap		x	x				x	10/379.7
46359	10/381.7	As above, carbonate with intergranular Gn, trace Ap, Qtz		x	x				x	10/381.7
46360	10/386.05	As above, more Qtz less carbonate, no Gn, brown Bt, Ap, Py-Ccp		x		x			x	10/386.05
46361	10/387.7	Breccia, quartzite clasts in Po matrix, trace carbonate, Bt, Ap		x		x			x	10/387.7

DP	Sample	Description	N	P	M	S	F	X	A	Location
46362	10/395.7	Calcareous quartzite gneiss, trace jarosite, Py, Qtz, trace garnet, Bt		x	x				x	10/395.7
46363	10/405.5	Skarn, coeval garnet,bustamite, overprinted by cummingtonite, green Bt		x	x				x	10/405.5
46364	10/421.2	Photograph. Grt vein with Bt selvages cut by Cal vein								
46365	10/426.8	Bt-Ms-Kfp-Qtz-garnet schist, Po vein with Ms+Kfs rim		x	x				x	10/426.8
46366	11/62.4	Mag, rhodochrosite laminations, jarosite, Ccp overprinting, quartzitic		x						11/62.4
46367	11/65.2	Rim of iron rich rock, Mag, rhodochrosite, Chl, garnet, Ba-rich Kfs		x	x	x			x	11/65.2
46368	11/71.3	Microcline-Qtz rock with Mag parallel to the foliation, Sd replaced by Chl		x	x	x			x	11/71.3
46369	11/87.85	Quartzite replaced by garnett->Chl, Mag, green Bt		x	x				x	11/87.85
46370	11/99.05	Folded,laminated iron-rich rock, Qtz-garnet replaced by Mag+carbonate		x		x			x	11/99.05
46371	11/108.2	Quartzite overprinted by pink garnett, green Bt, calcareous, laminated		x	x					11/108.2
46372	11/124.15	Qtz,bustamite overprinted by pyroxmangite, calcareous, brown Bt, garnets		x	x	x			x	11/124.15
46373	11/143.8	Quartzite, Fsp, Ms, trace garnet cut by Tur-Qtz vein and Hem-Kfs rims		x						11/143.8
46374	11/156.4	Iron-rich rock, garnet-Mag overprinting a Qtz-Mic-calcareous laminated rock		x					x	11/156.4
46375	11/161.55	Microcline-Qtz rock with Amp->Chl, Mag, brown Bt		x					x	11/161.55
46376	11/176.15	Qtz vein with relict Qtz-Ms D2 crenulated schist clast		x			x		x	11/176.15
46377	12/101.6	Ms-Qtz mylonitic schist, S2, trace Fsp, Gn vein with Mic selvages		x	x				x	12/101.6
46378	12/127.7	Quartzite with boudinaged Qtz-Ga vein + coarse Ms laths, traces of Py and Ccp		x						12/127.7
46379	12/132.1	Quartzite with green Bt-Ms-Py-Ccp-Gn vein and green Bt selvages		x	x				x	12/132.1
46380	12/163.5	Quartzite, trace Kfs, Plg, brown Bt laths, boudinaged Qtz vein with Ccp-Py		x	x				x	12/163.5
46381	12/180.45	Quartzite cut by Tur-sulphide-Qtz vein with Ms-Mic-Ab rims		x	x				x	12/180.45
46382	12/186.3	Quartzite overprinted by Mag, green Bt, Ap, monazite		x	x				x	12/186.3
46383	12/188.6	Breccia, silicified, Qtz with Mag, trace Py, Ccp		x			x		x	12/188.6
46384	12/203.7	Carbonate-quartzite boundary, Qtz-Mag, Cal-garnet, Mag-Gn-Py		x					x	12/203.7
46385	12/206.8	Qtz-brown Bt rock, S1, overprinted by garnet, brown-green Bt, S2		x					x	12/206.8
46386	12/232.83	Calcareous quartzite, laminated, Cal-Ap, Qtz-Fsp-Ap, Gn-Bt		x	x				x	12/232.83
46387	12/263.3	Skarn, quartzite overprinted by bustamite, carbonate, Ap, Mag, Gn, Po		x	x				x	12/263.3
46388	12/272.9	Skarn, knebelite with pyrosmalite rim, trace Cum, garnet-Ap, Py-Mag		x	x				x	12/272.9
46389	12/278.32	Skarn, garnet, Mag, Qtz, Cal overprinted by Cum radial laths, trace brown Bt		x	x				x	12/278.32
46390	12/284.35	Skarn,resorbed garnet with green Bt+Cum, Bst-garnet-Ap, Mag-Po		x					x	12/284.35
46391	12/318.1	Margin skarn, Qtz-Mag, garnet-Mag, Qtz-Fsp, Mag-Gn-Cum laminations		x					x	12/318.1
46392	12/324.0	Qtz-garnet rock, trace Cum, cut by Cal vein with green Bt selvages		x						12/324.0
46393	12/342.2	Photograph. Psammopelitic foliated rock, cut by discordant garnet vein								
46394	2/168.0	Photograph. Pyroxenoid layer cut by Mag veinlets, Gn, and traces of Py				x				2/168.0
46395	3/153.5	Photograph only. Psammopelite cut by discordant Grt- and carbonate vein								3/153.5
46414	3/253.15	Photograph only. Psammite cut by Tur±Qtz-Cal vein with Hem dusted Mic rim								3/253.15
46396	4/119.5	Boudinaged Qtz lenses, infilled with carbonate and Gn				x				4/119.5
46397	4/156.8	Qtz-Mag bands, faulted and boudinaged, with carbonate replacement				x				4/156.8
46398	5/69.5	Photograph only. Coarse Grt layer, cut by buckeld finer Grt vein								5/69.5
46399	5/126.7	Pyroxenoid layer cut by Bt vein with Grt selvages, overprinted by Cum laths				x				5/126.7
46400	6/41.5	Photograph only. Psammopelite cut by Tur vein with Ab selvages (~ 7/172.3)								6/41.5
46401	6/133.5	Quartzite cut by Grt vein, cut by Cal vein				x				6/133.5
46402	7/172.3	Quartizte cut by Tur, Cal vein, with Ab selvage; CCp veinlet cut Tur vein				x				7/172.3
46403	7/153.0	Qtz vein with Py and Asp precipitated in fractures				x				7/153.0
46404	7/185.6	Photograph only. Silicified rock wit Py parallel to relict foliation								7/185.6
46405	7/189.1	Silicified rock wit Ccp parallel to relict foliation				x				7/189.1
46406	7/253.2	Coarse Cal rock with Py and Gn infill				x				7/253.2
46407	DCA 0170	Skarn, pyroxmangite, Cum, garnet, Ap,recrystallized Qtz		x	x					MND 4
46408	DCA 0695	Garnet-amphibole gneiss, almandine,hastingsite, Qtz,Kfs, Oligoclase	x							7/106
46409	DCA 0696	Weathered microgabbro, Chl-limonite stained, Amp-Fsp, ophitic texture	x							7/140
46410	CJ 6.7	Milky white quartz vein CCY fault					x			
46411	CJ 7.1	Comb quartz vein CCY fault					x			
46412	CM 31.1B	Quartz Kfs bearing vein					x			MND 4
46413	21/336	Comb quartz vein CCY fault					x			7/106.0
Areas	MC	Maramungee Creek								
	MC-sz	Maramungee Creek shear zone								
	MC-east	Eastern part of the Maramungee Creek river section								
	MC-west	Western part of the Maramungee Creek river section								
	FR-gorge	Fullarton River Gorge								
	Fr-area	Fullarton River area, mainly south of the Fullarton River Gorge								
	Mallee Gap	Mallee Gap location								
	MG-area	Mallee Gap area								
	Boorama W	Boorama Waterhole area								
	Spring Crk	North of Spring Creek								
	PB	Percy Bore location								
	PB-east	East of Percy Bore								
	PB-south	South of Percy Bore								
	TA-east	East of Turpentine Antiform								
	TA-west	West of Turpentine Antiform								
	TA-nose	The nose of the Turpentine Anitform								
	DB	Daylight Bore locality								
	DB-east	East of Daylight Bore								
	DB-NE	Northeast of Daylight Bore								
	YT-west	West of Yellow Tank								
	YT-SW	Southwest of Yellow Tank								
	Fmile	Fairmile area								
	Fmile-north	North of Fairmile								
	Fmile-south	south of Fairmile								
	Kalkadoon	Kalkadoon deposit								
	LVT	Levuka Trend								
	CCY	Cloncurry Fault								

APPENDIX B

Sample Location Maps B1

Sample map 1- Overview map of the eastern part of the Cloncurry-Selwyn terrain. B2

Sample map A - The Maronan-Fairmile area. B3

Sample map B - Glen Idol-Fairmile overview map. B4

Sample map C - Fullarton River area map. B5

Sample map D - Fullarton River gorge map. B6

Sample map E - Mallee Gap area map. B7

Sample map F - North of Spring Creek area map. B8

Sample map G - Boorama Waterhole area map. B9

Sample map H - Maramungee Creek section map. B10

SAMPLE LOCATION MAPS

An overview of the geographical locations of various "sample location maps" is given first (similar to Figure 1.5). The numbers on the maps represent the field-location number, equivalent to the sample numbers in the "sample list".

The following sample maps are provided:

- Overview map	(Kalkadoon)
- Maronan-Fairmile map (A)	(PB, PB-east, PB-south, TA-east, TA-west, TA-nose, DB, DB-east, DB-NE, YT-west, YT-SW
- Glen Idol-Fairmile map (B)	(Fmile, Fmile-north, Fmile-south)
- Fullarton River area map (C)	(FR-area)
- Fullarton River gorge map (D)	(FR-gorge)
- Mallee Gap area map (E)	(Mallee Gap, MG-area)
- North of Spring Creek area map (F)	(Spring Crk)
- Boorama Waterhole area map (G)	(Boorama W)
- Maramungee Creek section map (H)	(MC, MC-sz, MC-east, MC-west)

The drill hole locations of the Maronan Prospect are shown on the "Maronan-Fairmile" map.

The "decimal period / dot" in the sample number on maps, is the location of the sample, e.g. -12.6- (12 is the 12th mapping day, 6 is the 6th outcrop stop, - . - is the sample location).

Sample map 1- Overview map of the eastern part of the Cloncurry-Selwyn terrain.

Sample Locations in the MARONAN-FAIRMILE area

Sample map B - Glen Idol-Fairmile overview map.

Sample map C - Fullarton River area map.

SAMPLE LOCATIONS IN THE FULLARTON RIVER SECTION

Sample map E - Mallee Gap area map
472000 mE
473000 mE
474000 mE
475000 mE
476000 mE
477000 mE
478000 mE
7649000 mN
7648000 mN
7647000 mN
7646000 mN
7645000 mN
7644000 mN
7643000 mN
7642000 mN
7641000 mN
7640000 mN
7639000 mN
Mallee Gap
MG1
Three Sisters
CLONCURRY FAULT
N
60.10
37.9
37.7
37.6
37.2
24.1
37.12
37.13
23.2
23.3
23.4
23.5
37.14
24.9
24.11
24.10
25.5
25.12
25.10
25.15
25.16
27.1
27.11
27.4
27.3
27.10
27.7
27.8
54.7
54.9
54.8
54.13
29.7*
*G
29.12
29.14
29.17
28.11
28.10
28.9
28.8
28.7
28.5
28.3
LEGEND
Cover alluvium
Psammitic schist interbedded with pelitic layers and amphibolite
Coarse muscovite biotite quartz feldspar schist, gneissic
Laminated and massive calc-silicate
Carbonate pods, interbedded with Kfs layers
Strongly foliated amphibolite / metadolerite
Coarse weakly foliated basic igneous rock (gabbro)
Coarse unfoliated quartz containing basic rock (diorite)
Angelay granite , hornblende, quartz two feldspars, with miarolitic cavities
Unfoliated granite, with zoned plagioclase crystals
Weakly to unfoliated fine grained leuco granite
Strongly foliated, mylonitic granite
Altered, albitized granite, white fine grained
Altered schist, biotite quartz sillimanite schist ± corundum overprinted by albite
Open space veins with red K-fsp, hematite, quartz/chalcedony infill ± sulphides
Breccias, consisting of altered granites, schists, metadolerites and calc-silicate rocks
Granitic / pegmatitic vein
White buck quartz vein
*G Goethite vein
Fault
High strain zone
Thrust
Antiform
Synform
S1
S2
S3
Lineation / fold axis

Sample map F - North of Spring Creek area map.

Sample map G - Boorama Waterhole area map.

Sample map H - Maramungee Creek section map.

APPENDIX C

Electron Microprobe Analyses	C1
Fe^{3+} calculations	C2
Other stoichiometry calculations	C3
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Table - amphibole analyses	C6
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Table - epidote analyses	C14
Table - apatite analyses	C14
Table - carbonate anayleses	C15
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Table - Maronan probe data	C16
Energy dispersive spectra of some minerals of the Maronan Prospect	C17

ELECTRON MICROPROBE ANALYSES

The quantitative analyses of the samples were preformed by a JOEL JXA-840A ELECTRON PROBE MICROANALYZER set at 15 kV, with a current beam of 15 μA, and with a counting interval of 60 to 120 seconds, at the Analytical Centre at James Cook University of North Queensland. Beam size generally was held to 2 μm, but was increased to 10 μm for delicate samples. All elements were analysed by energy dispersion method using an TN 5500 ED system, using standards whose energy spectra had been previously stored on a computer. Elements determined, using a ZAF correction program, were Si, Ti, Al, Cr, Fe, Mg, Mn, Ca, Na, K, P, and Cl , although not all were analysed on every run. Prior to microprobe analyses, polished thin sections were cleaned with 1,1,1 trichloroethane and carbon coated.

Precision, based on multiple analyses on a mineral, was estimated using the equation : % Error (1σ) = 100*standard deviation / average, and are tabulated below, Table A1.

Table A1 - Calculated errors for elements per mineral.

		SiO2	TiO2	Al2O3	FeO	Fe2O3	MnO	MgO	CaO	Na2O	K2O	Cl	P2O5	Total
Plg	Avg.	63.09	-	22.55	-	-	-	-	4.82	8.89	0.34	-	-	99.59
	St.Dev	1.43	-	1.28	-	-	-	-	1.27	0.82	0.44	-	-	0.45
	Error	2.26	-	5.67	-	-	-	-	26.40	9.26	130.70	-	-	0.45
Amp 1	Avg.	54.73	0.22	1.78	6.70	-	dl	19.13	11.59	0.43	0.36	na	-	94.80
	St.Dev	0.69	0.11	0.38	0.61	-	dl	0.48	0.39	0.43	0.15	na	-	1.08
	Error	1.25	51.28	21.48	9.03	-	dl	2.51	3.33	99.72	41.07	na	-	1.14
Amp 2	Avg.	57.64	dl	0.43	7.54	-	dl	19.27	11.94	dl	0.24	na	-	96.95
	St.Dev	0.85	dl	0.58	0.68	-	dl	0.81	0.22	dl	0.22	na	-	0.66
	Error	1.47	dl	132.55	9.04	-	dl	4.21	1.86	dl	95.14	na	-	0.68
Cpx 1	Avg.	56.00	-	0.22	5.79	-	-	14.60	22.32	0.85	-	-	-	99.66
	St.Dev	0.41	-	0.15	0.52	-	-	0.26	0.47	0.23	-	-	-	0.51
	Error	0.74	-	69.64	8.94	-	-	1.79	2.10	27.40	-	-	-	0.51
Cpx 2	Avg.	54.68	-	0.34	11.64	-	-	11.59	19.56	2.11	-	-	-	99.92
	St.Dev	0.25	-	0.30	0.92	-	-	0.70	0.74	0.60	-	-	-	0.06
	Error	0.46	-	88.35	7.89	-	-	6.08	3.80	28.61	-	-	-	0.06
Scap 1	Avg.	52.51	-	23.71	-	-	-		12.13	6.33	0.79	1.44	-	99.73
	St.Dev	0.46	-	0.66	-	-	-	-	0.30	0.59	0.21	0.48	-	0.54
	Error	0.88	-	2.79	-	-	-	-	2.50	9.39	26.07	33.03	-	0.54
Scap 2	Avg.	58.66	-	21.06	-	-	-	-	5.32	10.83	1.07	3.35	-	100.45
	St.Dev	1.04	-	0.90	-	-	-	-	0.25	0.48	0.22	0.49	-	0.30
	Error	1.78	-	4.26	-	-	-	-	4.75	4.39	20.89	14.64	-	0.30
Kfs	Avg.	65.42	-	16.96	-	-	-	-	0.27	0.78	16.22	-	-	99.64
	St.Dev	0.46	-	0.58	-	-	-	-	0.19	0.58	0.63	-	-	0.30
	Error	0.70	-	3.40	-	-	-	-	70.95	74.39	3.88	-	-	0.30
Ep	Avg.	39.09	dl	26.10		9.68	-	-	22.25	-	-	-	-	97.11
	St.Dev	0.28	dl	1.15	-	1.21	-	-	0.28	-	-	-		0.37
	Error	0.70	dl	4.41	-	12.50	-	-	1.27	-	-	-	-	0.38
Ap	Avg.	-	-	-	-	-	-	-	54.45	-	-	0.36	39.42	95.68
	St.Dev	-	-	-	-	-	-	-	1.04	-	-	0.35	0.78	0.62
	Error	-	-	-	-	-	-	-	1.91	-	-	99.52	1.97	0.65
Prh	Avg.	45.16	-	23.87	-	0.57	-	0.20	25.06	dl	-	-	-	94.88
	St.Dev	0.30	-	0.59	-	0.33	-	0.05	0.31	dl	-	-		0.97
	Error	0.67	-	2.49	-	58.15	-	22.86	1.23	dl	-	-	-	1.03

In the data tables, values with a "<" indicate values below detection limits, "na" indicate no analysis done for that element.

The following minerals, in the Doherty Formation were analysed by microprobe: plagioclase (0 An% - 40 An%), amphibole (hornblende-actinolite-tremolite), clinopyroxene (diopside-augite), titanite, magnetite, scapolite (marialite-meionite),

K-feldspar (microcline, orthoclase), epidote, biotite, chlorite, calcite, prehnite, apatite.

Other minerals subjected to qualitative analysis or indentified by microprobe, but not tabulated are: corundum, rutile, allenite, monazite. From the Maronan Prospect, tourmaline, muscovite, garnets, Fe-Mn silicates (bustamite, pyroxmangite, knebelite, cummingtonite) and sulphides were also probed.

Sample numbering: DP# is the department number. The first number before the slash is the area on the thin section; the second number is the analyses number. For example 5\2, 5 is area on thin section, 2 is analysis number.

Analyses that were substandard (semiquantitative) are not presented in following tables. However, some of these analyses were still used in graphical form in the thesis. Sensible molar ratios justify this action.

Fe^{3+} CALCULATIONS

Fe^{3+} in Epidote / Titanite

Fe^{3+} in epidote and titanite is calculated. Fe_2O_3 wt.% is recalculated from FeO(t) wt.% (obtained by microprobe), by the following formula: Fe_2O_3 wt.% = $(MW_{(Fe_2O_3,159.69)}/MW_{(FeO,71.85)}/2)$ x FeO(t) wt.%, with MW is the molecular weight. Hence, Fe_2O_3 wt.% = 1.11x FeO(t) wt.%.

Fe^{3+} in Garnet

Fe^{3+} was determined from Al^{3+} deficiencies in the octahedral site ($Fe^{3+} = 2 - Al^{3+}$).

Fe^{3+} in Amphiboles

Recalculating of the amphiboles in this study, uses the 13eCNK method described by Stout (1973) and Robinson *et al.* (1982). The amphiboles analysed are calcic amphiboles according to Leake (1978) classification. The amphiboles were first calculated with all Fe as Fe^{2+}. Calculations are done as follow.

- The amphiboles were calculated on a water-free basis, for 23(O), because the halogen and water contents are uncertain.
- The 13CNK indicates that the total cations, exclusive K, Na and Ca are calculated for 13 cations, which is common in calcic amphiboles (Veblen and Ribbe 1982).
- Total Si+Al in the T-site is 8.
- The sum of the cations in the C-site is 5 using excess Al, Ti, (Fe^{3+}), Mn, Mg, Fe^{2+}.
- The sum of the cations in B-site is 2 using excess Fe^{2+}, Mn, Mg, Ca, Na.
- The A-site hosts all the K and excess Na.

Recalculations were done as follows:

(a) 13 cations /Σ[molecular proportions of the cations in the T- and C-sites]

(b) [charge (46/(a))-(2x(Σatomic proportion of oxygen from each molecule - Fe^{2+} cations)-(2x Fe^{2+} molecular proportion)].

The Fe^{3+} is calculated as (a)x(b), and Fe^{2+} is recalculated for the sum of 5 cations in the C-site.

Amphibole classification after Leake (1978)

The amphiboles are classified according to Leake's (1978) subdivision for calcic amphiboles. The subdivision is made on the following element distribution and conditions: Ti<0.50, $(Na+K)_A<0.50$, $(Ca+Na)_B \geq 1.34$, $N_B<0.67$. Further subdivision depends on Si and $Mg/(Fe^{2+}+Mg)$. Calculating all the iron as Fe^{2+} or in the above method has little implications on the Si and $Mg/(Mg+Fe^{2+})$ ratio. Calculating the amphibole $Mg/(Mg+Fe^{2+})$ ratios by the 15eK method would have significant implications on the classification.

Iron oxides

The Fe^{2+} and Fe^{3+} are recalculated from FeO(t), based on the spinel structure. There are two spinel structures, normal (N) and inverse (I). Normal spinel structures contain 1/8 of the tetrahedral sites with 2+ cations and 1/2 of the octahedral sites with 3+ cations. The inverse (I) spinel structure contains 1/8 of the tetrahedral sites with 3+ cations, 1/2 octahedral sites with 2+ cations and 1/2 of the octahedral sites with 3+ cations. Magnetite [$Fe^{2+}Fe_2^{3+}O_4$] and ulvöspinel [$Fe_2^{2+}TiO_4$] contain the inverse spinel structure, and forms a continuous solid solution at high temperatures (> 600°C). The $2Fe^{3+} \leftrightarrow Fe^{2+} + Ti^{4+}$ replacement occurs if Ti is present in magnetite. If there is no titanium present in magnetite than the R^{3+}/R^{2+} cation ratio is 2.2:1.

OTHER STOICHIOMETRY CALCULATIONS

The CO_2 was in carbonates recalculated from assuming C is 1 in the chemical formula. Another method to calculate CO_2 is:

$$CO_2 wt.\% = \sum wt.\%(FeO, MnO, MgO, CaO) / MW(FeO, MnO, MgO, CaO) \times MW(CO_2).$$

The CO_2 content in scapolite is calculated by assuming C+Cl = 1 and Si+Al =12.

Plagioclase "Pristine" Calc-silicate

	DP#44631					DP#44663				DP#44665		44666
	1\1	2\2	2\2	2\3	2\4	1\1	1\2	2\1	3\1	2\1	2\2	1\1
							dusted					
SiO2	65.73	64.53	61.65	61.42	62.63	64.09	69.21	69.79	68.46	68.27	59.89	69.89
Al2O3	20.94	21.40	23.71	23.70	23.07	22.22	19.00	18.17	19.65	19.87	25.46	18.61
CaO	3.10	3.68	5.97	6.13	5.24	4.25	1.07	<0.20	1.09	1.43	7.36	0.42
Na2O	9.65	9.37	8.41	8.28	8.69	8.98	10.71	11.70	10.10	10.20	6.97	10.44
K2O	<0.20	0.48	<0.20	<0.20	0.22	<0.20	<0.20	<0.20	0.26	<0.20	<0.20	0.20
Total	99.42	99.45	99.74	99.53	99.85	99.55	99.99	99.65	99.55	99.78	99.68	99.57
O(8)												
Si	2.90	2.86	2.74	2.73	2.78	2.83	3.01	3.04	2.99	2.98	2.67	3.05
Al	1.09	1.12	1.25	1.25	1.21	1.16	0.98	0.94	1.02	1.03	1.34	0.96
Ca	0.15	0.17	0.28	0.29	0.25	0.20	0.05	-	0.05	0.07	0.35	0.02
Na	0.82	0.81	0.72	0.71	0.75	0.77	0.90	0.99	0.86	0.86	0.60	0.88
K	-	0.03	-	-	0.01	-	-	-	0.01	-	-	0.01
% An	15.1	17.3	28.2	29.0	24.7	20.7	5.2	0.0	5.5	7.2	36.9	2.2
% Kf	0.0	2.7	0.0	0.0	1.3	0.0	0.0	0.0	1.6	0.0	0.0	1.2
% Ab	84.9	80.0	71.8	71.0	74.1	79.3	94.8	100.0	92.9	92.8	63.1	96.6

"Moderately altered" Calc-silicate

	DP#44654		DP#44652						DP#44657				
	5\1	4\4	2R\1	2R\2	2R\3	3CS\1	4CS\1	4CS\2	1V\1	3R\1	3R\2	4CS\1	4CS\2
SiO2	67.14	67.66	68.43	68.87	68.31	68.48	68.44	68.33	66.01	66.08	66.24	66.31	65.77
Al2O3	19.27	19.34	19.61	19.39	19.63	19.49	18.91	19.24	20.88	20.42	20.81	20.71	21.01
CaO	0.35	<0.20	1.08	1.26	1.16	0.73	0.89	0.88	2.77	2.53	2.41	2.83	2.71
Na2O	11.75	11.66	10.53	10.32	10.54	11.04	11.08	11.03	9.80	10.39	10.14	9.96	10.31
K2O	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0.22	<0.20	<0.20	<0.20	0.20	<0.20	0.21
Total	98.51	98.66	99.65	99.83	99.65	99.74	99.54	99.48	99.45	99.41	99.80	99.80	100.00
O(8)													
Si	2.98	2.99	2.99	3.00	2.99	2.99	3.00	3.00	2.91	2.92	2.91	2.91	2.89
Al	1.01	1.01	1.02	1.00	1.02	1.01	0.98	1.00	1.09	1.07	1.08	1.08	1.09
Ca	0.02	-	0.05	0.06	0.05	0.03	0.04	0.04	0.13	0.12	0.11	0.13	0.13
Na	1.01	1.00	0.89	0.87	0.89	0.94	0.94	0.94	0.84	0.89	0.86	0.85	0.88
K	-	-	-	-	-	-	0.01	-	-	-	0.01	-	0.01
% An	1.6	0.0	5.4	6.3	5.7	3.5	4.2	4.2	13.5	11.9	11.5	13.6	12.5
% Kf	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	1.1	0.0	1.1
% Ab	98.4	100.0	94.6	93.7	94.3	96.5	94.6	95.8	86.5	88.1	87.4	86.4	86.3

"Altered" Calc-silicate

	DP#44624			DP#44672		44672	DP#44585									DP#44586				
	2\3	3\1	4\1	3\1	3\1A	1\1A	1\0	1\1	1\2	1\3	1\4	2\1	3\1	3\2	4\1	4\2	1\1	1B\1	1B\2	1B\3	1B\4
SiO2	64.09	66.46	67.18	67.33	66.98	67.19	68.96	68.77	68.58	68.32	68.68	66.80	67.47	67.84	69.62	68.70	65.75	66.80	65.96	69.34	66.61
Al2O3	21.03	19.75	19.26	19.37	19.52	19.13	18.37	18.40	18.48	18.63	18.23	19.80	19.36	19.18	17.98	18.21	20.24	20.03	19.97	17.67	20.22
CaO	2.15	0.69	<0.20	<0.20	0.20	0.29	0.40	0.24	1.00	0.39	0.40	1.89	1.58	1.79	0.27	0.53	2.61	2.62	2.23	0.23	2.37
Na2O	10.94	11.22	11.69	11.88	10.69	11.72	12.04	11.91	11.48	12.09	11.93	11.07	10.98	11.18	11.84	12.23	10.58	10.50	10.98	12.51	10.40
K2O	<0.20	0.38	<0.20	<0.20	0.91	0.90	<0.20	0.50	<0.20	0.45	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0.31	<0.20	0.20	<0.20	<0.20
Total	98.21	98.50	98.13	98.58	98.30	99.23	99.77	99.82	99.54	99.88	99.23	99.56	99.39	100.00	99.70	99.68	99.49	99.95	99.33	99.75	99.60
O(8)																					
Si	2.87	2.96	2.99	2.98	2.97	2.97	3.02	3.02	3.01	3.00	3.02	2.94	2.97	2.97	3.04	3.02	2.91	2.93	2.92	3.04	2.93
Al	1.11	1.04	1.01	1.01	1.02	1.00	0.95	0.96	0.96	0.97	0.95	1.03	1.01	1.00	0.93	0.95	1.06	1.04	1.05	0.92	1.05
Ca	0.10	0.03	-	-	0.01	0.01	0.02	0.01	0.05	0.02	0.02	0.09	0.07	0.08	0.01	0.03	0.12	0.12	0.11	0.01	0.11
Na	0.95	0.97	1.01	1.02	0.92	1.00	1.02	1.01	0.98	1.03	1.02	0.95	0.94	0.95	1.00	1.04	0.91	0.89	0.94	1.06	0.89
K	-	0.02	-	-	0.05	0.05	-	0.03	-	0.03	-	-	-	-	-	-	0.02	-	0.01	-	-
% An	9.8	3.2	0.0	0.0	1.0	1.3	1.8	1.1	4.6	1.7	1.8	8.6	7.4	8.1	1.2	2.4	11.8	12.1	10.0	1.0	11.2
% Kf	0.0	2.1	0.0	0.0	5.3	4.7	0.0	2.7	0.0	2.4	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	1.1	0.0	0.0
% Ab	90.2	94.7	100.0	100.0	93.8	94.0	98.2	96.3	95.4	95.9	98.2	91.4	92.6	91.9	98.8	97.6	86.5	87.9	89.0	99.0	88.8

Plagioclase "Altered" Calc-silicate

	DP#44586			DP#44638				DP#44674						44681	DP#44681						DP#46306				
	2\1	3\1	3\2	3CS\1	5CS\1	2CS\1	2CS\2	1\1	2\1	4\1	4\2	5\1	5\2	1\1	1\2	2\1	3\1	4\1	5\1	6\1	1\1	2\1	2\2	4\1	4\2
SiO2	69.18	66.88	67.02	68.97	68.26	67.32	66.86	68.27	67.93	67.79	67.57	68.88	67.83	69.66	69.25	69.70	68.28	68.94	68.99	68.81	69.55	69.44	69.48	70.29	69.67
Al2O3	18.19	19.41	19.78	18.97	18.73	19.90	19.98	19.48	19.47	19.29	19.60	18.70	19.28	18.46	18.74	18.42	19.13	18.71	18.55	18.93	18.63	18.14	18.30	18.82	18.45
CaO	0.31	2.34	2.39	0.70	0.37	1.65	1.55	0.93	0.95	1.10	1.21	0.43	0.92	0.32	0.32	0.27	0.63	0.47	0.25	0.34	<0.20	<0.20	<0.20	<0.20	<0.20
Na2O	12.02	10.84	10.35	11.20	11.48	10.95	10.97	11.00	11.28	11.22	11.08	11.32	11.44	11.50	11.26	11.19	11.43	11.49	11.68	11.38	11.46	11.87	11.89	10.55	11.60
K2O	<0.20	<0.20	<0.20	<0.20	0.44	<0.20	<0.20	0.23	0.26	0.21	0.21	0.24	0.28	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Total	99.69	99.46	99.53	99.83	99.28	99.81	99.37	99.92	99.89	99.62	99.66	99.56	99.74	99.93	99.56	99.58	99.48	99.61	99.47	99.46	99.64	99.45	99.66	99.66	99.72
O(8)																									
Si	3.03	2.95	2.95	3.01	3.01	2.95	2.95	2.98	2.98	2.98	2.97	3.02	2.98	3.03	3.03	3.04	3.00	3.02	3.02	3.01	3.04	3.04	3.04	3.05	3.04
Al	0.94	1.02	1.03	0.98	0.98	1.03	1.04	1.01	1.01	1.00	1.02	0.97	1.00	0.95	0.97	0.95	0.99	0.97	0.96	0.98	0.96	0.94	0.95	0.97	0.95
Ca	0.01	0.11	0.11	0.03	0.02	0.08	0.07	0.04	0.04	0.05	0.06	0.02	0.04	0.01	0.01	0.01	0.03	0.02	0.01	0.02	-	-	-	-	-
Na	1.02	0.93	0.88	0.95	0.98	0.93	0.94	0.93	0.96	0.96	0.94	0.96	0.97	0.97	0.95	0.95	0.97	0.97	0.99	0.97	0.97	1.01	1.01	0.89	0.98
K	-	-	-	-	0.02	-	-	0.01	0.01	0.01	0.01	0.01	0.02	-	-	-	-	-	-	-	-	-	-	-	-
% An	1.4	10.7	11.3	3.3	1.7	7.7	7.2	4.4	4.4	5.1	5.6	2.0	4.2	1.5	1.5	1.3	3.0	2.2	1.2	1.6	0.0	0.0	0.0	0.0	0.0
% Kf	0.0	0.0	0.0	0.0	2.4	0.0	0.0	1.3	1.4	1.2	1.1	1.3	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Ab	98.6	89.3	88.7	96.7	95.9	92.3	92.8	94.3	94.2	93.7	93.2	96.7	94.3	98.5	98.5	98.7	97.0	97.8	98.8	98.4	100.0	100.0	100.0	100.0	100.0

	DP#46311			46312	DP#46308								
	4\3	1\1	3\1	5\1	2\1	1	2\1	3\1	3\2	4\1	AB1	1\1	1\2
								dusted	dusted	dusted			
SiO2	70.21	69.47	69.23	69.50	70.10	69.94	70.25	68.29	69.97	69.40	65.17	68.84	69.52
Al2O3	18.81	18.35	19.01	18.35	18.37	18.35	18.31	19.67	18.48	18.17	20.48	18.24	18.77
CaO	<0.20	<0.20	0.50	<0.20	<0.20	0.34	<0.20	1.67	<0.20	0.35	3.10	0.44	0.55
Na2O	10.96	11.69	11.24	11.71	11.15	11.10	11.16	10.02	11.05	11.80	10.24	10.69	10.94
K2O	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0.29	<0.20	<0.20	1.72	<0.20
Total	99.97	99.50	99.97	99.56	99.62	99.73	99.72	99.65	99.79	99.72	98.99	99.92	99.79
O(8)													
Si	3.04	3.04	3.02	3.04	3.05	3.05	3.06	2.98	3.05	3.04	2.90	3.03	3.03
Al	0.97	0.95	0.98	0.95	0.95	0.95	0.94	1.02	0.95	0.94	1.08	0.95	0.97
Ca	-	-	0.02	-	-	0.02	-	0.08	-	0.02	0.15	0.02	0.03
Na	0.92	0.99	0.95	0.99	0.94	0.94	0.94	0.85	0.93	1.00	0.88	0.91	0.92
K	-	-	-	-	-	-	-	-	0.02	-	-	0.10	-
% An	0.0	0.0	2.4	0.0	0.0	1.7	0.0	8.4	0.0	1.6	14.3	2.0	2.7
% Kf	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	9.4	0.0
% Ab	100.0	100.0	97.6	100.0	100.0	98.3	100.0	91.6	98.3	98.4	85.7	88.6	97.3

"Altered" Schist

	DP#46323									DP#46328	
	1\3	2\1	2\2	3\2	4\1	5\1	1\1	1\2
SiO2	69.84	67.96	69.37	69.93	69.31	70.81	68.22	67.52
Al2O3	18.65	18.75	17.99	18.55	18.45	18.21	19.62	19.87
CaO	0.31	0.96	<0.20	<0.20	0.26	0.75	1.30	1.56
Na2O	11.01	10.93	12.35	11.11	11.53	10.62	10.39	10.73
K2O	<0.20	1.05	<0.20	0.47	0.37	<0.20	0.23	<0.20
Total	99.81	99.65	99.70	100.10	99.91	100.39	99.75	99.68
O(8)								
Si	3.04	2.99	3.04	3.04	3.03	3.06	2.98	2.96
Al	0.96	0.98	0.93	0.96	0.96	0.93	1.02	1.03
Ca	0.01	0.05	-	-	0.01	0.03	0.06	0.07
Na	0.93	0.93	1.05	0.94	0.98	0.89	0.88	0.91
K	-	0.06	-	0.03	0.02	-	0.01	-
% An	1.5	4.4	0.0	0.0	1.2	3.8	6.4	7.5
% Kf	0.0	5.7	0.0	2.7	2.0	0.0	1.3	0.0
% Ab	98.5	90.0	100.0	97.3	96.8	96.2	92.3	92.5

Plagioclase "Altered" Schist					Vein jog breccia (Vjb)										"Breccia" pseudo-igneous texture																															
	DP#46328				DP#44590					DP#44638					DP#46324										DP#46325		DP#44635		46326	DP#46326				DP#46313			DP#46313			DP#46315					DP#46317		
	2\1	2\2	2\3	2\4	1\1	1\2	1\3	1\4	2\1	1BX\1	1BX\2	1BX\3	4BX\1	4BX\2	1\1	1\2	2C\1	2C\2	2M\3	2M\4	2R\5	3\1	3\2	1\1	3\1	4\1	5\1	1\1	2\1	3\1	3\2	3\3	2\1	2\2	2\3	4\1	3\1	4\2	1\1	3\1	3\2	4\1	6\1	1\1	2\1	4\1
			rim																																												
SiO2	67.04	66.86	67.50	69.66	68.41	66.39	68.22	67.96	68.38	67.27	67.00	67.35	69.42	68.95	69.45	69.96	68.94	69.68	69.32	68.27	69.45	69.16	68.98	69.87	69.80	69.71	69.14	69.77	69.15	68.93	69.23	69.63	70.99	69.88	70.00	69.80	70.11	69.93	69.49	70.07	69.20	69.52	69.97	69.76	70.18	69.99
Al2O3	20.43	20.21	19.73	18.42	18.94	19.55	19.09	18.88	18.73	20.04	20.12	19.80	18.29	18.46	18.14	18.14	18.86	18.51	18.46	19.43	18.35	18.49	18.88	18.40	18.30	18.21	18.82	18.97	18.41	19.18	18.70	18.61	17.26	18.60	18.26	18.25	18.29	18.55	18.60	18.33	18.34	18.48	18.17	18.49	18.62	18.29
CaO	2.08	1.93	1.28	0.24	1.22	1.85	1.43	1.49	1.29	1.70	1.70	1.66	0.26	0.52	<0.20	<0.20	0.65	<0.20	<0.20	0.93	<0.20	<0.20	<0.20	0.24	<0.20	<0.20	0.54	<0.20	0.31	0.40	0.36	0.23	0.75	<0.20	<0.20	0.40	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Na2O	10.15	10.46	11.09	10.84	11.11	11.14	10.92	11.37	11.08	10.80	10.68	11.12	11.72	11.64	12.08	11.54	11.12	11.66	11.27	10.97	11.49	11.91	11.71	11.36	11.82	11.85	11.34	10.92	11.97	11.24	11.33	11.31	10.14	11.21	11.52	11.31	11.54	11.39	11.53	11.29	12.25	10.11	11.42	11.56	10.82	11.46
K2O	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0.28	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0.24	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	1.70	<0.20	<0.20	<0.20	<0.20
Total	99.71	99.46	99.60	99.15	99.68	98.92	99.66	99.69	99.76	99.81	99.50	99.93	99.70	99.57	99.66	99.64	99.57	99.85	99.05	99.61	99.28	99.56	99.58	99.87	99.92	99.77	99.84	99.90	99.84	99.75	99.61	99.78	99.13	99.70	99.78	99.76	99.95	99.87	99.63	99.69	99.79	99.82	99.56	99.81	99.62	99.74
O(8)																																														
Si	2.94	2.94	2.96	3.05	3.00	2.95	2.99	2.98	3.00	2.95	2.95	2.95	3.03	3.02	3.04	3.05	3.02	3.04	3.04	2.99	3.04	3.03	3.02	3.04	3.04	3.04	3.02	3.03	3.02	3.01	3.03	3.03	3.10	3.04	3.05	3.04	3.05	3.04	3.03	3.05	3.03	3.04	3.05	3.04	3.05	3.05
Al	1.06	1.05	1.03	0.96	0.98	1.03	0.99	0.98	0.97	1.04	1.05	1.03	0.95	0.96	0.94	0.94	0.98	0.96	0.96	1.01	0.95	0.96	0.98	0.95	0.95	0.94	0.97	0.98	0.95	0.99	0.97	0.96	0.89	0.96	0.94	0.94	0.94	0.96	0.96	0.95	0.95	0.95	0.94	0.95	0.96	0.94
Ca	0.10	0.09	0.06	0.01	0.06	0.09	0.07	0.07	0.06	0.08	0.08	0.08	0.01	0.02	-	-	0.03	-	-	0.04	-	-	-	0.01	-	-	0.03	-	0.01	0.02	0.02	0.01	0.04	-	-	0.02	-	-	-	-	-	-	-	-	-	-
Na	0.86	0.89	0.94	0.92	0.94	0.96	0.93	0.97	0.94	0.92	0.91	0.95	0.99	0.99	1.02	0.98	0.94	0.99	0.96	0.93	0.98	1.01	0.99	0.96	1.00	1.00	0.96	0.92	1.02	0.95	0.96	0.96	0.86	0.95	0.97	0.96	0.97	0.96	0.98	0.95	1.04	0.86	0.97	0.98	0.91	0.97
K	-	-	-	-	-	-	-	-	0.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	0.09	-	-	-	-
% An	10.2	9.3	6.0	1.2	5.7	8.4	6.8	6.7	6.0	8.0	8.1	7.6	1.2	2.4	0.0	0.0	3.1	0.0	0.0	4.5	0.0	0.0	0.0	1.2	0.0	0.0	2.6	0.0	1.4	1.9	1.7	1.1	3.9	0.0	0.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Kf	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.9	0.0	0.0	0.0	0.0
% Ab	89.8	90.7	94.0	98.8	94.3	91.6	93.2	93.3	92.5	92.0	91.9	92.4	98.8	97.6	100.0	100.0	96.9	100.0	100.0	95.5	100.0	100.0	100.0	98.8	100.0	100.0	97.4	98.6	98.6	98.1	98.3	98.9	96.1	100.0	100.0	98.1	100.0	100.0	100.0	100.0	100.0	90.1	100.0	100.0	100.0	100.0

Plagioclase "Breccia" pseudo-igneous texture														"Pristine" Metadolerite											"Altered" Metadolerite																
	DP#46316					DP#46307							46307	DP#46335				DP#46334							DP#46332						DP#46313			46305	DP#44598				DP#44625	
	1\1	3\1	4\1	5\1	6\1	1\1	1\2	2\1	3\1	3\2	4\1	5\1	6\1	1\1	2\1	4\1	5\1	1\1	1\2	2\1	2\2	3\1	3\2	3\3	1\1	1\2	1\3	2\1	5\1	5\2	2\1	3\1	4\1	1\1	1\1	1\2	1\3	1\4	3\1	3\2
													dusted												Ms	Ms														
SiO2	69.86	70.00	69.85	70.09	69.80	69.84	69.81	70.22	69.97	70.90	69.12	69.18	68.49	67.86	66.92	66.94	67.70	66.89	66.54	66.31	66.21	65.86	68.95	66.02	69.31	67.65	69.06	69.77	61.43	67.89	69.99	70.09	69.01	64.00	61.84	60.98	61.06	62.49	61.11	60.39
Al2O3	18.38	18.61	18.26	18.51	18.33	18.43	17.94	18.26	18.04	18.02	18.78	18.76	19.44	19.63	19.97	19.99	20.16	20.20	20.40	20.82	20.54	21.05	19.51	20.68	19.21	19.46	19.46	18.75	26.39	20.09	18.53	18.68	18.89	24.03	23.36	23.98	24.21	23.64	24.08	24.01
CaO	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0.39	0.63	0.87	1.96	1.63	1.89	1.80	2.37	2.25	2.76	2.56	3.22	0.38	2.76	<0.20	0.35	0.55	<0.20	0.62	0.93	0.20	<0.20	0.37	<0.20	6.27	6.73	6.28	6.12	7.26	6.89
Na2O	11.35	11.16	11.60	11.06	11.76	11.46	11.52	11.36	11.81	10.94	11.44	11.21	10.91	10.15	11.02	10.48	10.17	10.12	10.50	9.69	10.20	9.18	10.44	10.19	10.89	10.64	10.45	11.21	5.46	10.47	10.82	11.01	11.48	11.45	8.06	7.56	7.67	7.69	7.18	7.71
K2O	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0.26	<0.20	0.28	<0.20	<0.20	0.24	0.27	0.22	0.38	0.31	<0.20	0.35	1.24	<0.20	<0.20	5.17	0.81	<0.20	<0.20	<0.20	<0.20	<0.20	0.32	0.22	0.24	<0.20	0.25
Total	99.59	99.77	99.71	99.67	99.88	99.73	99.27	99.85	99.82	99.87	99.73	99.78	99.71	99.85	99.54	99.59	99.83	99.58	99.93	99.85	99.72	99.69	99.58	99.65	99.76	99.34	99.52	99.73	99.08	100.19	99.54	99.78	99.75	99.48	99.53	99.56	99.44	100.17	99.64	99.26
O(8)																																								
Si	3.04	3.04	3.05	3.05	3.04	3.04	3.06	3.05	3.05	3.08	3.02	3.02	2.99	2.97	2.94	2.95	2.96	2.94	2.92	2.91	2.92	2.90	3.01	2.91	3.02	2.98	3.01	3.04	2.74	2.97	3.05	3.04	3.01	2.82	2.75	2.72	2.72	2.76	2.72	2.71
Al	0.95	0.96	0.94	0.95	0.95	0.95	0.93	0.94	0.93	0.93	0.97	0.97	1.01	1.02	1.04	1.04	1.04	1.05	1.06	1.08	1.07	1.10	1.01	1.08	0.99	1.02	1.01	0.97	1.40	1.04	0.96	0.96	0.98	1.25	1.23	1.27	1.28	1.24	1.27	1.28
Ca	-	-	-	-	-	-	-	-	-	-	0.02	0.03	0.04	0.09	0.08	0.09	0.08	0.11	0.11	0.13	0.12	0.15	0.02	0.13	-	0.02	0.03	-	0.03	0.04	0.01	-	0.02	-	0.30	0.32	0.30	0.29	0.35	0.33
Na	0.96	0.94	0.98	0.93	0.99	0.97	0.98	0.96	1.00	0.92	0.97	0.95	0.92	0.86	0.94	0.89	0.86	0.86	0.89	0.83	0.87	0.78	0.88	0.87	0.92	0.91	0.88	0.95	0.47	0.89	0.91	0.93	0.97	0.98	0.70	0.65	0.66	0.66	0.62	0.67
K	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01	-	0.02	-	-	0.01	0.02	0.01	0.02	0.02	-	0.02	0.07	-	-	0.29	0.05	-	-	-	-	-	0.02	0.01	0.01	-	0.01
% An	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	3.0	4.2	9.5	7.5	8.9	8.9	11.5	10.4	13.4	12.1	15.9	1.9	13.0	0.0	1.6	2.8	0.0	3.7	4.4	1.0	0.0	1.7	0.0	30.1	32.4	30.8	30.1	35.8	32.6
% Kf	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	1.6	0.0	0.0	1.3	1.6	1.2	2.2	1.8	0.0	2.1	7.0	0.0	0.0	37.0	4.6	0.0	0.0	0.0	0.0	0.0	1.8	1.3	1.4	0.0	1.4
% Ab	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	98.2	97.0	95.8	89.0	92.5	89.5	91.1	88.5	88.2	85.1	86.7	81.9	96.2	87.0	97.9	91.4	97.2	100.0	59.3	90.9	99.0	100.0	98.3	100.0	69.9	65.8	68.0	68.5	64.2	66.0

Amphiboles	"Pristine" Calc-silicate																											"Moderately altered" Calc-silicate															
	DP#44629		DP#44602		DP#44628			DP#44618					DP#44627								44631		DP#44665		DP#44666			DP#44624					DP#44654									
	1\2	2\1	1\3	3\1	1\3	2\2	2\4	6\1	6\2	6\3	6\4	1\1	1\1	1\2	1\3	1\4	2\1	2\2	3\1	3\2	3\1	5\1	3\1	4\1	1\1	2\1	2\2	1\1	1\2	2\1	2\2	4\1	5\A	5\B	4\1	4\2	4\3	4\4	4\5	4\6	4\7	4\8
SiO 2	45.28	44.23	50.39	50.47	46.37	49.60	45.08	46.42	47.54	48.03	49.13	54.39	48.15	49.09	47.56	48.12	47.12	47.42	49.11	47.81	46.50	51.24	55.52	48.79	51.72	52.27	51.15	50.16	51.22	52.27	53.17	53.97	53.31	54.60	54.88	53.34	54.76	53.93	53.97	55.48	55.11	56.31
TiO 2	0.47	0.56	0.63	0.27	0.41	0.25	0.57	0.46	0.32	0.27	<0.20	<0.20	0.44	0.44	0.49	0.48	0.51	0.56	0.49	0.40	0.68	0.42	<0.20	0.40	0.30	<0.20	0.40	0.30	<0.20	0.25	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Al 2 O 3	8.63	8.94	3.61	3.94	7.87	6.66	8.34	8.07	6.63	7.47	5.89	1.25	8.56	7.61	8.11	8.61	8.54	9.07	8.26	8.68	9.02	5.98	1.99	8.66	5.85	5.60	6.58	4.90	4.32	3.59	2.72	3.39	2.00	1.66	0.50	1.82	2.17	2.50	2.49	0.51	0.60	0.35
FeO(t)	11.05	11.31	11.13	11.05	10.69	9.37	11.59	10.33	9.14	9.26	9.01	7.58	12.30	11.32	11.83	11.59	11.73	12.01	11.00	11.63	15.68	10.99	9.07	10.43	10.27	10.86	10.16	6.56	6.29	5.72	5.66	5.95	7.50	6.66	7.10	8.71	7.08	6.98	7.35	6.82	9.47	5.93
MnO	0.33	<0.20	<0.20	<0.20	0.21	0.43	0.40	0.22	0.23	0.43	0.20	<0.20	0.43	0.36	0.42	0.30	0.42	0.24	0.39	0.30	0.30	<0.20	<0.20	<0.20	0.25	0.24	<0.20	0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0.25	<0.20	<0.20	0.20	0.24	<0.20	<0.20	0.35
MgO	14.54	14.36	16.27	15.86	14.94	17.08	14.68	16.09	16.34	16.49	17.06	18.92	15.14	15.67	14.92	15.01	14.65	14.77	15.44	15.25	12.23	16.60	17.78	17.46	16.73	16.17	16.48	18.79	19.04	19.55	20.01	19.91	18.58	19.73	18.67	17.64	19.42	18.88	18.75	20.12	18.31	20.25
CaO	11.91	12.04	11.15	11.75	12.31	12.11	12.36	12.27	12.42	12.32	12.80	12.91	11.62	11.71	11.81	11.79	11.55	11.56	11.63	11.72	11.49	11.50	11.92	10.64	12.15	12.12	12.07	12.38	12.41	12.05	12.19	12.61	12.90	13.38	12.54	12.40	12.95	12.47	12.56	13.33	13.01	13.03
Na 2 O	1.24	1.74	1.97	1.42	1.15	1.16	1.35	1.47	1.08	0.94	1.07	<0.30	1.13	0.78	0.78	1.01	0.75	1.07	0.74	0.70	1.47	1.15	<0.30	1.31	0.36	0.73	1.01	1.36	1.13	0.89	0.96	0.99	<0.30	<0.30	<0.30	0.66	0.88	0.73	0.76	0.35	0.34	0.37
K 2 O	1.05	0.90	0.59	0.44	0.67	0.45	0.88	0.86	0.65	0.56	0.59	<0.20	1.14	0.83	1.15	1.06	1.00	1.20	0.87	1.12	1.39	0.70	0.25	0.83	0.58	0.35	0.69	0.54	0.43	0.30	0.27	0.25	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Cl	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
O=Cl																																										
Total	94.50	94.07	95.75	95.20	94.62	97.11	95.25	96.19	94.35	95.77	95.75	95.05	98.90	97.79	97.06	97.98	96.25	97.89	97.93	97.61	98.77	98.56	96.52	98.52	98.21	98.33	98.53	95.19	94.84	94.62	94.98	97.07	94.29	96.03	93.94	94.57	97.26	95.69	96.12	96.61	96.84	96.59
O(23)																																										
Si (T)	6.84	6.72	7.43	7.45	6.95	7.16	6.78	6.86	7.09	7.04	7.19	7.82	6.94	7.09	6.98	6.97	6.96	6.89	7.06	6.94	6.85	7.29	7.89	6.95	7.35	7.43	7.25	7.29	7.42	7.54	7.64	7.59	7.75	7.77	7.97	7.78	7.72	7.72	7.71	7.86	7.88	7.94
Al(T)	1.16	1.28	0.57	0.55	1.05	0.84	1.22	1.14	0.91	0.96	0.81	0.18	1.06	0.91	1.02	1.03	1.04	1.11	0.94	1.06	1.15	0.71	0.11	1.05	0.65	0.57	0.75	0.71	0.58	0.46	0.36	0.41	0.25	0.23	0.03	0.22	0.28	0.28	0.29	0.14	0.12	0.06
Al(C)	0.37	0.32	0.06	0.14	0.34	0.29	0.26	0.26	0.25	0.34	0.21	0.03	0.39	0.38	0.38	0.44	0.44	0.45	0.46	0.43	0.41	0.29	0.22	0.40	0.33	0.37	0.36	0.13	0.16	0.00	0.10	0.16	0.10	0.04	0.06	0.09	0.09	0.15	0.13	0.00	0.00	0.00
Ti(C)	0.05	0.06	0.07	0.03	0.05	0.03	0.06	0.05	0.04	0.03	-	-	0.05	0.05	0.05	0.05	0.06	0.06	0.05	0.04	0.08	0.04	-	0.04	0.03	-	0.04	0.03	-	0.03	-	-	-	-	-	-	-	-	-	-	-	-
Fe 3+(C)	0.47	0.38	0.29	0.20	0.34	0.61	0.48	0.55	0.32	0.55	0.25	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.22	0.36	0.32	0.17	0.20	0.07	0.07	0.04	0.06	0.13	0.11	0.09	0.07	0.00
Mg(C)	3.27	3.25	3.58	3.49	3.34	3.67	3.29	3.54	3.63	3.60	3.72	4.05	3.25	3.37	3.26	3.24	3.22	3.20	3.31	3.30	2.68	3.52	3.76	3.71	3.54	3.43	3.48	4.07	4.11	4.20	4.29	4.17	4.03	4.18	4.04	3.84	4.08	4.03	3.99	4.25	3.90	4.26
Fe(C)	1.30	1.35	1.29	1.31	1.27	1.01	1.37	1.15	1.08	1.03	1.06	0.89	1.31	1.19	1.31	1.27	1.28	1.28	1.16	1.21	1.83	1.14	0.99	0.85	1.08	1.20	1.10	0.74	0.70	0.60	0.61	0.65	0.88	0.77	0.86	1.05	0.83	0.82	0.88	0.81	1.11	0.70
Mn(C)	0.00	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-	0.00	0.00	-	0.00	-	-	-	-	-	-	0.01	-	-	0.00	0.00	-	-	0.04
Mg (B)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe(B)	0.09	0.09	0.08	0.06	0.07	0.12	0.09	0.13	0.06	0.11	0.05	0.02	0.18	0.18	0.14	0.14	0.17	0.18	0.16	0.20	0.10	0.17	0.09	0.39	0.14	0.09	0.10	0.05	0.06	0.09	0.07	0.05	0.03	0.02	0.00	0.01	0.00	0.01	0.00	0.00	0.02	0.00
Mn (B)	0.04	-	-	-	0.03	0.05	0.05	0.03	0.03	0.05	0.02	-	0.05	0.04	0.05	0.04	0.05	0.03	0.05	0.04	0.04	-	-	-	0.03	0.03	-	0.02	-	-	-	-	-	-	0.02	-	-	0.02	0.03	-	-	0.00
Ca(B)	1.93	1.96	1.76	1.86	1.98	1.87	1.99	1.94	1.98	1.94	2.01	1.99	1.79	1.81	1.86	1.83	1.83	1.80	1.79	1.82	1.81	1.75	1.81	1.62	1.85	1.85	1.83	1.93	1.93	1.86	1.88	1.90	2.01	2.04	1.95	1.94	1.96	1.91	1.92	2.02	1.99	1.97
Na(B)	0.00	0.00	0.16	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.06	-	0.00	0.00	0.03	0.06	0.00	0.01	0.03	0.03	0.05	-	-	-	0.05	0.03	0.05	0.04	0.00	0.00	0.03
Na(A)	0.36	0.51	0.41	0.32	0.33	0.32	0.39	0.42	0.31	0.27	0.30	-	0.32	0.22	0.22	0.28	0.21	0.30	0.20	0.20	0.37	0.26	-	0.36	0.10	0.17	0.22	0.38	0.30	0.22	0.24	0.22	-	-	-	0.14	0.22	0.15	0.17	0.10	0.09	0.07
K(A)	0.20	0.17	0.11	0.08	0.13	0.08	0.17	0.16	0.12	0.10	0.11	-	0.21	0.15	0.21	0.19	0.18	0.22	0.16	0.20	0.26	0.12	0.04	0.15	0.10	0.06	0.12	0.10	0.08	0.05	0.05	0.04	-	-	-	-	-	-	-	-	-	-
Cl																																										
[Ca + Na] B	1.93	1.96	1.92	1.94	1.98	1.87	1.99	1.94	1.98	1.94	2.01	1.99	1.79	1.81	1.86	1.83	1.83	1.80	1.79	1.82	1.86	1.81	1.81	1.62	1.85	1.88	1.89	1.93	1.94	1.90	1.91	1.95	2.01	2.04	1.95	1.99	1.98	1.96	1.97	2.02	1.99	2.00
[Na + K] A	0.56	0.68	0.52	0.40	0.46	0.41	0.56	0.58	0.44	0.37	0.41	0.00	0.52	0.37	0.43	0.48	0.40	0.52	0.36	0.40	0.63	0.38	0.04	0.51	0.20	0.23	0.34	0.48	0.38	0.27	0.28	0.26	0.00	0.00	0.00	0.14	0.22	0.15	0.17	0.10	0.09	0.07
Fe3+/Fe3++Fe2+	0.3	0.2	0.2	0.1	0.2	0.3	0.2	0.3	0.2	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.2	0.3	0.3	0.2	0.2	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.0
Fe3+/(Fe3++Alvi)	0.6	0.5	0.8	0.6	0.5	0.7	0.7	0.7	0.6	0.6	0.5	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.6	1.0	0.8	0.5	0.7	0.6	0.5	0.3	0.4	0.5	0.5	1.0	1.0	0.0
Mg/(Mg +Fe2+)	0.7	0.7	0.7	0.7	0.7	0.8	0.7	0.7	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.7	0.8	0.7	0.7	0.7	0.7	0.8	0.8	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9
Mg/(Mg+ FeT)	1.8	1.8	2.2	2.2	2.0	2.1	1.7	1.9	2.5	2.1	2.7	3.9	2.2	2.5	2.2	2.3	2.2	2.2	2.5	2.3	1.4	2.7	3.5	3.0	2.9	2.7	2.9	3.8	4.2	4.0	4.3	4.8	3.6	4.9	4.3	3.5	4.6	4.2	4.0	4.7	3.2	6.1
Si	6.84	6.72	7.43	7.45	6.95	7.16	6.78	6.86	7.09	7.04	7.19	7.82	6.94	7.09	6.98	6.97	6.96	6.89	7.06	6.94	6.85	7.29	7.89	6.95	7.35	7.43	7.25	7.29	7.42	7.54	7.64	7.59	7.75	7.77	7.97	7.78	7.72	7.72	7.71	7.86	7.88	7.94

Amphiboles	"Moderately altered" Calc-silicate									
	DP#44654					DP#44652				
	3\2	3\3	2\1	2\2	2\3	1V\1	1V\2	1V\4	3R\2	4\2
SiO 2	52.65	49.90	49.83	49.99	49.98	55.89	56.73	56.13	56.88	56.21
TiO 2	<0.20	0.26	0.25	<0.20	<0.20	<0.20	0.33	0.23	0.23	0.36
Al 2 O 3	3.88	5.04	5.35	5.36	5.35	2.74	2.02	2.80	1.73	2.60
FeO(t)	7.00	8.83	8.05	8.48	8.47	6.68	5.45	6.31	5.52	5.95
MnO	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
MgO	19.12	17.21	17.93	17.60	17.60	20.37	20.72	19.87	20.80	19.63
CaO	12.24	11.86	11.82	11.98	11.98	11.58	11.46	11.32	11.56	11.34
Na 2 O	1.09	1.58	1.45	1.54	1.54	1.03	1.21	1.60	1.13	1.87
K 2 O	0.42	0.57	0.69	0.62	0.62	0.47	0.42	0.39	0.37	0.42
Cl	na	na	na	na	na	na	na	na	na	na
O=Cl										
Total	96.40	95.25	95.37	95.57	95.54	98.76	98.32	98.65	98.22	98.38
O(23)										
Si (T)	7.50	7.32	7.27	7.29	7.29	7.73	7.83	7.76	7.86	7.79
Al(T)	0.50	0.68	0.73	0.71	0.71	0.27	0.17	0.24	0.14	0.21
Al(C)	0.15	0.19	0.19	0.21	0.21	0.18	0.16	0.22	0.14	0.21
Ti(C)	-	0.03	0.03	-	-	-	0.03	0.02	0.02	0.04
Fe 3+(C)	0.34	0.25	0.41	0.30	0.30	0.52	0.28	0.22	0.29	0.00
Mg(C)	4.06	3.76	3.90	3.82	3.83	4.20	4.26	4.09	4.28	4.05
Fe(C)	0.76	1.01	0.87	0.95	0.95	0.62	0.55	0.67	0.56	0.69
Mn(C)	-	-	-	-	-	-	-	-	-	-
Mg (B)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe(B)	0.08	0.07	0.12	0.09	0.09	0.15	0.08	0.06	0.08	0.00
Mn (B)	-	-	-	-	-	-	-	-	-	-
Ca(B)	1.87	1.86	1.85	1.87	1.87	1.72	1.69	1.68	1.71	1.68
Na(B)	0.04	0.07	0.04	0.04	0.04	0.13	0.22	0.26	0.21	0.32
Na(A)	0.26	0.38	0.37	0.39	0.39	0.14	0.10	0.17	0.10	0.19
K(A)	0.08	0.11	0.13	0.11	0.11	0.08	0.07	0.07	0.07	0.07
Cl										
[Ca + Na] B	1.90	1.93	1.88	1.91	1.91	1.85	1.92	1.94	1.92	2.00
[Na + K] A	0.34	0.49	0.50	0.51	0.51	0.22	0.17	0.24	0.16	0.26
Fe3+/Fe3++Fe2+	0.3	0.2	0.3	0.2	0.2	0.4	0.3	0.2	0.3	0.0
Fe3+/(Fe3++Alvi)	0.7	0.6	0.7	0.6	0.6	0.7	0.6	0.5	0.7	0.0
Mg/(Mg +Fe2+)	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.8	0.9	0.9
Mg/(Mg+ FeT)	3.5	2.8	2.8	2.9	2.9	3.2	4.7	4.3	4.6	5.9
Si	7.50	7.32	7.27	7.29	7.29	7.73	7.83	7.76	7.86	7.79

| Amphiboles | "Altered" Calc-silicate | | | | | | | | | |

Amphiboles		"Breccia" pseudo-igneous texture																																															
	44606	DP#46310				DP#46312			46315	46317	46316	DP#46307																																			
	3\1	2\2	2\3	7\1	1\4	7\1	7\2	1\1	3\2	3\2	1\1	1\2	1\3	1\3	1\5	2\1	3\1	5\1	5\2	6\1	6\2	7\1	1\2	1\3	1\6	1\7	3\1	2\1	2\1	2\2	2\4	2\5	2\6	1\1	JR	3\1	3\3	5\1	5\2	5\3	2\1	2\4
		lath	lath	lath	core	lath	lath		lath									clear	clear	clear	clear	clear													Jacky							
SiO 2	53.20	55.07	56.57	56.33	55.14	57.59	57.99	58.94	54.20	57.56	57.66	58.56	58.15	57.13	58.51	58.25	55.75	56.06	56.72	56.52	55.76	56.04	55.39	55.62	55.07	56.77	55.52	58.36	56.77	55.91	57.64	55.77	56.09	52.73	41.69	53.63	50.75	52.18	52.54	45.77	43.75	43.96
TiO 2	<0.20	<0.20	<0.20	<0.20	0.52	<0.20	0.33	<0.20	<0.20	<0.20	0.22	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0.54	0.34	0.30	0.51	0.43	0.32	0.32	0.24	<0.20	0.34	<0.20	<0.20	<0.20	<0.20	<0.20	0.34	<0.20	1.58	<0.20	<0.20	0.44	0.27	0.74	1.07	0.82
Al 2 O 3	1.07	0.63	0.41	1.48	2.67	0.30	1.08	0.41	1.28	0.72	0.27	0.50	0.20	0.67	0.36	<0.20	1.06	1.98	1.60	2.29	1.87	2.27	2.87	2.62	3.33	1.94	3.06	<0.20	1.21	1.05	1.54	1.07	0.98	4.57	10.90	3.91	6.59	5.75	5.31	9.26	10.46	10.24
FeO(t)	8.98	10.73	15.05	11.69	9.39	12.27	11.00	6.93	11.15	10.68	7.26	7.74	7.21	7.87	7.71	9.23	14.10	8.10	7.75	9.30	8.34	8.76	7.66	7.98	8.00	7.49	8.25	9.39	7.94	7.12	8.36	7.35	6.82	12.65	14.91	7.61	9.56	8.81	7.87	10.86	17.82	18.66
MnO	<0.20	<0.20	<0.20	0.34	<0.20	0.27	0.42	<0.20	0.42	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0.42	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0.28	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0.21	0.22	<0.20	<0.20	0.62	0.69	0.52	0.85	0.35	<0.20	<0.20
MgO	17.25	15.95	14.52	17.60	18.19	16.40	18.85	20.05	21.01	17.42	19.32	19.21	19.73	18.80	19.17	18.04	15.19	18.54	19.48	18.07	18.87	18.47	18.61	18.92	18.85	19.61	18.84	18.26	19.65	19.19	19.28	19.05	19.63	15.18	12.75	18.39	17.22	17.42	17.77	14.77	9.24	9.93
CaO	11.97	12.87	11.68	9.78	10.50	11.23	8.24	11.87	7.80	12.02	11.57	11.81	11.97	11.90	12.01	12.57	12.04	10.79	10.79	10.78	10.55	11.05	11.36	11.44	11.27	11.42	11.42	12.71	11.74	11.59	11.67	11.32	11.41	11.88	10.45	11.54	12.07	11.66	11.83	11.62	11.30	11.17
Na 2 O	0.85	0.91	0.57	0.53	1.69	0.77	0.74	0.61	<0.30	0.38	<0.30	<0.30	<0.30	<0.30	<0.30	<0.30	<0.30	1.11	1.04	1.15	0.77	1.09	1.50	1.33	1.42	1.14	0.91	<0.30	0.35	0.75	<0.30	<0.30	0.58	1.14	3.91	<0.30	0.48	0.34	<0.30	<0.30	1.23	1.60
K 2 O	<0.20	<0.20	<0.20	<0.20	0.57	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0.27	<0.20	<0.20	<0.20	0.40	0.35	0.38	0.37	0.43	<0.20	0.36	0.50	0.33	0.64	<0.20	0.33	0.22	0.36	0.36	0.32	0.34	1.56	0.31	0.74	0.59	0.63	1.26	1.26	1.20
Cl	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	<0.20	0.31	na	na	na	na	na	0.61	0.52
O=Cl																																		0.19	0.31						0.61	0.52
Total	93.32	96.17	98.79	97.74	98.67	98.81	98.65	98.81	95.85	98.78	96.30	97.82	97.26	96.64	97.77	98.09	98.57	97.52	98.06	98.79	97.03	98.53	97.70	98.58	98.96	98.70	98.98	98.72	97.99	95.81	98.85	95.11	96.39	98.30	97.75	96.00	98.10	97.71	97.05	94.63	96.13	97.57
O(23)																																																
Si (T)	7.88	7.95	8.00	7.76	7.65	8.00	7.76	8.00	7.29	8.00	8.00	8.00	8.00	8.00	8.00	8.00	7.90	7.82	7.81	7.79	7.75	7.74	7.76	7.74	7.67	7.87	7.72	8.00	7.92	7.95	7.94	7.97	7.93	7.54	6.28	7.65	7.22	7.39	7.46	6.85	6.68	6.65
Al(T)	0.12	0.05	0.00	0.24	0.35	0.00	0.24	0.00	0.71	0.00	0.00	0.00	0.00	0.00	0.00	-	0.10	0.18	0.19	0.21	0.25	0.26	0.24	0.26	0.33	0.13	0.28	-	0.08	0.05	0.06	0.03	0.07	0.46	1.72	0.35	0.78	0.61	0.54	1.15	1.32	1.35
Al(C)	0.07	0.06	0.07	0.01	0.10	0.05	0.00	0.06	0.00	0.11	0.04	0.08	0.03	0.11	0.06	-	0.07	0.15	0.08	0.17	0.06	0.12	0.23	0.17	0.21	0.18	0.22	-	0.12	0.12	0.19	0.15	0.10	0.31	0.21	0.31	0.33	0.35	0.35	0.48	0.57	0.47
Ti(C)	-	-	-	-	0.00	-	0.00	-	-	-	0.00	-	-	-	-	-	-	0.00	0.00	0.00	0.01	0.02	0.03	0.03	0.03	-	0.04	-	-	-	-	-	0.04	-	0.18	-	-	0.05	0.03	0.08	0.12	0.09
Fe 3+(C)	0.00	0.00	0.10	1.21	0.52	0.25	1.72	0.18	2.91	0.14	0.32	0.23	0.25	0.18	0.15	0.00	0.38	0.38	0.56	0.45	0.70	0.41	0.23	0.30	0.41	0.35	0.41	0.00	0.49	0.22	0.51	0.47	0.38	0.00	0.00	0.75	0.81	0.71	0.69	0.89	0.32	0.65
Mg(C)	3.81	3.43	3.09	3.71	3.81	3.44	3.90	4.10	4.49	3.62	4.05	3.96	4.08	3.95	3.96	3.75	3.23	3.89	4.05	3.75	3.97	3.84	3.88	3.92	3.91	4.05	3.90	3.78	4.09	4.07	3.96	4.06	4.14	3.23	2.86	3.91	3.65	3.68	3.76	3.29	2.10	2.24
Fe(C)	1.11	1.30	1.69	0.07	0.52	1.20	0.00	0.59	0.00	1.09	0.52	0.65	0.58	0.74	0.73	1.08	1.31	0.52	0.28	0.60	0.20	0.56	0.85	0.85	0.85	0.77	0.84	1.09	0.79	0.79	0.83	0.77	0.73	1.46	1.72	0.77	0.99	0.90	0.84	1.14	2.19	2.19
Mn(C)	-	-	-	0.00	-	0.00	0.00	-	0.00	-	-	-	-	-	-	-	0.00	-	-	-	-	-	-	-	0.00	-	-	-	-	-	-	0.00	0.00	-	-	0.00	0.00	0.00	0.00	0.00	-	-
Mg (B)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe(B)	0.00	0.63	0.01	0.06	0.05	0.00	0.00	0.02	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.05	0.00	0.04	0.05	0.02	0.07	0.04	0.04	0.08	0.08	0.10	0.12	0.00	0.14	0.05	0.13	0.11	0.08	0.05	0.16	0.14	0.15	0.14	0.10	0.21	0.08	0.17
Mn (B)	-	-	-	0.04	-	0.03	0.64	-	1.96	-	-	-	-	-	-	-	0.05	-	-	-	-	-	-	-	0.03	-	-	-	-	-	-	0.03	0.03	-	-	0.07	0.08	0.06	0.10	0.04	-	-
Ca(B)	1.90	1.99	1.78	1.48	1.58	1.68	1.18	1.74	1.20	1.79	1.73	1.74	1.77	1.79	1.78	1.88	1.84	1.63	1.61	1.61	1.60	1.65	1.70	1.71	1.68	1.70	1.70	1.90	1.76	1.76	1.72	1.73	1.73	1.82	1.69	1.76	1.84	1.77	1.80	1.86	1.85	1.81
Na(B)	0.10	0.00	0.16	0.15	0.37	0.21	0.18	0.16	-	0.10	-	-	-	-	-	-	-	0.30	0.28	0.31	0.21	0.29	0.23	0.21	0.20	0.21	0.18	-	0.10	0.17	-	-	0.16	0.11	0.16	-	0.00	0.03	-	-	0.06	0.00
Na(A)	0.14	0.25	0.00	0.00	0.09	0.00	0.02	0.00	-	0.00	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.18	0.15	0.18	0.10	0.06	-	0.00	0.04	-	-	0.00	0.21	0.98	-	0.13	0.06	-	-	0.30	0.46
K(A)	-	-	-	-	0.10	-	-	-	-	-	-	-	-	0.05	-	-	-	0.07	0.06	0.07	0.07	0.08	-	0.06	0.09	0.06	0.11	-	0.06	0.04	0.06	0.06	0.06	0.06	0.30	0.06	0.13	0.11	0.11	0.23	0.24	0.23
Cl																																		0.04	0.08						0.16	0.12
[Ca + Na] B	2.00	1.99	1.94	1.63	1.95	1.89	1.36	1.90	1.20	1.89	1.73	1.74	1.77	1.79	1.78	1.88	1.84	1.93	1.89	1.92	1.81	1.94	1.93	1.92	1.88	1.90	1.88	1.90	1.85	1.94	1.72	1.73	1.89	1.93	1.84	1.76	1.84	1.80	1.80	1.86	1.91	1.81
[Na + K] A	0.14	0.25	0.00	0.00	0.19	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.07	0.06	0.07	0.07	0.08	0.18	0.21	0.27	0.16	0.17	0.00	0.06	0.07	0.06	0.06	0.06	0.27	1.28	0.06	0.27	0.17	0.11	0.23	0.55	0.69
Fe3+/Fe3++Fe2+	0.0	0.0	0.1	0.9	0.5	0.2	1.0	0.2	1.0	0.1	0.4	0.3	0.3	0.2	0.2	0.0	0.2	0.4	0.6	0.4	0.7	0.4	0.2	0.2	0.3	0.3	0.3	0.0	0.3	0.2	0.3	0.3	0.3	0.0	0.0	0.5	0.4	0.4	0.4	0.4	0.1	0.2
Fe3+/(Fe3++Alvi)	0.0	0.0	0.6	1.0	0.8	0.8	1.0	0.7	1.0	0.6	0.9	0.7	0.9	0.6	0.7	-	0.8	0.7	0.9	0.7	0.9	0.8	0.5	0.6	0.7	0.7	0.6	-	0.8	0.6	0.7	0.8	0.8	0.0	0.0	0.7	0.7	0.7	0.7	0.7	0.4	0.6
Mg/(Mg +Fe2+)	0.8	0.6	0.6	1.0	0.9	0.7	1.0	0.9	1.0	0.8	0.9	0.9	0.9	0.8	0.8	0.8	0.7	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.6	0.8	0.8	0.8	0.8	0.7	0.5	0.5
Mg/(Mg+ FeT)	3.4	1.8	1.7	2.8	3.5	2.4	2.3	5.2	1.5	2.9	4.8	4.4	4.9	4.3	4.4	3.3	1.9	4.1	4.5	3.5	4.1	3.8	3.5	3.2	2.9	3.3	2.9	3.5	2.9	3.8	2.7	3.0	3.5	2.1	1.5	2.4	1.9	2.1	2.3	1.5	0.8	0.7
Si	7.88	7.95	8.00	7.76	7.65	8.00	7.76	8.00	7.29	8.00	8.00	8.00	8.00	8.00	8.00	8.00	7.90	7.82	7.81	7.79	7.75	7.74	7.76	7.74	7.67	7.87	7.72	8.00	7.92	7.95	7.94	7.97	7.93	7.54	6.28	7.65	7.22	7.39	7.46	6.85	6.68	6.65

CPX	"Moderately altered" CS + Vein						"Altered" Calc-silicate																											"Breccia" pseudo-igneous texture with "Altered" Schist clasts									
	44654	DP#44657					DP#44672		DP#44586					DP#44674				DP#44681				DP#46308					DP#46311				46323	DP#46325								46314
	4\1	1V\1	1V\2	1V\3	1V\4	2V\1	4\1	4\6	2\1	2\2	3\1	2\2	3\3	4\1	4\2	5\1	5\2	1\1	1\2	1\3	1\4	1\1	1\2	4\1	4\1B	4\2	4\3	1\1	2\1	3\1	4\1	5\1	1\1	1\2	1\3	2\1	2\2	3\1	3\2	4\1	3\1
SiO2	47.14	55.11	55.37	54.37	54.95	54.90	52.81	53.02	55.56	56.12	55.49	55.88	55.38	54.71	55.55	58.18	54.41	54.57	55.18	54.21	55.49	54.35	53.27	54.63	54.72	54.11	54.61	55.04	54.72	55.11	55.12	56.62	54.57	54.95	54.60	55.35	55.10	55.34	55.03	55.58	55.51
Al2O3	2.43	0.72	0.74	0.84	0.82	0.65	0.56	0.78	<0.20	0.23	0.31	<0.20	<0.20	0.50	0.63	<0.20	0.54	0.57	0.44	0.38	<0.20	<0.20	0.85	0.28	0.41	0.43	0.52	0.45	0.76	0.26	0.42	0.48	0.64	0.84	0.76	0.70	0.95	<0.20	0.64	0.54	0.32
FeO	19.28	6.42	6.57	6.01	6.10	6.00	8.66	8.71	6.09	5.98	6.50	5.60	6.57	8.92	8.17	7.45	9.85	11.18	12.16	9.97	6.82	9.80	13.73	12.24	11.04	11.83	11.52	7.97	7.85	7.62	7.28	7.96	10.43	10.82	12.48	8.38	8.02	8.88	8.30	7.09	8.35
MgO	10.00	14.19	14.20	14.40	14.48	14.76	13.00	13.33	14.68	14.55	14.04	14.64	14.51	12.70	13.80	12.66	12.58	11.25	10.40	12.57	13.54	12.12	9.35	11.24	11.94	11.33	11.07	13.52	13.64	13.76	13.83	14.82	11.43	11.18	9.84	13.37	13.41	12.96	13.61	13.99	13.45
CaO	20.77	21.87	21.63	22.81	21.54	21.83	22.32	22.44	22.79	22.16	21.79	22.48	21.83	21.37	19.64	20.75	21.00	20.13	17.27	19.83	23.18	22.69	21.02	19.17	19.95	19.99	19.91	21.80	21.79	21.62	21.73	19.04	19.62	19.19	20.28	19.87	20.57	21.00	20.19	20.08	20.69
Na2O	<0.30	1.60	1.31	1.27	1.80	1.20	1.66	1.45	0.52	0.81	1.65	0.88	1.07	1.53	1.74	0.43	1.43	2.05	4.18	2.70	0.50	0.91	1.38	2.36	1.85	1.93	2.17	1.11	0.86	1.20	1.19	0.31	2.67	2.71	1.92	1.94	1.54	1.69	2.05	2.22	1.50
Total	99.62	99.91	99.82	99.70	99.69	99.33	99.01	99.73	99.63	99.85	99.78	99.48	99.35	99.72	99.52	99.48	99.80	99.74	99.64	99.66	99.53	99.87	99.60	99.92	99.92	99.62	99.80	99.89	99.62	99.57	99.57	99.23	99.35	99.68	99.87	99.61	99.59	99.87	99.81	99.51	99.82
O(6)																																									
Si	1.86	2.03	2.04	2.01	2.02	2.03	2.00	1.99	2.04	2.05	2.04	2.05	2.04	2.04	2.05	2.13	2.03	2.05	2.08	2.03	2.05	2.04	2.03	2.05	2.05	2.04	2.05	2.04	2.03	2.04	2.04	2.08	2.05	2.06	2.06	2.05	2.04	2.06	2.04	2.05	2.05
Al	0.11	0.03	0.03	0.04	0.04	0.03	0.02	0.03	-	0.01	0.01	-	-	0.02	0.03	-	0.02	0.03	0.02	0.02	-	-	0.04	0.01	0.02	0.02	0.02	0.02	0.03	0.01	0.02	0.02	0.03	0.04	0.03	0.03	0.04	-	0.03	0.02	0.01
Fe	0.64	0.20	0.20	0.19	0.19	0.19	0.27	0.27	0.19	0.18	0.20	0.17	0.20	0.28	0.25	0.23	0.31	0.35	0.38	0.31	0.21	0.31	0.44	0.38	0.35	0.37	0.36	0.25	0.24	0.24	0.23	0.24	0.33	0.34	0.39	0.26	0.25	0.28	0.26	0.22	0.26
Mg	0.59	0.78	0.78	0.79	0.79	0.81	0.73	0.74	0.81	0.79	0.77	0.80	0.80	0.70	0.76	0.69	0.70	0.63	0.58	0.70	0.75	0.68	0.53	0.63	0.67	0.64	0.62	0.75	0.75	0.76	0.76	0.81	0.64	0.62	0.55	0.74	0.74	0.72	0.75	0.77	0.74
Ca	0.88	0.86	0.85	0.90	0.85	0.86	0.90	0.90	0.90	0.87	0.86	0.89	0.86	0.85	0.78	0.81	0.84	0.81	0.70	0.80	0.92	0.91	0.86	0.77	0.80	0.81	0.80	0.86	0.87	0.86	0.86	0.75	0.79	0.77	0.82	0.79	0.82	0.84	0.80	0.79	0.82
Na	-	0.11	0.09	0.09	0.13	0.09	0.12	0.11	0.04	0.06	0.12	0.06	0.08	0.11	0.12	0.03	0.10	0.15	0.31	0.20	0.04	0.07	0.10	0.17	0.13	0.14	0.16	0.08	0.06	0.09	0.09	0.02	0.19	0.20	0.14	0.14	0.11	0.12	0.15	0.16	0.11
%Mg	28.0	42.3	42.5	42.1	43.4	43.6	38.3	38.8	42.6	43.0	42.1	43.1	42.8	38.4	42.5	39.9	37.9	35.2	35.1	38.8	39.8	35.7	29.1	35.3	36.8	35.0	34.7	40.2	40.5	41.0	41.2	44.9	36.4	36.0	31.3	41.3	41.0	39.2	41.5	43.2	40.8
%Fe	30.3	10.8	11.0	9.9	10.2	10.0	14.3	14.2	9.9	9.9	10.9	9.3	10.9	15.1	14.1	13.2	16.6	19.6	23.0	17.3	11.2	16.2	24.0	21.5	19.1	20.5	20.3	13.3	13.1	12.7	12.2	13.5	18.6	19.6	22.3	14.5	13.8	15.1	14.2	12.3	14.2
%Ca	41.8	46.9	46.5	48.0	46.4	46.4	47.3	47.0	47.5	47.1	47.0	47.6	46.3	46.5	43.4	47.0	45.5	45.2	41.9	44.0	49.0	48.1	47.0	43.2	44.2	44.4	45.0	46.6	46.5	46.3	46.6	41.5	44.9	44.4	46.4	44.2	45.2	45.7	44.3	44.6	45.1
Kd	0.7	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.9	0.8	0.8	0.7	0.8	1.0	0.9	0.9	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.7	0.8	0.8	0.9	0.8	0.8	0.8	0.8	0.8	0.8

CPX	"Breccia" pseudo-igneous texture with "Altered" Schist clasts															"Pristine" Metadolerite								"Altered" Metadolerite																	
	DP#46314						DP#46312						DP#46317			DP#46335			DP#46334					DP#46305		DP#46313			DP#46332											DP#44598		
	3\1	3\2	5\1	5\2	5\3	5\4	2\1	2\2	2\3	3\1	6\1	6\2	2\1	2\2	2\3	1\1	4\1	5\1	1\1	1\2	2\1	4\1	4\2	2\1	2\2	1\2	5\1	6\1	1\1	1\2	2\1	2\2	2\3	3\1	3\2	5\1	2\1	2\2	2\3
SiO2	55.51	55.87	55.44	55.25	54.76	55.16	55.10	54.93	55.67	55.18	54.88	55.23	54.99	55.10	55.20	54.71	54.54	54.67	55.10	55.21	54.34	54.57	54.62	54.32	54.60	54.84	55.50	55.34	54.55	54.20	53.83	53.58	54.47	55.19	54.73	53.42	54.93	55.17	55.00
Al2O3	0.32	<0.20	0.74	0.73	0.77	0.55	0.58	0.50	<0.20	0.62	0.65	0.65	<0.20	<0.20	0.22	0.70	0.70	0.56	0.61	<0.20	0.54	0.82	0.71	1.86	0.92	0.76	0.79	0.61	0.62	0.56	2.14	2.07	0.36	0.37	0.70	2.19	<0.20	0.27	0.47
FeO	8.35	8.07	9.06	8.23	9.96	7.46	9.67	9.04	8.24	8.48	11.28	8.91	8.91	7.98	8.54	9.61	9.47	9.66	9.61	8.52	9.41	9.41	9.12	6.86	6.17	9.04	8.91	8.67	8.44	9.51	6.56	5.99	7.94	6.74	7.66	6.04	9.24	8.51	8.07
MgO	13.45	13.58	12.73	13.29	12.37	13.90	12.11	13.03	13.38	12.90	11.39	13.04	12.97	13.33	13.04	12.19	12.37	12.41	12.38	12.99	12.52	12.62	12.67	13.38	14.65	12.57	12.70	12.82	13.21	12.41	13.76	14.19	14.00	13.96	13.61	14.30	12.86	13.06	13.06
CaO	20.69	20.68	19.76	20.36	19.66	21.64	19.78	19.93	21.22	20.65	19.14	20.06	20.92	21.49	21.33	20.94	20.65	21.12	20.90	22.01	21.61	21.12	21.06	21.14	22.23	20.12	20.12	20.77	21.12	21.28	22.62	22.34	22.01	22.20	22.17	22.23	21.98	22.46	22.12
Na2O	1.50	1.45	2.12	1.82	2.29	0.93	2.24	2.14	1.36	1.93	2.31	1.71	2.04	1.60	1.36	1.56	1.82	1.38	1.02	0.89	1.17	1.11	1.48	2.12	1.35	2.17	2.19	1.53	1.62	1.28	<0.30	1.03	0.46	0.78	0.67	0.92	<0.30	<0.30	0.40
Total	99.82	99.64	99.84	99.68	99.80	99.64	99.47	99.57	99.87	99.77	99.64	99.59	99.82	99.50	99.68	99.71	99.54	99.78	99.62	99.61	99.59	99.66	99.68	99.69	99.92	99.51	100.21	99.74	99.56	99.22	98.91	99.20	99.24	99.22	99.54	99.10	99.01	99.47	99.12
O(6)																																							
Si	2.05	2.06	2.05	2.05	2.04	2.04	2.06	2.04	2.06	2.05	2.06	2.05	2.05	2.05	2.05	2.04	2.04	2.04	2.05	2.05	2.03	2.03	2.04	2.01	2.01	2.04	2.05	2.05	2.03	2.03	1.99	1.99	2.03	2.04	2.03	1.98	2.05	2.05	2.05
Al	0.01	-	0.03	0.03	0.03	0.02	0.03	0.02	-	0.03	0.03	0.03	-	-	0.01	0.03	0.03	0.02	0.03	-	0.02	0.04	0.03	0.08	0.04	0.03	0.03	0.03	0.03	0.02	0.09	0.09	0.02	0.02	0.03	0.10	-	0.01	0.02
Fe	0.26	0.25	0.28	0.25	0.31	0.23	0.30	0.28	0.25	0.26	0.35	0.28	0.28	0.25	0.27	0.30	0.30	0.30	0.30	0.26	0.29	0.29	0.28	0.21	0.19	0.28	0.28	0.27	0.26	0.30	0.20	0.19	0.25	0.21	0.24	0.19	0.29	0.26	0.25
Mg	0.74	0.75	0.70	0.73	0.69	0.77	0.67	0.72	0.74	0.71	0.64	0.72	0.72	0.74	0.72	0.68	0.69	0.69	0.69	0.72	0.70	0.70	0.70	0.74	0.80	0.70	0.70	0.71	0.73	0.69	0.76	0.78	0.78	0.77	0.75	0.79	0.72	0.72	0.72
Ca	0.82	0.82	0.78	0.81	0.79	0.86	0.79	0.79	0.84	0.82	0.77	0.80	0.83	0.85	0.85	0.84	0.83	0.84	0.83	0.88	0.87	0.84	0.84	0.84	0.88	0.80	0.80	0.83	0.84	0.86	0.90	0.89	0.88	0.88	0.88	0.88	0.88	0.89	0.88
Na	0.11	0.10	0.15	0.13	0.17	0.07	0.16	0.15	0.10	0.14	0.17	0.12	0.15	0.12	0.10	0.11	0.13	0.10	0.07	0.06	0.08	0.08	0.11	0.15	0.10	0.16	0.16	0.11	0.12	0.09	-	0.07	0.03	0.06	0.05	0.07	-	-	0.03
%Mg	40.8	41.2	39.8	40.8	38.5	41.3	38.1	40.2	40.2	39.7	36.2	40.2	39.3	40.1	39.3	37.3	38.0	37.6	37.8	38.7	37.6	38.1	38.5	41.3	43.0	39.1	39.5	39.3	39.9	37.6	40.8	42.2	40.8	41.4	40.2	42.5	38.0	38.4	39.0
%Fe	14.2	13.7	15.9	14.2	17.4	12.4	17.1	15.6	13.9	14.6	20.1	15.4	15.1	13.5	14.4	16.5	16.3	16.4	16.4	14.2	15.8	16.0	15.5	11.9	10.2	15.8	15.5	14.9	14.3	16.1	10.9	10.0	13.0	11.2	12.7	10.1	15.3	14.0	13.5
%Ca	45.1	45.1	44.4	45.0	44.0	46.2	44.8	44.2	45.9	45.7	43.7	44.4	45.6	46.4	46.2	46.1	45.6	46.0	45.8	47.1	46.6	45.9	46.0	46.9	46.9	45.1	45.0	45.8	45.8	46.3	48.2	47.8	46.2	47.4	47.1	47.5	46.7	47.5	47.5
Kd	0.8	0.8	0.8	0.8	0.8	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.8	0.9	0.8	0.9	0.9	0.8	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9

Kd=Ca/(Fe+Mg)

Titanite	"Pristine" CS		"Moderately altered" Calc-silicate					"Altered" Calc-silicate										VJB			Breccia psd-ign		Altered schist			Altered Metadolerite		
	44627	4463	44654	DP#44652			44657	44585	DP#44586			DP#44674			44681	46311	46308	DP#44590			DP#46317		DP#46323			46335	46334	44625
	1\1	1\1	4\1	3\1	3\2	3\3	2\1	4\1	2\1	3\1	4\1	1\1	2\1	4\1	1\1	4\1	1\1	2\1	1\2	2\3	2\1	4\1	1\1	1\2	1\3	5\1	2\1	2\1
SiO2	31.84	32.04	31.62	31.83	32.08	31.20	32.20	32.49	31.94	32.13	32.33	31.39	31.59	31.64	31.55	31.80	32.25	31.76	32.68	31.90	31.75	31.25	31.98	31.64	32.24	31.90	31.32	31.08
TiO2	37.58	37.41	33.79	38.43	38.27	38.50	37.64	38.36	39.11	38.19	37.69	38.51	39.63	39.14	38.98	38.26	36.64	39.83	38.26	39.54	38.96	39.03	38.17	38.26	38.63	38.53	38.88	39.89
Al2O3	1.97	1.83	2.82	0.99	1.04	0.96	1.84	1.61	0.69	0.99	1.01	1.18	1.15	0.95	0.86	1.55	2.50	0.51	<0.20	1.04	0.82	1.05	0.88	1.03	0.84	1.47	1.30	0.88
Fe2O3	1.79	2.01	1.95	2.74	2.26	2.84	2.50	1.02	2.08	2.22	2.51	1.97	1.02	1.63	2.11	1.39	1.86	1.76	1.67	2.20	1.22	2.31	1.86	1.98	1.65	1.57	1.54	1.20
CaO	26.55	26.87	28.18	26.18	26.15	26.09	25.98	25.93	26.17	26.27	26.30	26.61	26.31	26.50	26.56	26.58	26.82	26.11	26.12	25.45	27.04	26.32	26.96	27.16	26.40	26.42	26.42	25.72
Total	99.73	100.17	98.36	100.17	99.80	99.59	100.16	99.41	99.99	99.80	99.83	99.66	99.70	99.85	100.06	99.57	100.06	99.97	98.73	100.12	99.80	99.96	99.84	100.05	99.75	99.89	99.46	98.77
O(5)																												
Si	1.02	1.02	1.03	1.02	1.02	1.01	1.03	1.03	1.02	1.02	1.03	1.01	1.01	1.01	1.01	1.02	1.03	1.01	1.05	1.02	1.01	1.00	1.02	1.01	1.03	1.02	1.00	1.00
Ti	0.93	0.92	0.85	0.95	0.95	0.96	0.93	0.94	0.97	0.94	0.93	0.96	0.98	0.97	0.97	0.95	0.90	0.98	0.95	0.98	0.96	0.97	0.95	0.95	0.96	0.95	0.97	1.00
Al	0.08	0.07	0.11	0.04	0.04	0.04	0.07	0.06	0.03	0.04	0.04	0.05	0.04	0.04	0.03	0.06	0.10	0.02	-	0.04	0.03	0.04	0.03	0.04	0.03	0.06	0.05	0.03
Fe	0.04	0.05	0.05	0.07	0.06	0.07	0.06	0.02	0.05	0.05	0.06	0.05	0.02	0.04	0.05	0.03	0.05	0.04	0.04	0.05	0.03	0.06	0.05	0.05	0.04	0.04	0.04	0.03
Ca	0.93	0.94	1.00	0.91	0.91	0.92	0.90	0.90	0.91	0.91	0.92	0.93	0.92	0.92	0.93	0.93	0.93	0.91	0.92	0.89	0.94	0.92	0.94	0.95	0.92	0.92	0.93	0.91
Ti/Fe	21.2	18.8	17.5	14.2	17.1	13.7	15.2	38.1	19.0	17.4	15.2	19.7	39.2	24.3	18.7	27.9	19.9	22.8	23.1	18.1	32.2	17.0	20.7	19.5	23.6	24.8	25.5	33.6
Ti/Al	12.2	13.1	7.7	24.9	23.6	25.7	13.1	15.3	36.1	24.7	23.9	21.0	22.1	26.4	29.1	15.8	9.4	50.1	-	24.5	30.5	23.8	27.9	23.9	29.5	16.8	19.2	29.1
Al/Fe	1.7	1.4	2.3	0.6	0.7	0.5	1.2	2.5	0.5	0.7	0.6	0.9	1.8	0.9	0.6	1.8	2.1	0.5	-	0.7	1.1	0.7	0.7	0.8	0.8	1.5	1.3	1.2

Iron-oxides	"Pristine" Calc-silicate													"Moderately altered" Calc-silicate					"Altered" Calc-silicate										
	DP#44600				44602	DP#44627			44631	DP#44663			44665	DP#44652			DP#44657		DP#44672			DP#44585		DP#44638			44651	DP#44674	
	1\1	1\2	2\1	2\3	2\1	1\2	1\3	2\4	2\1	1\1	3\1	5\1	1\1	3\1	3\2	3\3	1\1	2\1	1\4	6\1	6\2	2\1	2\1	3\1	3\3	3\4	1\1	1\1	1\2
TiO2	<0.20	<0.20	<0.20	<0.20	<0.20	7.73	10.37	9.83	11.09	10.66	11.83	11.06	6.45	9.26	10.04	6.73	8.65	10.60	<0.20	<0.20	<0.20	8.90	8.90	9.75	17.38	17.70	5.47	7.24	17.99
Fe2O3	68.08	68.15	68.01	67.72	67.84	54.64	47.84	49.38	46.84	48.30	45.83	46.80	55.77	50.95	49.21	54.92	51.52	49.01	67.62	68.27	68.60	50.78	50.78	48.96	34.18	34.75	57.18	55.05	34.03
FeO(t)	30.63	30.66	30.60	30.47	30.52	38.48	40.17	39.90	41.02	40.90	41.90	40.96	36.70	39.58	40.19	36.82	38.74	41.10	30.42	30.71	30.86	38.85	38.85	39.56	46.63	47.47	35.56	37.79	47.66
Total	98.71	98.82	98.60	98.18	98.37	100.84	98.39	99.10	98.95	99.87	99.57	98.82	98.92	99.79	99.43	98.47	98.92	100.71	98.04	98.98	99.46	98.53	98.53	98.26	98.19	99.93	98.21	100.08	99.67
O(4)																													
Ti	-	-	-	-	-	0.22	0.30	0.28	0.32	0.31	0.34	0.32	0.19	0.27	0.29	0.20	0.25	0.30	-	-	-	0.26	0.26	0.28	0.50	0.50	0.16	0.21	0.51
Fe3+	2.00	2.00	2.00	2.00	2.00	1.56	1.40	1.43	1.36	1.39	1.32	1.36	1.62	1.47	1.42	1.61	1.50	1.40	2.00	2.00	2.00	1.48	1.48	1.43	0.99	0.99	1.68	1.58	0.97
Fe2+	1.00	1.00	1.00	1.00	1.00	1.22	1.30	1.28	1.32	1.31	1.34	1.32	1.19	1.27	1.29	1.20	1.25	1.30	1.00	1.00	1.00	1.26	1.26	1.28	1.50	1.50	1.16	1.21	1.51
Uvs	-	-	-	-	-	22.0	30.2	28.5	32.1	30.6	34.0	32.1	18.8	26.7	29.0	19.7	25.1	30.2	-	-	-	25.9	25.9	28.5	50.4	50.5	16.1	20.8	51.4
Mag	100.0	100.0	100.0	100.0	100.0	78.0	69.8	71.5	67.9	69.4	66.0	67.9	81.2	73.3	71.0	80.3	74.9	69.8	100.0	100.0	100.0	74.1	74.1	71.5	49.6	49.5	83.9	79.2	48.6
X-Usp	-	-	-	-	-	0.0	0.2	0.1	0.2	0.2	0.2	0.2	0.0	0.1	0.1	0.0	0.1	0.2	-	-	-	0.1	0.1	0.1	0.5	0.5	0.1	0.0	0.5
X-Ilm	-	-	-	-	-	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.2	0.2	0.1	-	-	-	0.2	0.2	0.1	0.0	0.0	0.1	0.2	0.0
X-Mag	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
X-Hem	0.7	0.7	0.7	0.7	0.7	0.4	0.4	0.4	0.3	0.4	0.3	0.3	0.5	0.4	0.4	0.5	0.4	0.4	0.7	0.7	0.7	0.4	0.4	0.4	0.2	0.2	0.5	0.5	0.2

Iron-oxide	"Altered" Schist + clast			"Breccia" pseudo-igneous texture					"Altered" Metadolerite				
	DP#46323			DP#46315			46310		DP#46316		DP#44625		
	2\1	3\1	5\1	1\1	1\2	5\1	1\1	2\1	3\1	3\2	1\1	3\2	5\1
TiO2	<0.20	<0.20	<0.20	<0.20	<0.20	0.32	<0.20	<0.20	<0.20	<0.20	0.34	8.18	7.51
Fe2O3	68.83	69.79	69.74	69.32	68.58	69.25	69.45	70.25	69.93	70.01	68.11	52.93	53.82
FeO(t)	30.97	31.40	31.38	31.19	31.13	31.74	31.25	31.61	31.46	31.50	31.26	38.53	37.71
Total	99.80	101.18	101.12	100.51	99.71	101.32	100.70	101.86	101.39	101.50	99.71	99.64	99.04
O(4)													
Ti	-	-	-	-	-	0.01	-	-	-	-	0.01	0.24	0.22
Fe3+	2.00	2.00	2.00	2.00	1.99	1.98	2.00	2.00	2.00	2.00	1.98	1.53	1.56
Fe2+	1.00	1.00	1.00	1.00	1.00	1.01	1.00	1.00	1.00	1.00	1.01	1.24	1.22
Uvs	-	-	-	-	-	0.9	-	-	-	-	1.0	23.6	21.8
Mag	100.0	100.0	100.0	100.0	100.0	99.1	100.0	100.0	100.0	100.0	99.0	76.4	78.2
X-Usp	-	-	-	-	-	0.0	-	-	-	-	0.0	0.1	0.0
X-Ilm	-	-	-	-	-	0.0	-	-	-	-	0.0	0.2	0.2
X-Mag	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
X-Hem	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.4	0.4

Scapolite	"Pristine" CS	"Altered" CS				"Altered" Metadolerite/Metabasalt										Vein at margin Metadolerite					V1 type vein in "Altered" Calc-silicate								
	44618	DP#44651				DP#44625									46305	DP#44598					DP#44636								
	2\5	1\1	1\2	1\3	1\4	2\1	2\1B	2\3	4\2	4\2	4\3	4\4	4\5	4\6	3\1	1\1	1\2	1\3	1\4	1\5	1\2	1\2	1\3	1\4	1\5	1\6	1\7	1\9	1\10
SiO2	47.21	51.59	51.35	50.74	51.37	51.48	52.73	52.87	52.66	52.36	51.68	52.34	51.31	52.15	58.64	56.54	56.26	55.52	54.53	55.88	59.43	57.89	57.53	57.48	58.62	58.22	57.50	57.60	58.71
Al2O3	24.40	24.13	23.75	23.46	23.79	23.55	23.72	23.23	24.02	23.40	24.50	23.36	24.21	23.84	22.19	22.17	22.36	23.09	22.21	22.15	20.49	21.63	21.04	21.34	21.03	21.27	21.66	21.08	21.53
CaO	13.12	12.47	12.55	12.24	11.94	12.33	12.16	10.95	12.06	12.19	12.27	11.86	12.94	11.86	6.42	7.96	7.92	8.62	8.95	7.95	5.36	5.27	5.75	5.61	4.81	5.59	5.59	6.04	5.98
Na2O	6.82	5.68	5.22	5.75	6.33	6.26	6.47	5.99	6.08	6.58	6.19	6.96	5.88	6.50	9.87	8.82	8.89	8.69	8.39	9.57	10.67	10.99	10.70	10.33	10.90	11.08	11.41	10.83	10.69
K2O	0.70	0.95	1.01	0.97	0.98	0.80	0.82	0.70	0.76	0.82	0.84	0.77	0.60	0.80	0.57	1.10	0.93	0.98	0.92	0.78	1.10	1.03	1.24	1.04	1.17	1.30	1.07	1.04	0.88
Cl	1.32	1.31	1.41	1.27	1.57	1.26	1.51	0.98	1.28	1.60	1.61	1.45	1.09	1.56	2.87	2.77	2.66	2.45	2.43	2.77	3.52	3.18	3.38	3.20	3.44	3.28	3.25	3.46	3.24
CO2	3.00	3.27	3.10	3.22	2.91	3.28	3.06	3.69	3.36	2.91	2.93	3.09	3.53	2.97	1.62	1.64	1.76	2.02	1.92	1.57	0.74	1.11	0.85	1.09	0.81	1.02	1.04	0.75	1.12
O=Cl	0.30	0.30	0.32	0.29	0.35	0.28	0.34	0.22	0.29	0.36	0.36	0.33	0.25	0.35	0.65	0.62	0.60	0.55	0.55	0.62	0.79	0.72	0.76	0.72	0.78	0.74	0.73	0.78	0.73
Total	96.27	99.11	98.07	97.36	98.54	98.68	100.13	98.19	99.93	99.52	99.66	99.50	99.34	99.53	101.53	100.38	100.17	100.82	98.80	100.05	100.51	100.38	99.72	99.37	100.00	101.02	100.79	100.02	101.41
Si+Al=12																													
Si	7.44	7.72	7.75	7.75	7.75	7.78	7.83	7.89	7.79	7.84	7.68	7.85	7.70	7.78	8.28	8.19	8.16	8.04	8.09	8.17	8.52	8.32	8.38	8.34	8.42	8.37	8.30	8.37	8.37
Al	4.56	4.28	4.25	4.25	4.25	4.22	4.17	4.11	4.21	4.15	4.32	4.15	4.30	4.22	3.72	3.81	3.84	3.96	3.91	3.84	3.48	3.69	3.63	3.67	3.58	3.63	3.70	3.63	3.64
Ca	2.21	2.00	2.03	2.00	1.93	2.00	1.93	1.75	1.91	1.96	1.95	1.91	2.08	1.90	0.97	1.24	1.23	1.34	1.42	1.24	0.82	0.81	0.90	0.87	0.74	0.86	0.86	0.94	0.91
Na	2.08	1.65	1.53	1.70	1.85	1.84	1.86	1.73	1.74	1.91	1.78	2.02	1.71	1.88	2.70	2.48	2.50	2.44	2.41	2.71	2.97	3.06	3.02	2.90	3.04	3.09	3.19	3.05	2.95
K	0.14	0.18	0.19	0.19	0.19	0.15	0.16	0.13	0.14	0.16	0.16	0.15	0.11	0.15	0.10	0.20	0.17	0.18	0.17	0.15	0.20	0.19	0.23	0.19	0.21	0.24	0.20	0.19	0.16
Cl	0.35	0.33	0.36	0.33	0.40	0.32	0.38	0.25	0.32	0.41	0.41	0.37	0.28	0.39	0.69	0.68	0.65	0.60	0.61	0.69	0.86	0.77	0.83	0.79	0.84	0.80	0.79	0.85	0.78
C	0.65	0.67	0.64	0.67	0.60	0.68	0.62	0.75	0.68	0.60	0.59	0.63	0.72	0.61	0.31	0.32	0.35	0.40	0.39	0.31	0.14	0.22	0.17	0.22	0.16	0.20	0.20	0.15	0.22
Eq.An	51.9	42.7	41.6	41.6	41.8	40.7	39.1	37.0	40.4	38.5	43.9	38.4	43.5	40.6	23.9	26.9	28.1	32.1	30.2	27.9	16.0	22.8	21.1	22.3	19.3	20.9	23.5	21.0	21.2
%Me	49.9	52.2	54.1	51.4	48.6	50.1	48.9	48.4	50.3	48.6	50.1	46.7	53.3	48.6	25.7	31.5	31.5	33.8	35.5	30.3	20.6	20.0	21.6	22.0	18.6	20.6	20.3	22.5	22.7
%Kfs	3.2	4.7	5.2	4.9	4.8	3.9	3.9	3.7	3.8	3.9	4.1	3.6	2.9	3.9	2.7	5.2	4.4	4.6	4.3	3.5	5.0	4.6	5.6	4.8	5.4	5.7	4.6	4.6	4.0
%Ab	46.9	43.0	40.7	43.7	46.6	46.0	47.1	47.9	45.9	47.5	45.8	49.6	43.8	47.9	71.6	63.3	64.1	61.6	60.2	66.1	74.3	75.4	72.8	73.2	76.1	73.7	75.1	72.9	73.4
Al/(Al+Si)	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.4	0.3	0.4	0.3	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Ln Kd	-0.6	-0.9	-0.9	-0.9	-0.9	-0.9	-1.0	-1.1	-0.9	-1.0	-0.8	-1.0	-0.8	-0.9	-1.9	-1.7	-1.6	-1.3	-1.4	-1.6	-2.7	-2.0	-2.2	-2.0	-2.3	-2.2	-1.9	-2.2	-2.1
Kd	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.2	0.2	0.2	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Xcl-Scp	0.4	0.3	0.4	0.3	0.4	0.3	0.4	0.2	0.3	0.4	0.4	0.4	0.3	0.4	0.7	0.7	0.7	0.6	0.6	0.7	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.8
Xcaco3-Scp	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Xnacl-Scp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Xnacl-Fl	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.3	0.2	0.1	0.2	0.3	0.4	0.4	0.4	0.3	0.4	0.4	0.5	0.6	0.5	0.5	0.4	0.5	0.6	0.4

CO2 calculated assuming C+Cl=1

K-feldspar	"Pristine" Calc-silicate										"Moderately altered" Calc-silicate						"Altered" Calc-silicate														
	DP#44627			44631	DP#4663			DP#44665		44666	44654	DP#44652			DP#44657		44672	DP#44585		DP#44586							DP#44651				DP#44681	
	1\1	1\2	2\1	3\1	3\1	4\1	4\2	2\1	5\1	1\1	2\3	2\1	2\2	3\1	1\1	3\1	4\1	4\1	4\2	2\1	1B\2	1B\3	1B\5	2\1	2\2	2\3	1\1	1\2	1\3	2\1	2\2	2\3
																															dusted	dusted
SiO2	64.79	64.66	64.68	64.54	64.86	64.02	64.50	64.59	64.44	64.84	63.54	64.48	64.32	64.96	64.26	64.01	63.98	64.73	64.08	65.16	63.96	64.48	64.59	64.59	64.86	64.90	64.04	64.10	65.36	64.32	64.10	64.21
Al2O3	17.13	16.94	17.18	17.39	17.65	17.13	17.42	17.31	17.53	17.13	18.09	17.39	17.69	17.42	17.79	17.72	18.16	17.39	16.90	16.93	17.34	16.58	17.29	17.00	16.70	17.26	16.98	17.03	16.36	17.02	17.41	17.63
CaO	<0.20	0.25	0.30	0.29	<0.20	<0.20	0.35	0.21	<0.20	0.32	<0.20	<0.20	0.24	0.25	0.23	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0.34	0.24	0.40	<0.20	<0.20	<0.20	<0.20	<0.20	0.39	0.41
Na2O	0.56	<0.30	0.44	0.38	<0.30	0.71	0.53	0.55	0.51	0.63	0.33	0.65	0.42	0.51	0.33	0.72	<0.30	<0.30	<0.30	0.61	0.72	0.99	<0.30	<0.30	<0.30	<0.30	<0.30	0.49	0.66	0.33	0.33	<0.30
K2O	16.68	16.86	16.79	17.11	17.00	16.46	16.58	17.02	16.87	16.33	16.45	17.30	17.07	16.80	17.08	16.86	16.65	17.05	17.25	16.71	16.79	16.42	16.71	17.23	17.59	17.47	17.07	16.65	16.71	16.75	17.20	17.04
Total	99.17	98.71	99.38	99.71	99.51	98.32	99.38	99.67	99.35	99.26	98.41	99.82	99.73	99.94	99.69	99.32	98.79	99.17	98.23	99.41	98.80	98.48	98.92	99.06	99.55	99.63	98.08	98.27	99.08	98.41	99.43	99.30
O(8)																																
Al	0.95	0.94	0.95	0.96	0.97	0.96	0.96	0.96	0.97	0.95	1.00	0.96	0.98	0.96	0.98	0.98	1.00	0.96	0.95	0.94	0.97	0.92	0.96	0.94	0.93	0.95	0.95	0.95	0.91	0.95	0.96	0.98
Ca	-	0.01	0.02	0.01	-	-	0.02	0.01	-	0.02	-	-	0.01	0.01	0.01	-	-	-	-	-	-	-	0.02	0.01	0.02	-	-	-	-	-	0.02	0.02
Na	0.05	-	0.04	0.03	-	0.06	0.05	0.05	0.05	0.06	0.03	0.06	0.04	0.05	0.03	0.07	-	-	-	0.06	0.07	0.09	-	-	-	-	-	0.04	0.06	0.03	0.03	-
K	0.99	1.01	1.00	1.02	1.01	0.99	0.99	1.01	1.00	0.97	0.99	1.03	1.02	0.99	1.02	1.01	0.99	1.01	1.04	0.99	1.01	0.99	1.00	1.03	1.05	1.04	1.03	1.00	1.00	1.00	1.02	1.01
% An	-	1.2	1.4	1.4	-	-	1.6	1.0	-	1.5	-	-	1.1	1.2	1.1	-	-	-	-	-	-	-	1.7	1.2	1.9	-	-	-	-	-	1.8	2.0
% Kf	95.1	100.0	96.2	96.8	100.0	93.8	95.4	95.4	95.6	94.5	97.0	94.6	96.4	95.6	97.2	93.9	100.0	100.0	100.0	94.7	93.9	91.6	100.0	100.0	100.0	100.0	100.0	95.7	94.3	97.1	97.2	100.0
% Ab	5.1	-	1.6	1.4	-	6.6	1.8	2.5	4.5	2.3	3.0	5.7	1.8	2.1	1.4	6.5	-	-	-	5.5	6.5	9.2	-	-	-	-	-	4.5	6.0	3.0	1.0	-

K-feldspar	"Altered" Calc-silicate							"Altered" Schist									"Breccia" pseudo-igneous texture											"Altered" Metadolerite				
	DP#44681			DP#46306				DP#46328				DP#46329		DP#46323			46314	DP#46315		46317	DP#46307					DP#46324		46305	DP#44625			
	4\1	5\1	6\1	1\1	1\2	3\1	3\2	1\1	1\2	1\3	2\1	1\1	1\2	2\1	3\1	3\2	4\1	2\1	4\1	2\1	3\1	3\2	4\1	5\1	5\2	3\1	3\2	3\1	3\1	3\2	5\1	5\1
						dusted	dusted																									
SiO2	64.16	61.91	64.29	63.80	64.37	63.85	64.09	64.54	64.56	64.40	64.15	64.29	64.18	64.35	64.43	64.72	64.48	64.89	64.53	64.45	64.99	64.61	64.65	64.61	64.56	64.69	64.38	64.79	65.05	65.18	65.27	65.57
Al2O3	17.56	19.35	17.73	17.74	17.53	17.43	17.56	17.29	17.52	17.58	17.38	17.89	18.01	17.38	17.91	17.26	17.51	17.14	17.21	17.88	17.20	17.09	17.27	17.44	17.27	17.33	17.72	17.55	17.14	17.08	17.19	16.72
CaO	<0.20	0.25	0.41	0.37	0.31	0.43	<0.20	0.33	0.33	<0.20	0.28	<0.20	<0.20	0.36	<0.20	0.23	0.34	<0.20	0.34	0.20	0.20	0.24	0.26	0.23	<0.20	0.23	0.35	0.34	0.29	0.27	0.29	0.24
Na2O	<0.30	0.34	<0.30	0.38	<0.30	0.40	<0.30	0.46	0.36	0.32	<0.30	0.84	0.85	0.30	0.39	<0.30	0.32	<0.30	<0.30	0.38	0.32	<0.30	<0.30	0.34	<0.30	<0.30	<0.30	0.39	0.93	0.80	1.01	0.54
K2O	17.58	16.32	17.01	17.21	17.37	16.99	17.81	17.22	17.14	17.04	17.07	16.35	16.22	17.03	16.29	16.69	17.10	16.93	17.08	16.74	17.14	17.23	17.56	17.18	17.48	17.55	16.92	16.87	16.40	16.63	15.94	16.50
Total	99.30	98.16	99.45	99.51	99.57	99.10	99.46	99.83	99.91	99.33	98.87	99.38	99.25	99.42	99.02	98.90	99.76	98.96	99.17	99.65	99.86	99.16	99.74	99.80	99.32	99.79	99.37	99.95	99.81	99.96	99.70	99.57
O(8)																																
Si	3.00	2.91	3.00	2.99	3.01	2.99	3.00	3.01	3.00	3.01	3.01	2.99	2.99	3.01	3.00	3.02	3.00	3.03	3.02	3.00	3.02	3.03	3.02	3.01	3.02	3.02	3.00	3.01	3.02	3.02	3.03	3.05
Al	0.97	1.08	0.98	0.98	0.97	0.97	0.97	0.96	0.97	0.97	0.97	0.99	0.99	0.96	0.99	0.96	0.97	0.95	0.95	0.99	0.95	0.95	0.96	0.96	0.96	0.96	0.98	0.97	0.94	0.94	0.94	0.92
Ca	-	0.01	0.02	0.02	0.02	0.02	-	0.02	0.02	-	0.01	-	-	0.02	-	0.01	0.02	-	0.02	0.01	0.01	0.01	0.01	0.01	-	0.01	0.02	0.02	0.01	0.01	0.01	0.01
Na	-	0.03	-	0.03	-	0.04	-	0.04	0.03	0.03	-	0.08	0.08	0.03	0.04	-	0.03	-	-	0.03	0.03	-	-	0.03	-	-	-	0.04	0.08	0.07	0.09	0.05
K	1.05	0.98	1.01	1.03	1.03	1.02	1.06	1.02	1.02	1.01	1.02	0.97	0.96	1.02	0.97	0.99	1.02	1.01	1.02	0.99	1.02	1.03	1.04	1.02	1.04	1.04	1.01	1.00	0.97	0.98	0.94	0.98
% An	-	1.2	2.0	1.7	1.5	2.0	-	1.5	1.6	-	1.3	-	-	1.7	-	1.1	1.6	-	1.6	1.0	1.0	1.1	1.2	1.1	-	1.1	1.7	1.6	1.3	1.3	1.4	1.2
% Kf	100.0	96.9	100.0	96.8	100.0	96.5	100.0	96.1	96.9	97.2	100.0	92.7	92.6	97.4	96.5	100.0	97.2	100.0	100.0	96.7	97.2	100.0	100.0	97.0	100.0	100.0	100.0	96.6	92.1	93.2	91.2	95.3
% Ab	-	1.4	-	1.2	-	1.2	-	1.6	1.3	2.8	-	7.8	7.9	1.0	3.6	-	1.1	-	-	1.7	1.5	-	-	1.5	-	-	-	1.3	3.6	3.2	3.9	2.3

Epidote	"Pristine" Calc-silicate				Less Altered	"Altered" Schist + "Breccia" psd-ign texture					Pristine Metadolerite		"Altered" Metadolerite							
	DP#44663			DP#44666	DP#44654	DP#46323		DP#46307		DP#46325	DP#46305		DP#46313		DP#44625					
	1\1	1\2	2\1	2\1	1\1	2\1	2\2	2\1	6\1	3\2	1\1	1\2	2\1	1	1\1	1\2	1\3	1\4	2\2	2\3
SiO2	38.69	39.04	39.25	39.30	38.65	39.98	39.44	39.13	38.96	39.37	39.48	39.27	39.03	39.14	39.12	39.04	38.99	39.38	39.12	39.38
TiO2	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Al2O3	20.11	21.80	20.84	21.06	21.58	28.05	24.24	21.03	19.69	23.00	21.75	22.62	27.04	25.16	24.48	19.97	21.79	21.64	21.67	22.90
Fe2O3	18.17	15.37	18.04	15.74	15.44	7.06	11.97	16.66	17.66	13.83	15.37	13.33	8.64	10.72	11.65	17.14	15.57	14.46	14.94	13.96
CaO	21.86	21.80	21.76	21.97	22.34	22.34	21.77	22.00	21.40	21.56	21.82	21.94	22.30	22.19	22.27	21.64	22.34	22.14	21.58	21.64
Total	98.82	98.01	99.90	98.07	98.01	97.43	97.42	98.83	97.70	97.76	98.42	97.16	97.02	97.21	97.52	97.79	98.69	97.62	97.31	97.88
O(12.5)																				
Si	3.08	3.10	3.07	3.13	3.06	3.10	3.11	3.10	3.12	3.10	3.12	3.12	3.05	3.08	3.08	3.13	3.08	3.13	3.12	3.11
Ti	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Al	1.89	2.04	1.92	1.97	2.02	2.56	2.25	1.96	1.86	2.14	2.03	2.12	2.49	2.34	2.28	1.89	2.03	2.03	2.04	2.13
Fe	1.09	0.92	1.06	0.94	0.92	0.41	0.71	0.99	1.06	0.82	0.91	0.80	0.51	0.64	0.69	1.03	0.93	0.87	0.90	0.83
Ca	1.87	1.86	1.83	1.87	1.90	1.85	1.84	1.87	1.84	1.82	1.85	1.87	1.87	1.87	1.88	1.86	1.89	1.89	1.85	1.83
Ps	36.6	31.0	35.6	32.3	31.3	13.8	24.0	33.6	36.4	27.7	31.1	27.3	16.9	21.4	23.3	35.4	31.3	29.9	30.6	28.0

Ps=100*Fe/(Fe+Al)

Apatite	"Pristine" CS	"Altered" Calc-silicate										"Altered" Schist								Maronan Prospect		
	DP#44628	DP#44585			DP#44638		DP#44586				DP#44674	DP#44606								DP#46361		
	2\1	1\2	2	3	7	8	1	2	5	6	3\1	6\1	6\2	5\1	5\2	5\3	1B	2B	4	1\1	1\3	1\4
CaO	54.44	56.58	54.79	57.99	54.54	54.57	55.09	55.21	54.68	54.72	52.55	54.12	53.93	54.61	54.28	53.88	50.83	58.04	54.08	53.96	53.81	53.62
Cl	<0.30	<0.30	<0.30	<0.30	<0.30	<0.30	<0.30	<0.30	<0.30	<0.30	0.58	0.45	0.40	0.42	0.43	0.42	<0.30	<0.30	<0.30	<0.30	<0.30	<0.30
H2O	1.67	1.73	1.65	1.72	1.65	1.64	1.68	1.69	1.65	1.66	1.56	1.55	1.63	1.65	1.66	1.67	1.69	1.68	1.64	1.66	1.66	1.66
P2O5	40.35	41.18	38.93	38.60	39.11	39.25	39.11	39.14	39.20	39.17	40.50	40.38	40.90	41.48	41.90	41.17	43.18	39.02	39.39	38.08	38.22	38.57
O=Cl	-	-	-	-	-	-	-	-	-	-	0.13	0.10	0.09	0.09	0.10	0.09	-	-	-	-	-	-
Total	96.46	99.56	95.48	98.34	95.44	95.66	95.95	96.06	95.67	95.67	95.07	96.39	96.76	98.06	98.17	97.04	95.88	98.93	95.29	93.71	93.69	93.87
O(26)																						
Ca	10.15	10.26	10.40	10.80	10.34	10.33	10.41	10.42	10.35	10.36	9.91	10.12	10.01	10.00	9.90	9.95	9.33	10.74	10.25	10.44	10.40	10.33
Cl	-	-	-	-	-	-	-	-	-	-	0.17	0.13	0.12	0.12	0.12	0.12	-	-	-	-	-	-
OH	1.94	1.95	1.95	1.99	1.95	1.93	1.97	1.99	1.94	1.96	1.83	1.81	1.88	1.88	1.88	1.92	1.93	1.93	1.94	2.00	2.00	1.99
P	5.94	5.90	5.84	5.68	5.86	5.87	5.84	5.83	5.86	5.86	6.04	5.96	6.00	6.00	6.04	6.01	6.27	5.70	5.90	5.82	5.84	5.87
X-Cl	-	-	-	-	-	-	-	-	-	-	0.1	0.1	0.1	0.1	0.1	0.1	-	-	-	-	-	-
X-OH	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.0	1.0	1.0

Carbonate	"Breccia" pseudo-igneous texture																
	DP#46315				DP#46316						DP#46324			DP#46325		DP#46326	
	1\2	1\3	5\1	2\1	1\1	2\1	2\2	4\1	7\1	7\2	4\1	1\2	1\3	1\1	1\3	2\2	3\1
FeO	1.70	6.40	1.23	<0.20	1.98	0.67	5.91	3.19	2.59	0.95	<0.20	<0.20	<0.20	0.76	0.60	<0.20	<0.20
MnO	0.76	0.78	1.37	0.25	1.96	<0.20	0.33	0.27	0.32	<0.20	<0.20	<0.20	0.27	<0.20	<0.20	<0.20	<0.20
MgO	1.70	0.90	0.64	<0.20	1.31	2.59	2.46	3.79	2.86	3.01	<0.20	<0.20	<0.20	0.69	0.65	<0.20	<0.20
CaO	50.68	46.92	53.07	55.56	50.75	52.87	47.00	48.62	49.19	50.65	56.61	56.50	56.50	54.94	54.79	55.67	55.33
CO2	43.23	42.31	43.94	43.76	43.68	44.83	43.40	44.41	43.50	43.62	44.43	44.34	44.51	44.34	44.07	43.85	43.65
Total	98.07	97.31	100.24	99.57	99.68	100.96	99.10	100.28	98.45	98.23	101.04	100.84	101.29	100.73	100.11	99.52	98.98
O(3)																	
Fe	0.02	0.09	0.02	-	0.03	0.01	0.08	0.04	0.04	0.01	-	-	-	0.01	0.01	-	-
Mn	0.01	0.01	0.02	0.00	0.03	-	0.00	0.00	0.00	-	-	-	0.00	-	-	-	-
Mg	0.04	0.02	0.02	-	0.03	0.06	0.06	0.09	0.07	0.08	-	-	-	0.02	0.02	-	-
Ca	0.92	0.87	0.95	1.00	0.91	0.93	0.85	0.86	0.89	0.91	1.00	1.00	1.00	0.97	0.98	1.00	0.99
C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
siderite	2.5	10.2	1.7	-	2.9	0.9	9.1	4.6	3.8	1.3	-	-	-	1.1	0.8	-	-
rhodochrosite	1.1	1.1	1.9	0.3	2.8	-	0.5	0.4	0.5	-	-	-	0.4	-	-	-	-
magnesite	4.3	2.3	1.6	-	3.3	6.3	6.2	9.3	7.2	7.5	-	-	-	1.7	1.6	-	-
calcite	92.2	87.2	94.8	99.7	91.2	92.7	85.0	85.9	88.7	91.1	100.0	100.0	99.6	97.3	97.6	100.0	100.0

Prehnite	Vein controlled			
DP#46309				
	4\1	4\2	3	4
SiO2	45.23	45.10	45.08	44.32
Al2O3	24.12	23.63	23.73	23.27
Fe2O3	0.65	0.50	0.62	1.56
MgO	0.20	<0.20	<0.20	0.28
CaO	25.13	24.99	24.70	25.04
Na2O	<0.20	<0.20	<0.20	0.32
Total	95.55	94.21	94.13	94.79
O(11)				
Si	3.08	3.11	3.11	3.06
Al	1.94	1.92	1.93	1.90
Fe	0.03	0.03	0.03	0.08
Mg	0.02	-	-	0.04
Ca	1.84	1.85	1.83	1.86
Na	-	-	-	0.04
100*Fe/(Fe+Al)	1.7	1.3	1.6	4.1

Maronan Probe Data

Mag	DP#46367		46368	DP#46389		
	2\1	1\2	1\2	1\1	1\2	2\1
TiO2	<0.20	<0.20	0.76	0.56	0.32	0.49
Fe2O3	67.25	66.82	66.81	66.69	66.63	65.41
FeO	29.57	29.52	30.07	30.38	30.1	30.31
MnO	0.69	0.50	<0.20	0.58	0.45	<0.20
Total	97.5	97.87	96.92	98.11	97.5	96.21
O(4)						
Ti	-	-	0.00	0.02	0.01	0.01
Fe3+	2.00	2.00	1.00	1.00	0.99	1.01
Fe2+	0.98	0.98	2.00	1.97	1.97	1.96
Mn	0.02	0.02	-	0.02	0.02	-
Uvs	-	-	0.0	1.7	1.0	1.5
Mag	100	100	100.0	98.4	99.1	98.5

Apatite	DP#46363					DP#46367		46381	DP#46361		
	1\1	1\2	3\1	1\1B	1\2	1\1	1\2	4\1	1\1	1\3	1\4
CaO	54.35	53.92	53.81	53.57	53.16	52.95	51.51	52.87	53.96	53.81	53.62
Cl	na	na	na	na	na	na	na	<0.20	<0.30	<0.30	<0.30
H2O	1.55	1.62	1.67	1.67	1.66	1.67	1.68	1.68	1.66	1.66	1.66
P2O5	40.05	40.00	40.18	40.00	40.00	40.93	40.71	41.05	38.08	38.22	38.57
O=Cl								-	17.54	17.24	16.71
Total	96.16	95.26	96.08	96.26	95.45	95.22	93.84	96.32	93.71	93.69	93.87
O(26)											
Ca	10.33	10.36	10.20	10.10	10.14	10.19	10.00	9.98	10.44	10.40	10.33
Cl								-	-	-	-
OH	1.81	1.85	1.88	1.91	1.90	1.91	1.91	1.89	2.00	2.00	1.99
P	6.08	6.11	6.09	6.03	6.06	6.23	6.24	6.12	5.82	5.84	5.87
X-Cl	-	-	-	-	-	-	-	-	-	-	-
X-OH	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Bst	46363	DP#46407	Pyroxmangite				
	1\1	1	2	3	4	5	6
SiO2	44.90	46.14	46.25	46.47	45.87	46.57	46.47
FeO	26.70	26.01	26.17	26.89	26.18	27.34	26.98
MnO	21.23	24.51	23.80	23.72	23.36	23.35	23.11
MgO	0.52	0.35	0.47	0.26	<0.20	0.29	0.43
CaO	4.16	1.59	1.66	1.92	1.69	1.76	2.00
Total	97.51	98.60	98.36	99.27	97.10	99.31	99.00
	O(6)	O(6)	O(6)	O(6)	O(6)	O(6)	O(6)
Si	1.99	2.02	2.03	2.02	2.02	2.02	2.02
Fe	0.99	0.91	0.88	0.87	0.87	0.86	0.85
Mn	0.80	0.02	0.03	0.02	-	0.02	0.03
Mg	0.03	0.07	0.08	0.09	0.08	0.08	0.09
Ca	0.20	0.03	0.00	0.00	0.10	0.00	0.00
X-Fe	49.0	88.0	89.0	89.1	82.7	89.6	87.5
X-Mn	39.5	2.2	3.1	1.7	0.0	2.1	2.9
X-Mg	1.7	7.2	7.9	9.1	7.6	8.3	9.6
X-Ca	9.8	2.6	0.0	0.0	9.7	0.0	0.0

Knb 46388
1\3
29.24
47.69
20.06
<0.20
<0.20
96.98
O(4)
1.01
1.38
0.59
-
-
70.1
29.9
0.0
0.0

	DP#46389		Cum-Dan			
	1\1	1\2	1\3	3\1	3\2	3\3
SiO2	50.19	49.05	48.48	48.62	48.32	48.06
Al2O3	<0.20	0.40	0.30	0.32	0.24	<0.20
FeO	38.09	37.85	38.07	37.79	37.56	38.65
MnO	6.88	7.52	7.68	7.89	7.31	7.34
MgO	1.67	1.24	1.71	1.68	1.15	1.40
CaO	<0.20	0.25	0.22	0.39	<0.20	<0.20
Total	96.83	96.31	96.46	96.69	94.59	95.44
	O(23)	O(23)	O(23)	O(23)	O(23)	O(23)
Si	8.21	8.12	8.04	8.04	8.15	8.08
Al	-	0.08	0.06	0.06	0.05	-
Fe	5.21	5.24	5.28	5.23	5.30	5.44
Mn	0.95	1.05	1.08	1.11	1.04	1.05
Mg	0.41	0.31	0.42	0.42	0.29	0.35
Ca	-	0.04	0.04	0.07	-	-
X-Mn	0.1	0.2	0.2	0.2	0.2	0.2
Mg/Fe	0.1	0.1	0.1	0.1	0.1	0.1
X-Fe	0.9	0.9	0.9	0.9	0.9	0.9

Pyros	46388
	1\4
SiO2	32.55
FeO	29.20
MnO	21.02
Na2O	0.92
H20	8.22
Cl	0.90
O=Cl	0.20
Total	93.16
	O(25)
Si	5.94
Fe	4.45
Mn	3.25
Na	0.33
OH	10.00
Cl	0.28
Mn/Fe	0.7
OH calc as 10	

Carbonates	DP#46350			DP#46367							DP#46368		DP#46371				
	2\1	1\2	3\1	4\1	4\2	4\3	1\1	1\3	1\4	1\1B	2\1	2\2	1\1	1\1B	1\2	1\3	1\4
FeO	58.40	58.18	59.05	<0.20	<0.20	<0.20	2.84	<0.20	<0.20	<0.20	46.54	49.94	2.08	43.40	3.16	1.69	1.87
MnO	<0.20	0.22	<0.20	45.53	44.18	45.10	43.05	47.40	44.78	44.25	2.70	2.86	6.26	3.04	6.86	37.49	41.83
Mg	<0.20	<0.20	<0.20	2.95	2.77	2.77	1.99	2.28	2.97	2.85	1.79	1.93	0.20	4.86	<0.20	0.46	1.36
CaO	<0.20	0.44	<0.20	7.19	8.03	8.21	7.56	6.62	7.90	7.75	4.20	3.92	45.64	5.21	46.99	15.87	9.88
CO2	38.96	39.06	38.94	41.79	42.14	41.45	41.32	41.32	41.28	41.70	41.19	39.10	43.31	41.31	41.99	41.99	41.68
Total	97.35	97.90	97.99	97.47	97.11	97.54	96.76	97.62	96.92	96.54	96.41	97.75	97.50	97.82	98.99	97.50	96.62
O(3)																	
Fe	0.93	0.93	0.95	-	-	-	0.04	-	-	-	0.72	0.78	0.03	0.66	0.05	0.03	0.03
Mn	-	0.00	-	0.70	0.68	0.69	0.66	0.73	0.69	0.68	0.04	0.05	0.09	0.05	0.10	0.58	0.65
Mg	-	-	-	0.08	0.07	0.08	0.05	0.06	0.08	0.08	0.05	0.05	0.01	0.13	-	0.01	0.04
Ca	-	0.01	-	0.14	0.16	0.16	0.15	0.13	0.15	0.15	0.08	0.08	0.84	0.10	0.87	0.31	0.19
C	1.02	1.02	1.02	1.03	1.04	1.03	1.02	1.03	1.03	1.03	1.04	1.00	1.02	1.03	0.99	1.04	1.04
Sd	100.0	98.7	100.0	-	-	-	4.8	-	-	0.0	80.5	81.5	3.1	70.2	4.5	2.8	3.2
Rds	-	0.4	-	76.1	74.6	74.7	73.1	79.3	74.6	74.9	4.7	4.7	9.4	5.0	9.9	62.4	71.4
Mgs	-	-	-	8.7	8.2	8.1	6.0	6.7	8.7	8.5	5.5	5.6	0.5	14.0	-	1.4	4.1
Cal	-	1.0	-	15.2	17.2	17.2	16.2	14.0	16.7	16.6	9.3	8.2	86.9	10.8	85.6	33.4	21.3

Garnet			DP#46340				46371	46372	46389
	1\1	1\2	2\4	2\6	3\1	3\2	3\2	2\1
SiO2	35.96	36.36	36.63	36.78	36.16	36.22	37.47	36.08
Al2O3	19.95	20.20	20.46	20.14	20.28	18.88	20.17	20.32
FeO	21.08	21.10	26.04	25.92	25.11	17.95	13.85	20.22
MnO	15.90	15.75	8.18	8.33	8.89	18.37	25.29	19.58
MgO	0.42	<0.20	0.81	0.98	0.45	0.39	0.20	0.39
CaO	4.59	4.69	5.87	6.02	7.08	6.04	1.30	2.00
Total	97.90	98.11	97.98	98.17	97.97	97.85	98.27	98.57
O(12)								
Si	3.00	3.02	3.02	3.03	2.99	3.03	3.09	3.00
Al	1.96	1.98	1.99	1.95	1.98	1.86	1.96	1.99
Fe 2+	1.43	1.44	1.79	1.74	1.71	1.12	0.96	1.40
Fe 3+	0.04	0.02	0.00	0.05	0.03	0.14		0.01
Mn	1.12	1.11	0.57	0.58	0.62	1.30	1.77	1.38
Mg	0.05	-	0.10	0.12	0.06	0.05	0.02	0.05
Ca	0.41	0.42	0.52	0.53	0.63	0.54	0.11	0.18
Alm	46.9	48.3	60.2	57.6	56.2	0.0	33.4	46.4
Grs	13.4	14.0	17.4	17.6	20.6	17.2	4.0	5.9
Prp	1.7	0.0	3.3	4.0	1.8	1.6	0.9	1.6
Sps	36.7	37.0	19.1	19.3	20.5	41.4	61.8	45.8
Adr	1.2	0.7	0.0	1.5	0.9	4.4		0.3

Biotite	46363	DP#46382		
	1\0	3\1	3\2	3\3
SiO2	29.16	37.43	38.29	38.54
TiO2	<0.20	2.13	2.10	2.18
Al2O3	10.47	14.70	13.78	13.73
FeO	35.95	21.62	20.11	19.73
BaO	6.71	na	na	na
MnO	1.84	0.28	0.23	0.35
MgO	1.19	11.80	11.99	12.08
CaO	<0.20	<0.20	0.22	<0.20
Na2O	<0.30	<0.30	<0.30	<0.30
K2O	6.57	9.28	9.93	10.11
Cl	3.91	0.36	0.34	0.29
S	2.02	<0.30	<0.30	<0.30
O=Cl	0.88	0.08	0.08	0.07
O=S	0.50	-	-	-
Total	96.43	97.51	96.91	97.14
O(22)				
Si	5.24	5.63	5.77	5.79
Ti	-	0.24	0.24	0.25
Al	2.23	2.62	2.46	2.44
Fe	5.41	2.72	2.53	2.48
Ba	0.47			
Mn	0.28	0.04	0.03	0.04
Mg	0.32	2.64	2.69	2.70
Ca	-	-	0.03	-
Na	-	-	-	-
K	1.51	1.78	1.91	1.94
Cl	1.19	0.09	0.09	0.07
S	0.68	-	-	-
X-Mg	0.1	0.5	0.5	0.5
X-Mg=Mg/(Fe+Mg)				

Kfs	46367
	3\2
SiO2	62.59
Al2O3	18.76
FeO	0.46
BaO	0.51
MnO	0.45
CaO	<0.20
Na2O	0.87
K2O	15.16
Total	98.80
O(8)	
Si	2.95
Al	1.05
Fe	0.02
Ba	0.01
Mn	0.02
Ca	-
Na	0.08
K	0.91
Kfs%	91.1
An%	-
Ab%	7.9
Ba%	0.9

Tur	DP#46340		Tourmaline		
	1\1	1\2	1\3	1\4	1\5
SiO2	33.59	33.43	33.76	33.79	33.42
TiO2	0.85	0.75	0.79	0.81	0.32
Al2O3	29.95	29.77	29.10	29.71	29.87
Cr2O3	<0.25	<0.25	<0.25	<0.25	<0.25
FeO	10.95	12.05	11.25	11.70	12.87
MnO	<0.20	<0.20	<0.20	<0.20	0.30
MgO	4.35	4.48	5.00	4.96	3.94
CaO	1.25	1.22	1.37	1.45	1.10
Na2O	1.85	1.97	2.06	1.94	1.94
K2O	<0.20	<0.20	<0.20	<0.20	<0.20
Total	82.79	83.67	83.34	84.36	83.75
O(24.5)					
Si	5.85	5.80	5.86	5.82	5.83
Ti	0.11	0.10	0.10	0.10	0.04
Al	6.18	6.12	5.99	6.06	6.18
Cr	-	-	-	-	-
Fe	1.59	1.75	1.63	1.68	1.88
Mn	-	-	-	-	0.04
Mg	1.13	1.16	1.29	1.27	1.02
Ca	0.23	0.23	0.26	0.27	0.20
Na	0.63	0.66	0.69	0.65	0.66
K	-	-	-	-	-

Plg	DP#46350					DP#46381		
	1\1	1\2	1\3	1\3b	2\1	4\1	4\2	4\2
SiO2	62.49	61.93	62.74	61.70	61.36	67.33	67.52	66.63
Al2O3	23.36	23.19	23.57	23.32	22.77	20.03	20.06	20.08
CaO	4.28	4.45	4.65	4.52	4.52	0.48	0.60	0.69
Na2O	9.79	9.35	9.32	9.60	9.59	12.35	12.03	12.23
Total	100.20	99.39	100.29	99.14	99.24	100.19	100.21	99.61
O(8)								
Si	2.77	2.76	2.77	2.76	2.76	2.95	2.95	2.94
Al	1.23	1.23	1.23	1.24	1.21	1.04	1.04	1.05
Ca	0.20	0.21	0.22	0.22	0.22	0.02	0.03	0.03
Na	0.84	0.81	0.80	0.83	0.84	1.05	1.02	1.04
An%	19.2	20.6	21.6	20.6	20.3	2.1	2.7	3.0
Ab%	79.3	78.2	78.4	79.4	78.0	97.9	97.3	97.0

ENERGY DISPERSIVE SPECTRA of some MINERALS of the Maronan Prospect

Cassiterite (SnO_2) and possibly small traces of herzenbergite (SnS), probably also berndtite (SnS_2) were probed in the Maronan Prospect. The tin oxides are more common than tin sulphides. Cassiterite occurs as subrounded grains. Cassiterite appears in fractures of pyroxenoids, feldspars, carbonates and garnets, while the tin sulphides only occur in the pyroxenoids. However, the above might also be polishing material.

The occurrence of tin as a late overprinting stage suggest reducing conditions. Pyrrhotite is the stable iron mineral during cassiterite mineralization, indicating that the oxygen fugacity is in the order of $10^{-30.1}$ atmosphere at 350°C (Patterson *et al.* 1981). Based on the presence of arsenopyrite and pyrrhotite as the stable sulphides during cassiterite mineralization Patterson *et al.* (1981) calculated a $\log_{10} f_{S2}$ in the order of -9.6 to -12.3 atmosphere.

Uranium was also probed, possibly in the form as oxide, pitchblende (UO_2), with lead and traces of iron (Figure A.1). This was found in magnetite, as a rounded grain. Silver appears to be native. Monazite and allanite are observed as minor traces in green alteration biotites. Jarosite and viyanite (not shown) are observed in gossans east of Percy Bore. Monazite is also observed in the "altered corundum bearing" schist.

Figure A.1 - Energy dispersive spectra of unusual minerals of the Maronan Prospect, and gossans nearby.

APPENDIX D

Density measurements	D1
XRF method	D1
XRF sample preparation	D2
Neutron activation analyses	D3
Table - XRF data 1 - Pristine, Moderate, Altered Calc-silicate	D4
Table - XRF data 2 - Vein jog breccias, Breccias pseudo-igneous texture, schist	D5
Table - XRF data 3 - Metadolerite	D6
Table - NAA - Maronan data	D7
Table - XRF - Maronan data - MND7	D8
Table - REE data - Maronan data	D9

DENSITY MEASUREMENTS

The densities of some large hand specimens determined by the principle of Archimedes. Special care was taken to select homogeneous material. The volume was determined by measuring the apparent loss in weight when weighed specimen is immersed in a liquid of known specific gravity (in this case water of 26°-27°C). The immersed specimen displaces an amount of liquid equal to its own volume and its weight is apparently diminished by the weight of the liquid displaced. If W_a is the weight of the specimen in air and W_l is the weight of the specimen when immersed in liquid of specific gravity L, the specific gravity of the specimen is than SG = $(W_a \times L)/(W_a - W_l)$. The data is tabulated in Table A2.

Table A2 - Density data of specific specimen from the Maramungee Creek section.

Sample	Type	W_{air}	W_{liquid}	SG	Sample	Type	W_{air}	W_{liquid}	SG
DP#44586	CS_h-A	1783	1131	2.625	DP#44609	Schist	142	87	2.479
DP#44638	CS_h-A	45	28	2.541	DP#44610	Schist	529	327	2.310
DP#44652	CS_h-A	416	262	2.593	DP#44607	Clast	1644	1022	2.537
M134A	CS_h-B	770	489	2.631	DP#44608	Bx	557	354	2.634
M134E	CS_h-A	1132	729	2.697	DP#44597	MD	1418	955	2.940
DP#44653	CS_m-A	486	306	2.592	DP#44598	MD+V	116	73	2.590
DP#44590	Vjb	2688	1691	2.588	DP#44675	MD	539	359	2.875
DP#44638*	Vjb	829	521	2.584	DP#44678	MD	131	83	2.620

NB. Temperature and specific gravity for water is respectively 26°-27°C and SG_{H2O} = 0.96 kg/m^3. CS_h-A+B-Altered calc-silicate, CS_m-A-Moderately altered calc-silicate, Vjb-vein jog breccia, Schist-Corundum bearing schist, Clast-altered schist clast, Bx-breccia matrix with pseudo-igneous texture, MD-metadolerite, V-vein, SG-specific gravity. Weight in grams. * sample DP#44638 is split in CS and Vjb.

XRF METHOD

The XRF setup used for major and trace element analysis of whole rock samples in this study is a SIEMENS 303 SEQUENTIAL X-RAY FLUORESCENCE SPECTROMETER, done at the Advanced Analytical Centre at James Cook University of North Queensland. The X-rays are generated in an X-ray tube by heating a W filament, so it ionises by giving off electrons, which are attracted by an anode. These X-rays are the source of photons to bombard the sample elements. The elements then give off secondary X-rays, the fluorescent X-rays, with different energies, and are read by detectors. Calibration of the SIEMENS 303 was done by the personnel of the Advanced Analytical Centre, using international rock standards. Samples used for analyses, were despatched in batches to overcome any instrumental drift.

In the XRF data tables, values with a "dl" indicate values below detection limits, "-" indicate no analysis for that element. Duplicates were made of some samples to ensure the reliability of the analyses. There were totally 90 samples involved in major and trace analysis. Precision, based on duplicates, was estimated using the

equation : % Error (1σ) = 100*standard deviation / average, and are tabulated below, Table A3.

Table A3 - Errors estimated on duplicates.

	Major elements							Trace elements					
	Series 1			Series 2				Series 1			Series 2		
	Avg.	St. Dev	Error	Avg.	St. Dev	Error		Avg.	St. Dev	Error	Avg.	St. Dev	Error
SiO2	58.75	0.68	1.16	64.19	0.35	0.54	Rb	192.70	2.16	1.12	20.65	1.38	6.69
TiO2	0.71	0.12	17.18	0.60	0.14	22.71	Sr	139.60	0.92	0.66	64.15	0.46	0.72
Al2O3	16.45	0.41	2.50	14.11	0.57	4.01	Sc	16.00	0.00	0.00	11.05	0.27	2.41
Fe2O3t	6.75	0.03	0.39	2.84	0.51	17.88	V	95.95	1.70	1.77	59.00	1.68	2.85
MnO	0.06	0.03	43.95	0.05	0.08	186.87	Cr	85.90	1.72	2.01	61.35	2.27	3.70
MgO	2.83	0.25	8.83	2.93	0.27	9.22	Co	51.60	3.87	7.50	47.60	2.55	5.36
CaO	4.41	0.21	4.67	5.91	0.20	3.43	Ni	32.05	1.16	3.62	13.55	1.43	10.57
Na2O	3.14	0.12	3.79	7.56	0.29	3.90	Zn	18.15	2.01	11.06	10.10	1.64	16.23
K2O	4.93	0.49	9.90	0.62	0.25	40.76	Ga	27.20	0.53	1.96	20.95	1.22	5.82
P2O5	0.14	0.13	94.40	0.15	0.20	134.12	Y	26.85	0.46	1.72	35.70	1.80	5.05
LOI	1.08	0.19	17.49	0.94	0.22	23.79	Zr	177.60	3.28	1.85	191.55	3.02	1.58
Total	98.76	0.51	0.52	99.39	0.63	0.63	Nb	15.20	1.06	7.00	13.55	0.80	5.89

XRF SAMPLE PREPARATION

- Preparation of samples for major components

1. Powdered whole rock sample was weighted and than heated in a oven set at 1100°C for 12 hours. Weight again after cooling to obtain the datum of lost of ignition (LOI).
2. Weigh 0.42 g and mix it well with 2.2 g flux (Lithium Borate flux), using an electronic scale. The mixed powders were than placed in a platinum crucible.
3. Heat the crucible at 1100°C for 5 minutes, than agitate the sample for 20 minutes at the same temperature.
4. Take the crucible out and quickly pore the liquid melt into a graphite mould set at 200°C and leave for 5 minutes.
5. Remove the glass disc from the graphitic mould onto a hot plate set at 70°C for at least 30 minutes for annealing.

- Preparation of trace element analysis samples

Samples were made as powder pallets for trace element analysis. The procedure is as follows.

1. Mix 2 g powdered sample with a few drops of PVA (poly vinyl acetate) and put into a steel cylinder with a aluminium sleeve of 2mm thick. A plastic piston of the same inner diameter as the aluminium sleeve was then inserted into the sleeve and pressed firmly by hand.
2. Carefully remove the piston and the sleeve. Put 2 g of boric acid into the cylinder and insert a steel piston and put the whole cylinder into a hydraulic press.
3. Pump the presser to increase the pressure to 2000 bar, and leave for a few minutes.
4. Remove the pellet from the cylinder.

- Whole Rock Geochemistry from MND 7

MND 7 was selected by Billiton Australia, for a study of whole rock geochemistry in an attempt to characterise the lithologies and alteration halo patterns. The initial sampling of MND 7 core was on a metre intervals, taken into account lithological boundaries. These samples consisted of sawn half core which was despatched to Australian Assay Laboratories in Townsville. These samples were analysed for Cu, Pb, Zn, Ag, As and Mn by AAS and Au by 50 gram fire assay. A triple acid digest was used in the Mn sample preparation to approximate total digestion. Pulps of these original samples were then composited into approximately 5m samples, taken lithology boundaries into account, and were analysed for the following oxide elements, SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, K_2O, Na_2O by XRF and the following trace elements by XRF, Rb, Sr, Ba, Y and Zr. The weighted average of the original Cu, Pb, Zn, Ag, As and Au assays was calculated for each of the composited intervals.

NEUTRON ACTIVATION ANALYSES

Approximately 30 grams of powdered whole rock sample was sent to BECQUEREL LABORATORIES Pty. in Sydney NSW. NAA has a low detection limit for specific elements, such as gold and rare earth elements. The sample is placed in a vail, exposed to a neutron flux and the resulting element's radioactivity is counted to give an estimate of the elements concentration. The gamma rays are detected by solid state detectors, and is counted using pulse height selection and energy dispersion of the spectrum.

The neutron flux is in the order of 10^{12}n/cm^2/sec. This flux has detection limits for most elements of 10^{-3} to 10 μg. The samples are bundled together with a reference standard and flux monitors. The principle sources of errors are the counting uncertainties, uneven exposure of samples and standard to the neutron flux. However, the uncertainties are as low as 1 to 3 % (pers. comn. Becquerel Laboratories 1995). Elements analysed by NAA are: Au, Ag, Fe, Na, K, Rb, Cs, Ba, Sc, Cr, Co, Zn, As, Sb, Se, Br, La, Ce, Sm, Eu, Yb, Lu, Ir, Mo, Hf, Ta, Th, W, and U.

In the NAA data tables, values with a "dl" indicate values below detection limits, however in last REE Table "<" indicate values below detection limits. Detection limits are given in the NAA data tables.

Table - XRF data 1

	Pristine Calc-silicate (CS-A)								(CSm-B)		Moderately Altered Calc-silicate (CSm-A)							
Sample	29CS	74CS	81	83	83d	88CS	89	97	115	140	8CS	79	143	143B	147	151	157ACS	157B
DP#	44601	44622	44627	44629	44629d	44631	44632	44634	44637	44651	44591	44626	44653	44654	44657	44662	44665	44666
SiO2	59.44	65.74	64.00	58.42	59.08	71.42	61.43	62.04	63.26	62.02	68.04	59.75	64.83	64.81	62.99	62.03	63.80	64.36
TiO2	0.67	0.63	0.67	0.70	0.72	0.54	0.77	0.71	0.53	0.60	0.61	0.68	0.59	0.61	0.59	0.84	0.62	0.68
Al2O3	17.18	15.14	14.45	16.33	16.57	13.18	16.96	14.82	18.36	14.67	12.06	16.59	13.82	14.65	14.86	15.56	14.51	13.78
Fe2O3t	6.65	4.79	5.65	6.75	6.75	3.79	6.60	5.87	5.12	5.19	7.07	6.70	5.57	5.59	5.64	5.80	5.66	5.68
MnO	0.05	0.04	0.07	0.06	0.06	0.02	0.06	0.09	0.04	0.08	0.01	0.04	0.05	0.04	0.02	0.03	0.03	0.04
MgO	3.15	2.45	2.73	2.78	2.87	2.83	3.38	2.69	2.93	2.95	3.01	3.02	2.69	3.46	2.80	2.54	3.13	3.50
CaO	3.09	1.40	3.64	4.44	4.38	2.16	2.59	4.06	1.59	4.65	2.80	3.22	4.27	3.59	4.17	3.17	4.36	2.67
Na2O	3.24	2.88	2.45	3.15	3.13	3.05	4.98	3.24	1.66	1.75	3.55	4.99	3.91	4.82	5.52	2.79	2.42	2.28
K2O	4.48	6.01	5.57	4.76	5.10	3.00	2.31	5.10	7.47	5.60	2.52	3.97	3.41	3.63	1.94	6.17	4.54	6.41
P2O5	0.15	0.15	0.15	0.13	0.15	0.15	0.15	0.15	0.15	0.12	0.19	0.15	0.15	0.14	0.15	0.14	0.16	0.16
LOI	1.36	1.87	1.44	1.05	1.10	1.92	1.47	1.24	2.37	2.44	0.97	2.09	2.16	1.14	1.29	1.18	1.76	1.70
Total	98.49	100.12	99.83	98.57	98.94	101.08	99.71	99.03	102.49	100.06	99.84	100.22	100.48	102.47	99.01	99.26	100.01	100.27
Rb	250	192	205	189	196	100	170	203	245	197	120	186	142	127	69	193	172	198
Sr	104	93	151	140	139	111	200	157	127	131	91	79	114	97	105	132	138	117
Sc	15	12	12	16	16	10	15	13	11	11	11	15	10	12	12	14	11	12
V	87	76	88	94	98	57	87	81	90	76	107	88	71	71	81	89	76	78
Cr	65	67	72	84	88	53	89	76	62	59	106	80	61	63	68	97	65	70
Co	37	31	41	62	41	45	43	46	36	52	52	31	44	57	43	34	28	41
Ni	29	25	28	31	33	16	32	27	27	26	31	33	30	25	30	28	27	30
Zn	14	12	18	15	21	13	27	12	31	30	3	19	13	8	8	5	239	19
Ga	28	23	22	27	27	20	29	21	26	21	21	25	22	19	27	23	24	19
Y	18	19	29	27	27	16	21	28	18	26	17	26	29	20	24	22	26	29
Zr	178	258	238	185	170	292	230	224	176	216	322	159	226	191	226	209	221	233
Nb	16	15	15	14	16	14	15	16	14	14	9	14	13	14	15	19	13	14

	Altered Calc-silicate (CSh-A)										Altered Calc-silicate (CSh-B)						
Sample	3	34	70	76	77	116CS	117CS	118	119	141	60A	60B	61	61d	168	170	171
DP#	44586	44602	44621	44623	44624	44638	44639	44640	44641	44652	44612	44613	44614	44614d	44671	44673	44674
SiO2	59.50	61.43	60.43	59.41	56.37	60.28	57.13	58.91	60.45	60.50	60.79	62.56	64.10	64.27	61.46	62.48	66.14
TiO2	1.04	0.76	0.65	0.67	0.71	0.66	0.65	0.56	0.58	0.64	0.68	0.66	0.58	0.61	0.53	0.64	0.48
Al2O3	14.38	17.97	15.91	16.97	18.49	18.57	17.09	14.22	14.70	16.32	15.31	15.51	13.89	14.34	13.52	14.01	13.19
Fe2O3t	4.51	3.72	4.55	6.95	7.02	5.50	5.75	6.78	6.08	5.50	3.08	5.64	2.66	3.02	4.71	5.80	3.52
MnO	0.04	0.01	0.03	0.03	0.03	0.03	0.02	0.04	0.03	0.01	0.05	0.03	0.04	0.05	0.04	0.03	0.04
MgO	4.20	2.29	3.28	2.77	3.07	1.94	2.63	4.10	3.39	2.91	3.09	1.37	2.88	2.98	3.83	3.20	3.08
CaO	7.25	2.62	4.29	4.29	4.36	3.17	3.37	6.60	5.55	2.56	6.22	2.25	5.88	5.94	6.62	3.72	5.68
Na2O	7.24	9.03	6.97	6.77	6.85	8.12	7.41	7.27	6.20	8.85	7.87	6.83	7.50	7.62	7.28	6.23	6.87
K2O	0.44	0.82	2.79	1.05	1.77	1.29	0.92	0.43	1.99	0.51	0.55	2.07	0.57	0.66	0.49	2.10	0.36
P2O5	0.10	0.04	0.17	0.18	0.15	0.15	0.13	0.15	0.18	0.11	0.15	0.15	0.12	0.18	0.20	0.14	0.14
LOI	0.90	1.08	2.24	1.29	2.20	0.94	1.10	0.74	0.75	0.76	1.05	1.59	0.90	0.97	0.77	1.09	0.88
Total	99.59	98.80	100.34	99.38	100.05	99.66	95.28	98.83	98.94	98.69	98.84	98.65	99.12	99.67	98.47	98.48	99.38
Rb	160	23	89	36	78	37	32	17	53	10	15	64	19	22	15	58	11
Sr	81	138	61	134	154	94	98	62	86	30	88	79	64	64	45	68	60
Sc	14	25	13	10	17	14	14	14	13	15	11	14	11	11	10	13	11
V	73	76	81	74	95	89	85	107	66	78	79	68	57	61	85	70	83
Cr	66	75	80	73	91	79	79	75	63	76	83	69	58	65	55	64	51
Co	78	60	29	43	26	37	27	33	34	45	57	45	52	43	35	33	33
Ni	27	18	25	29	40	19	31	29	27	27	15	23	12	15	19	32	12
Zn	6	5	14	45	17	7	6	17	5	5	16	9	8	12	13	8	12
Ga	19	30	23	27	31	29	28	26	24	27	24	26	20	22	24	24	21
Y	28	24	25	24	22	18	30	16	21	29	25	31	33	38	32	16	21
Zr	195	253	196	172	152	224	197	193	141	167	163	173	185	198	201	210	198
Nb	15	26	14	12	15	11	16	5	12	14	10	14	13	14	13	11	7

Table - XRF data 2

	Vein jog Breccias								Breccias pseudo-igneous texture								Clasts	
Sample	1	6	7	116	4	145	149B	169	50	51B	55B	58	130	131	135	135B	20	55A
DP#	44585	44589	44590	44638	44587	44656	44660	44672	44603	44605	44608	44611	44644	44645	44648	44649	44596	44607
SiO2	57.87	60.36	61.48	58.16	61.93	60.24	59.37	59.41	60.46	61.27	61.55	60.82	61.40	62.90	58.66	57.10	65.32	63.48
TiO2	0.46	0.63	0.78	0.68	0.67	0.54	0.65	0.59	0.09	0.09	0.62	0.80	0.63	0.74	1.08	0.54	0.81	1.45
Al2O3	11.52	14.27	14.78	14.37	17.66	13.84	15.57	13.59	13.58	12.58	12.52	14.19	12.82	11.57	13.10	12.27	14.82	17.03
Fe2O3t	6.96	4.53	2.91	6.77	4.47	5.38	7.27	6.89	4.09	5.29	4.70	3.49	4.52	6.67	4.57	6.13	2.43	1.20
MnO	0.04	0.02	0.03	0.04	0.02	0.02	0.02	0.03	0.07	0.05	0.04	0.03	0.03	0.04	0.07	0.06	0.02	0.01
MgO	9.31	4.15	5.30	5.83	1.12	5.78	3.49	3.87	3.92	5.09	6.49	3.82	4.25	5.72	4.80	5.23	1.87	1.71
CaO	7.07	5.22	4.71	4.73	1.33	3.89	2.43	4.21	7.39	6.12	5.06	7.12	6.96	4.76	8.84	9.38	3.35	2.64
Na2O	5.15	8.02	7.24	6.71	9.47	7.72	8.35	6.85	6.92	7.26	7.23	7.39	7.13	5.71	6.98	6.31	8.17	9.88
K2O	0.54	0.38	0.83	0.77	0.65	0.22	0.41	1.53	1.07	0.21	0.17	0.56	0.41	0.32	0.14	0.15	0.49	0.32
P2O5	0.14	0.13	0.26	0.13	0.04	0.03	0.08	0.13	0.13	0.04	0.04	0.02	0.05	0.04	0.13	0.02	0.15	0.36
LOI	1.44	0.87	1.15	1.34	0.79	0.95	0.94	0.97	0.81	0.95	1.01	0.91	1.18	1.34	1.59	2.16	1.98	0.85
Total	100.49	98.59	99.46	99.53	98.14	98.60	98.57	98.07	98.53	98.96	99.44	99.15	99.37	99.80	99.95	99.35	99.40	98.94
Rb	13	11	24	34	16	6	15	43	30	8	5	20	13	12	7	6	16	10
Sr	54	42	60	75	39	20	21	37	131	58	17	98	61	47	97	104	72	24
Sc	21	15	16	23	6	19	11	19	17	24	28	14	16	24	24	23	5	10
V	76	64	48	92	74	66	59	123	126	150	117	172	149	123	144	147	71	73
Cr	73	76	59	81	70	70	75	75	70	105	110	70	71	85	82	84	76	46
Co	86	47	29	45	57	37	58	59	38	60	50	54	60	66	41	45	70	60
Ni	94	28	30	61	12	56	33	34	16	26	32	9	14	41	21	28	8	8
Zn	16	6	10	11	7	8	6	9	11	11	15	6	7	15	34	19	5	6
Ga	21	22	22	24	28	23	25	24	22	23	22	23	22	22	22	24	21	28
Y	21	15	84	20	8	8	9	14	21	13	38	48	44	36	54	32	32	80
Zr	140	206	181	124	423	116	166	261	162	183	180	170	331	160	201	270	213	221
Nb	8	14	22	10	8	7	11	11	3	3	14	23	15	17	21	13	21	28

	SCHIST			
Sample	19	56	57	120A
DP#	44595	44609	44610	44642
SiO2	78.53	70.23	69.10	72.44
TiO2	0.36	0.53	0.53	0.52
Al2O3	9.39	13.77	14.61	13.08
Fe2O3t	3.16	4.95	4.79	4.43
MnO	0.03	0.05	0.06	0.07
MgO	0.67	1.22	1.28	1.40
CaO	0.74	0.53	0.54	0.90
Na2O	3.67	3.43	3.60	1.78
K2O	1.61	3.79	3.93	3.34
P2O5	0.09	0.14	0.12	0.12
LOI	0.83	1.09	1.08	1.86
Total	99.07	99.73	99.64	99.95
Rb	83	185	186	280
Sr	61	46	52	79
Sc	6	10	11	9
V	37	61	58	55
Cr	46	72	77	71
Co	181	75	98	67
Ni	5	24	22	22
Zn	12	43	47	57
Ga	12	20	21	18
Y	20	27	27	19
Zr	225	189	203	209
Nb	11	16	16	15

Table - XRF data 3

METADOLERITE

Sample	121	9	10	14	136	90	99	163B	63	22	166	167	134F	134G	5	78	172	172B	172C	172D	172E
DP#	44643	44592	44593	44594	44650	44633	44635	44667	44616	44597	44669	44670	44646	44647	44588	44625	44675	44676	44677	44678	44679
Type	A	A	A	A	A	A	A	A	A	A	A	A	B	A/B	A/B	A/B	B/A	B	B	B	B/A
SiO2	49.59	47.24	49.38	48.43	48.02	48.90	48.47	48.69	55.09	49.05	50.45	49.92	54.01	49.23	54.87	52.16	61.97	60.70	54.94	47.23	55.55
TiO2	1.55	1.63	1.42	1.78	1.24	1.79	1.33	1.19	1.76	1.20	1.13	1.15	1.49	1.59	2.20	1.56	0.61	0.60	1.40	1.15	0.51
Al2O3	13.19	12.90	14.24	14.07	13.57	12.53	13.49	14.47	12.87	14.89	15.90	16.58	14.12	12.32	13.08	14.03	14.28	12.73	13.72	13.14	16.54
Fe2O3	11.67	8.93	6.44	9.30	12.01	11.55	11.47	10.56	6.52	11.35	8.32	7.78	7.55	12.55	5.70	10.70	3.37	3.47	7.90	11.74	5.02
FeO	3.93	5.32	5.88	5.74	0.95	3.56	2.33	1.61	0.74	0.75	2.27	2.90	2.33	1.34	0.79	2.04	1.72	0.72	0.83	0.51	0.22
MnO	0.25	0.11	0.16	0.11	0.16	0.16	0.16	0.15	0.10	0.14	0.13	0.13	0.13	0.14	0.06	0.15	0.03	0.05	0.08	0.07	0.04
MgO	5.84	6.72	5.53	5.60	6.14	5.76	5.36	6.37	6.31	5.44	6.55	6.20	5.49	6.18	7.06	4.35	3.27	4.71	7.77	7.36	5.24
CaO	8.59	11.10	10.67	8.83	9.44	8.71	9.76	11.18	11.01	10.22	10.36	10.17	7.74	11.25	8.08	9.97	4.13	9.10	7.87	10.60	9.04
Na2O	0.72	3.15	4.01	3.98	3.90	2.43	3.16	3.48	4.49	3.96	3.25	3.22	2.57	2.94	5.34	2.62	4.24	6.96	4.41	4.66	7.22
K2O	1.20	0.99	0.71	0.87	1.06	0.85	0.85	0.84	0.44	0.57	1.11	1.03	4.68	1.25	0.43	1.48	4.75	0.18	1.45	0.72	0.70
P2O5	0.10	0.11	0.18	0.15	0.09	0.14	0.10	0.07	0.10	0.11	0.09	0.09	0.13	0.09	0.08	0.11	0.13	0.09	0.05	0.05	0.06
LOI	2.43	1.39	1.03	1.90	1.74	1.50	1.07	0.72	1.00	1.05	1.82	1.49	1.83	1.70	1.64	1.89	1.11	0.95	2.39	1.19	2.36
SUM	99.06	99.60	99.65	100.75	98.31	97.88	97.55	99.33	100.43	98.70	101.37	100.66	102.06	100.58	99.33	101.05	99.61	100.26	102.82	98.43	102.50
Rb	91	26	20	24	46	22	30	18	7	14	39	35	233	32	10	74	10	6	38	15	9
Cs	-	-	-	-	-	-	-	-	-	dl	1	-	dl	dl	-	-	dl	1	dl	dl	dl
Sr	95	136	188	163	187	106	158	151	173	175	193	199	302	92	137	146	137	49	70	97	171
Ba	-	-	-	-	-	-	-	-	-	dl	200	-	1450	137	-	-	142	dl	dl	dl	dl
Sc	48	45	47	44	47	51	42	48	48	36	38	37	35	49	54	45	36	32	46	28	17
V	402	419	361	402	319	437	337	330	336	310	277	276	329	378	181	362	308	106	235	108	105
Cr	116	149	69	93	100	31	101	131	83	96	149	114	62	96	109	76	114	93	121	89	93
Co	103	123	97	97	79	105	98	84	126	78	83	94	57	73	84	88	50	65	51	52	61
Ni	82	98	63	104	86	66	56	77	40	62	82	81	47	68	54	56	45	20	78	47	41
Zn	121	17	55	40	41	44	51	62	12	34	29	31	37	31	18	35	8	9	31	10	8
Pb	5	1	2	2	12	2	5	2	3	1	1	4	1	1	3	7	1	50	4	17	1
Cu	-	-	-	-	-	-	-	-	-	74	87	-	8	17	-	-	17	19	22	31	dl
Ga	22	23	23	25	21	24	22	22	18	19	21	21	22	25	20	23	17	19	19	23	18
As	1	1	1	2	3	1	1	1	2	1	1	2	3	1	1	2	1	dl	1	2	1
Br	-	-	-	-	-	-	-	-	-	17	dl	-	2	dl	-	-	21	dl	dl	dl	55
S	-	-	-	-	-	-	-	-	-	486	75	-	38	18	-	-	882	22	8	dl	851
C	-	-	-	-	-	-	-	-	-	806	441	-	651	514	-	-	907	307	215	206	1518
La	-	-	-	-	-	-	-	-	-	10	9	-	45	10	-	-	9	23	19	36	8
Ce	-	-	-	-	-	-	-	-	-	19	18	-	65	19	-	-	21	83	62	133	19
Nd	-	-	-	-	-	-	-	-	-	13	11	-	43	11	-	-	12	36	32	59	10
Sm	-	-	-	-	-	-	-	-	-	3.4	3.2	-	8.3	3.0	-	-	3.1	6.1	5.6	9.4	2.7
Eu	-	-	-	-	-	-	-	-	-	0.7	1.0	-	1.9	0.6	-	-	1.1	1.4	1.3	2.3	0.7
Gd	-	-	-	-	-	-	-	-	-	2.8	3.3	-	8.2	3.0	-	-	3.5	4.9	4.9	6.2	2.5
Tb	-	-	-	-	-	-	-	-	-	0.5	0.6	-	1.4	0.5	-	-	0.6	0.8	0.8	1.1	0.4
Ho	-	-	-	-	-	-	-	-	-	0.7	0.8	-	1.9	0.8	-	-	0.8	1.1	1.1	1.3	0.6
Yb	-	-	-	-	-	-	-	-	-	1.8	1.9	-	4.7	2.2	-	-	1.7	2.6	2.4	3.5	1.5
Lu	-	-	-	-	-	-	-	-	-	0.26	0.27	-	0.67	0.31	-	-	0.24	0.40	0.33	0.55	0.21
Y	31	31	24	35	24	38	28	24	34	22	23	23	46	26	81	32	21	28	28	36	16
Zr	88	109	84	121	75	109	93	65	109	84	76	72	165	101	128	95	64	177	87	135	101
Nb	8	9	7	11	7	10	9	7	14	7	7	7	14	9	36	9	7	10	12	17	7
Hf	-	-	-	-	-	-	-	-	-	1.9	2.0	-	4.1	2.4	-	-	1.4	4.1	2.1	3.4	2.6
Ta	-	-	-	-	-	-	-	-	-	1.8	2.0	-	1.9	0.9	-	-	0.7	1.9	1.3	1.3	1.7
Th	-	-	-	-	-	-	-	-	-	2.7	2.4	-	4.3	2.8	-	-	2.0	6.0	4.2	8.7	3.4
DI	29.9	32.5	37.8	39.2	39.2	34.9	35.9	34.5	43.9	37.2	35.1	34.6	51.4	34.9	48.6	40.4	72.7	62.2	46.8	37.3	56.6
K/Rb	131	385	355	363	231	382	286	460	609	415	288	296	201	386	427	201	4615	296	386	498	791
Y/Nb	4	3	3	3	3	4	3	4	3	3	3	3	3	3	2	4	3	3	2	2	2
Zr/Nb	12	12	11	12	10	11	11	10	8	13	11	10	12	11	4	11	10	17	7	8	14
Zr/Y	3	3	3	4	3	3	3	3	3	4	3	3	4	4	2	3	3	6	3	4	6

NAA DP#	drillhole/depth	Rock type dl=detection limit	Au-ppb 5	Ag 5	Fe% 0.5	Na% 0.01	K% 0.2	Rb 20	Cs 1	Ba 100	Sc 0.1	Cr 5	Co 1	Zn 100	As 1	Sb 0.2	Se 5	Br 2	La 0.5	Ce 2	Sm 0.2	Eu 0.5	Yb 0.5	Lu 0.2	Ir-ppb 20	Mo 5	Hf 0.5	Ta 1	Th 0.5	W 2	U 2
46383	12/188.6	Au-Bx+Py	871	dl	4.9	0.04	dl	dl	dl	dl	0.6	21	49	163	25	3.8	dl	dl	18.4	21	0.9	dl	dl	dl	dl	dl	dl	dl	dl	15	dl
46371	11/108.2	Au-CCG+Mag+Bt	1410	dl	20.8	dl	0.3	84	7	473	7.0	43	51	dl	59	4.1	dl	dl	21.7	47	6.3	2.5	4.9	0.7	dl	50	1.8	dl	5.9	dl	31
46369	11/87.25	Au-Dolerite	5080	dl	32.7	dl	0.2	90	5	205	8.5	64	609	306	23	4.3	dl	dl	10.8	23	5.6	3.4	2.1	0.3	dl	34	2.0	dl	9.1	dl	20
46382	12/186.3	Au-Fe-rock	756	18	31.9	0.86	1.4	107	3	270	9.2	56	18	647	16	9.3	20	dl	795.0	854	33.9	2.4	2.3	0.4	dl	12	4.6	3	21.2	7	9
46350	10/339.4	Au-Schist+Py vein	2350	dl	14.5	2.19	2.3	200	5	1640	7.4	68	224	dl	17	1.1	dl	dl	21.5	45	3.6	1.3	1.3	dl	dl	10	2.8	dl	13.9	8	5
46381	12/180.45	Au-Schist+Tur	1260	dl	4.9	2.62	1.6	122	2	929	8.8	41	101	dl	12	4.1	dl	dl	4.7	11	1.7	0.5	1.5	dl	dl	15	5.5	2	1.2	9	8
46344	10/309.85	Au-Vein-Qtz+Mag	335	dl	28.3	dl	dl	dl	dl	dl	0.8	32	56	dl	65	11.2	dl	dl	0.7	2	0.4	0.5	dl	dl	dl	dl	0.7	dl	dl	60	5
46361	10/387.7	Bx+Po	8	dl	37.6	dl	dl	35	2	338	0.5	13	489	dl	5	1.1	dl	dl	10.0	16	2.9	4.9	0.6	dl	dl	dl	dl	dl	0.6	3	0
46347	10/325.25	CCG	13	dl	25.3	0.02	1.2	95	3	461	5.3	31	707	dl	97	169.0	20	dl	17.2	33	3.3	1.3	0.7	dl	dl	17	dl	dl	1.9	7	9
46348	10/326.3	CCG	254	dl	7.5	0.04	0.3	48	2	498	3.9	52	176	200	260	40.7	7	dl	54.7	93	11.9	10.3	3.5	0.5	dl	68	1.6	dl	5.4	9	40
46349	10/328.05	CCG	34	45	1.6	dl	dl	dl	dl	dl	1.2	36	5	dl	26	55.9	dl	dl	56.3	101	13.0	8.8	3.1	0.4	dl	15	dl	dl	1.4	dl	8
46353	10/356.5	CCG	42	dl	8.5	0.02	dl	dl	dl	dl	1.7	36	14	dl	190	5.3	dl	dl	51.3	93	10.9	14.4	2.4	0.3	dl	19	dl	dl	1.2	dl	11
46355	10/363.9	CCG	dl	dl	3.5	0.03	dl	dl	dl	108	1.9	36	4	dl	69	1.0	dl	dl	58.8	114	19.0	18.1	4.0	0.6	dl	25	dl	dl	0.8	dl	14
46358	10/379.4	CCG+Qtz	24	13	4.5	0.03	dl	dl	dl	2080	0.7	53	19	dl	743	9.7	dl	dl	43.0	78	10.5	17.9	2.5	0.3	dl	28	dl	dl	dl	3	16
46359	10/381.7	CCG+Qtz	58	357	2.4	dl	dl	dl	dl	416	1.0	18	4	1400	77	410.0	dl	dl	27.7	46	6.9	13.9	1.2	0.3	dl	8	dl	dl	0.7	7	9
46360	10/386.05	CCG+Qtz	8	dl	12.9	dl	dl	dl	dl	538	0.7	32	219	dl	32	3.7	dl	dl	19.5	39	9.5	12.0	2.6	0.3	dl	dl	dl	dl	dl	dl	dl
46362	10/395.7	CCG+Qtz	58	dl	16.5	dl	dl	dl	dl	226	1.1	12	15	115	16	2.2	dl	dl	17.1	28	3.1	8.0	1.4	dl	dl	12	dl	dl	0.9	6	7
46384	12/203.7	CCG+Qtz	27	dl	3.3	dl	dl	dl	dl	dl	2.0	14	24	dl	1100	11.3	dl	dl	56.8	93	5.4	5.3	2.7	0.4	dl	5	dl	dl	0.6	68	dl
46393	12/232.83	CCG+Qtz	153	366	3.6	dl	0.6	dl	dl	dl	1.3	44	44	dl	2320	427.0	dl	6	27.3	48	3.7	6.4	0.7	dl	dl	13	dl	dl	1.0	3	11
46475	11/161.55	Dolerite	87	12	23.8	0.11	2.5	145	10	2090	3.8	28	629	230	7	4.5	8	dl	71.9	142	7.0	1.3	1.0	dl	dl	dl	3.1	dl	6.7	dl	dl
46367	11/65.2	Fe-rock	dl	dl	22.4	0.09	1.4	111	3	2880	6.5	32	28	308	26	1.7	dl	dl	29.0	50	5.0	1.2	4.2	0.6	dl	16	1.7	dl	4.9	dl	9
46370	11/99.05	Fe-rock	75	8	37.2	dl	dl	dl	dl	dl	2.2	47	159	228	37	2.5	dl	dl	14.6	26	3.7	3.1	2.0	0.3	dl	94	dl	dl	2.1	3	56
46374	11/156.4	Fe-rock	dl	dl	31.1	dl	0.6	43	4	9320	5.7	47	15	621	123	1.2	dl	dl	51.5	93	10.8	1.9	3.6	0.5	dl	44	1.8	dl	6.3	dl	25
46346	10/316.3	Pegmatite vein	dl	dl	5.3	0.45	9.9	509	11	11500	15.6	54	18	112	9	1.3	dl	dl	26.4	31	2.2	0.7	dl	dl	dl	dl	1.1	dl	3.3	dl	dl
46354	10/361.8	Schist	16	dl	10.3	1.07	0.5	75	2	405	4.4	53	239	dl	21	1.2	9	dl	61.3	102	11.7	4.2	2.2	0.3	dl	22	2.5	2	8.2	4	13
46365	10/426.8	Schist	12	dl	11.0	0.22	4.8	315	3	3490	11.3	66	115	123	3	1.0	dl	dl	51.3	104	8.0	1.6	7.7	1.0	dl	dl	3.5	dl	14.5	5	4
46379	12/132.1	Schist	dl	dl	1.9	0.05	2.6	76	dl	651	2.8	36	2	134	3	2.6	dl	dl	19.5	40	3.3	0.7	0.9	dl	dl	dl	8.1	dl	6.9	4	dl
46380	12/163.5	Schist	32	dl	1.8	1.72	0.7	25	dl	255	1.5	34	4	dl	5	1.0	dl	dl	17.1	30	2.7	0.5	1.1	dl	dl	68	11.5	dl	6.1	5	9
46385	12/206.75	Schist	0	dl	11.2	0.04	0.7	114	6	413	5.0	67	17	337	39	5.9	dl	dl	16.6	39	9.8	7.3	2.0	0.3	dl	69	1.7	dl	7.9	11	41
46357	10/368.95	Schist	14	dl	23.2	dl	dl	dl	2	157	0.3	19	526	dl	440	0.6	dl	dl	14.2	33	9.6	9.1	1.0	dl	dl	14	dl	dl	dl	6	10
46352	10/352.45	Schist	8	dl	2.3	2.57	3.0	119	dl	3320	9.3	60	18	dl	13	0.8	dl	dl	35.2	71	5.5	2.0	1.5	dl	dl	dl	4.6	2	13.6	4	dl
46351	10/349.8	Schist	28	dl	22.3	0.14	0.3	dl	dl	380	1.2	24	883	dl	29	0.8	8	dl	5.4	11	1.1	dl	dl	dl	dl	12	0.9	3	2.1	18	dl
46368	11/71.5	Schist	7	dl	46.6	0.14	2.2	148	14	1580	3.5	32	6	366	25	21.8	dl	dl	19.1	32	3.8	1.1	2.0	0.3	dl	30	1.1	dl	2.9	25	17
46377	12/101.6	Schist+Ga vein	135	702	2.3	0.09	4.1	191	2	784	8.3	57	12	311	20	577.0	dl	dl	44.7	68	3.4	1.4	1.0	dl	dl	10	5.1	dl	13.4	10	dl
46363	10/405.5	Fe-Mn silicate rock	46	75	15.1	dl	0.7	121	6	12300	1.9	41	5	296	45	57.1	dl	dl	42.1	56	3.4	5.3	1.3	dl	dl	54	dl	dl	3.1	dl	32
46372	11/124.15	Fe-Mn silicate rock	15	dl	19.3	dl	1.7	357	28	3090	3.8	40	20	226	8	6.7	dl	dl	11.7	30	5.1	1.8	1.8	dl	dl	48	dl	2	2.5	dl	28
46387	12/263.3	Fe-Mn silicate rock	98	166	14.1	0.02	0.4	32	2	5590	0.7	46	28	454	42	135.0	9	dl	77.7	99	7.7	8.3	1.5	dl	dl	110	1.1	dl	4.0	dl	62
46388	12/272.9	Fe-Mn silicate rock	32	8	33.6	dl	dl	dl	dl	132	1.1	72	44	dl	18	2.2	11	dl	43.5	60	4.9	6.0	0.8	dl	dl	15	0.7	dl	1.3	4	9
46389	12/278.28	Fe-Mn silicate rock	36	637	19.3	dl	0.4	22	dl	169	4.4	55	6	212	9	207.0	dl	dl	108.0	160	10.4	4.0	2.5	0.4	dl	30	2.0	dl	7.2	6	18
46391	12/318.8	Fe-Mn silicate rock	10	dl	13.9	dl	dl	dl	dl	dl	1.6	35	9	111	43	2.0	dl	dl	6.1	12	2.3	0.6	0.6	dl	dl	26	dl	dl	1.5	3	4
46390	12/284.35	Skarn+schist	7	dl	22.2	dl	0.3	107	6	4640	2.6	55	23	387	9	2.9	dl	dl	13.6	28	3.8	2.3	1.9	dl	dl	21	1.6	dl	6.8	dl	14
46341	10/261.4	Vein-Qtz	29	dl	3.1	dl	dl	dl	dl	dl	0.6	43	23	dl	164	72.8	dl	dl	13.9	26	3.4	2.0	0.7	dl	dl	dl	1.8	dl	1.2	33	3
46342	10/270.65	Vein-Qtz	dl	dl	20.2	dl	dl	dl	dl	dl	0.9	60	8	dl	17	30.7	dl	dl	2.3	5	0.8	dl	0.6	dl	dl	9	1.4	dl	dl	49	7
46343	10/277.6	Vein-Qtz	dl	dl	2.3	dl	dl	dl	dl	dl	0.2	23	5	dl	6	2.4	dl	dl	0.7	dl	dl	dl	dl	dl	dl	dl	dl	dl	dl	dl	dl
46375	11/176.15	Vein-Qtz	dl	dl	2.3	0.08	2.7	198	13	1610	6.1	45	11	dl	dl	1.1	dl	dl	2.0	5	0.4	dl	0.8	dl	dl	dl	1.4	dl	dl	3	dl
46356	10/365.55	Vein-Qtz+Mag	10	7	12.8	dl	dl	dl	dl	dl	0.3	13	150	dl	59	1.3	dl	dl	39.9	70	8.3	6.6	1.1	dl	dl	dl	dl	dl	dl	39	dl

Table - XRF-MND 7

MND7 XRF	Rock logged	Rock Billiton	Top interval	Bottom interval	depth average	SiO2	Al2O3	Fe2O3	MgO	CaO	Na2O	K2O	sub-total	Au	Cu	Pb	Zn	Ag	As	Ba	Mn	Zr	Sr	Rb	Y	Mag. Sus.	K2O/ Na2O
1	FSP	FSP	65.7	71.1	68.4	79.6	9.2	2.4	0.07	0.11	0.10	4.91	96.41	0.00	6	17	17	0	4	2055	2732	208	30	174	33	23	49.1
2	FSP	FSP	71.1	75.9	73.5	66.9	15.3	3.5	0.18	0.19	0.16	5.07	91.30	0.00	11	69	19	0	5	2097	4211	189	39	298	47	24	31.7
3	FSP	FSP	75.9	80.7	78.3	56.6	20.5	5.1	0.37	0.38	0.47	6.44	89.86	0.13	10	47	20	0	5	2246	5198	167	37	357	61	48	13.7
4	FSP	FSP	80.7	83.2	81.9	67.2	15.3	4.3	0.31	0.41	0.53	6.24	94.29	0.03	10	17	32	0	2	2398	3067	158	39	314	41	64	11.8
5	SP	SP	83.2	88.1	85.6	62.2	18.0	4.5	0.36	0.48	0.27	6.90	92.71	0.00	6	48	20	1	4	2643	3170	169	42	371	52	29	25.6
6	SP	SP	88.1	92.9	90.5	62.9	17.1	5.0	0.41	0.82	0.18	5.98	92.39	0.00	32	23	24	0	4	2360	5150	160	41	362	48	33	33.2
7	SP	SP	92.9	97.7	95.3	69.1	14.7	4.2	0.28	0.68	0.24	5.96	95.16	0.00	6	56	26	1	3	2471	3182	170	37	288	42	39	24.8
8	SP	SP	97.7	102.6	100.1	61.0	18.2	5.2	0.39	0.52	0.24	6.44	91.99	0.00	6	39	24	1	2	2889	3549	154	36	323	50	18	26.8
9	SP	ASP	103.8	108.6	106.2	64.6	13.1	8.2	0.51	1.97	1.75	3.12	93.25	0.01	26	68	37	0	8	1348	9456	177	38	173	45	256	1.8
10	SP	GSP	108.6	113.4	111.0	57.6	17.1	9.0	0.56	1.35	0.57	5.49	91.67	0.02	19	170	40	1	5	3189	8043	163	51	328	56	102	9.6
11	SP	GSP	113.4	118.2	115.8	53.7	18.8	9.6	0.59	0.62	0.28	7.31	90.90	0.01	16	43	139	0	9	4650	7792	155	65	415	42	40	26.1
12	SP	GSP	118.2	120.6	119.4	40.8	13.8	21.2	0.93	2.25	0.25	4.17	83.40	0.00	83	48	180	1	30	5033	36000	137	68	247	70	460	16.7
13	Grt	BIF	120.6	123.0	121.8	15.0	6.6	44.5	0.99	4.74	0.34	0.53	72.70	0.01	206	129	453	2	507	1017	92960	91	70	37	48	24560	1.6
14	Grt	BIF	123.0	127.9	125.4	11.4	5.9	49.2	0.94	4.29	0.46	0.03	72.25	0.00	148	743	577	2	168	61	1E+05	79	49	5	56	20800	0.1
15	BIF	BIF	127.9	132.7	130.3	17.9	8.9	26.2	1.26	12.50	0.44	0.65	67.84	0.00	173	12521	736	4	237	559	63147	163	117	27	238	12299	1.5
16	BIF	BIF	132.7	135.1	133.9	39.7	16.8	20.3	2.50	2.25	1.07	1.45	84.07	0.14	145	801	603	9	32	613	9860	234	56	104	94	2592	1.4
17	DOL	DOL	135.1	139.3	137.2	43.2	14.1	19.6	3.51	3.74	1.27	1.43	86.85	0.02	71	357	176	1	21	802	8800	229	82	104	76	936	1.1
18	DOL	DOL	139.3	141.1	140.2	63.6	1.5	8.9	0.08	8.30	0.05	0.73	83.19	0.17	1246	20608	175	50	1254	274	2213	173	25	63	169	124	14.6
19	DOL	DOL	141.1	147.1	144.1	86.9	0.6	7.6	0.03	1.50	0.05	0.13	96.83	0.02	1237	2249	16	4	4820	301	664	14	5	5	36	49	2.6
20	SIL	SIL	147.1	152.6	149.8	84.1	0.5	7.5	0.22	2.97	0.05	0.09	95.43	0.06	543	974	50	4	854	54	3714	12	15	5	57	103	1.8
21	SIL	SIL	152.6	157.4	155.0	85.7	0.1	8.7	0.36	0.96	0.05	0.07	95.98	0.00	158	726	41	2	21	70	5977	0	5	58	33	65	1.4
22	SIL	BIF	157.4	162.8	160.1	72.7	2.9	7.5	0.32	4.62	0.05	0.62	88.68	0.11	416	12120	52	12	35	331	2907	126	87	59	108	34	12.4
23	SIL	SIL	162.8	167.0	164.9	83.4	2.0	5.6	0.47	4.32	0.05	0.40	96.25	0.00	725	5600	23	7	42	253	2058	49	26	25	63	0	8.0
24	DOL	SIL	167.6	171.2	169.4	47.0	1.9	16.4	0.23	9.30	0.05	0.58	75.41	0.06	962	10407	40	10	247	201	8540	144	31	50	106	1451	11.6
25	SIL	BIF	171.2	173.6	172.4	82.8	0.4	7.4	0.17	2.07	0.05	0.26	93.12	0.00	192	6440	61	8	994	256	14020	34	5		43	210	5.2
26	SIL	SIL	174.2	178.1	176.2	87.0	0.0	7.8	0.09	1.30	0.05	0.04	96.28	0.00	477	411	13	1	1210	39	5333	0	5		35	233	0.8
27	SIL	SIL	178.1	181.1	179.6	78.1	1.6	7.2	0.27	4.32	0.39	0.25	92.13	1.17	8293	3695	60	8	107	99	4493	38	17	5	59	145	0.6
28	CCG	SIL	182.9	188.9	185.9	37.1	6.0	10.2	0.35	24.20	0.05	1.03	78.96	0.00	410	5619	42	3	95	388	8720	83	43	46	87	187	20.6
29	SP	CCG	189.9	193.3	191.6	57.8	17.1	10.2	0.50	2.36	0.28	3.83	92.07	0.09	63	216	57	1	53	3290	4141	158	35	236	54	56	13.7
30	SP	SP	193.3	199.3	196.3	73.8	11.8	5.6	0.32	1.10	0.31	3.45	96.38	0.03	68	79	44	0	21	3258	1624	182	22	161	28	56	11.1
31	SP	SP	199.3	204.1	201.7	67.8	10.2	6.8	0.27	5.63	0.17	2.72	93.59	0.00	75	75	28	0	936	2817	4415	144	22	125	35	56	16.0
32	CCG	SP	204.1	210.2	207.1	49.1	6.9	8.7	0.22	15.40	0.12	1.82	82.23	0.01	71	15460	30	8	123	730	5752	162	45	113	67	38	15.2
33	SP	CCG	210.8	216.2	213.5	65.5	15.4	6.2	0.47	1.66	0.24	4.83	94.30	0.01	36	208	42	0	52	3191	2053	145	23	218	40	44	20.1
34	SP	SP	216.2	221.0	218.6	67.5	13.7	7.0	0.37	2.39	0.28	4.48	95.72	0.01	16	34	40	0	23	1909	2122	172	23	217	40	45	16.0
35	SP	SP	221.0	225.8	223.4	70.2	14.1	5.0	0.30	1.55	0.86	4.25	96.26	0.00	62	24	16	0	42	2486	1346	179	34	213	37	1900	4.9
36	SP	SP	225.8	230.6	228.2	74.6	11.5	4.2	0.22	1.58	0.22	4.49	96.81	0.00	31	16	21	0	11	2117	1456	216	20	202	33	39	20.4
37	SP	SP	230.6	235.5	233.1	75.9	9.8	3.3	0.20	1.82	0.39	3.76	95.19	0.00	120	62	25	0	5	2462	1077	220	18	169	31	33	9.6
38	SP	SP	235.5	240.3	237.9	71.3	13.4	4.4	0.27	1.56	0.05	4.51	95.49	0.02	265	21	14	0	9	2869	968	172	24	207	36	50	90.2
39	CCG	SP	240.3	244.5	242.4	26.4	8.3	8.8	0.06	31.60	0.17	0.54	75.85	0.02	417	27437	645	47	81	2568	18592	141	86	40	63	37520	3.2
40	CBX	CCG	244.5	249.3	246.9	40.0	7.7	9.0	0.10	15.42	0.05	2.45	74.71	0.01	364	58852	217	41	46	4983	14075	262	59	171	52	2427	49.0
41	CBX	CCG	248.1	254.1	251.1	58.0	1.7	9.4	0.04	17.80	0.05	0.12	87.08	0.11	553	6144	18	8	311	402	5151	43	67	5	54	1327	2.4
42	CCG	CCG	254.1	259.0	256.6	26.9	0.5	11.7	0.05	33.60	0.05	0.12	72.87	0.73	1274	519	31	3	5654	144	12544	48	136	5	70	6037	2.4
43	CCG	CCG	259.0	263.8	261.4	23.6	0.5	22.3	0.05	25.90	0.05	0.12	72.52	0.19	1773	1729	267	6	5872	224	10602	46	112	5	42	8537	2.4
44	CBX	CCG	263.8	268.6	266.2	48.7	1.4	13.1	0.07	14.20	0.05	0.48	78.00	0.13	1036	39462	147	63	1080	431	4936	187	51	71	42	9088	9.6
45	CCG	CCG	268.6	273.4	271.0	56.6	6.5	12.4	0.11	7.80	3.10	2.21	88.75	0.07	450	23780	619	53	307	6604	5631	213	42	136	39	6267	0.7
46	SP	CCG	273.4	279.4	276.4	64.6	15.8	7.6	0.15	1.33	0.14	5.56	95.18	0.00	25	126	88	0	10	3845	2942	174	21	296	46	37	39.7
47	SP	SP	280.7	285.4	283.1	71.8	12.8	5.7	0.13	2.04	0.57	4.26	97.30	0.00	36	33	45	0	5	2007	2531	181	27	212	39	44	7.5
48	SP	SP	285.4	290.3	287.9	65.5	16.8	6.6	0.15	1.19	0.05	5.80	96.09	0.00	52	24	50	0	17	2614	1819	161	21	291	47	51	116.0
49	SP	SP	290.3	295.1	292.7	66.4	15.8	6.5	0.16	1.42	0.25	2.75	93.28	0.00	31	6	45	0	9	2560	1736	180	27	304	46	27	11.0
50	SP	SP	295.1	299.9	297.5	65.3	16.2	5.9	0.16	1.67	0.30	3.00	92.53	0.00	23	21	70	0	9	2550	1856	157	29	291	48	16	10.0
51	SP	SP	299.9	304.8	302.3	66.6	16.0	5.9	0.10	1.73	0.23	4.27	94.83	0.00	17	31	60	0	4	2524	1614	169	25	290	40	6	18.6
52	SP	SP	304.8	309.6	307.2	74.4	11.9	4.8	0.11	2.20	0.26	3.04	96.71	0.00	38	51	40	0	4	2122	1849	211	27	222	34	16	11.7
53	SP	SP	309.6	314.4	312.0	64.5	17.7	5.6	0.38	1.09	0.14	6.02	95.43	0.00	45	31	58	0	5	2963	1233	172	24	331	50	34	43.0
54	SP	SP	314.4	319.2	316.8	68.8	14.2	5.3	0.21	1.85	0.17	5.47	96.00	0.00	15	21	44	0	3	2366	1366	196	34	267	44	33	32.2
55	SP	SP	319.2	324.0	321.6	67.4	16.1	5.6	0.21	1.53	0.14	6.11	97.09	0.00	41	23	46	0	15	2558	1152	169	29	305	46	23	43.6
56	SP	SP	324.0	328.9	326.4	66.0	16.6	5.9	0.13	1.68	0.10	5.28	95.69	0.00	24	28	53	0	8	2499	1127	172	27	309	49	34	52.8
57	SP	SP	328.9	333.7	331.3	64.2	16.8	6.3	0.18	1.96	0.14	5.41	94.99	0.00	42	13	52	0	8	2535	1247	169	30	325	48	37	38.6

Rock type abbreviations

FSP____ Feldsphatic
SP____ psammite
ASP___ Altered psammite
GSP___ Garnet bearing psammite
Grt____ Garnet rich
DOL___ Dolerite
BIF____ Banded Iron Formation
SIL____ Silicified
CCG___ Calcareous units
CBX___ Brecciated Calcareous units
Mag.___ Magnetic
Sus.___ Susceptibility

REE TABLE - Rare earth elements and metal abundance for different lithologies and dominant mineral constituents (alteration stages) of the Maronan Prospect (based on NAA).

									LREE/HREE*			Pb		Cu		Au	
DP#	Sample #	La	Ce	Sm	Eu	Eu*	Gd	Yb	Lu		Eu/Eu*		Zn	Pb/(Pb+Zn+Cu)			Ag
Psammopelite / Quartzitic schist																	
46365	10/426.8	51	104	8.0	1.6	3.0	10.4	7.7	0.99	3	0.54	39	69	90	0.55	12	< 5
46379	12/132.1	20	40	3.3	0.7	1.1	3.6	0.9	0.09	6	0.63	4120	5090	160	0.98	< 5	< 5
46380	12/163.5	17	30	2.7	0.5	1.0	3.1	1.1	0.13	5	0.54	60	40	600	0.14	32	< 5
46350	10/339.4	22	45	3.6	1.3	1.3	4.0	1.3	0.15	5	1.05	50	23	1040	0.07	2350	< 5
46352	10/352.45	35	71	5.5	2.0	1.9	6.0	1.5	0.22	6	1.04	87	21	970	0.10	8	< 5
46354	10/361.8	61	102	11.7	4.2	4.0	12.4	2.2	0.26	6	1.06	266	37	1930	0.14	16	< 5
46377	12/101.6	45	68	3.4	1.4	1.2	3.7	1.0	0.11	11	1.20	25000	69	37	1.00	135	702
	Average	36	66	5.5	1.7	1.9	6.2	2.2	0.28	6	0.87						
	StDev	4	5	1.8	1.1	1.1	1.9	1.6	0.56	2	0.53						
Pyroxenoid rich (stage 1)																	
46348	10/326.3	55	93	11.9	10.3	4.1	13.0	3.5	0.46	4	2.51	11000	38	386	0.97	254	< 5
46363	10/405.5	42	56	3.4	5.3	1.2	3.8	1.3	0.22	8	4.45	15320	290	98	0.99	46	75
46369	11/87.25*	11	23	5.6	3.4	2.0	6.3	2.1	0.30	2	1.71	43	143	99	0.65	5080	< 5
46385	12/206.75	17	39	9.8	7.3	3.3	10.4	2.0	0.25	3	2.20	38000	1780	1120	0.97	< 5	< 5
46387	12/263.3	78	99	7.7	8.3	2.6	8.1	1.5	0.22	9	3.19	28000	560	398	0.99	98	166
46388	12/272.9*	44	60	4.9	6.0	1.7	5.2	0.8	0.09	9	3.63	1040	177	187	0.87	32	8
46390	12/284.35*	14	28	3.8	2.3	1.3	4.4	1.9	0.25	3	1.68	610	393	294	0.77	7	< 5
	Average	37	57	6.7	6.1	2.3	7.3	1.9	0.26	5	2.77						
	StDev	5	5	1.8	1.7	1.0	1.8	0.9	0.33	2	1.02						
Quartz veins (stage 2 and 6)																	
46342	10/270.65*	2	5	0.8	0.2	0.3	1.0	0.6	0.09	2	0.58	1030	231	55	0.96	< 5	< 5
46343	10/277.6	1	2	0.2	0.1	0.1	0.4	0.5	0.08	1	0.91	276	73	100	0.78	< 5	< 5
46344	10/309.85*	1	2	0.4	0.2	0.1	0.5	0.5	0.08	1	1.23	760	142	142	0.86	335	< 5
46376	11/176.15	2	5	0.4	0.2	0.2	0.7	0.8	0.13	1	0.99	71	41	23	0.83	< 5	< 5
46381	12/180.45	5	11	1.7	0.6	0.6	2.1	1.5	0.23	2	1.01	35	12	1420	0.03	1260	< 5
	Average	2	5	0.7	0.2	0.3	0.9	0.8	0.12	1	0.95						
	StDev	1	2	0.8	0.5	0.5	0.8	0.7	0.25	1	0.49						
Garnet-magnetite rich (stage 3)																	
46366	11/65.2*	29	50	5.0	1.2	1.8	6.3	4.2	0.59	3	0.64	211	286	222	0.69	< 5	< 5
46371	11/108.2*	22	47	6.3	2.5	2.3	7.8	4.9	0.70	2	1.09	29	98	56	0.69	1410	< 5
46374	11/124.15*	12	30	5.1	1.8	1.8	5.7	1.8	0.24	3	0.99	60	63	80	0.60	15	< 5
46372	11/156.4*	52	93	10.8	1.9	3.7	11.9	3.6	0.54	4	0.52	146	600	40	0.95	< 5	< 5
46389	12/278.28*	108	160	10.4	4.0	3.6	11.2	2.5	0.38	9	1.11	38000	137	113	1.00	36	637
46391	12/318.8	6	12	2.3	0.6	0.8	2.5	0.6	0.06	3	0.79	10060	390	330	0.97	10	< 5
	Average	38	65	6.7	2.0	2.3	7.6	2.9	0.42	4	0.86						
	StDev	6	7	1.8	1.1	1.1	1.9	1.3	0.49	2	0.50						
Calcareous Gneiss (stage 4)																	
46349	10/328.05	56	101	13.0	8.8	4.4	13.9	3.1	0.40	5	1.99	71000	15	95	1.00	34	45
46353	10/356.5	51	93	10.9	14.4	3.7	11.6	2.4	0.33	5	3.87	1185	30	98	0.93	42	< 5
46355	10/363.9	59	114	19.0	18.1	6.5	20.2	4.0	0.55	4	2.79	4070	16	291	0.93	< 5	< 5
46358	10/379.4	43	78	10.5	17.9	3.6	11.3	2.5	0.33	4	4.98	4590	33	377	0.92	24	13
46359	10/381.7	28	46	6.9	13.9	2.3	7.3	1.2	0.25	4	5.94	48000	1300	680	0.99	58	357
46360	10/386.05	20	39	9.5	12.0	3.3	10.3	2.6	0.32	3	3.66	2784	1510	2170	0.66	8	< 5
46362	10/395.7	17	28	3.1	8.0	1.1	3.6	1.4	0.17	4	7.26	59	42	440	0.19	58	< 5
46370	11/99.05*	15	26	3.7	3.1	1.3	4.4	2.0	0.25	3	2.36	115	156	270	0.50	75	8
46384	12/203.7	57	93	5.4	5.3	1.9	6.2	2.7	0.44	6	2.82	18000	83	104	0.99	27	< 5
46386	12/232.83	27	48	3.7	6.4	1.3	3.9	0.7	0.09	8	5.11	77000	72	102	1.00	153	366
	Average	37	67	8.6	10.8	2.9	9.3	2.3	0.31	5	4.08						
	StDev	4	6	2.2	2.3	1.3	2.3	1.0	0.36	1	1.31						
Fe-Cu sulphide rich (stage 5)																	
46347	10/325.25*	17	33	3.3	1.3	1.1	3.5	0.7	0.06	6	1.17	20000	208	17000	0.54	13	< 5
46351	10/349.8*	5	11	1.1	0.4	0.4	1.3	0.5	0.08	4	1.00	31	-	-	-	28	< 5
46356	10/365.55	40	70	8.3	6.6	2.8	8.6	1.1	0.11	6	2.37	227	29	3310	0.07	10	7
46357	10/368.95*	14	33	9.6	9.1	3.2	9.9	1.0	0.12	3	2.82	85	22	645	0.14	14	< 5
46361	10/387.7*	10	16	2.9	4.9	1.0	3.1	0.6	0.04	4	4.96	76	56	198	0.40	8	< 5
	Average	17	33	5.1	4.5	1.7	5.3	0.8	0.08	5	2.46						
	StDev	4	5	1.9	1.9	1.1	1.9	0.5	0.19	1	1.26						

N.B. Rare earth elements, lead, zinc and copper are in ppm; gold in ppb. Pb-Zn-Cu values are from assay data. Samples values below the detection limit are calculated. Detection limits are La-0.5, Ce-2.0, Sm-0.2, Eu-0.5, Yb-0.5, Lu-0.2. Gd and Eu* calculated from respectivaly Sm-Yb and Sm-Gd. Samples with -*- contain more than 19% iron, as magnetite and/or hematite and/or pyrite and/or chalcopyrite and/or pyrrhotite. StDev = standard deviation.

APPENDIX E

Strain analysis data and method E1
Orientation analysis E2

STRAIN ANALYSIS DATA and METHOD

When a circle or ellipse, with ellipticity R_i, is homogeneously deformed, the result is always a new ellipse. The ellipticity, in a plane, is defined as $R = (1+e_1)/(1+e_2)$, with e_1 and e_2 as the principle planes. This final ellipse, R_f, is a function of:

- initial form and orientation of the initial undeformed object
- the form and orientation of the superimposed strain ellipse, R_s.

The angle between the long axis of the initial ellipse and the maximum elongation of the strain ellipse is defined as "Ø'".

Final strain ellipse can be measured directly in the field, or in the laboratory on orientated rock slabs or photographs. Measurements of the long and short axis and Ø' of the final strain ellipse, should by done in the principal XY-YZ-ZX planes. These planes are defined by the foliation and form-orientation shape of the objects of interest, which are known as the *principal planes of finite strain.*

R_f/Ø' plots provide an excellent way in separating the component of tectonic strain superimposed on the initial shape of the marker objects (Ramsay and Huber 1983). Strain measurements plotted in this manner can provide information on the minimum and maximum R_f and the fluctuation, F, which is the maximum spread of Ø'. Two situations can occur: $R_i > R_s$, or $R_i < R_s$. The relationships between the initial-stress-final ellipse are as follows:

$R_i > R_s$: $(R_{f\max}/R_{f\min})^{0.5} = R_{i\text{-}\max}$
$(R_{f\max}/R_{f\min})^{0.5} = R_s$

$R_i < R_s$: $(R_{f\max}/R_{f\min})^{0.5} = R_s$
$(R_{f\max}/R_{f\min})^{0.5} = R_{i\text{-}\max}$

The measured fluctuation, F, is a function of R_i and R_s and can be measured, but also calculated as followed:

$$F = \tan^{-1}\frac{R_s\left(R_i^2 - 1\right)}{\left(\left(R_i^2 R_s^2 - 1\right)\left(R_s^2 - R_i^2\right)\right)^{1/2}}$$

The strain measurements done on deformed albite clasts of the vein jog breccia of the Maramungee shear zone, is tabulated in Table A4.

Table A4- Strain measurement data obtained from sample DP#44590. Final ellipse measurement on principle planes of vein jog breccia clasts.

Ø' - xy	Rf-xy	Ø' - xy	Rf-xy	Ø' - yz	Rf-yz	Ø' - yz	Rf-yz	Ø' - zx	Rf-zx	Ø' - zx	Rf-zx	Ø' - zx	Rf-zx
11	1.55	7	1.88	44	1.63	42	1.32	-3	3.87	9	2.33	-11	2.67
18	1.17	7	2.93	72	1.21	51	2.09	-2	4.29	9	3.11	-4	4.38
17	1.67	5	2.32	73	1.25	60	1.90	-1	3.00	8	3.18	10	3.20
35	1.49	28	1.67	65	2.30	52	1.77	0	3.00	11	2.24	0	4.23
12	1.90	11	2.82	50	2.00	63	1.87	0	2.50	5	1.93	-2	3.34
20	3.33	13	2.42	55	1.71	76	1.49	-1	2.67	1	1.81	9	3.00
-5	2.00	8	3.60	-9	1.67	60	2.07	0	2.14	2	1.50	-4	2.69
-6	2.50	20	2.00	54	1.49	62	1.82	-2	3.13	9	4.67	7	2.41
20	3.33	24	3.00	31	1.90	-10	1.70	0	3.21	10	2.60	-1	2.22
30	2.20	15	3.68	72	1.81	60	2.14	4	4.17	-13	1.82	1	2.71
13	3.33	10	2.80	66	1.60	53	3.07	7	2.62	0	2.45	-9	4.50
20	3.00	10	3.21	53	1.68	79	2.14	8	2.25	-13	2.11	0	3.00
-1	3.2	28	2.11	73	1.98	62	1.05	12	3.36	0	2.45	-9	2.83
0	1.81	14	2.18	60	1.64	68	1.24	13	3.55	17	2.11	12	3.17
-2	2.78	15	2.26	64	2.07	43	1.24	-6	2.11	6	2.57	1	2.80
18	3.39	27	3.00	50	1.73	70	1.70	7	2.89	10	1.73	7	2.22
-2	1.59	17	1.91	51	1.69	83	2.07	31	2.32	6	2.50		
-8	2.00	10	4.00	32	2.92	51	1.11	-7	1.48	7	1.79		
-3	1.89	18	2.05	85	1.00	72	1.22	4	2.90	11	2.92		
17	2.16	18	2.00	88	1.13	72	1.85	4	2.90	3	3.13		
16	2.16	19	3.00	85	1.64	80	1.10	4	3.62	10	2.13		
7	1.88			90	1.29	23	1.50	3	2.40	0	3.06		
16	2.16			86	1.54	90	1.00	8	3.41	0	3.00		
12	2.15			-5	1.07			-16	4.24	-2	2.30		

ORIENTATION ANALYSIS

The orientations of geological planes and lineations, are measured in the field by means of a geological compass (compass needle and clinometer). A 6° to the east of north declination correction was done on the geological structural measurements in the eastern Cloncurry-Selwyn terrain.

Planar geological structural fabrics that were measured are, bedding, various phases of foliation planes and fault planes. Lineations obtained are, fold-axes, mineral lineations and stretching lineations. The planes are measured by determining the horizontal *strike* line, the angle of *dip* and the direction of dip. Lineations were recorded by determining the direction or *azimuth* of a line and the angle of *plunge*, which is the angle measured in a vertical plane through the lineation and the horizontal.

Orientations of these geological structural elements are plotted, projected on an *equal area net*. The concept of projection is that a lower hemisphere is represented / projected on the equatorial (horizontal, circular) plane. The earths longitude and latitude meridians are projected as respectively, *great circles* and *small circles*.

The main advantage of using a projection method for geometrical analysis is that large amount of data can be illustrated in a single diagram.

APPENDIX F

Fluid inclusion techniques, data and calculations F1

- Freezing and heating calibrations F1
- Freezing experiments F2
- Heating experiments F3
- Volume measurements and Fill calculations F3
- Salinity calculations F4
- Potter's (1977) corrected homogenization temperature curves F5
  - Table - Fluid inclusion data F7
  - Table - Fluid inclusion Fill data F9
  - Table - Fluid inclusion salinity data F11

FLUID INCLUSION TECHNIQUES, DATA and CALCULATIONS

-Freezing and heating calibrations

Freezing and heating experiments were done on a Reynold heating and freezing stage. Temperatures were controlled by adjustable heating coils in combination with dry liquid nitrogen gas. The temperatures were measured by a thermocouple, which was calibrated by known melting points of CO_2 (-56.6°C), for the lower values, while the meniscus of water was used to calibrate the higher temperature (374.1°C).

The lower temperature calibration was done on H_2O-CO_2 fluid inclusions with a composition of 25 mole% CO_2. At room temperature the inclusion contains three phases: liquid CO_2, vapour CO_2 and liquid H_2O. At a temperature of -56.6°C, the three phases are at equilibrium, the triple point of CO_2. At this point, freezing or heating will have no effect on the temperature, until one of the phases present is lost.

The critical point of H_2O was used to calibrate the higher temperature thermocouple readings. At room temperature, the fluid inclusion contain ~32 vol% liquid H_2O and ~68 vol% H_2O vapour. With increasing temperature, the meniscus between the liquid and vapour phases with slowly disappear, this because the densities of the liquid and vapour phases will approach each other. Immediately below the critical temperature (374.1°C), the meniscus will be very faint and the inclusion will contain ~50 vol% liquid and ~50 vol% vapour. At the critical temperature the meniscus will disappear and the fluid inclusion homogenizes.

The calibration showed that the temperature readings of the thermocouple are 1.2°C to low around -56.6°C and 0.4°C to high at temperatures around 374.1°C (Table A5). Before additional "pressure corrections" were done, temperatures were first corrected for this thermocouple reading error, by means of the following equation: $T_{true} = 0.996 \times T_{reading} + 0.986$.

Table A5 - Calibration results for temperature corrections on thermo-couple readings.

Low temperature calibration		High temperature calibration	
Melting of CO_2 (-56.6°C)	Δx	Critical point of H_2O (374.1°C)	Δx
-58.0	-1.4	374.2	+0.1
-58.3	-1.7	375.1	+0.9
-57.4	-0.8	374.4	+0.3
-57.6	-1.0	374.3	+0.2
-58.8	-2.2	374.5°C average	+0.4°C average to high
-56.6	-0.0		
-58.4	-1.8		
-57.8°C average	-1.2°C average to low		

-Freezing experiments

Freezing of fluid inclusions was first conducted before heating experiments. Homogenization of fluid inclusions (by heating) would result in disappearance of additional salts. On cooling the fluid would stay metastable and solids would not reappear for days or even months. On freezing first, the salt crystal can act as a nucleating surface for hydrosalts and ice.

Freezing experiments can give important information on the composition of the fluid trapped during crystallization. The principle behind this technic in obtaining the fluid composition from freezing experiments is that every salt(s)-water system has its own unique eutectic temperature (see fluid-inclusion chapter). Melting temperatures of various hydrosalts and ice can give additional information on the salinity of the fluid; this by comparing the obtained melting temperatures with experimental and theoretical phase diagrams.

Fluid inclusions were rapidly frozen to temperatures below -120°C, by using liquid nitrogen. The inclusions were then allowed to re-equilibrate with room temperature. The re-equilibrium heating rate can be controlled by reintroducing liquid nitrogen. Because of the metastable behaviour of the fluid inclusion, temperatures have to be lowered way below the eutectic temperature of the expected salt-water system. During this rapid lowering of the temperature the following phenomena can be observed:

1) In the frozen liquid phase, the fluid inclusion becomes (in general) more grainy in appearance.

2) The vapour bubble shrinks, or even disappears, or gets a ragged surface appearance, this is attributed to ice crystals.

3) Depending on the salt-water system, a colour change can be seen. A brown colouring is diagnostic for a $CaCl_2$-NaCl-H_2O system.

4) There is apparent no visible change. However on heating melting on ice can be recognized, indicting that the inclusion was frozen.

During the slowly heating up of the frozen fluid inclusion, the following processes have to be noted. i) The first melting temperature, and ii) the melting of hydrosalts or ice. The first melting can be recognized by a) the appearance of a meniscus separating ice from newly formed liquid phase, b) granulation in inclusion which in first instance did not display graininess, c) coarsening of graininess, d) change in brown colouring, melting of antarcticite. This first melting is tabulated in the fluid

inclusion data table as T_{eutct}/T_{fm}. Melting of the salt-hydrates are more difficult to recognize. Antarcticite melting can be observed by a more speckled appearance and slight change in brown colouring. The hydrohalite melting is perceptible by forming of a meniscus between the liquid in subrounded hydrohalite crystals ($T_{m\text{-}NaCl}$). The final melting can generally be recognized by disappearance of the meniscus separating ice from the liquid phase. Restoration of the vapour bubble spherical shape and movement of the vapour bubble to it pre-freezing locations are indications that temperatures are close to final melting temperatures ($T_{m\text{-}salt}/T_{ice}$).

-Heating experiments

Homogenization of fluid inclusions, due to heating to the homogenization temperature are more straightforward and changes are easy to recognize. Depending on the type of fluid inclusion, liquid-vapour or liquid-vapour-solid, respectively one or two homogenization temperatures have to be recorded. In the case of a liquid-vapour fluid inclusion, the fluid inclusion can homogenize to a liquid or vapour, depending on the degree of fill. In a three phase inclusion, the dissolution temperature ($T_{h\text{-}solid}$) of the daughter mineral has to be recorded, in addition to liquid to vapour, or vapour to liquid homogenization temperature ($T_{h\text{-}vapour}$).

-Volume measurement and Fill calculations

Fluid inclusions represent constant-volume and constant-mass systems (Bodnar 1983). Hence, the total volume (V) of the fluid inclusion is equal to the total mass (M) of the inclusion divided by the total density (D) of the inclusion contents: V=M/D (i). At a particular temperature, the total mass, M, is the sum of the masses of the individual phases in the inclusion: $M = \sum m_i$. The mass of the individual phase, m_i, is equal to the volume, v_i, of that phase multiplicate by its density, d_i: $m_i = v_i \times d_i$. (ii). The volume of the particular phase at a particular temperature is the difference of the total volume, V, minus the volume of the other phases present in the fluid inclusion: $v_i = V - \sum v_j$ (iii). With increasing temperatures, volumes of phases would generally increase, while the densities of the phases would decrease. The physical properties of the phases, such as the diameter of the vapour bubble (r=lenght V) and the edge lenght (r=length S) of the solid cubes, can be measured under the microscope (at room temperature). These dimensions, of the phases, are converted to the volume of the solid ($v_{i\text{-}solid}=r^3$) and the volume of the vapour bubble ($v_{i\text{-}vapour}=1/6\pi r^3$). The volume of the fluid inclusion can be calculated if the volume of the phases present are known. In a three phase, L-V-S, fluid inclusion, the volume of the vapour and solid can be measured. The fluid inclusion volume can be

calculated if (n-1) volume phases are known; this can be seen if equations (ii) and (iii) are substituted in equation (i). Densities of the fluid inclusions are calculated according to Bodnar (1983) (density polynomial equation A1, quoted in the appendix), at the homogenization temperatures with equivalent salinities used. Densities calculated for $CaCl_2$-H_2O systems, used equation 16 from Zhang and Frantz (1987). This density equation, as a function of temperature, pressure and composition, is the combined result of synthetic fluid inclusion studies with published density data for liquid-vapour curves. The regression equation 16, of Zhang and Frantz (1987), for the density (ρ) is as follows:

$$\rho=g_1+g_2T+g_3T^2+g_4T^3+g_5m+g_6m^2+g_7m^3+g_8Tm+g_9Tm^2+g_{10}T^2m$$

with -g- as constants presented in Table VII of Zhang and Frantz (1987), T the homogenization temperature and -m- the molality. The molality is calculated by equation 18 of Zhang and Frantz (1987): m=1000wt%/MW(100-wt%), and MW is the molecular weight of the solute.

Once the volume of the fluid inclusion is calculated, the volume of the liquid phase can be calculated. Subsequently the degree of fill (F) can be obtained: $F=V_L/(V_L+V_V\pm V_S)$. The degree of fill (F) is an index that quantifies the amount of liquid, vapour or solid in the fluid inclusion (relative to each other), and indicates if the fluid inclusion is liquid- or vapour dominant. This has some genetic implications, e.g. if boiling occurred.

-Salinity calculations

Freezing temperature depressions are a function of the fluid composition. The more complex salt-water system, the lower the eutectic point. Based on the unique eutectic point, fluids from the sodic-calcic alteration stage are modelled in the NaCl-$CaCl_2$-H_2O system. Melt temperatures of antarcticite, hydrohalite and ice are plotted on experimental NaCl-$CaCl_2$-H_2O phase diagrams. The weight percent of NaCl and $CaCl_2$ can be obtained from these diagrams. The salinity is generally expressed as "equivalent weight percent NaCl" (Eq.wt% NaCl), which is the sum of the individual weight percent salts in the fluid inclusion. These Eq.wt% NaCl based on freezing / melting temperatures are checked against experimental obtained algorithm equations and phase-volume salinity obtained calculations.

Fluid inclusions with brown discolouration on freezing and eutectic temperatures in the order of -50° to -58°C indicated that these fluid inclusions can be modelled in a NaCl-$CaCl_2$-H_2O system. The equation in Zhang and Frantz (1989): wt%$CaCl_2$ =

$0.1545 - 1.736T_m - 0.0396T_m^2 - 0.00034T_m^3$ was used for the $NaCl-CaCl_2-H_2O$ fluid inclusion in the cases were only one melting temperature was obtained.

In the case of the fluid inclusions in the "altered" schists (corundum bearing), freezing point depressions indicated a $NaCl-KCl-H_2O$ type of system. In those cases the equations of Hall *et al.* (1988) was used.

Phase-volume salinity calculations was done on L-V-S type only fluid inclusions and calculated for the $NaCl-CaCl_2-KCl-H_2O$ and $NaCl-CaCl_2-H_2O$ systems. Volumes of the fluid inclusions and containing phases were calculated according Bodnar (1983) method. By knowing the composition at the eutectic point of the liquid phase (Table 5.2) and identifying the daughter crystal as halite (SG_{halite} is 2.17), the salinity of the fluid inclusion can be calculated. An example for a fluid inclusion in a $NaCl-CaCl_2-KCl-H_2O$ system:

wt% of NaCl $= (V_{NaCl} \times SG_{NaCl}) + (wt\%_{NaCl\text{-}liquid} \times V_{liquid} \times \rho_{liquid})$

wt% of $CaCl_2$= $(wt\%_{CaCl_2\text{-}liquid} \times V_{liquid} \times \rho_{liquid})$

wt% of KCl = $(wt\%_{KCl\text{-}liquid} \times V_{liquid} \times \rho_{liquid})$

The same type of phase-volume salinity calculations can be done for the $NaCl-CaCl_2-H_2O$ system. However, based on this method, a minimum salinity of 31.7 Eq.wt% NaCl (for the $NaCl-CaCl_2-H_2O$ system) and 48.7 Eq.wt% NaCl (for the $NaCl-CaCl_2-KCl-H_2O$ system) would be obtained if no daughter minerals are present. Therefore, salinities based on this method would give maximum salinity values, compared to freezing obtained salinities.

-Potter's (1977) corrected homogenization temperature curves

Fluid inclusion are trapped droplets of fluid during crystallization of a mineral at certain pressure and temperature conditions. The temperature at which the fluid inclusion homogenize, using the Reynold stage at 1 atmosphere pressure, have to be corrected for this pressure difference. Potter (1977) constructed a series of "pressure-correction" graphs for correcting the homogenization temperatures, provided the pressure during entrapment can be independently obtained and Eq.wt% NaCl of the fluid is known. Based on Potter's graphs, homogenization corrections can be done for entrapment pressure upto 2 kbar and 25 Eq.wt% NaCl. The corrected homogenization temperatures are therefore minimum temperatures. Corrected homogenization temperatures, listed in the "fluid inclusion data table", for 3 kbar pressures are extrapolated from Potter's graph and are only listed for comparison.

The following fluid inclusion tables are listed below: i) FI-data sheets with freezing and heating temperatures, corrected homogenization temperatures and salinities, ii) volume measurements and fill, iii) salinities calculated with the "phase-volume" method.

The following abbreviations are used in the fluid inclusion tables

Teutc	= eutectic point
Tfm	= first melt
Tm-NaCl	= melt of hydrohalite
Tm-salt	= melt of salthydrate
Tm-ice	= melting of ice
Th-vapor	= vapor homogenization temperature
Th-solid	= solid dissolution temperature
Tcr1	= corrected homogenization temperature
1.5/20	= homogenization temperature corrected for 1.5 kbar and 20 Eq.wt% NaCl, based on Potter (1977)
wt%NaCl	= salinity if NaCl-H_2O system only
wt%Salt	= salinity in multiple salt-water system
Eq.NaCl	= equivalent wt% NaCl
L	= liquid phase
V	= vapor phase
S	= solid phase, if no comment, than halite
M164	= sample number
#4	= fluid inclusion number
uncontrd	= uncontrolled
htng	= heating
bcm	= became
bwrn	= brown
CCY	= Cloncurry fault

N.B. becoming brown on freezing indicate a NaCl-$CaCl_2$-H_2O system.

-FLUID INCLUSION DATA 1-

Sample No	Teutct/Tfm	Tm-nacl	Tm-salt/ice	Th-v	Th-s	Tcr1	Tcr2	Tcr3	wt%NaCl	wt%Salt	Eq.NaCl	ρ	P	Comment
M155A / DP# 44664						1.5/25	2/25	3/25						Quartz hematite vein
# 1	-49.0	-32.0		160		290	332	456		30.1	30.1	1.197	743	L-V-S halite triangular 15 μm
	-42.0									28.4	28.4			
average	-45.5	-32.0		160		290	332	456		29.3	29.3	1.188	715	
# 2	-49.0	-32.0		154	175	307	349	445	30.7		30.7	1.163	915	L-V-S rectangular 12 μm
	-41.0													
average	-45.0	-32.0		154	175	307	349	445	30.7		30.7	1.163	915	
# 3					184	316	359	459	31.1		31.1	1.153	1031	L-V-S rectangular 10 μm
# 4				168	180	312	355	455	30.9		30.9	1.157	977	L-V-S elongated 15 μm
# 5				130	182	314	357	457	30.9		30.9	1.153	999	L-V-S elongated 10 μm
# 6				150	185	317	360	460	31.1		31.1	1.151	1042	L-V-S elongated 10 μm
# 7				179	298	440	491	603	38.0		38.0	1.216	3720	L-V-S elongated 10 μm
# 8					209	343	388	491	32.3		32.3	1.125	1409	L-S
# 9				170	216	351	396	511	33.2		33.2	1.125	1569	L-V-S
# 10					194	327	371	480	31.6		31.6	1.143	1174	L-V-S
M69B / DP# 44620						1.5/20	2/20	3/25						Fl in Qtz+ Ttn vein in Ab-Act±Di rock
# 1				189		331	373	458						L-V < 5 μm
# 2		-23.0		179		320	361	469		23.1	23.1	1.107	651	L-V < 5 μm
M171 / DP#44674.0						1.5/25	2/25	3/25						Fl in Qtz in Ab-Act±Di rock
# 1		-38.0		266	248	405	453	566	34.5		34.5	1.040	2540	L-V-S halite subrounded 18 μm
		-37.8			276	416	465	571	36.4		36.4	1.038	2973	
		-38.7			258	396	444	566	35.2		35.2	1.064	2460	
					283	423	473	571	36.8		36.8	1.026	3183	
average		-38.2		266	266	405	454	568	35.7		35.7	1.052	2681	
# 2				266		405	453	566						L-V elongated 15 μm
# 3				248		385	432	556						L-V-S kidney shape 15 μm
# 4					276	416	465	571	36.2		36.2	1.036	2948	L-V-S rectangular 20 μm
# 5					282	422	472	571	36.8		36.8	1.028	3160	L-V-S spherical 15 μm
# 6				166	258	396	444	566	35.1		35.1	1.063	2449	L-V-S spherical 18 μm
M61 / DP# 44614						1.5/25	2/25	3/25						Fl in Qtz in Ab-Act±Di rock
# 1		-30.8	-7.7	170	235	371	417	528	33.7		33.7	1.093	1904	L-V-S halite rectangular 13 μm
				138	330	476	528	650	40.6		40.6	1.255	5103	
				170		301	343	528						
average		-30.8	-7.7	159	283	423	473	568	37.2		37.2	1.031	3225	
# 2				157	230	366	412	518		33.4	33.4	1.188	1799	L-V-S solid slight greenish 10 μm (Fe)
# 3				239		376	422	530						L-V subrounded 8 μm, w/ black solid
# 4				262		400	449	562						L-V subrounded 6 μm
# 5	-53.7	-38.6		201		335	379	528		27.7	27.7	1.138	1048	L-V rounded 5 μm
	-47.7													
average	-50.7	-38.6		201		335	379	528		27.7	27.7	1.138	1048	
M8 / DP# 44591						1.5/25	2/25	3/25						Quartz ilmenite albite vein resheared
# 1				173		304	347	451						L-V elongated 13 μm
# 2					187	320	363	483	31.2		31.2	1.149	1070	L-S halite subrounded 15 μm
# 3	-69.1	-46.5	-31.8	175		307	349	453		26.2	26.2	1.142	734	L-V
# 4	-58.1	-39.8	-29.6	186		319	361	466		25.6	25.6	1.127	805	L-V
# 5		-48.1		157		287	329	427		29.1	29.1	1.187	682	L-V subrounded 10 μm
# 6	-64.9	-48.1	-33.7							26.7	26.7			L
# 7				261	185	399	448	561	31.1		31.1	1.021	2100	L-V-S elongated 15 μm
# 8				246		383	430	537						L-V subrounded 12 μm
# 9				156	180	312	355	458	30.9		30.9	1.157	977	L-V-S rectangular 13 μm
# 10	-52.9			186		319	361	466						L-V irregular 13 μm
# 11	-53.6	-44.0		181		313	356	459		28.8	28.8	1.166	894	L-V elongated 8 μm
# 12	-53.7	-41.6		187		320	363	467		28.3	28.3	1.156	932	L-V rounded 5 μm
# 13	-54.4	-40.3		180		312	355	458		28.1	28.1	1.159	855	L-V irregular 10 μm
# 14				112	218	353	398	505	32.3		32.3	1.107	1535	L-V-S subrounded 10 μm
# 15				137		265	306	407						L-V rounded 10 μm
# 16					183	315	358	463		31.0	31.0	1.191	1015	L-V elongated 20 μm
# 17				138	158	288	330	428	29.9		29.9	1.181	718	L-V-S elongated 20 μm
# 18				220	230	366	412	518	33.0		33.0	1.093	1767	L-V-S subrounded 15 μm, hom->vapor
# 19				222		357	402	508						L-V elongated 15 μm
# 20				152		282	323	423						L-V subrounded 10 μm
# 21				180		312	355	458						L-V-S elongated 13 μm
# 22					181	313	356	459	30.9		30.9	1.155	988	L-V-S rounded 15 μm
# 23					206	340	384	491	32.1		32.1	1.127	1356	L-V-S rhombohedral 20 μm
# 24					184	316	359	464	31.1		31.1	1.153	1031	L-V-S rectangular 15 μm
# 25				168	208	342	386	493	32.3		32.3	1.127	1396	L-V-S elongated 18 μm
# 26				117	205	339	383	490	32.1		32.1	1.129	1343	L-V-S subrounded 10 μm
# 27				150	202	336	380	484	32.0		32.0	1.134	1298	L-V-S square 10 μm
# 28	-58.8													L-V-S elongated 18 μm
M86 / DP# 44630						1.5/25	2/25	3/25						Quartz vein with traces of biotite
# 1	-60.8	-28.2	-12.8	131	130	259	299	391	5.2	12.8	18.0	1.096	256	L-V-S elongated 40 μm
	-66.8	-46.8	-18.7	134		262	302	399	1.8	22.3	24.1	1.151	386	became brown on freezing
			-21.7							22.7	22.7			H2O-NaCl-CaCl2 system
			-20.8						3.0	22.2	22.2			
average	-63.8	-37.5	-18.5	133	130	261	301	395	2.6	19.4	22.0	1.131	338	
# 2				133		261	301	398						L-V irregular 45 μm became brown
														H20-NaCl-CaCl2 system
# 3				123		250	289	383						L-V rectangular 15 μm
				121		248	287	381						
average				122		249	288	382						
# 4				143		272	312	412						L-V needle shape elongated 45 μm
				133		261	301	398						
average				138		266	307	405						
# 5		-47.0	-22.7	146	131	275	316	414	1.7	21.8	23.5	1.137	442	L-V-S halite irregular 50 μm
		-48.6		146		275	316	414		28.9	28.9	1.193	584	became brown on freezing
	-72.0	-38.0		142		271	311	410		28.9	28.9	1.196	553	H2O-NaCl-CaCl2 system
average	-72.0	-44.5	-22.7	145	131	274	314	413	2.3	21.7	24.0	1.142	447	
# 6	-56.2													L-V subrounded 10 μm became brown
# 7	-49.2		-21.3							22.5	22.5			L-V irregular 15 μm became brown
# 8			-24 9							24.1	24.1			L-V-S elongated 10 μm
# 9			-25.6							24.3	24.3			L needle shape 12 μm
# 10	-60.0		5.8 ?											L-V-S triangular 15 μm
M164 / DP# 44668						1.5/20	2/20	3/25						Quartz vein in foliated granite sheet
# 1		-22.7	-20.4	142		278	317	412	9.2	13.1	22.3	1.128	391	L-V subrounded 15 μm
		-27.0	-19.4						16.0	8.2	24.2			
average		-24.9	-19.9	142		278	317	412	11.6	12.4	24.0	1.144	430	
# 2	-44.0	-21.5	-15.8							19.3	19.3			L-V rounded 15 μm
	-40.6	-23.0	-16.9	141		277	316	411	13.2	8.6	21.8	1.124	375	
	-45.0	-32.0												
average	-43.2	-25.5	-16.4	141		277	316	411	9.5	12.6	22.1	1.127	382	
# 3	-44.0		-17.0	130		266	303	400		20.2	20.2	1.117	290	L-V subrounded elongated 15 μm
	-43.6	-31.0	-19.0						5.2	18.3	23.5			
	-43.8		-22.0	133		269	307	403						

-FLUID INCLUSION DATA 2-

Sample No	Teutct/Tfm	Tm-nacl	Tm-salt/ice	Th-v	Th-s	Tcr1	Tcr2	Tcr3	wt%NaCl	wt%Salt	Eq.NaCl	ρ	P	Comment
average	-43.8	-31.0	-19.3	132		268	306	402	5.2	18.2	23.4	1.146	360	
# 4	-46.5	-22.5	-20.3	138		274	313	408	14.5	8.8	23.3	1.140	391	L-V subrounded 13 μm
	-44.1													became brown on freezing
	-43.0	-31.0	-19.4	132		268	306	402	5.2	18.2	23.4	1.146	360	H2O-NaCl-CaCl2 system
average	-44.5	-26.8	-19.9	135		271	309	404	8.1	15.8	23.9	1.148	387	
# 5	-46.5	-31.2	-21.4						5.0	18.5	23.5			L-V subrounded 14 μm
	-45.0	-26.0	-22.4	136		272	310	406	9.5	15.6	25.1	1.160	419	
	-43.0	-30.2	-20.5						5.1	18.2	23.3			
average	-44.8	-29.1	-21.4	136		272	310	406	5.7	17.9	23.6	1.145	386	
# 6	-46.1	-32.0	-22.0	144		281	320	414	4.9	19.4	24.3	1.146	450	L-V rounded 18 μm
	-46.1	-31.0	-18.0	144		281	320	414	5.2	17.1	22.3	1.126	402	
	-46.0		-22.4						4.8	19.5	24.3			
	-44.0		-22.0						4.9	19.4	24.3			
average	-45.6	-31.0	-21.1	144		281	320	414	5.4	18.6	24.0	1.143	442	
# 7	-44.0	-31.0	-20.0	143		280	318	413	5.3	18.3	23.6	1.140	427	L-V
			-22.0	132		268	306	402	4.9	19.4	24.3	1.154	378	
average	-44.0	-31.0	-21.0	138		274	313	408	5.4	18.6	24.0	1.147	407	
# 8	-46.0	-32.0	-15.5						4.7	16.2	20.9			L-V
	-45.0	-30.0	-17.4	138		274	313	408	6.1	18.4	24.5	1.152	418	
	-42.5													
average	-44.5	-31.0	-16.5	138		274	313	408	5.0	16.3	21.3	1.121	349	
# 9	-44.0	-30.6	-14.2	134		270	308	404	4.3	15.4	19.7	1.109	299	L-V
	-45.0	-31.2	-16.6						4.6	16.5	21.1			
	-43.2													
average	-44.1	-30.9	-15.4	134		270	308	404	4.9	15.7	20.6	1.117	316	
M51A / DP# 44604						1.5/20	2/20							Qtz stringers in sheared/altered schist
# 1	-37.8		-16.8	168		307	348			19.8	19.8	1.084	472	L-V subrounded 10 μm
			-16.2	192		335	377			19.3	19.3	1.059	600	
average	-37.8		-16.5	180		321	363			19.5	19.5	1.071	533	
# 2			-15.4							18.7	18.7			L needle shape (necking) 15 μm
			-20.2							21.9	21.9			
average			-17.8							20.4	20.4			
# 3	-45.8		-17.4	175		315	357			20.2	20.2	1.082	525	L-V kidney subrounded 10 μm
	-41.8		-21.9	171		311	352			22.8	22.8	1.111	584	
average	-43.8		-19.7	173		313	354			21.6	21.6	1.097	558	
# 4			-23.0	172		312	353			23.3	23.3	1.115	608	L-V subrounded 5 μm
			-14.1							17.7	17.7			
average			-18.6	172		312	353			21.4	21.4	1.096	545	
# 5	-37.8		-16.6	168		307	348			19.9	19.9	1.085	475	L-V elongated 15 μm
			-16.7	164		303	343			19.9	19.9	1.088	452	
average	-37.8		-16.6	166		305	346			19.9	19.9	1.087	464	
# 6	-42.1		-17.3							20.4	20.4			L-V elongated subrounded 18 μm
	-37.8		-14.7	190		333	375			18.4	18.4	1.052	554	
	-45.8		-13.0	172		312	353			16.9	16.9	1.054	409	
	-43.8		-14.8							18.5	18.5			
average	-42.3		-15.0	181		322	364			18.6	18.6	1.062	508	
# 7			-17.1	173		313	354			20.2	20.2	1.084	513	L-V subrounded 12 μm
			-19.1							21.7	21.7			
average			-18.0	173		313	354			20.9	20.9	1.090	536	
# 8	-37.8		-21.4	170		310	351			22.5	22.5	1.108	567	L-V±S (?) elongated 13 μm
# 9				169		308	349							L-V subrounded 12 μm
# 10			-24.3	165		304	345			23.8	23.8	1.125	575	L-V rounded 10 μm
			-22.2							22.9	22.9			
average			-23.2	165		304	345			23.2	23.2	1.119	556	
# 11				185		327	369							L-V rounded 12 μm
# 12	-45.8		-15.3	187		329	371			18.9	18.9	1.059	554	L-V subrounded 15 μm
# 13	-45.8		-17.5	184		326	367			20.6	20.6	1.078	596	L-V triangular elongated 15 μm
# 14	-41.8		-21.6	167		306	347			23.6	23.6	1.122	582	L-V kidney shape 14 μm
# 15	-44.8		-16.6	153		291	330			19.9	19.9	1.097	394	L-V elongated 15 μm
# 16				185		327	369							L-V triangular 10 μm
# 17	-47.8		-15.8	187		329	371			19.3	19.3	1.063	568	L-V rounded 15 μm
# 18	-45.7		-18.4	182		323	365			21.2	21.2	1.086	604	L-V irregular 15 μm
M120A / DP# 44642						1.5/20	2/20							FI in quartz in retrograde schist
# 1		-22.3		185		327	369			22.9	22.9	1.100	689	L-V rounded 10 μm
		-20.9		187		329	371			22.2	22.2	1.091	676	
		-20.8		187		329	371			22.2	22.2	1.091	676	
		-21.6								22.6	22.6			
		-21.4								22.5	22.5			
		-21.4								22.5	22.5			
		-21.1								22.3	22.3			
		-21.1								22.3	22.3			
		-21.4								22.5	22.5			
average		-21.4		186		328	370			22.5	22.5	1.095	681	
# 2		-21.7		187		329	371			22.7	22.7	1.096	696	L-V elongated 8 μm
		-22.5		188		330	372			23.0	23.0	1.099	715	
		-20.9		184		326	367			22.2	22.2	1.094	655	
		-20.7								22.1	22.1			
		-21.2								22.4	22.4			
		-22.0								22.8	22.8			
average		-21.5		186		328	370			22.6	22.6	1.096	684	
# 3				186		328	370							L-V elongated subrounded 5 μm
				175		315	357							
average				181		322	364							
# 4				188		330	372							L-V subrounded rounded 4 μm
				188		330	372							
				188		330	372							
				195		338	381							
average				190		333	375							
# 5				187		329	371							L-V rounded 4 μm
				186		328	370							
				221		369	412							
average				198		342	384							
# 6				179		320	361							L-V rounded 4 μm
				184		326	367							
average				182		323	365							
# 7				185		327	369							L-V subrounded 8 μm
39.1B / DP# 46303						1.5/25	2/25							Granite sheet sheared with Qtz overprint
# 1	-50.4		-33.8	180		312	355			26.7	26.7	1.144	797	L-V±S rectangular 10 μm
	-47.8		-39.8	182		314	357			27.6	27.6	1.152	853	possibly small multiple solids
			-39.8											
			-32.8							26.5	26.5			
average	-49.1		-36.3	181		313	356			27.3	27.3	1.149	831	
# 2	-53.8	-41.8 (?)	-31.8	183	271	410	459			26.2	26.2	1.057	1795	L-V-S triangular 8 μm
	-49.8		-34.8	182	280	420	470			26.9	26.9	1.057	1989	solid subrounded KCl (?)
	-49.7		-32.9	204		338	382			26.5	26.5	1.122	1017	
average	-51.1	-41.8	-33.2	190	276	416	465			26.6	26.6	1.057	1902	

-FLUID INCLUSION DATA 3-

Sample No	Teutct/Tfm	Tm-nacl	Tm-salt/ice	Th-v	Th-s	Tcr1	Tcr2	Tcr3	wt%NaCl	wt%Salt	Eq.NaCl	ρ	P	Comment
# 3	-52.8		-35.8		194	327	371			27.2	27.2	1.138	951	L-V-S subrounded 8 μm
	-52.8		-29.8	168	279	419	468			25.7	25.7	1.043	1859	solid hard to see ± fluid index
	-48.8		-41.8							28.4	28.4			
	-49.8		-38.8							27.8	27.8			
average	-51.1		-36.6	168	237	373	420			27.3	27.3	1.102	1438	
# 4				167		298	340							L-V elongated 4 μm
# 5				188		321	364							L-V elongated 4 μm
				184		316	359							
average				186		319	361							
# 6	-39.8		-23.8	183		315	358			23.6	23.6	1.109	700	L-V
	-46.8		-23.9	208		342	386			23.7	23.7	1.089	913	
			-23.6	167		298	340			23.5	23.5	1.121	579	
			-20.2							22.5	22.5			
average	-43.3		-22.9	186		319	361			23.2	23.2	1.102	708	
M118 / DP# 44640						1.5/20	2/20							Qtz-Hmt-Kfs-Act tension gash vein
# 1	-68.8	-53.8	-22.2	168		307	348		0.6	21.0	21.6	1.101	526	L-V rhombohedral 5 μm
	-60.8	-50.8	-17.8	154		292	331		1.0	19.0	20.0	1.097	401	negative crystal shape
	-58.8	-51.8	-21.2						0.6	20.5	21.1			brown colouring on freezing
	-60.8	-50.7	-18.7						0.2	19.0	19.2			H2O-NaCl-CaCl2 system (?)
		-51.8	-18.8							21.2	21.2			
			-19.0							21.0	21.0			
			-18.7											
average	-62.3	-51.8	-19.5	161		299	340		1.2	21.2	22.4	1.115	506	
# 2			-8.8	168		307	348			12.6	12.6	1.018	278	L-V rhombohedral 5 μm
				253		405	449							negative crystal shape
				222		370	413							
average			-8.8	214		361	404			12.6	12.6	0.973	458	
# 3				167		298	340							L-V rhombohedral < 5 μm
# 4	-60.8	-51.8	-39.9						1.8	28.6	30.2			L-V rectangular 7 μm
	-59.3	-51.4	-43.8						1.8	28.6	30.2			corrected for 25 wt%
		-52.3	-43.2	165		296	338							corrected for 25 wt%
		-50.8	-43.8											
		-51.8	-42.8											
			-43.7											
average	-60.1	-51.6	-42.9	165		296	338		1.8	28.6	30.2	1.195	794	corrected for 25 wt%
# 5	-60.8	-50.9	-31.5						2.0	25.0	27.0			L-V rounded 8 μm
	-61.8	-52.9	-35.2						2.1	27.0	29.1			solid doubtful
	-61.2	-51.8	-35.5						2.1	27.0	29.1			bubble moves at -38 °C
	-60.8		-35.5											
	-62.5		-35.8											
			-35.5											
average	-61.4	-51.9	-34.9						2.0	25.1	27.1			
# 6			-14.8											L-V elongated 5 μm
# 7			-21.2			1.5/20	2/20							L elongated 8 μm
# 8	-61.6	-50.2	-15.8	216		363	406		1.4	18.4	19.8	1.041	788	L-V triangular 10 μm
# 9		-49.8	-6.0	173		313	354		0.6	8.6	9.2	0.983	209	L-V square 10 μm
		-40.7	-21.1	168		307	348		0.9	20.5	21.4	1.099	520	
average		-45.3	-13.6	168		307	348		1.1	17.2	18.3	1.070	429	
CM31.1B / DP# 46412						1.5/25	2/25							Quartz K-feldspar bearing vein
# 1				142	165	296	338		30.3		30.3	1.175	798	L-V-S halite rectangular 20 μm
					161	291	333		30.0		30.0	1.177	749	
average				142	163	294	335		30.1		30.1	1.175	771	
# 2				133	166	297	339		30.3		30.3	1.173	807	L-V-S elongated 20 μm
# 3	-65.8			139		267	308							L-V elongated 15 μm
				164		295	336							
average	-65.8			152		282	323							
# 4				140		268	309							L-V bottle shape 10 μm
# 5				195		328	372							L-V elongated 10 μm
# 6 *				72	< 160	290	332		30.1		30.1	1.181	743	L-V-S halite 10 μm
				148		277	318		30.1		30.1	1.205	636	uncontrolled heating
				123		250	289		30.1		30.1	1.260	440	
average				114	< 160	290	332		30.1		30.1	1.181	743	
# 7 *					< 160	290	332							L-V-S irregular 15 μm uncontrld htng
# 8 *	-51.6													L-V-S irregular 15 μm uncontrld htng
	-53.1													
average	-52.4				< 160	290	332							
# 9 *				184		316	359							L-V elongated 13 μm bcm brwn
# 10 *			0.1											L-V rectangular 8 μm bcm brwn
# 11 *	-48.5			164	< 160	295	336							L-V-S halite subrounded 20 μm
				163		294	335							became brown on freezing
average	-48.5			164	< 160	295	336							H2O-NaCl-CaCl2 system
# 12 *	-47.8	-30.6	-19.5						5.3	18.1	23.4			L-V elongated 10 μm
			-20.4											became brown on freezing
average	-47.8	-30.6	-20.0						5.3	18.2	23.4			
# 13 *	-62.8	-36.8	-18.0						2.4	19.4	21.8			L-V bottle shape 12 μm
	-47.8	-25.8	-18.1	152		282	323		9.5	13.5	23.0	1.127	466	became brown on freezing
	-43.8		-18.5							20.9	20.9			H2O-NaCl-CaCl2
	-52.2		-19.6							21.5	21.5			
	-46.8		-16.8							19.8	19.8			
	-47.8													
average	-50.2	-31.3	-18.2	152		282	323		5.3	17.6	22.9	1.126	464	
# 14 *			-19.1	115		241	280			21.7	21.7	1.141	250	L-V subrounded 10 μm
# 15	-50.6			300	230	442	493			33.5	33.5	1.132	3114	L-V-S rectangular 20 μm
	-47.8													halite 5 μm bubble 10 μm
average	-49.2			300	230	442	493			33.5	33.5	1.132	3114	
# 16	-50.8	-26.8	9.8	175		307	349			1.1	1.1	0.908	29	L-V rectangular 15 μm
	-52.2		10.1							0.3	0.3			became brown on freezing
	-50.6													CO2 (?) caltrace (?)
average	-51.2		10.0	175		307	349							H2O-NaCl-CaCl2
# 17		-23.8	5.9	102		227	265			10.0	10.0	1.045	82	L-V kidney 10 μm CO2 (?)
# 18		-37.8	-24.8	166		297	339		2.4	22.2	24.6	1.132	607	L-V subrounded 13 μm
# 19				210		344	389							L-V elongated 12 μm
# 20				164		295	336							L-V elongated 12 μm bcm brwn
# 21		-36.8		165		296	338							L-V rounded 15 μm bcm brwn
# 22	-47.8			168		299	341							L-V elongated 15 μm
# 23				166		297	339			27.4	27.4	1.162	702	L-V elongated 15 μm bcm brwn
# 24	-50.4			162		292	334							L-V-S (?) irregular 20 μm bcm brwn
# 25				171		302	344							L-V elongated 13 μm
# 26				165		296	338							L-V rectangular 13 μm
# 27					114	240	279			28.4	28.4	1.209	349	L-V-S halite rctnglr 15 μm bcm brwn
CJ7.1 / DP# 46411						1.5/25	2/25							Comb quartz vein CCY fault
# 1	-54.7	-31.2	-22.9	152		282	323		5.3	18.4	23.7	1.134	485	L-V elongated 10 μm
	-45.0		-23.6							23.5	23.5			
	-44.0		-23.1							23.3	23.3			
	-46.8		-19.9							21.7	21.7			
	-47.0		-23.4							23.4	23.4			

-FLUID INCLUSION DATA 4-

Sample No	Teutct/Tfm	Tm-nacl	Tm-salt/ice	Th-v	Th-s	Tcr1	Tcr2	Tcr3	wt%NaCl	wt%Salt	Eq.NaCl	ρ	P	Comment
average	-47.5	-31.2	-22.6	152		282	323		5.4	18.8	24.2	1.139	498	
# 2				161		291	333							L-V subrounded 4 μm
# 3			-40.4	162		292	334			28.1	28.1	1.173	692	L-V triangular 4 μm
# 4				158		288	330							L-V elongated 5 μm
# 5				159		289	331							L-V square 5 μm
# 6				107		232	271							L-V rectangular 4 μm
# 7	-50.8		-35.8							27.2	27.2			L-V kidney 5μm
	-61.8		-39.4							27.9	27.9			
			-39.6	148		277	318			27.9	27.9	1.181	572	
			-39.3							27.9	27.9			
			-38.8							23.8	23.8			
			-39.0							27.9	27.9			
average	-55.5		-38.7	148		277	318			27.7	27.7	1.178	566	
# 8	-51.0		-49.9	130		257	298			30.4	30.4	1.222	498	L-V rounded 10 μm
	-51.2			126		253	293							
average	-51.1		-49.9	128		255	295			30.4	30.4	1.223	483	
# 9				125		252	292							L-V
# 10				199		333	376							L-V rectangular 13 μm
				128		255	295							
				122		249	288							
average				150		279	320							
# 11				119		245	285							L-V subrounded 5 μm
# 12				118		244	284							L-V triangular 3 μm
# 13			-41.8	86		209	247			28.4	28.4	1.227	202	L-V rectangular 10 μm
# 14				128		255	295							L-V subrounded 4 μm
# 15				128		255	295							L-V square 5 μm
# 16	-41.8		-20.3						0.8	21.1	21.9			L-V kidney 8 μm
# 17				155		285	326							L-V elongated 8 μm
# 18				147		276	317							L-V subrounded 8 μm
# 19	-52.8		-41.8	102		227	265			28.0	28.4	1.217	281	L-V kidney 10 μm
# 20	-53.1		-50.6	139		267	308			30.7	30.7	1.219	577	L-V triangular 10 μm
			-50.5	138		266	307			30.6	30.6	1.218	566	
			-51.0	138		266	307			30.8	30.8	1.221	571	
			-51.7							31.0	31.0			
average	-53.1		-50.9	138		266	307			30.8	30.8	1.221	571	
# 21	-53.8		-38.3							27.7	27.7			L-V-S (?) irregular 12 μm
CJ6.7 / DP# 46410						1.5/20	2/20							Milky white quartz vein CCY fault
# 1			-25.6	108		242	278			24.3	24.3	1.170	255	L-V rhombohedral 5 μm
# 2			-22.2	55		184	218			22.9	22.9	1.187	66	L-V subrounded 5 μm
			-22.4	69		200	233			23.0	23.0	1.181	101	
			-20.3							21.9	21.9			
			-19.5							21.5	21.5			
average			-21.1	62		192	225			22.2	22.2	1.177	79	
# 3			-21.9	113		248	284			22.8	22.8	1.153	257	L-V subrounded 5 μm
# 4			-22.4	158		296	336			23.0	23.0	1.123	504	L-V-S (?) rectangular 5 μm
			-19.1	190		333	375			21.2	21.2	1.079	659	
			-21.9							22.8	22.8			
average			-21.1	172		312	353			22.3	22.3	1.105	574	
# 5			-21.8							22.7	22.7			L-V kidney 5 μm
			-19.7	154		292	331			21.6	21.6	1.112	442	
			-20.8							22.2	22.2			
average			-20.8	154		292	331			22.2	22.2	1.118	457	
# 6	-45.8		-23.2						1.4	21.6	23.0			L-V-S (?) elongated 10 μm
			-20.7	158		296	336		1.3	20.8	22.8	1.121	498	
			-18.7						1.2	19.8	21.5			
			-18.7											
average	-45.8		-20.3	158		296	336		1.3	20.7	23.0	1.123	504	
# 7			-18.7	105		239	274			21.0	21.0	1.141	201	L-V kidney 8 μm
# 8			-20.3	184		326	367			21.9	21.9	1.091	643	L-V elongated 10 μm
# 9			-18.3	183		324	366			20.7	20.7	1.080	593	L-V subrounded 10 μm
# 10			-18.5	110		244	280			20.9	20.9	1.137	219	L-V square 10 μm
# 11	-52.6		-38.7	122		257	294			27.7	27.7	1.196	386	L-V rectangular 8 μm
	-52.8													
	-50.8													
average	-52.1		-38.7	122		257	294		1.8	27.8	29.6	1.217	423	
# 12	-52.8													L-V subrounded 6 μm
	-50.9		-26.8	170		310	351			24.8	24.8	1.131	644	
	-47.5													
	-45.4													
average	-49.2		-26.8	170		310	351		1.3	24.3	25.6	1.140	671	
# 13				176		316	358							L-V rounded 5 μm
# 14				151		288	328							L-V kidney 8 μm
# 15				184		326	367							L-V subrounded 5 μm
21/336 / DP# 46413		No browning (H2O-NaCl-CaCl2 ??				1.5/25	2/25							Comb quartz vein CCY fault
# 1	-54.5		-45.8	129	164	295	336		0.4	28.0	28.4	1.174	719	L-V-S (?) triangular 12 μm
	-53.2		-41.8						0.4	28.1	28.5			bubble moves at -47 °C
			-34.6							26.9	26.9			
			-34.2							26.8	26.8			
average	-53.8		-39.1	129	164	295	336		1.6	28.2	29.8	1.191	770	
# 2	-54.8		-32.8		202	336	380		0.4	26.0	26.4	1.123	992	calculated for 25wt%
	-51.8		-34.8						0.5	25.9	26.4			L-V-S triangular 15 μm
	-53.8		-39.8						0.5	27.9	28.4			solid slight greenish (FeCl2 ?)
average	-52.7		-35.8		202	336	380		1.6	28.2	29.8	1.162	1172	
# 3				60		181	220							L-V rectangular 5 μm
# 4				133		261	301							L-V subrounded 3 μm
# 5				63	176	308	350			30.7	30.7	1.193	925	L-V-S triangular 10 μm sbrnd solid
# 6					198	332	375			31.8	31.8	1.190	1235	L-V rounded 3 μm
# 7				65		186	225							L-V elongated 8 μm
# 8				119		245	285							L-V subrounded 10 μm
# 9			-19.2	112	169	300	342			21.3	21.3	1.098	523	L-V-S needle 10 μm
# 10	-50.8		-29.5	71		193	231		1.7	25.0	26.7	1.217	129	L-V triangular 5 μm
# 11			-29.6	69		190	229			25.7	25.7	1.208	116	L-V rectangular 10 μm
			-21.8	72		203	236			22.7	22.7	1.176	108	calculated for 20wt%
			-19.4							21.4	21.4			
average			-23.6	71		202	235			23.5	23.5	1.185	110	
# 12			-21.4	67		198	231			22.5	22.5	1.177	93	L-V subrounded 7 μm
# 13			-20.3							21.9	21.9			L-V rounded 5 μm
			-18.4							20.8	20.8			
average			-19.4							21.4	21.4			
# 14			-19.6		158	296	336			21.5	21.5	1.108	462	L-S rounded 5 μm two solids
			-16.8		187	329	371			19.8	19.8	1.068	586	
average			-18.2		173	313	354			20.7	20.7	1.089	529	
# 15				62		1.5/25	2/25							L-V triangular 12 μm
# 16					166	297	150			30.3	30.3	1.195	807	L-V-S triangular 12 μm

-FLUID INCLUSION FILL DATA 1

Bodnar 1983	ρ	Lenght S	Lenght V	Vol S μ^3	Vol V μ^3	V Fl	Fill-L	Fill-solid	Fill-vapour
M155A / DP# 44664									
# 1	1.120	4.0	2.2	64	6	1048	0.9	0.1	0.0
average	1.115	4.0	2.2	64	6	984	0.9	0.1	0.0
# 2	1.107	2.3	1.4	13	2	183	0.9	0.1	0.0
# 3	1.098	4.4	3.3	88	19	1262	0.9	0.1	0.0
# 4	1.102	2.3	1.7	13	2	185	0.9	0.1	0.0
# 5	1.099	2.2	2.1	11	5	190	0.9	0.1	0.0
# 6	1.097	3.8	1.1	54	1	635	0.9	0.1	0.0
# 7	0.951	4.4	1.4	88	2	430	0.8	0.2	0.0
# 8	1.073	6.7		296	0	2793	0.9	0.1	0.0
# 9	1.067	2.9	1.2	24	1	227	0.9	0.1	0.0
# 10	1.088	2.6	0.9	17	0	183	0.9	0.1	0.0
M69B / DP# 44620									
# 2	1.054		2.1	0	5	38	0.9	0.0	0.1
M171 / DP# 44674									
# 1	1.000	2.8	2.0	22	4	157	0.8	0.1	0.0
	0.987	2.8	2.0	22	4	147	0.8	0.1	0.0
	1.013	2.8	2.0	22	4	168	0.8	0.1	0.0
	0.976	2.8	2.0	22	4	140	0.8	0.2	0.0
average	1.002	2.8	2.0	22	4	158	0.8	0.1	0.0
# 4	0.987	5.5	1.8	166	3	955	0.8	0.2	0.0
# 5	0.978	3.0	1.7	27	3	160	0.8	0.2	0.0
# 6	1.013	3.4	1.9	39	4	276	0.8	0.1	0.0
M61 / DP# 44614									
# 1	1.043	2.6	1.8	17	3	156	0.9	0.1	0.0
	0.887		1.8	0	3	12	0.7	0.0	0.3
average	0.977		1.8	0	3	17	0.8	0.0	0.2
# 2	1.049	2.0	1.0	8	1	68	0.9	0.1	0.0
# 5	1.059		0.8	0	0	3	0.9	0.0	0.1
average	1.059		0.8	0	0	3	0.9	0.0	0.1
M8 / DP# 44591									
# 2	1.095	2.1		10	0	113	0.9	0.1	0.0
# 3	1.078	2.1	3.1	10	16	258	0.9	0.0	0.1
# 4	1.063		3.0	0	14	124	0.9	0.0	0.1
# 5	1.117		2.3	0	6	90	0.9	0.0	0.1
# 7	0.998	3.6	2.4	46	8	316	0.8	0.1	0.0
# 9	1.102	1.4	4.0	3	34	445	0.9	0.0	0.1
# 11	1.088		2.6	0	9	96	0.9	0.0	0.1
# 12	1.078		2.0	0	4	41	0.9	0.0	0.1
# 13	1.085		4.0	0	34	350	0.9	0.0	0.1
# 14	1.061	3.7	1.6	51	2	460	0.9	0.1	0.0
# 16	1.099		2.9	0	12	145	0.9	0.0	0.1
# 17	1.121	4.3	3.0	79	14	1414	0.9	0.1	0.0
# 18	1.047	3.4	6.0	40	113	1208	0.9	0.0	0.1
# 22	1.101	3.3	3.0	37	14	618	0.9	0.1	0.0
# 23	1.076	4.0	2.2	64	6	672	0.9	0.1	0.0
# 24	1.098	2.5	2.0	16	4	233	0.9	0.1	0.0
# 25	1.074	3.0	1.0	27	1	262	0.9	0.1	0.0
# 26	1.077	2.0	0.8	8	0	81	0.9	0.1	0.0
# 27	1.080	3.0	0.8	27	0	274	0.9	0.1	0.0
M86 / DP# 44630									
# 1	1.063	4.7	2.5	103	9	978	0.9	0.1	0.0
	1.105	4.7	2.5	103	9	1414	0.9	0.1	0.0
average	1.091	4.7	2.5	103	9	1226	0.9	0.1	0.0
# 5	1.089	4.7	5.9	103	110	2310	0.9	0.0	0.0
	1.127	4.7	5.9	103	110	3520	0.9	0.0	0.0
	1.132	4.7	5.9	103	110	3738	0.9	0.0	0.0
average	1.094	4.7	5.9	103	110	2416	0.9	0.0	0.0
M164 / DP# 44668									
# 1	1.085		3.0	0	14	147	0.9	0.0	0.1
	1.082		3.1	0	16	158	0.9	0.0	0.1
average	1.084		3.1	0	16	161	0.9	0.0	0.1
# 3	1.080		2.2	0	6	56	0.9	0.0	0.1
average	1.102		2.2	0	6	68	0.9	0.0	0.1
# 4	1.096		1.0	0	1	6	0.9	0.0	0.1
	1.102		1.0	0	1	6	0.9	0.0	0.1
average	1.103		1.0	0	1	6	0.9	0.0	0.1
	1.111		1.6	0	2	29	0.9	0.0	0.1
# 6	1.097		1.8	0	3	36	0.9	0.0	0.1
	1.083		1.8	0	3	31	0.9	0.0	0.1
average	1.095		1.8	0	3	35	0.9	0.0	0.1
M51A / DP# 44604									
# 1	1.042		1.8	0	3	23	0.9	0.0	0.1
	1.015		1.8	0	3	20	0.8	0.0	0.2
average	1.028		1.8	0	3	21	0.9	0.0	0.1
# 3	1.038		1.1	0	1	5	0.9	0.0	0.1
	1.060		1.1	0	1	6	0.9	0.0	0.1
average	1.050		1.1	0	1	6	0.9	0.0	0.1
# 4	1.062		2.0	0	4	37	0.9	0.0	0.1
# 5	1.043		2.0	0	4	32	0.9	0.0	0.1
	1.047		2.0	0	4	33	0.9	0.0	0.1
average	1.045		2.0	0	4	32	0.9	0.0	0.1
# 6	1.011		2.2	0	6	35	0.8	0.0	0.2
	1.018		2.2	0	6	37	0.8	0.0	0.2
average	1.021		2.2	0	6	37	0.9	0.0	0.1
# 7	1.040		3.0	0	14	106	0.9	0.0	0.1
average	1.045		3.0	0	14	109	0.9	0.0	0.1
# 8	1.059		4.0	0	34	285	0.9	0.0	0.1
# 10	1.073		3.6	0	24	231	0.9	0.0	0.1
average	1.069		3.6	0	24	223	0.9	0.0	0.1
# 12	1.017		3.8	0	29	189	0.8	0.0	0.2
# 13	1.032		2.1	0	5	35	0.9	0.0	0.1
# 14	1.069		3.2	0	17	158	0.9	0.0	0.1
# 15	1.057		3.9	0	31	261	0.9	0.0	0.1
# 17	1.020		4.6	0	51	340	0.8	0.0	0.2
# 18	1.038		4.1	0	36	267	0.9	0.0	0.1
M120A / DP# 44642									
# 1	1.046		2.0	0	4	33	0.9	0.0	0.1
	1.040		2.0	0	4	31	0.9	0.0	0.1
	1.040		2.0	0	4	31	0.9	0.0	0.1
average	1.043		2.0	0	4	32	0.9	0.0	0.1
# 2	1.043		1.0	0	1	4	0.9	0.0	0.1
	1.044		1.0	0	1	4	0.9	0.0	0.1
	1.043		1.0	0	1	4	0.9	0.0	0.1
average	1.043		1.0	0	1	4	0.9	0.0	0.1
39.1B / DP# 46303									
# 1	1.076		2.0	0	4	41	0.9	0.0	0.1
	1.080		2.0	0	4	42	0.9	0.0	0.1
average	1.079		2.0	0	4	41	0.9	0.0	0.1
# 2	0.967	4.0	4.0	64	34	501	0.8	0.1	0.1
	0.958	4.0	4.0	64	34	484	0.8	0.1	0.1
	1.048	4.0	4.0	64	34	770	0.9	0.1	0.0
average	0.962	4.0	4.0	64	34	492	0.8	0.1	0.1
# 3	1.064	3.0	3.5	27	22	435	0.9	0.1	0.1
	0.954	3.0	3.5	27	22	242	0.8	0.1	0.1
average	1.014	3.0	3.5	27	22	318	0.8	0.1	0.1

FLUID INCLUSION FILL DATA 2

Bodnar 1983	ρ	Lenght S	Lenght V	Vol S μ^3	Vol V μ^3	V Fl	Fill L	Fill solid	Fill vapour
M118 / DP# 44640									
# 1	1.055		1.8	0	3	25	0.9	0.0	0.1
	1.057		1.8	0	3	26	0.9	0.0	0.1
average	1.067		1.8	0	3	28	0.9	0.0	0.1
# 2	0.991		1.6	0	2	12	0.8	0.0	0.2
average	0.945		1.6	0	2	10	0.8	0.0	0.2
#4 average	1.115		0.7	0	0	3	0.9	0.0	0.1
# 8	0.993		2.9	0	13	74	0.8	0.0	0.2
# 9	0.962		2.5	0	8	41	0.8	0.0	0.2
	1.053		2.5	0	8	67	0.9	0.0	0.1
average	1.032		2.5	0	8	58	0.9	0.0	0.1
CM 31.1B / DP# 46412									
# 1	1.116	5.8	3.2	195	17	3024	0.9	0.1	0.0
	1.118	5.8	3.2	195	17	3122	0.9	0.1	0.0
average	1.117	5.8	3.2	195	17	3061	0.9	0.1	0.0
# 2	1.115	5.2	3.0	141	14	2175	0.9	0.1	0.0
# 6	1.120	5.0	6.2	125	125	3755	0.9	0.0	0.0
	1.134	5.0	6.2	125	125	4507	0.9	0.0	0.0
	1.160	5.0	6.2	125	125	7469	1.0	0.0	0.0
average	1.120	5.0	6.2	125	125	3755	0.9	0.0	0.0
# 13	1.080		14.0	0	1437	14380	0.9	0.0	0.1
average	1.079		14.0	0	1437	14296	0.9	0.0	0.1
# 15	0.948	5.0	7.5	125	221	1646	0.8	0.1	0.1
average	0.948	5.0	7.5	125	221	1646	0.8	0.1	0.1
# 16	0.904		4.0	0	34	136	0.8	0.0	0.2
# 17	1.027		2.2	0	6	39	0.9	0.0	0.1
# 18	1.077		1.8	0	3	30	0.9	0.0	0.1
# 23	1.096		3.1	0	16	180	0.9	0.0	0.1
# 27	1.156	5.0	4.1	125	36	4398	1.0	0.0	0.0
CJ 7.1 / DP# 46411									
# 1	1.085		1.5	0	2	18	0.9	0.0	0.1
average	1.089		1.5	0	2	19	0.9	0.0	0.1
# 2									
# 3	1.105		0.6	0	0	1	0.9	0.0	0.1
# 7	1.118		0.8	0	0	4	0.9	0.0	0.1
average	1.117		0.8	0	0	4	0.9	0.0	0.1
#8 average	1.157		0.6	0	0	3	1.0	0.0	0.0
# 13	1.181		1.2	0	1	56	1.0	0.0	0.0
# 19	1.167		1.0	0	1	20	1.0	0.0	0.0
# 20	1.147		1.0	0	0	11	1.0	0.0	0.0
	1.148		1.0	0	0	11	1.0	0.0	0.0
	1.149		1.0	0	0	11	1.0	0.0	0.0
average	1.149		1.0	0	0	11	1.0	0.0	0.0
CJ 6.7 / DP# 46410									
# 1	1.130		1.7	0	3	44	0.9	0.0	0.1
# 2	1.160		1.7	0	3	76	1.0	0.0	0.0
	1.151		1.7	0	3	63	1.0	0.0	0.0
average	1.149		1.7	0	3	61	1.0	0.0	0.0
# 3	1.114		2.0	0	4	59	0.9	0.0	0.1
# 4	1.074	1.6	1.0	4	1	44	0.9	0.1	0.0
	1.030	1.6	1.0	4	1	33	0.9	0.1	0.0
average	1.056	1.6	1.0	4	1	38	0.9	0.1	0.0
# 5									
	1.068	1.1	0.8	1	0	15	0.9	0.1	0.0
average	1.073	1.1	0.8	1	0	15	0.9	0.1	0.0
# 6	1.073	1.1	2.1	1	5	58	0.9	0.0	0.1
average	1.074	1.1	2.1	1	5	59	0.9	0.0	0.1
# 7	1.107		2.2	0	6	72	0.9	0.0	0.1
# 8	1.041		3.0	0	14	106	0.9	0.0	0.1
# 9	1.034		2.0	0	4	30	0.9	0.0	0.1
# 10	1.102		1.9	0	4	44	0.9	0.0	0.1
# 11	1.143		1.8	0	3	64	1.0	0.0	0.0
average	1.157		1.8	0	3	86	1.0	0.0	0.0
# 12	1.075		0.9	0	0	4	0.9	0.0	0.1
average	1.080		0.9	0	0	4	0.9	0.0	0.1
21/336 / DP# 46413									
# 1	1.105	1.3	1.8	2	3	68	0.9	0.0	0.0
average	1.114	1.3	1.8	2	3	76	0.9	0.0	0.0
# 2	1.050	2.0	1.3	8	1	74	0.9	0.1	0.0
average	1.069	2.0	1.3	8	1	85	0.9	0.1	0.0
# 5	1.105	1.7	2.1	5	5	125	0.9	0.0	0.0
# 6	1.084		0.5	0	0	1	0.9	0.0	0.1
# 9	1.052	1.3	0.7	2	0	19	0.9	0.1	0.0
# 10	1.180		0.7	0	0	9	1.0	0.0	0.0
# 11	1.173		1.0	0	1	23	1.0	0.0	0.0
	1.146		1.0	0	1	12	1.0	0.0	0.0
average	1.153		1.0	0	1	13	1.0	0.0	0.0
# 12	1.148		0.5	0	0	1	1.0	0.0	0.0
# 14	1.064	5.0		125	0	1101	0.9	0.1	0.0
	1.023	5.0		125	0	850	0.9	0.1	0.0
average	1.044	5.0		125	0	959	0.9	0.1	0.0

DP#	Sample No	Fill-L	Fill-solid	Fill-vapour	Sal/fill	EqNaCl freezing	wt NaCl (NaCl-CaCl2-H2O system)	wt CaCl2 (NaCl-CaCl2-H2O system)	EqNaCl-Fill	wtNaCl (NaCl-CaCl2-KCl-H2O system)	wtCaCl2 (NaCl-CaCl2-KCl-H2O system)	wtKCl (NaCl-CaCl2-KCl-H2O system)	EqNaCl
44664	M155A# 1	0.9	0.1	0.0	37.8	30.1	13.0	26.5	39.5	11.8	39.8	2.9	54.4
	# 2	0.9	0.1	0.0	39.5	30.7	14.5	26.0	40.6	13.4	39.1	2.8	55.3
	# 3	0.9	0.1	0.0	39.7	31.1	14.8	26.0	40.7	13.6	39.0	2.8	55.4
	# 4	0.9	0.1	0.0	39.5	30.9	14.6	26.0	40.6	13.4	39.1	2.8	55.3
	# 5	0.9	0.1	0.0	37.4	30.9	12.8	26.6	39.4	11.6	39.9	2.9	54.4
	# 6	0.9	0.1	0.0	42.7	31.1	17.2	25.2	42.4	16.0	37.9	2.7	56.6
	# 7	0.8	0.2	0.0	72.3	38.0	38.4	18.8	57.2	37.4	28.2	2.0	67.7
	# 8	0.9	0.1	0.0	47.4	32.3	21.0	24.1	45.1	19.9	36.1	2.6	58.6
	# 9	0.9	0.1	0.0	47.5	33.2	21.2	24.0	45.2	20.0	36.1	2.6	58.7
	# 10	0.9	0.1	0.0	44.0	31.6	18.3	24.9	43.2	17.2	37.4	2.7	57.2
44620	M69B# 2	0.9	0.0	0.1	26.0	23.1	1.8	29.9	31.7	0.6	44.8	3.2	48.7
44674	M171# 1	0.8	0.1	0.0	55.9	35.7	28.0	21.9	50.0	26.9	33.0	2.4	62.3
	# 4	0.8	0.2	0.0	64.1	36.2	33.3	20.3	53.6	32.2	30.6	2.2	65.0
	# 5	0.8	0.2	0.0	63.4	36.8	33.0	20.4	53.4	32.0	30.7	2.2	64.8
	# 6	0.8	0.1	0.0	56.4	35.1	28.1	21.9	50.0	27.0	32.9	2.4	62.3
44614	M61#1	0.8	0.2	0.0	60.6	37.2	31.4	20.9	52.3	30.4	31.4	2.3	64.0
	# 2	0.9	0.1	0.0	50.3	33.4	23.5	23.3	46.8	22.3	35.0	2.5	59.9
	# 5	0.9	0.0	0.1	26.0	27.7	1.8	29.9	31.7	0.6	44.8	3.2	48.7
44591	M8# 2	0.9	0.1	0.0	43.3	31.2	17.6	25.1	42.7	16.5	37.7	2.7	56.9
	# 3	0.9	0.0	0.1	33.7	26.2	9.6	27.5	37.2	8.5	41.3	3.0	52.7
	# 4	0.9	0.0	0.1	26.0	25.6	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 5	0.9	0.0	0.1	26.0	29.1	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 7	0.8	0.1	0.0	57.2	31.1	28.9	21.7	50.6	27.8	32.5	2.3	62.7
	# 9	0.9	0.0	0.1	27.3	30.9	3.2	29.5	32.7	2.0	44.2	3.2	49.4
	# 11	0.9	0.0	0.1	26.0	28.8	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 12	0.9	0.0	0.1	26.0	28.3	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 13	0.9	0.0	0.1	26.0	28.1	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 14	0.9	0.1	0.0	48.7	32.3	22.1	23.7	45.9	21.0	35.6	2.6	59.2
	# 16	0.9	0.0	0.1	26.0	31.0	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 17	0.9	0.1	0.0	36.7	29.9	12.1	26.8	38.9	10.9	40.2	2.9	54.0
	# 18	0.9	0.0	0.1	32.9	33.0	9.1	27.7	36.8	7.9	41.5	3.0	52.4
	# 22	0.9	0.1	0.0	37.8	30.9	13.1	26.5	39.6	12.0	39.7	2.9	54.5
	# 23	0.9	0.1	0.0	45.1	32.1	19.3	24.6	43.9	18.2	36.9	2.7	57.7
	# 24	0.9	0.1	0.0	39.2	31.1	14.3	26.1	40.5	13.2	39.2	2.8	55.1
	# 25	0.9	0.1	0.0	46.7	32.3	20.5	24.2	44.7	19.4	36.4	2.6	58.3
	# 26	0.9	0.1	0.0	45.9	32.1	19.9	24.4	44.3	18.7	36.7	2.6	58.0
	# 27	0.9	0.1	0.0	45.7	32.0	19.7	24.5	44.2	18.6	36.7	2.6	57.9
44630	M86#1	0.9	0.1	0.0	42.7	22.0	17.2	25.2	42.5	16.1	37.9	2.7	56.6
	#5	0.9	0.0	0.0	34.4	24.0	10.2	27.4	37.6	9.1	41.0	2.9	53.0
44668	M164# 1	0.9	0.0	0.1	0.0	22.3	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	#2	0.9	0.0	0.1	0.0	21.8	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 3	0.9	0.0	0.1	0.0	20.2	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 4	0.9	0.0	0.1	0.0	23.3	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	#5	0.9	0.0	0.1	0.0	25.1	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 6	0.9	0.0	0.1	0.0	24.3	1.8	29.9	31.7	0.6	44.8	3.2	48.7
44604	M51# 1	0.9	0.0	0.1	0.0	19.8	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	#3	0.9	0.0	0.1	0.0	22.8	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 4	0.9	0.0	0.1	0.0	23.3	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 5	0.9	0.0	0.1	0.0	19.9	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 6	0.8	0.0	0.2	0.0	16.9	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 7	0.9	0.0	0.1	0.0	20.2	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 8	0.9	0.0	0.1	0.0	22.5	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 10	0.9	0.0	0.1	0.0	23.8	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 12	0.8	0.0	0.2	0.0	18.9	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 13	0.9	0.0	0.1	0.0	20.6	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 14	0.9	0.0	0.1	0.0	23.6	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 15	0.9	0.0	0.1	0.0	19.9	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 17	0.8	0.0	0.2	0.0	19.3	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 18	0.9	0.0	0.1	0.0	21.2	1.8	29.9	31.7	0.6	44.8	3.2	48.7
44642	M120A# 1	0.9	0.0	0.1	0.0	22.9	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 2	0.9	0.0	0.1	0.0	22.7	1.8	29.9	31.7	0.6	44.8	3.2	48.7
46303	39.1B# 1	0.9	0.0	0.1	0.0	26.7	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 2	0.8	0.1	0.1	54.5	26.2	27.8	22.0	49.8	26.7	33.1	2.4	62.1
	# 3	0.9	0.1	0.1	38.6	27.2	14.2	26.2	40.4	13.0	39.2	2.8	55.1
44640	M118# 1	0.9	0.0	0.1	0.0	21.6	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 2	0.8	0.0	0.2	0.0	12.6	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 4	0.9	0.0	0.1	0.0	30.2	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 8	0.8	0.0	0.2	0.0	19.8	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 9	0.8	0.0	0.2	0.0	9.2	1.8	29.9	31.7	0.6	44.8	3.2	48.7
46412	M31.1B# 1	0.9	0.1	0.0	38.3	30.1	13.5	26.4	39.8	12.3	39.6	2.8	54.7
	# 2	0.9	0.1	0.0	38.5	30.3	13.7	26.3	40.0	12.5	39.5	2.8	54.8
	# 6 *	0.9	0.0	0.0	32.4	30.1	8.2	28.0	36.2	7.0	41.9	3.0	52.0
	# 13	0.9	0.0	0.1	0.0	23.0	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 15	0.8	0.1	0.1	43.3	33.5	19.7	24.5	44.2	18.5	36.7	2.6	57.9
	# 16	0.8	0.0	0.2	0.0	1.1	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 17	0.9	0.0	0.1	0.0	10.0	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 18	0.9	0.0	0.1	0.0	24.6	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 23	0.9	0.0	0.1	0.0	27.4	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 27	1.0	0.0	0.0	31.3	28.4	7.0	28.3	35.4	5.8	42.5	3.1	51.4
46411	CJ7.1# 1	0.9	0.0	0.1	0.0	23.7	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 3	0.9	0.0	0.1	0.0	28.1	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 7	0.9	0.0	0.1	0.0	27.9	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 8	1.0	0.0	0.0	0.0	30.4	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 13	1.0	0.0	0.0	0.0	28.4	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 19	1.0	0.0	0.0	0.0	28.4	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 20	1.0	0.0	0.0	0.0	30.7	1.8	29.9	31.7	0.6	44.8	3.2	48.7
46410	CJ6.7# 1	0.9	0.0	0.1	0.0	24.3	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 2	1.0	0.0	0.0	0.0	22.9	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 3	0.9	0.0	0.1	0.0	22.8	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 4	0.9	0.1	0.0	44.7	23.0	19.0	24.7	43.7	17.8	37.1	2.7	57.6
	# 5	0.9	0.1	0.0	44.5	21.6	18.9	24.7	43.6	17.8	37.1	2.7	57.5
	# 6	0.9	0.0	0.1	30.6	22.8	6.7	28.4	35.1	5.5	42.6	3.1	51.2
	# 7	0.9	0.0	0.1	0.0	21.0	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 8	0.9	0.0	0.1	0.0	21.9	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 9	0.9	0.0	0.1	0.0	20.7	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 10	0.9	0.0	0.1	0.0	20.9	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 11	1.0	0.0	0.0	0.0	27.7	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 12	0.9	0.0	0.1	0.0	24.8	1.8	29.9	31.7	0.6	44.8	3.2	48.7
46413	21/336# 1	0.9	0.0	0.0	32.8	28.4	8.7	27.8	36.5	7.5	41.7	3.0	52.2
	# 2	0.9	0.1	0.0	48.3	26.4	22.0	23.8	45.8	20.9	35.7	2.6	59.1
	# 5	0.9	0.0	0.0	34.2	30.7		27.5		8.7	41.2	3.0	52.9
	# 6	0.9	0.0	0.1	0.0	31.8	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 9	0.9	0.1	0.0	49.7	21.3	23.0	23.5	46.5	21.9	35.2	2.5	59.6
	# 10	1.0	0.0	0.0	0.0	26.7	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 11	1.0	0.0	0.0	0.0	25.7	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 12	1.0	0.0	0.0	0.0	22.5	1.8	29.9	31.7	0.6	44.8	3.2	48.7
	# 14	0.9	0.1	0.0	49.1	21.5	22.3	23.7	46.0	21.2	35.5	2.6	59.3

APPENDIX G

Additional drill logs from the Maronan Prospect G1
Schematic drill hole colomn of "zone 1", MND 6 G1
Schematic drill hole colomn of "zone 3", MND 4 G2
Major elements plotted versus lithology, MND 7 G3
Minor-trace elements plotted versus lithology, MND 7 G4

ADDITIONAL DRILL LOGS from the MARONAN PROSPECT

Schematic drill hole column of "zone 1", MND 6. Thickness of the lines represent the relative abundance of the minerals. Thick lines represent abundant occurrence, thin lines represent minerals that occur less frequent, and dashed lines represent local occurrence of minerals.

ADDITIONAL DRILL LOG continued

Schematic drill hole colomn of "zone 3", MND 4.

ADDITIONAL DRILL LOG continued

Whole rock analyses of *major elements* of MND 7, plotted against drill hole depth and lithology.

ADDITIONAL DRILL LOG continued

Whole rock analyses of *minor-trace elements* of MND 7, plotted against drill hole depth and lithology.

APPENDIX H

Lead isotopes and age dating of the Maronan Prospect H1
Stress analysis of the Maronan Prospect H4
Biotite - garnet temperatures H6
Petrographic grid H7

LEAD ISOTOPES and AGE DATING of the MARONAN PROSPECT

A small study on lead isotopes, based on data from Billiton, has been conducted for the Maronan Prospect. Isotopes are elements with the same atomic number, but with different atomic weights, due to different amount of neutrons. There are "stable isotopes" and "unstable isotopes", radioactive species, depending on the detection limits of the radioactive decay times. The unstable isotopes, especially lead isotopes, can be used for radiometric age dating (Cumming and Richards 1975, McNaughton 1991, Stacey and Kramers 1975).

Common lead isotopes are: ^{204}Pb, ^{206}Pb, ^{207}Pb and ^{208}Pb. These are products of radioactive decay of the isotopes $^{238}U \rightarrow {}^{206}Pb$, $^{235}U \rightarrow {}^{207}Pb$ and $^{232}Th \rightarrow {}^{208}Pb$. Of these, only ^{204}Pb is non-radiogenic and this isotope is therefore used to correct for the initial lead decay (initial lead + contaminated lead). The common lead composition is expressed by the ratios $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$.

An independent age can be obtained from the isotopic lead ratios, for instance the $^{207}Pb/^{206}Pb$ ratio. This ratio is time dependent because of different decay constants of ^{235}U and ^{238}U:

$$^{207}Pb/^{206}Pb = {}^{1}/_{137.88} \times (e^{\lambda 1T}-1)/(e^{\lambda 2T}-1) \qquad (A.1)$$

with -T- as the age and $^{1}/_{137.88}$ as the present-day isotopic $^{235}U/^{232}U$ ratio; $\lambda 1$ is the decay constant of ^{235}U (9.8485×10^{-10} yr^{-1}) and $\lambda 2$ as the decay constant of ^{238}U (1.55123×10^{-10} yr^{-1}). The linear difference between the initial- and present-day lead isotope $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios are defined as the *isochron*. The trajectory that a sample follows in time from the initial to the present-day ratios is defined as the *growth curve*. The curvature of the growth curve is dependent on the initial $^{238}U/^{204}Pb$ ratio (μ). A higher μ would produce more ^{206}Pb and ^{207}Pb relative to ^{204}Pb. The Canyon Diablo meteorite is the standard for the primitive, primeval lead, because it contains no U (μ=0) and Th (Stacey and Kramers 1975). The assumption is made that this primitive, primeval lead was formed at a single time at the start of earth formation, 4570 Ma years ago and that the earth, the moon and the meteorite originated from the same system. This is called the "single stage" evolution model. An alternative model was proposed by Stacey and Kramers (1975) as the "two-stage" lead evolution model. Lead initially developed 4570 Ma ago with a μ=7.19. At 3700 Ma ago differentiation processes in the earth causes the start of the second stage with a μ~9.74.

Table A6 - Lead isotope ratios and obtained ages of the Maronan Prospect.

Sample	Rock type	Au g/t	Cu %	Pb %	Ag g/t	Zn ppm	208Pb/205Pb	207Pb/206Pb	206Pb/204Pb	207Pb/204Pb	208Pb/204Pb	Single stage	Two stage
M7/188-189m	CCG	6.38	3.14	0.30	32	92	2.2222	0.9596	16.068	15.419	35.707	1498	1618
M7/216-217m	CCG	-	0.01	6.10	29	96	2.2227	0.9603	16.017	15.382	25.602	1527	1598
M10/325-326m	CCG	0.24	1.70	2.00	5	208	2.2178	0.9583	16.058	15.389	25.613	1505	1577
M10/328-329m	CCG	-	0.01	7.10	63	15	2.2239	0.9607	16.031	15.401	35.651	1520	1619
M12/266-267m	Fe-Mn	-	0.01	6.60	22	1080	2.2228	0.9602	16.024	15.387	35.619	1523	1602
Percy Bore	Qtz-vein	-	0.01	2.43	9	1300	2.2189	0.9593	16.051	15.397	35.615	1508	1531
CB1/178-179m		-	0.02	0.19	6	3070	2.2076	0.9531	16.188	15.428	35.736	1432	1539

N.B. Samples -M- is Maronan Prospect, -CB- is Casablanca ± 15 km SSE of Maronan. Rock types, CCG = calcareous gneiss, Fe-Mn = Fe-Mn silicate rich, Qtz-vein is quartz vein with sulphides in albitized rock. Single- and two-stage ages are in Ma. Note that the "single stage" ages are similar to the Williams Granite ages (Page 1993), and are also close to Ar-Ar ages from the alteration (P.J. Williams pers. com. 1995).

- Lead Isotope Results

The lead isotope results of the Maronan Prospect are tabulated in Table A6. Lead isotopes were obtained from samples containing galena. These were taken from the calcareous gneiss units and from a predominantly pyroxenoid rich unit of the Maronan Prospect. Also a sample from the Percy Bore locality was analysed (Figure 3.4E shows the rock type). A sample from the Casablanca Prospect (± 15km SSE of Maronan Prospect) was analysed. This is a blind, under cover, prospect with a circular aeromagnetic signature, which possibly indicate a shallow igneous intrusion.

Ages obtained vary by approximately 100 Ma, depending on the model used (Table A6). Both methods, however, show possible mineralization ages younger than the surrounding country rocks. This is consistent with the findings that the mineralization is epigenetic. On the two-stage method, mineralization would have occurred during D_1 and D_2 compressional deformation of the Isan Orogony. Based on drill core observations and overprinting relationships, this mineralization timing is rather unlikely. The single-stage model, however, render ages which are compatible with the drill core observations. Timing of mineralization obtained by this method falls between the D_2 and D_3 compressional deformation phases. Ages obtained for the copper ± gold mineralization are younger than the base-metal mineralization and supports the idea that there was possibly an earlier galena phase. The Cu±Au is almost synchronous with the D_3 deformation. The uniformity of the isotope ratios of the Maronan Prospect and the Percy Bore sample indicate a similar mineralization fluid. Only $^{208}Pb/^{204}Pb$ varies in two samples of the Maronan Prospect, in different drill holes, meaning that the initial ^{232}Th concentration was not the same.

Shen-su Sun and Page (1994) plotting the lead ratios of major lead-zinc deposits on a Cumming and Richards (1975) based modified growth curve $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ plot. By plotting the Maronan Prospect isotope data on the Shen-su Sun

and Page (1994) modified plot (Figure A.2), the ages of the mineralization of the Maronan Prospect appears much older. The age metals of the Maronan Prospect are quite similar to that of other base-metal deposits in the Eastern Fold Belt (Pegmont, Fairmile and Dugald River). Although, based on this plot, it looks like that the deposits of the Eastern Fold Belt have ages close to the Mount Isa Group. However, Shen-su Sun and Page (1994) do not reject the possibility that Pb-Zn mineralization in the Mount Isa Inlier could have occurred during an other favourable ore-forming episode. Also the possibility that relict traces of diagenetic lead can effect the timing ages of lead isotopes (Gulson *et al.* 1983).

Figure A.2 - A $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ plot from Shun-se Sun and Page (1994). Lead isotope data from this study superimposed on this plot.

STRESS ANALYSES of the MARONAN PROSPECT

Ore deposits are often related to some kind of trap, structural, stratigraphical or chemical, which will dictate the geometry of the orebody. This section analyses the diviatorical stress orientations which controls the morphology of the mineralization.

The occurrence of numerous veining and small scale faults observed in the Maronan drill cores are the basis for a kinematic analysis. Vein and fault orientations allow determination of the directions of the principle stresses. These stress directions obviously post-date the main D_2 ductile deformation phase, which has an overall E-W σ_1 direction. Stress orientation can be obtained (Figure 7.9), based on the contour maxima of the open-space veins in Figure 7.2.

Two types of microfaults occur in the Maronan Prospect, shear veins/faults and conjugate faults. The principle stress orientation of intersecting shear faults can be obtained as follows. The plane that contains the poles of the the two faults and the striae, also contains σ_1 and σ_3 (Figure A.3A). For the second type, stress orientations can be obtained from the conjugates fault intersection, which corresponds to σ_2; σ_1 is located 90° to σ_2 in the acute angle of two conjugate faults (Figure A.3B).

Figure A.3 - Stress orientation diagrams based on the open-space vein data from Figure 7.2. There are two sets of orientations of the principle stresses. If the subhorizontal and layer-parallel open-space veins forms a conjugate fault set, than the principle stress field is orientated as in diagram -**B**-. But if the layer-parallel veins are formed due to shearing and the subhorizontal veins are associated fractures, than diagram -**A**- would be the more realistic stress field.

Open-space layer-parallel veins are concentrated in parasitic D_2 fold hinge zones and in zones of high strain, while the subhorizontal veins predominant in the limb regions. Subhorizontal veins cut the layer-parallel ones, with a stress field illustrated in Figure A.3A. This implies that layer-parallel open-space veins are formed due to shearing and with subhorizontal veins as their conjugate fractures.

The orientation of stresses depends on the nature and geometry of the body and on the presence of discontinuities and heterogeneities (Oliver *et al.* 1990, Ridley 1993, Peacock and Sanderson 1992). Although an average stress orientation is obtained from the orientation of open-space veining, on a smaller scale the stress is very heterogenous (Figure A.4).

Figure A.4 - Diagram of stress directions based on faults and vein orientations. Barren faults (no sulphides) have generally horizontal NW-SE σ2, moderately plunging NNE-SSW σ1 and moderately NE-SW plunging σ3 stress orientations. Mineralized veins (with sulphides) have two type of directions: i) σ1 vertical, σ2 horizontal N-S and σ3 horizontal E-W, or ii) σ1 horizontal E-W, σ2 horizontal N-S and σ3 vertical. Consistent with normal faulting in the first case, and thrusting in the second.

BIOTITE-GARNET TEMPERATURES

The peak metamorphic temperatures in the micaceous rocks in the Maronan Prospect are in the order of 600°C (calculated from garnet-biotite pairs, using Ferry and Spear 1978).

Serious errors are introduced if large amounts of Fe^{3+} are present in garnets. Also trace elements as Ti, F and Cl in biotites can effect the geothermometer calibration (Essene 1983). For biotite-garnet rims exchange reactions in the metasediments, an average K_D of 0.21 is obtained which correspond to a metamorphic temperature of 613±65°C. Green pleochroic chlorine and barium bearing biotite coexisting with spessartine-rich garnet give unrealistic temperatures of > 1000°C for K_D of 0.48, which is beyond the biotite dehydration curve (Table A7).

Table A7 - Distribution coefficient and biotite-garnet temperatures, based on the Ferry and Spear (1978) geothermometer, from the Maronan Prospect.

BIOTITE - GARNET TEMPERATURES					
Sample	Description	K_D	StDev	T °C	StDev
DP#46340 n=9	Schist, garnet rims used	0.208	0.04	613	65
DP#46340 n=6	Schist, garnet cores used	0.102	0.03	404	75
DP#46371 n=3	Calcareous gneiss	0.153	0.05	516	88
DP#43663 n=4	Pyroxenoid layer Cl-biotite	0.480	0.198	1131	404
DP#46372	Pyroxenoid layer Cl-biotite	0.480		1102	

N.B. K_D is distribution coefficient, $K_D = \frac{X_{Fe-Bi} / X_{Mg-Bi}}{X_{Fe-Gt} / X_{Mg-Gt}}$ StDev is standard deviation, -n- is amount of biotite-garnet pairs.

PETROGRAPHIC GRID

Petrographic grids were calculated using THERMOCALC v2.2b1. Reactions and temperatures versus pressures are tabulated below. Abbreviations in the reactions are used in THERMOCALC program.

THERMOCALC v2.2b1, (thermodynamic dataset produced at 19.27 on Mon 6 Sep, 1993).

1) 3cc + 2q + tr = 5di + 3CO2 + H2O
2) cc + q + ru = sph + CO2
3) 2cc + q + hb = 4di + cor + 2CO2 + H2O
4) 2cc + 3q + 5cor + 4tr + H2O = 5hb + 2CO2
5) cc + 2hb = 3di + 2cor + tr + CO2 + H2O
6) 3hb = q + 2di + 3cor + 2tr + H2O
7) 3sph + tr = q + 5di + 3ru + H2O
8) 2sph + hb = q + 4di + cor + 2ru + H2O
9) 5hb + 2ru = 2sph + q + 5cor + 4tr + H2O
10) di + hb + ru = sph + cor + tr
11) 3cc + 2q + tr = 5di + 3CO2 + H2O
12) ky = and
13) sill = and
14) ky = sill
15) mu + q = sill + ksp + H2O

Thermodynamics of reactions (0 = a + bT + cP + RT ln K)
linearised at T = 475, P = 5.0, x(CO2) = 0.200
(a, b and c includes fluid fugacities; ln K includes x(CO2), x(H2O))

	a	sd(a)	b	c	ln_K	sd(ln_K)
1	264.85	1.11	-0.30427	5.435	-5.051	0.223
2	63.16	0.39	-0.08071	2.106	-1.609	0.074
3	179.58	1.17	-0.20099	3.217	-3.442	0.149
4	161.51	4.64	-0.21213	5.655	-2.996	0.149
5	94.31	1.86	-0.09771	0.999	-1.833	0.075
6	9.03	2.74	0.00557	-1.219	-0.223	0.011
7	75.35	1.55	-0.06215	-0.883	-0.223	0.011
8	53.25	1.37	-0.03958	-0.995	-0.223	0.011
9	-35.18	4.69	0.05072	-1.443	-0.223	0.011
10	-22.11	1.05	0.02257	-0.112	0	0
11	264.85	1.11	-0.30427	5.435	-5.051	0.223
12	4.01	0.08	-0.00896	0.742	0	0
13	-4.32	0.11	0.00416	0.175	0	0
14	8.33	0.08	-0.01312	0.567	0	0
15	63.45	0.24	-0.07427	1.438	0	0

Temperatures for in the range 50 <-> 900°C; (for x(CO2) = 0.2 and x(H2O) = 0.8) uncertainties at or near 5.0 kbars.

T°C	0.0010	1.001	2.001	3.001	4.001	5.001	6.001	7.001	8.001	9.001	10.000	sdT	sdP
1	212.01	464.61	504.69	532.93	555.81	575.57	592.27	606.66	619.40	630.82	641.16	6	0.32
2	151.97	381.47	425.61	458.64	486.73	512.00	534.20	554.11	572.43	589.52	605.60	7	0.29
3	209.95	476.77	517.07	544.86	566.91	585.56	600.92	613.79	624.83	634.43	642.81	7	0.42
4	228.37	402.78	443.58	475.28	503.14	528.86	552.32	574.12	594.81	614.65	633.81	20	0.82
5	205.04	512.31	554.29	581.41	601.37	616.92	628.34	636.56	642.35	646.13	648.21	17	1.4
6	178.38	+	*	*	*	99.10	80.62	61.85	-	-	-	34	1.8
	102.46	166.75	251.20	352.24	439.33	559.37	34	1.8					
7	411.59	795.15	830.74	844.39	848.62	847.27	842.03	833.85	823.30	810.79	796.62	23	7.1
8	242.65	541.04	579.77	604.55	622.83	637.16	647.96	656.03	662.06	666.43	669.40	10	0.83
9	-	-	-	-	-	-	-	-	-	-	-		
	506.62	518.74	538.94	561.93	586.25	611.31	636.77	662.46	688.23	714.00	97	3.6	
10	700.57	706.23	711.83	717.38	722.87	728.30	733.68	739.00	744.27	749.48	754.62	46	8.4
11	212.01	464.61	504.69	532.93	555.81	575.57	592.27	606.66	619.40	630.82	641.16	6	0.32
12	185.62	263.75	343.03	423.81	506.36	590.86	677.47	766.29	857.40	+	+	9	0.11
13	826.78	766.54	709.45	655.64	605.04	557.53	512.88	470.85	431.19	393.67	358.10	28	0.60
14	362.42	405.11	448.27	491.91	536.03	580.60	625.61	671.01	716.73	762.73	808.87	7	0.15
15	293.77	571.97	608.94	639.72	667.90	694.59	720.26	745.20	769.55	793.45	816.95	3	0.14

APPENDIX I

Quantitative methods I1
Average pristine calc-silicate composition I1
Theoretical back ground on mass-transfer calculations I1
Results of the quantitative methods I2
Establishing the volume factor F_V I2

Quantitative methods

Average pristine calc-silicate composition

Estimations on mass transfer during the main sodic-calcic alteration event, whether qualitative or quantitative, have to be related to an unaltered, pristine parent rock. Based on the inter-element plots and the structural setting in the Maramungee Creek section in relation with inferred "low", "medium" and "high" fluid:rock ratio zones, it is assumed that the "pristine" calc-silicate rocks (CS_l-A) are the unaltered parent rock of the "moderately altered" (CS_m-A) and the more "altered" calc-silicate rocks (CS_h-A and CS_h-B). It is impossible to know the precise composition of the parent rock prior to the alteration in the inferred "medium" and "high" F:R ratio zones. Instead changes in petrochemistry have to be related to an average pristine calc-silicate rock (APCSR), based on the assumption that all alteration affected calc-silicate rocks are roughly derived from the same precursor, pristine calc-silicate rock. APCSR was calculated by averaging the "pristine" calc-silicate analyses and is tabulated in Table A8.

Table A8 - Average pristine calc-silicate rock composition, based on averaging pristine calc-silicate analyses in the Maramungee Creek section.

Average Pristine Calc-Silicate Rock - APCSR											
Major	wt.%	stdev	Major	wt.%	stdev	Trace	ppm	stdev	Trace	ppm	stdev
SiO2	62.88	4.64	CaO	3.31	1.16	Rb	191	45	Ni	27	6
TiO2	0.66	0.06	Na2O	3.02	0.28	Sr	128	25	Zn	15	3
Al2O3	15.38	1.39	K2O	4.86	0.96	Sc	13	2	Ga	24	3
Fe2O3	5.75	1.13	P2O5	0.15	0.01	V	83	14	Y	23	5
MnO	0.06	0.02	LOI	1.43	0.35	Cr	72	12	Zr	221	46
MgO	2.79	0.21	Total	98.85	0.86	Co	43	10	Nb	15	1

N.B. LOI - lost on ignition, average s.g. 2.60, stdev is standard deviation

Theoretical back ground on mass-transfer calculations

To study and quantify metasomatic processes, some estimate of gains and losses of elements has to be determined. Gresens (1967) derived an equations that enables one to calculate these gains and losses during alteration:

$$\Delta x_i = 100\left[F_v\left(g^o/g^a\right)c_i^a - c_i^o\right] \qquad \text{(I1)}$$

where Δx_i = losses or gains in grams of component -*i*- during the alteration; F_V = the volume factor, which is the ratio of volumes after and before the alteration; g = the specific gravity; c_i = the weight fraction of component -*i*-; superscripts -o- and -a- refer to the original/unaltered and altered rocks, respectively. Babcock (1973) pointed out, that in order to use this equation, the following data must be known or at least sensibly inferred: i) the chemical composition of the precursor and altered rock, ii) the densities of both rock types, and iii) the volume change or the magnitude of

mass or chemical transfer of any element. The first two, can easily be obtained. The third factor causes the most problem, F_V or Δx_i has to be determined, or estimated in order to solve the equation. Procedures to solve this problem are given by Gresens (1967). i) Volume changes can be assessed from geological data. ii) If it can be established that there is no volume change, $F_V = 1$, than the mass change can be calculated. iii) If an element behaves immobile during alteration, then $\Delta x_i = 0$ and F_V can be obtained. iv) A clustering criteria of immobile element can be used. If a number of components are acting immobile and the obtained F_V are clustered together, than statistically a favourable F_V can be estimated.

Grant (1986) revised Gresens' equation by rewriting it as a concentration ratio and derived and introduced the "isocon" diagram. The weight fraction of the elements is related to the mass of the original/unaltered and altered specimen by the following derived equation:

$$c_i^a = \left(M^o / M^a\right) c_i^o \qquad \text{(I2)}$$

The best fit of a straight line through the origin for a series of elements in a concentration/isocon diagram represents immobile elements, with the mass ratio (M^o/M^a) as the slope of the line. A slope larger than unity indicate a volume and / or a mass decrease and visa versa. A constant volume line would go through the origin with a 45° slope. Elements that plot above the immobile line are enriched, while elements that fall below the constant volume line are depleted relative to the original/unaltered parent rock. The disadvantage of this method is that only pairs of altered and presumed unaltered rock analyses can be compared.

The following sections deals more with the volume factor and mass transfer using the original Gresens (1967) method.

Results of the quantitative methods

Establishing the volume factor F_V

From field evidence, any large volume increase in the high F:R ratio zone of the Maramungee Creek shear zone can be excluded. Although some volume increase did occur evidently by the occurrence of structurally controlled dilational veins and vein jog breccias. The abundant occurrence of megabreccias, close to the Doherty Formation - Maronan supergroup contact, are interpreted as indicating a volume increase during the alteration. The moderately F:R ratio zone, adjacent to the shear- and breccia zones, will only exhibit small volume changes.

Histograms of F_V values calculated for zero mass change for all major elements, relative to the APCSR, and for all samples, are given in Figure A.5. The "pristine" calc-silicate would obviously be clustering around $F_V = 1$, this because that rock type is used for calculating the APCSR. The "moderately altered" calc-silicates are also clustering around $F_V = 1$, indicating zero volume change during the sodic-calcic alteration. For the "altered" calc-silicates and the two breccia types a bimodal distribution of the F_V values occurred, with sporadically large >>1 volume factor values. The "altered" calc-silicates, however, still exhibit a pronounced peak at $F_V \approx 1$. For the high F:R ratio zone ("altered" calc-silicates and breccia zones), the data show a considerable spread. The peculiar bimodal distribution with a peak smaller than $F_V = 1$, indicates that during the sodic-calcic alteration and associated brecciation the volume decreased or that the mass increased. The latter is possibly more likely.

Figure A.5 - Histograms of volume factors required for zero mass changes during the sodic-calcic alteration, relative to APCSR, and for all major elements. Clear maxima at $F_V \approx 1$ is seen for the "pristine" and "moderately altered" calc-silicates. Areas of high F:R ratio zone show bimodal F_V distribution. $F_V = 5.1$ is a cumulative of $F_V > 5$ values. Arrows indicate harmonic mean.

Figure A.6 - Histogram of volume factors of major elements, required for zero mass change during sodic-calcic alteration and brecciation, with reference to APCSR. Silica, titanium and aluminium appears to be more "immobile" than other elements. Potassium, sodium and calcium are behaving very "mobile". Volume factors $F_V > 5$ are cumulative.

A better understanding of the mobility of the elements can be established by calculating the volume factor of the major elements for the different rock types relative to APCSR, for zero mass change. The histograms for the elements are given

in Figure A.6. Immobile behaviour of elements will exhibit a narrow spread around the $F_V = 1$ volume factor. Silica appears to act relative immobile, with a very narrow spread in the volume factor. Silica only requires a slight volume increase to maintain zero mass change. Titanium and aluminium behave in a similar fashion, but illustrates a larger scatter. Elements that are only "weakly" mobile are iron and magnesium. Volume factors values for iron, exhibit a positive skewing to larger F_V values. Magnesium and also calcium and sodium, exhibit relative more volume factor values smaller than 1, indicating mass increase. For the above elements, volume factors are clustered around unity for the "pristine" and "moderately altered" calc-silicates. The clustering of volume factor values, $F_V \approx 0.5$, for the sodium, means a fixed mass increase. Potassium illustrates extreme mobility, with a large spread to volume factor values greater than unity. For the "pristine" calc-silicates, potassium is still clustered around unity, however, extreme large positive volume factor values are calculated for the potassium in the "altered" calc-silicates and breccias. These large spread in, $F_V >> 1$, volume factor values indicate that potassium was decreased irregularly in mass. This is possible due to the fact that the conditions for the minerals to "release" potassium was locally controlled. From these element volume factor histograms (Figure A.6) it can be deduced that the sodic-calcic alteration, mass increase, occur at the expense (dilution) of the potassium, with a mass decrease.

Gresens' (1967) equation (I1), can not be solved for a whole rock by assuming a single or a group of elements to act immobile, and using their volume factors. By assuming that during the sodic-calcic alteration, the mass stayed relatively constant, or that the total mass change will be at a minimum, volume factors for total rocks can be calculated. Histograms of volume factors for "total" rocks are illustrated in Figure A.7. The major components were only used for this method. This approach is less sensitive to variations in the reference rock, illustrated by a narrow spread in volume factor values, $F_V = 0.97 - 1.05$ (excluding extremes). The "pristine" calc-silicates cluster around $F_V = 1$, with most of the samples illustrating little volume change. The "moderately altered" calc-silicates show volume factors, slightly smaller than unity, indicating a slight volume decrease (or mass increase at constant volume). The "altered" calc-silicates show a slight skewing to volume factors slightly larger than unity, while the breccias a large peak illustrate at $F_V > 1$. This method gives reasonable results in relation to the geological field data regarding the volume changes during the alteration and brecciation processes.

Figure A.7 - Histogram of volume factors of "totals" of major elements only. This approach is less sensitive to variations in the reference rock, illustrated by the narrow spread. Legend as in Figure A.6.