CHAPTER 5

DEFORMATION AND EMPLACEMENT STRUCTURES

5.1 INTRODUCTION

The Sybella Batholith, comprises early mafic and later hybrid and felsic intrusions that were emplaced into strongly deformed country rocks that included gneisses and amphibolites of the May Downs Gneiss, and the Eastern Creek Volcanics of the Haslingden Group, Cover Sequence 2. The sedimentary and volcanic history of the Mount Isa Inlier indicates that it was an area of intracratonic rifting during the period 1800-1670 Ma (Blake 1987; Stewart & Blake 1992 and references therein; O'Dea *et al.* 1997) (Figure 1.3). At the time of the emplacement of the Sybella Batholith, the inlier experienced large magnitude extension (O'Dea *et al.* 1997), which coincided with deposition of Cover Sequence 3. There is also an increasing amount of evidence for extensional tectonics for the central and eastern parts of the inlier (Passchier 1986; Holcombe *et al.* 1991; Pearson *et al.* 1992). However, the little evidence that has been presented in the western part of the inlier for syndepositional faulting, various authors (Bell 1983; Connors *et al.* 1992 etc) have shown that some of these structures were formed during later faulting in the Isan Orogeny, long after rifting. One of the problems in recognizing early extensional tectonics in the Mount Isa Inlier is that deformation during the Isan Orogeny has tilted and folded brittle faults and overprinted or re-used many of the earlier structures and fabrics.

In multiply deformed terranes it can be very difficult to unravel the inter-relationships between magma intrusion, metamorphism and deformation. Several potential cause and effect relationships between the emplacement of intrusives and deformation in the surrounding country rocks are possible. Deformation may result in local or regional extensional zones that can accommodate passive, syn-tectonic emplacement of magmas, whereas forceful emplacement of an intrusion causes deformation of adjacent country rocks (Paterson & Fowler 1993; Paterson & Vernon 1995; Vigneresse 1995; Vigneresse *et al.* 1999). Similarly, metamorphism may be the cause or result of magma generation and emplacement. Country rocks intruded by granites potentially contain significant information about pre-emplacement structures and syn-emplacement deformation processes. In the case of the Mount Isa Inlier, the earlier structures associated with the emplacement of the Sybella Batholith have been overprinted by the deformation and metamorphism during the Isan Orogeny.

Previous correlations of structures identified in this study are from areas immediately adjacent to, and within the Sybella Batholith (Table 5-1). The correlation was compiled in conjunction with a review of the metamorphic features attributed to Isan Orogeny, although a thorough revision was outside the scope of this study. Only Wilson (1975) recognized the pre-emplacement timing of some of the deformation in the country rocks. He also stated that the Queen Elizabeth Phase of the Sybella Batholith was coeval with the Judenan folding (Table 5-1). Page & Bell (1986) also interpreted the pervasive fabric within the Queen Elizabeth Pluton to the south as being associated with deformation during the emplacement of the granite, although they believed it was during D_1 (1610 Ma) of the Isan Orogeny. Once age dates of approximately 1670 Ma for the Main Phase of the Sybella Batholith was established, pre-existing structural interpretations were discounted, as the age of the batholith meant that it was too old to have been emplaced during the Isan Orogeny. The deformation in the granite and the country rocks has now been correlated with the Isan Orogeny $D_{2,}$ and it has also been inferred that all deformation post-dates the emplacement of the Sybella Batholith. Metamorphic features in the country rocks described as D_1 or “early D_2” by Connors *et al.* (1992) and Rubenach (1992) respectively, may have been misidentified and evidence for an earlier thermal event incorporated into the Isan Orogeny.

Fabrics in plutons are generally developed from magmatic flow to solid-state flow (Paterson *et al.* 1989; Bouchez et al 1992; Karlstrom et al 1993; Miller & Paterson 1994). Magmatic flow is defined by Paterson *et al.* (1989) as deformation by displacement of melt, with consequent rigid-body rotation of crystals, and without sufficient interference between crystals to cause plastic deformation. A continuum exists between magmatic and solid-state processes to form foliations in granites, and criteria for their identification are described by Paterson *et al.* (1989). The fabrics in the granites mainly reflect the final stages of emplacement. Experimental work (Arzi 1978;

		This study	Structural features west of Mt Isa (Wilson 1975)	Mount Novit Ranges (Connors *et al.* 1992)	Bell & Hickey	PTt metamorphism (Rubenach 1992)	Approximate age range (Ma)
	Deposition of Haslingden group						1790-1760
	Basement Event deformation and metamorphism	$D_{B\text{-}S}$	F1 (pre Judenan Folds) intruded by granite	$D^N{}_1$ Recorded in cordierite porphs		Early D_2 structures Cordierite and biotite growth in MDG	
	Sybella Event Deformation and intrusion of the Sybella Granite	Ds	F2 "Sybella granite is coeval with S2" Judenan Folds				Queen Elizabeth 1660±5, 1655±4 (Connors & Page 1995) Main phase 1671±8 (Page & Bell, 1986) B-quartz phase 1668±24 (Page & Bell 1986) Kitty Plain microgranite 1673±2.5 (Coleborn 1999)
	Deposition of the Mount Isa Group						1655 Ma (tuff bed)
ISAN OROGENY	D1 Thrusts, gently dipping foliations during N-S shortening				D_1		1610 Ma (Page & Bell 1986) (Controversial Rb-Sr age of granite)
ISAN OROGENY	D2 EW compresion resulting in tight NS folding and main fabric development	D_2 reactivation of D_S fabrics by D_2 and folding		$D^N{}_2$ peak metamorphism	D_2 peak metamorphism well developed schistocity near vertical lineation	Late D_2 structures Sillimanite-K-feldspar growth and pervasive fabric	approx 1575 Ma (Hand & Rubatto 2002) (monazite in D2 fabric)
ISAN OROGENY	Intrusion of pre-syn deformational Mica Creek Pegmatites						1565±5 and 1532±7 (Connors & Page 1995)
ISAN OROGENY	D3-D5	Overprinting deformation	Lena Creek folds and King Gully folds	$D^N{}_{3\text{-}5}$	flat event D_3 (previously $D_{2.5}$) D_4 EW compression with upright folding (otherwise D_3)		
	Intrusion of post deformational Mica Creek Pegmatites						1480±14 or older (Connors & Page 1995)

Table 5.1 Correlation of deformation identified within this study and previous workers. Dashed arrows indicate the change from the original interpretation to new interpretation.

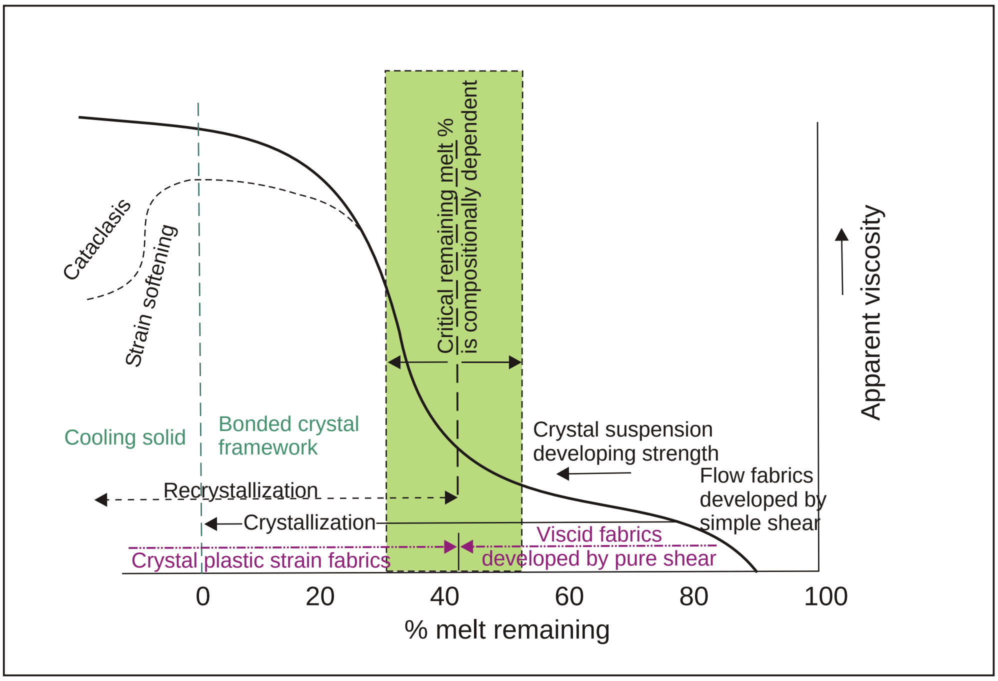


Figure 5.1 Arzi (1978) type diagram illustrating the transition from suspension-like behaviour in the magmatic state to solid-state deformation (modified from van der Molen & Patterson 1979).

van der Molen & Patterson 1979) suggests that there is a critical melt fraction in the range of 50% - 70% crystals which marks a sharp increase in the viscosity of the magma and a transition from suspension like behavior to more complex solid-state deformation (Figure 5.1). The transition between magmatic and solid-state deformation is conventionally determined by the onset of intracrystalline deformation in quartz, the most ductile mineral. Incipient deformation of quartz in the solid-state with few percent of strain results in undulose extinction, sub-grains and new grains, however as it affects neither the quartz grain shapes or the magmatic texture it is not observable in the field. As a result, some of these rocks were indistinguishable from the purely magmatic ones. Weak deformation, such as that which occurred in the later Isan Orogeny, superimposed on an earlier magmatic fabric would be indistinguishable, unless it occurred at an oblique angle or formed at lower temperature.

This structural study is based on the mapping of planar and linear structures of the northeastern Sybella Batholith and immediately adjacent rocks which formed in a magmatic state or after crystallization in the solid state (Figure 5.2). Structural mapping of the Easter Egg (Figure 5.3), Guns Knob (Figure 5.4) and Kitty Plains (Figures 5.5-6) regions identified significant variations in the intensity and type of structures formed before the Isan Orogeny, which was otherwise unidentified within this region. The dominant layer parallel cleavage within the country rocks (May Downs Gneiss and Eastern Creek Volcanics) is generally interpreted as S_2 (Isan Orogeny). However, this study has indicated that it may in part be a composite fabric with an earlier pre- or syn-intrusion related fabric (Basement Event or Sybella Event, respectively) that was reactivated during D_2 of the Isan Orogeny. Structures related to granite emplacement are designated S_S and L_S for foliations and lineations respectively.

5.2 STRUCTURES FORMED PRIOR TO BATHOLITH EMPLACEMENT

The country rocks marginal to the Sybella Batholith include units from the May Downs Gneiss (MDG) and Eastern Creek Volcanics (ECV). Folds within the ECV's in subarea 2 in the Guns Knob region have shallowly plunging axes that vary in trend from W to NW (Figure 5.4). Intrusive margins of the Main Phase granite are discordant to, and cut

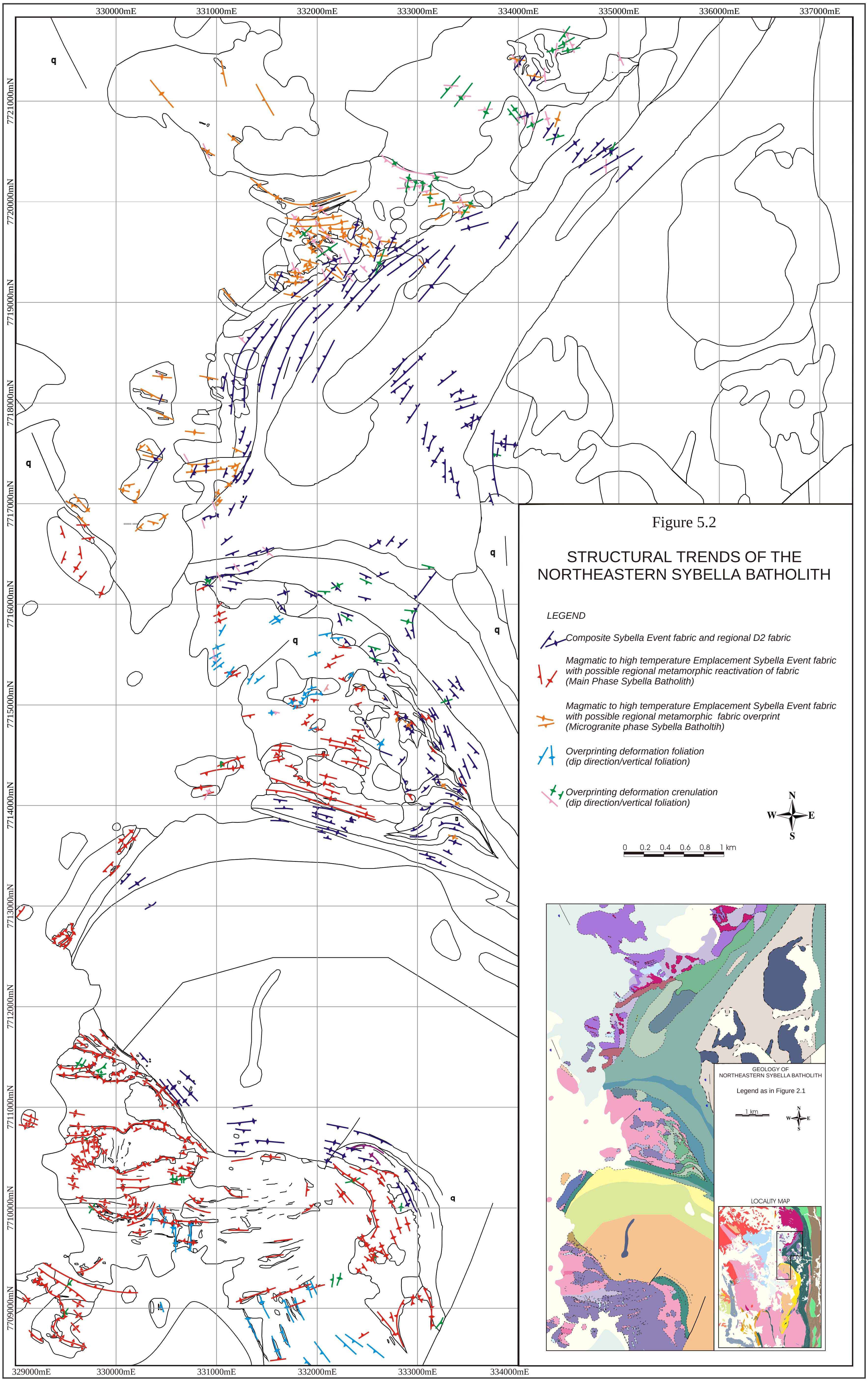
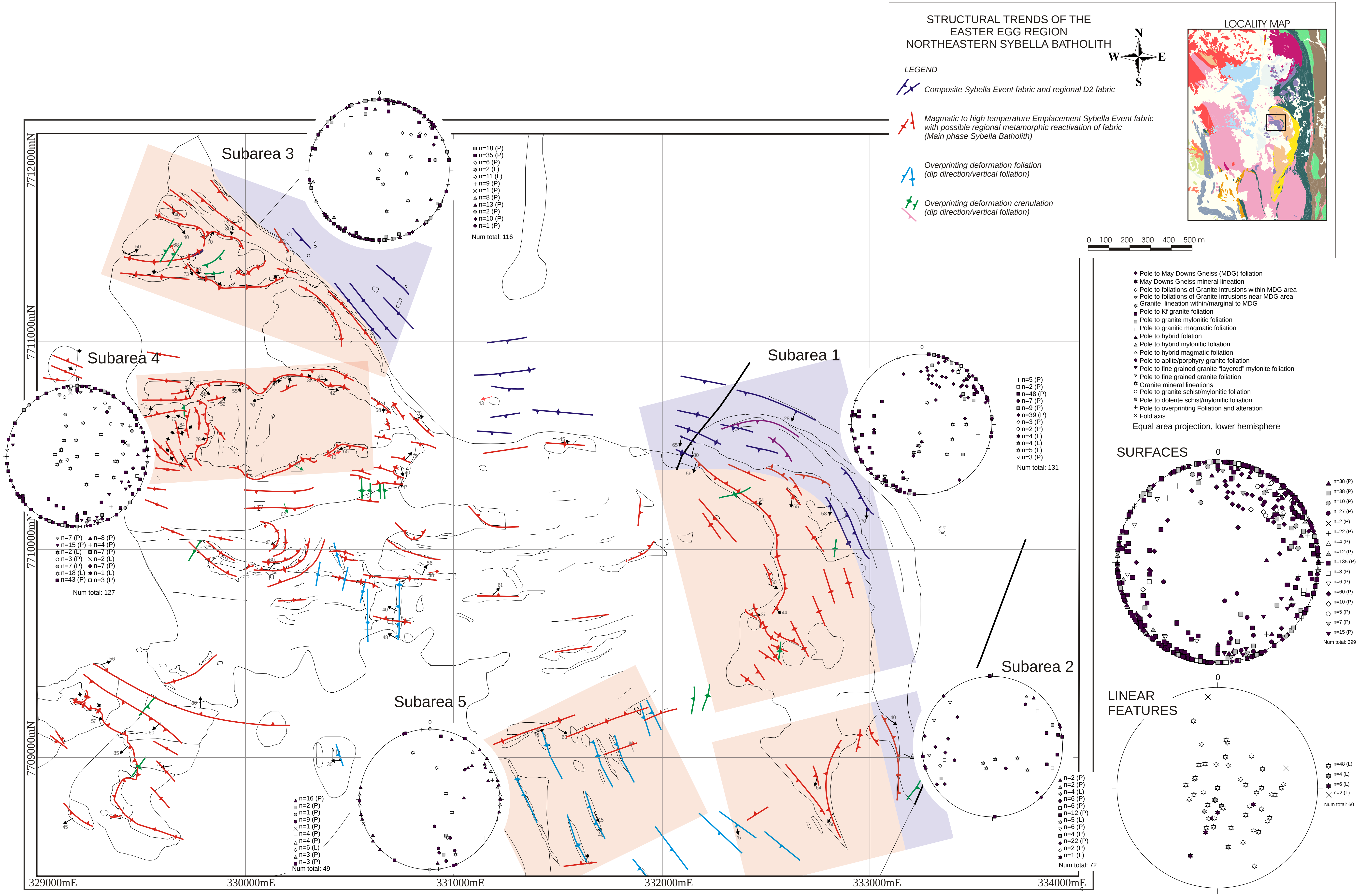
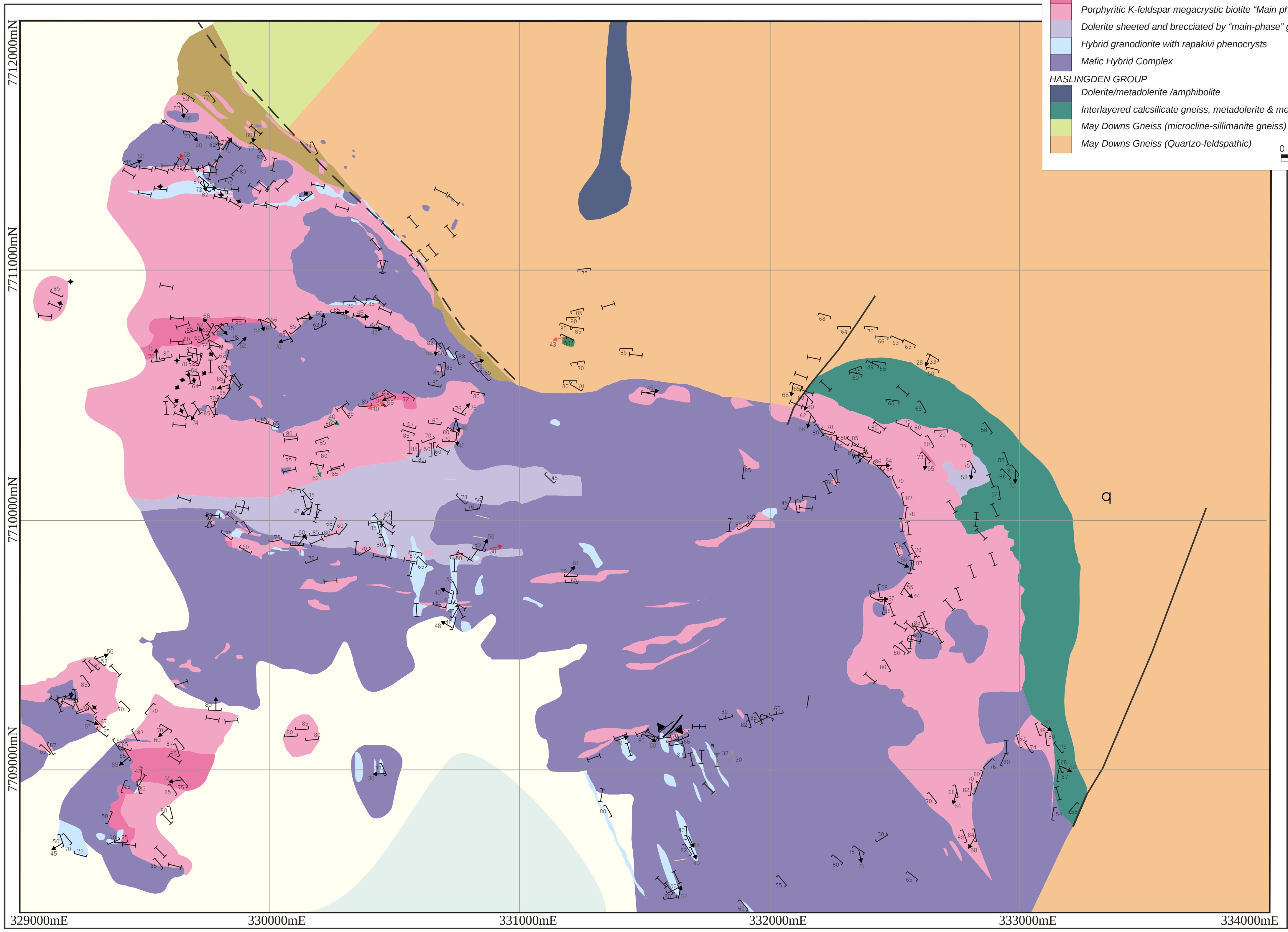
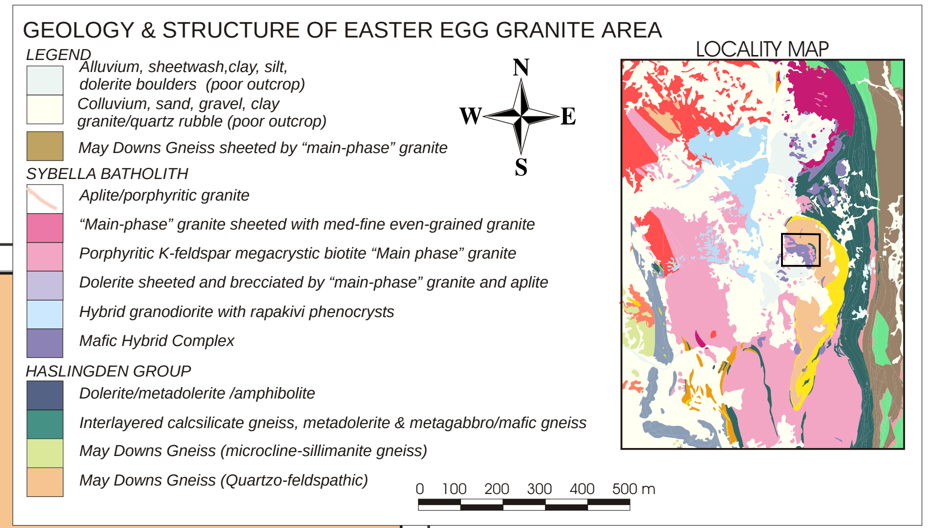


Figure 5.2

STRUCTURAL TRENDS OF THE NORTHEASTERN SYBELLA BATHOLITH


STRUCTURAL TRENDS OF THE
EASTER EGG REGION
NORTHEASTERN SYBELLA BATHOLITH
N
S
E
W
LOCALITY MAP
LEGEND
Composite Sybella Event fabric and regional D2 fabric
Magmatic to high temperature Emplacement Sybella Event fabric
with possible regional metamorphic reactivation of fabric
(Main phase Sybella Batholith)
Overprinting deformation foliation
(dip direction/vertical foliation)
Overprinting deformation crenulation
(dip direction/vertical foliation)
0 100 200 300 400 500 m
Subarea 1
Subarea 2
Subarea 3
Subarea 4
Subarea 5
7712000mN
7711000mN
7710000mN
7709000mN
329000mE
330000mE
331000mE
332000mE
333000mE
334000mE
Num total: 116
Num total: 131
Num total: 127
Num total: 72
Num total: 49
Pole to May Downs Gneiss (MDG) foliation
May Downs Gneiss mineral lineation
Pole to foliations of Granite intrusions within MDG area
Pole to foliations of Granite intrusions near MDG area
Granite lineation within/marginal to MDG
Pole to Kf granite foliation
Pole to granite mylonitic foliation
Pole to granitic magmatic foliation
Pole to hybrid folation
Pole to hybrid mylonitic foliation
Pole to hybrid magmatic foliation
Pole to aplite/porphyry granite foliation
Pole to fine grained granite “layered” mylonite foliation
Pole to fine grained granite foliation
Granite mineral lineations
Pole to granite schist/mylonitic foliation
Pole to dolerite schist/mylonitic foliation
Pole to overprinting Foliation and alteration
Fold axis
Equal area projection, lower hemisphere
SURFACES
Num total: 399
LINEAR FEATURES
Num total: 60





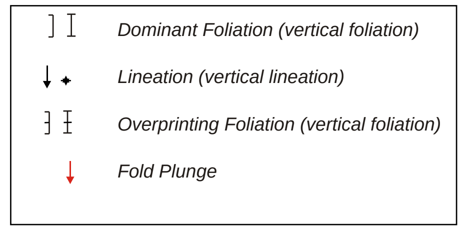
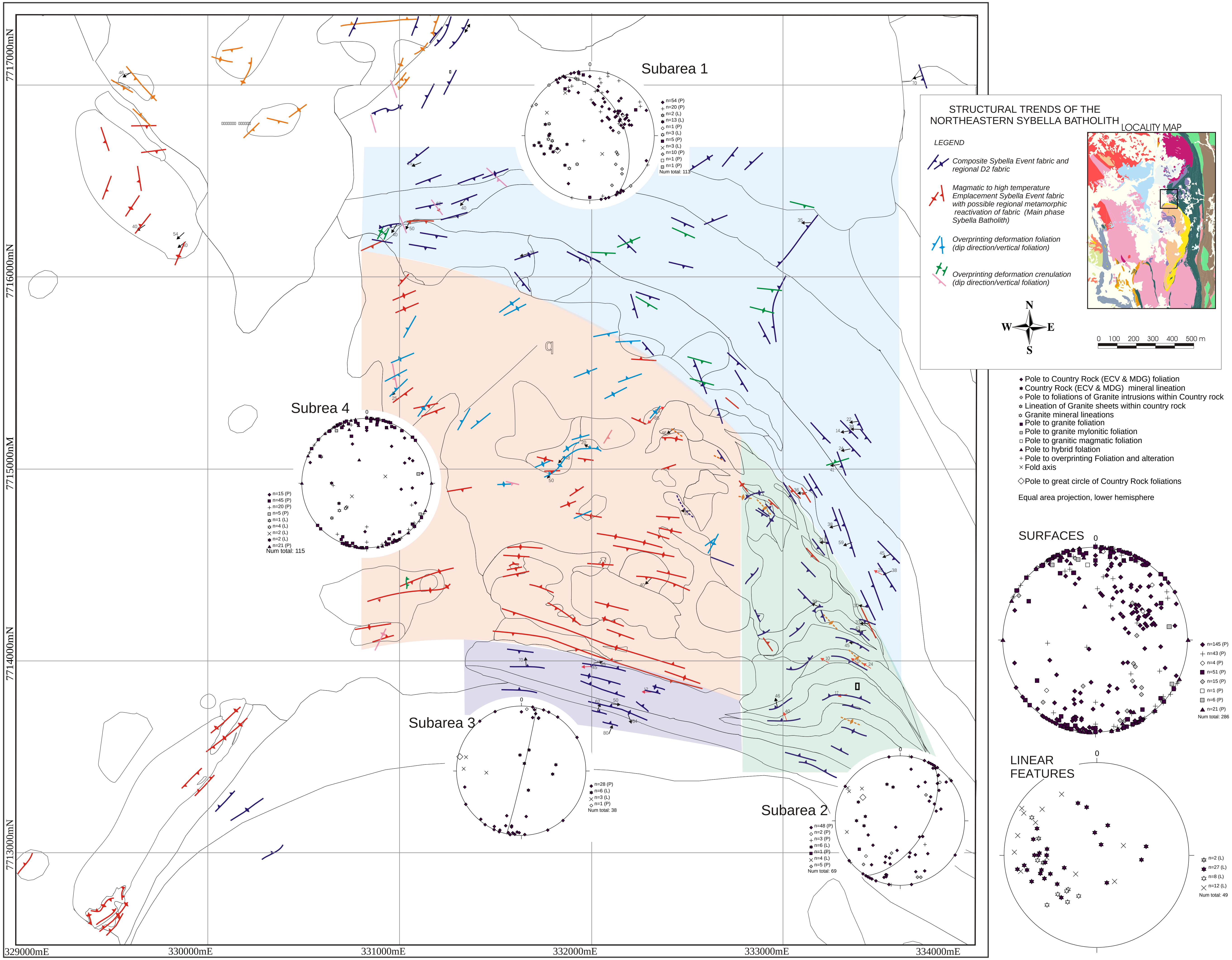
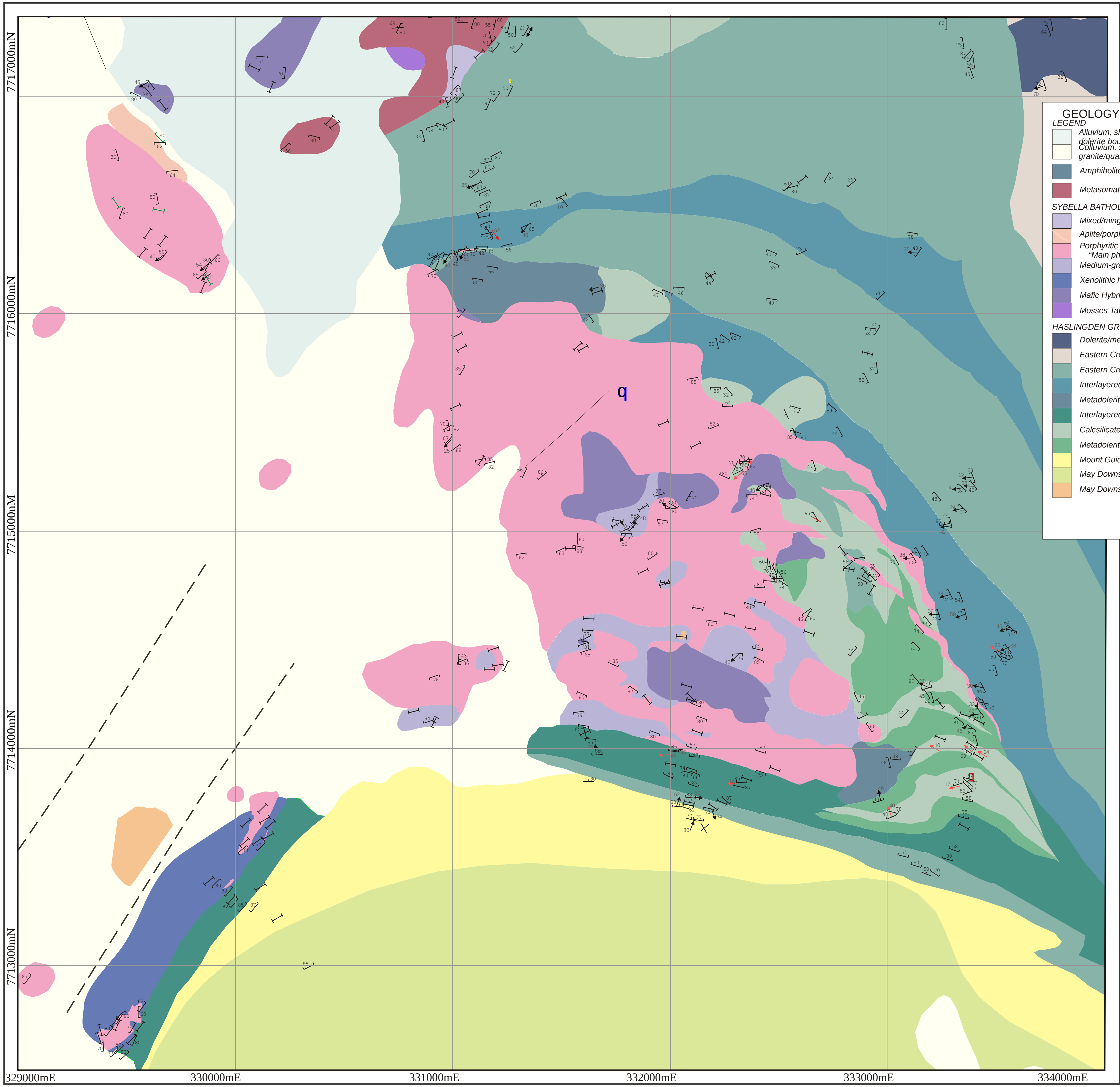


Figure 5.3 Structural geology of the Easter Egg Granite Region

Facing page - Structural trends and stereonets of subareas.
This page - Mafic Hybrid Complex shows magmatic textures and is generally undeformed, whereas the rapakivi hybrid shows some fabric development (magmatic to solid-state), and the main phase granite is generally strongly deformed (magmatic and high-temperature solid-state fabrics).

Subvertical foliations that mirror internal intrusive contacts dominate the structural pattern of the region.


STRUCTURAL TRENDS OF THE NORTHEASTERN SYBELLA BATHOLITH
LOCALITY MAP
LEGEND
Composite Sybella Event fabric and regional D2 fabric
Magmatic to high temperature Emplacement Sybella Event fabric with possible regional metamorphic reactivation of fabric (Main phase Sybella Batholith)
Overprinting deformation foliation (dip direction/vertical foliation)
Overprinting deformation crenulation (dip direction/vertical foliation)
N
W
E
S
0 100 200 300 400 500 m
Pole to Country Rock (ECV & MDG) foliation
Country Rock (ECV & MDG) mineral lineation
Pole to foliations of Granite intrusions within Country rock
Lineation of Granite sheets within country rock
Granite mineral lineations
Pole to granite foliation
Pole to granite mylonitic foliation
Pole to granitic magmatic foliation
Pole to hybrid folation
Pole to overprinting Foliation and alteration
Fold axis
Pole to great circle of Country Rock foliations
Equal area projection, lower hemisphere
Subarea 1
n=54 (P)
n=20 (P)
n=2 (L)
n=13 (L)
n=1 (P)
n=3 (L)
n=5 (P)
n=3 (L)
n=10 (P)
n=1 (P)
n=1 (P)
Num total: 113
Subrea 4
n=15 (P)
n=45 (P)
n=20 (P)
n=5 (P)
n=1 (L)
n=4 (L)
n=2 (L)
n=2 (L)
n=21 (P)
Num total: 115
Subarea 3
n=28 (P)
n=6 (L)
n=3 (L)
n=1 (P)
Num total: 38
Subarea 2
n=48 (P)
n=2 (P)
n=3 (P)
n=6 (L)
n=1 (P)
n=4 (L)
n=5 (P)
Num total: 69
SURFACES
n=145 (P)
n=43 (P)
n=4 (P)
n=51 (P)
n=15 (P)
n=1 (P)
n=6 (P)
n=21 (P)
Num total: 286
LINEAR FEATURES
n=2 (L)
n=27 (L)
n=8 (L)
n=12 (L)
Num total: 49
7717000mN
7716000mN
7715000mN
7714000mN
7713000mN
329000mE
330000mE
331000mE
332000mE
333000mE
334000mE



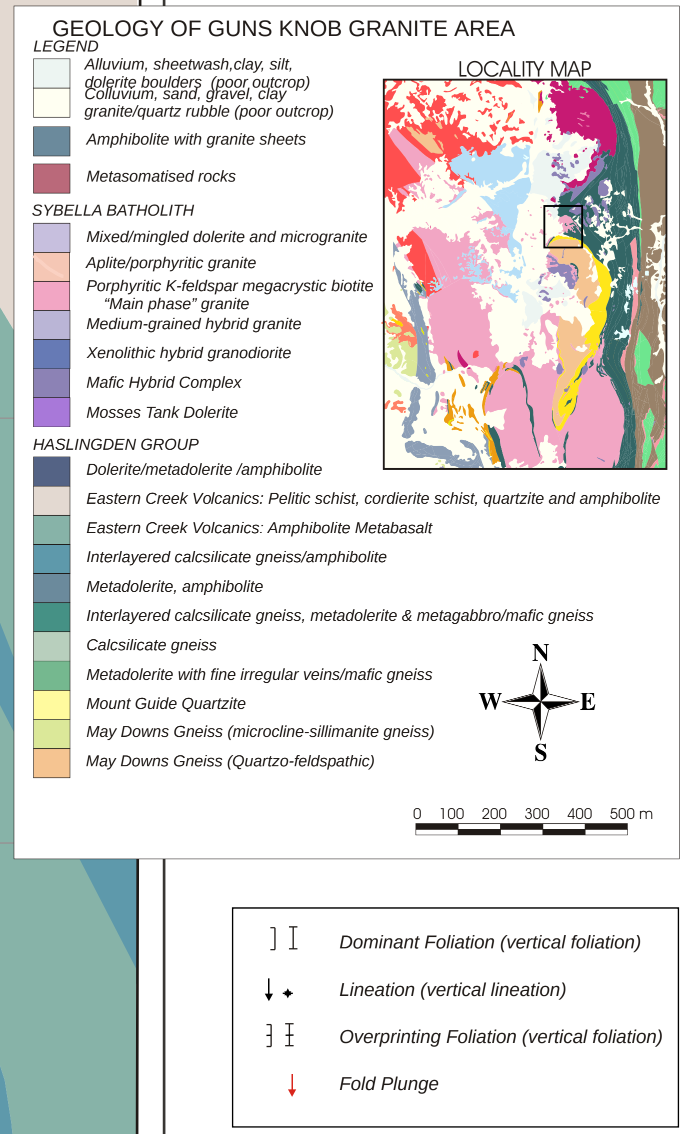
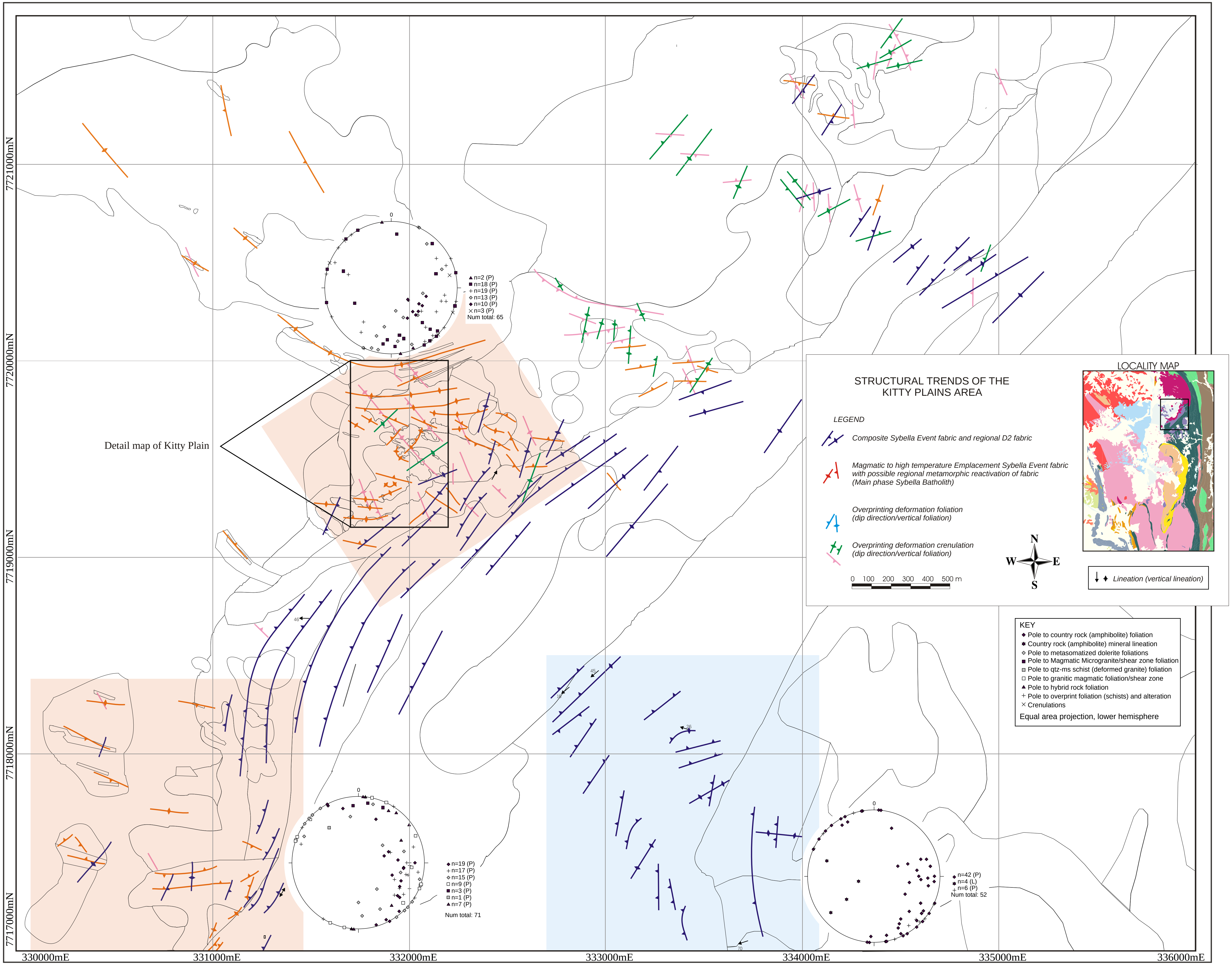


Figure 5.4 Structural geology of the Guns Knob Region

Facing page - Structural trends and stereonets of subareas.
This page - Granite show predominantly weak magmatic fabrics with poor lineations developed.

Granite intrudes the strongly foliated and folded country rocks (amphibolite, mafic gneiss and calcsilicate) and includes xenoliths that were deformed prior to their inclusion. Map pattern shows open folding and the sheeted nature of the northeastern margin of the main phase granite.



STRUCTURAL TRENDS OF THE
KITTY PLAINS AREA
LEGEND
Composite Sybella Event fabric and regional D2 fabric
Magmatic to high temperature Emplacement Sybella Event fabric
with possible regional metamorphic reactivation of fabric
(Main phase Sybella Batholith)
Overprinting deformation foliation
(dip direction/vertical foliation)
Overprinting deformation crenulation
(dip direction/vertical foliation)
0 100 200 300 400 500 m
N
W
E
S
LOCALITY MAP
Lineation (vertical lineation)
KEY
Pole to country rock (amphibolite) foliation
Country rock (amphibolite) mineral lineation
Pole to metasomatized dolerite foliations
Pole to Magmatic Microgranite/shear zone foliation
Pole to qtz-ms schist (deformed granite) foliation
Pole to granitic magmatic foliation/shear zone
Pole to hybrid rock foliation
Pole to overprint foliation (schists) and alteration
Crenulations
Equal area projection, lower hemisphere
Detail map of Kitty Plain
n=2 (P)
n=18 (P)
n=19 (P)
n=13 (P)
n=10 (P)
n=3 (P)
Num total: 65
n=19 (P)
n=17 (P)
n=15 (P)
n=9 (P)
n=3 (P)
n=1 (P)
n=7 (P)
Num total: 71
n=42 (P)
n=4 (L)
n=6 (P)
Num total: 52
7721000mN
7720000mN
7719000mN
7718000mN
7717000mN
330000mE
331000mE
332000mE
333000mE
334000mE
335000mE
336000mE

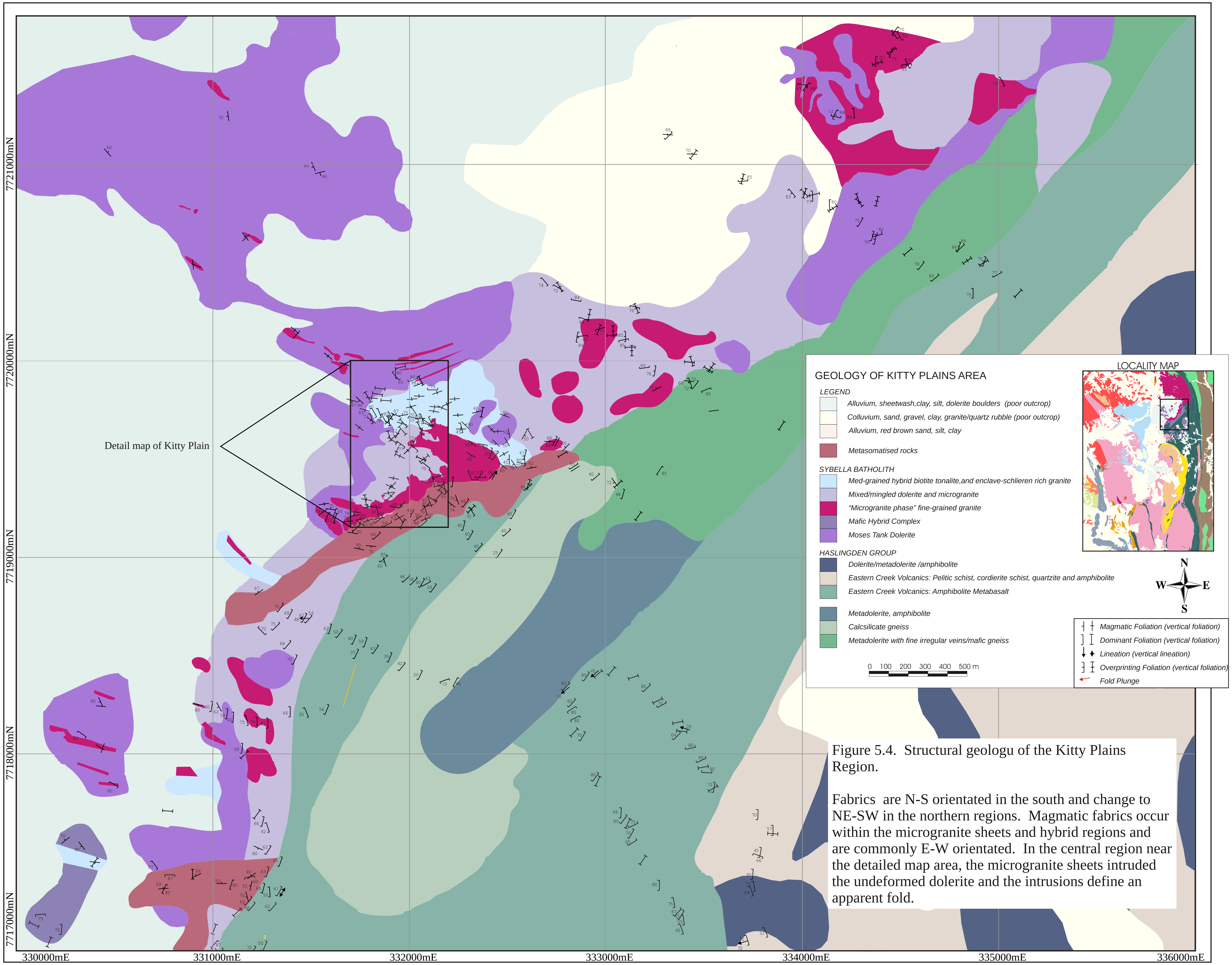
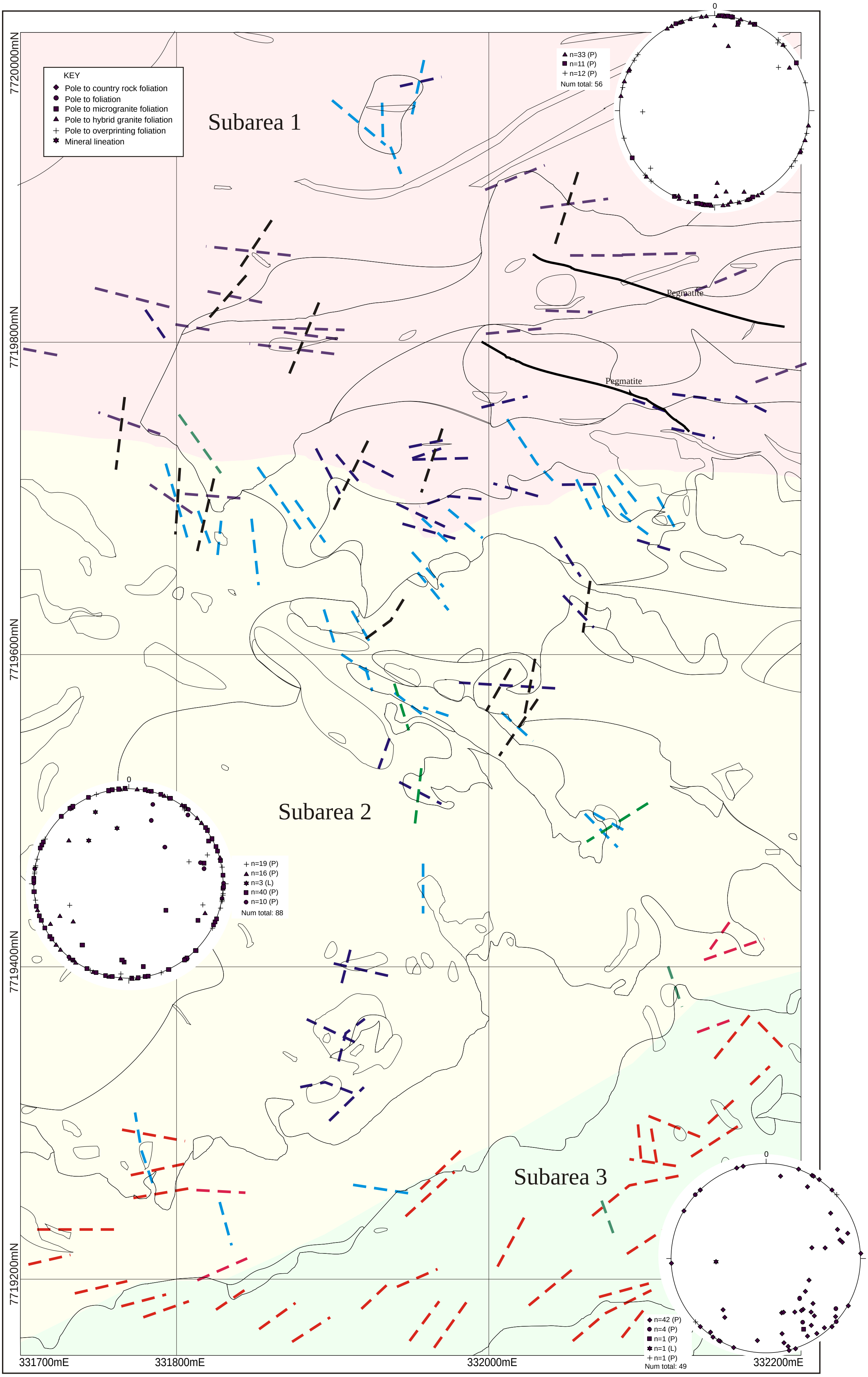
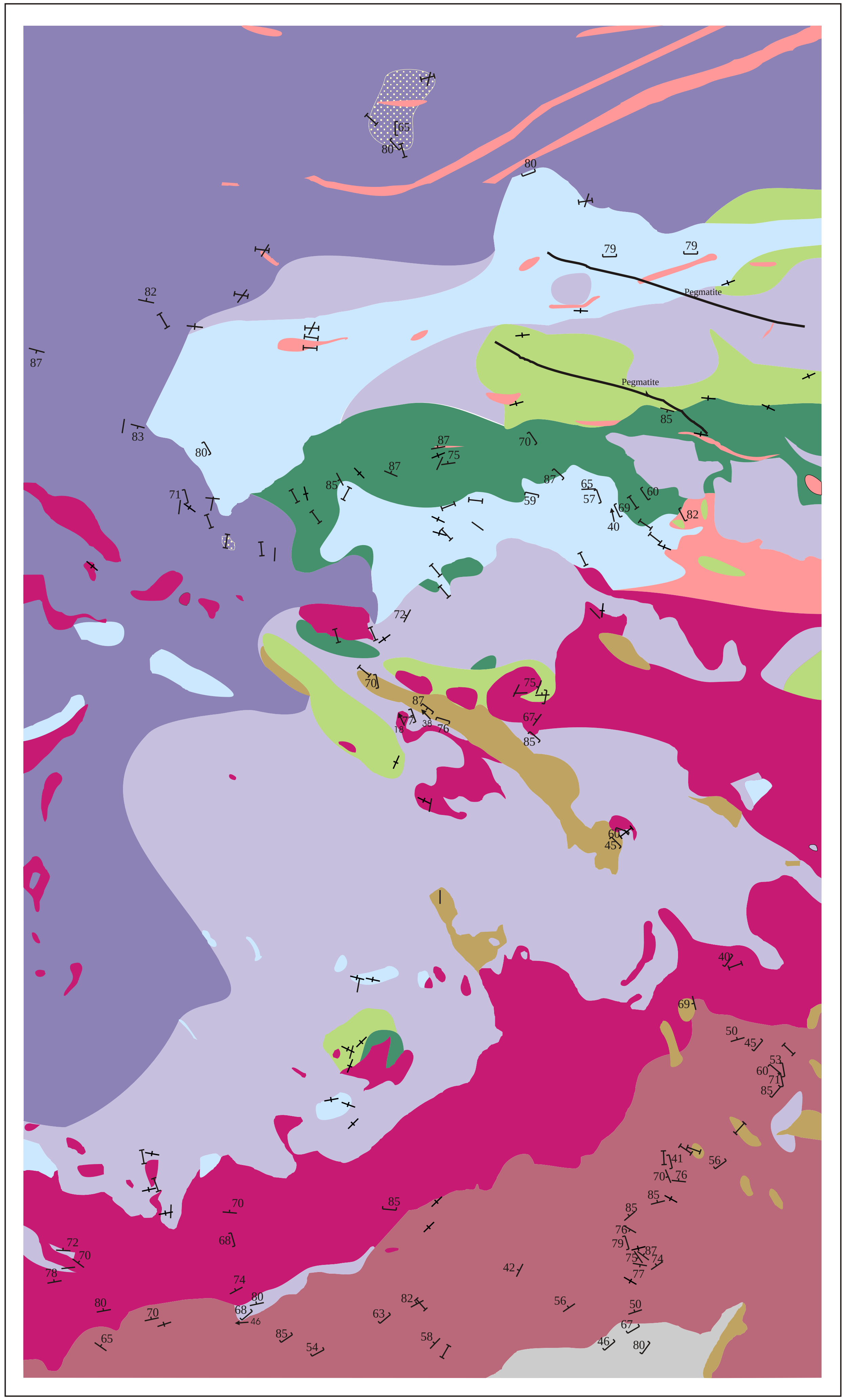


Figure 5.4. Structural geologu of the Kitty Plains Region.

Fabrics are N-S orientated in the south and change to NE-SW in the northern regions. Magmatic fabrics occur within the microgranite sheets and hybrid regions and are commonly E-W orientated. In the central region near the detailed map area, the microgranite sheets intruded the undeformed dolerite and the intrusions define an apparent fold.



KEY
Pole to country rock foliation
Pole to foliation
Pole to micrognanite foliation
Pole to hybrid granite foliation
Pole to overprinting foliation
Mineral lineation
Subarea 1
Subarea 2
Subarea 3
Pegmatite
Pegmatite
0
n=33 (P)
n=11 (P)
n=12 (P)
Num total: 56
0
n=19 (P)
n=16 (P)
n=3 (L)
n=40 (P)
n=10 (P)
Num total: 88
0
n=42 (P)
n=4 (P)
n=1 (P)
n=1 (L)
n=1 (P)
Num total: 49
7720000mN
7719800mN
7719600mN
7719400mN
7719200mN
331700mE
331800mE
332000mE
332200mE



DETAILED MAP OF KITTY PLAIN

LEGEND

- *Qtz-chl-ms schist (altered granite/dolerite)*
- *Chlorite schist with tourmaline and albite*
- *Grey schist (qtz-bt-ms magnetite bearing)*
- *Metasomatised rocks*

SYBELLA BATHOLITH

- *Enclave schlieren bearing deformed granite*
- *Enclave rich granite*
- *Med-grained hybrid granodiorite*
- *Dolerite brecciated and veined by granite/hybrid*
- *Med-coarse grained K-feldspar porphyritic granite*
- *"Micr既granite phase" fine-med grained granite*
- *Mosses Tank Dolerite*

- *Creeks*
- *Roads*

0 20 40 60 80 100m

LOCALITY MAP

Figure 5.6 Detailed Map of Structure and Geology within the Kitty Plains Region

Facing page - structural trends and stereonets of subareas. This page- Significant feature is an east-west trending magmatic shear zone within the enclave-rich microgranite and hybrids. In the northern portion of the map microgranite sheets intrude the Mosses Tank Dolerite as apparent open folds. Fabrics within the microgranite closely mirror the margin of their intrusive contacts. Dolerite is undeformed.
The country rocks in the southern portion of the map are strongly metasomatised and complexly deformed, however they have an overall NE trend moderately dipping to the NW.

across these folds which indicates that the folding occurred before emplacement of the plutonic rocks (pre-1670 Ma). Lineations in subareas 3 and western parts of subarea 2 have a scattered N to E trend and are moderate to steeply plunging compared to the SW moderate to shallow plunging lineations in the nearby granite (subarea 4) and ECV's (subarea 1). The mineral lineations in the eastern portion of subarea 2 are WSW trending and moderately plunging, which is similar to those in the adjacent subarea 1. The Main Phase granite that cuts the folds in subarea 2 has lineations that are concordant with those in the ECV's from subarea 1, and are interpreted to have formed later (discussed in sections 5.3 and 5.4).

Undeformed phases of the Main Phase granite intrude foliated mafic gneisses of the MDG and EGV's within the Easter Egg region (Figure 5.3). The granite intrusive contact cuts across the pervasive fabric in the gneisses, which indicates that granite emplacement took place after the deformation of the gneisses (Figure 2.8c). Wilson (1975) also noted intrusions of the Main Phase granite that intruded and truncated folded layering in the May Downs Gneiss and Mount Guide Quartzite near the Queen Elizabeth Pluton to the south. Along the margin of this undeformed granite intrusive, large regions of brecciated and rotated blocks of gneiss that are up to several metres in size occur within the Main Phase granite. Sheets of deformed Main Phase granite and medium-grained granite also intruded parallel to the foliation in the unbrecciated gneisses and amphibolites. Foliations and lineations in the eastern margin of the Main Phase granite and adjacent MDG (subareas 1 and 2; Figure 5.3) both strike NW, dip steeply and plunge in a SSE and ESE direction respectively. This may be interpreted as a reactivation of an earlier fabric formed during the Basement Event (S_B) within the MDG during the emplacement of the granite in the Sybella Event (D_S). Alternatively, the fabrics could be related to doming that was associated with the intrusion of the batholith, which explains the co-linear and co-planar relationship.

Xenoliths of amphibolite, calcsilicate (Eastern Creek Volcanics) and rocks interpreted as clasts from the May Downs Gneiss occur within the granite. These xenoliths are generally strongly foliated, are commonly folded and randomly orientated within the granite (Figure 2.14cd). The xenoliths are interpreted to have been locally derived rather than being exotic to the region, as they occur in greater abundances near the margins of the granite sheets, and are similar in composition to the adjacent country rock. The presence of dismembered folds and an earlier foliation in the xenoliths is further evidence of at least two phases of deformation before granite intrusion.

Amphibolites marginal to the Sybella Batholith have greatly varying textures, and range from metagabbros to metadolerites and metabasalts. These are interbedded with minor quartzite and calcsilicate rock. The tectonic foliation or layering is sub-parallel to the bedding. The metagabbros and metadolerites are coarse-grained and probably intruded as sills that may be part of the Sybella Batholith intrusive suite, although later deformation has obscured the original relationship.

Felsic veining or migmatite development within some of the mafic rocks (amphibolites, metadolerites or metagabbros) resulted in a layered structure, hence these rocks are termed mafic gneisses. Mineralogy away from the veining is comprised of amphibole, plagioclase, quartz and opaque minerals. Relic pyroxene occurs within the large amphibole grains (Figure 5.7a). Amphiboles occur as large clusters (or clots up to 5mm; Figure 5.7b) with numerous quartz inclusions (sieve texture), or as single large grains whose elongation defines the lineation. The veining has a magmatic texture defined by subhedral plagioclase, interstitial and undeformed quartz, clinopyroxene minor potassic feldspar and opaques (Figure 5.7c, 5.8ab). Clinopyroxene is commonly coarse-grained, and occurs within and near the margins of the veins (Figure 5.7c). Plagioclase phenocrysts (zoned or unzoned) occur within the felsic veins and in regions marginal to the veining (Figure 5.8a). The contact between the felsic veins and host mafic rock is sharp to gradational, and forms continuous veins and discontinuous blebs. The veins or melt segregations are parallel to the foliation in the amphibolites and accentuate the dominant foliation. This feature is common in migmatitic terranes, as melt migrates primarily parallel to any pre-existing foliation (Brown 1994). Since the migmatitic veining appears undeformed, the melts are interpreted to be related to a metamorphic event that largely postdates foliation development. This melting event may therefore be related to an increase in temperatures during the Sybella Batholith emplacement, but after foliation development. Alternatively, the migmatite may have formed during the Isan Orogeny. This is similar to the two phases of melting within the May Downs Gneiss, with an early phase parallel to foliation that was folded by S_2, and a

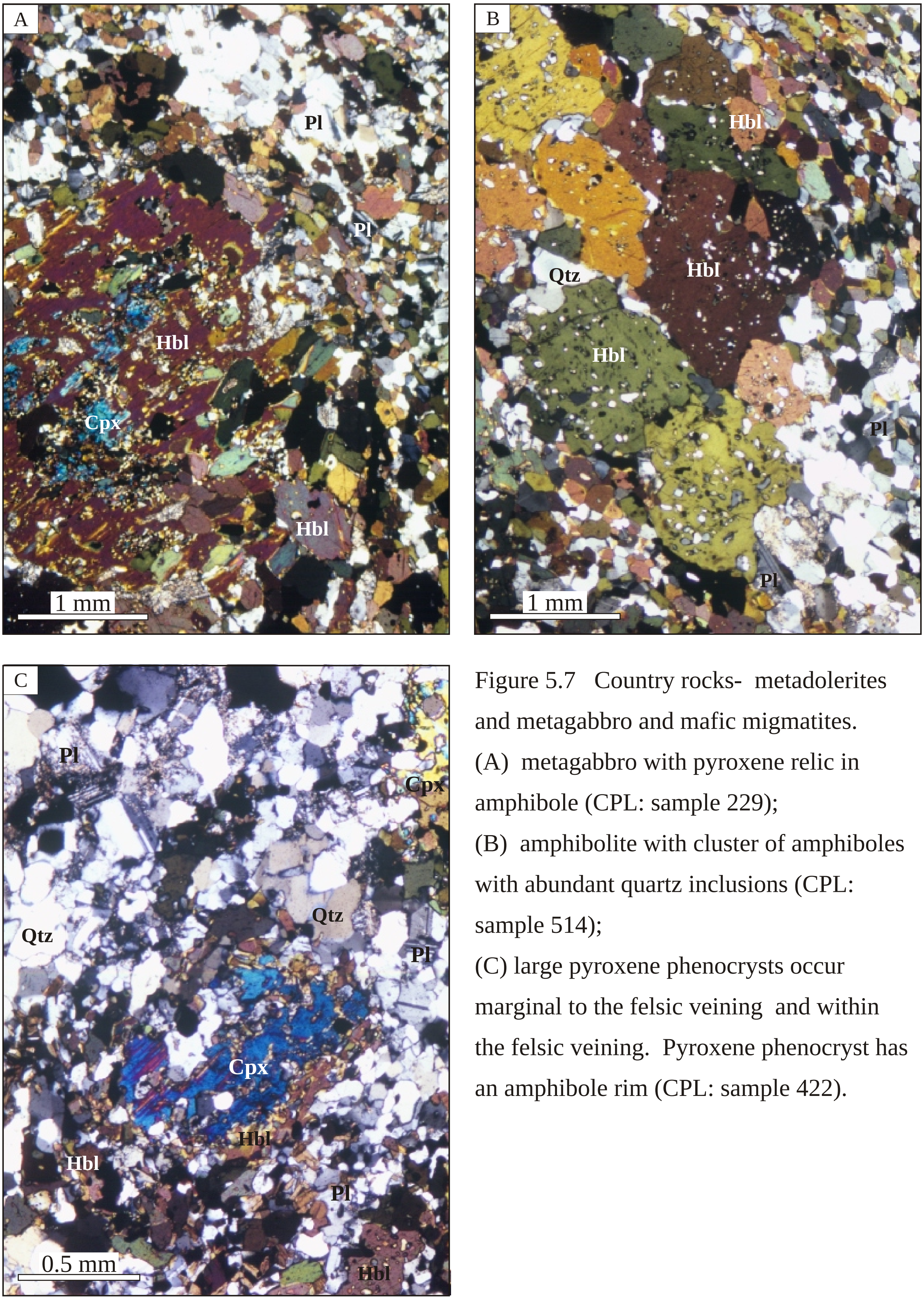


Figure 5.7 Country rocks- metadolerites and metagabbro and mafic migmatites.
(A) metagabbro with pyroxene relic in amphibole (CPL: sample 229);
(B) amphibolite with cluster of amphiboles with abundant quartz inclusions (CPL: sample 514);
(C) large pyroxene phenocrysts occur marginal to the felsic veining and within the felsic veining. Pyroxene phenocryst has an amphibole rim (CPL: sample 422).

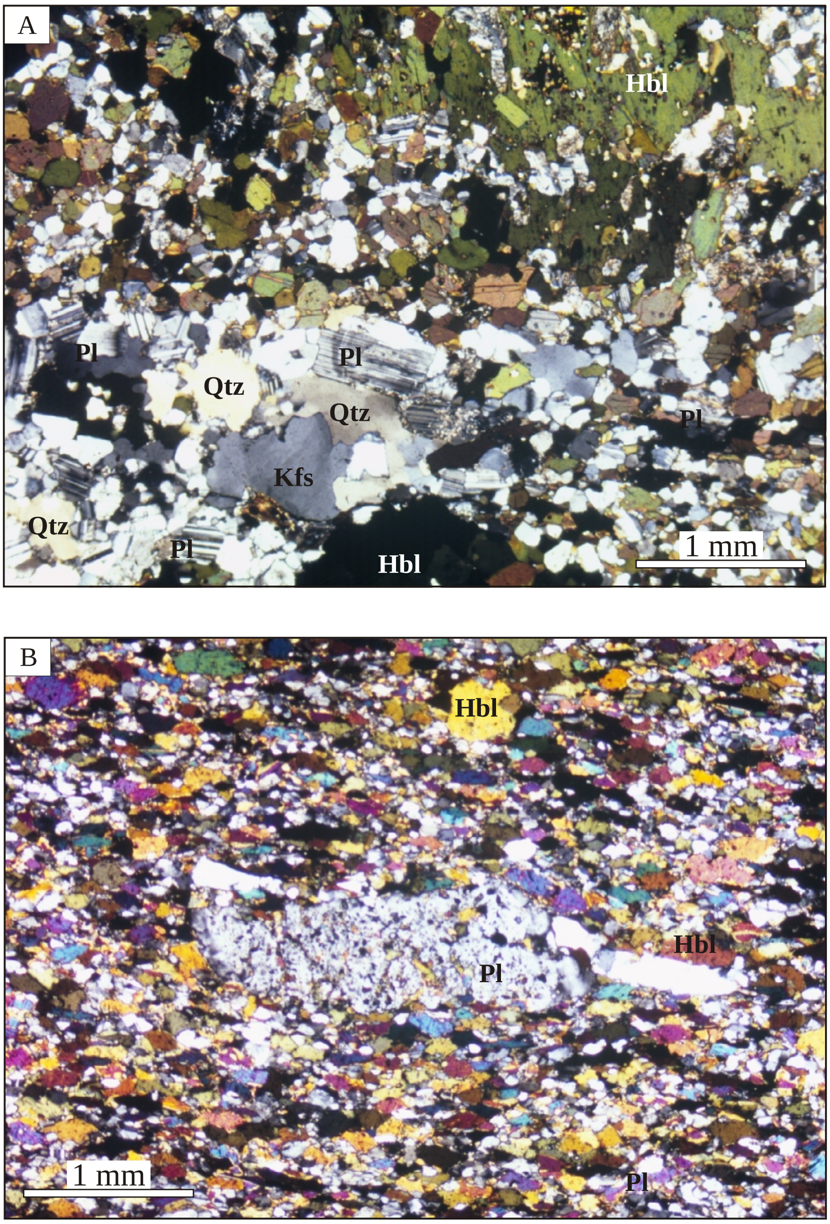


Figure 5.8 Country rocks- mafic gneisses.

(A) Inclusion-rich amphibole with quartz- plagioclase-rich vein below. Plagioclase is aligned in vein. Quartz shows high-temperature deformation with chessboard subgrain development (sample 229);

(B) Inclusion-rich plagioclase phenocryst in mafic gneiss with aligned amphibole (CPL: sample 418);

second phase that was axial planar to the folds (Connors *et al.* 1992).

5.3 STRUCTURES FORMED DURING BATHOLITH EMPLACEMENT

Evidence cited in Section 5.2 indicates that the Main Phase granites within the areas studied postdate the D_B structures within the country rocks. The rocks of the Mafic Hybrid Complex and Mosses Tank Dolerite are generally unfoliated, and quartz and mineral textures appear undeformed. Net-vein complexes, magmatic shear zones, compositional banding in the granite, individual microgranitoid enclaves or swarms of enclaves and the alignment of phenocrysts, indicates that deformation accompanied the emplacement of the hybrid and granitic phases of the Sybella Batholith. This deformation is referred to as the Sybella Event (D_S) and related planar fabrics, S_S.

Three stages of development for the fabric were determined:

(1) magmatic flow, marked by the predominant preferential alignment of euhedral to subhedral feldspars, quartz phenocrysts, schlieren layering and mafic and hybrid enclaves;

(2) submagmatic/high-temperature solid-state flow, characterized by submagmatic fractures of aligned phenocrysts filled with minerals similar in composition, and continuous with, the groundmass; high-temperature chessboard subgrains in quartz; aligned phenocrysts in a recrystallized groundmass;

(3) moderate-high temperature solid-state flow, marked by plastic deformation (dynamic recrystallization) of the K-feldspar megacrysts which indicated that the temperature was above 600°C (Paterson *et al.* 1989).

The foliation within the Sybella granite is characterized by a roughly margin parallel pattern with foliation intensity increasing towards the contact with the host rock (Figures 5.2-6). Inward from the marginal foliation is an unmodified magmatic flow foliation that is defined by aligned euhedral porphyritic feldspar crystals. The submagmatic and high-temperature deformation is interpreted to record a continuum in deformation during emplacement.

5.3.1 Main Phase Granite Suite

The Main Phase granite occurs in both the Gun's Knob and Easter Egg areas, where there is significant variation in the intensity and type of deformation. Observations from outcrop and on a number of thin sections suggest that the deformation during the late stages of emplacement was heterogeneous. The granite within the Guns Knob area shows a weak magmatic foliation developed at outcrop scale and limited localized high-temperature subsolidus deformation. Magmatic flow foliations occur locally within the granite in the Easter Egg region, however submagmatic/high-temperature to moderate-high temperature solid-state flow is predominant within the region. The lower temperature solid-state deformation, in addition to being a result of continuous magmatic to solid-state deformation, may be related to overprinting regional metamorphism and deformation. This deformation may also obscure earlier high-temperature fabrics by recrystallization.

Guns Knob Region

The broad outcrop pattern of granite within this region is characterized by an open fold with a north-south trending fold axis (Figure 5.4). The sheeted margins of the granite are roughly parallel to the fabric within the Eastern Creek Volcanics to the north and east of the pluton, however the sheets crosscut the folded fabrics within subarea 2. This is highlighted by the differences in fabric orientations between the subareas, with steep to subvertical east-west oriented foliation, and moderately southeast plunging lineations in the granites, compared to the partial great circle foliation girdle of moderate to steep fabrics in the ECVs, and moderately west plunging lineations (Figures 5.4 and 5.9).

A strong magmatic to submagmatic fabric within the pluton and near the margins of the pluton within the approximate parallel-sided sheeted bodies of granite, is defined by the preferred orientation of euhedral feldspar and biotite, and aligned oval-shaped quartz phenocrysts in the granites (Figure 5.10ac). Groundmass quartz appears undeformed with single grains that have no subgrain or new grain development (Figure 5.10d). Graphic textures within the groundmass minerals (Figure 5.10e) and the underformed nature of the majority of the quartz grains indicates that deformation within the Guns Knob granites was not accompanied by significant strain-induced recrystallization.

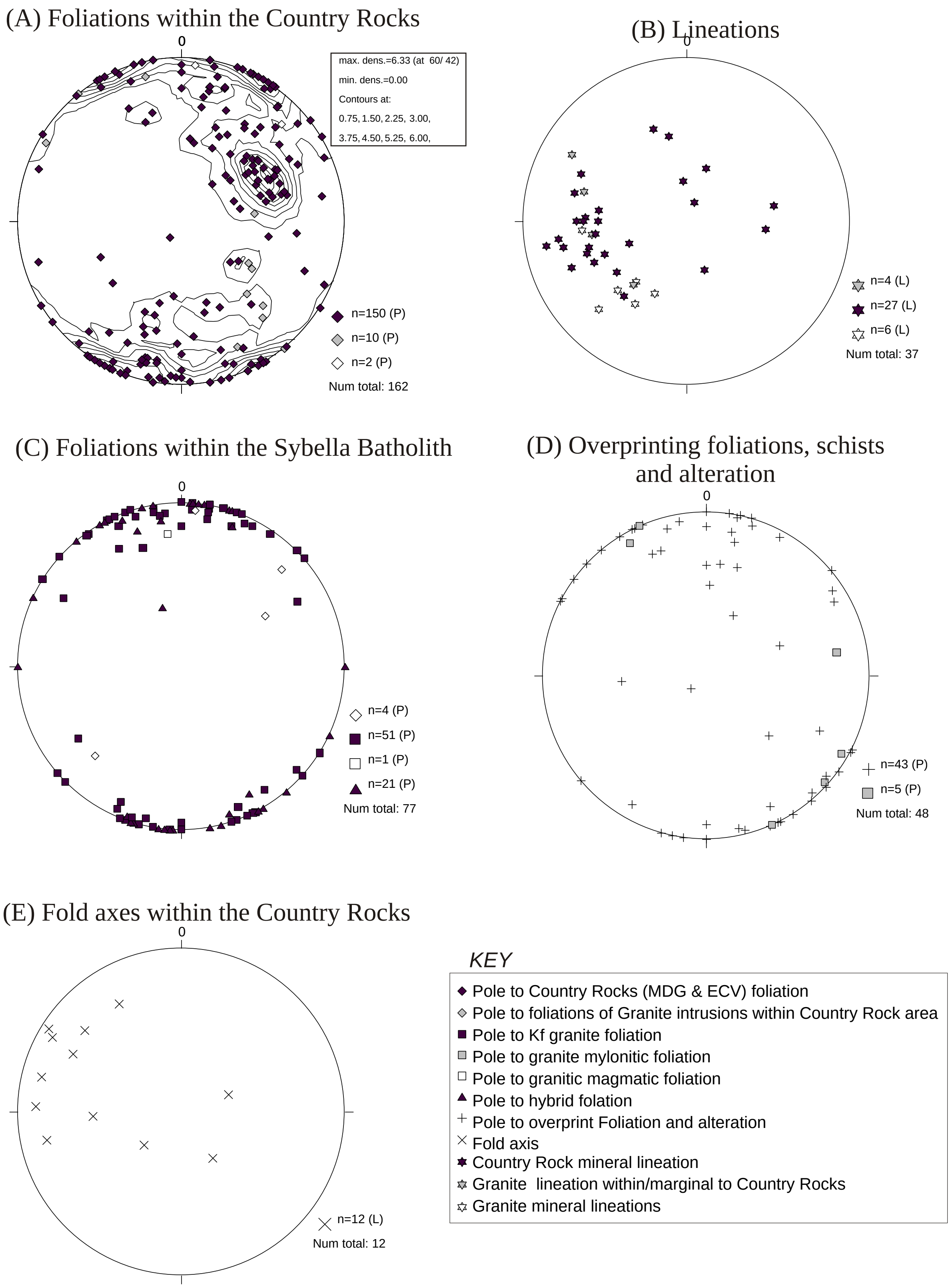


Figure 5.9 Guns Knob region Stereonet diagrams, equal area projection, lower hemisphere. Country rocks have steep to moderately dipping foliations that form a partial great circle girdle. Main Phase granite has subvertical E-W orientated foliations and are not folded. Granite sheets located at the pluton margins within the country rocks have magmatic foliations that are similar in orientation and dip to the surrounding rocks.

However, quartz phenocrysts have a chessboard pattern of subgrains that is characteristic of high temperature solid-state deformation (Figure 5.10f; Blenkinsop 2000). Recrystallization of quartz phenocrysts to a mosaic of new grains also indicates that solid-state deformation occurred. This high-temperature deformation resulted from the continuation of magmatic flow after the crystallization of quartz phenocrysts, when the groundmass was not fully crystallized, which is why the quartz in the groundmass is undeformed. The appearance of undulose extinction, sub-grains and new grains within quartz in the granites indicates that there was incipient solid-state deformation (Figure 5.10a). This was not observed in the field, as it affected neither the quartz grain shapes nor the magmatic texture. As a result, some of these rocks were indistinguishable from the purely magmatic ones.

Quartz-feldspar intergrowths occur along the margins of K-feldspar megacrysts (Figure 5.10b), although there appears to be no foliation-parallel orientation that would result from deformation induced K-feldspar replacement (Simpson and Wintsch 1989 and Paterson *et al.* 1989).

Ellipsoid microgranitoid enclaves lie in the plane that is defined by the granite magmatic foliation, and are elongated in an orientation similar to the lineation in the granite (Figure 2.15g and Figure 5.11). The foliation in the enclaves is parallel to the magmatic foliation in the host granite. These enclaves were used as a proxy for the magmatic fabric in regions where there appeared to be no observable foliation in the granite. Strongly foliated, folded and randomly orientated xenoliths of country rock within the sheeted granite contacts are blocky and appear unmodified by any strain within the granite (Figure 2.14c and 5.12a). This also indicates that the alignment of enclaves and phenocrysts within the sheets was a result of magmatic flow as the granite deformed around the solid xenoliths. The majority of the intrusive contacts between the early-formed Mafic Hybrid Complex and the foliated Main Phase granites (e.g. Figure 5.12b) show no evidence at outcrop scale of deformation after the emplacement of the granite. The sharp contacts, and angular and brecciated fragments of the hybrid in the granite appear unmodified. Therefore, fabrics within the smaller Main Phase granite intrusions are also interpreted to be related to magmatic flow.

.

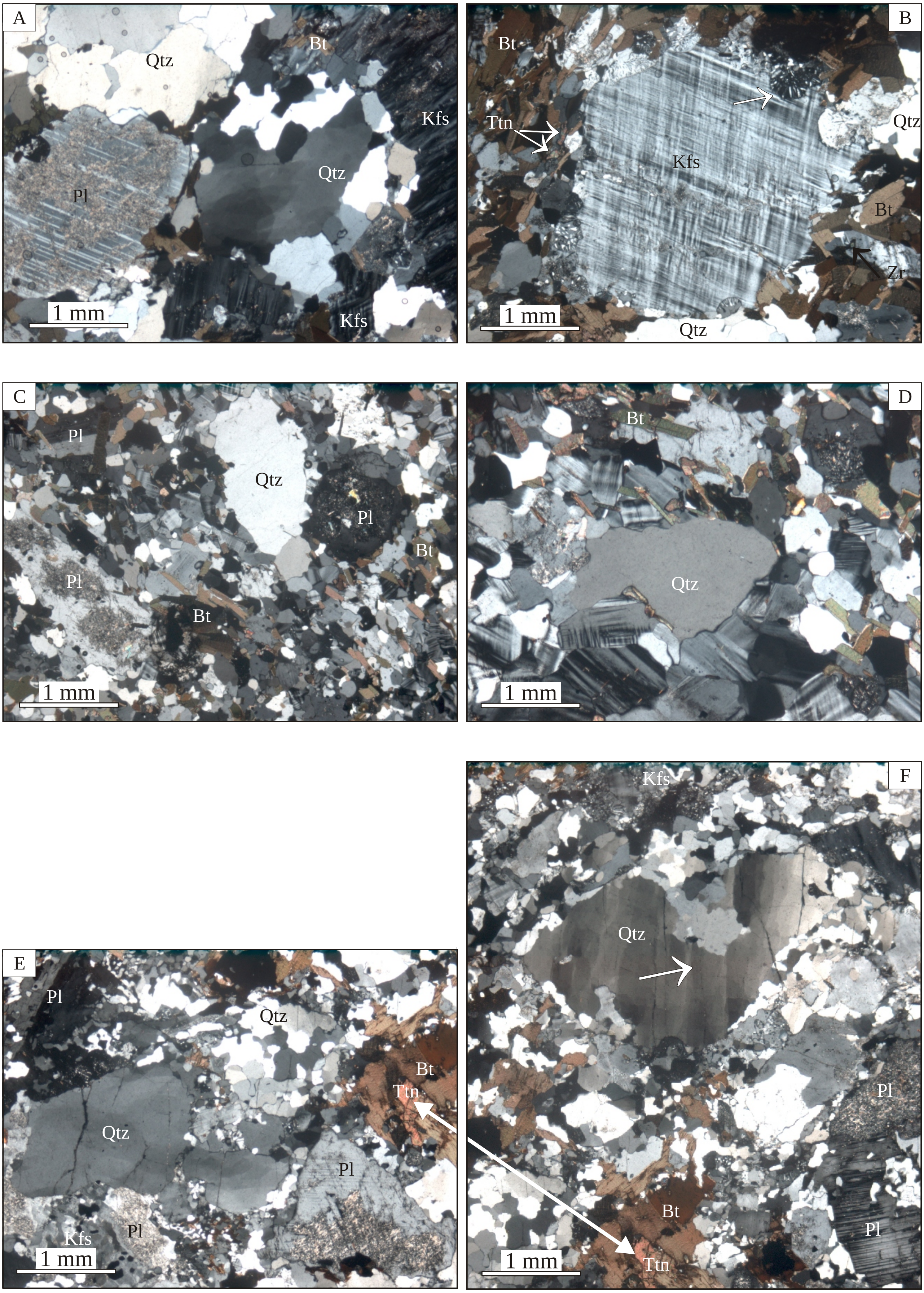

A
Qtz
Bt
Kfs
Qtz
Pl
1 mm
Kfs
B
Bt
Ttn
Qtz
Kfs
Bt
Zr
1 mm
Qtz
C
Pl
Qtz
Pl
Bt
Pl
Bt
1 mm
D
Bt
Qtz
1 mm
E
Pl
Qtz
Bt
Ttn
Qtz
Pl
Kfs
Pl
1 mm
F
Kfs
Qtz
Pl
Bt
Pl
1 mm
Ttn

Figure 5.10 Guns Knob magmatic textures with solid state overprinting deformation

(A) Rounded plagioclase and quartz phenocrysts in the Main Phase granite. The quartz phenocrysts have recrystallized, however the overall grain shape has not changed, therefore the rock has experienced little strain (sample 226); XPL.

(B) K-feldspar megacrysts have quartz-feldspar intergrowths developed at the margins (arrow), which probably resulted from deformation-induced replacement (sample 226); XPL.

(C) Quartz and plagioclase phenocrysts and biotite grains in the groundmass are aligned indicating a magmatic foliation (sample 242); XPL.

(D) The quartz in the groundmass (same sample as “C”) is undeformed and biotite is still aligned supporting the fabric primarily magmatic (sample 242); XPL.

(E) and (F) Arrow indicates the overlap of the photomicrograph. Quartz shows a variation in the textures resulting from deformation. Quartz phenocryst on the left in “E” appears undeformed with original grain shape and no internal deformation recorded. However, the quartz phenocryst above it has recrystallized, although the grain shape has not changed. In “F” the quartz phenocryst has developed a chessboard pattern of subgrains (arrow) characteristic of high temperature deformation, and in places new grains developed (sample 207); XPL.

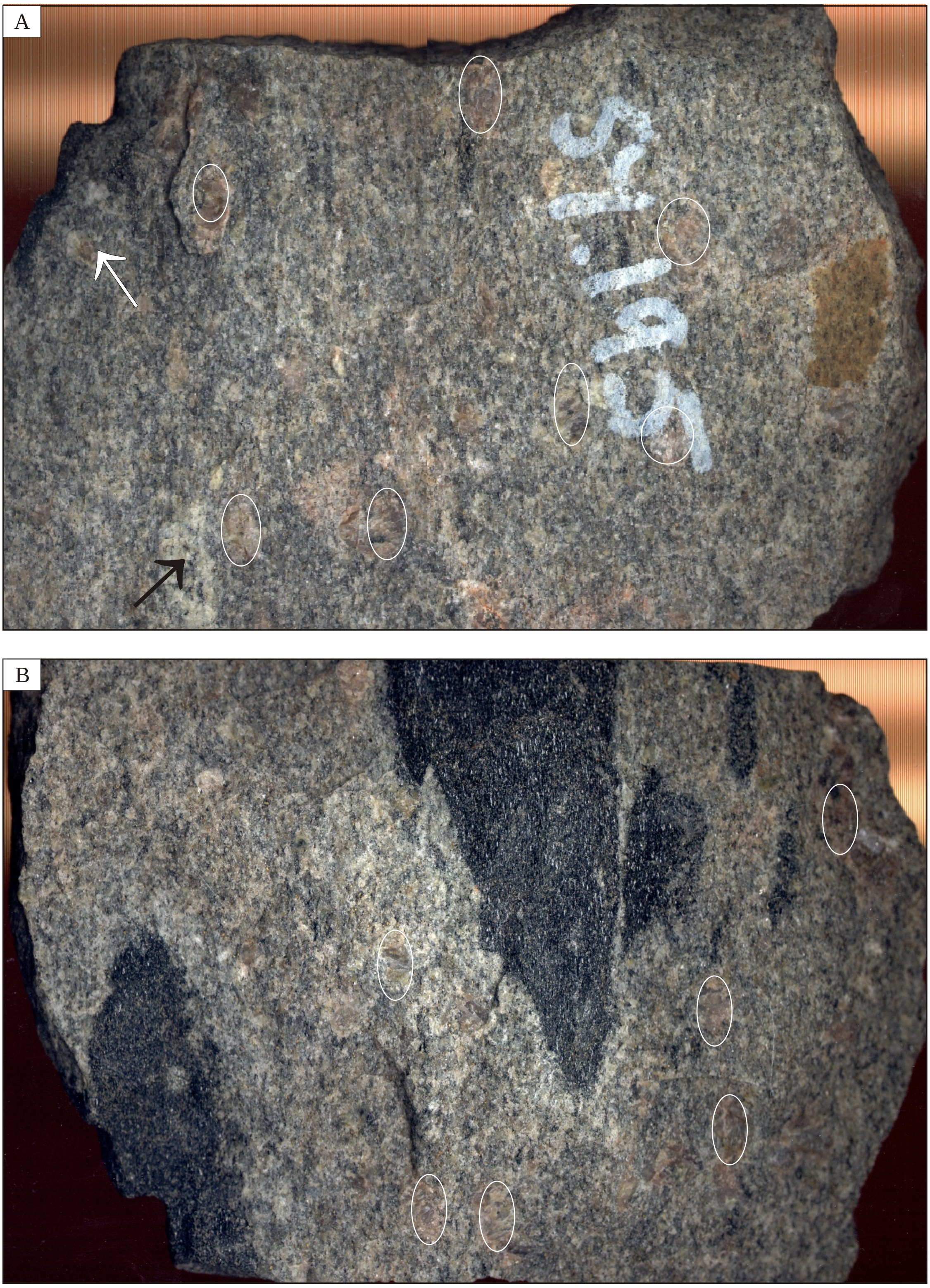


Figure 5.11 Hand specimen of Main Phase granite. A strong alignment of K-feldspar phenocrysts (white circles) is observed in (A). Rapakivi texture is common (white arrow). Clusters of minerals within the granite are also common and a plagioclase-biotite cluster is indicated by the black arrow. Both biotite-rich enclaves and K-feldspar phenocrysts are aligned in (B). The alignment of both enclaves and phenocrysts is used as an indicator of magmatic foliation.

(a)

(b)

(c)

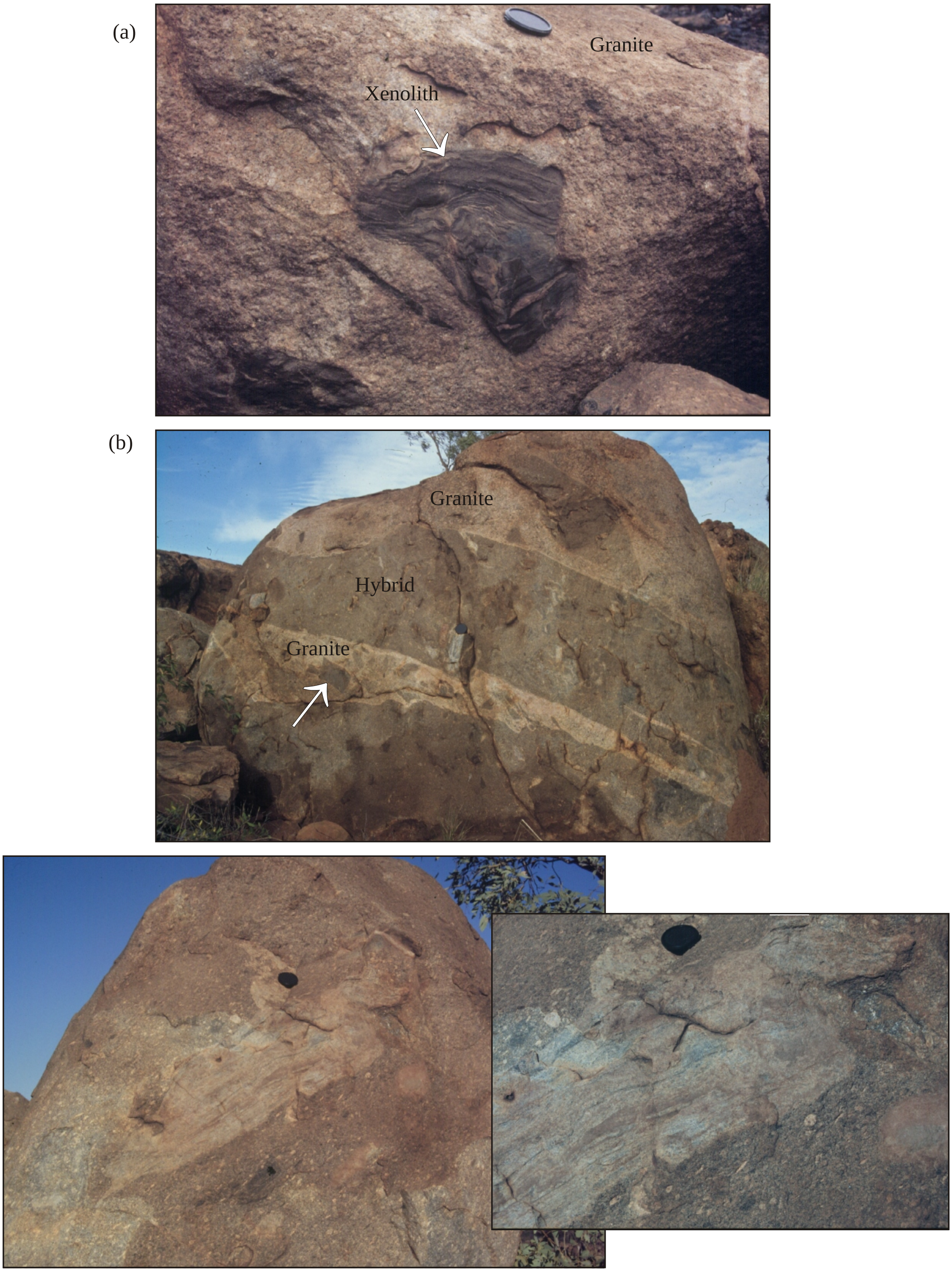


Figure 5.12 Guns Knob region; (a) The Main Phase granite has a weak magmatic foliation defined by the alignment of biotite and feldspar phenocrysts. The strongly foliated country rock xenolith that is included has a different orientation to that in the granite. This indicates that deformation (D_B) within the country rocks occurred prior to the emplacement of the Batholith. (b) Main Phase granite intruding hybrid granite with sharp and angular boundaries and brecciated fragments of hybrid in the granite (arrow). (c) Xenolith of foliated country rock within Main Phase granitic hybrid. The xenolith has irregular and sharp to diffuse contacts with the hybrid.

Enclave and xenolith-rich hybrid granodiorite in the southwest of the Guns Knob area shows a greater complexity in the interaction between the granite and the May Downs Gneiss. Contacts between the hybrid granite and xenolith appear to have been modified after incorporation into the granite (Figure 5.12c). This may indicate that the deformation that resulted in the strong fabric in the MDG (Basement Event) may have been continuous with the emplacement of the early hybrid phases of the batholith.

Easter Egg Region

The sheeted nature of the Main Phase granite is also evident in the Easter Egg region and is seen in the outcrop pattern in Figure 5.3. The edges of the granites contain deformation features that indicates that emplacement of the granite was accompanied by deformation. A high temperature (amphibolite facies) subsolidus fabric occurs along the margins and within the Easter Egg pluton. This fabric is parallel to the dominant foliation in the host May Downs Gneiss (Figure 5.13a). Generally, the Mafic Hybrid Complex and rapakivi granitoids are unfoliated and undeformed, with the strongly deformed Main Phase granite foliation wrapped around contacts. Compositional variation (increased biotite content) appears to be broadly parallel with contacts and internal granite fabrics. Internal contacts between granite and the Mafic Hybrid Complex are variable in orientation at a metre scale. The fabrics in the granite are steep to subvertical and strike parallel to granite margins, irrespective of its orientation, which results in the great circle girdle stereographic distribution (Figure 5.14c).

Away from the margins of the pluton, the foliation in the Main Phase granite is defined by the preferred alignment of euhedral to subhedral K-feldspar megacrysts, biotite and quartz pods. The lineation is absent to weakly developed. The predominant alignment of subhedral K-feldspar megacrysts and biotite within the foliation in the granite is indicative of magmatic flow, and the fabrics in the granite groundmass wrap around the aligned megacrysts (Figure 5.15a). A gradation exists from magmatic flow fabric towards the center of the pluton, to solid-state flow fabric at the pluton margins.

Figure 5.13 *EASTER EGG REGION STEREONET DIAGRAMS*

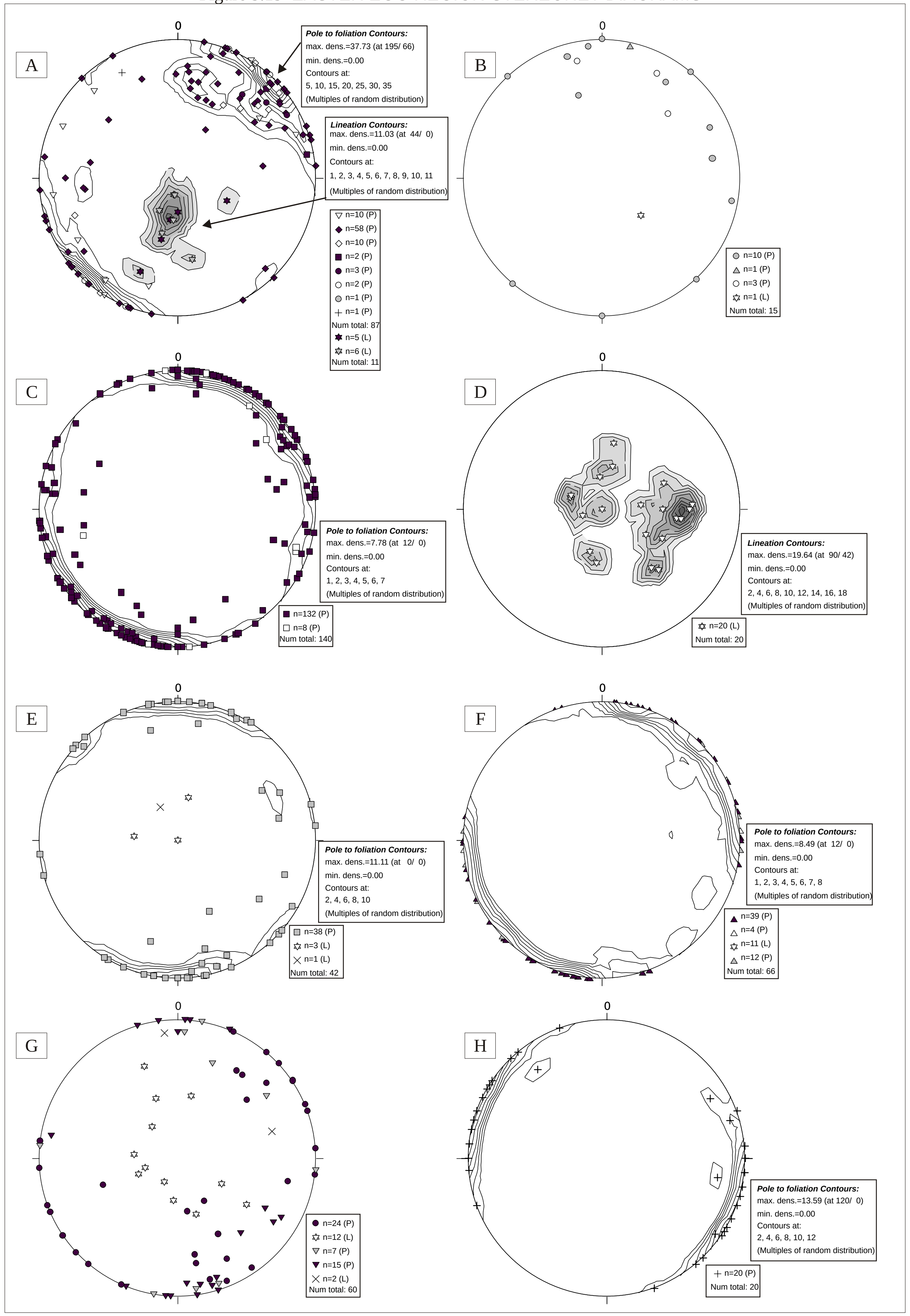


Figure 5.14 *SUBAREA 4 EASTER EGG REGION*

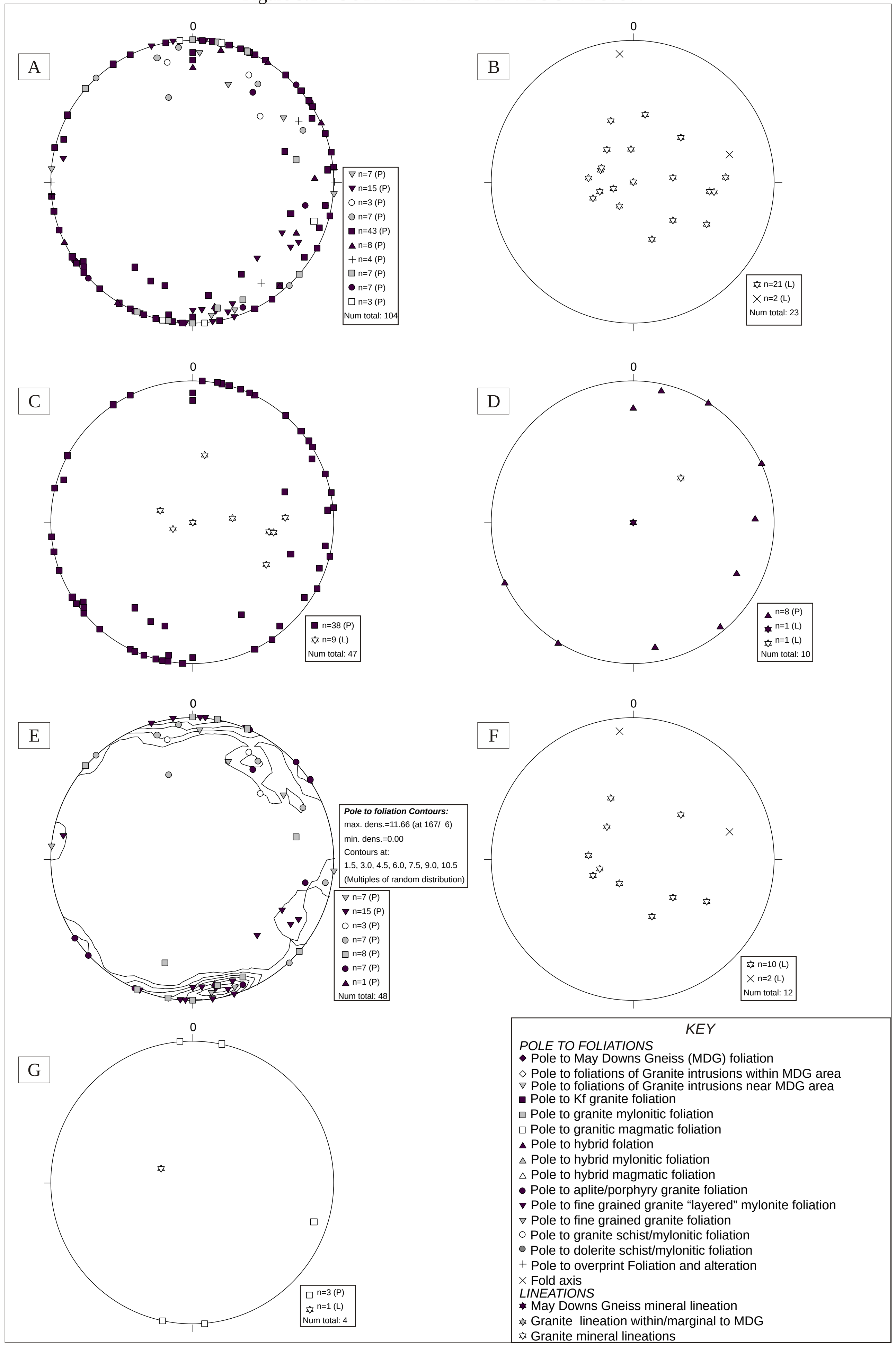


Figure 5.13 Easter Egg Region Stereonet diagrams, equal area projection, lower hemisphere

(A) May Downs Gneiss foliations and lineations;

(B) Granite and dolerite schists/mylonites

(C) Main Phase granites, magmatic to submagmatic foliations;

(D) Main Phase granites, magmatic to submagmatic lineations;

(E) Granite mylonitic foliations;

(F) Rapakivi hybrid foliations;

(G) Aplite, porphyritic and fine-grained layered granite foliations;

(H) Overprinting deformation and alteration.

Figure 5.14 Subarea 4, Easter Egg Region Stereonet diagrams, equal area projection, lower hemisphere.

(A) All foliations within subarea 4;

(B) All lineations and fold axis within area 4;

(C) Granite foliations and lineations;

(D) Hybrid foliations

(E) Strong deformation and mylonitic foliations including aplite, porphyritic granite and fine-grained layered granite foliations;

(F) Lineations within the strong deformation and mylonitic foliations;

(G) Magmatic granitic foliations

The granite has also developed L-S-, S- and L-tectonite fabrics (Figure 5.15cd). Vertical L-tectonites form in areas adjacent to dolerite bodies that terminate in roughly north-south blocks (e.g. subarea 4 and north below subarea 3; Figure 5.3), and in between two dolerite bodies (e.g. parts of subarea 3). These rocks are host to extremely elongate (up to two metres long) biotite-rich enclaves that occur as discrete biotite rich zones aligned in the lineation. Variation in the intensity of the fabric in the granites reflects internal compositional heterogeneities and the impact of competent dolerite bodies during granite emplacement and subsequent deformation.

Near the margin of the pluton (and areas described above) the Main Phase granite has an alignment of coarse biotite, amphibole and discontinuous layers of quartz and feldspar (Figure 5.16) that forms strong linear and weak planar fabrics. The discontinuous layers of quartz and feldspar are a result of high temperature deformation of phenocrysts.

K-feldspar phenocrysts show varying degrees of deformation, ranging from a large single grain (microcline K-feldspar) progressing to clusters of recrystallized smaller equant grains, to a monomineralic K-feldspar ribbon. The most common occurrence is K-feldspar augen, which has a large grain at the core that is transitional to a mantle of smaller recrystallized grains that formed a ribbon structure (Figure 5.16a). This texture is indicative of temperatures above 450°C (Passchier & Trouw 1998). In some localities augen are absent and feldspar formed monomineralic ribbons similar to quartz, which is indicative of higher-grade conditions. Recrystallized microcline commonly has triple point junctions. Where myrmekite has formed, it is generally located along crystal faces parallel to the foliation. This is a feature common in granites deformed at medium- to high-temperature conditions (Simpson and Wintsch 1989 and Paterson *et al.* 1989).

In thin section, quartz formed large elongated grains with subgrains with or without zones of recrystallized new grains. Both the subgrains and new grains have undulose extinction. Grain boundary migration has occurred with new grains present along bulging grain boundaries (Figure 5.16b), and subgrain rotation lead to the formation of new grains (Figure 5.16c). Subgrains pass laterally into zones of small, dynamically recrystallized grains. Quartz ribbons contain sutured, but generally straight grain boundaries that are at a high angle to the ribbon boundary. These quartz microstructures indicate a period of medium to high temperature deformation that was followed by a lower temperature deformation.

Another noteworthy feature is that the temperature data that was calculated using the amphibolite-plagioclase thermometer of Holland & Blundy (1994) yielded temperatures significantly greater than 700°C in the granites (Section 3.4.2). This is within the magmatic to sub-magmatic temperature range for the granite, and indicates that the amphiboles and plagioclase grains did not change in composition during later deformation. Whole-rock Rb-Sr isotopic ages also indicate that they have not been reset by a later amphibolite facies deformation, as they give an isochron age of 1656 ± 21 Ma (Farquharson & Wilson 1971) that is within error of more recent zircon age dating of the granite (see Section 4.4.1). This data also supports the development of the pervasive fabric within the Main Phase granite as having resulted from deformation during the emplacement of the batholith that continued as the granites solidified.

East-west trending equigraniular granites mainly intruded the Main Phase granite at Main Phase granite/dolerite boundaries (Figures 5.3 and 5.14e), and appear to have localized ongoing deformation during the Sybella Event (Figure 5.15b). At the time of the later granite intrusion, the Main Phase granite had to have a high proportion of crystals to allow propagation of fractures and emplacement of this later phase. This would also have allowed for regionally extensive subsolidus (to solid-state) fabrics to develop subparallel to a preexisting magmatic fabric in the Main Phase granite during ongoing crystallization.

Rapakivi Granitoids

The rapakivi granitoid intrusions within the Mafic Hybrid Complex are generally unfoliated, with their magmatic textures preserved. However some of the intrusions have experienced an overprinting high-temperature deformation. Minerals such as amphiboles and plagioclase have no preferred orientation, and apatite is acicular within late mineral phases. In regions where the hybrid is transitional to granite (due to

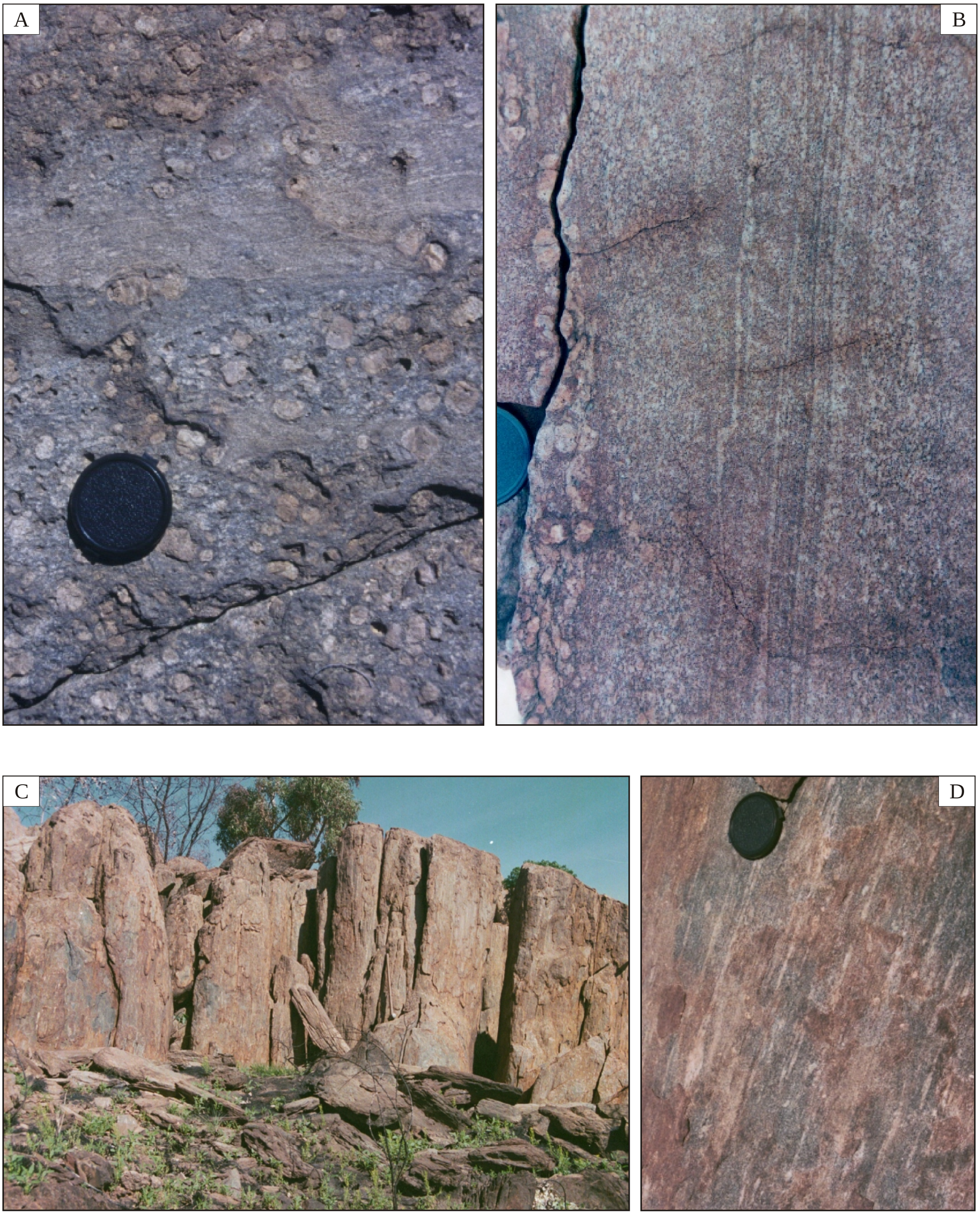


Figure 5.15 (A) Magmatic alignment of subhedral K-feldspar phenocrysts in Main Phase granite with a late fine-grained intrusion parallel to fabric (also with a strong internal fabric). The fine-grained intrusions have strong fabrics (magmatic to submagmatic) developed as seen in nearby intrusion (B). (C) Vertical L-tectonites occur in between more competent dolerite bodies and at the margins of them. This may have been the result of localization of strain during deformation. (D) Hybrid L-tectonite with mineral grains, particularly K-feldspar (white) and quartz being extremely stretched with aspect ratios of 1 or 2:100.

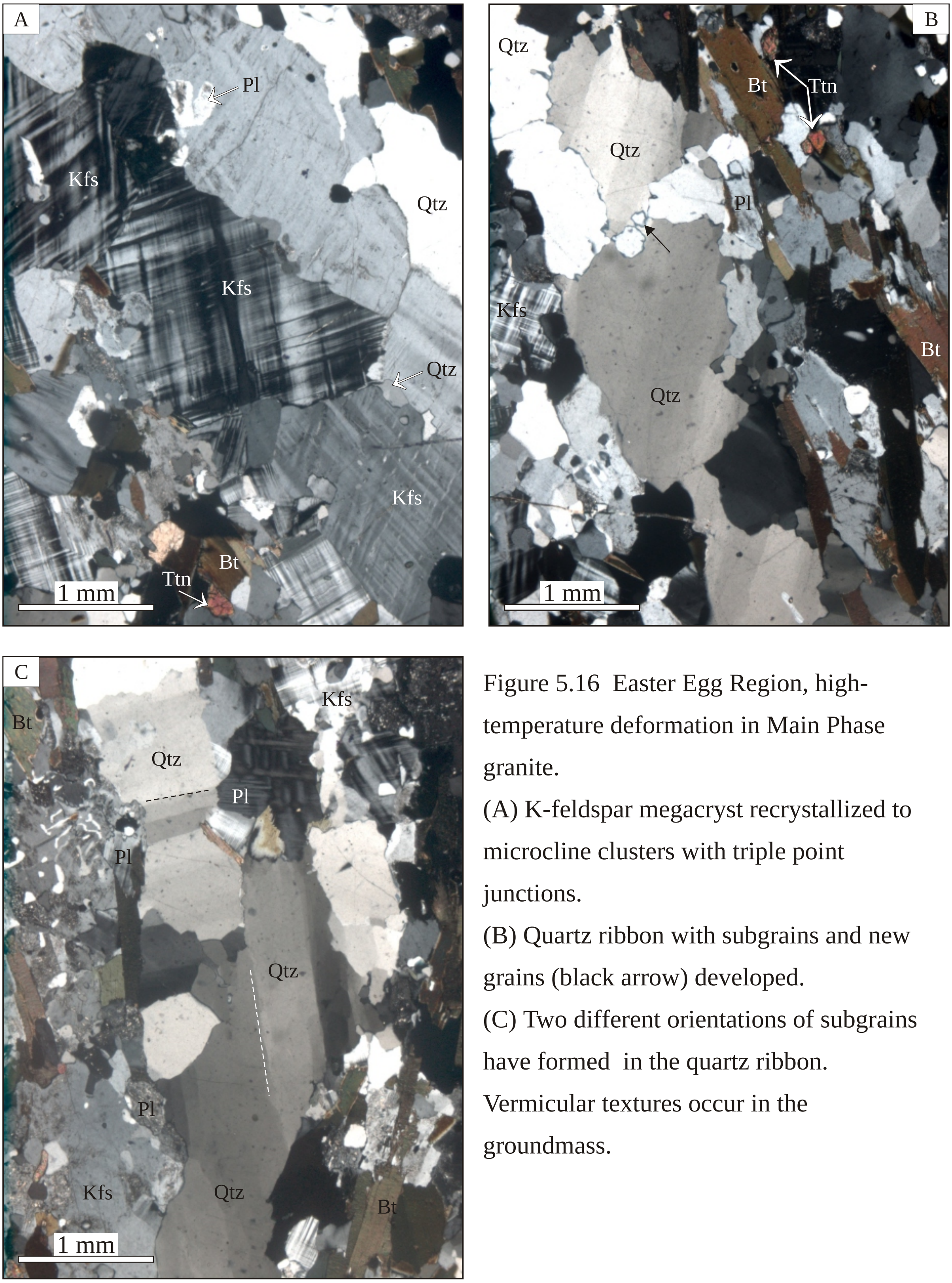


Figure 5.16 Easter Egg Region, high-temperature deformation in Main Phase granite.

(A) K-feldspar megacryst recrystallized to microcline clusters with triple point junctions.

(B) Quartz ribbon with subgrains and new grains (black arrow) developed.

(C) Two different orientations of subgrains have formed in the quartz ribbon. Vermicular textures occur in the groundmass.

localized mixing), the hybrid has a weak magmatic alignment of minerals. Quartz within the groundmass occurs interstitially, is undeformed and shows no subgrain development or recrystallization (Figure 5.17b). Quartz ocelli or xenocrysts range from completely undeformed (Figure 5.17a), to having undulose extinction, to having formed sub-grains that are indicative of dynamic recrystallization and recovery by grain boundary migration. The recrystallized quartz grains retain equant to oval shapes that suggests a minor component of solid-state strain, which indicates that there was incipient solid-state deformation. Mosaic patterns in quartz are indicative of extreme grain boundary mobility, and therefore high temperatures (Gapais & Barbarin 1986). However, this may be the result of an unrelated later deformation event (Paterson *et al.* 1996).

Hybrid intrusions that are marginal to L-tectonites within the Main Phase granite, also contain L-tectonites. This deformation within the rapakivi granitoids is restricted to subarea 3 (Figure 5.3).

Porphyritic to Aplitic Main Phase Granite

The porphyritic granite intrusions post-date the emplacement of the Main Phase granites and are largely unaffected by the strong deformation that is recorded within the Main Phase Granite. Porphyritic granite sheets intruded the diorite (Mafic Hybrid Complex, MHC) in predominantly east-west trending sheets. Locally, these sheets have a folded appearance (Figure 5.3) however this is confined within an area of irregular and mixed dolerite and granite intrusion. Porphyritic granite also intruded the MHC in a north-south orientation in subarea 4 of the Easter Egg region. Fabrics within the porphyritic granite sheets are parallel to intrusion margins. The quartz grains have an elliptical shape and commonly show subgrain development. The subgrain pattern is essentially made up of two sets of sub-perpendicular boundaries that resemble a chessboard pattern, which is typical of high temperature plastic strain in quartz (Figure 5.17c; Blenkinsop 2000). This texture may indicate that submagmatic high-temperature deformation occurred after emplacement, but did not significantly affect the igneous textures within the later porphyritic granites. The symplectite intergrowths within the groundmass indicate that later deformation had not caused significant recrystallization of the groundmass (Figure 5.17d).

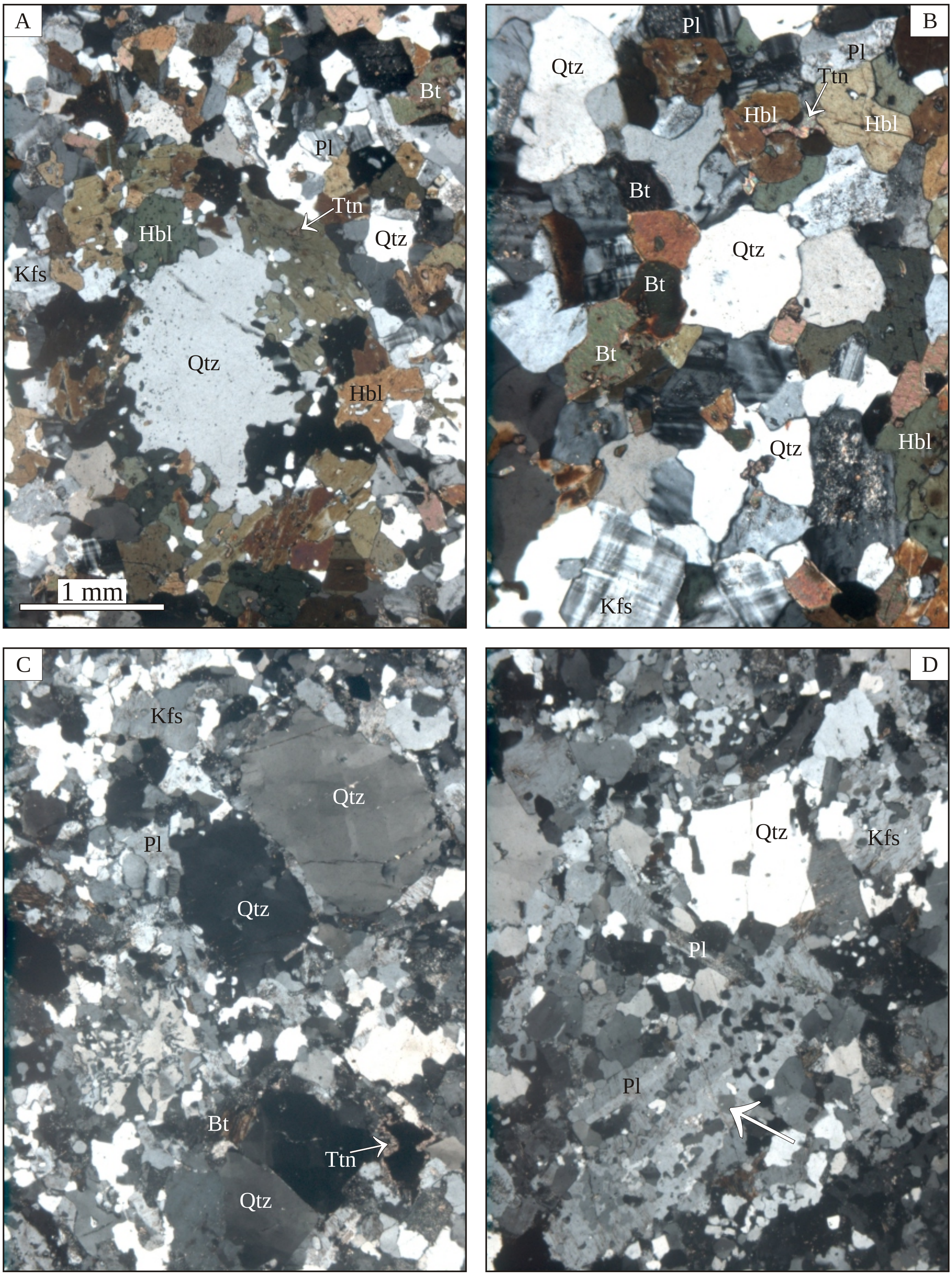


Figure 5.17 Easter Egg Region high-temperature deformation of rapakivi granitoid hybrid and K-feldspar porphyritic granite. (A) Quartz ocelli within the rapakivi hybrid was undeformed, even though the sample was located within 5 metres of a strongly deformed Main Phase granite sheet (sample 314); XPL. (B) The hybrid also has undeformed quartz in the groundmass forming irregular and interstitial grains (sample 314); XPL. (C) Porphyritic granite has quartz phenocrysts with high-temperature chessboard subgrain development whilst quartz in the groundmass was undeformed (sample 324) XPL. (D) Graphic and pegmatitic intergrowths in the groundmass indicate that the rock was not recrystallized during later deformation. Plagioclase phenocryst has an inclusion-rich zone (sample 324); XPL.

A primary igneous texture defined by the alignment of minerals and undeformed quartz grains is preserved where the fine-grained granites intruded and locally hybridized with the mafic magmas within the Mafic Hybrid Complex (Figure 2.15). The aplitic granite also intruded the Main Phase megacrystic granite as thin (less than one metre wide) sheets as mentioned above. The sheets are parallel to a strong magmatic foliation within the Main Phase granite, and are themselves strongly foliated (Figure 2.15). This indicates that emplacement of the later stages of the Sybella Batholith is both syn-deformational (aplite) and post-deformational (porphyritic granite).

5.3.2 Kitty Plains Microgranite

The southern-most portion of the microgranite pluton is a southwest trending protrusion that extends from the main body (to the north) along the approximate boundary between Mosses Tank Dolerite (MTD) to the west, and country rocks of ECV to the east. This zone is largely granite and dolerite breccia where the granite formed the groundmass and dolerite occurs as numerous angular xenoliths or enclaves. Where the granite intruded the dolerite complex as sheets, they have a margin parallel, subvertical to vertical magmatic fabric that is defined by the predominant orientation of feldspars and mafic minerals within the microgranite. Plagioclase is euhedral with well-developed twinning and preserved zoning, that is typical of igneous structures. The twin planes and long axis of the grains are comonly aligned parallel to the foliation and enclave contacts (Figure 5.19a-d). Therefore, in this case the dolerite was solid or near solid, was able to be intruded by sheets of granite, and was unable to form large volumes of hybrid magmas, although minor hybrids formed at the margins. An apparent open fold is defined by the orientation of the thin granite sheets that intrude the MTD to the north of the detailed map (Figure 5.5). This may be related to the emplacement of the granite or a later folding event.

Localized vertical to steeply north-dipping and east-west orientated magmatic shear zones occur within the Kitty Plain area (Figure 5.6 and Figure 5.18). The small microgranite intrusions within the crackle-brecciated dolerite that are marginal to the magmatic shear zones, have strong margin-parallel, subvertical, and randomly-oriented foliations (Figure 5.18). As described in Section 2.4, schlieren formed within the shear

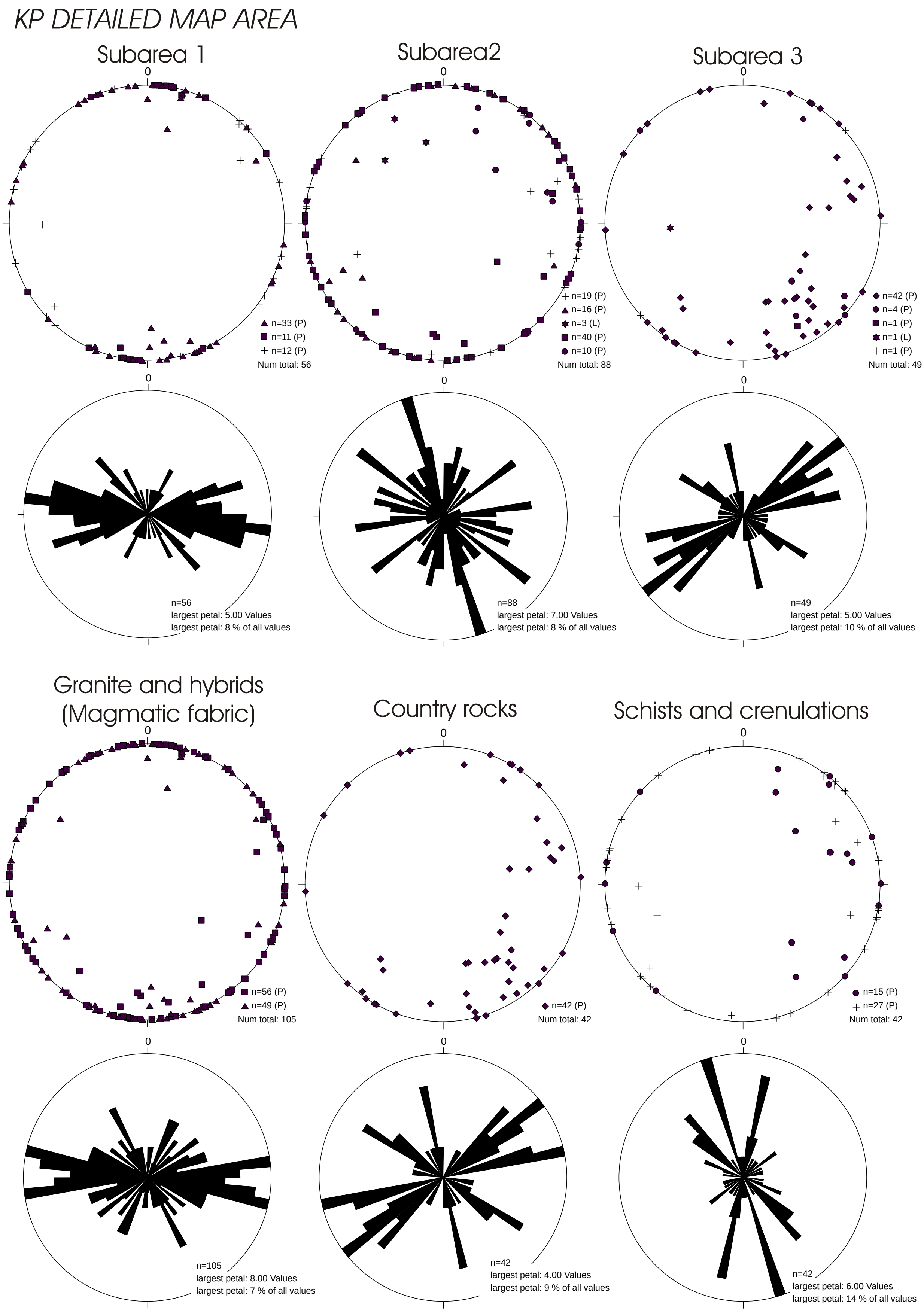


Figure 5.18 Kitty Plain Detailed map area Stereonet diagrams, equal area projection, lower hemisphere. Legend of symbols as in Figure 5.5. Rose Diagrams illustrate strike of foliations. Strike direction: 5.0 classes.

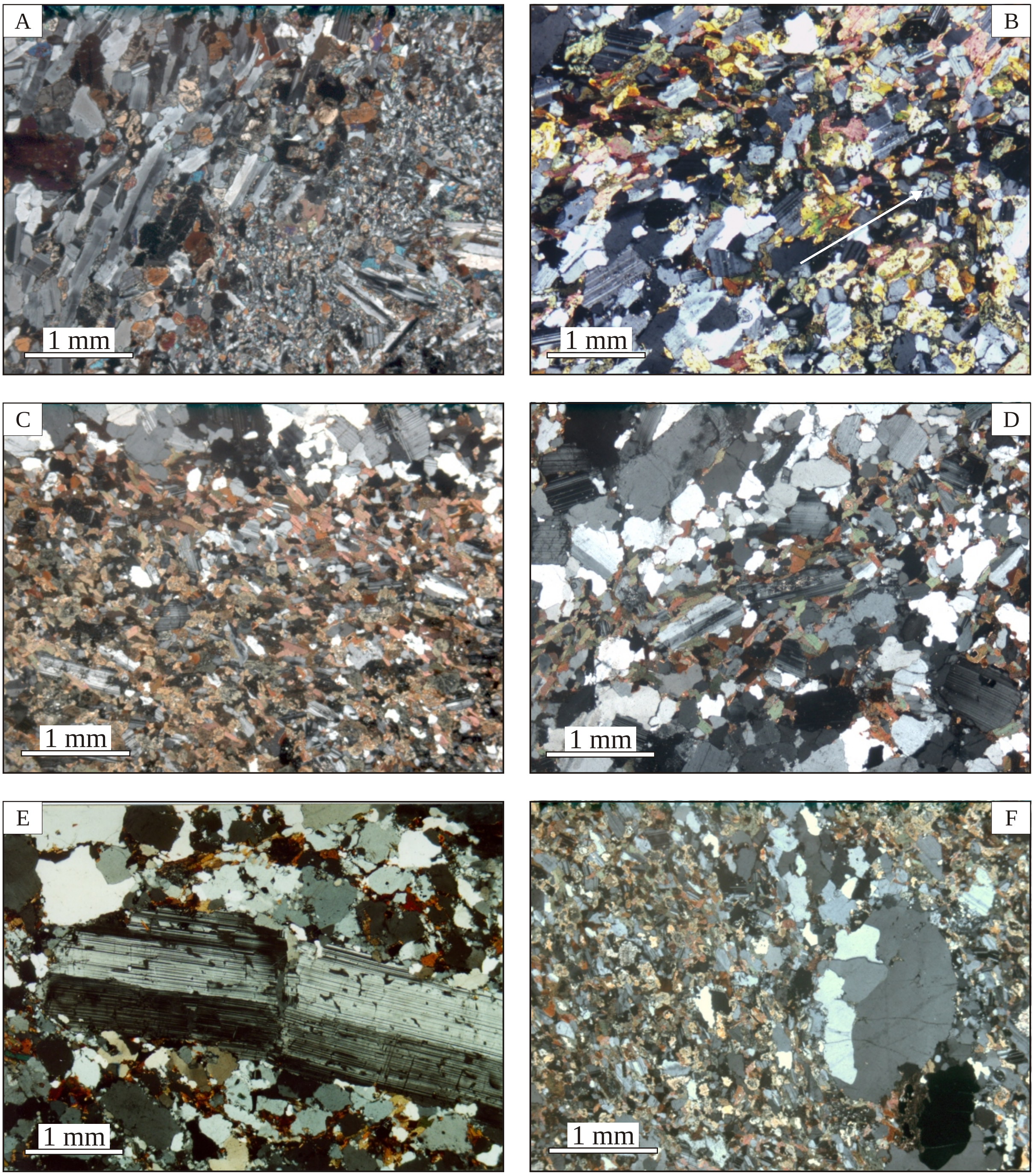


Figure 5.19 Magmatic textures in Kitty Plains microgranite, hybrid and enclave. (A) Magmatic alignment of plagioclase at dolerite-dolerite contact (sample 19) XPL; (B) Alignment of plagioclase and mafic minerals indicated by arrow (sample 281) XPL; (C) Alignment of plagiocalse and mafic minerals in mafic enclave. Magmatic quartz textures are evident in the granite groundmass (sample 289) XPL; (D) End whisp of an enclave with aligned plagioclase in granite groundmass (sample 289) XPL; (E) Microcracking of aligned phenocrysts has infill minerals continuous with groundmass minerals indicating continual deformation as the granite solidifies (sample 281) XPL; (F) Quartz phenocrysts have new grain development which resulted from deformation that continued from magmatic to submagmatic. Minerals are aligned in groundmass (sample 281) XPL.

zones from the elongation and breakup of mafic enclaves. The plagioclase and mafic minerals within schlieren are aligned in a magmatic foliation that is continuous with the foliation in the microgranite (Figure 5.19cd). Micro-cracking of plagioclase phenocrysts within this magmatic fabric indicates that deformation became brittle during the later stages of crystallization. However, the cracks are sealed with minerals that are similar to that in the groundmass, which indicates that melt was still present (Figure 5.19e). This feature has also been observed in other syn-deformational granites (Bouchez *et al.* 1992; Blenkinsop 2000), and is interpreted as micro-cracking of a grain network in the presence of melt during ongoing deformation as the microgranite solidified. Quartz phenocrysts show recrystallization to a mosaic (Figure 5.19f), and are indicative of high-temperature deformation.

5.4 STRUCTURES FORMED AFTER BATHOLITH EMPLACEMENT (ISAN OROGENY)

It is difficult to assess the extent of deformation that overprinted D_B and D_S fabrics within the country rocks and batholith, respectively. Reactivation of early fabrics during a high-temperature regional metamorphic/deformation event (of similar orientation), would produce intensification of some fabrics. Regional deformation was heterogeneous due to the distribution of undeformed dolerites and large bodies of granite, which caused strain shadows around the competent intrusive bodies to develop.

Cross-cutting fabrics in the granites are localized at outcrop scale but there is limited associated mesoscopic folding. Correlation of overprinting fabrics at different localities within the batholith was not possible in this study. At microscopic scale, incipient solid-state deformation is ubiquitous throughout the plutons.

Within the country rocks, particularly the Eastern Creek Volcanics, the structural pattern is dominated by a phase of intense folding that accompanied metamorphic mineral growth (regional D_2; Bell & Hickey 1998). This has partly obliterated some evidence of early sedimentary and tectonic structures, and in some locations, the early structures have been intensely folded that resulted in deceptively simple structures. The early D_B fabrics identified in the ECV's and May Downs Gneiss have been reactivated and/or strongly folded in regions where the original foliation was concordant with the overprinting and approximately north-south pervasive foliation (e.g. Guns Knob subarea 1; Kitty Plains eastern regions). The strain shadows around the more competent granite and dolerite plutons would account for the variation in orientation of the pervasive foliation within the ECVs in these areas.

The pervasive fabric (S_2) was also found to overprint an older cleavage within the Mount Novit Ranges to the south (Connors & Lister 1995), and the earlier fabric is correlated here with the pre- to syn-Sybella fabric developed during $D_{B\text{-}S}$. Monazite aligned in the peak metamorphic (c. 600°C) foliation (S_2) of a cordierite-orthoamphibole gneiss within the Hazeldene region to the east of the Sybella Batholith, were dated at around 1575 Ma (Hand & Rubatto 2002). A second phase of partial melting associated with this peak metamorphic event (D_2) in the May Downs Gneiss is axial planar to folds, and fold the earlier phase of partial melting. Partial melting of the Main Phase granite is associated with quartz-feldspar segregations and biotite selvages (Connors & Page 1995) within the Mica Creek area at the northern margin of the Queen Elizabeth Pluton. These segregations are parallel to or locally cross-cut the pervasive fabric in the granite (here termed S_S), with the latter fabric reoriented into parallelism with the segregations (Connors *et al.* 1992).

Guns Knob Region

As mentioned previously, very little solid-state deformation is identified within the Main Phase granite of this region. However, a solid-state fabric in the granite within the Guns Knob region has a NE trend and subvertical dip (Figure 5.2) that overprints internal granite intrusive contacts (Figure 5.20a). This foliation is localized within a narrow zone that is approximately 200 m wide. The overprinting fabrics are generally weakly developed in outcrop, with the fabric dominated by the magmatic alignment of enclaves and K-feldspar phenocrysts. In thin section, the microstructures within these zones are dominated by an overprinting biotite-quartz foliation, which is perpendicular to the enclave-granite contact (Figure 5.21). In the southwest of the Guns Knob region, a large raft of May Downs Gneiss is found within the Sybella Batholith. A faulted contact is interpreted from the geophysical data, and has a northeast trending orientation, which may be continuous with the strong overprinting fabric described within the granite along strike. Mylonitic foliations that are marginal to the dolerite bodies (in an east-west orientation) may be a result of either localization of ongoing deformation during the Sybella Event or are a product of overprinting Isan deformation.

Alteration of the granite to quartz-muscovite-albite schist is associated with a large quartz blow. A dominant northeast-trending fabric in the granite appears transitional to the schist with increasing alteration. The schistose fabric has in places been overprinted by NNW to NW trending crenulations. The strong overprinting northeast-orientated fabric may be the same generation of fabric that was identified within the Kitty Plains region (as a weak overprinting fabric), and within subarea 3 (Figure 5.3) of the Easter Egg region (as strong overprinting fabric).

One to two metres wide zones of epidote and chlorite schist trend approximately E-W to ESE-WNW occur within ECV amphibolite in the northeast portion of subarea 1. This is consistent with a strong fabric in a nearby quartz blow, but not in the surrounding amphibolites.

Easter Egg Region

The distribution of overprinting fabrics has been significantly affected by the irregularity of the intrusive bodies and the large proportion of mafic bodies. Isan deformation was localized within narrow (less than 5 metre wide) zones at intrusive margins and host-rock contacts. Folding was observed at only one locality within the Main Phase granite (Figure 5.20b), with quartz localized within the hinge zone of the fold. One to two metres wide zones of net-veined dolerite and aplite near the margins of the large competent dolerite bodies were also folded at outcrop scale (Figure 5.20c). The outcrop pattern within the Easter Egg region may be a result of intrusion, or alternatively could have resulted from folding during later deformation/s, which is partly illustrated by the apparent large scale folding in the aplite and porphyritic granite dykes (Figure 5.3). However, no overprinting fabrics and only high-temperature recrystallization of quartz phenocrysts were identified within these dykes.

Northeast trending intensification of fabrics and localized overprinting fabrics were observed in granite outcrop. These appeared to be developed at the ends of (or in between) dolerite bodies (subareas 3 and 4). At microscopic scale, biotite was aligned in an oblique orientation with respect to the pervasive fabric. Discrete micro-shear zones of fine-grained recrystallization cut across the high temperature fabric that indicates low to medium temperature deformation (Figure 5.22a-c; Passchier & Trouw 1998). Fabrics within the rapakivi hybrid sheets in subarea 5 and in the central Easter Egg region have north- to northwest-trending solid-state fabrics of variable shallow to steep dip. The overprinting fabrics preferentially deformed the granite sheets because of a similarity in orientation of the two structures. The extent of this solid-state fabric is limited, and the intensity and presence of the deformation is variable over a distance of less than five metres.

Local veining and alteration occurs in the granite and country rocks. Epidote and hematite (± calcite and quartz) alteration and veining was associated with localized shearing and mylonite development (Figure 5.20d). This low-temperature, high-strain mylonitization occurred within metre-wide north to northeasterly oriented zones in the Easter Egg region. At a microscopic scale, tight folds occur in the groundmass around K-feldspar megacrysts (Figure 5.22d-f). The K-feldspar megacrysts show little recrystallization, however there is a sharp boundary between old feldspars cores that have undulose extinction and thin mantles of fine-grained feldspar. This is indicative of low to medium grade conditions (400-500°C; Passchier & Trouw 1998).

Northeast-striking faults show sinistral movement where they crosscut and offset other structures. Discrete zones of shear bands of less than a metre wide also show sinistral sense of shear.

Kitty Plain Region

Within the Kitty plain region the magmatic fabric within the microgranite has been clearly overprinted by a solid state fabric. Internal parts of the mingled and mixed microgranite sheets and dolerite show granitic banding, and schlieren that was displaced by and overprinting fabric (Figure 5.20e). A northwest-striking foliation (Figure 5.5-6), crenulated and folded (Figure 5.20f) a strong magmatic fabric that is defined by aligned feldspars in the microgranite. This occurs only locally, where the magmatic fabric is at an oblique orientation (i.e. EW) to the NW-oriented overprinting fabric.

Pegmatites crosscut all igneous intrusive contacts (and their internal fabrics; Figure 5.6). The dolerite contains quartz-talc-chlorite-tourmaline alteration proximal to the pegmatites. The pegmatites generally strike northwest and have a pervasive northwest striking cleavage that is associated with the pegmatitic alteration selvage, and also contains an overprinting north-northwest trending crenulation cleavage. Other metamorphic and metasomatic rocks occur within the Kitty plains region. These include albitites, quartz-muscovite schists, quartz-chlorite schists, quartz-cordierite schists, phlogopite-chlorite schists and metasomatised amphibolites. All of the schists have a pervasive foliation and a variably developed overprinting crenulation. In the detailed mapped area (Figure 5.6), the quartz-muscovite and quartz-chlorite schists have a NW orientation (Figure 5.20g). These schists have developed crenulations and curved crenulations that indicates at least two stages of fabric development after the formation of the strong foliation (Figure 5.23). The alteration may have localized overprinting deformation that is otherwise not seen at outcrop-scale, but is observed as incipient deformation in the solid state at microscopic scale throughout the plutons.

5.5 DISCUSSION

Understanding the thermal and structural evolution of the Mount Isa Inlier has been the focus of numerous studies. Emplacement of the Sybella Batholith and other large granitic bodies during extensional episodes in the Mount Isa Inlier was proposed by Wyborn *et al.* (1988) in order to account for the apparent anorogenic nature of these intrusions. Although faults and shear zones related to early extension have been proposed throughout much of the inlier, none have been documented near the Sybella Batholith. However, extensional structures may have been obscured by compressional deformation (Connors & Page 1995). Emplacement of large granitic sills during active extension has been presented in the literature. Hutton *et al.* (1990) proposed the intrusion of rapakivi granites as large sheets along ductile extensional shear zones. The

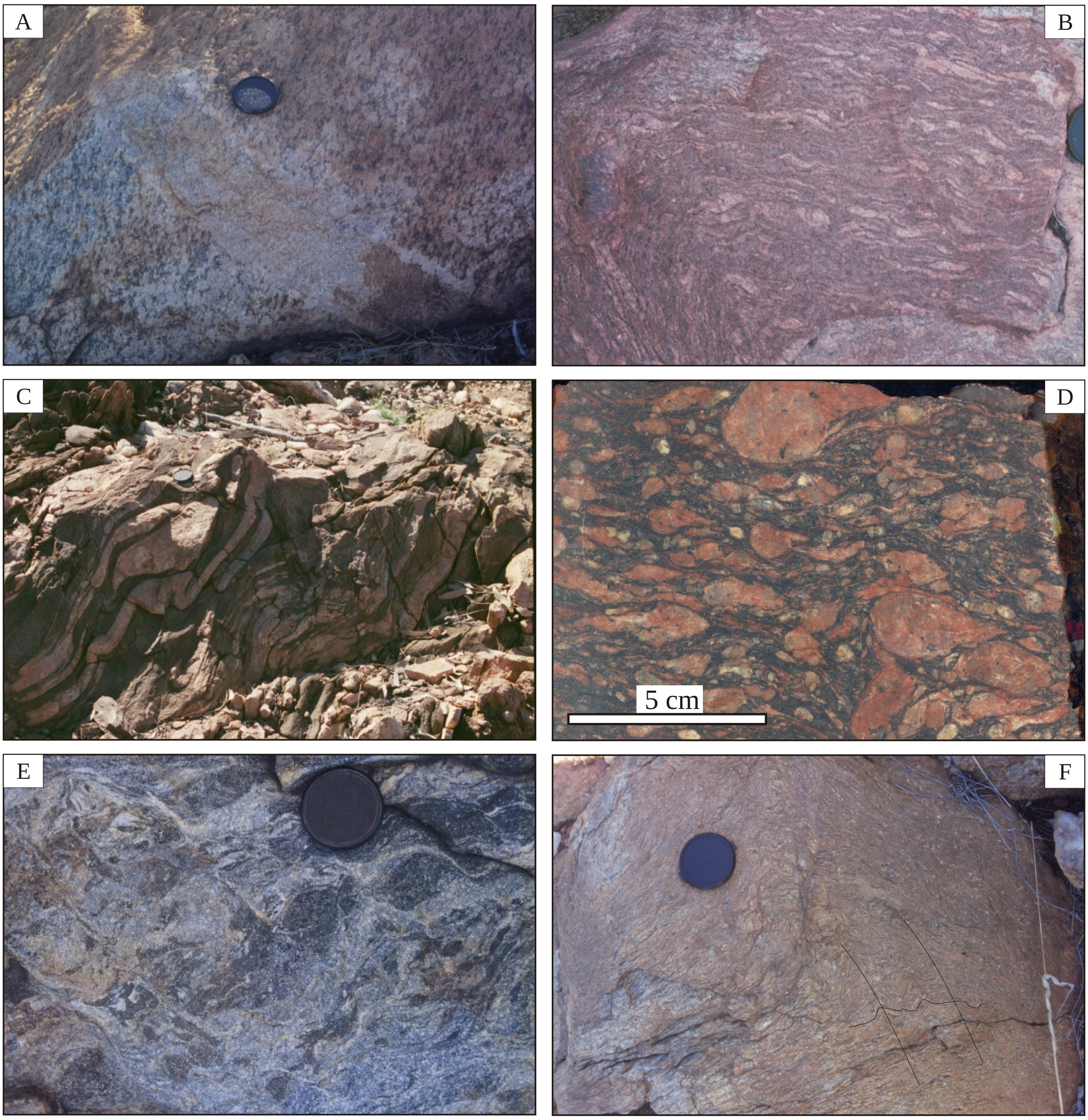


Figure 5.20 Late stage deformation features (A) Main Phase granite in Guns Knob region with overprinting fabric oblique to internal compositional contacts (vertical view); (B) Folding of Main Phase granite high temperature foliation within Easter Egg region with quartz localised in fold hinges (vertical view); (C) Two possible stages of folding of net-veining aplite intrusions in dolerite, refolded fold with schlieren in aplite wrapped around fold hinges (vertical view); (D) Epidote-hematite alteration associated with mylonite development in localised high strain zones within Main Phase granite (sample 318 horizontal view); (E) Late shears cutting across magmatic fabrics within the microgranite and schlieren at Kitty Plains (horizontal view); (F) Folding of microgranite (vertical view); (G) Microgranite altered to quartz-muscovite schist with strong foliation and overprinting folding (vertical view). Lens cap 50 mm.

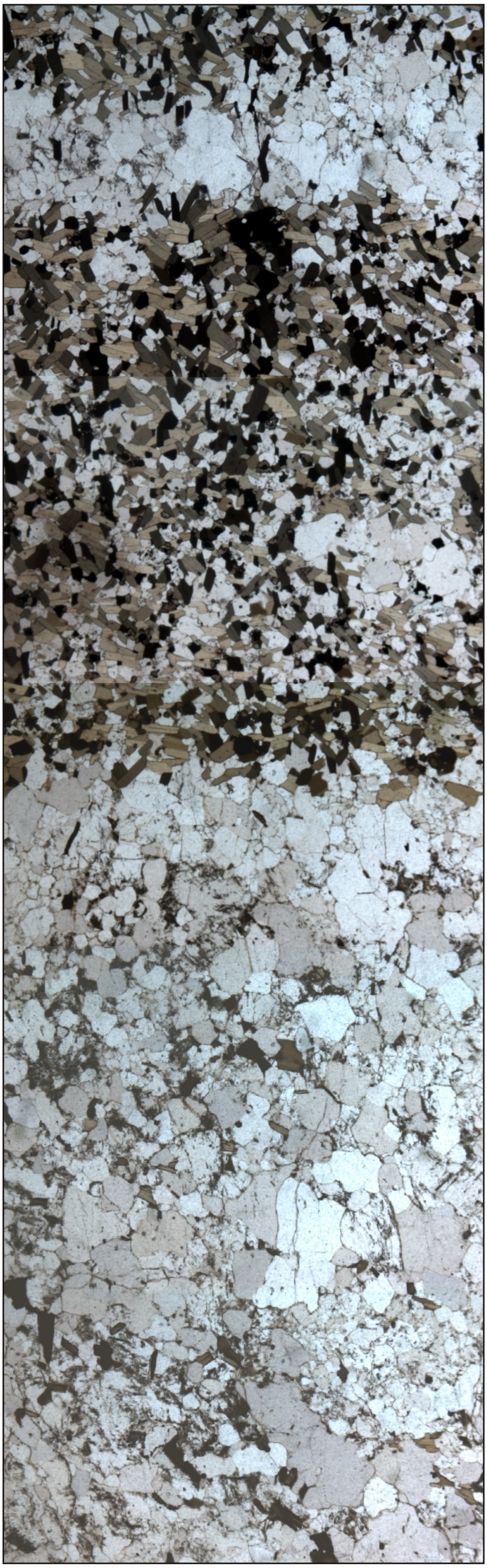


Figure 5.21 Overprinting deformation (Isan Orogeny) within Gun's Knob region. Illustrates the contact of a mafic enclave across the image (with aligned K-feldspars in hand sample) with an overprinting fabric, vertical on image. Biotite is aligned in this orientation and quartz is recrystallized with long axis parallel. Sample 195. PPL. Width of view 4.6 mm.

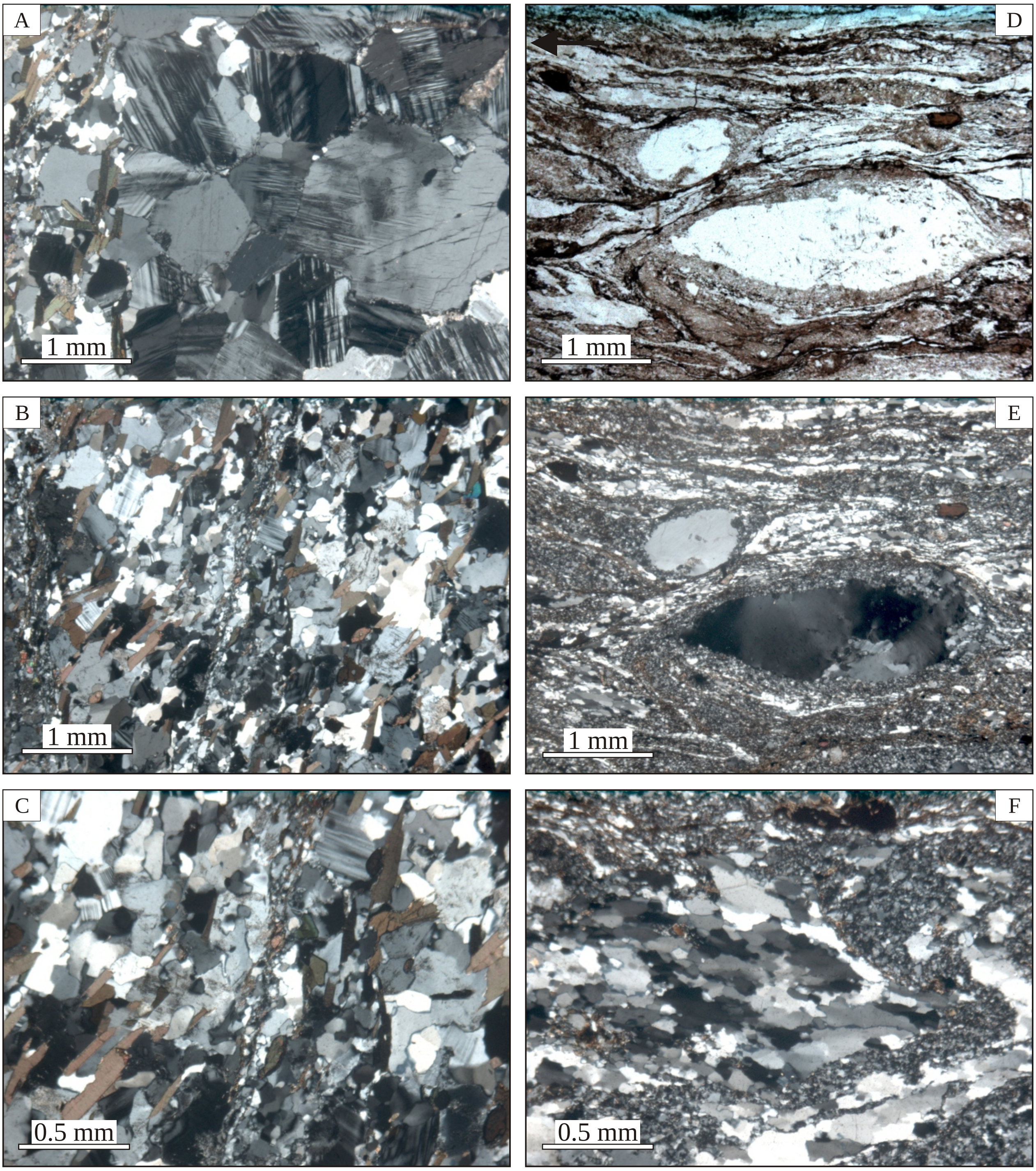


Figure 5.22 Easter Egg Region overprinting deformation (Isan Orogeny)

(A) Fine-grained zones of recrystallization cut across the recrystallized K-feldspar ribbon (sample 307) XPL

(B)-(C) Fine-grained zones of recrystallization cutting across the pervasive foliation (sample 307) XPL

(D)-(E) Fine-grained recrystallization of groundmass and edges pf phenocrysts in low-temperature/ high-strain zones (sample 318) PPL and XPL

(F) Folded mylonitic rock with coarser elongated quartz with subgrains parallel to the axial plane (sample 318) XPL.

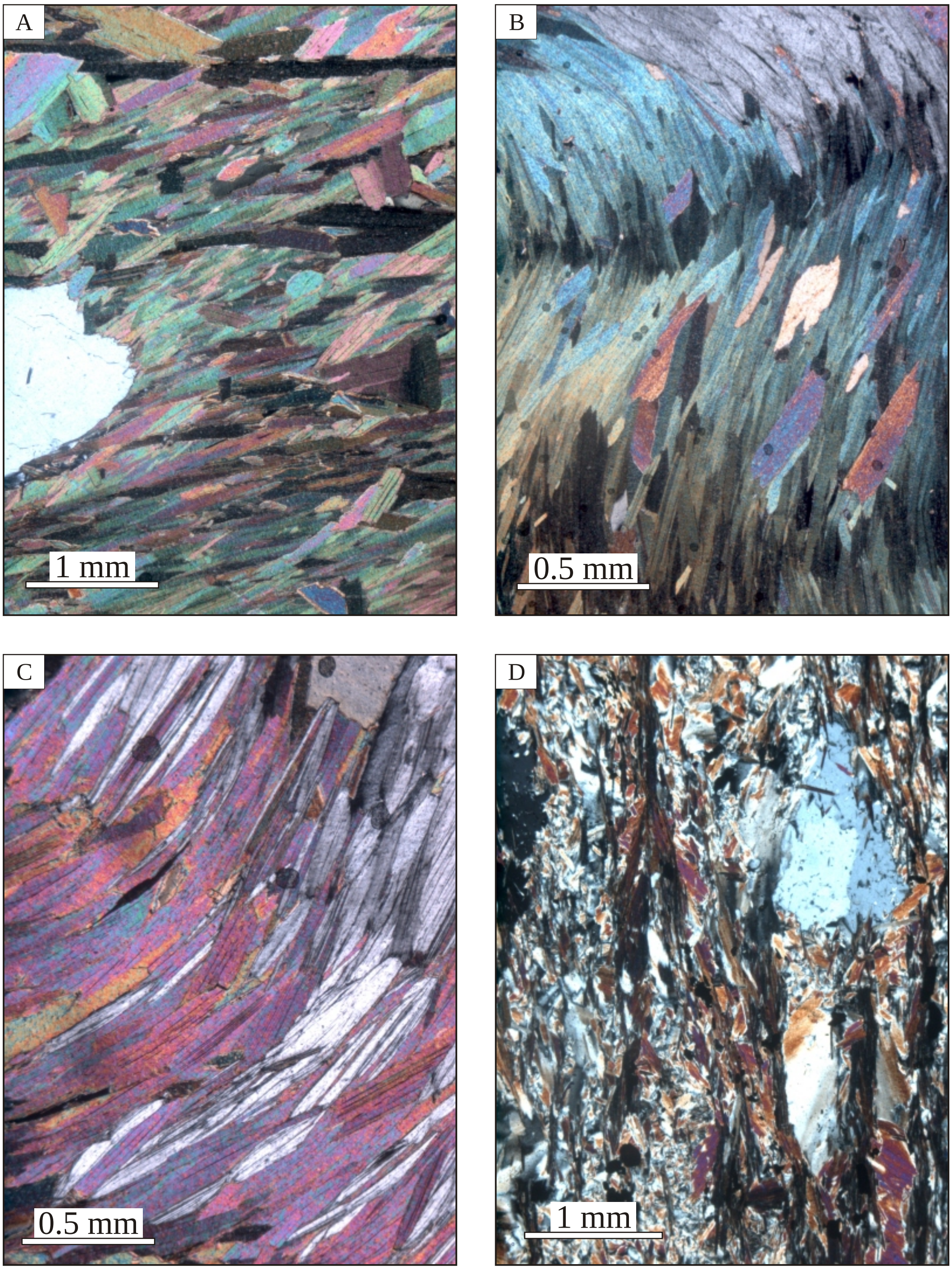


Figure 5.23 Kitty Plains overprinting deformation. Isan Orogeny.
(A) Phlogopite-chlorite schist with strong fabric and crenulation cleavage developed. Phenocrysts of plagioclase occur within the matrix. The precursor to this schist is interpreted to be dolerite. Sample 54/1 from Coleborn 1999. (B) Phlogopite-chlorite schist with crenulation cleavage. Sample 54/1 from Coleborn 1999. (C) Crenulation cleavage with intergrown phlogopite and plagioclase. Sample 54/1 from Coleborn 1999. (D) Quartz-chlorite schist. Sample 51/2 from Coleborn 1999.

structural relationships described in the previous sections show that the northeastern Sybella Batholith was deformed during the transition from magmatic to submagmatic to high-temperature solid-state conditions. Deformation during this continuum was synchronous with, or after the deformation that is preserved within the May Downs Gneiss and Eastern Creek Volcanics.

The Sybella Batholith has been historically interpreted as being emplaced syntectonically during Isan Orogenic deformation, with the pervasive amphibolite facies fabrics forming at this time (Page & Bell 1986; Wilson 1975). Since then dating has identified a large time gap between emplacement (1670 Ma) and the known periods of deformation during the Isan Orogeny (1590 Ma). This has led to the characterization of the fabric within the Main Phase granites as being related to the Isan Orogeny and not to syntectonic emplacement deformation as previously thought (Wyborn *et al.* 1988; Connors *et al.* 1992). Indication of deformation within the May Downs Gneiss and Eastern Creek Volcanics (deposition age of 1760 Ma) prior to the granite emplacement was found within this study and historically by Wilson (1975). This points to a period of deformation that occurred synchronous with extensional rifting within the western part of the Isa rift basin prior to granite emplacement, which possibly continued during emplacement.

In view of the new evidence for early deformation and a revised structural interpretation of the areas adjacent to the Sybella Batholith, a review of the metamorphic evidence that is attributed to the Isan Orogeny was necessary, although a thorough revision was outside the scope of this study (Table 5-1). The dominant layer parallel cleavage within the May Downs Gneiss is generally interpreted as S_2, however this study has indicated that it may in part be a composite fabric due to the reactivation of S_B by D_S or D_2. Evidence for a thermal event earlier than the Isan Orogeny may have been mis-identified as "early D_2" compared to the "late D_2" metamorphism. Early cordierite porphyroblasts that grew pre- or syn-D_2 (Connors *et al.* 1992; Rubenach 1992) may possibly be attributed to $D_{B/S}$. Partial melt in the amphibolites and the early partial melt phase within the May Downs Gneiss that are folded, are also interpreted to have formed at this time ($D_{B/S}$). Partial melt segregations in the Queen Elizabeth Pluton that contain subparallel D_2 and folding (Connors *et al.* 1992), may be representative of the second thermal peak during the Isan Orogeny. The second phase of partial melting or pegmatite intrusion in the May Downs Gneiss (melts axial planar to D_2 folds) is also thought to be Isan Orogeny.

The history of the Isan Orogenic deformation in the Western Fold Belt is complicated by the underlying basin architecture. The main phase of the Isan deformation in the Western Fold Belt was almost entirely thick-skinned, as shortening across the area inverted many of the original basement faults which produced steep, basement-cutting thrusts (Lister *et al*. 1999, O'Dea & Lister 1995; Betts *et al.* 1998). Shortening against large-scale steep faults, created a buttressing effect where deformation was localized within the hanging-wall of one of the faults, whilst the foot-wall block remained rigid. Movement of the bounding faults also permitted deformation within one block to be independent of deformation in the surrounding rocks (Lister *et al*. 1999, O'Dea & Lister 1995). Buttressing against basin faults may also be responsible, at least in part, for the poly-phased nature of the larger-scale deformation regime.

The Isan Orogeny in the Western Fold Belt began with north-south shortening, that locally produced east-west trending folds but no pervasive cleavage (O'Dea & Lister 1999). This deformation is similar in style to the early north-south shortening events identified in the Kalkadoon-Leichhardt Belt and Eastern Fold Belt, which suggests there was an early north-south shortening event that was pervasive across the Mount Isa Inlier. Within the Western Fold Belt an early, bedding-parallel foliation has been correlated with the early, bedding-parallel foliation in the Eastern Fold Belt (O'Dea *et al.* 1997). However, evidence from this study suggests that the early bedding-parallel foliation is not a product of the Isan Orogeny, but is a product of extensional tectonics that was associated with the development of the Isa Superbasin.

East-west shortening during D_2 began with the development of a strong regional fabric that was associated with peak metamorphism in the area (Rubenach 1992; Connors & Lister 1995; Connors & Page 1995). This period of shortening involved poly-phased deformation on a series of steep, west-verging thrusts that produced multiple generations of fabrics and structures within one broad event (Connors & Lister 1995; Connors & Page 1995; O'Dea *et al.* 1997; MacCready *et al.* 1998). Whether the Isan

Orogeny was continuous or episodic in nature is still being debated. A syntectonic pegmatite dyke that intruded prior to or during D_2 has U-Pb zircon analysis with a bimodal age distribution of 1565 ± 5 and 1532 ± 7 Ma (Connors & Page 1995). In the Hazeldene region west of Mount Isa, cordierite-orthoamphibole gneiss contains monazite that is aligned parallel to the regional peak metamorphic (c. 600°C) foliation (D_2), and dated at around 1575 Ma (Hand & Rubatto 2002). A post-tectonic generation of pegmatite has a U-Pb age (Zircon) of 1480 ± 14 Ma, which provided a minimum age for the Isan Deformation in the Western Fold Belt (Connors & Page 1995). The minimum age of deformation can be further constrained to 1500 Ma, assuming that deformation in the Western Fold Belt ceased at the same time as in the Eastern Fold Belt (Wyborn *et al.* 1988; O'Dea *et al.* 1997; Page & Sun 1998). However, correlation over such a large distance and across three belts of vastly different structural character, is unreliable.

5.5.1 Macroscopic Relationships

The May Downs Fault defines the contact between the western margin of the Sybella Batholith, and the McNamara Group (Mount Isa Group equivalents; Connors & Page 1995). The northern and eastern margins of the batholith are in contact with the Haslingden group, are the granite is largely subparallel or parallel to the stratigraphy. The Main Phase Queen Elizabeth pluton formed as an extensive folded sill (Connors & Page 1995), and contains gravity and magnetic data that suggests that the pluton is shallow bottomed and does not extend at depth. In contrast, the microgranite phase is interpreted to form a steep-sided plug that is based on gravity and magnetic data (D. Leaman pers comm, 1992 in Connors & Page 1995).

Deformation and metamorphism in the May Downs Gneiss and Eastern Creek Volcanics occurred prior to, and was possibly continuous with the emplacement of the intrusive units of the Sybella Batholith. This deformation may have been associated with extensional tectonics during basin development, and was previously unrecognized. Magmatic to submagmatic fabrics that are parallel to internal and external contacts developed during emplacement of the Sybella Batholith.

The northeastern portion of the Sybella Batholith has a high volume of undeformed mafic intrusives that are thought to have affected the extent and nature of the fabrics that formed in this region during the Isan Orogeny. The granites within all regions have steeply-dipping to subvertical fabrics of variable orientation that commonly formed sheeted bodies within both the country rocks and dolerite complex. The lack of a pervasive schistosity or other (Isan Orogeny-related) fabric within this portion of the batholith overprinting the early high-temperature magmatic to solid-state transitional fabric (other than biotite), indicated that it was not significantly modified after the syn- to post-emplacement fabrics developed. However, large-scale, north-south open folds within both the Guns Knob and Kitty Plains regions are interpreted to be the effect of east-west compression during the regional Isan Orogeny deformation.

Reconstruction of the original shape and orientation of the plutons in the northern areas is based on the interpretation of original fabrics. Most of the steep dipping (generally >80°) fabrics were either flat lying fabrics that were steepened by deformation and large-scale folding, or they were originally emplacement related steep dipping fabrics that underwent little modification during later deformation.

In regions to the south, including the Queen Elizabeth Pluton, geophysical models that are based on the Mount Isa Deep Seismic Transect have led to the Main Phase of the Sybella Batholith being interpreted as thin, 2-3 km thick sheets (Drummond *et al.* 1998; MacCready *et al.* 1998). It has been demonstrated by previous workers (Connors *et al.* 1992; Connors & Page 1995) that these thin sheets of Main Phase granite had experienced west-over-east thrusting and folding during D_2 metamorphism and deformation. Isan Orogeny D_2 and related fabrics may have developed within the southern domains in preference to the northern Sybella Batholith because of the paucity of mafic intrusives and the inferred thinness of the granite sheets.

During peak metamorphism and deformation (D_2), the interbedded metasediments and metavolcanics accommodated more strain than the thick layers of granite due to the greater competency of the granite (Connors & Lister 1995). Partial melting occurred in the country rocks and at the northern margin of the Queen Elizabeth Pluton (Connors *et al.* 1992), was accompanied by localized reactivation of intrusion-related fabrics in the

Main Phase granite. Large-scale north-south trending folds that lack an axial planar cleavage within the Queen Elizabeth pluton (F_{3b} or F_4 folds; Connors & Lister 1995) may be the equivalent of the large scale folds in Guns Knob region.

5.6 SUMMARY

- Deformation in the Eastern Creek Volcanics and May Downs Gneiss occurred prior to the emplacement of Sybella Batholith.
- The Mafic Hybrid Complex and Mosses Tank Dolerite are predominantly unfoliated and undeformed, with magmatic textures.
- The granites within all regions commonly formed sheeted bodies within both the country rocks and dolerite complex.
- Emplacement of the Main Phase granite was accompanied by deformation (Sybella Event) that formed a strong subvertical, variably orientated, transitional magmatic to high-temperature solid-state foliation, which continued during progressive crystallization of the granite, and deformation within the country rocks.
- Magmatic shear zones within the Microgranite phase of the Sybella Batholith indicate the deformation that accompanied the emplacement of the granite dated at 1673 Ma.
- The lack of a pervasive schistosity or other (Isan Orogeny-related) fabric within the northeastern portion of the batholith overprinting the early high-temperature magmatic to solid-state transitional fabric (other than biotite), indicated that it was not significantly modified after the syn- to post-emplacement fabrics developed.
- Incipient solid-state deformation is ubiquitous throughout the plutons although a pervasive cleavage commonly wasn't identified.
- Regional Isan Orogeny deformation (1570-1500 Ma) in the northeastern Sybella Batholith was heterogeneous due to the distribution of undeformed dolerites and large bodies of granite, which caused strain shadows around the competent intrusive bodies to develop.

- Isan Orogeny D_2 may have had a greater effect with increased folding and deformation related fabrics may have developed within the southern domains in preference to the northern Sybella Batholith because of the paucity of mafic intrusives and the inferred thinness (2-3 km thick), of the granite sheets.
- Reactivation of early fabrics during a high-temperature, low-pressure regional metamorphic/deformation event (of similar orientation) produced intensification of some fabrics and andalusite/sillimanite porphyroblast growth (Rubenach 1992).
- Large-scale north-south open folding seen in both the Guns Knob and Kitty Plains regions may be interpreted to be either the effect of syn-Sybella Batholith emplacement and pluton expansion or east-west compression during the regional Isan Orogeny deformation.
- The interbedded metasediments and metavolcanics accommodated more strain during D_2 than the thick layers of granite, due to the greater competency of the granite compared to the interlayered country rocks.
- Northeast and northwest overprinting fabrics (Isan Orogeny) were unable to be correlated across different domains and rock types. The fabrics were accompanied by, or preceded alteration within the granites.

CHAPTER 6

SYNTHESIS: GRANITE GENESIS, EVOLUTION AND EMPLACEMENT

6.1 INTRODUCTION

The previous chapters have described the different facets and nature of the Sybella Batholith. This section is aimed at utilizing the available information and interpretations to present a model for development of the Sybella Batholith and what it means for the part of the Western Fold Belt into which it was emplaced. The intrusion of the granites and associated mafic rocks were emplaced contemporaneous with extensional tectonics.

6.2 MELT SOURCE AND GENERATION

The batholith was emplaced at a time when there was significant episodic rifting and development of the Isa superbasin. It was suggested by Page (1988) that there was a high geothermal gradient at ~ 1670 Ma over large areas of northern Australia. A deep seismic transect across the Mount Isa Inlier identified a high velocity body that occurs in the middle crust of intermediate to mafic composition (Drummond *et al.* 1998). It has been interpreted as a major crustal boundary that dips to the west (Drummond *et al.* 1998). Several models for the origin of the high velocity layers were presented by MacCready *et al.* (1998) with the preferred model being that the high velocity rocks originated as mafic underplate related to the pre-Isan Orogenic rift history where high heat-flow resulted from thinning of the crust accompanied by mantle upwelling and magmatic underplating. During orogenic shortening, the mafic underplates were under-thrust by continental crust to be emplaced at mid-crustal levels.

Production of large volumes of granitic magma in the continental crust is commonly attributed to intrusions of basalt that trigger partial melting in the lower to middle crust (e.g. Huppert & Sparks 1988). In the Sybella Batholith, gabbroic to dioritic rocks of the Mafic Hybrid Complex and Mosses Tank Dolerite represent a significant component, pointing to mantle involvement in magma genesis. However, the mafic melts are subalkaline tholeiitic, and show iron enrichment and depletion in MgO. This is explained by the removal of pyroxene from the original magma at depth and hence at least a two-stage evolution for the mafic melts. This is supported by the presence of inherited zircons in the Eastern Creek Volcanics, which have variable ages that group in the periods of 2100-1800 Ma and 2700-2500 Ma. These zircons represent relics of magmatic source and/or xenocrysts collected during passage through older underlying crust. This indicates evidence of involvement of Archean crust during the Proterozoic magmatism prior to the Sybella Batholith (Page 1988). Sm-Nd ages of the granites also indicate that initial mantle fractionation took place in lower crustal material on average 2300-2100 Ma ago.

The Sybella Batholith is part of a series of rapakivi-type felsic batholiths that intruded the Mount Isa, Tennant Creek and Granites-Tanami Inliers at approximately 1670 Ma (Page 1988). These intrusives have A-type geochemical affinities with high Zr, Nb, Y, Ti and high K, U, Th. The potassic incompatible and radiogenic element rich character of the Sybella Batholith suggested that the source material was fertile in these elements, and that these intrusions were likely to be the initial melt products of a previously unmelted source. The most suitable source materials are calc-alkaline rocks (Section 4.5) and this implies significant volumes of calc-alkaline source rocks at depth. The high magmatic temperatures (860-930 °C), low water contents and geochemistry of the magmas are consistent with dehydration melting of calcalkaline granitoids at shallow crustal levels (<8-10 kbars) giving rise to A-type granitic melts. Attaining the high melting temperature so close to the earth's surface requires the addition of hot mafic magmas to the crust. The shallow origin of A-type granites is in turn a consequence of their formation in an extensional or noncompressive tectonic setting, where the crust tends to thin (Patino Douce 1997).

6.3 MAGMATIC EVOLUTION

The occurrence of contemporaneous mafic and felsic magmas within the Sybella Batholith is a common feature in other 'A-type' rapakivi granites, and in this region contributed to the interaction between the magmas. The role of fractionation and mixing of magmas varied in their importance between the mafic and felsic units of the Sybella Batholith.

As mentioned above, crystal fractionation occurred within the mafic magmas as they exhibit strong iron enrichment and MgO depletion, related to the removal of early-formed pyroxene from the original magma at depth. In addition to fractionation, the Mafic Hybrid Complex magmas interacted with felsic magma to some extent prior to emplacement within the complex. The Mafic Hybrid Complex intruded into the May Downs Gneiss and Eastern Creek Volcanics in variably hybridized batches and there is a lack of mafic rocks of uncontaminated composition. Hybridization was possible between dry, silicic, high temperature magmas and mafic magmas in the upper crust as the magma's viscosities are similar (Frost & Mahood 1987).

Emplacement of relatively homogenous intermediate rapakivi granitoid hybrids into the mafic hybrids was widespread although the hybrids are volumetrically minor components of the batholith. This indicates that hybridization occurred at depth prior to emplacement. The intrusion of the rapakivi granitoids into the still molten Mafic Hybrid complex led to further interaction (mingling and mixing) at emplacement level.

The Main Phase granite intruded into the Mafic Hybrid Complex, and the granite contains mafic and hybrid enclaves (molten) and xenoliths (solid). The extent of fractional crystallization in the felsic rocks appears limited however porphyritic granite and aplite intruded the complex. The limited development of pegmatite of similar age suggests that conditions remained largely anhydrous throughout crystallization of this suite. Field and petrographic characteristics generally indicate that Main Phase granites within the Sybella Batholith were emplaced as a phenocryst-rich magma. The granite magmas are thought to result from crystallization of initially almost crystal free magmas, as indicated by lack of restite and high melting temperatures. The Main Phase granite magmas were emplaced with no or limited fractionation during ascent.

In the northern region of Kitty Plains, the microgranite intruded into a complex dolerite body (Mosses Tank Dolerites) and local hybridization and brecciation occurred along the granite contacts. The lower temperature determined for the microgranite probably inhibited the production of homogenous hybrids.

6.4 PLUTON EMPLACEMENT

The Sybella Batholith was emplaced at middle to upper crustal levels into the deformed units of the Lower Haslingden group (Eastern Creek Volcanics and May Downs Gneiss). The intrusion of granite into high-temperature, low-pressure conditions is entirely consistent with the high temperature, dry nature of the rapakivi granites. The episodic nature of the emplacement of various phases of the batholith – batches of variously hybridized mafic magmas, small sheet-like intrusions of rapakivi granitoid hybrid magmas within the mafic magmas, the sheeted margin of the Main Phase and microgranite intrusions that coalesced into large uniform bodies of magma – indicates different intrusive styles.

Mechanisms of ascent and emplacement of plutons such as stoping, diapirism, dyking, accommodation in faults and shear zones, and in situ ballooning are commonly cited. Pluton emplacement mechanisms have traditionally been divided into two basic types: forcible emplacement (including doming, diapirism and ballooning); and permitted emplacement (involving stoping, cauldron subsidence and sheeting). These two categories are end-member processes and a combination of mechanisms is likely to have contributed to the final emplacement (Paterson & Vernon 1995). Recently authors have proposed models of pluton emplacement that rely on local or regional extension (Hutton *et al.* 1990; Pearson *et al.* 1992; Paterson & Fowler 1993; Walker *et al.* 1995; Hogan *et al.* 1998).

Extensional environment described by Wyborn *et al.* (1988) and the anorogenic nature (described by Lister *et al.* 1986) of the region the Sybella Batholith intruded into, does not at first seem to correlate, however Hutton *et al.* (1990) proposed an emplacement mechanism of intrusion of rapakivi granites as large sheets along ductile extensional shear zones. Plutons associated with extensional deformation are generally very thin (2-3 km thick) with local, deep root-zones with vertical lineations that indicate magma feeder zones, and sub horizontal foliation planes (Vigneresse 1995). Geophysics of the Sybella Batholith indicated that the southern extent of the Main Phase granite regions was originally a thin, flat-lying sheet that was folded by later deformation during the Isan Orogeny. However, the granites in the northeastern portion of the Sybella Batholith have steeply dipping to subvertical fabrics of variable orientation developed and commonly have sheeted contacts with both the country rocks and mafic complex. The original orientation and nature of the intrusion is strongly affected by the presence of large bodies of mafic magmas. Granites intruded along vertical contacts between the mafic complex and country rocks, and as sheets with the mafic complex itself, rather than as large thin flat lying sheets. Once the ambient temperatures were elevated above the solidus, further intrusion of felsic magma no longer formed a sheeted margin and the sheets coalesced (Yoshinobu *et al.* 1998). Discordant and irregular pluton margins and large rafts and xenoliths near the margins of the plutons are indicative of some stoping of the country rocks.

Emplacement of the Sybella Batholith was accompanied by deformation forming a strong, transitional magmatic to high-temperature solid-state fabric that continued during progressive crystallization. The identification of magmatic shear zones within the Kitty Plains Microgranite also indicated that granites were emplaced into a tectonically active region.

6.5 POST EMPLACEMENT EVENTS

The nature of the regional deformation Isan Orogeny (1570-1500 Ma) is heterogeneous due to the distribution of undeformed dolerites and large bodies of granite and strain shadows around these competent intrusive bodies. The magmatic to high-temperature solid-state transitional fabric indicated that a large portion of the Batholith was not significantly modified after the Sybella Event emplacement fabrics. Insipient deformation in the solid-state with low strain is ubiquitous throughout the plutons, although a pervasive cleavage wasn't identified. Large-scale north-south open folding seen in both the Guns Knob and Kitty Plains regions is interpreted to be the effect of east-west compression during the regional Isan Orogeny deformation. The Main Phase granite in the southern regions has been interpreted as being thin (2-3 km thick) sheets that experienced west-over-east thrusting and folding during D_2 metamorphism and deformation. The paucity of mafic intrusives within the southern domains and the inferred thinness of the granite sheets may have contributed towards the greater effect of D_2 with increased folding and deformation within these areas. The interbedded metasediments and metavolcanics within the Haslingden Group accommodated more strain during D_2 than the thick layers of granite due to the greater competency of the granite compared to the interlayered country rocks. Reactivation of early fabrics during a high-temperature regional metamorphic/deformation event (of similar orientation) produced intensification of some fabrics. Northeast and northwest overprinting Isan Orogeny fabrics in the Sybella Batholith were unable to be correlated across different domains and rock types. This late deformation was accompanied, or preceded by alteration within the granites.

REFERENCES

Abdel-Rahman A.-F. M. & El-Kibbi M. M. 2001. Anorogenic magmatism: chemical evolution of the Mount El-Sibai A-type complex (Egypt), and implications for the origin of within plate felsic magmas. *Geological Magazine* **138**, 67-85.

Allegre C. J., Treuil M., Minster J. F., Minster B. & Albarede F. 1977. Systematic use of trace elements in igneous processes. Part I: Fractional crystallization processes in volcanic suites. *Contributions to Mineralogy and Petrology* **60**, 57-75.

Anderson J. L. & Bender E. E. 1989. Nature and origin of Proterozoic A-type granitic magmatism in the southwestern United States of America. *Lithos* **23**, 19-52.

Anderson J. L. & Smith D. R. 1995. The effects of temperature and fO2 on the Al-in-hornblende barometer. *American Mineralogist* **80**, 549-559.

Andersson U. B. & Eklund O. 1994. Cellular plagioclase intergrowths as a result of crystal-magma mixing in the Proterozoic Aland rapakivi batholith, SW Finland. *Contributions to Mineralogy and Petrology* **119**, 124-136.

Arzi A. A. 1978. Critical phenomena in the rheology of partially melted rocks. *Tectonophysics* **44**, 173-184.

Bacon R. C. 1986. Magmatic inclusions in silicic and intermediate volcanic rocks. *Journal of Geophysical Research* **91**, 6091-6112.

Bell T. H. 1983. Thrusting and duplex formation in Mount Isa, Queensland, Australia. *Nature* **304**, 493-497.

Bell T. H. 1991. The role of thrusting in the structural development of the Mount Isa Mine and its relevance to exploration in the surrounding region. *Economic Geology* **86**, 1602-1625.

Bell T. H. & Hickey K. A. 1998. Multiple deformations with successive subvertical and subhorizontal axial planes in the Mount Isa region: their impact on geometric development and significance for mineralization and exploration. *Economic Geology* **93**, 1369-1389.

Betts P. G., Lister G. S. & O'Dea M. G. 1998. Asymmetric extension of the Middle Proterozoic lithosphere, Mount Isa terrane, Queensland, Australia. *Tectonophysics* **296**, 293-316.

Blake D. H. 1981. Intrusive felsic-mafic net-veined complexes in north Queensland. *BMR Journal of Australian Geology and Geophysics* **6**, 95-99.

Blake D. H. 1987. Geology of the Mount Isa Inlier and environs. Queensland and Northern Territory. *BMR Geology and Geophysics, Australia Bulletin* **225**, 85pp.

Blake D. H., Bultitude R. J., Donchak P. J. T., Wyborn L. A. I. & Hone I. G. 1984. Geology of the Duchess-Urandangi region, Mount Isa Inlier, Queensland, Australia. *Bureau of Mineral Resources, Bulletin* **219**, 96.

Blake D. H. & Stewart A. J. 1992a. The BMR 1983-1990 Mount Isa Project: result, some remaining problems and bibliography. *In*: Stewart A. J. & Blake D. H. eds. *Detailed Studies of the Mount Isa Inlier* Australian Government Publishing Service, Canberra. **Bulletin 243** pp.

Blake D. H. & Stewart A. J. 1992b. Stratigraphic and tectonic framework, Mount Isa Inlier. *In*: Stewart A. J. & Blake D. H. eds. *Detailed Studies of the Mount Isa Inlier* Australian Government Publishing Service, Canberra. **Bulletin 243** pp. 1-.

Blenkinsop T. G. 2000. *Deformation microstructures and mechanisms in minerals and rocks*. Kluwer Academic Publishers, Dordrecht. pp. 150.

Bouchez J. L., Delas C., Gleizes G., Nedlec A. & Cuney M. 1992. Submagmatic microfractures in granites. *Geology* **20**, 35-38.

Brown M. 1994. The generation, segregation, ascent and emplacement of granite magma: the migmatite-to-crustally-derived granite connection in thickened orogens. *Earth-Science Reviews* **36**, 83-130.

Bussell M. A. 1991. Enclaves in the Mesozoic and Cenozoic granitoids of the Peruvian coastal Batholith. *In*: Didier J. & Barbarin B. eds. *Enclaves and granite petrology* pp. 155-. Developments in Petrology **13**.

Bussy F. 1990. The rapakivi texture of feldspars in a plutonic mixing environment: a dissolution-recrystallisation process? *Geological Journal* **25**, 319-324.

Castro A., Moreno-Ventas I. & De La Rosa J. D. 1990. Microgranular enclaves as indicators of hybridization processes in granitoid rocks, Hercynian Belt, Spain. *Geological Journal* **24**, 391-404.

Chappell B. W., White A. J. R. & Wyborn D. 1987. The importance of residual source material (restite) in granite petrogenesis. *Journal of Petrology* **28**, 1111-1138.

Cherry M. E. & Trembath L. T. 1978. The Pressure Quench Formation of Rapakivi Texture. *Contributions to Mineralogy and Petrology* **68**, 1-6.

Coleborn D. 1999. Geophysical analysis of the Sybella Batholith, Mount Isa Inlier, NW Queensland. Honours thesis, James Cook University, Townsville (unpubl.).

Collins L. G. 1997. Article 24: Magmatic resorption versus subsolidus metasomatism; two different styles of K-feldspar replacement of plagioclase. *In*: eds. *Myrmekite and Metasomatic Granite* pp.

Collins W. J., Beams S. D., White A. J. R. & Chappell B. W. 1982. Nature and origin of A-Type granites with particular reference to Southeastern Australia. *Contributions to Mineralogy and Petrology* **80**, 189-200.

Connors K. A. & Lister G. S. 1995. Polyphase deformation in the western Mount Isa Inlier, Australia; episodic or continuous deformation? *Journal of Structural Geology* **17**, 305-328.

Connors K. A. & Page R. W. 1995. Relationships between magmatism, metamorphism and deformation in the western Mount Isa Inlier, Australia. *Precambrian Research* **71**, 131-153.

Connors K. A., Proffett J. M., Lister G. S., Scott R. J., Oliver N. H. S. & Young D. M. 1991. Geology of the Mount Novit Ranges 1:25,000 map sheet. *Australian Geological Survey Organization*

Connors K. A., Proffett J. M., Lister G. S., Scott R. S., Oliver N. H. S. & Young D. J. 1992. Geology of the Mount Novit Ranges, southwest of Mount Isa mine. *In*: Stewart A. J. & Blake D. H. eds. *Detailed Studies of the Mount Isa Inlier* Australian Government Publishing Service, Canberra. **Bulletin 243** pp. 137-.

Czamanske G. K. & Wones D. R. 1973. Oxidation During Magmatic Differentiation, Finnmarka Complex, Oslo Area, Norway; Part 2, The Mafic Silicates. *Journal of Petrology* **14**, 349-380.

Dall'Agnol R., Costi H. T., da S. Leite A. A., de Magalhaes M. S. & Teixeira N. P. 1999. Rapakivi granites from Brazil and adjacent areas. *Precambrian Research* **95**, 9-39.

De Paolo D. J. 1981. Trace element and isotopic effects of combined wallrock assimilation and fractional crystalization. *Earth and Planetary Science Letters* **53**, 189-202.

Dempster T. J., Jenkin G. R. T. & Rogers G. 1994. The origin of rapakivi texture. *Journal of Petrology* **35**, 963-981.

Didier J. & Barbarin B. 1991. Enclaves and Granite Petrology. **13**, pp. 625. Elsevier Science Publishers B.V.,

D'Lemos R. S. 1996. Mixing between granitic and dioritic crystal mushes, Guernsey, Channel Islands, UK. *Lithos* **38**, 233-257.

Drummond B. J., Goleby B. R., Goncharov A. G., Wyborn L. A. I., Collins C. D. N. & MacCready T. 1998. Crustal-scale structures in the Proterozoic Mount Isa Inlier of north Australia: their seismic response and influence on mineralization. *Tectonophysics* **288**, 43-56.

Ellis D. J. & Wyborn L. A. I. 1984. Petrology and geochemistry of Proterozoic dolerites from the Mount Isa Inlier. *BMR Journal of Australian Geology and Geophysics* **9**, 19-32.

Etheridge M. A., Rutland R. W. R. & Wyborn L. A. I. 1987. Orogenesis and tectonic process in the early to Middle Proterozoic of northern Australia. *In*: Kroner A. eds. *Precambrian Lithospheric Evolution* American Geophysical union Geodynamics Ser, **17** pp. 131-147.

Farquharson R. B. & Richards J. R. 1970. Whole-rock U-Th-Pb and Rb-Sr ages of the Sybella microgranite and pegmatite, Mount Isa, Queensland. *Journal of the Geological Society of Australia* **17**, 53-58.

Farquharson R. B. & Wilson C. J. L. 1971. Rationalization of geochronology and structure at Mount Isa. *Economic Geology* **66**, 574-582.

Fernandez A. N. & Gasquet D. R. 1994. Relative rheological evolution of chemically contrasted coeval magmas: example of the Tichka plutonic complex (Morocco). *Contributions to Mineralogy and Petrology* **116**, 316-326.

Frost C. D. & Frost B. R. 1997. Reduced rapakivi-type granites: the tholeiitic connection. *Geology* **25**, 647-650.

Frost C. D., Frost B. R., Chamberlain K. R. & Edwards B. R. 1999. Petrogenesis of the 1.43 Ga Sherman Batholith, SE Wyoming, USA: a Reduced Rapakivi-type Anorogenic Granite. *Journal of Petrology* **40**, 1771-1802.

Frost T. P. & Mahood G. A. 1987. Field, chemical, and physical constraints on mafic-felsic magma interaction in the Lamarack Granodiorite Sierra Nevada, California. *Geological Society of America Bulletin* **99**, 272-291.

Gapais D. & Barbarin B. 1986. Quartz fabric transition in a cooling syntectonic granite (Hermitage Massif, France). *Tectonophysics* **125**, 357-370.

Gencalioglu Kuscu G. & Floyd P. A. 2001. Mineral compositional and textural evidence for magma mingling in the Saraykent volcanics. *Lithos* **56**, 201-320.

Gunter J. 1996. The May Downs Gneiss: A palaeoproterozoic arc terrain in the basement of the Mount Isa Block, Northwest Queensland. hons thesis, University of Queensland, (unpubl.).

Haapala I. & Ramo O. T. 1999. Rapakivi granites adn related rocks: an introduction. *Precambrian Research* **95**, 1-7.

Hammerstrom J. M. & Zen E.-A. 1986. Aluminium in hornblende: an empirical igneous geobarometer. *American Mineralogist* **71**, 1297-1313.

Hand M. & Rubatto D. 2002. The scale of the thermal problem in the Mt Isa Inlier. *16th Australian Geological Convention, Geoscience 2002, Expanding Horizons* 173.

Hanson G. N. 1978. The application of trace elements to the petrogenesis of igneous rocks of granitic composition. *Earth and Planetary Science Letters* **38**, 26-43.

Harrison T. M. & Watson E. B. 1984. The behaviour of apatite during crustal anatexis: equilibrium and kinetic considerations. *Geochimica et Cosmochimica Acta* **48**, 1467-1477.

Hibbard M. J. 1965. Origin of some alkali-feldspar phenocrysts and their bearing on petrogenesis. *American Journal of Science* **263**, 245-261.

Hibbard M. J. 1979. Myrmekite as a marker between preaqueous and postaqueous phase saturation in granitic systems. *Geolocical Society America Bulletin* **90**, 1047-1062.

Hibbard M. J. 1981. The Magma Mixing Origin of mantled feldspars. *Contributions to Mineralogy and Petrology* **76**, 158-170.

Hibbard M. J. 1991. Textural anatomy of twelve magma-mixed granitoid systems. *In*: Didier J. & Barbarin B. eds. *Enclaves and granite petrology* pp. 431-444. Developments in Petrology **13**.

Hogan J. P., Price J. D. & Gilbert M. C. 1998. Magma traps and driving pressure: consequences for pluton shape and emplacement in an extensional regime. *Journal of Structural Geology* **20**, 1155-1168.

Holcombe R. J., Pearson P. J. & Oliver N. H. S. 1991. Geometry of a Middle Proterozoic extensional decollement in northeastern Australia. *Tectonophysics* **191**, 255-274.

Holland T. & Blundy J. 1994. Non-ideal interactions in calcic amphibole and their bearing on amphibole plagioclase thermometry. *Contributions to Mineralogy and Petrology* **116**, 433-447.

Holtz F., Johannes W., Tamic N. & Behrens H. 2001. Maximum and minimum water contents of granitic melts generated in the crust: a reevaluation and implications. *Lithos* **56**, 1-14.

Holtz F., Scaillet B., Behrens H., Schultze F. & Pichavant M. 1996. Water content of felsic melts: application to the rheological properties of granitic magmas. *Transactions - Royal Society of Edinburgh: Earth Sciences* **87**, 57-64.

Huppert H. E. & Sparks R. S. J. 1988. The generation of Granitc magmas by intrusion of basalt into continental crust. *Journal of Petrology* **29**, 599-624.

Hutton D. H. W., Dempster T. J., Brown P. E. & Becker S. D. 1990. A new mechanism of granite emplacement: intrusion in active extensional shear zones. *Nature* **343**, 452-455.

Irvine T. N. & Barager W. R. A. 1971. A guide to the chemical classification of common volcanic rocks. *Canadian Journal of Earth Sciences* **8**, 523-548.

Johnson & Rutherford 1989. Experimental calibration of Al-in hornblende geobarometer with application to Long Valley caldera (California) volcanic rocks. *Geology* **17**, 837-841.

Langmuir C. H., Vocke R. D., Hanson G. N. & Hart S. R. 1978. A general mixing equation with applications to icelandic basalts. *Earth and Planetary Science Letters* **37**, 380-392.

Le Maitre R. W. 1989. *A classification of igneous rocks and glossary of terms*. Blackwell Scientific Publications, Oxford. pp. 193.

Leake B. E. & et.al 1997. Nomenclature of amphiboles: report of the subcommittee on amphiboles of the International Mineralogical Association, commission on new minerals and mineral names. *Canadian Mineralogist* **35**, 219-246.

Lister G. S., Etheridge M. A. & Symonds P. A. 1986. Detachment faulting and the evolution of passive continental margins. *Geology* **14**, 246-250.

Loiselle M. C. & Wones D. R. 1979. Characteristics and origin of anorogenic granites. *Geological Society of America Abstracts with Programs* **11**, 468.

MacCready T., Goleby B. R., Goncharov A. G., Drummond B. J. & Lister G. S. 1998. A framework of overprinting orogens based on interpretation of the Mount Isa Deep Seismic Transect. *Economic Geology* **93**, 1422-1434.

McCarthy T. C. & Patino Douce A. E. 1997. Experimental evidence for high-temperature felsic melts formed during basaltic intrusion of the deep crust. *Geology* **25**, 463-466.

Miller R. B. & Paterson S. R. 1994. The transition from magmatic to high temperature solid state deformation: implications from the Mount Stuart batholith, Washington. *Journal of Structural Geology* **16**, 853-865.

Nekvasil H. 1991. Ascent of felsic magmas and formation of rapakivi. *American Mineralogist* **76**, 1279-1290.

Nijman W., van Lochem J. H., Spliehoff H. & Feijth J. 1992. Deformation model and sedimentation patterns of the Proterozoic of the Paroo Range, Mount Isa Inlier, Queensland. *In*: Stewart A. J. & Blake D. H. eds. *Detailed Studies of the Mount Isa Inlier* Australian Government Publishing Service, Canberra. **Bulletin 243** pp.

Noyes H. J., Wones D. R. & Frey F. A. 1983. A tale of two plutons: geochemical evidence bearing on the origin and differentiation of the Red Lake and Eagle Peak plutons, central Sierra Nevada, California. *Journal of Geology* **91**, 487-509.

O'Dea M. G., Lister G. S., MacCready T., Betts P. G., Oliver N. H. S., Pound K. S., Huang W. & Valenta R. K. 1997. Geodynamic evolution of the Proterozoic Mount Isa terrain. *In*: Burg J. P. & Ford M. eds. *Orogeny Through Time* Geological Society Special Publication, **121** pp. 99-122.

O'Dea M. G. & Lister G. S. 1995. The role of ductility contrast and basement architecture in the structural evolution of the Crystal Creek block, Mount Isa Inlier, NW Queensland, Australia. *Journal of Structural Geology* **17**, 949-960.

Oliver N. H. S., Holcombe R. J., Hill E. J. & Pearson P. J. 1991. Tectono-metamorphic evolution of the Mary Kathleen Fold Belt, northwest Queensland: A reflection of mantle plume processes? *Australian Journal of Earth Sciences* **38**, 425-455.

Page R. W. 1988. Geochronology of Early to Middle Proterozoic fold belts in Northern Australia: A review. *Precambrian Research* **40/41**, 1-19.

Page R. W. & Bell T. H. 1986. Isotopic and structural responses of granite to successive deformation and metamorphism. *Journal of Geology* **94**, 365-379.

Page R. W. & Sun S.-S. 1998. Aspects of geochronology and crustal evolution in the Eastern Fold Belt, Mount Isa Inlier. *Australian Journal of Earth Sciences* **45**, 343-361.

Page R. W. & Sweet I. H. 1998. Geochronology of basin phases in the Western Mount Isa Inlier, and correlation with the McArthur Basin. *Australian Journal of Earth Sciences* **45**, 219-232.

Passchier C. W. 1986. Evidence for early extensional tectonics in the Proterozoic Mount Isa Inlier, Australia. *Geology* **14**, 1008-1011.

Passchier C. W. & Trouw R. A. J. 1998. *Micro-tectonics*. Springer, Berlin. pp. 289.

Paterson S. R. & Fowler T. K. 1993a. Extensional pluton emplacement models: Do they work for large plutonic complexes? *Geology* **21**, 781-784.

Paterson S. R. & Fowler T. K. 1993b. Re-examining pluton emplacement processes. *Journal of Structural Geology* **15**, 191-206.

Paterson S. R., Fowler T. K. J. & Miller R. B. 1996. Pluton emplacement in arcs: a crustal-scale exchange process. *Transactions - Royal Society of Edinburgh: Earth Sciences* **87**, 115-123.

Paterson S. R. & Vernon R. H. 1995. Bursting the bubble of ballooning plutons: a return to nested diapirs emplaced by multiple processes. *GSA Bulletin* **107**, 1356-1380.

Paterson S. R., Vernon R. H. & Tobisch O. T. 1989. A review of criteria for the identification of magmatic and tectonic foliations in granitoids. *Journal of Structural Geology* **11**, 349-363.

Patino Douce A. E. 1997. Generation of metaluminous A-type granites by low-pressure melting of calc-alkaline granitoids. *Geology* **25**, 743-746.

Pearce J. A. & Cann J. R. 1973. Tectonic setting of basic volcanic rocks determined using trace element analysis. *Earth and Planetary Science Letters* **19**, 290-300.

Pearce J. A., Harris N. B. W. & Tindle A. G. 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology* **25**, 956-983.

Pearson P. J., Holcombe R. J. & Page R. W. 1992. Synkinematic emplacement of the middle Proterozoic Wonga Batholith into a mid-crustal extensional shear zone, Mount Isa Inlier, Queensland, Australia. *In*: Stewart A. J. & Blake D. H. eds. *Detailed Studies of the Mount Isa Inlier* Australian Government Publishing Service, Canberra. **Bulletin 243** pp.

Ramo O. T. & Haapala I. 1995. One hundred years of Rapakivi Granite. *Mineralogy and Petrology* **52**, 129-185.

Reinhardt J. & Rubenach M. J. 1988. Temperature-time relationships across metamorphic zones: evidence from porphyroblast-matrix relationships in progressively deformed metapelites. *Tectonophysics* **158**, 141-161.

Roberts M. P. & Clemens J. D. 1993. Origin of high-potassium, calc-alkaline, I-type granitoids. *Geology* **21**, 825-828.

Rollinson H. R. 1993. *Using Geochemical Data: Evaluation, Presentation, Interpretation*. Longman Scientific and Technical, New York. pp. 344.

Rubenach M. J. 1992. Proterozoic low-pressure/high-temperature metamorphism and an anti clockwise P-T-t path for the Hazeldene area, Mount Isa Inlier, Queensland, Australia. *Journal of Metamorphic Geology* **10**, 333-346.

Salonsaari P. T. & Haapala I. 1994. The Jaala-Iitti Rapakivi complex. An example of bimodal magmatism and hybridization in the Wiborg Rapakivi Batholith, Southeastern Finland. *Mineralogy and Petrology* **50**, 21-34.

Simpson C. & Wintsch R. P. 1989. Evidence for deformation induced K-feldspar replacement by myrmekite. *Journal of Metamorphic Geology* **7**, 261-275.

Sisois I. 2000. Magma mixing and mingling at the Slaughter-yard Creek Complex, magnetic high, within the Sybella Batholith, Mount Isa, northeast Australia: field relationships, petrography and geochemistry. Honours thesis, James Cook University, Townsville, Queensland (unpubl.).

Smith D. R., Barnes C. G., Shannon W. M., Roback R. & James E. 1997. Petrogenesis of Mid-Proterozoic granitic magmas: examples from the central and west Texas. *Precambrian Research* **85**, 53-79.

Sparks R. S. J., Huppert H. E. & Turner J. S. 1984. The fluid dynamics of evolving magma chambers. **A310**, 511-534.

Sparks R. S. J. & Marshall L. A. 1986. Thermal and mechanical constraints on mixing between mafic and silicic magmas. *Journal of Volcanology Geothermal Research* **29**, 99-124.

Stewart A. J. & Blake D. H. 1992. Detailed studies of the Mount Isa Inlier. **Bulletin 243**, pp. 374. Australian Government Publishing Service, Canberra.

Streckeisen A. 1976. To each plutonic rock its proper name. *Earth Science Reviews* **12**, 1-33.

Sun S.-S. & McDonough W. F. 1989. Chemical and isotopic systematics of ocean basalts: implications for mantle compostion and processes. *In*: Saunders A. D. & Norry M. J. eds. *Magmatism in the Ocean Basins* Geological Society of London Special Publication, **42** pp. 313-345.

Turner J. S. & Campbell I. H. 1986. Convection and mixing in magma chambers. *Earth Science Reviews* **23**, 255-352.

Turner S. P., Foden J. D. & Morrison R. S. 1992. Derivation of some A-type magmas by fractionation of basaltic magma: an example from the Padthaway Ridge, South Australia. *Lithos* **28**, 151-179.

van der Molen I. & Patterson M. S. 1979. Experimental deformation of partially melted granite. *Contributions to Mineralogy and Petrology* **70**, 299-318.

Vernon R. H. 1983. Restite, xenoliths and microgranitoid enclaves in granites. *Journal and Proceedings, Royal Society of New South Wales* **116**, 77-103.

Vernon R. H. 1986. K-Feldspar megacrysts in granites - phenocrysts, not porphyroblasts. *Earth-Science Reviews* **23**, 1-63.

Vernon R. H. 1991a. Interpretation of microstructures of microgranitoid enclaves. *In*: Didier J. & Barbarin B. eds. *Enclaves and granite petrology* pp. 277-291. Developments in Petrology **13**.

Vernon R. H. 1991b. Questions about myrmekite in deformed rocks. *Journal of Structural Geology* **13**, 979-985.

Vigneresse J. L. 1995. Control of granite emplacement by regional deformation. *Tectonophysics* **249**, 173-186.

Vigneresse J.-L., Tikoff B. & Ameglio L. 1999. Modification of the regional stress field by magma intrusion and formation of tabular granitic plutons. *Tectonophysics* **302**, 203-224.

Walker G. P. L. & Skelhorn R. R. 1966. Some associations of acid and basic rocks. *Earth Science Reviews* **2**, 93-109.

Walker J. D., Fletcher J. M., Fillmore R. P., Martin M. W., Taylor W. J., Glazner A. F. & Bartley J. M. 1995. Connection between igneous activity and extension in the central Mojave metamorphic core complex, California. *Journal of Geophysical Research* **100**, 477-494.

Wallace P. J. & Carmichael I. S. E. 1994. Petrology of the Volcan Tequila, Jalisco, Mexico: disequilibrium phenocryst assemblages and evolution of the subvolcanic magma system. *Contributions to Mineralogy and Petrology* **117**, 345-361.

Watson E. B. & Harrison T. M. 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth and Planetary Science Letters* **64**, 295-304.

Wellman P. 1992. Structure of the Mount Isa region inferred from gravity and magnetic anomalies. *In*: Stewart A. J. & Blake D. H. eds. *Detailed Studies of the Mount Isa Inlier* Australian Government Publishing Service, Canberra. **Bulletin 243** pp. 15-27.

Whalen J. B. & Currie K. L. 1984. The Topsails igneous terrane, Western Newfoundland: evidence for magma mixing. *Contributions to Mineralogy and Petrology* **87**, 319-327.

Whalen J. B., Currie K. L. & Chappell B. W. 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. *Contributions to Mineralogy and Petrology* **95**, 407-419.

White A. J. R. & Chappell B. W. 1977. Ultrametamorphism. *Tectonophysics* **43**, 7-22.

Wilson C. J. L. 1972. The stratigraphic and metamorphic sequence west of Mount Isa, and associated igneous intrusions. *Proceedings of the Australian Institute of Mining and Metallurgy* **243**, 27-42.

Wilson C. J. L. 1975. Structural features west of Mount Isa. *Journal of geological society of Australia* **22**, 457-476.

Wones D. R. 1981. Mafic silicates as indicators of intensive variables in granitic magmas. *Mining Geology (Japan)* **31**, 191-212.

Wones D. R. 1989. Significance of the assemblage titanite + magnetite + quartz in granitic rocks. *American Mineralogist* **74**, 744-749.

Wones D. R. & Gilbert M. C. 1982. Chapter 3, Amphiboles in the igneous environment; Introduction. *In*: Veblen D. R. & Ribbe P. H. eds. *Reviews in Mineralogy. Amphiboles: petrology and experimental phase relations* Mineralogical Society of America, **9B** pp. 355-389.

Wyborn L. A. I. 1987. The petrology and geochemistry of alteration assemblages in the Eastern Creek Volcanics, as a guide to copper and uranium mobility associated with regional deformation, Mount Isa, Queensland. *In*: Pharaoh T. C., Beckinsale R. D. & Rickard D. eds. *Geochemistry and mineralization of*

Proterozoic Volcanics Suites Geological Society Special Publication, No. 33, pp. 425-434.

Wyborn L. A. I., Page R. W. & McCulloch M. T. 1988. Petrology, geochronology, and isotope geochemistry of the post-1820 Ma granites of the Mount Isa Inlier: mechanisms for the generation of Proterozoic anorogenic granites. *Precambrian Research* **40/41**, 509-541.

Wyborn L. A. I., Page R. W. & Parker A. J. 1987. Geochemical and geochronological signatures in Australian Proterozoic igneous rocks. *In*: Pharaoh T. C., Beckinsale, R.D., and Rickard, D. eds. *Geochemistry and mineralization of Proterozoic Volcanics Suites* Geological Society Special Publication, No.33, pp. 337-394.

Wyllie P. J. & Wolf M. B. 1993. Amphibolite dehydration-melting: sorting out the solidus. *In*: Prichard H. M., Alabaster T., Harris N. B. W. & Neary C. R. eds. *Magmatic Process and Plate Tectonics* Geological Society of London Special Publication, **76** pp. 405-416.

Yoshinobu A. S., Okaya D. A. & Paterson S. R. 1998. Modeling the thermal evolution of fault-controlled magma emplacement models: implications for the solidification of granitoid plutons. *Journal of Structural Geology* **20**, 1205-1218.