Evolution of the Sybella Batholith: Petrographic, geochemical and structural development of an A-type intrusive complex, Northwest Queensland

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ABSTRACT

The Sybella Batholith is an A-type composite granitoid complex that was emplaced as a series of distinct phases. The first phase began with the intrusion of tholeiitic doleritic (Mosses Tank Dolerite, 45-55 wt% SiO_2) and dioritic hybrid magmas (Mafic Hybrid Complex, 58.2 - 65 wt % SiO_2). The second phase involved intrusion of a minor suite of rapakivi hybrid (63-69 wt % SiO_2). Subsequent phases included the volumetrically largest part of the batholith, the high-K, Fe-enriched K-feldspar megacrystic syenogranites (known as ‘Main Phase’, approximately 70 wt % SiO_2), associated porphyritic and aplitic dykes, and a phase of microgranites (75-77 wt % SiO_2). Intruded during an extensional phase during the development of the Mount Isa Basin, the Sybella Batholith is ideal for the assessment of petrogenetic processes (including magma mixing and mingling) that gave rise to a composite batholith, and also the effect of syn- to post-magmatic deformation during emplacement (~1670 Ma) and subsequent metamorphism and deformation during the Isan Orogeny (1590-1500 Ma).

Mixing and mingling were significant processes in the evolution of the batholith. In the mafic rocks in both the Easter Egg and Guns Knob regions, hybridization was found to have taken place to some extent at a deeper level before the magmas were emplaced as distinct intrusions to form the Mafic Hybrid Complex. Within the Mafic Hybrid Complex there is a lack of mafic rocks that show no contamination with felsic magmas. Minor hybridization also occurred locally at emplacement level. The Main Phase granite, although relatively homogeneous, displays features indicative of hybridization at depth (rapakivi textures) and of interaction with the Mafic Hybrid Complex at emplacement level with true hybrid rocks at the contacts. In the northern Kitty Plains region, fractionation was probably the dominant process in the evolution of the mafic rocks of the Mosses Tank Dolerite (MTD), with hybridization limited to the contacts with intruded sheets of microgranite. Along the eastern margin of the pluton, large areas of MTD were brecciated by the intruding microgranite as rheological contrast between felsic and mafic magmas inhibited voluminous mixing. However, behaviour of the dolerite transitional between solid and liquid was observed along many of the intrusive contacts and within magmatic shear zones (dated at ~1673 Ma) with partially solidified mafic enclaves being mechanically broken-up during high strain forming schlieren and hybrids.

Few methods for determining the intensive parameters (T, P, fO_2, fH_2O) of granitic magmas are applicable to rapakivi A-type magmas, the main difficulty being that the granites consists of disequilibrium mineral assemblages (different generations and order of mafic/silicic minerals etc) and the high Fe-content of minerals. However, calculated temperatures of 850-900°C at approximately 4 kbars for the Main Phase granite are similar to other A-type granites. The absence of source rock restites is also indicative of high magma temperatures. The composition of minerals in the Main Phase granite is indicative of relatively low fO_2 for granites; however it was still higher than the initially low fO_2 in the Mafic Hybrid Complex. Oxidation of the mafic magmas during mixing resulted in abundant magnetite and other mineralogical changes. The occurrence of large biotite flakes ± late amphibole in the mafic units, and the apparent late crystallization of mafic minerals in the granites indicates H_2O undersaturated magmas. The low water fugacities and high-temperature of the melts enabled the magmas to intrude into the upper crust at relatively shallow depths.

The Main Phase of the Sybella Batholith contains 64.32 ppm Nd and 11.40 ppm Sm, and has a εNd of –3.86. A T_2 model source age of 2419 Ma was calculated using the emplacement age of ~1670 Ma. The Nd and Sm contents of the main phase hybrids have a positive correlation with the SiO_2, which is not consistent with fractionation (fractionation of amphibole would partition Nd and Sm from the melt), but rather mixing between the mafic and felsic end member magmas. No mafic end member was analysed; however a mafic enclave from within the Main Phase granite (with similar geochemical properties to the dolerites) had the lowest εNd of –6.15 and a T_2 model source age of 2587 Ma. The older model source age for the mafic rocks indicates that the melt from the mantle source region (dolerite) was probably contaminated with radiogenically older crustal material (Archaen crust). This is also consistent with the intrusion's enriched LREE, K and Rb contents. The microgranite contains 41.46 ppm Nd and 6.96 ppm Sm, has a εNd of –2.24 and a T_2 model source age of 2300 Ma. These values are outside the range determined for the Main Phase granites and are likely to represent a different source. The Mosses Tank Dolerite has a εNd of –2.27 and a T_2 model source age of 2303 Ma suggesting the dolerite was also contaminated with radiogenically older crustal material.

The shallow origin of A-type granites is a result of tectonic extension that is associated with crustal thinning and mantle upwelling possibly in a back-arc setting (Giles *et al.* 2002). Fluid absent partial melting of metaluminous protoliths (metamorphosed igneous rocks in the lower crust) heated by underplated or intraplated mafic magma produced the potassic incompatible and radiogenic element-rich high-temperature character of the Sybella Batholith. However, in the Sybella Batholith, the mafic rocks are iron-enriched resulting from fractionation of minerals at depth rather than direct emplacement from the mantle.

The Sybella Batholith was emplaced into strongly deformed country rocks of mafic and felsic gneisses and amphibolites of the May Downs Gneiss and Eastern Creek Volcanics of the Haslingden Group, Cover Sequence 2. At the time of the emplacement of the Sybella Batholith, the Mount Isa Inlier experienced large magnitude extension (O'Dea *et al.* 1997) and a suite of sedimentary basins developed in areas of extension (i.e Cover Sequence 3). In the Sybella Batholith, three stages of development for the fabric were determined: (1) magmatic flow; (2) submagmatic/high-temperature solid-state flow; (3) moderate-high temperature solid-state flow, marked by plastic deformation with temperature above 600°C. Deformation was heterogeneous with the first and second processes dominant within the northern regions at Kitty Plain and Guns Knob and occurring locally within the Easter Egg region. The second and third processes predominate within the Easter Egg Region. The third process may have related to either deformation during emplacement or overprinting regional metamorphism and deformation during the Isan Orogeny. The later deformation has also obscured earlier primary magmatic features or high-temperature fabrics by recrystallization and reactivation.

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During a PhD, you learn a lot from people,
about people and most of all,
about yourself.

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CHAPTER 1

INTRODUCTION AND REGIONAL GEOLOGY

1.1 INTRODUCTION

The 1600 km^2 Sybella Batholith in the Western Fold Belt of the Mount Isa Inlier is a composite granitoid complex dominated by a K-rich rapakivi granite phase, but also containing mafic (gabbro, dolerite), intermediate (diorite and quartz-diorite) and felsic (granodiorite and monzogranite) phases. The Sybella Batholith was intruded during an extensional phase in the development of the Mount Isa Basin (O'Dea *et al.* 1997). It offers an excellent opportunity to assess the nature of petrogenetic processes that gave rise to a composite batholith, and also the effect of syn- to post-magmatic deformation associated with emplacement (~1670 Ma) and subsequent metamorphism and deformation during the Isan Orogeny (~1550 Ma). Extensive work has been undertaken within the Western Fold Belt of the Mount Isa Inlier, far NW Queensland (Figure 1.1). However much of this work has focused on the structure and the geology of the sedimentary sequences which host Cu-Pb-Zn-Ag mineralization and impact on ore deposit exploration models (Stewart & Blake 1992 and references therein). Studies of the Sybella Batholith are restricted to brief geochemical overviews of the suites (Wyborn *et al.* 1988; Connors & Page 1995; Ellis & Wyborn 1984; Wyborn *et al.* 1987) as the granites have been viewed as having little potential to contain mineralization or as a source of fluids for the mineralization.

Granite batholiths are an important component of the continental crust. A major step in understanding crustal differentiation is to identify the processes by which granitoid magmas are formed, fractional crystallization of a mafic parent magma and/or partial melting of pre-existing crustal rocks. Compositional variation within large plutonic complexes also arises from (1) variation in source rock composition; (2) variation in melting conditions; (3) complex chemical and physical interactions between mafic and felsic magmas; and (4) crustal contamination and assimilation. The geochemistry and mineralogy of the resulting granitoid rocks reflect not only the kinds of protoliths from

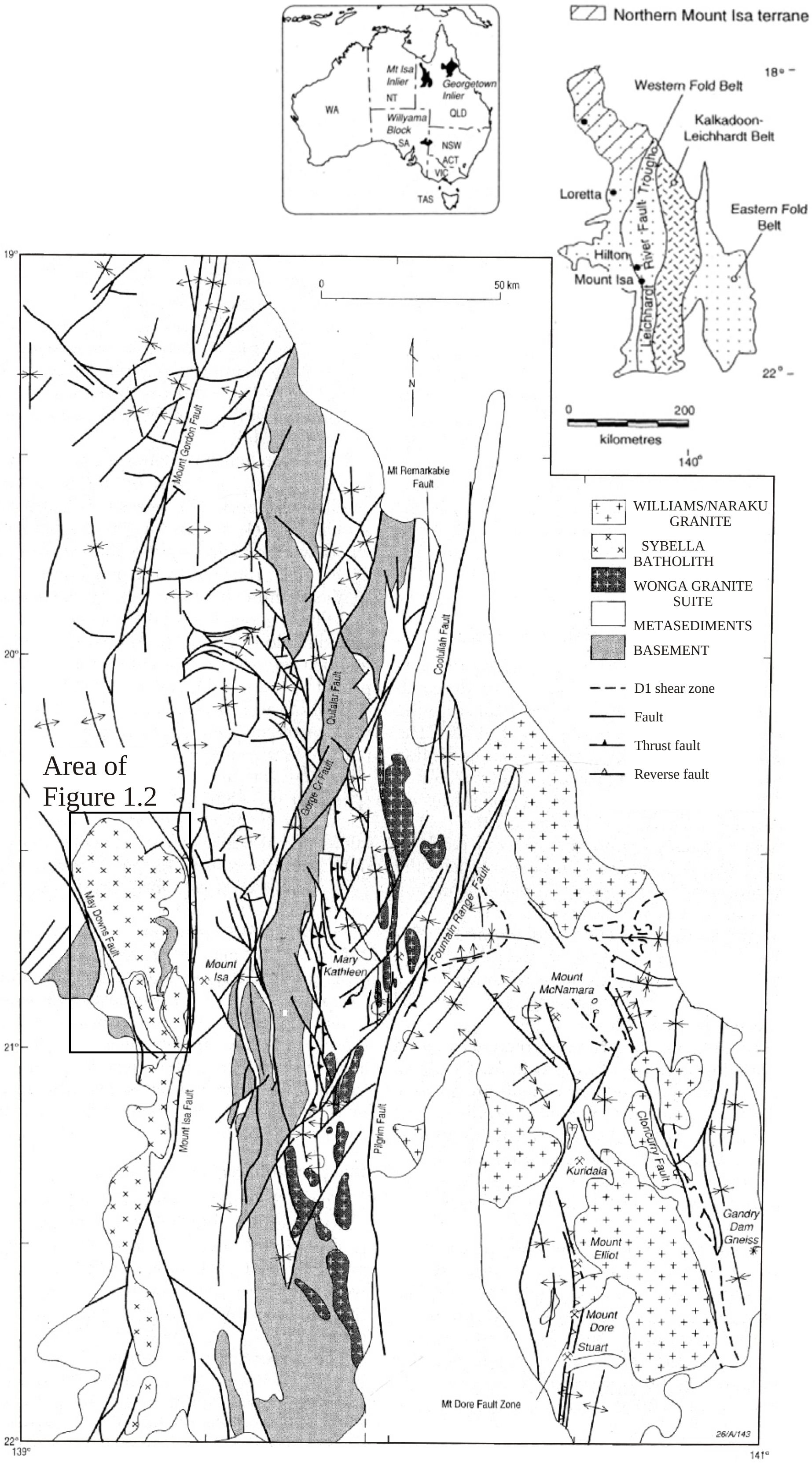


Figure 1.1 Simplified map of the major stuctures and magmatic provinces of the Mount Isa Inlier. Modified from MacCready et al (1998).

which they were derived, but also the conditions under which the magmas were formed, evolved, mixed and eventually solidified.

Studies of the processes that lead to the genesis of granitoid rocks with diverse compositions have resulted in the formulation of several hypotheses. One current model involves magmatic differentiation in which magmas evolve toward a more felsic composition by fractional crystallization (e.g. Allegre *et al.* 1977; Sparks *et al.* 1984; Turner & Campbell 1986). This may involve crystal settling, or sidewall crystallization, in which the intrusion becomes more felsic towards the centre. Magmas may change their composition by assimilating country rocks or stoped blocks (De Paolo 1981). Variable degrees of partial melting in the source area may also produce co-magmatic suites of contrasting compositions. With rising temperatures above the solidus, magmas produced from crustal protoliths shift from granitic to granodioritic in composition (Robertson & Wyllie 1971). Other models include the partial melting of different protoliths in a heterogeneous source region (Noyes *et al.* 1983), hybridization between mantle and crustal derived magmas (Sparks & Marshall 1986) and restite unmixing (White & Chappell 1977; Chappell *et al.* 1987). With such diverse processes, mineralogical, geochemical and isotopic data can be very difficult to interpret, leading to the formulation of different and sometimes conflicting petrogenetic histories for granitic rocks (e.g. mixing versus restite unmixing). Consequently, studies of these rocks should integrate several techniques such as detailed mapping, petrography and geochemistry of the rocks to increase confidence in the resulting model. This study attempts to constrain the relationships between the various rocks that form the Sybella Batholith using such an approach.

Granitoid rocks may be divided into those generated during evolution of a fold belt (orogenic) and those that are not associated with compressional structures, and that were emplaced after a known orogenic event (anorogenic) (Whalen *et al.* 1987; Frost *et al.* 1999). The genesis of anorogenic granitoids remains controversial, especially because of the diversity of rocks grouped under that category, commonly termed ‘A-type’ (Collins *et al.* 1982). A-type granites are characterized by high inferred magmatic temperatures, low H_2O, high Fe enrichment, and high K contents and are typically enriched in incompatible elements including rare earth elements, Zr, Nb and Ta and poor in Sr, Ti and Eu (Frost *et al.* 1999). Many models have been proposed for the origin of A-type granites, including fractionation of mantle derived mafic magmas, with or without crustal assimilation (Loiselle & Wones 1979; Turner *et al.* 1992) and partial melting of crustal materials (Whalen *et al.* 1987; Anderson & Bender 1989; Frost & Frost 1997).

The Sybella Batholith has many attributes that are characteristic of rapakivi A-type granites, including: (1) an extensional (Connors & Page 1995) tectonic setting of rapakivi granites; (2) the bimodal character of the magmatism (Haapala & Ramo 1999); (3) petrographic characteristics, principally the K-feldspar megacrystic or porphyritic nature, (4) geochemical properties, such as low water content, enrichment in fluorine, some large-ion lithophile and rare earth elements, and Fe relative to Mg (Anderson & Bender 1989); and (5) physical conditions of crystallization, such as high temperature. The granites within the Sybella Batholith were intruded over a period of 20 million years between 1675 and 1655 Ma. They varied temporally, texturally and geochemically during this time, ranging from porphyritic, to coarse- and fine-grained granites, with net-veining, enclave-rich hybrids and dolerites commonly associated. Regional geological mapping of igneous intrusions and geochemical studies around the Sybella Batholith (Figure 1.2) have determined a suite of coeval potassic granitoids, namely the main phase, microgranite and β-quartz phase, and detailed mapping in this study and others (Coleborn 1999; Sisois 2000), have assisted in the identification of hybridized dolerites and granites related to these granitoids. This work integrates the study of field relations, petrology, mineral chemistry and crystallization textures, whole rock geochemistry, and radiogenic isotope data in an attempt to assess which of the processes of magma genesis discussed previously are relevant to the Sybella Batholith. In particular, the process of mixing and hybridization as a major mechanism in creating variation within the batholith is considered.

The characterization of emplacement related magmatic to post-magmatic fabrics within the granites and the continuous interaction between deformation and magma reflects the dynamic character of the whole process of magma transport and emplacement (Paterson & Fowler 1993; Brown 1994). The shallow and high temperature intrusion of the batholith and its emplacement into an extensional regime, and the spatial relationships

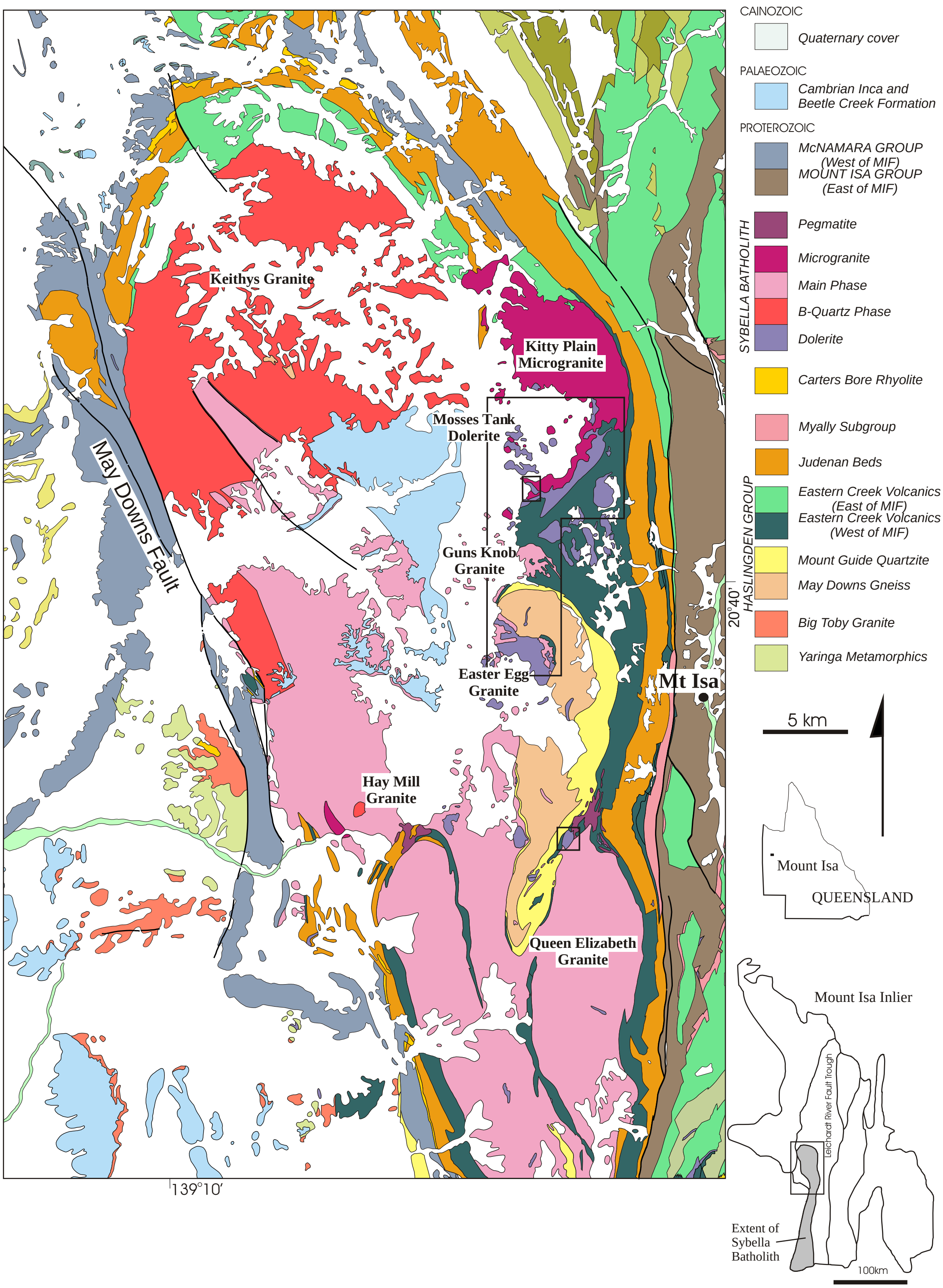


Figure 1.2 Simplified geological map of Northern Sybella Batholith and surrounding country rocks. Modified from Mount Isa geological map sheet 6756. Informal pluton names from Denaro *et al* 2001.

and timing between granite emplacement and structural development of the Western Fold Belt, have a significant influence on the interpretation of the structural and metamorphic evolution of the region. Current understanding is that emplacement of the batholith post-dated and preceded the Barramundi and Isan Orogeny respectively, by tens to hundreds of millions of years (Figure 1.3). This study has identified significant deformation accompanied the emplacement of the batholith, adding to the deformation history in the area. The origin and structural history of the May Downs Gneiss (country rocks to the batholith) was controversial as the deformation - although historically attributed to the Barramundi Orogenic event (Wilson 1975) - had been considered to be related to the later Isan Orogeny (Connors *et al.* 1992). Relationships between the batholith and its country rocks have clarified the May Downs Gneiss as having undergone multiple deformations prior to the intrusion of the batholith.

A greater understanding of such a volumetrically large component of the Western Fold Belt will inevitably contribute to new interpretations for this part of the Inlier, in both a local structural context and a regional tectonic framework.

1.2 AIMS

The principal objective of this project is to determine the evolution of the batholith including magma source and petrogenetic processes, emplacement mechanisms, effect of syn-magmatic deformation, and post emplacement tectonic features.

In order to achieve this, it is the author's aim to:

1. To identify the different phases within the Sybella Batholith and determine their age relative to each other;
2. To determine the source composition and the geotectonic setting of dolerite and granitoid generation and emplacement;
3. To determine the significance and implications of physiochemical processes related to magma mixing within the batholith;

4. To resolve the problem of the timing of the deformation within the May Downs Gneiss and batholith and its relation to emplacement deformation and Isan Orogeny;
5. To use existing knowledge of the factors that control granitoid emplacement and magma chamber processes to propose a model for the evolution of the batholith and related basin development.

1.3 APPROACH

A number of field, petrological and analytical techniques were applied to determine the nature, origin and interaction between the granitoids in the Sybella Batholith (see each section for relevant details). These include:

- Detailed geological mapping of igneous intrusions, structure, and alteration within and immediately adjacent to the batholith. A combination of geophysical mapping, aerial photography, detailed mapping by pace and compass traverse and sampling was utilized.
- Petrographic identification of mineralogy and textures (200 TS), and electron microprobe analysis of different mineral phases (20 PS) was used to determine the crystallization history.
- Analysis of the trace and major element geochemistry of key representative samples was used to identify geochemical trends in the magma evolution, and was followed by geochemical modelling to constrain possible magma evolution processes.
- Sm-Nd, Rb-Sr, Pb isotope geochemistry was used to determine melt source.
- Detailed structural and textural analysis (30 orientated TS) was used to differentiate domains of magmatic, sub-magmatic and solid-state deformation fabrics.

1.4 REGIONAL GEOLOGY OF THE MOUNT ISA INLIER

The Mount Isa Inlier has been subdivided into three major tectonic domains bounded by regional-scale north-striking fault zones. These are termed the Western Fold Belt, the central Kalkadoon-Leichhardt Belt and the Eastern Fold Belt (Blake 1987; Figure 1.1). Two major tectonostratigraphic cycles are evident in the Mount Isa Inlier, an early basement that was deformed and regionally metamorphosed during the Barramundi Orogeny (1900-1870 Ma), and a later protracted period of intracontinental rifting characterized by voluminous bimodal magmatism and predominantly clastic sedimentation in a shallow-marine to fluvial environment. Igneous and sedimentary rocks younger than the Barramundi Orogeny were formed and deposited during at least four episodes of rifting and associated post-rift subsidence, resulting in the development of a complex extensional rift system (Figure 1.3, O'Dea *et al.* 1997). These rifting events are termed the Leichhardt Rift Event, the Myally Rift Event and the Mount Isa Rift Event, which included episodic rifting (Betts *et al.* 1998). The rocks of the Mount Isa Inlier were divided by Blake (1987) into three cover sequences representing the rift-sag cycles. However, later studies (e.g. O'Dea *et al.* 1997) have divided the rocks into 4 cover sequences with the stratigraphic make up of Cover Sequences 1 and 2 of Blake (1987) unchanged and the former Cover Sequence 3 divided into Cover Sequences 3 and 4 representing separate basin forming events. Cover Sequence 1 (1870-1850 Ma) consists predominantly of felsic volcanics and coeval granites and is largely restricted to the Kalkadoon Leichardt Belt in the central portion of the inlier (Blake & Stewart 1992a). The Eastern and Western Fold Belts are dominated by Cover Sequences 2 (1790-1740 Ma) and 3 (1680-1625 Ma). Cover Sequence 2 (Haslingden Group) is a rift-sag cycle, which is comprised of fluvial and shallow marine/lacustrine sedimentary rocks and bimodal volcanics. Cover Sequences 3 and 4 (Surprise Creek Formation, Mount Isa Group, McNamara Group) are represented mainly by finer-grained sedimentary rocks and lesser bimodal volcanics (O'Dea *et al.* 1997). Rifting was terminated by the Isan Orogeny between 1610-1500 Ma (Page & Bell, 1986), which resulted in the Proterozoic rocks being tightly folded, faulted, and regionally metamorphosed to mainly greenschist and amphibolite facies grades.

The Mount Isa Inlier has a long history of igneous activity with large granitoid batholiths emplaced over an extensive period of time from 1860 to 1480 Ma (Wyborn *et al.* 1988). U-Pb zircon dating indicates that the Proterozoic magmatism occurred in distinct cycles or pulses at approximately 1870 to 1840 Ma (Kalkadoon and Ewan Batholiths), 1820 Ma (Yeldham Granite), 1800 to 1780 Ma (Big Toby Granite), 1760 to

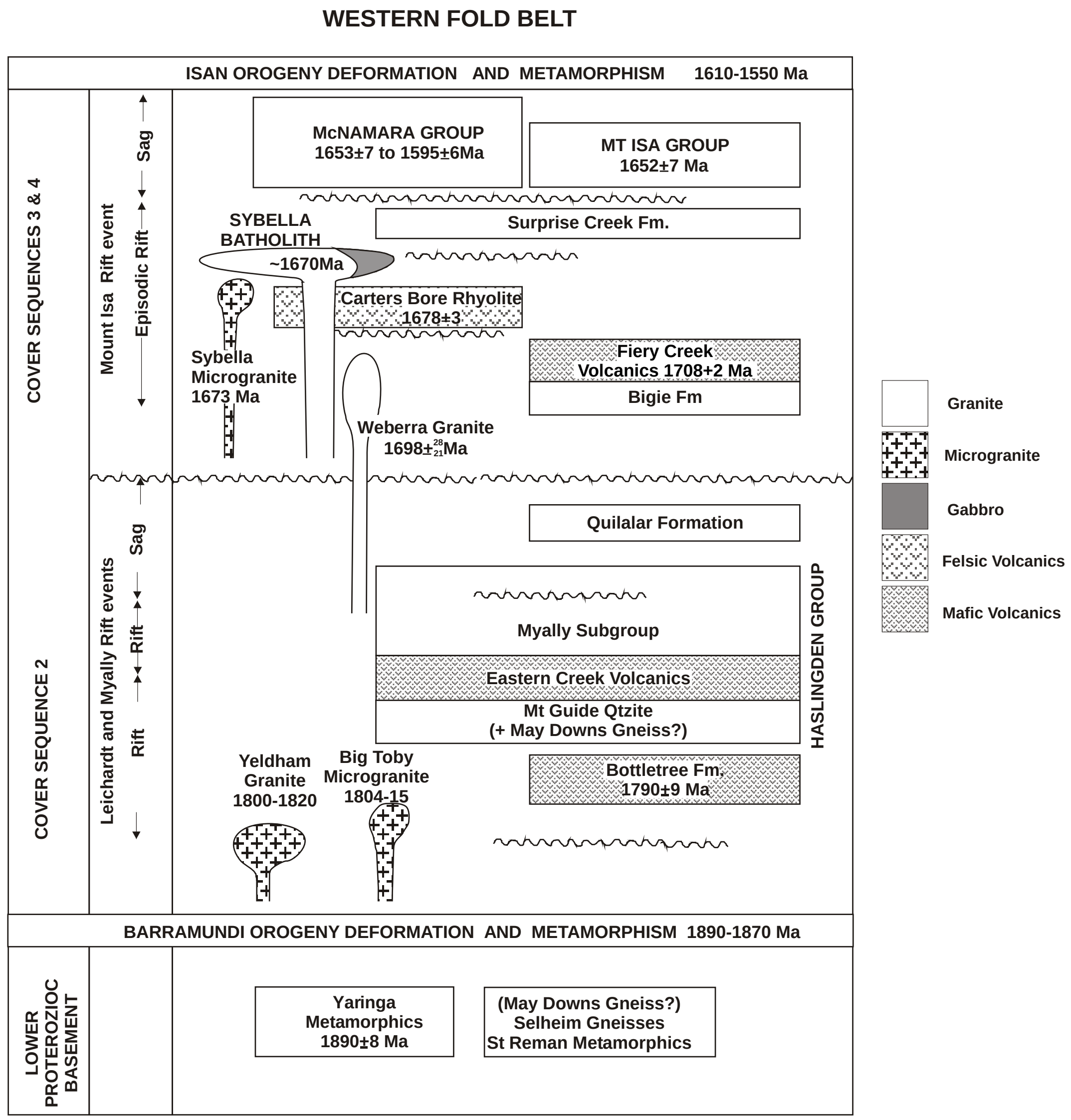


Figure 1.3 Schematic diagram of relationships of the gabbroids, granitoids and volcanic rocks to major structural and stratigraphic events in the Mount Isa Inlier. Modified from Blake & Stewart (1992), Wyborne *et al.* (1988), Odea *et al.* (1997), Betts *et al.* (1998).

1720 Ma (Wonga Batholith), 1700 Ma (Weberra Granite), 1670 to 1650 Ma (Sybella Batholith), and 1550-1480 Ma (Williams and Naraku Batholiths) (Blake 1987; Wyborn *et al.* 1987; Wyborn *et al.* 1988; Connors & Page 1995). Magmatism was predominantly bimodal, resulting in abundant mafic and felsic rocks with very few of intermediate composition. Mixed intrusions and net-veined complexes are developed where mafic and felsic magmas were emplaced synchronously (Blake 1981, 1987). The igneous rocks are associated with either rift sequences of sedimentary basins (with bimodal associations) or the orogenic deformation event (felsic associations). Many of the intrusions have been metamorphosed and deformed during the Isan Orogeny and now consist of metagranite, metadolerite or amphibolite, however the deformation is variable and the original compositions and textures are commonly preserved.

1.4.1 Regional Structural Framework

The Mount Isa Inlier has had a complex history of Proterozoic deformation dominated by periods of extension, shortening and transcurrent faulting. Two main orogenies involving deformation and regional metamorphism have affected the Mount Isa Inlier. The older Barramundi Orogeny affected the basement sequence but predated Cover Sequence 1 volcanism. The younger Isan Orogeny took place after Cover Sequence 4 had been deposited.

The Barramundi Orogeny (ca 1870 Ma; Etheridge *et al.* 1987) produced upright folds and a north-trending foliation in the basement units such as the Yaringa Metamorphics, implying east-west shortening (Blake & Stewart 1992b). The Barramundi Orogeny was followed by a protracted period of extension, intracontinental rifting, and post-rift subsidence from ~1800 to 1600 Ma (Betts *et al.* 1998). Extensional faulting accompanied the deposition of Cover Sequences 2 and 3, and some of the igneous intrusions may be associated with this extension (Blake & Stewart 1992b; O'Dea *et al.* 1997). Several examples of extensional deformation affecting Cover Sequence 2, but predating the Isan Orogeny have been reported in the Kalkadoon-Leichardt Belt (Holcombe *et al.* 1991; Oliver *et al.* 1991; Pearson *et al.* 1992). Many of these extensional deformational features were overprinted and obscured by subsequent ductile compressional deformation during the Isan Orogeny (Passchier 1986).

The Isan Orogeny involved shortening of a complex intraplate rift system and its deformation and metamorphic history was extremely heterogeneous (Stewart & Blake 1992 and references therein). Metamorphic assemblages within the inlier range from sub-greenschist facies to upper amphibolite facies, and are characterized by low pressure/high temperature anticlockwise P-T-t paths (Reinhardt & Rubenach 1988; Rubenach 1992).

Structural studies undertaken in the Western Fold Belt suggest the Isan Orogeny consisted of three significant deformation events but the structural history is strongly debated (Bell 1983, 1991; Connors & Lister 1995; Nijman *et al.* 1992; Stewart & Blake 1992). An early phase of thrusting and folding resulting from N-S compression (D_1 of Bell 1983) has been recognized in some regions. The timing of D_1 structures is controversial as Rb-Sr whole rock age of a "D_1" site in the Sybella Batholith of around 1610 Ma (Page & Bell 1986) may have been partially reset during peak metamorphism and D_2 deformation. The dominant phase, generally D_2 (Bell 1983, 1991) at around 1550 Ma (Page & Bell 1986; Connors & Page 1995) involved east-west compression and sub-greenschist to amphibolite facies regional metamorphism. This resulted in the north-south structural grain characteristic of most of the Mount Isa Inlier defined by upright regional folds with strongly developed axial planar cleavages and faults. The third deformation, D_3 of Bell (1983), dated at 1510 Ma by Page & Bell (1986), produced N to NW-trending folds and crenulation cleavages locally, and is associated with retrograde metamorphism. However, the similar orientation of D_2 and D_3 shortening directions commonly resulted in D_3 strain being accommodated by the reactivation of pre-existing D_2 structures (Bell & Hickey 1998).

The D_1-D_2-D_3 scheme of the Mount Isa Inlier has lead to problems correlating structures across the Inlier and relating them to the same period of deformation (Connors & Lister 1995; Stewart & Blake 1992). Deformation and timing of peak metamorphism is increasingly interpreted as having occurred at different times in different parts of the inlier. Structural studies have tended to focus on detailed analysis of smaller regions and do not attempt to correlate with a region-wide scheme (e.g. Stewart & Blake 1992). However, new data indicate that correlation is possible, with D_2 regional metamorphism approximately synchronously across the Mount Isa Inlier at around 1575 Ma (Hand & Rubatto 2002).

Major strike-slip faulting took place along north-south faults such as the Pilgrim, Quilalar, and possibly the Mount Isa Fault after the folding related to the Isan Orogeny (Wellman 1992). Emplacement of the Williams and Naraku Batholiths in the Eastern Fold Belt implies crustal extension at around 1500 Ma (Blake & Stewart 1992b).

1.4.2 Sybella Batholith, Western Fold Belt, Mount Isa Inlier

Emplacement of the Sybella Batholith in the Western Fold Belt of the Mount Isa Inlier occurred during a long-lived intercontinental extensional rifting in the Middle Proterozoic (O'Dea *et al.* 1997). The intrusion of the Sybella Batholith (~1670 to 1655 Ma: Page & Bell 1986; Connors & Page 1995) and extrusion of the Carters Bore Rhyolite (1678 ± 2 Ma: Page & Sweet 1998) occurred west of the Mount Fault system during the youngest phase of magmatism associated with extension during the Mount Isa Rift Event (Betts *et al.* 1998; Figure 1.3).

The Sybella Batholith consists of elongate plutons that are aerially extensive covering 1600 km^2 and form a N-S trending belt along the west and northwest flanks of the Mount Isa Rift. The Sybella Batholith is composed of five distinct phases: a "main phase" (1671 ± 8 Ma: Page & Bell 1986; including the Queen Elizabeth Pluton, 1660 ± 5 Ma, 1655 ± 4 Ma: Connors & Page 1995), "β-quartz phase" (1668 ± 24 Ma: Page & Bell 1986), "microgranite" (1673 ± 2.5 Ma: Coleborn 1999), pegmatites (1532 ± 7 Ma, 1480 ± 14 Ma: Connors & Page 1995) and "Kahko phase" (Figure 1.2). The pegmatites that occur within the Sybella Batholith and surrounding country rock are known as the Mica Creek Pegmatites and were emplaced late during D_2 (1532 ±7 Ma: Connors & Page 1995). These are thought to be unrelated to the Sybella Batholith as is the younger phase of pegmatites which post-dates ductile deformation (post D_3 emplacement age of 1480 ±14 Ma: Connors & Page 1995).

The formal and informal members of the Sybella Batholith are: (1) main phase granite: Hay Mill Granite, Easter Egg Granite, Guns Knob Granite, Queen Elizabeth Granite; (2) β-quartz phase: Keithys Granite; (3) microgranite phase: Kitty Plain Microgranite; and

(4) Mosses Tank Dolerite (Figure 1.2). The southern half of the batholith consists largely of the "main phase" granite, which has variable grain size and commonly has albite or oligoclase rims on K-feldspar phenocrysts. The "β-quartz phase" forms the northwestern pluton termed Keithys Granite, is a fractionated I type granite and contains phenocrysts of β-quartz and K-feldspar with albite rims (Wyborn *et al.* 1988). The "Kahko phase", which is of minor occurrence in the southern part of the batholith, has been described by Blake *et al.* (1984), and is not mentioned further in this study. The "microgranite" occurs in the northeast of the Batholith, and contains abundant xenoliths and less ferromagnesian minerals than the "main phase" and "β-quartz phase" and may be unrelated (Wyborn *et al.* 1988).

The plutons intrude the May Downs Gneiss, Mount Guide Quartzite, and Eastern Creek Volcanics of the Haslingden Group of Cover Sequence 2 (Wyborn *et al.* 1988) and the Myally Subgroup. The main phase granite has a sill like geometry (Drummond *et al.* 1998). Bedding subparallel contacts occur along the northern and eastern pluton margins, and the western margin is in fault contact with the McNamara Group (Connors & Page 1995). Although the batholith was emplaced in an extensional period during deposition of Cover Sequence 3, there has been no documentation of fault or shear zones near the Sybella Batholith that may have controlled emplacement (Connors & Page 1995).

The Sybella Batholith has been regionally metamorphosed and deformed some 60 Ma prior to the three main deformational and metamorphic events of the Isan Orogeny (Page & Bell 1986). The penetrative fabric identified in the Sybella Batholith is parallel to both intrusive margins and to the fabric in the country rock. It has been correlated with D_2 by Connors *et al.* (1991; 1992) on the basis of its amphibolite facies mineral assemblage of biotite, hornblende and K-feldspar. The structures within the Sybella Batholith and their relationship to those within the country rock are discussed further as part of this study.

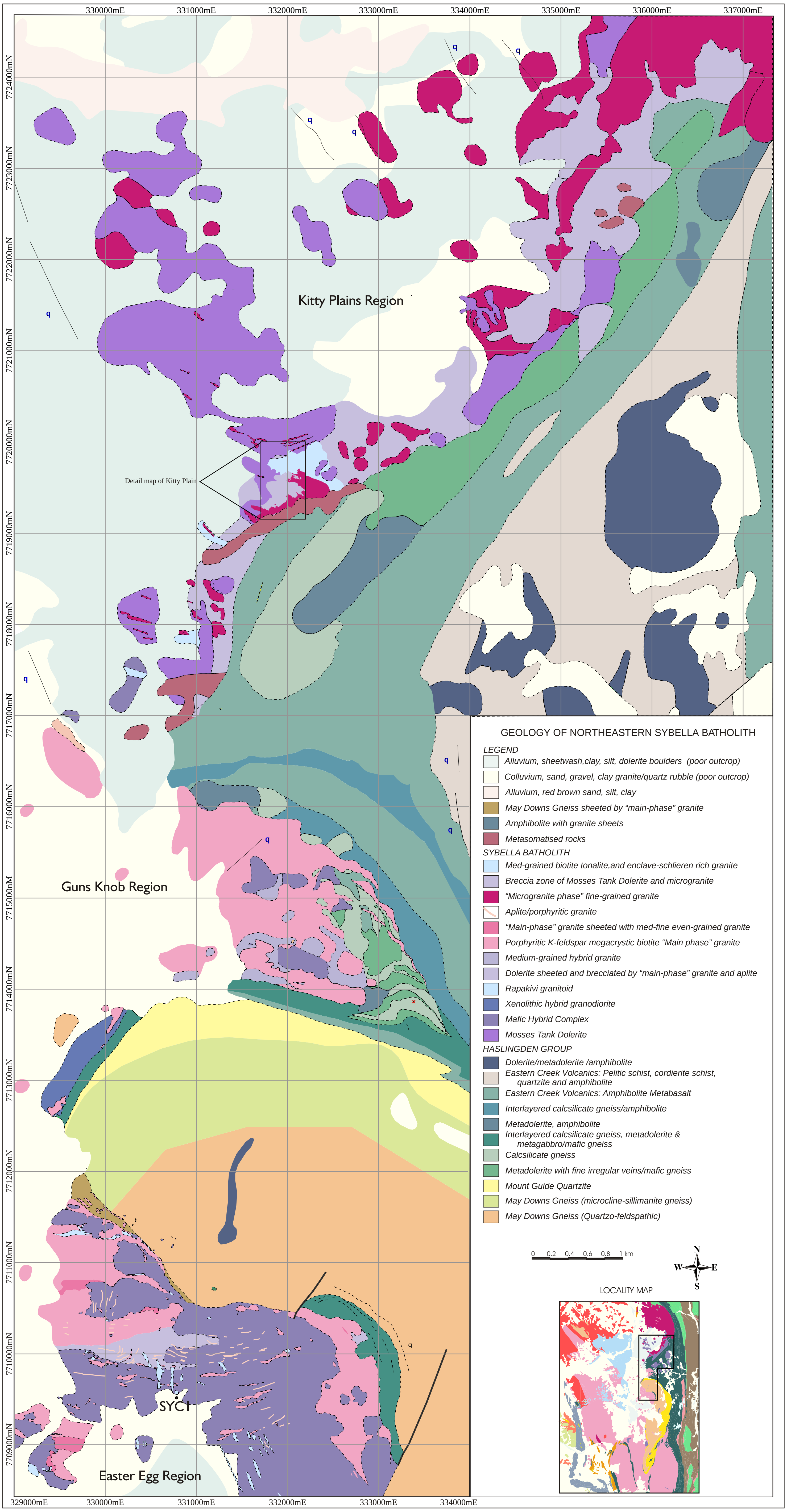
CHAPTER 2

FIELD RELATIONSHIPS

2.1 INTRODUCTION

The study is focused on the northeastern plutons of the Sybella Batholith, located approximately 5km west of the Mount Isa Fault (Figure 1.2). This area includes: the northeastern intrusive margin within the Kitty Plain region; Guns Knob region; and the Easter Egg region (Figure 2.1). The area described is semi arid and outcrops typically have a sparse cover of scrubby turpentine shrubs, low trees and spinifex grass. The Sybella Batholith within the map area consists of five main rock types: (1) Mosses Tank dolerite (W2 dolerites of Ellis & Wyborn 1984); (2) magnetite-rich diorite to quartz-diorite hybrids (Mafic Hybrid Complex); (3) rapakivi granitoids; (4) Main Phase granite; and (5) Kitty Plain microgranite. The Main Phase granite comprises the largest outcropping area of the batholith, although in the northern region there are significant mafic and intermediate intrusions. In this region, the Main Phase granite intruded as a sheeted complex that in places coalesced to form larger intrusive bodies. Field mapping was complimented by lithological logging of 500 m of SYC1 diamond drill core from the Easter Egg granite (locally termed “Slaughter Yard”) from Mount Isa Mines Exploration (Figure 2.2).

This chapter looks at the field relationships of these rocks to determine the extent and role of fractionation, mingling, and hybridization prior to emplacement (at depth) and during the intrusion of different phases of the batholith. Petrographic and geochemical evidence is presented in Chapters 3 and 4 respectively. Previous workers have not discussed the intrusive relationships between the mafic, intermediate and felsic phases in the northeastern Sybella Batholith, although the geochemical variation in the Mosses Tank Dolerite near microgranite intrusions was interpreted to have resulted from hybridization (Ellis & Wyborn 1984) and net-veining between these units was observed by Blake (1981). However, interactions between any of the other intrusions have not been studied.



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Kitty Plains Region
Detail map of Kitty Plain
Guns Knob Region
Easter Egg Region
SYC1
GEOLOGY OF NORTHEASTERN SYBELLA BATHOLITH
LEGEND
Alluvium, sheetwash,clay, silt, dolerite boulders (poor outcrop)
Colluvium, sand, gravel, clay granite/quartz rubble (poor outcrop)
Alluvium, red brown sand, silt, clay
May Downs Gneiss sheeted by “main-phase” granite
Amphibolite with granite sheets
Metasomatised rocks
SYBELLA BATHOLITH
Med-grained biotite tonalite,and enclave-schlieren rich granite
Breccia zone of Mosses Tank Dolerite and microgranite
“Microgranite phase” fine-grained granite
Aplite/porphyritic granite
“Main-phase” granite sheeted with med-fine even-grained granite
Porphyritic K-feldspar megacrystic biotite “Main phase” granite
Medium-grained hybrid granite
Dolerite sheeted and brecciated by “main-phase” granite and aplite
Rapakivi granitoid
Xenolithic hybrid granodiorite
Mafic Hybrid Complex
Mosses Tank Dolerite
HASLINGDEN GROUP
Dolerite/metadolerite /amphibolite
Eastern Creek Volcanics: Pelitic schist, cordierite schist, quartzite and amphibolite
Eastern Creek Volcanics: Amphibolite Metabasalt
Interlayered calcsilicate gneiss/amphibolite
Metadolerite, amphibolite
Interlayered calcsilicate gneiss, metadolerite & metagabbro/mafic gneiss
Calcsilicate gneiss
Metadolerite with fine irregular veins/mafic gneiss
Mount Guide Quartzite
May Downs Gneiss (microcline-sillimanite gneiss)
May Downs Gneiss (Quartzo-feldspathic)
0 0.2 0.4 0.6 0.8 1 km
N
W
E
S
LOCALITY MAP

Figure 2.1

Geological map of northeastern Sybella Batholith. Different phases of the Sybella Batholith intrude the Haslingden Group rocks (Eastern Creek Volcanics, May Downs Gneiss and Mount Guide Quartzite) and include: (1) the northern Mosses Tank Dolerite; (2) the southern magnetite-rich dolerite to diorite Mafic Hybrid Complex; (3) rapakivi granitoids; (4) Main Phase granite (Guns Knob and Easter Egg Granite); and (5) the southern portion of the Kitty Plain Microgranite. The granites and felsic hybrids intruded as sheets into the mafic complex and surrounding country rocks.

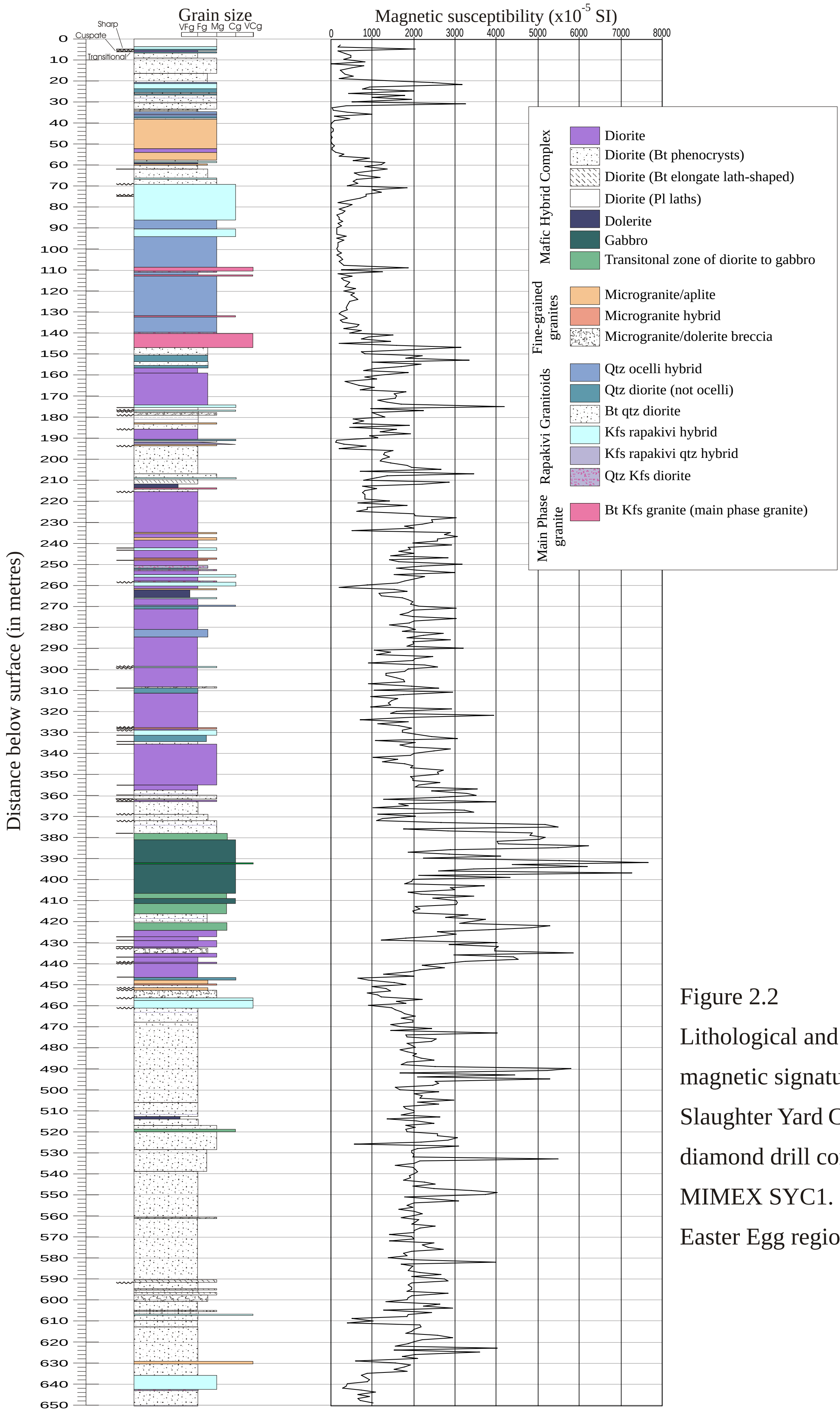


Figure 2.2 Lithological and magnetic signature of Slaughter Yard Creek diamond drill core MIMEX SYC1. Easter Egg region.

Mingling and mixing of magmas of contrasting (and similar) compositions within the batholith is an important indication of processes that occurred during the evolution of magmas within the region (Sparks & Marshall 1986; Huppert & Sparks 1988). Magmas that blended to form a homogeneous composition are “mixed” or “hybrid” magmas, whereas “mingling” refers to magmas that are mixed physically, but remain heterogeneous with the presence of enclaves, banding etc. Features that enable recognition of mixing of magmas at mesoscopic or outcrop scale include the occurrence of mantled or unmantled quartz and K-feldspar xenocrysts (minerals that did not crystallize in the rocks they are observed in), presence of large crystals (e.g. plagioclase phenocrysts) in a fine-grained groundmass, the presence of enclaves, and gradational or diffuse contacts between rocks of different composition with an intermediate composition (e.g. Vernon 1983; Didier & Barbarin 1991 and references therein). In addition, the distinction is made between enclaves, which are globules of magmas included while molten, and xenoliths, which are solid fragments of rock derived from external source (Vernon 1983). This distinction is important in determining the timing relationships between the different rock types.

The degree of interaction between the compositionally different (and similar) magmas can in part be determined by the nature of the intrusive contacts. Contacts can be characterized as transitional over a number of metres, gradational over tens of centimetres, diffuse over one to two centimetres, or sharp (including lobate and crenulate). The type of contact is indicative of the rheological properties of the different magmas at the time of intrusion and the tectonic influences acting during their emplacement. The nature of contacts between the different units in the batholith and their intrusive relationships were characterized in this fashion.

The Sybella Batholith intruded undifferentiated mafic and metasedimentary units of the Eastern Creek Volcanics and the May Downs Gneiss. These country rocks were strongly deformed prior to emplacement of the batholith and may represent either basement otherwise unidentified in the region or units from the Haslingden Group deformed before (or early synchronous) with the intrusion of the granite (Stewart & Blake 1992 and reference therein; Figure 1.3). A variety of foliations developed in different parts of the batholith. The origin of these foliations and their timing of formation relative to magma flow and crystallization are discussed in Chapter 5.

The I.U.G.S. nomenclature (Streckeisen 1976) for igneous rocks is followed, and the term granitoid is applied to the broad spectrum of granitic compositions, namely tonalite, granodiorite and granite.

2.2 BROAD SCALE RELATIONSHIPS AND GEOPHYSICS

Geophysical surveying carried out by Mount Isa Mines has highlighted some of the distinctive characteristics of the batholith (e.g. Coleborn 1999). Radiometric (Figure 2.3) and aeromagnetic (Figure 2.4-5) images are from Coleborn (1999) and interpretations of the geophysical signatures of the different phases of the Batholith and structures are based on the extensive field mapping undertaken during this project (Figure 2.1). Figure 2.5 is a detailed aeromagnetic image, with domains defined by Coleborn (1999) and unit outlines from Figure 1.2 overlaid to enable easy correlation. The radiometric dataset used a red/green/blue algorithm that assigns red to potassium, green to uranium, blue to thorium. Many of the geological units mapped in this study (Figure 2.1) and Mount Isa regional geological mapping (Figure 1.2) are identifiable from the aeromagnetic and radiometric images. A map of the north Sybella Batholith compiled from the different rock units is in Figure 2.6 and Table 2.1 highlights the distinctive character of the different units.

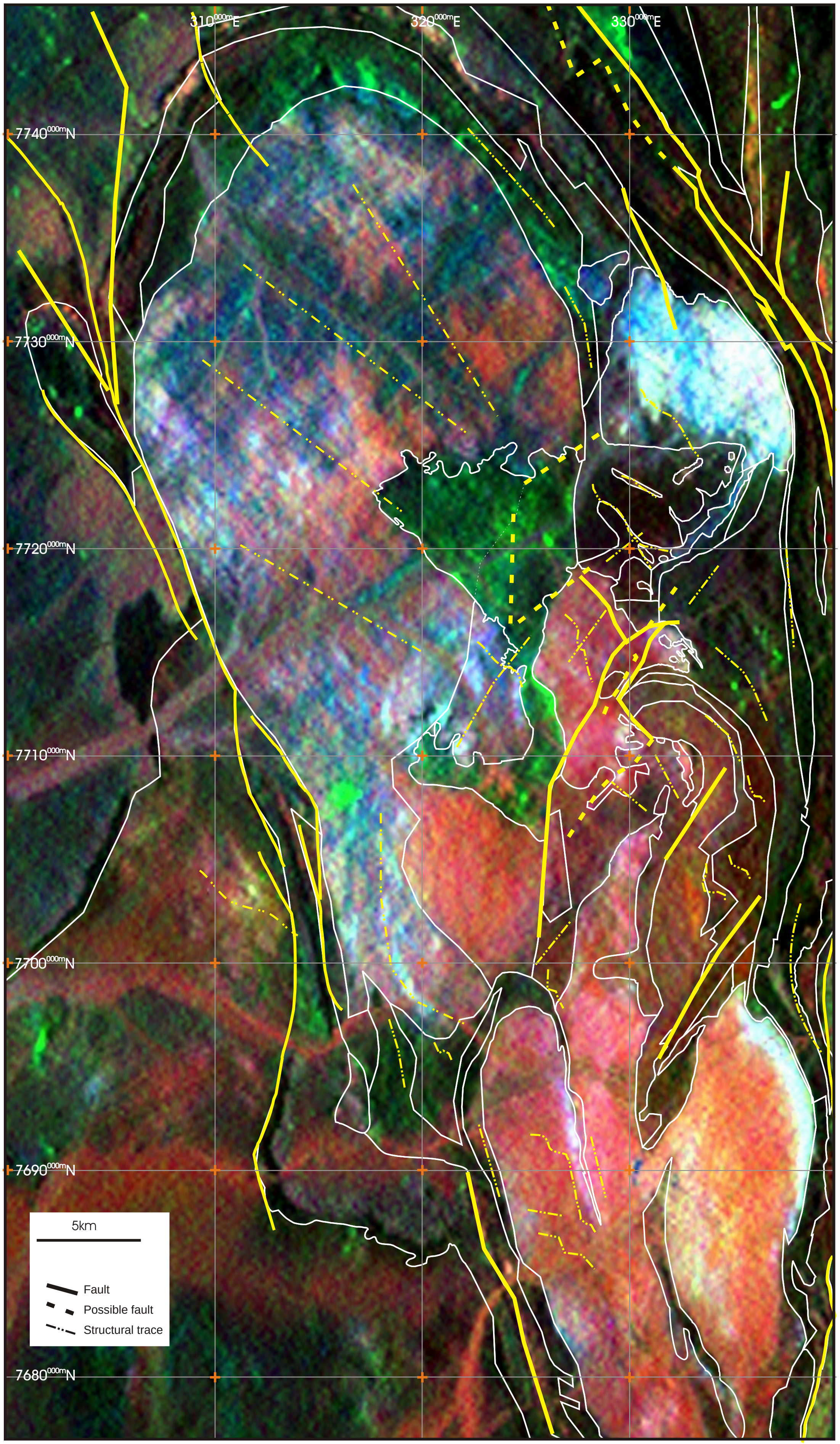
Emplacement of the Sybella Batholith magmas occurred as distinct phases (Figures 1.2 and 2.1). The broadly doleritic to dioritic magmas of the Mafic Hybrid Complex and Mosses Tank Dolerite represents a significant mafic component in the batholith and a suite of rapakivi granitoids represents a minor constituent. Other phases include the volumetrically largest part of the batholith, the K-feldspar megacrystic syenogranites known as ‘Main Phase’ (Wyborn *et al.* 1988), and associated porphyritic and aplitic dykes, and a phase of microgranites. The β-quartz phase is located in the northwestern section of the Sybella Batholith, outside the studied areas, but is identified in the geophysical maps.

UNIT	GEOPHYSICAL PROPERTY-RADIOMETRICS	GEOPHYSICAL PROPERTY – MAGNETICS	COMMENT
Beetle Creek	Green	Low	Cover
MOUNT ISA GROUP	Lt green/orange/pink	Low	
McNAMARA GROUP	Blue/green/pink	Low	
SYBELLA BATHOLITH			
Hybrid granite		High	
Microgranite	Blue/white	Low	NW orient structure
Main Phase granite	Pink/orange/white	Low	NW structures folded by NE fabric
B-Quartz Phase granite	Blue/white/pink	Low	NW orient structure
Kitty Plains Dolerite	Dark red/green	Low	Large scale net veining by microgranite
Dolerite to quartz-diorite	Mottled pink/blue/green	High	NW orient structure
HASLINGDEN GROUP			
Myally Subgroup		Low	
Eastern Creek Volcanics	Green/blue	High	
Mount Guide Quartzite	Mottled orange/green	Low	
May Downs Gneiss (pelitic and psammitic members)	2 units blue/green mottle yellow/orange/pink	Low (high edge or metagabbro ECV? Or dolerite plunge beneath)	Large scale fold with late NE orientated folding

Table 2.1 Geophysical properties of the Northern Sybella Batholith.

Two distinctive groups of mafic intrusions with different magnetic signatures (Figures 2.4) occur within the area of Figure 2.1. Within the northern section at Kitty Plains, the Mosses Tank Dolerites are a suite of mafic rocks that have very low magnetic susceptibilities. These dolerites were intruded by microgranite and this is indicated by the higher radiometric signature in a network pattern. The rounded and clustered appearance of the dolerite intrusions in the magnetic image (Figure 2.5) may be correlated with the complex nature of the dolerites in outcrop, and interpreted as indicating multiple intrusions rather than a single large intrusion. The mafic intrusions associated with the Guns Knob and Easter Egg granites to the south of Kitty Plains collectively called the Mafic Hybrid Complex, have very high magnetic susceptibilities. The mafic intrusion at the southern end of Kitty Plain is more highly magnetic than the northern low magnetic dolerites and is correlated with the Mafic Hybrid Complex. Both the Mosses Tank Dolerites and the Mafic Hybrid Complex are coincident with large gravity anomalies.

The radiometric images of the north Sybella Batholith clearly differentiate the different granitic phases (Table 2.1, Figure 2.3). The phases of the granites appear uniform in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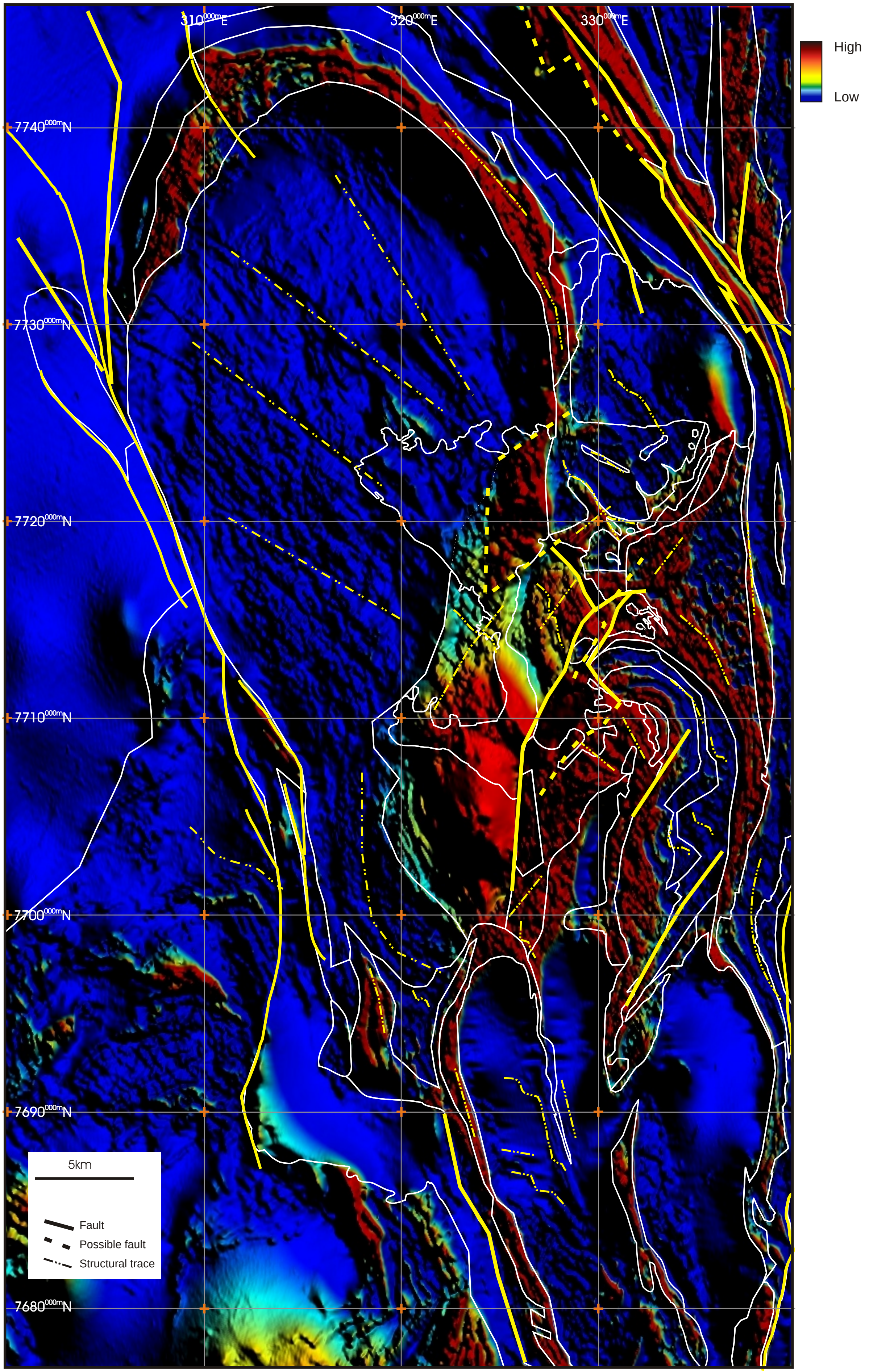
7700000mN
7690000mN
7680000mN
5km
Fault
Possible fault
Structural trace

Figure 2.3

Radiometric U-K-Th image with interpreted structures (yellow), structural grain (yellow dashed line) and interpreted geological boundaries (white) of the northern Sybella Batholith. The Main Phase granite is highly potassic, the β-Quartz phase (Keithys Granite) is less potassic but contains more uranium and thorium, and the Kitty Plains microgranite is enriched in uranium and thorium. Data from MIM Exploration with Red/Green/Blue Algorithm from Coleborn (1999).

Red – Potassium
Green – Uranium
Blue – Thorium



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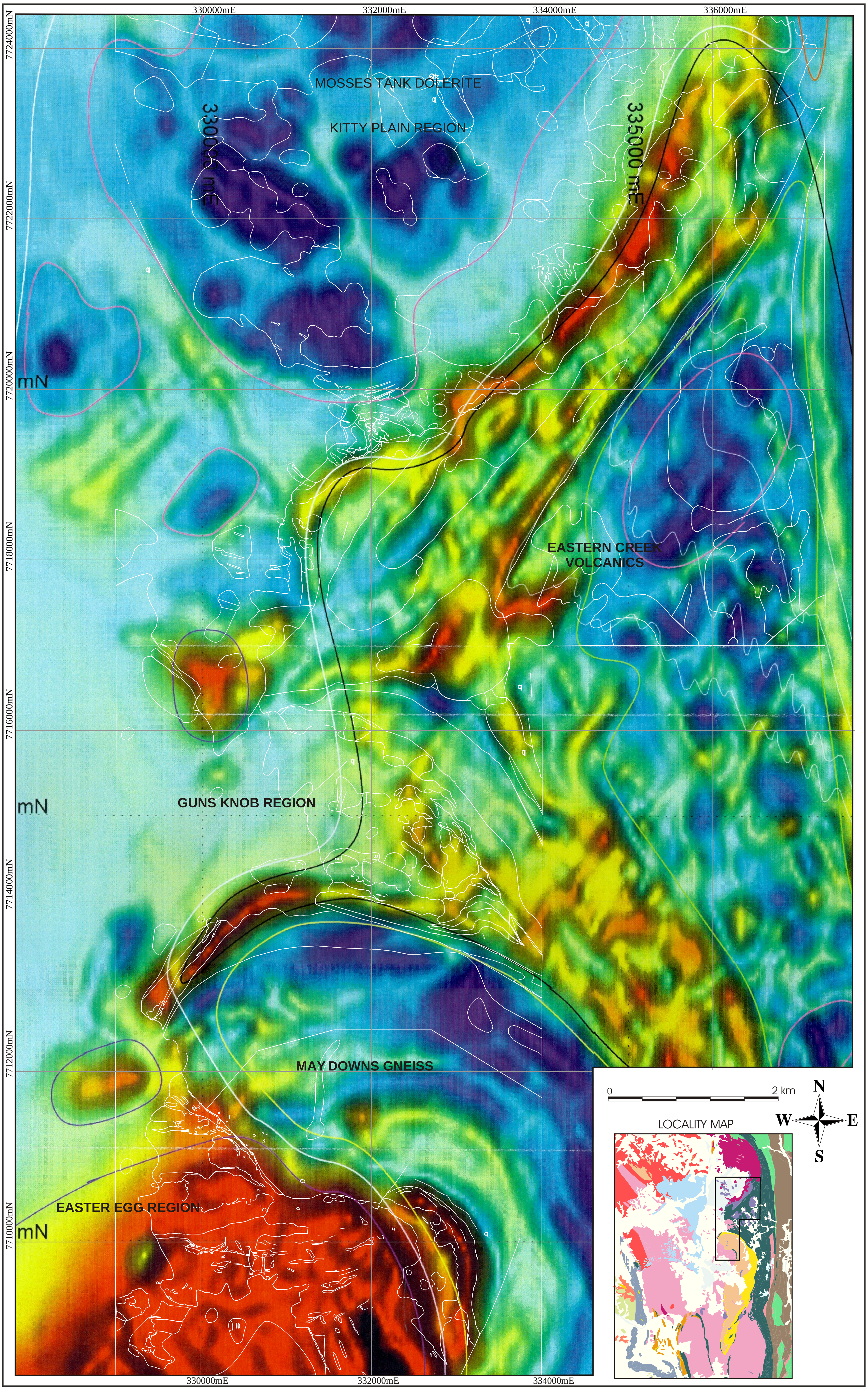
7730000mN
7720000mN
7710000mN
7700000mN
7690000mN
7680000mN
5km
Fault
Possible fault
Structural trace
High
Low

Figure 2.4

Aeromagnetic image with interpreted structures (yellow), structural grain (yellow dashed line) and interpreted geological boundaries (white) of the northern Sybella Batholith. The Main Phase granite, β-Quartz phase granite (Keithys Granite) and the Kitty Plains microgranite, and the Mosses Tank Dolerite has low detected magnetic susceptibility, whereas the Mafic Hybrid Complex within the Easter Egg Granite region is strongly magnetic. Data from MIM Exploration with ER Mapper Colourdrape with overhead sunshade from Coleborn (1999).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7712000mN
7710000mN
MOSSES TANK DOLERITE
KITTY PLAIN REGION
330000 mE
335000 mE
mN
EASTERN CREEK VOLCANICS
GUNS KNOB REGION
mN
MAY DOWNS GNEISS
EASTER EGG REGION
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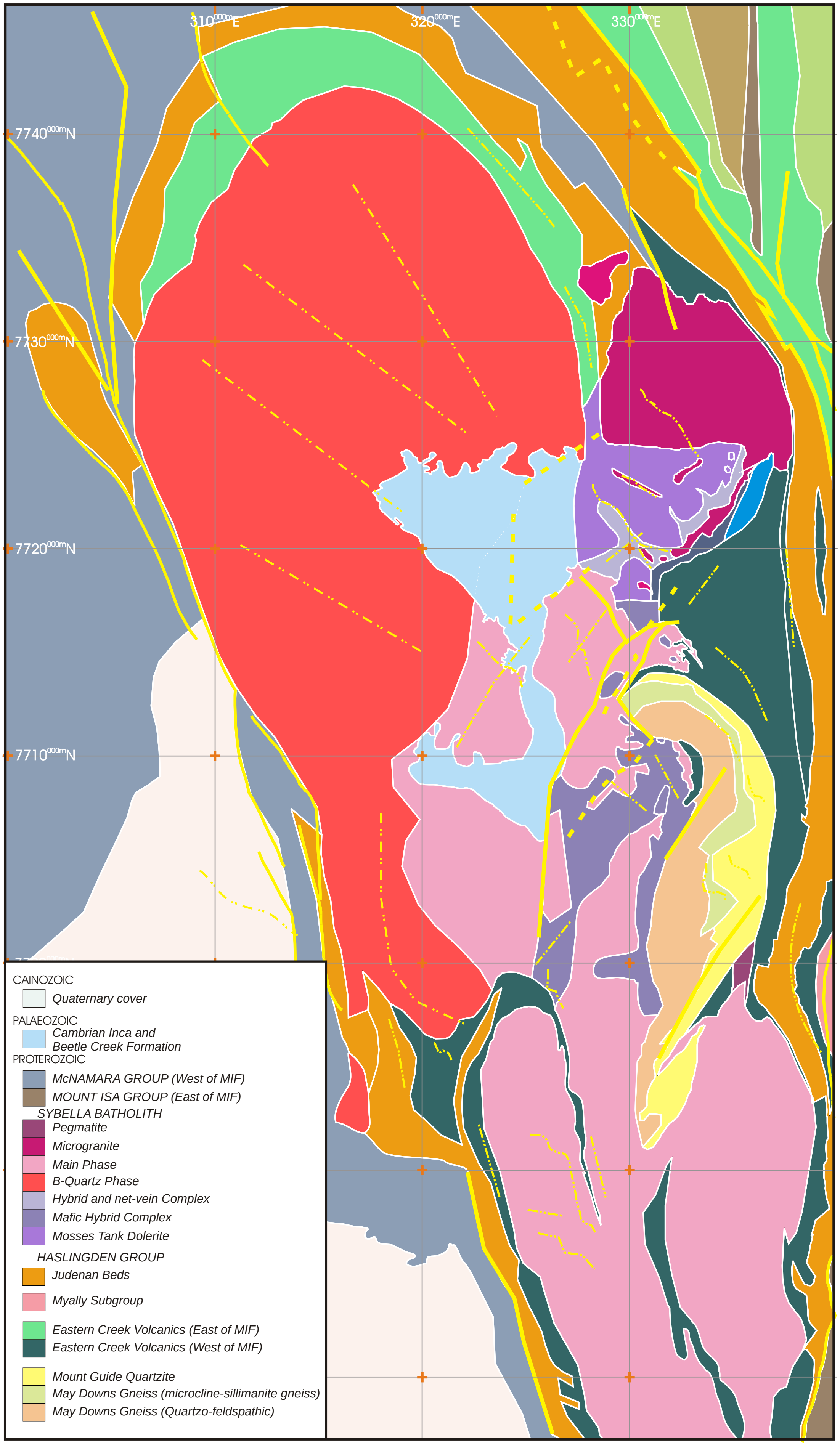
LOCALITY MAP

Figure 2.5

Detailed aeromagnetic image, with domains defined by Coleborn (1999) and unit outlines from Figure 1.2 overlaid. Data from MIM Exploration with ER Mapper Colourdrape with overhead sunshade from Coleborn (1999).



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7740000mN
7730000mN
7720000mN
7710000mN
CAINOZOIC
Quaternary cover
PALAEOZOIC
Cambrian Inca and
Beetle Creek Formation
PROTEROZOIC
McNAMARA GROUP (West of MIF)
MOUNT ISA GROUP (East of MIF)
SYBELLA BATHOLITH
Pegmatite
Microgranite
Main Phase
B-Quartz Phase
Hybrid and net-vein Complex
Mafic Hybrid Complex
Mosses Tank Dolerite
HASLINGDEN GROUP
Judenan Beds
Myally Subgroup
Eastern Creek Volcanics (East of MIF)
Eastern Creek Volcanics (West of MIF)
Mount Guide Quartzite
May Downs Gneiss (microcline-sillimanite gneiss)
May Downs Gneiss (Quartzo-feldspathic)

Figure 2.6

Compilation of geological units from geophysical data and regional mapping.

composition at the resolution depicted in the image. Porphyritic dykes and fine-grained granite which are whiter in colour on the radiometric image (Figure 2.3) occur near the margins of the Main Phase granites. Felsic intrusions have a uniformly low magnetic intensity signature; where there is interaction with the mafic magmas, the mixed and mingled units are more highly magnetic. This is particularly apparent at the margin of the Kitty Plains microgranite, where mapping has identified a complex mixed and mingled unit. Microgranite dykes with hybrid margins and magmatic shear zones with abundant magma mingling and hybridization correlate with structural/magnetic trends on Figures 2.4-5.

2.3 COUNTRY ROCKS

The Sybella Batholith intrudes the May Downs Gneiss and mafic gneiss, amphibolite and calcsilicate units currently assigned to the Eastern Creek Volcanics (ECV's), the basal units of the Haslingden Group (Figure 2.1). The batholith generally intrudes subparallel to the bedding and foliation in the country rocks, however it locally crosscuts the stratigraphy and tectonic fabrics. The May Downs Gneiss has historically been correlated with basement deformed in the Barramundi Orogeny but more recently was interpreted as the basal unit of the Haslingden Group by Connors *et al.* (1992).

2.3.1 May Downs Gneiss

The May Downs Gneiss (MDG) comprises three packages of rocks; quartzo-feldspathic gneisses, microcline-sillimanite gneisses and schists, and mafic gneisses (Figure 2.1). These rocks have undergone at least two major and one minor deformation (Gunter 1996), and two phases of partial melting. The older phase of migmatitic veins are concordant with the S_1 layer parallel foliation whereas a younger generation of veins are parallel to the axial planes of F_2 folds and the S_2 foliation (Connors *et al.* 1992). Because of the high strain and multiple deformation events that these rocks have been subjected to, the relationship of the mafic gneisses to the other rocks is unknown. Thin beds of quartzite occur at the margin of the May Downs Gneiss and these quartzite layers have strong upright folding (Figure 2.7b). Cross-beds in the quartzite indicate a sedimentary protolith. The quartzite units have been correlated with Mount Guide Quartzite, but may be quartzite layer from the MDG tectonically thickened by a series of folding events. This unit shares a boundary with the amphibolites and gneisses and it appears conformable.

The quartzo-feldspathic gneiss is compositely layered and comprises alternating biotite-rich and quartzo-feldspathic biotite-poor layers, the thickness of which varies from 5 to 100 mm (Figure 2.7a). Layer parallel and discordant leucosomes occur widely. The layering has been interpreted as bedding (Connors *et al.* 1992), and is parallel to bedding in the overlying Mount Guide Quartzite. Layering within the gneiss shows complex folding. Various small mafic and felsic intrusions occur within the May Downs Gneiss.

Microcline-sillimanite gneiss does not appear to be interlayered with sediments. It is irregularly foliated, with the dominant foliation broadly parallel to the quartzo-feldspathic and mafic gneisses (Gunter 1996). This unit is characterized by pink K-feldspar porphyroblasts, layering defined by metamorphic differentiation of biotite and microcline, and paucity of migmatitic melts (Gunter 1996). Cordierite is preserved in localized pods.

The mafic components of the May Downs Gneiss include foliated and massive amphibolites, metadolerites and metagabbros. These units exhibit varying degrees of migmatitic layering from absent to comprising approximately 20% of an outcrop. The metadolerite/gabbro is a complexly foliated hornblende (± pyroxene) – plagioclase gneiss with migmatitic layering that may be partial melt leucosomes (Figure 2.7c). Some of the migmatites were externally derived and injected into the mafic rocks (Figure 2.7d), although some appears to be internally derived with leucosomes not interconnecting and with no apparent migration of melt. The mafic gneiss was distinguished from the other mafic amphibolites by the presence of the migmatitic layering. Well-foliated mafic amphibolites occur in contact with migmatitic mafic gneisses (Figure 2.7e) and generally behave as a more competent body, although boudinage of the amphibolite and deformation in surrounding rocks obscure original relationships. Isoclinal and rootless folding and intrafolial folds indicate predominant foliation is associated with shearing as well as a folding deformation. The mafic units contain minor siliceous and calc-silicate interbeds (Figure 2.7fg) and they are located both within the main body of quartzo-feldspathic gneisses of the May Downs Gneiss and at the margin within the ECV's. The relationships between the mafic gneisses and the interlayered quartzites and calcsilicates are ambiguous.

Significant deformation in the mafic gneiss occurred prior to the emplacement of the batholith as unfoliated phases of Sybella granite intruded parallel to (Figure 2.7h) and crosscut (Figure 2.8a-c) strongly deformed amphibolite and mafic gneisses. Magmatic brecciation occurred along the sheeted northeastern margin of the undeformed granite in the Easter Egg region (Figure 2.8d). Clasts of amphibolite within the breccia have strong fabrics that are randomly orientated. In other areas, strongly foliated xenoliths of May Downs Gneiss, calcsilicate and amphibolite occur within weakly- to undeformed Main Phase granite (Figure 2.14cd) also indicating strong deformation prior to (or early synchronous with) emplacement of the Sybella Batholith at approximately 1670 Ma.

2.3.2 Eastern Creek Volcanics

The Eastern Creek Volcanics near the contact of the Sybella Batholith consist of a sequence of interlayered metabasalts and metasediments intruded by mafic igneous units that occur as sills, stocks and plugs (Wyborn 1987). Amphibolites are strongly deformed, lineated, and vesicles are preserved in some regions indicating a volcanic origin. Marginal to the contact with the Sybella Batholith, metadolerites and metagabbros occur as sills (20 m wide) with interbeds of calcsilicate and quartz-rich layers (5-6m wide)(Figure 2.8g). Some of the calcsilicates are sedimentary in origin and others are possibly a result of metasomatism of the mafic intrusives as layers are commonly not continuous for any large extent. (Figure 2.8gh and 2.9c). Metadolerite generally outcrops as rounded boulders or when more gneissic, as strongly layered pavement outcrops. Mafic gneisses are transitional to amphibolite (Figure 2.8f) with a strong cleavage and lineation developed, commonly outcropping in cigar-shaped or flattened platy rods. In some regions, partial melting of the metadolerite occurred with the formation of small (5 mm), oblate segregations to thin bands 1-2mm wide that define a fabric when deformed (Figure 2.8f). Gneissic banding in the metadolerites and metagabbro appears similar to the banding in the mafic gneisses within the May Downs Gneiss (Figure 2.7cd). A distinction between the mafic gneisses from within the MDG and ECV's was unable to be made. It is possible that the boundary between the MDG and basal ECV's (with interlayered calcsilicate, quartzite and mafic gneiss) is transitional, as the units appear conformable.

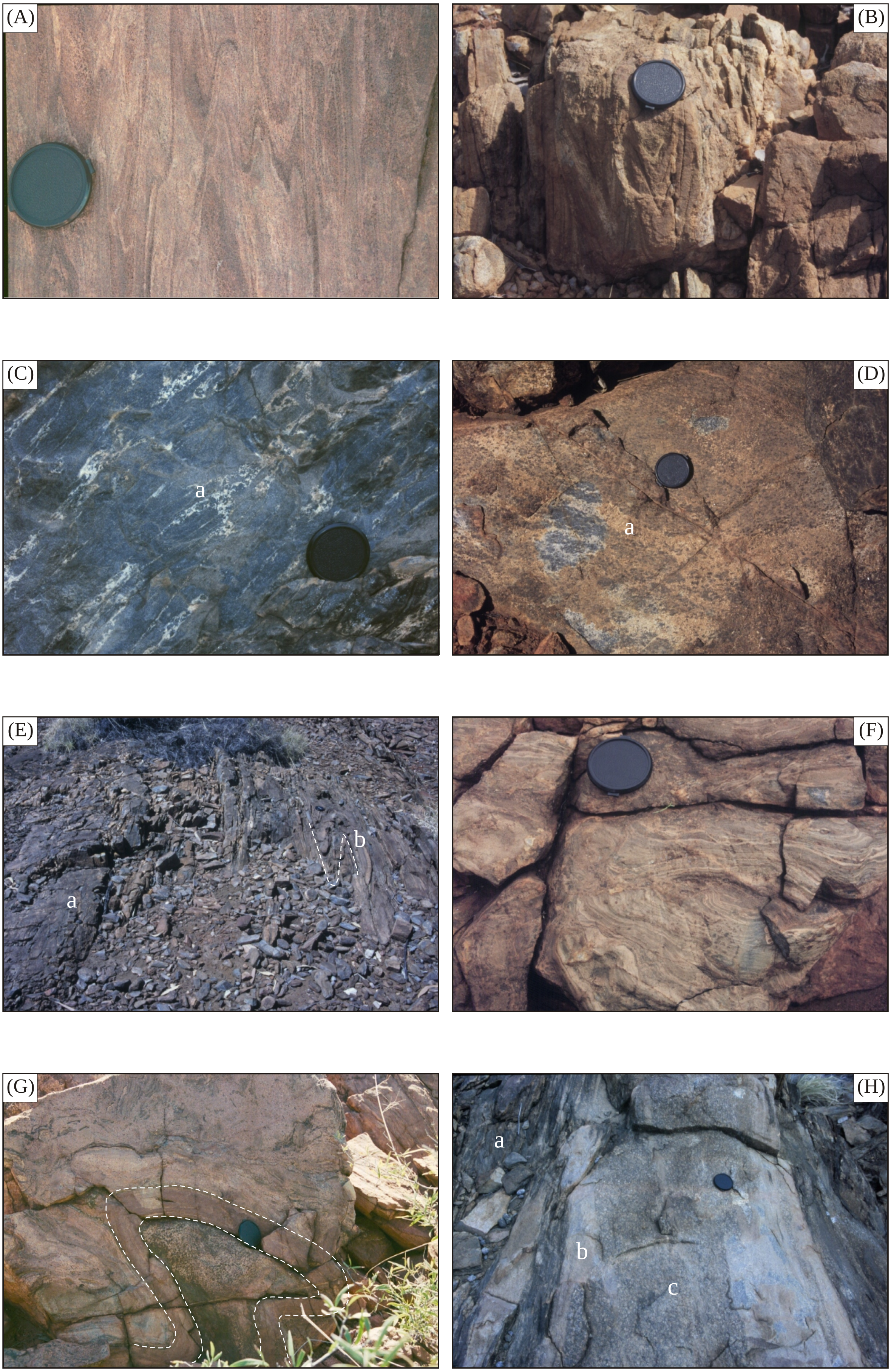

(A)
(B)
(C)
a
(D)
a
(E)
a
b
(F)
(G)
(H)
a
b
c

Figure 2.7

Country Rocks to the Sybella Batholith

(A) Strongly folded quartzo-feldspathic unit of May Downs Gneiss with biotite-rich layers. Rootless folds are common. Pavement outcrop.

(B) Quartzite layer with isoclinal fold. Vertical face, with bedding perpendicular.

(C) Mafic gneiss from within the May Downs Gneiss with migmatite layers parallel to the foliation (a), which are composed of plagioclase, quartz and pyroxene phenocrysts.

(D) The mafic gneiss locally has significant felsic layers that are up to 5 cm wide (a). These layers are generally parallel to the foliation, but also crosscut it.

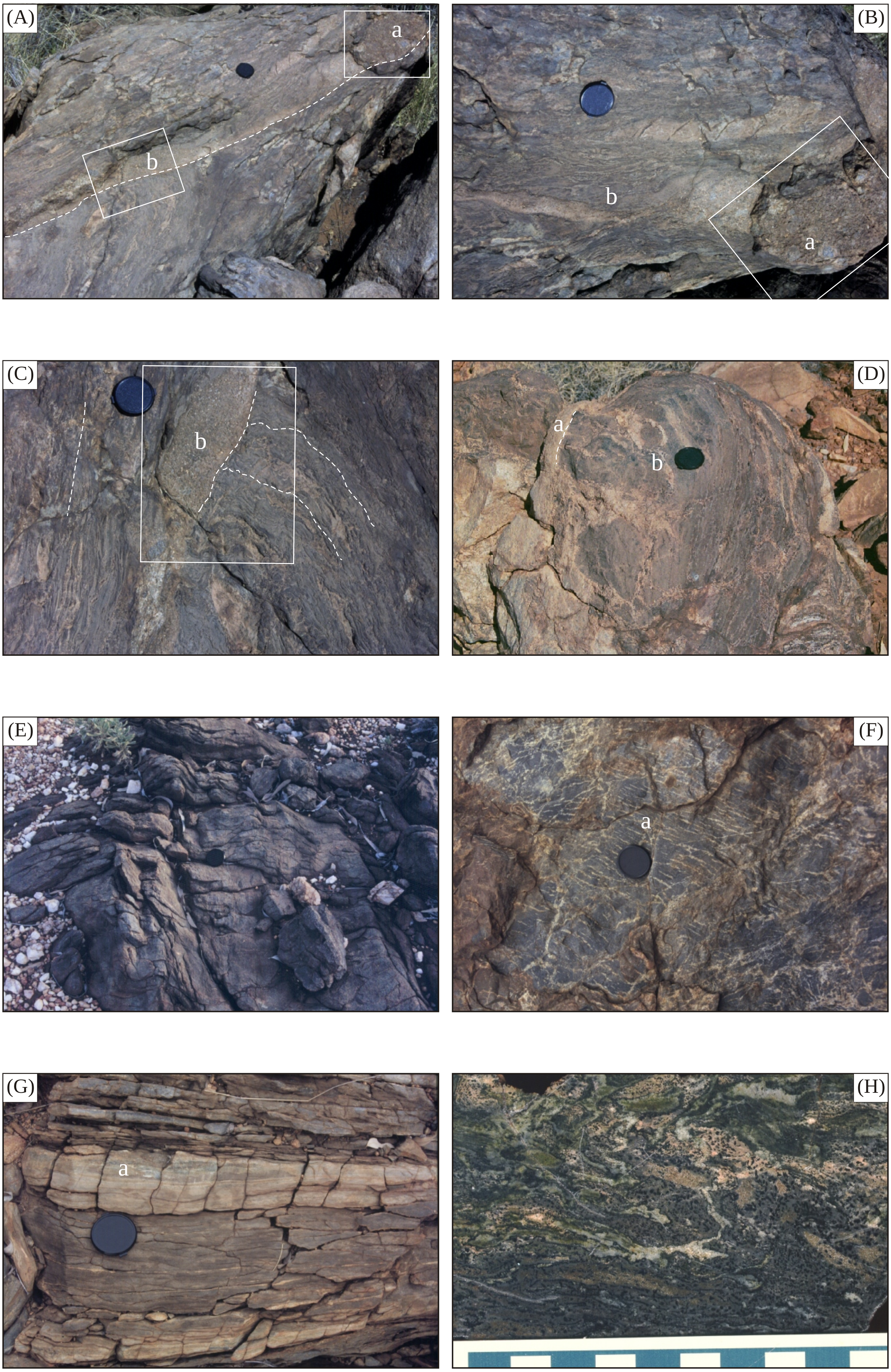
(E) Variation within the mafic units of the May Downs Gneiss ranges from a competent amphibolite body with no migmatite development (a), in contact with the strongly layered and folded mafic gneiss (b).

(F) Calc-silicates are strongly deformed, however the fabric is commonly irregular. They occur within the mafic gneiss/amphibolite units of the May Downs Gneiss and Eastern Creek Volcanics.

(G) Calc-silicate with quartz-rich layer folded around a metagabbro boudin is possibly a refolded fold within the May Downs Gneiss.

(H) Sybella Granite intrusion occurs parallel to the fabric in mafic gneiss (a). The granite has a fine-grained selvage (b) and coarse-grained phenocrystic texture characteristic of the Main Phase granite that is weakly deformed.

Lens cap used for scale is 55 mm.


(A)
a
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(B)
b
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(D)
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(H)

Figure 2.8

(A) Undeformed granite intruding across the fabric in the mafic gneiss; areas (a) and (b) are enlarged in (B) and (C).

(B) K-feldspar phenocrysts in granite (a) have a rapakivi texture similar to phases within the Sybella Batholith. The granite intruded parallel to the fabric in the mafic gneiss but also developed boudinage within the granite (b).

(C) Foliation in the mafic gneiss was rotated into parallelism with granite intrusion (b) but is also truncated by the granite.

(D) Irregular granite veinlets intruding amphibolite with small granite dyke on left side of boulder (a), illustrating contact zone marginal to larger granite intrusion.

(E) Folded amphibolite of the Eastern Creek Volcanics.

(F) Strongly aligned migmatite (partial melts) in metadolerite within the Eastern Creek Volcanics.

(G) Amphibolite with layers (possibly either felsic igneous intrusions or metasedimentary origin).

(H) Calc-silicate with numerous folds developed with epidote alteration (green) overprinting the fabrics.

Lens cap used for scale is 55 mm.

2.3.3 Metasomatic rocks of the Sybella Batholith

Alteration occurred marginal to the Sybella Batholith within the Eastern Creek Volcanics and May Downs Gneiss and within the different phases of the Batholith. In many localities metasomatism commonly resulted in the localization of post-emplacement deformation (during the Isan Orogeny) forming schists (with or without crenulations) within the granites and dolerites in areas that are otherwise undeformed.

Amphibolites, metadolerite and mafic gneisses marginal to the Sybella Batholith have experienced a range of metasomatism inferred to have occurred prior to or resulting from emplacement of the batholith. Skarn is locally developed within the metadolerites and mafic gneisses (Figure 2.9a) with alteration penetrating across fabric or layering. The origin of some of the calcsilicates may be a result of metasomatism of mafic and/or granitic components of the mafic gneisses and amphibolites (Figure 2.8g). Xenoliths of altered and deformed country rocks occur within the sheeted granites close to the contacts, having been incorporated during the later stages of emplacement (Figure 2.14c). Alteration of rounded "pillows" within the mafic gneisses occur (Figure 2.9b) and the origin of these are undetermined. Na-Ca metasomatism of amphibolites or metadolerites at the eastern margin of Kitty Plains is widespread. In outcrop, the rock appears red/brown to white with black to red/brown spots (Figure 2.9c) and in some localities it appears to be associated with granitic veining. Alteration of the Mosses Tank Dolerites occurred locally and may be similar to the metasomatism in the adjacent metadolerites of the country rocks (Figure 2.9d) with crosscutting Na-Ca alteration (albitization and pyroxene veining). Albitization of the microgranites in the Kitty Plains is common along the eastern margin of the batholith.

Alteration of granitic and country rocks is also associated with deformation during the Isan Orogeny. Formation of talc-chlorite alteration (with tourmaline porphyroblasts) of dolerites is commonly found in association with northwest-orientated pegmatites (Mica Creek Pegmatites; D_2 age, Isan Orogeny). Quartz-muscovite schists (+ chlorite + rutile), quartz-chlorite schists, quartz-cordierite schist result from metasomatism and deformation of microgranite, hybridized granite and mixed dolerite-granite rocks. Phlogopite-chlorite-plagioclase schist (crenulated) protolith was a dolerite and the albitites' protolith was microgranite. Epidote-chlorite schists are locally developed and

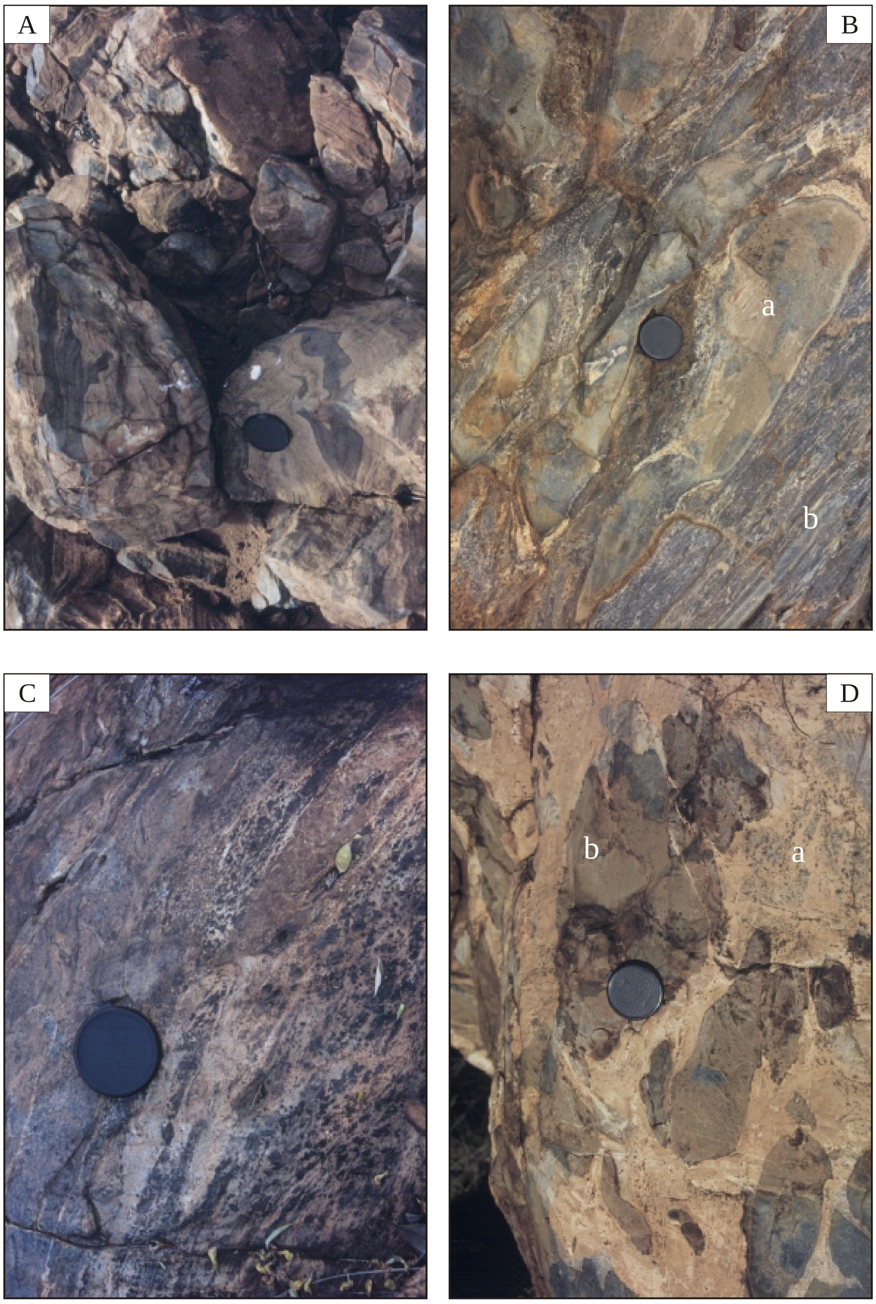

Figure 2.9

(A) Metasomatic alteration (including garnet and pyroxene) of amphibolite with layer parallel and crosscutting relationships.

(B) Oblate shaped zones of alteration occur within the migmatitic mafic gneiss.

(C) Na-Ca alteration of metadolerite/amphibolite ocurrs marginal to the Kitty Plains microgranite.

(D) Alteration of Mosses Tank Dolerite resulted in “bleaching” of the dolerite by albitization and crosscutting pyroxene veins (a), leaving relatively unaltered dolerite “pillows” (b).

result from alteration and deformation of amphibolites in the country rocks. Albitization and deformation of Main Phase granite associated with intrusion of pegmatite produced coarse-grained quartz-muscovite schists in the Guns Knob area. The orientation of the fabric within the altered rocks is different from the regional fabric development indicating a later time of formation. Epidote-hematite alteration cuts the granite and hybrid rocks in zones generally less than one metre wide in the Easter Egg area. Quartz and calcite are commonly associated with this veining. These zones tend to be strongly deformed locally and orientated in a north to north-east direction crosscutting the foliation within surrounding granite

2.4 SYBELLA BATHOLITH INTRUSIVES

2.4.1 Mafic Intrusive Suite

Mafic intrusions were emplaced throughout the development of the Sybella Batholith; most of the mafic intrusions were relatively early in the overall batholith history prior to the emplacement of the granite phases. The relative ages were inferred from field relationships. The mafic intrusive suite was divided into two main groups. The first is the group of low magnetic intensity dolerites from Kitty Plains Region collectively named the Mosses Tank Dolerite. The second includes the high magnetic susceptibility gabbroic to diorite rocks in the Easter Egg and Guns Knob regions referred to as the Mafic Hybrid Complex. The Mosses Tank Dolerites have been intruded by the microgranite, and the Mafic Hybrid Complex has been intruded by the rapakivi granitoids and Main Phase granite. The mafic intrusives exhibit a range of features resulting from the interaction of the magmas, including magmas of similar (mafic-mafic) and different (mafic-felsic) compositions.

MOSSES TANK DOLERITE

Located west of Mount Isa at Kitty Plains, the dolerites crop out as low hills on alluvial, predominantly black soil plains. The dolerites (W2 of Ellis & Wyborn 1984) were originally thought to occur as plugs intruding into the Sybella Batholith west of Mount Isa, however this study has revealed that the dolerites themselves are intruded by the microgranites. A range of fine- to coarse-grained dolerites occur within Kitty Plain, however the distribution of these units are irregular and contacts between them commonly transitional. Similarly, the magnetite content of the dolerites varies greatly from strongly magnetic in the fine- to medium grained dolerite with biotite phenocrysts (SI = 1660 - 8000 x 10^{-5}) to weakly or non-magnetic in the medium- to coarse-grained dolerite (SI < 400 x 10^{-5}). Evidence of the coeval and composite nature of the mafic intrusions at Kitty Plains is the formation of composite dykes with enclaves that have chilled and crenulate margins (Figures 2.10ac). Pillowing of dolerites within dolerite intrusions also occurs at a larger scale (Figures 2.10bd).

The Mosses Tank Dolerites intruded the Eastern Creek Volcanics (amphibolite metagabbro, metadolerite, metabasalt) to the east (Figure 2.1). Determining the extent of the Mosses Tank Dolerites was problematic, as the change from dolerites to amphibolites/metadolerites of the Eastern Creek Volcanics commonly appeared transitional with an increase in deformation and the appearance of migmatitic veining and metasomatism rather than a change in the original rock composition. Within the Mosses Tank Dolerite pluton, zones of amphibolite occur between the dolerite hills on Kitty Plain indicating localized deformation in otherwise undeformed rocks.

MAFIC HYBRID COMPLEX

In outcrop, the variation of the mafic rocks occurs on such a scale that it was unable to be represented at the scale of the map presented in Figure 2.1. Drill hole data (Figure 2.2 and Appendix I) identified a series of mafic intrusions that vary in grain-size and mineral assemblage and have different intrusive contacts. The mafic intrusions range from fine- to coarse-grained and equigranular to porphyritic with biotite and/or plagioclase phenocrysts (Figures 2.2, 2.11 ab). Three distinct groups of mafic intrusions were identified within the Mafic Hybrid Complex: (1) Coarse-grained gabbro (SI = 2000 - 7700 x 10^{-5}); (2) fine- to medium, equigranular dolerite to diorite (SI = 1000 - 3000 x 10^{-5}); and (3) fine- to medium-grained biotite porphyritic dolerite to diorite (SI = 1500 - 3000 x 10^{-5}).

Contacts between different mafic intrusions vary from transitional (over +1 m), to gradational (over +10 cm), to diffuse (1-2 cm). Contacts of this type indicate that after the magmas were emplaced interaction and hybridization between the different magmas

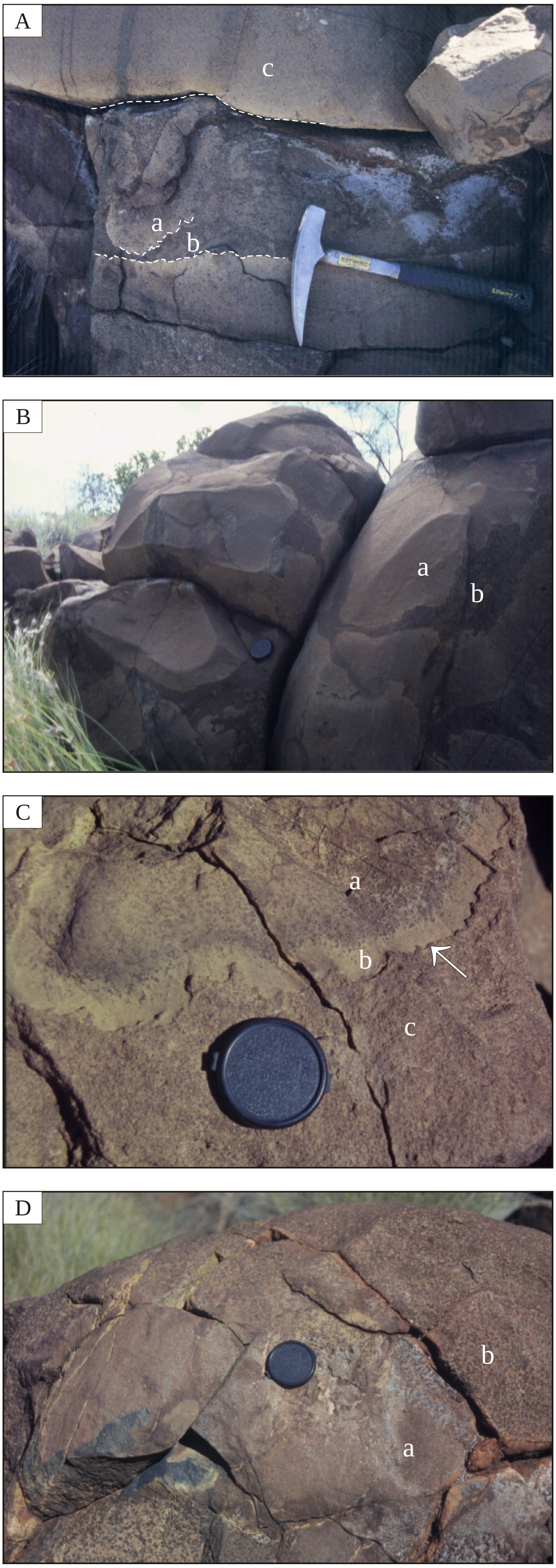
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Figure 2.10 Mosses Tank Dolerite intrusives

(A) A composite dyke with small fine-grained irregular pillows (a), in a coarse-grained matrix (b) has intruded the host dolerite (c). The host dolerite is also fine-grained and may have been included as the enclaves in the dyke.

(B) Pillows of fine-grained dolerite (a) occur within a coarse-grained dolerite (b). The contacts are irregular.

(C) The dolerite enclave shows a clearly defined medium-grained core (a) to fine-grained rim (b) in contact with the coarser grained host dolerite (c). The arrow indicates the cuspate and irregular contact between the host and enclave.

(D) Enclaves of fine-grained dolerite (a) occur in a coarse-grained metagabbro (sample 80) (b). The coarse-grained pyroxene in the metagabbro has been replaced by amphibole.

Lens cap used for scale is 55 mm.

Head of geological hammer is 18 cm long.

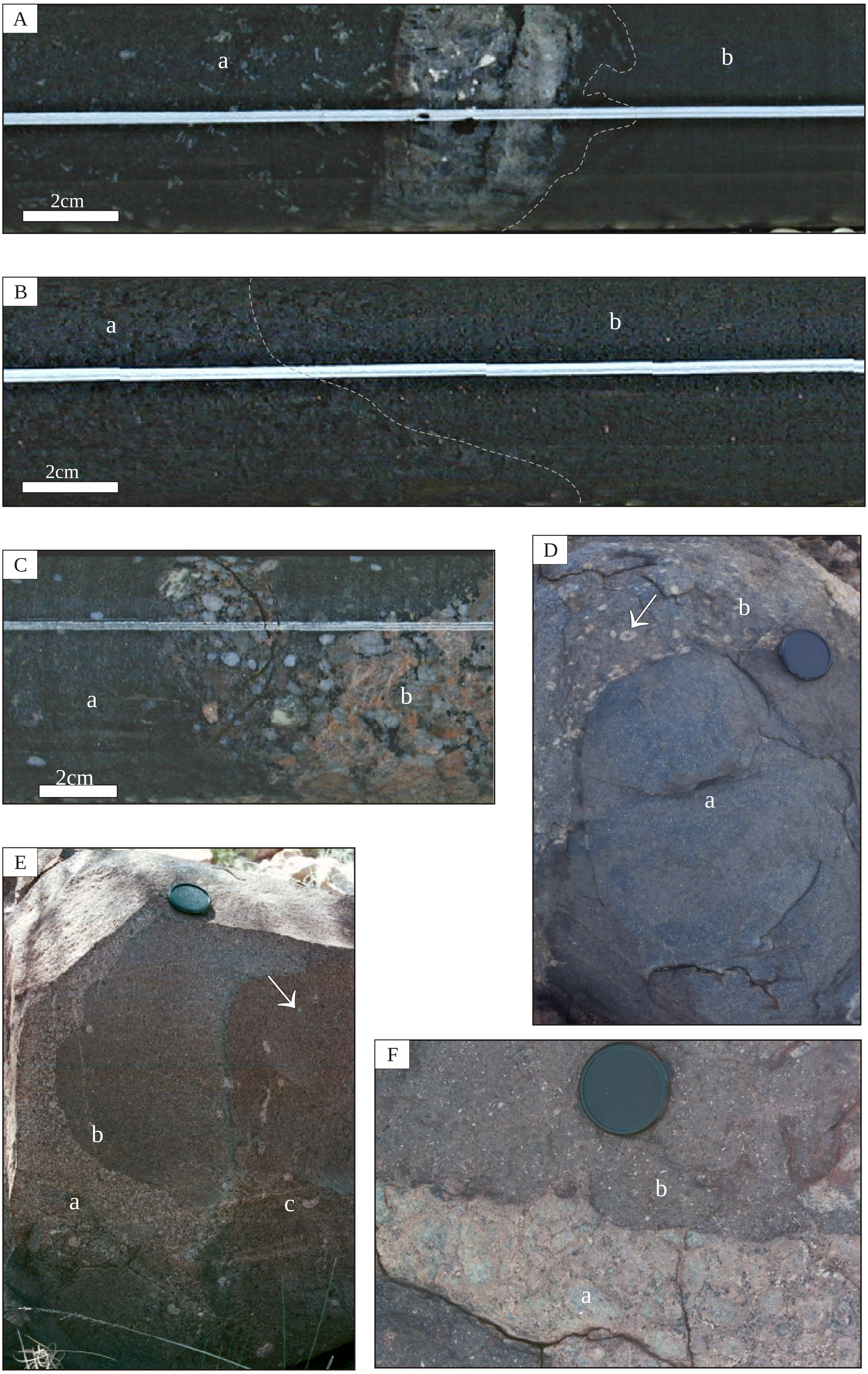
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Figure 2.11 Mafic Hybrid Complex

(A) The contact between the plagioclase phenocrystic medium-grained dolerite (a) and very fine-grained dolerite (b) is sharp and cuspate. Hybrid intruded near the contact within the phenocrystic dolerite. SYC1 Drill core, MIMEX.

(B) The contact between phenocrystic and elongate biotite-rich medium-grained dolerite (a) and fine, even-grained biotite-rich dolerite (b) is sharp. SYC1 Drill core, MIMEX.

(C) The quartz ocelli-rich diorite (a) is intruded by the Main Phase granite. The quartz in (a) was included in the mafic unit because of mixing with felsic magma. Hybridization between the granite and quartz-diorite occurs at the contact. SYC1 Drill core, MIMEX.

(D) Contact between mafic hybrid (a) and rapakivi granitoid (b). The rapakivi granitoid has large grey K-feldspar xenocrysts with white plagioclase rims (arrow). This unit (b) mixed at depth and intruded as a single intrusion, which did not interact with the mafic hybrid during its emplacement as shown by the sharp contact.

(E) A medium-grained hybrid with few K-feldspar phenocrysts (a) intruded the quartz xenocryst (arrow) bearing diorite (b). The contacts between the units are initially sharp but they become blurred as the hybrid intrudes further into the diorite. Interaction between the units forms an intermediate hybrid (c).

(F) Granite (a) intruded the plagioclase-rich diorite (b) with a predominantly sharp contact, however over a very small distance the boundary is blurred and this nature indicates that the diorite was not completely solidified at the time of granite intrusion.

Lens cap used for scale is 55 mm.

was able to occur (Figure 2.11e-f). Cuspate and sharp contacts also occur between the different mafic intrusions and this indicates that there was limited interaction of the magmas at emplacement level and variation was the result of the mafic magmas having evolved, fractionated and in some cases hybridized at depth before emplacement (Figure 2.11c).

Compositional variation within the gabbro to diorites and the intrusive relationships indicate a complex magmatic history. Large K-feldspar phenocrysts and rounded quartz grains rimmed by pyroxene and/or amphibole occur within different phases of the Mafic Hybrid Complex. These mineral grains are xenocrysts. Textures show that they are in disequilibrium, crystallizing in magma other than the mafic rock where they were observed and included in the mafic magma during hybridization. Xenocrystic-rich dolerite to diorite units occur as distinct intrusions within the mafic complex and throughout the core. Additionally, (in many of the mafic intrusions) the occurrence of xenocrysts commonly increases towards a gradational contact with rapakivi and quartz-rich intrusions (Figure 2.11ce). These features indicate that hybridization of some of the mafic magmas with felsic magma took place before emplacement into the batholith.

2.4.2 Main Phase Potassic Granitoid suite

The potassic granitoids consist of “Main Phase” megacrystic syenogranite (the dominant granite identified within the Easter Egg Region and Guns Knob Region), porphyritic to aplitic granite dykes and a suite of K-feldspar rapakivi granitoids. The granites were emplaced into the Mafic Hybrid Complex in the following sequence: rapakivi granitoids, Main Phase granite, porphyritic granite.

Many of these granitic rocks and rapakivi hybrids are locally strongly deformed, with L- and S-tectonite fabrics, and commonly have regions that display mineral recrystallization and mylonitic fabrics (discussed in Chapter 5).

RAPAKIVI GRANITOIDS

Textural and intrusive relationships indicate that the rapakivi granitoids were emplaced as discontinuous sheets, and irregular patches (Figure 2.1) into the Mafic Hybrid Complex. These granitoids represent volumetrically a minor constituent of the batholith. Contacts range from gradational to sharp (Figure 2.12ab). There is a large compositional variation within the rapakivi granitoids, although from the logged section of drill core, the granitoids were emplaced as distinct batches of crystal-rich magmas. Magnetic susceptibility measurements of many of the larger hybrid intrusions ranges from 0 to 300 x 10^{-5} SI, however where the hybrid intruded into the mafic units in very small intrusions, the magnetic intensity ranged up to 4000 x 10^{-5} SI (Figure 2.2).

The rapakivi-bearing granitoids range from quartz-diorite to granodiorite in composition. The predominant characteristics of the rapakivi granitoids include the large plagioclase rimmed K-feldspar phenocrysts, quartz xenocrysts, and clusters of mafic minerals in a medium to coarse-grained quartz-diorite to granodiorite groundmass (Figure 2.12d). The K-feldspar megacrysts within the hybrids are generally < 50 mm in size, grey in colour and rimmed by plagioclase. The thickness of the plagioclase mantle ranges from being incomplete or thin (Figure 2.12a) to very thick (10-15 mm) with minor or absent K-feldspar cores (Figure 2.12c). The K-feldspar megacrysts appear at mesoscopic scale to be zoned themselves with an inner core and outer rim (Figure 2.12a), are generally rounded, commonly exhibiting resorption prior to development of plagioclase mantle (Figure 2.12eg). Rounded and resorbed quartz xenocrysts (up to 15 mm in size) may be rimmed or unrimmed by mafic minerals. Clusters of mafic minerals, mafic microgranitoid enclaves (generally < 20 mm), occur heterogeneously throughout the groundmass (Figure 2.12d). These textures indicate that mixing between mafic and felsic magmas was a key component in forming the rapakivi granitoids, and aid in understanding the nature and compositional development of the batholith.

The varying proportion of phenocrysts results in the unit's characteristic textures. They range from rocks with numerous rounded and resorbed quartz xenocrysts (mantled or unmantled by mafic minerals) in a coarse-grained granodiorite groundmass with rare rapakivi K-feldspar xenocrysts (Figure 2.12b), to intrusions with greater than 60 percent

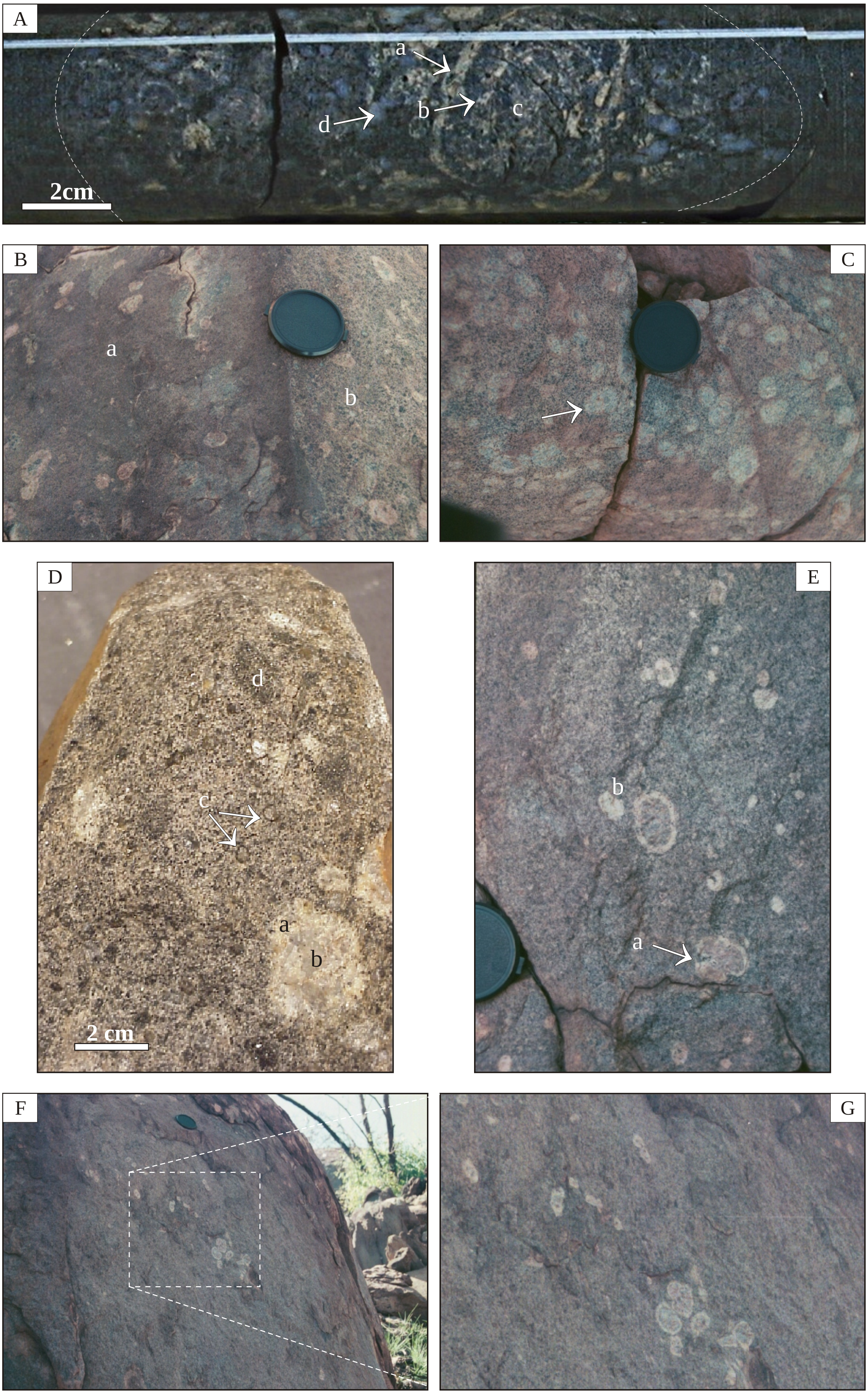
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Figure 2.12 Rapakivi Granitoids

(A) SYC1 Drill core from Easter Egg Region illustrating the diffuse intrusive contacts between dolerite and rapakivi granitoid intrusion. The large K-feldspar megacryst is zoned and has an outer rim of plagioclase (a), outer (b) and inner core (c) of K-feldspar. Large rounded quartz also occurs within the hybrid (d).

(B) Mafic hybrid with K-feldspar xenocrysts with very thick rapakivi rims (a) with a sharp contact with rapakivi-bearing granodiorite (b).

(C) Rapakivi granitoid with numerous rapakivi K-feldspars. Some of the rapakivi-textured phenocrysts have small or absent K-feldspar cores (arrow).

(D) Rapakivi granodiorite has large rounded K-feldspars with inclusion-rich plagioclase rims (a) with a grey K-feldspar core (b). Rounded quartz grains surrounded by mafic minerals (quartz ocelli) (c) occur in the matrix and clusters of mafic minerals (d) result from incomplete mixing of the mafic and felsic magmas.

(E) Rounded and irregular shaped rapakivi K-feldspar in quartz diorite hybrid (Mafic Hybrid Complex) (a) and some of the smaller rapakivi have thicker plagioclase rims and very small cores (b).

(F) Mafic hybrid with zone of rapakivi granitoid cutting across the outcrop leaving a trail of rapakivi K-feldspar.

(G) Close-up of the rapakivi trail in hybrid.

Lens cap used for scale is 55 mm.

rapakivi K-feldspar xenocrysts and containing mafic clusters and quartz xenocrysts in the groundmass (e.g. Figure 2.12c).

The gradational boundaries and the discontinuous sheet-like nature of the intrusions indicates that the rapakivi granitoids interacted with the still molten diorite, but the diorite was crystallized enough to allow propagation of fractures and intrusion (Figure 2.11f). Localized mixing during emplacement of the rapakivi granitoids occurred with trails of large rapakivi xenocrysts within quartz-diorite (Figure 2.12fg) marking the intrusive pathway and gradational boundaries with a zone of mixing between the diorite and rapakivi granitoid evident in core. Rapakivi granitoids intrusions are therefore interpreted to have been emplaced late during the crystallization of the Mafic Hybrid Complex, and prior to the emplacement of “Main Phase” granite.

“MAIN PHASE” MEGACRYSTIC SYENOGRANITE

The megacrystic Main Phase granite intruded the rapakivi granitoids, Mafic Hybrid Complex and country rocks (Eastern Creek Volcanics and May Downs Gneiss). The Main Phase granite is thought to have intruded into the country rocks as a shallow sheet (Connors *et al.* 1992), and the sheeted nature of the margins of the granite was evident from mapping outcrop as depicted in Figure 2.1.

The Main Phase granite intrusions are largely compositionally homogeneous with little variation, however biotite-rich zones within the Main Phase granite are present and small biotite-rich granite intrusions occur locally (Figure 2.13c). The Main Phase granites have distinctive K-feldspar megacrysts that are pink to white in colour. The granite in the Easter Egg region has two distinct crystal size populations with large rounded megacrysts of K-feldspar (up to 40 mm in size) and smaller subhedral K-feldspar in the groundmass (approximately 20 mm; Figure 2.13a). The granite in the Guns Knob Region has a less distinctive bimodal K-feldspar population, with K-feldspar phenocrysts < 20 mm in size and smaller K-feldspar in the groundmass (Figure 2.13b). The granite also contains small phenocrysts of plagioclase and rounded quartz and the groundmass minerals vary from medium- to coarse-grained. Magnetic susceptibility measurements of the Main Phase granite were commonly less that 500 x

10^{-5} SI although a few anomalous measurements up to 2000 x 10^{-5} SI were noted (Figure 2.2). The fabrics developed within the Main Phase granites range from mesoscopically undeformed (Figure 2.13b), to a magmatic alignment of K-feldspar phenocrysts, to L- and LS-tectonites (Figure 2.13de), mylonites and schists (discussed in Chapter 5).

Several different types of enclaves and xenoliths occur within the Main Phase granites, and the most common are the rounded hybrid enclaves with K-feldspar xenocrysts (Figure 2.13f). The K-feldspar xenocrysts are similar to the megacrysts in the enclosing granite. The occurrence of K-feldspar xenocrysts in mafic enclaves indicates that the enclaves were either molten when entrained in the granite which enabled the exchange of phenocrysts between the magmas, or that the enclaves were derived from an earlier formed hybrid which became entrained during emplacement. In the undeformed to weakly deformed granites these enclaves are rounded to oval shaped with a strong fabric defined by biotite alignment. Where the granite is strongly deformed, the mafic enclaves are stretched and occur as elongated biotite-rich zones. Angular xenoliths of rapakivi hybrid granitoid have been found in the Main Phase granite indicating that some of the hybrids were solid at time of inclusion (Figure 2.14a). The Main Phase granite was also intruded by dolerite indicating that mafic magmatism continued throughout the batholiths development. The dolerite pillowed within the granite, occurring as enclaves with sharp, crenulate and in some places chilled (finer-grained) contacts (Figure 2.14b).

Sheets of Main Phase granite near the margin of the batholith commonly have numerous xenoliths of country rock including May Downs Gneiss (MDG), foliated amphibolite and calcsilicate from the Eastern Creek Volcanics. The xenoliths of the Eastern Creek Volcanics units generally have a strong fabric developed with folds and alteration present indicating that the country rocks had experienced earlier deformation and alteration before granite emplacement (Figure 2.14c). Large rafts of MDG occur within the Main Phase granite. The MDG had also been strongly folded and deformed before its inclusion within the granite as the folds and compositional layers are truncated by the mesocopically undeformed granite (Figure 2.14d).

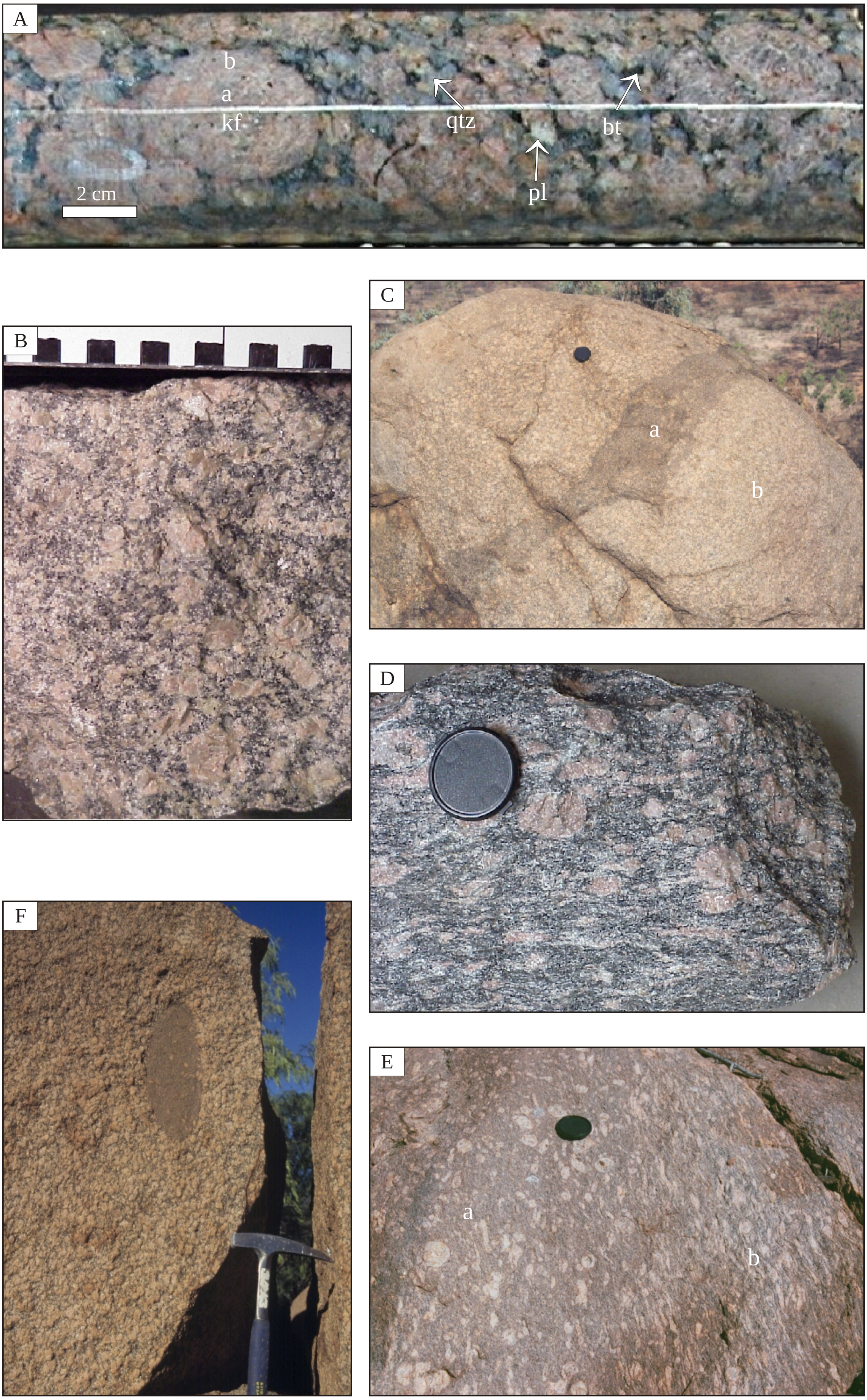
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Figure 2.13 Main Phase granite

(A) Main Phase granite from SCY1 drill core with a bimodal distribution of K-feldspar. K-feldspar megacrysts has core (a) and rim (b) morphology.

(B) Undeformed Main Phase granite from the Guns Knob region, with large (16 mm) K-feldspar and small groundmass K-feldspar. Centimetre scale.

(C) Undeformed Main Phase granite from Guns Knob region with biotite-rich granite dyke.

(D) Strongly deformed L-tectonite Main Phase granite from Easter Egg region

(E) Heterogeneously deformed Main Phase granite, with macroscopically undeformed granite (a) next to strongly deformed granite (b).

(F) Vertical outcrop face of the Main Phase granite, Guns Knob region. The biotite-rich enclave has K-feldspar xenocrysts that were included during an earlier mixing event. The enclave is aligned in a weak magmatic foliation.

Lens cap used for scale is 55 mm.

Head of geological hammer is 18 cm long.

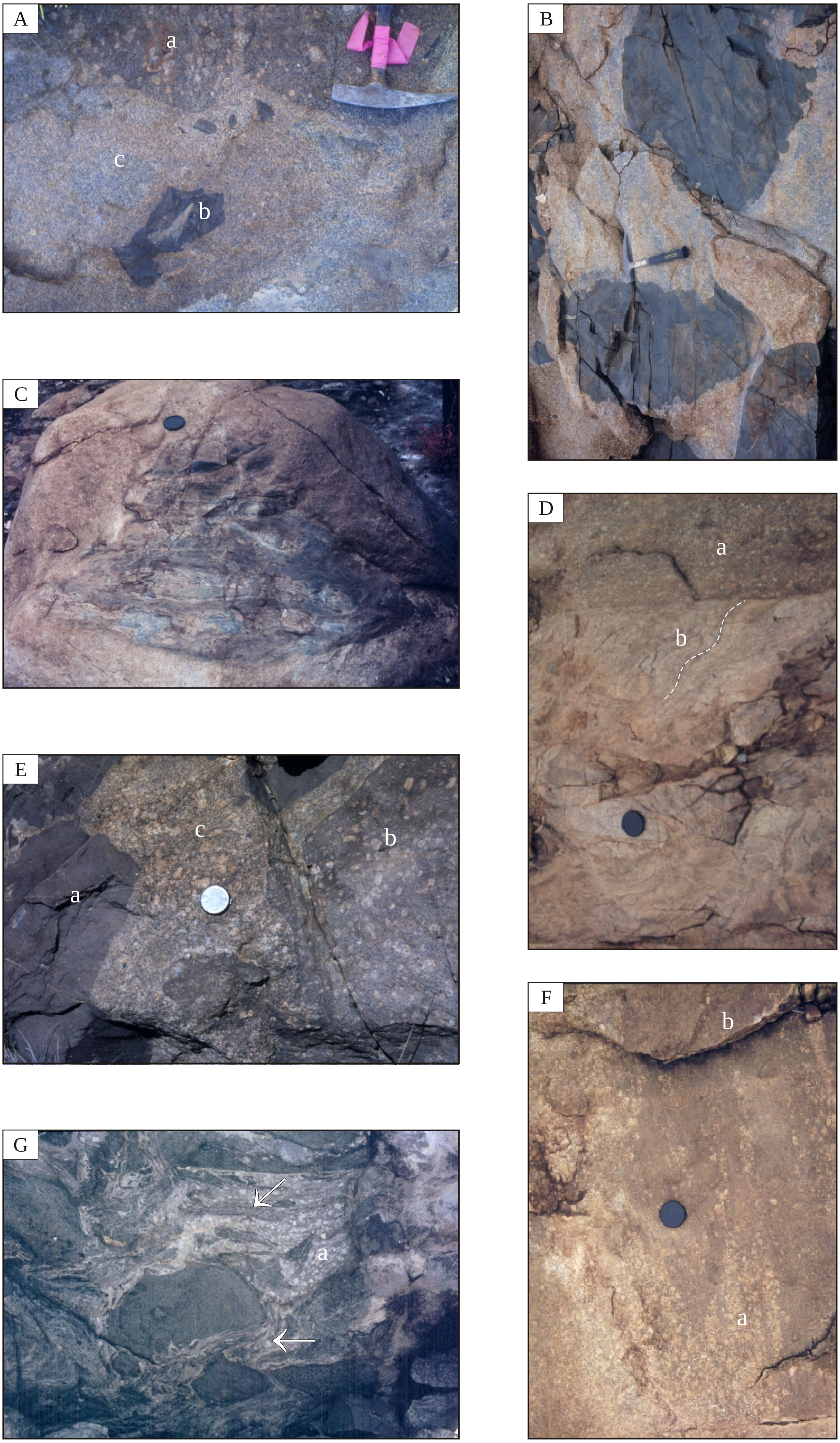
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Figure 2.14 Enclaves and xenoliths in the Main Phase granite.

(A) Angular rapakivi hybrid xenolith (a) and more mafic xenoliths (b) occur in the Main Phase granite indicating that they were solid at the time of their inclusion.

(B) Pillows of dolerite with crenulate contacts within Main Phase granite indicate coeval mafic and felsic magmatism. Pavement outcrop.

(C) Main Phase granite with xenolith of strongly deformed migmatitic mafic gneiss from the Eastern Creek Volcanics

(D) The undeformed Main Phase granite (a) is host to a large raft of the quartzo-feldspathic unit of the May Downs Gneiss (b). The fabric within the MDG is truncated by the sharp contact with the Main Phase granite. Pavement outcrop.

(E) The dolerite (a) and rapakivi hybrid (b) was intruded by the Main Phase granite (c). The contact between the Main Phase granite and rapakivi granitoid is gradational in places indicating local interaction between the magmas.

(F) Main Phase granite (a) intruded a hybrid (b). The interaction of the magmas due to emplacement during deformation resulted in trails of K-feldspar within the hybrid. Pavement outcrop.

(G) Main Phase granite (a) intruded and interacted with dolerite during deformation contributing to the formation of schlieren (arrows) and local hybrids. Vertical outcrop.

Lens cap used for scale is 55 mm.

Head of geological hammer is 18 cm long.

Where Main Phase granite sheets intruded the rapakivi granitoids, the contacts range from being sharp to gradational over a distance of a few metres (Figure 2.14e). Outcrops also illustrate the coeval granite-hybrid relationship with the interfingering of Main Phase granite and hybrid (Figure 2.14f). The interaction between the hybrid and the Main Phase granite was probably accentuated by deformation during emplacement as the trains of phenocrysts are aligned in a magmatic foliation.

The Main Phase granite generally intruded the units of the Mafic Hybrid Complex with sharp contacts, as the Mafic Hybrid complex was nearly solidified. However, interaction occurred at a small (centimetre) scale and local hybrids were produced (Figure 2.11f). A small net-vein complex formed at one location at the contact between the granite and the Mafic Hybrid Complex. The strongly aligned mafic enclaves in the granite, both with magmatic fabrics, indicate emplacement was accompanied by deformation. This is also shown by the formation of hybrids and schlieren at one location where Main Phase granite intruded as sheets in the dolerite (Figures 2.14g).

PORPHYRITIC AND APLITIC SYENOGRANITE

The Main Phase granite and the Mafic Hybrid Complex were intruded by fine-grained and commonly porphyritic granite dykes (Figure 2.15ab). These dykes commonly vary in composition along strike from porphyritic granite to aplite and are pegmatitic in places. The aplitic and porphyritic granite sheets are approximately 1.5 metres wide and commonly occur subparallel to the margin of the Main Phase granite sheets. The fabrics within the porphyritic granites are parallel to the margins. Where the aplite/porphyritic granite intrudes the Mafic Hybrid Complex in the Easter Egg region, the orientations vary, and dips range from sub-vertical to shallow and are openly folded (Figure 2.1). In places where the porphyritic granite intrudes the diorite as small (one metre wide) sheets, the granite changes in composition and is dominated by rounded quartz phenocrysts in a fine-grained groundmass (Figure 2.15c).

The porphyritic nature and fine-grained groundmass of these granite sheets indicates a shallow level of intrusion, and the paucity of pegmatites related to the Sybella Batholith in this region indicates that the magmas were undersaturated in water.

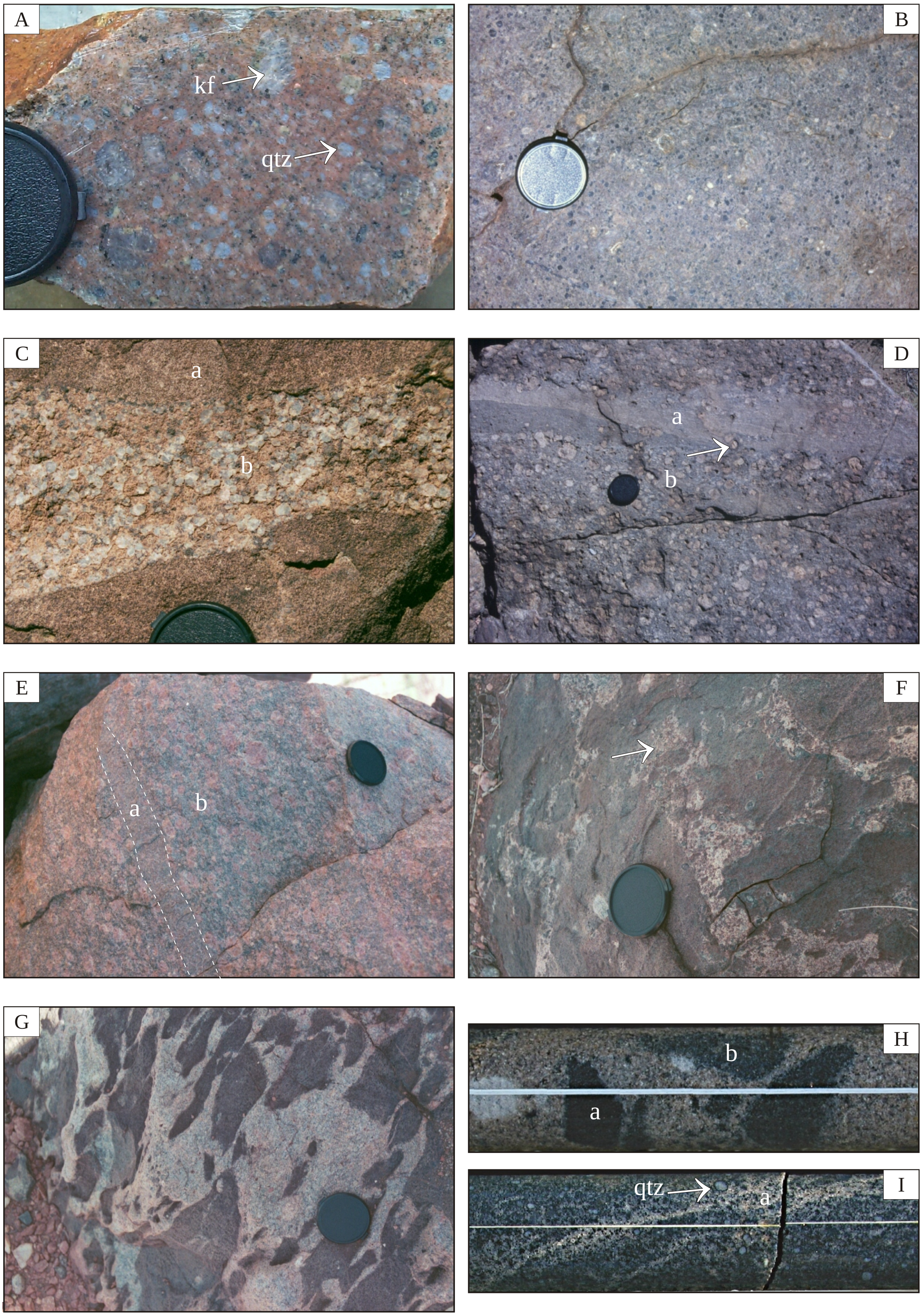
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Figure 2.15 Late stage intrusions

(A) and (B) K-feldspar porphyritic intrusion with large rounded K-feldspar and quartz grains in a fine-grained groundmass with low mafic mineral content

(C) Quartz-diorite (a) with crosscutting dyke with numerous rounded quartz grains.

(D) Fine, even-grained granitic intrusion (a) in Main Phase granite (b). Intrusion is parallel to magmatic fabric in granite. Foliation in the fine-grained dyke wraps around the K-feldspar megacrysts at the contact (arrow).

(E) Fine-grained granite (a) intruded parallel to the strongly deformed Main Phase granite.

(F) Irregular netveining of dolerite by an intrusion of fine to medium-grained granite. Hybridization occurred at the diffuse boundaries (arrow).

(G) Enclave-rich medium-grained granite intruded and disrupted dolerite into enclaves;

(H) Medium-grained intrusion with variously hybridized mafic enclaves (a,b) and local hybridization of the granite

(I) Fine veinlet intruded into dolerite and caused local hybridization.

Lens cap used for scale is 55 mm.

A fine- to medium, equigranular granite with very low mafic mineral content intrudes the Main Phase granite, occurring predominantly along some of the margins of the Main Phase granite (Figure 2.1) and parallel to the fabric developed in the granite (Figure 2.15de). The equigranular granite has similar geochemistry to the porphyritic granite (Sisois 2000) and may be a related phase. This granite is rarely phenocrystic but commonly contains enclaves of hybrid megacrystic granite. Magmatic brecciation, net-veining, the formation of enclaves and hybridization by the intrusion of this fine- to medium-grained granite into a partly to completely solidified Mafic Hybrid Complex are common occurrences although it generally occurs in areas of less than 5 m^2 (Figure 2.15f-i). Magnetic susceptibility measurements of this unit were low (<100 x 10^{-5} SI), however the hybrids formed from the interaction with dolerite resulted in higher magnetite content (1000 – 3000 x 10^{-5} SI; Figure 2.2).

2.4.3 Microgranite suite

The microgranite suite occurs in the northeast of the batholith and is compositionally and texturally different from the Main Phase granites. This is highlighted by the distinctive radiometric signature of this phase in comparison to the rest of the batholith (Figure 2.3). The microgranite locally crosscuts the stratigraphy and is interpreted to form a steep sided plug based on gravity and magnetic data (Connors & Page 1995). The main intrusion occurs to the north of the map area and extends to the south along the eastern margin of the batholith intruding the Mosses Tank Dolerite and Eastern Creek Volcanics (Figure 2.1). The eastern margin is a strongly mixed and/or mingled zone and the sheeted distribution of microgranite within the dolerites (Figure 2.16) indicates a complex relationship. Magmatic shear zones are associated with the emplacement of microgranite sheets in the southern parts of Kitty Plain and contributed to the interaction of mafic and felsic magmas.

MICROGRANITE

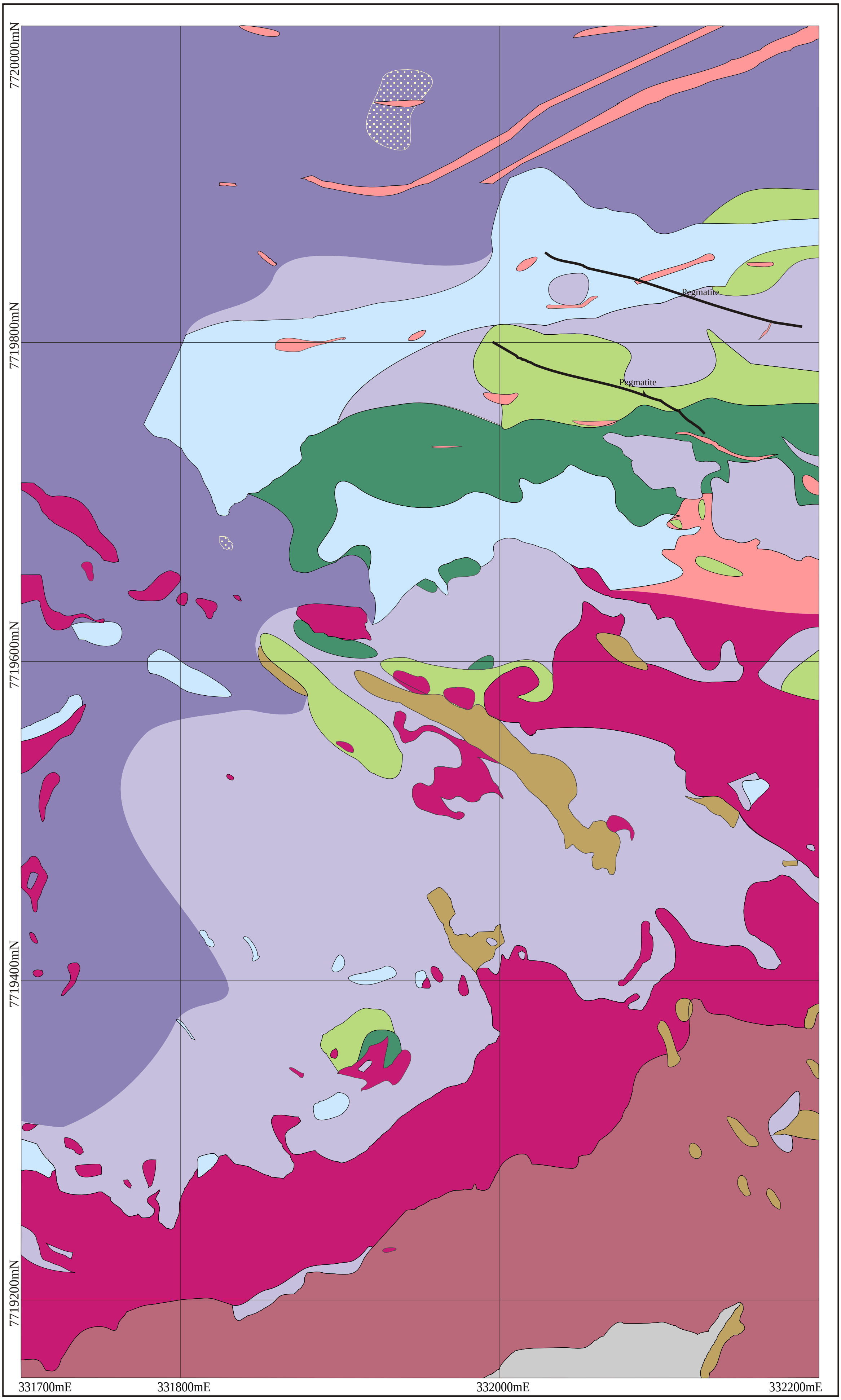
The predominant microgranite phase is even textured, is medium to fine-grained and has a high K-feldspar and low mafic mineral content (Figure 2.17a). This intruded an earlier phase of medium-grained microgranite that has K-feldspar phenocrysts that are < 5 mm in size (Figure 2.17b). Net-vein complexes are commonly found at the dolerite/granite margins (Blake 1981), and it is considered that the microgranite intrusions were emplaced syn- to post-crystallization of the Mosses Tank Dolerite (Joplin 1955; Walker & Skelhorn 1966; Ellis & Wyborn 1984). This is depicted at both the scale of the regional map (Figure 2.1) and in the detailed map at Kitty Plain (Figure 2.16). Where the granite intruded the dolerite as sheets (commonly orientated north-west; Figure 2.1), the margin of the microgranite and dolerites show minor zones of granodioritic hybrid (one to two metres wide) and the inclusion of some enclaves (Figure 2.17c). This hybrid is heterogeneous and imperfectly mixed with small clusters of mafic minerals (Figure 2.17d) possibly representing the disaggregated dolerite component. Contacts between hybrid and dolerite are sharp to gradational, and where the hybrid intruded the dolerite, further hybridization and formation of cuspate enclaves occurred (Figure 2.17ef).

A large zone of mingled microgranite and dolerite occurs predominantly along the eastern margin along the contact with the country rocks (Figure 2.1). The mafic enclaves and xenoliths show very little interaction with the microgranite in this region and are commonly angular to subrounded (Figure 2.17gh).

ENCLAVE-RICH MICROGRANITE AND HYBRIDS

Detailed mapping within the Kitty Plains region (Figure 2.16) shows zonation associated with the emplacement of microgranite sheets into the Mosses Tank Dolerites. Distal to the microgranite sheets the dolerite shows original intrusive textures. With increased proximity to the microgranite sheets, the dolerite has a crackle breccia developed with infill of granite around angular dolerite fragments (Figure 2.17h). Closer to the central granite intrusion the proportion of granite increases to a matrix supported breccia, where the dolerite fragments are more rounded and irregular shaped (Figure 2.18ab). Marginal to the granite sheets the dolerite enclaves are strongly aligned parallel to the magmatic fabric in the granite and the enclaves are stretched and broken up forming schlieren rich layers and hybrids (Figure 2.18c-e).

The development of a magmatic shear zone during emplacement of microgranite sheets increased the interaction between the granite and the diorite enabling the mechanical disintegration and hybridization of magmas (Figure 2.16). Initial intrusion of



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7719800mN
7719600mN
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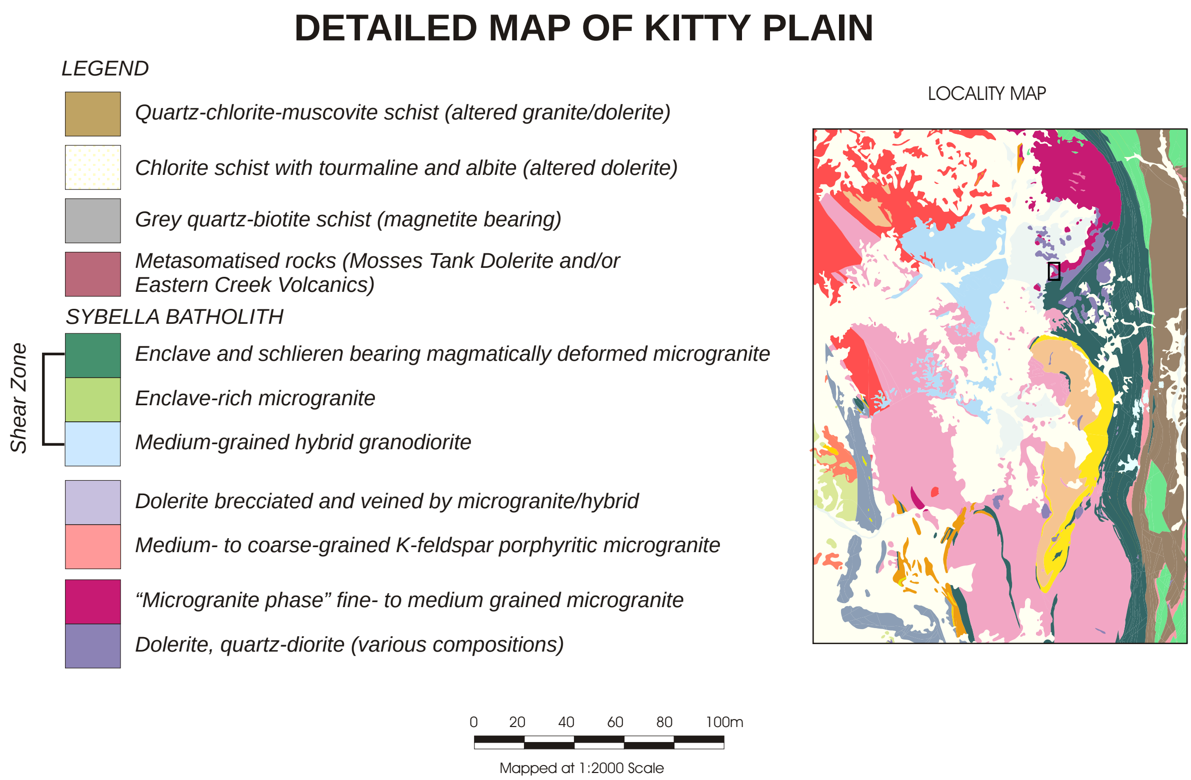
Figure 2.16 Microgranite sheets intruded the Mosses Tank Dolerite.
Strongly aligned enclaves and schlieren within microgranite and hybrid granite indicate the location of a magmatic shear zone.
There is an overall zonation: distal to the microcrogranite sheets, the dolerite shows no interaction with the granite; progressively closer, the dolerite shows increasing brecciation and finally disintegration into an enclave- and schlieren-rich hybridized granite.



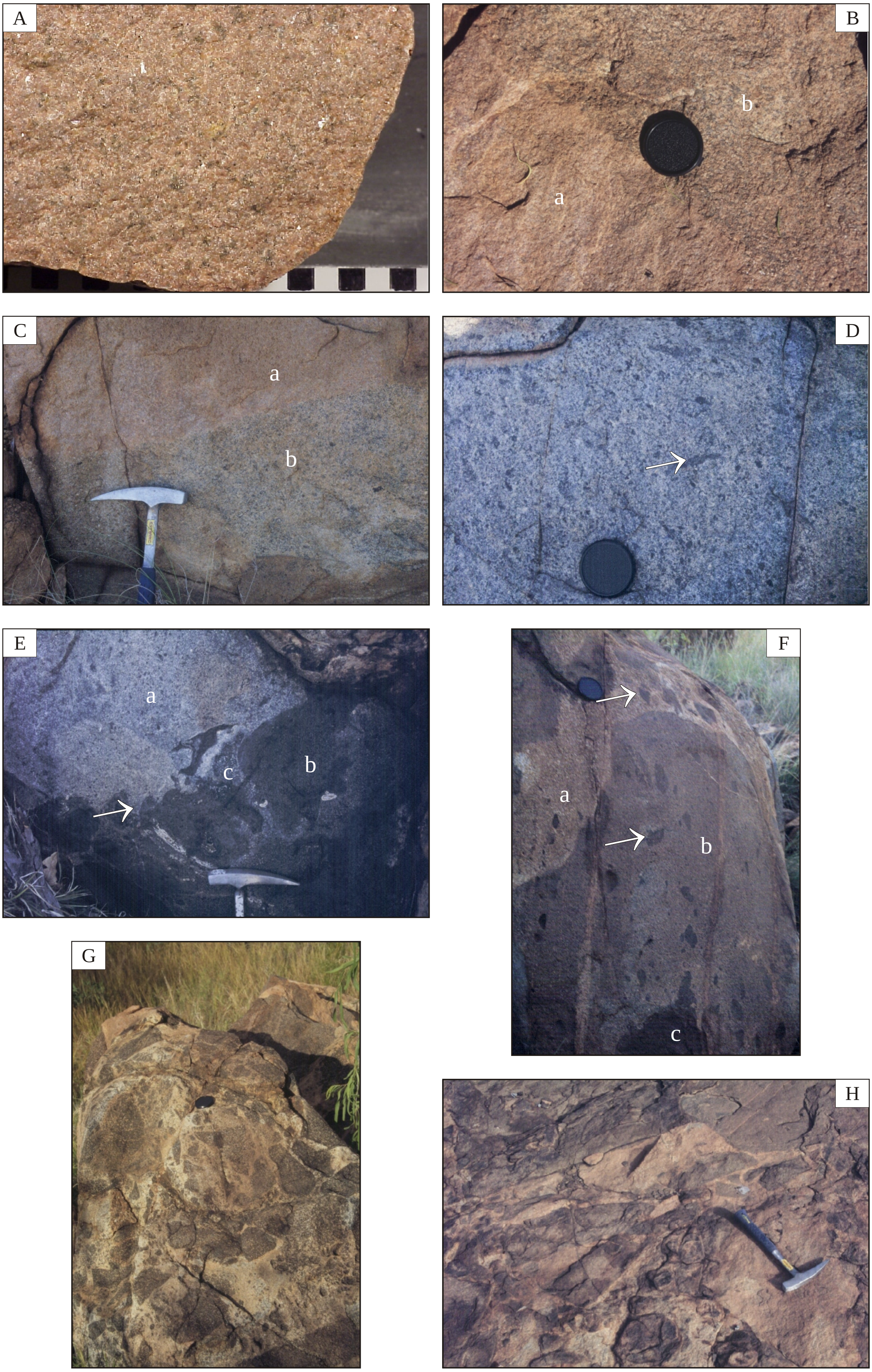

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Figure 2.17 Kitty Plains Microgranite

(A) Fine- to medium-grained microgranite (K-feldspar-rich and poor in mafic minerals). Centimetre scale.

(B) Fine-grained microgranite (a) intruding a coarser-grained microgranite (b)

(C) Microgranite (a) dyke in sharp contact with hybrid granite (b). The hybrid has higher mafic mineral content and small mafic enclaves.

(D) Heterogeneous and incompletely mixed granite hybrid with small mafic enclaves (arrow).

(E) Heterogeneous hybrid granite (a) with cuspate and gradational contacts (arrow) with dolerite (b). The hybrid has interacted with the dolerite to produce an intermediate rock (c).

(F) Microgranite (a) intruding hybrid (b) with mafic enclaves (arrows) and diorite (c);

(G) Mixed unit of microgranite matrix with numerous angular to subrounded enclaves and xenoliths

(H) Brecciation of dolerite by microgranite with the formation of angular xenoliths.

Lens cap used for scale is 55 mm.

Head of geological hammer is 18 cm long.

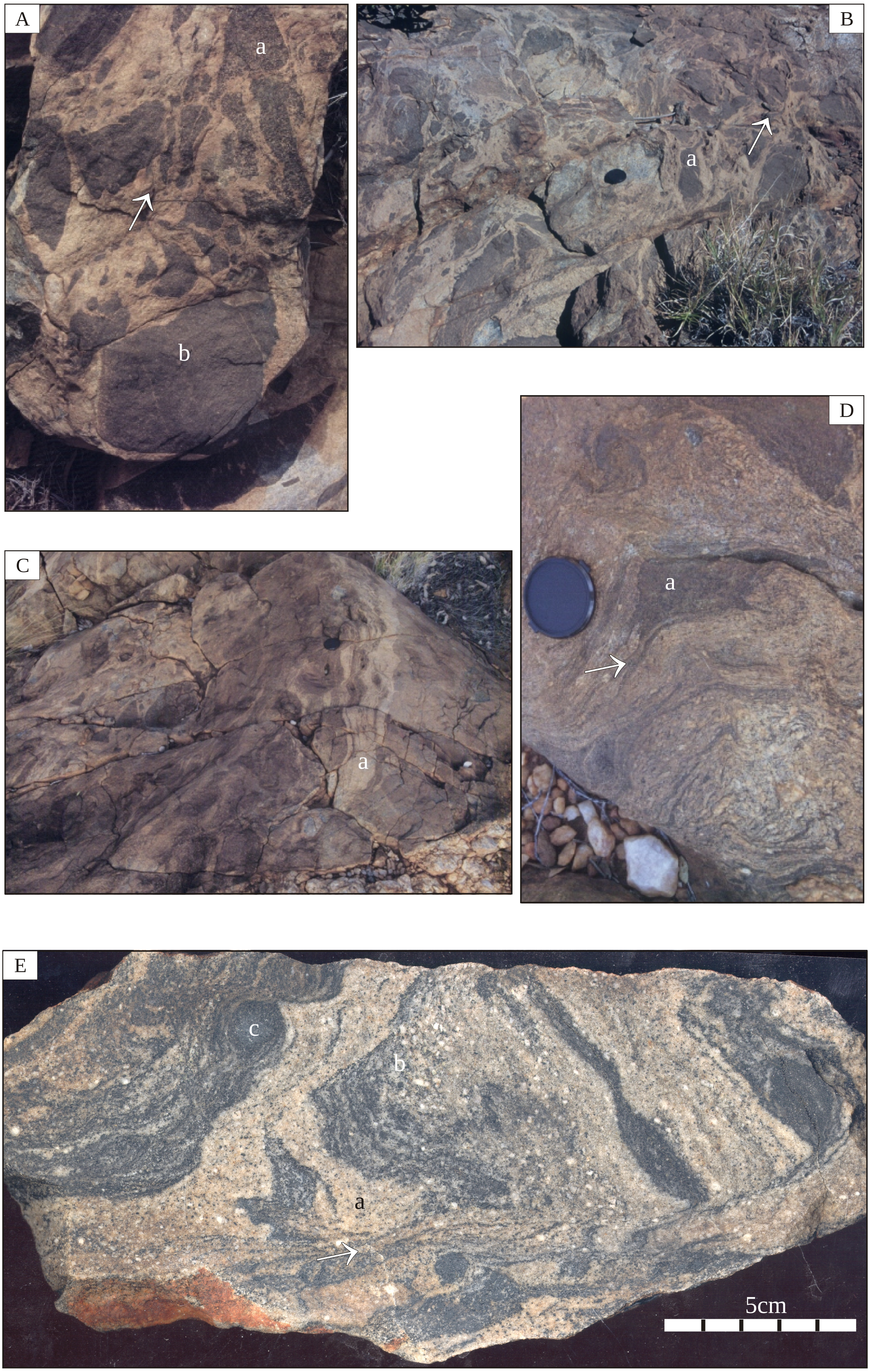
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Figure 2.18 Microgranite and Mosses Tank Dolerite interaction.

(A) Brecciated dolerite (a) and (b) in microgranite. The clasts generally have sharp contacts with the granite, however a weak alignment of the enclaves (arrow) is interpreted to have resulted from the magmatic flow of the microgranite in the shear zone.

(B) Rounded and brecciated enclaves occur in an anastamosing microgranite matrix. The granite appears to wrap around the enclaves (arrow) and they appear elongated (a).

(C) Microgranite (a) intruding an earlier formed hybrid within the shear zone. The microgranite has a strong fabric with the enclaves elongated and broken up with schlieren developed by the mechanical interaction of the magmas.

(D) Hybridization occurred within the microgranite as a mechanical process within the shear zone. Enclaves (a) were drawn out into the magmatically deformed microgranite (arrow) resulting in hybridization and an increased mafic mineral content of the granite.

(E) The medium-grained microgranite (a), schlieren (b) and more unmodified mafic enclaves (c) show a strong magmatic alignment. A later shear with crosscutting biotite-rich layers occurs oblique to earlier fabric (arrow) indicating that deformation continued after the emplacement of the microgranite.

Lens cap used for scale is 55 mm.

microgranite into dolerite was interpreted to have been accompanied by magmatic brecciation of the mafic units. Small fractures within the dolerite were intruded by microgranite creating a network of microgranite or crackle breccia. With increased intrusion of microgranite magma, the fractures widened into wedge shapes and dislodged or broke off angular fragments of dolerite into the microgranite creating a breccia or jigsaw arrangement of angular xenoliths (Figure 2.17h, 2.18a). Interaction between the dolerite xenoliths and microgranite matrix was limited and very little hybridization occurred at this stage.

With increased intrusion of microgranite, strong magmatic fabrics developed in response to localized strain (magmatic shear zone). The magmatic flow of the microgranite entrained and aligned the dolerite xenoliths, and modification of the xenoliths resulted due to the mechanical interaction. The enclaves or xenoliths became rounded, commonly oval shaped (Figure 2.18b). With increasing magmatic deformation, hybridization of the microgranite occurred, and schlieren and mineral banding developed as a result of the enclaves being drawn out into thin bands of mafic minerals (Figure 2.18c-e).

Thin microgranite dykes (0.5-2 m wide) intruded the strongly, magmatically deformed hybrid zone and terminated in irregular lenses that interacted with the mixed unit (Figure 2.16). This microgranite is largely undeformed with a weak magmatic fabric (alignment of K-feldspar phenocrysts) developed. Coleborn (1999) dated this weakly deformed microgranite from within the shear zone (at 1673 ± 2.5 Ma), which was within error of the Main Phase granites of the Sybella Batholith.

The medium- to fine-grained granites that intruded the Main Phase granites and mingled with the mafic units in the Easter Egg and Guns Knob regions may be associated with the Kitty Plains microgranites, however this is yet to be tested.

2.5 DISCUSSION

Relationships between different intrusive phases in the Sybella Batholith were identified through detailed and regional mapping. The sheet-like shape of the granitoid intrusions, the occurrence of xenoliths of the country rocks, mafic rocks, and rapakivi granitoids within the granites, and the formation of breccia textures are a few of the indicators of timing of the intrusions. Figure 2.19 summarises the relationships between the units within the northern region of Kitty Plain and the southern Guns Knob and Easter Egg regions. In all regions, the mafic phases were interpreted to have been emplaced first, followed by the rapakivi graitioids in the southern region and then the felsic granites were emplaced. In the southern region emplacement of the Main Phase granite was accompanied by minor hybridization and in the northern region, significant brecciation of the dolerite and localized hybridization occurred. Correlation of the timing of microgranite emplacement from the Kitty Plains region with the Main Phase granite was unable to be ascertained, as there appeared to be no overlap of units outside their respective regions and the available age dates were within error.

The nature of the intrusive contacts between the mafic complexes, the rapakivi granitoids, the Main Phase granite and the microgranites demonstrates interaction between penecontemporaneous partly crystallized magma mushes. Physical mixing and mingling was recognized in the batholith at outcrop scale on the basis of: (1) enclaves; (2) disaggregated enclaves; (3) incorporation of xenocrysts; (4) mineral overgrowths; and (5) gradational contacts between different magmas where an intermediate composition was formed. Generally where interaction of mafic and felsic magmas has occurred, the two components intermingled to form a mixed rock in which the original magmas are still easily discernable. This includes net-veined complexes, and mafic inclusions or enclaves with lobed, and occasionally chilled margins within a felsic host. It is interpreted that the units of the Mafic Hybrid Complex, rapakivi granitoids, and localized intermediate granitoids at the margins of the microgranite sheets formed by the process of mixing mafic and felsic magmas. The Main Phase granite shows evidence such as enclaves, biotite rich zones and rapakivi textures for having interacted with mafic magmas, however it does not appear to have resulted in significant contamination as the composition appears largely uniform in outcrop. The Mosses Tank Dolerite and the microgranite appear to be primary magmas. Interpretations based on field relationships need to be verified with other data such as petrographic and geochemical data which are presented in Chapters 3 and 4 respectively.

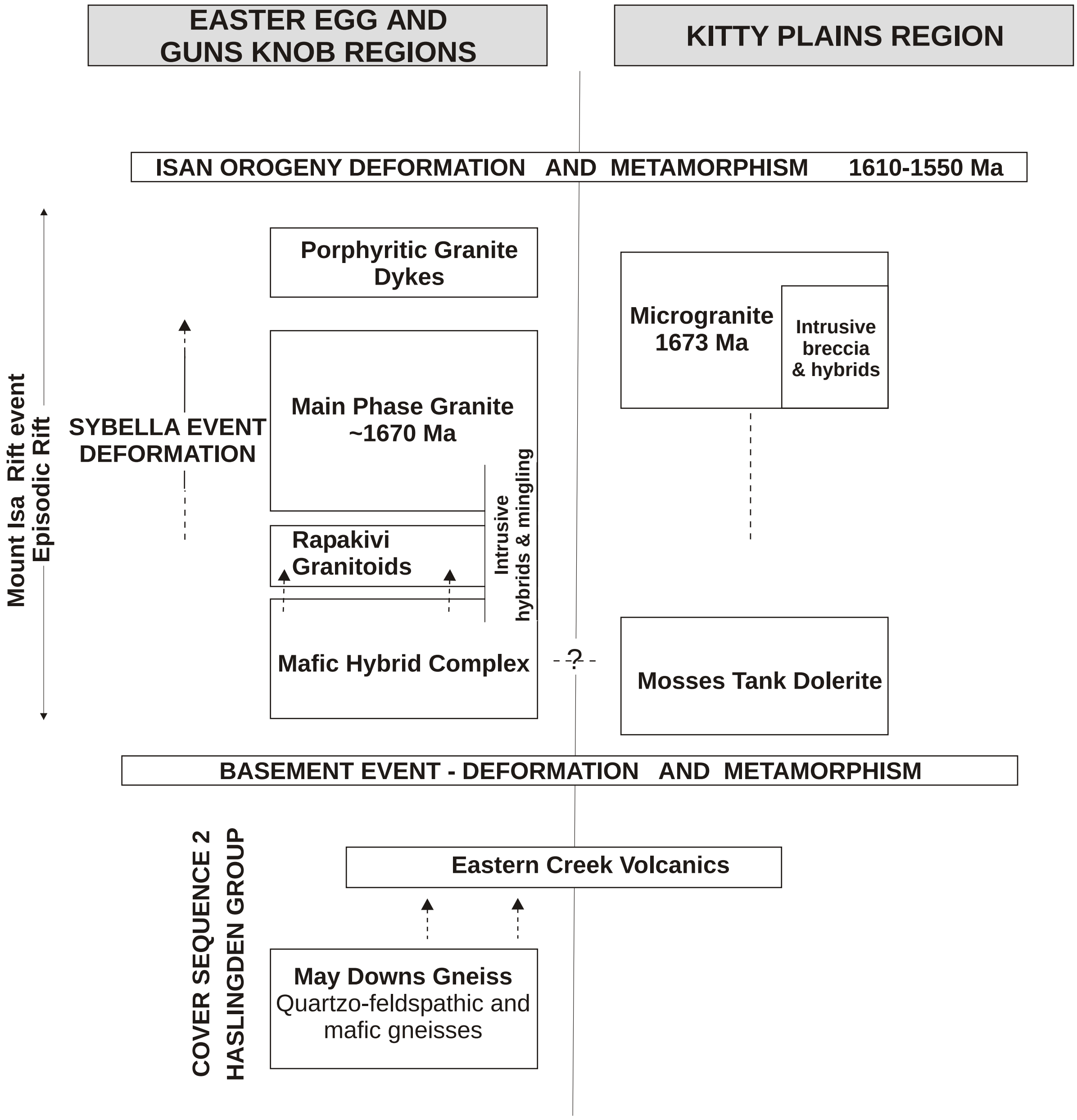

Figure 2.19 Realtionships between intrusive units of the Sybella Batholtih, country rocks and deformation

The importance of hybridization has been considered in both volcanic (Bacon 1986; Gencalioglu Kuscu & Floyd 2001) and plutonic environments (Whalen & Currie 1984; Frost & Mahood 1987). The mixing of basic and acid magmas may produce variable amounts of more or less homogeneous hybrids and the ability of the magmas to mix depends on their physical properties (Sparks & Marshall 1986). The volume of hybrid rocks and their SiO_2 content depends on several parameters such as the compositional contrast between the two end members, the viscosity contrast (dependent on temperature, crystalinity and water content of the two magmas), the cooling rate and the degree of turbulent stirring (Frost & Mahood 1987). Mechanical stirring (tectonic shearing, forced convection, ascent in a conduit) appears to be an efficient mechanism for hybridization to occur. Therefore, a wide range of interaction between magmas of contrasting compositions may be identified at large and small scales, and vary from mingling to complete hybridization. This process has been identified as being a major contributor to the evolution of particularly the mafic and intermediate compositions within the Sybella Batholith.

2.5.1 Mixing during emplacement

Observational evidence for small scale mixing of magmas during emplacement appears conclusive. The interaction of magmas and hybridization at emplacement level is evidenced by the gradational boundaries between both the Kitty Plains microgranite and Mosses Tank Dolerites in the northern region and Main Phase granites and Mafic Hybrid Complex in southern regions. The transitional behaviour between solid and liquid was observed along many of the intrusive contacts. It is thought that the mafic units (Mafic Hybrid Complex and Mosses Tank Dolerite) were only partially solidified when the felsic units intruded them and there was no sharp internal solid-liquid boundary at that time. When viscosities were similar between the mafic and felsic magmas, interlobed contacts form (Fernandez & Gasquet 1994) and true hybrid rocks occurred at the contacts of the mafic and felsic (Figure 2.20a). Trails of rapakivi feldspars within the mafic hybrid complex in outcrop (e.g. Figure 2.12) and drill core were derived from the intrusion of rapakivi hybrid into partly solidified mafic magmas. Gradational contacts defined only by the increase in quartz and K-feldspars in those zones illustrate that mixing and interaction between magmas of similar viscosities occurred.

The interaction of the Mosses Tank Dolerite with the microgranite was generally limited to mingling and magmatic brecciation to produce large zones of enclave/xenolith-rich microgranite. The predominance of brecciation of the dolerite by the microgranite and sheeting or dyking of the microgranite through the dolerite indicates there was too much of a contrast in the rheological properties of the magmas which prevented the formation of homogeneous hybrids. The ability of the microgranite magma to brecciate the dolerite over a large area (depicted in Figure 2.16) suggests a warm environment where the microgranite dykes were not limited by "freezing". When the dolerite reached the stage where it behaved as a solid (although not completely crystalline) and the felsic magma still had relatively high mobility, breccia structures typically resulted (Figure 2.20bi). Because the felsic magma is more mobile than mafic magma, structures in which felsic intrude mafic are frequently observed. With continued intrusion of the granite, the brecciated complex with both angular mafic blocks and the partially solidified mafic enclaves behaved as viscoelastic materials that cracked under high strain rates and flowed viscously under low strain rates (Figure 2.20bii). Where the mafic magma was more viscous than the felsic magma, but not entirely crystallized, many structures such as dislocated smooth lobed contacts and dolerite veined by granite with smooth contacts can be observed. Under a continuing high strain rate, the mechanical break-up (or deformation of magmatic breccia) formed schlieren and hybrids within the magmatic shear zone (Figure 2.20biii).

2.5.2 Mixing at depth prior to emplacement

A number of observations suggest that hybridization between mafic and felsic magmas took place at a deeper level before the mafic magmas were emplaced to form the Mafic Hybrid Complex. A range of texturally (and geochemically) distinct mafic hybrid magmas, with pyroxene replaced by hornblende, increased quartz and K-feldspar in the groundmass, as well as varying proportions of quartz ocelli (mantled quartz xenocrysts) and plagioclase mantled K-feldspar xenocrysts occur as discrete bodies within the Mafic Hybrid Complex. The relatively homogeneous rapakivi hybrid rocks are relatively widespread although they are aerially minor in outcrop. These hybrids were emplaced into the complex as distinct intrusions and interaction between crystal-rich magmas resulted in mingling and local hybridization. The megacrystic Main Phase granite, although relatively homogeneous, displays features resulting from hybridization

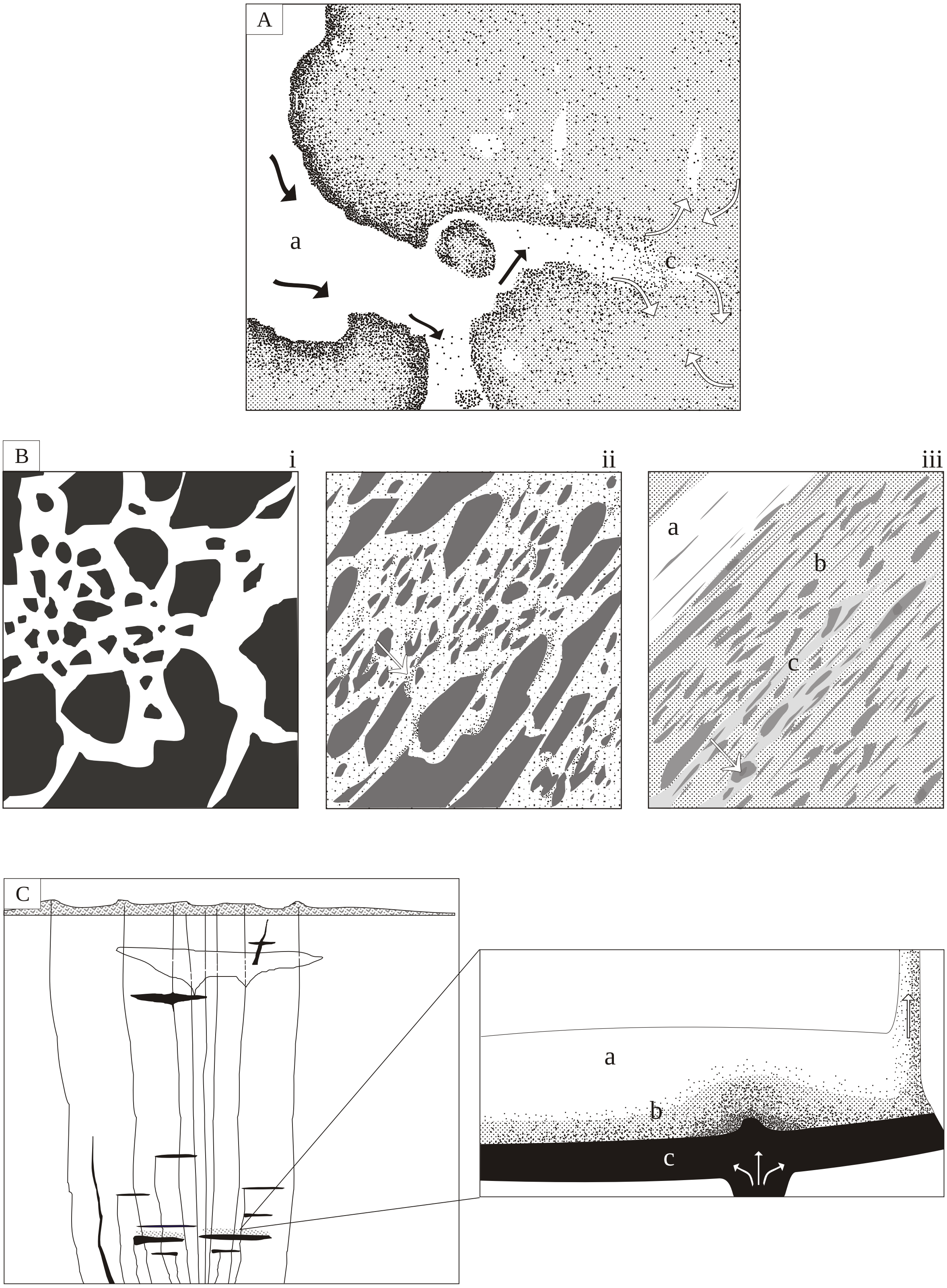
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Figure 2.20 Schematic diagrams of mixing processes

(A) Emplacement related mixing: the intrusion of granitic magma (a) into diorite mush results in the initial undercooling (b) and then breach of the partly solidified carapace by small volumes of granite, as indicated by black arrows. This leads to mixing and mingling between mafic and felsic mushes as indicated by white arrows, and the formation of hybrid magma (c).

(B) Mechanical mixing resulted from intrusion of granite magma into partially solidified mafic magma during deformation. (i) Breccia structures with sharp contacts and little interaction with granite intrusion initially form. (ii) With increasing magmatic flow in the shear zone, the enclaves are aligned and have smooth rounded contacts and minor mixing with the granite intrusion results in the formation of hybrid zones (arrow). (iii) Late microgranite intrusions into the shear zone (a) have magmatic foliations and little interaction with the surrounding mixed and hybridized units (b). Schieren develop as the enclaves become extremely stretched (c) and well-mixed hybrid zones develop due to the continued shearing. Double enclaves (as indicated by the arrow) result from the episodic intrusion of microgranite magmas and interaction of hybrid and dolerite magmas in the shear zone.

(C) Mixing and hybridization occur at depth, and results in the emplacement of batches of variously hybridized mafic magmas. The inset illustrates the partial melting and generation of felsic magmas (a) resulting from the heat supplied by the intrusion of basaltic magmas (c) into the lower crust. Repeated injections of basic magma into the magma chamber can produce zones of mixing and mingling, resulting in hybrid magmas (b). Intrusions of magmas from such chambers (as indicated by the arrow) can produce quartz-feldspar porphyry dykes and rapakivi granites, dolerite dykes and gabbroic rocks, composite dykes and hybrid complexes (from the mingling and mixing zone) including the occurrence of rapakivi textures, areas of increased mafic minerals, and rounded non-chilled hybrid enclaves.

Mixing is thought to be a likely process involved in the generation of orogenic granitoids whereby the intrusion of basaltic magmas into the lower crust supplies heat and causes partial melting and generation of felsic magmas (Huppert & Sparks 1988). Repeated injections of basic magma into the magma chamber can produce zones of mixing and mingling, resulting in hybrid magmas with enclaves (Figure 2.20c). Intrusions of magmas from such chambers can produce quartz-feldspar porphyry dykes and rapakivi granites, diabase dykes and gabbroic rocks, composite dykes and hybrid complexes (from the mingling and mixing zone) (Salonsaari & Haapala 1994). Hybridization of dry liquidus felsic magmas like the Sybella Batholith is possible as the mafic magma is never quenched and maintains its low viscosity (Frost & Mahood 1987). Hybridization probably continued during emplacement of the batholith. In this view, the mantle derived component is represented by the mafic stocks and dykes emplaced at different stages of the batholith’s history, especially at its beginning and by the mafic inclusions of the granitoids.