(1993). The D2 folds and thrusts were reactivated by this event and a series of northwest trending strike slip zones developed (eg, the Pine Creek shear zone). The main mineralising event in the Pine Creek Geosyncline appears to be synchronous with D4 deformation. D4 structures appear to have also been locally modified by granite intrusion forming localised high strain zones in and around the granite contacts. A series of northeast trending normal faults were developed late during D4, which cut and offset all the earlier structures. These structures appear to be synchronous with gold mineralisation at Big Howley, whereas mineralisation at Mt. Todd appears to be related to both normal and D4 strike-slip faulting (Poxon and Hein, 1994).

Numerous fault reactivations, including the Coronet Fault system which hosts the U-Au mineralisation of the South Alligator region, and minor open folding has affected the Pine Creek Geosyncline in the Middle Proterozoic and possibly Mesozoic.

3.2. Metamorphism

The Pine Creek Geosyncline has undergone regional lower greenschist facies metamorphism in the east to upper greenschist facies metamorphism in the west (Stuart-Smith et al., 1993). The mineralogies in the metasediments are consistent with peak metamorphic conditions of upper greenschist facies (to top of garnet zone). These include garnets that are almandine in composition. The garnets are free of inclusions and formed prior to the formation of the D2 C-S fabrics, which wrap around the garnets. The garnets have been retrogressed to chlorite during a later metamorphic or hydrothermal event. Other diagnostic minerals formed in the metasediments during the regional metamorphic event are biotite and chlorite which define the S1 and S2 cleavages. Zamu Dolerite in general has been metamorphosed to an amphibole, chlorite, sericite, biotite and minor albite assemblage. The peak metamorphic assemblages preserved in the dolerite are also overprinted by hydrothermal alteration.

The effects of regional metamorphism are largely obliterated by contact metamorphism during granitoid intrusion. Most of the contact aureole around the Cullen Batholith is of the albite-epidote hornfels facies with a narrower inner zone of hornblende hornfels facies rocks. Typical assemblages present in the various rock types are given in Table 3. The boundary between the facies is marked by the appearance of hornblende which lies within 500 metres of granite contacts. In some areas for example at the Western Arm this boundary is laterally over 10 kilometres away from the Burnside Pluton. Rare K-feldspar-cordierite hornfels lithologies, present around the McMinns Bluff, Allamber Springs and McCarthy's granites, suggest that the granites of the Cullen Batholith intruded at a depth of less than 6 kilometres (Stuart-Smith et al., 1993, see Fig. 3 and Fig. 15).

At such depths contact aureoles would be expected to only extend up to 750 metres from a granite contact. However the contact aureole around the Cullen Batholith can extend up to 15 kilometres from any granite contact suggesting that the batholith must be shallow dipping in places.

4. The Cullen Batholith

The Cullen Batholith represents the central part of the large plutonic complex (the Pine Creek Plutonic Complex, this study). The Pine Creek Plutonic Complex (Fig. 1) comprises from east to west the Jim Jim Granite, Malone Creek Granite, Grace Creek Granite, Cullen Granite and granites of the Litchfield Complex. The separate granite plutons are believed to be connected at a shallow depth as one granitic basement (Tucker et al., 1980).

The complex has been variously described as "late intrusive leucogranite" (Richards et al., 1977), as typical "post-tectonic or late-syntectonic magmas" (Smart et al., 1976), as "solid state diapiric intrusions" (Stephansson & Johnson, 1976) and as "I-type mantle-derived syn-to post-orogenic granitoids " (Stuart-Smith et al., 1993).

The Plutonic Complex comprises a series of Igneous Suites. These suites are the broadest subdivision of the Complex, and rocks of one suite may be present in more than one pluton. The term pluton is used in the sense of Pitcher (1978) to define a body formed by one or more related magmas which were emplaced more or less simultaneously and are bounded by a single contact surface. Each pluton is given a name which relates to its geographic location.

4.1. Anatomy of the Cullen Batholith

The Cullen Batholith intrudes into the Early Proterozoic metasediments and Zamu Dolerite, which form the central portion of the Pine Creek Geosyncline. The discordant margins of the individual plutons are readily defined on satellite imagery and aerial photography by resistant hornfels ridges, which rise up to 200 m above the level of the granite plutons. The interiors of granite plutons are generally marked by topographic flats or depressions. The Pine Creek shear zone follows an embayment of Early Proterozoic metasediments within the Cullen Batholith dividing it into two major segments (western and eastern segment). The batholith is overlain by Middle Proterozoic and Cambrian sediments in the west.

According to Stuart-Smith et al. (1993), the Cullen Batholith comprises twenty-three plutons. Which are coalesced or interconnected at shallow depths of less than 3 kilometres. Many of them show a high degree of autonomy in location, shape and internal structure. The total area of exposed granites in the Cullen Batholith is about 4,000 km^2 which consists of one large, almost continuous granite outcrop and several smaller satellite bosses isolated by country rocks. The principal granite plutons include: the Allamber Springs Granite, McMinns Bluff Granite, Minglo Granite, Tabletop Granite, Umbrawarra Granite, Driffield

Table 3. Typical assemblages of the contact aureole around the Cullen Batholith (Stuart-Smith et al. 1993)

Rock Type	Regional Metamorphism (Nimbuwah Event 1870 Ma)		Contact Metamorphism (1835-1820 Ma)		
	Lower Greenschist	Upper Greenschist	Albite-epidote Hornfels Facies	Hornblende Hornfels Facies	K-feldspar-cordierite Hornfels Facies
Pelitic rocks	Sericite + quartz + chlorite	Biotite + muscovite + quartz + garnet	Muscovite ± biotite ± cordierite ± quartz Muscovite + chiastolite ± graphite Muscovite + cordierite ± graphite	Muscovite + biotite ± cordierite ± albite ± quartz ± hornblende Muscovite + cordierite + graphite	Cordierite + andalusite + K-feldspar + biotite + quartz
Quartzose and feldspathic sandstone	Sericite/muscovite + chlorite + epidote		Muscovite + quartz ± albite ± biotite	Muscovite + quartz ± albite ± biotite	
Greywacke	Sericite/muscovite + chlorite + epidote		Muscovite + quartz + biotite ± K-feldspar ± albite ± epidote ± actinolite ± calcite ± sphene	Muscovite + K-feldspar + quartz ± albite ± biotite + hornblende	
Tuff	Chlorite + sericite + quartz	Biotite + muscovite + quartz	Muscovite + quartz ± biotite ± albite ± K-feldspar ± clinozoisite ± calcite	Muscovite + quartz ± biotite ± albite ± K-feldspar ± clinozoisite ± calcite	
Carbonate rocks	Dolomite + quartz	Tremolite + garnet + biotite + quartz	Calcite + tremolite + epidote Calcite + tremolite + zoisite + sphene + quartz Tremolite ± biotite ± quartz	Grossular + calcite Diopside + quartz + calcite Diopside + vesuvianite ± calcite ± sphene ± wollastonite ± grossular	
Dolerite	Chlorite + sericite + epidote + zeolites	Actinolite + biotite	Tremolite/actinolite + biotite + epidote/clinozoisite ± calcite	Hornblende ± biotite ± plagioclase ± K-feldspar ± calcite ± sphene ± quartz	

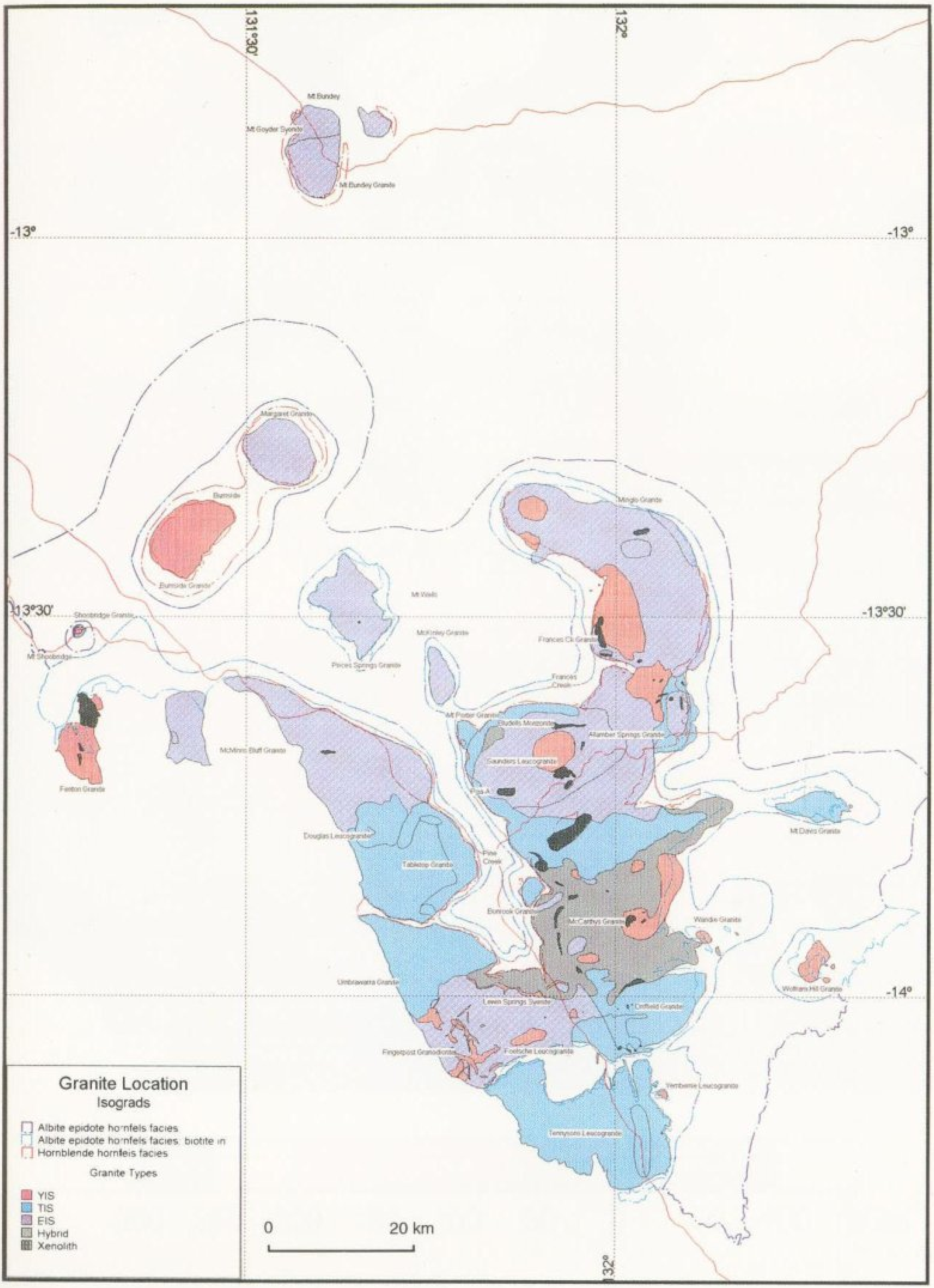

Figure 3. The Cullen Batholith. Igneous suites, plutons and rock types.

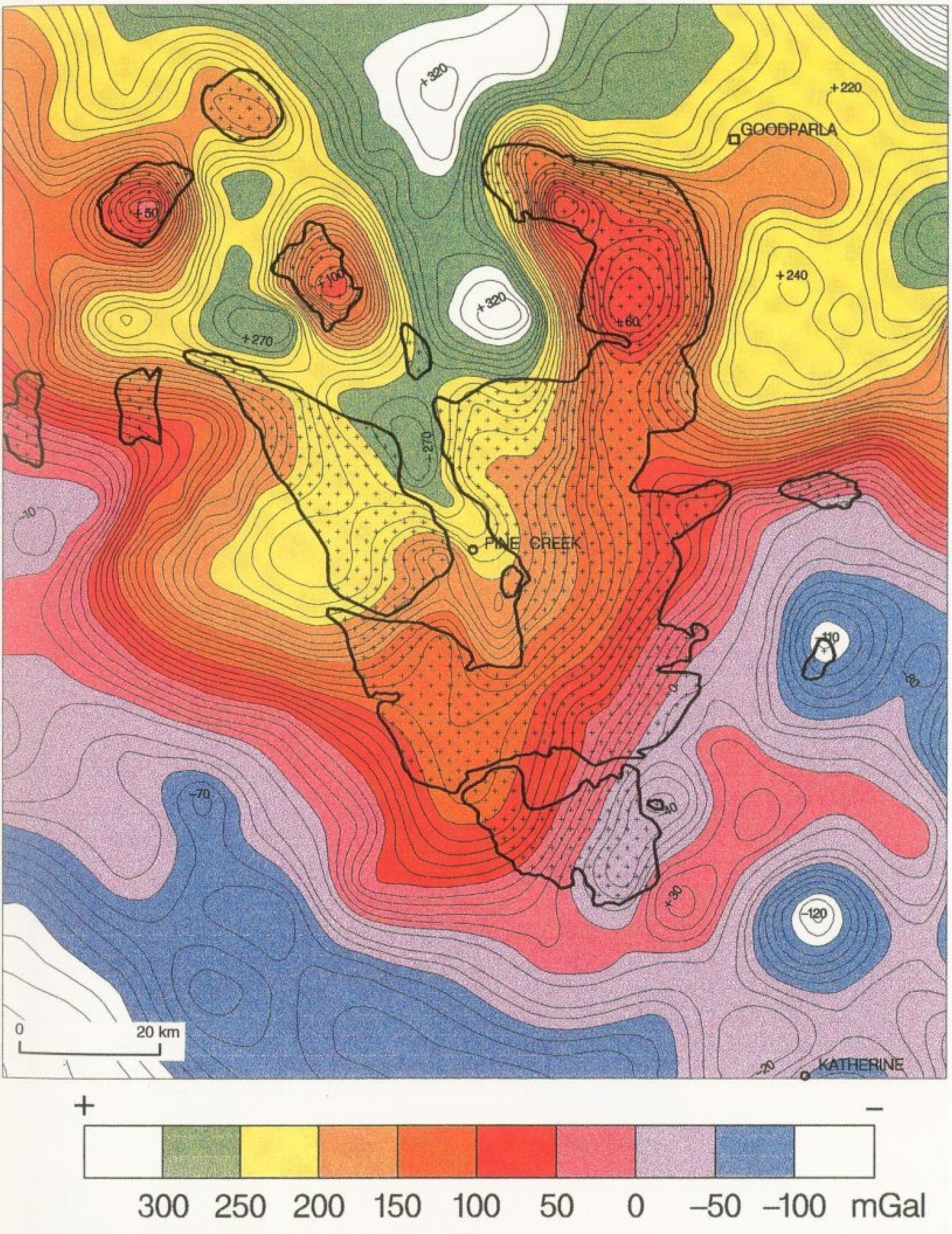

Figure 4. The Cullen Batholith. Gravity map (Bouguer anomaly contours).

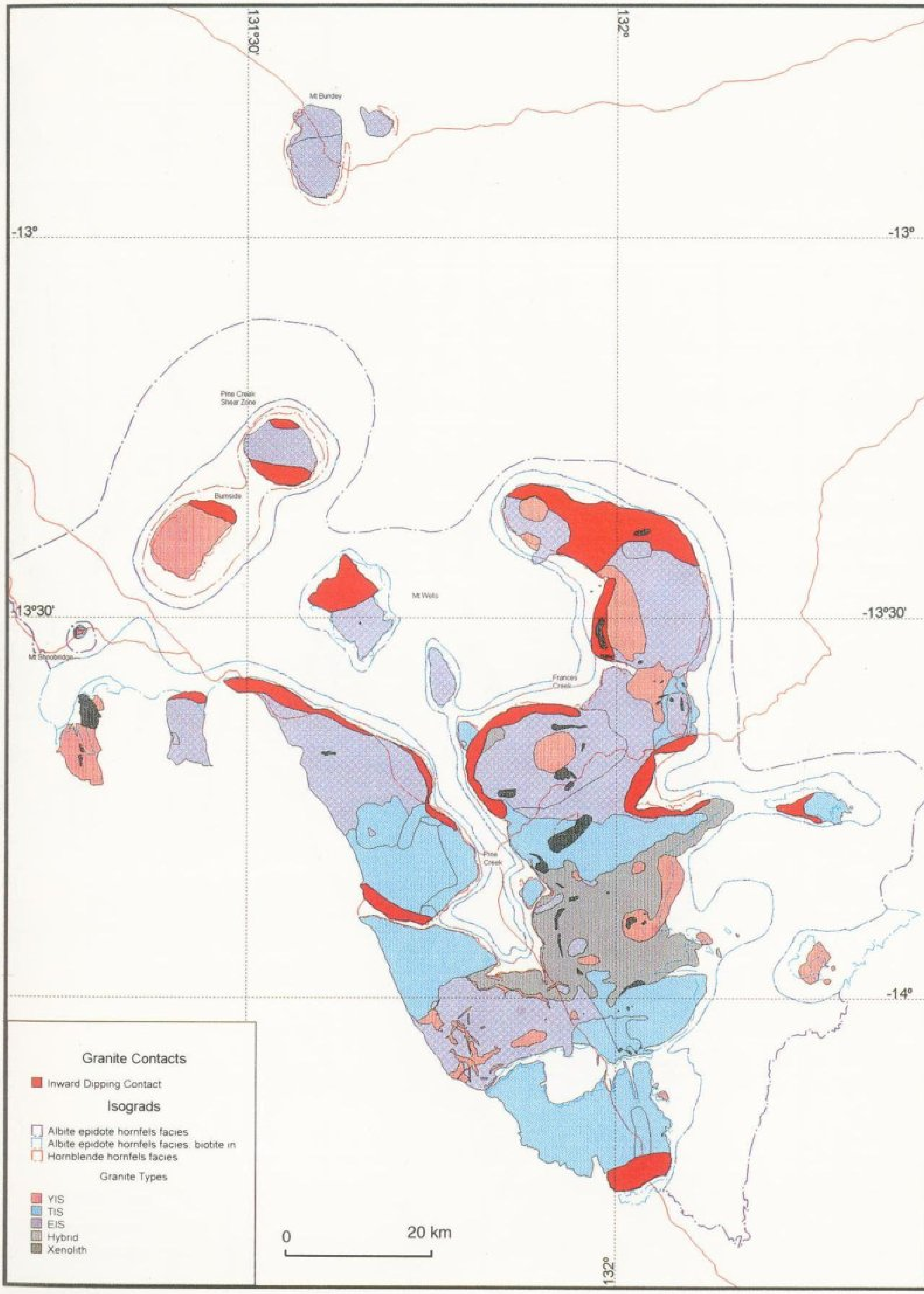

Figure 5. The Cullen Batholith. Inward dipping granite contacts.

Figure 6. The Cullen Batholith. Offprint of the country rock pattern into the Batholith roof. Black – Zamu dolerite, Bludells monzonite, and hornfels, red – trend lines of the ghost stratigraphy accross granite outcrop.

Granite, Fingerpost Granite, McCarthys Granite and Tennysons Granite. Satellite bodies include the Shoobridge Granite, Burnside Granite, Margaret Granite, Prices Springs Granite and McKinlay Granite in the north-west and Wandie Granite, Yenberrie Granite, Mount Davis Granite and Wolfram Hill Granite in the south-east (Fig. 3 and Fig. 15).

4.2. Shape of the Batholith

The depth of the Pine Creek Plutonic Complex was modelled by Stuart-Smith et al. (1993) on the basis of intensity and extensity of the plutonic thermal aureole and gravity measurements. In general, the gravity field over the Cullen Batholith has a gentle north-south trending regional, gradient, indicating a thicker and/or lower density crust in the south. The detail pattern of the Bouguer anomalies (Fig. 4) indicates that the intrusive centre of the horseshoe -shaped Cullen Batholith occurs at the southern margin of the Pine Creek Geosyncline. The batholith appears to thin to the north and more commonly occurs as isolated, deep rooted, satellite intrusions (ie. Burnside Pluton).

A three-dimensional shape analysis of the plutons that comprise the Cullen Batholith was made utilising geophysical modelling, and also on a detailed study of zonation, the geochemistry of the outer contacts of the plutons, the petrographic composition of the plutons and the asymmetry of the thermal aureole associated with each pluton.

The majority of the negative gravity Bouguer anomalies correspond with individual granitic intrusions of the batholith. Localised low gravity anomalies have either a flat base (ie. Fingerpost, Margaret, Frances Creek and McMinns Bluff plutons) or smooth symmetrical lows depending on the width of the anomaly (ie. Burnside, Prices Springs and Wolfram Hill plutons). According to Tucker et al. (1980) the contrasting gravity anomalies are related to the vertical shape of many of the plutons. The flat anomaly centres are interpreted as tabular intrusions with subhorizontal lower contacts at relatively shallow depths of approximately 4 to 5 kilometres. The contacts of these plutons may either dip out or inwards towards the pluton centre (Tucker et al., 1980). The circular bullseye Bouguer anomalies may be interpreted as deep rooted diapiric intrusions which pinch out at a depth of about 15 kilometres.

An assessment of the dips of the contact zones of the Allamber Springs pluton and McMinns pluton has been made using the overlapping of magnetic anomalies within the local host rocks with the granite contact zones in conjunction with the width of the thermal aureole of the pluton (see Fig. 5).

Many of the plutons in the Cullen Batholith contain roof pendants or have shallowly outward-dipping contacts suggesting that the present erosion level is close to the roof zone of the batholith. The roof pendants generally comprise large blocks of granitised Early Proterozoic metasediments that surround the batholith and/or tabular rafts of Bludells Monzonite. The Bludells Monzonite is believed to be a hybrid rock with a variety of compositions that lie between

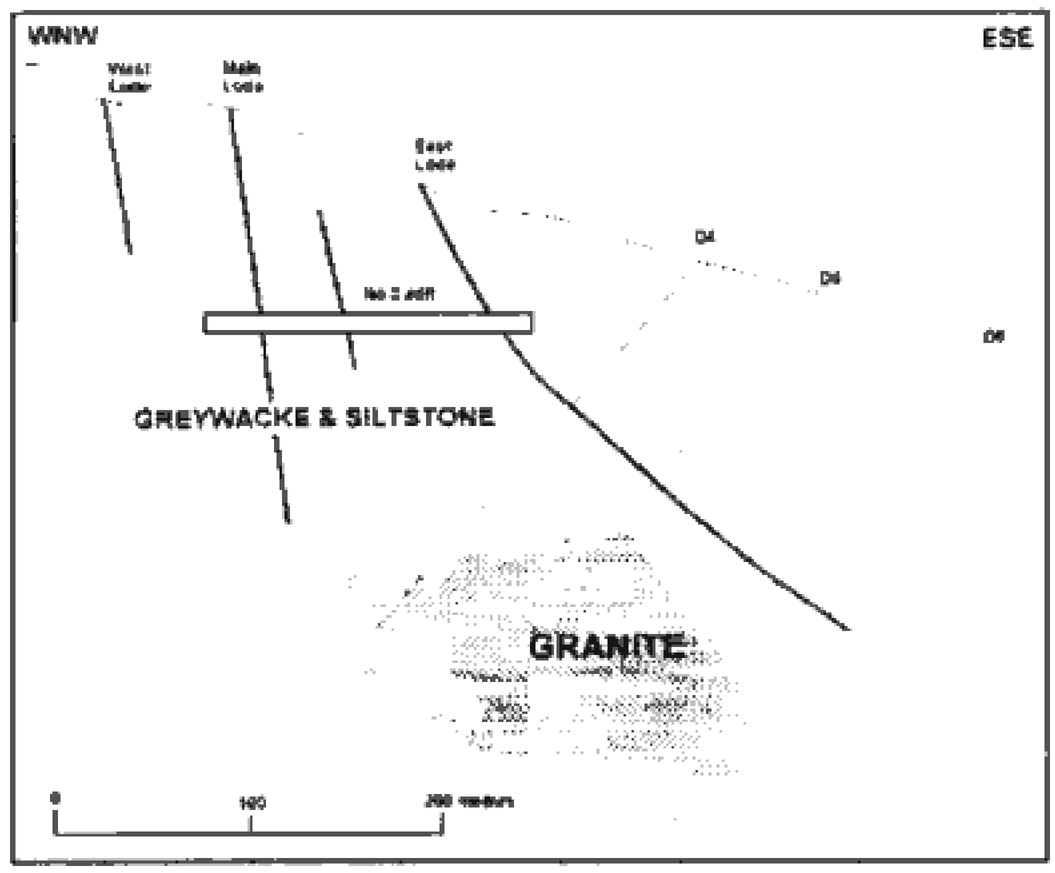

Figure 7. Schematic cross-section of the Mount Wells granite stock. (After Ahmad, 1993).

granite and Zamu Dolerite (see Fig. 6). Roof pendants are abundant in the McCarthys Granite, Frances Creek Granite and Allamber Springs Granite. A horizontal granite roof has also been intersected during drilling at the Mount Wells tin mine. The drilling intersected a hidden granite stock at a depth of 250 metres below the present land surface (Fig. 7). The drilling also suggested that this granite has inward-dipping contacts (pers. comm. A. Jetner and Ahmad 1993).

The presence of numerous roof pendants, the distribution of the thermal aureole around the batholith magmatic-hydrothermal breccias and the presence of K-feldspar-cordierite facies contact mineral assemblages all suggest a shallow to moderate level of intrusion. This is confirmed by the extrusion of co-magmatic felsic volcanics within the Edith River Group. Further the level of intrusion of the granites appears to have been restricted to the same stratigraphic level as the Zamu Dolerite. This along with the preponderance of xenoliths with a composition similar to Zamu Dolerite within the roof zones of many of the plutons suggests that the initial level of intrusion of the granite plutons was controlled initially by D2 and D3 structures and the presence of Zamu Dolerite. The detailed topography of the roof of the batholith and the overall shape and volume of individual plutons may play one of the key roles in the extent of the development of the thermal aureole around the batholith, which consequently would control the dimensions and channelling of hydrothermal systems and the distribution of economic tin and gold mineralisation around the Cullen Batholith (see Fig. 8 and Fig. 2).

Many plutons of the Pine Creek complex are circular or oval in shape (Fig. 9). Some are suggestive of ring or caldera structures. The Malone granite is an example, which lies to the east of the Cullen Batholith. Here the granite is believed to be a caldera pluton intruding into its own felsic volcanic ejecta (Edith River Group of volca-

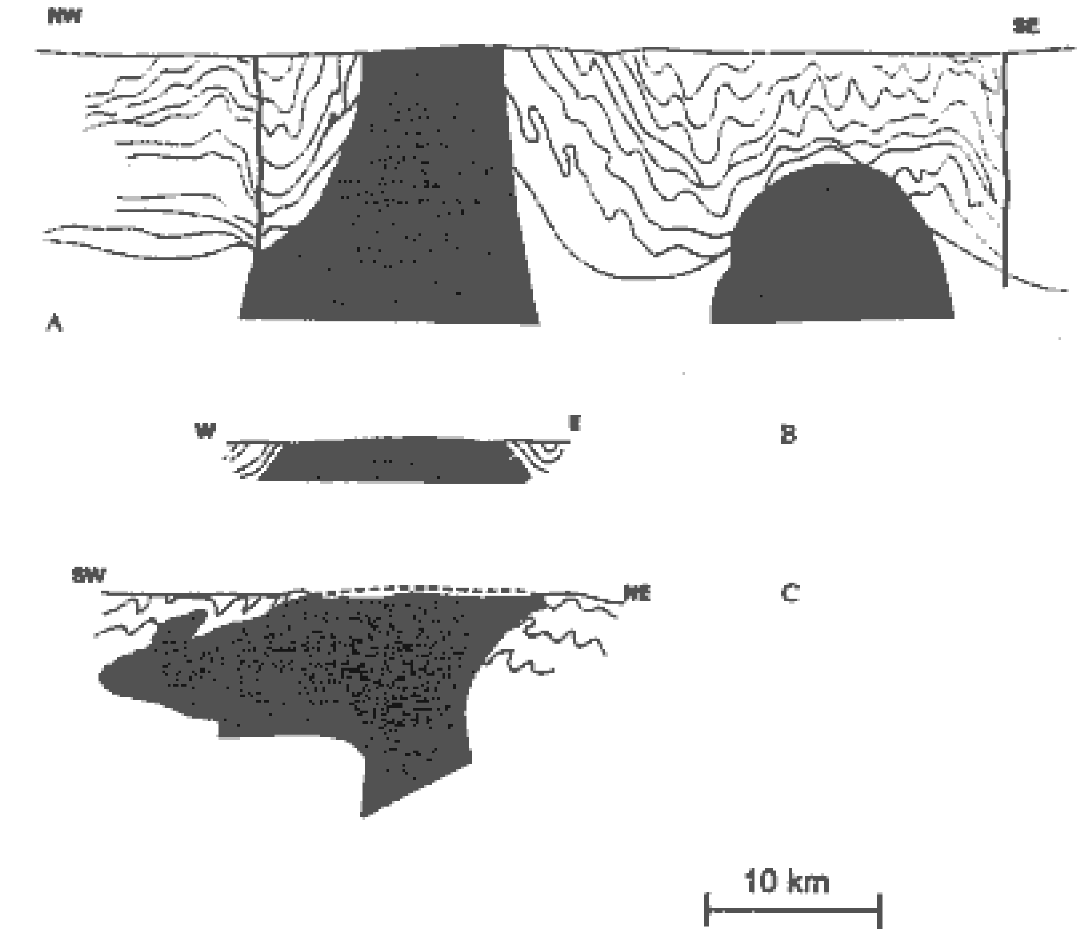

Figure 8. Different versions of the geological cross-sections of the Burnside granite according to. A – Needham 1978, B – D'Addarario & Pillinger 1985, C – this study.

The Allamber Springs Pluton has a similar ring-like structure. However, it has a subsolvus granite at the periphery of the granite and a hypersolvus granite (Saunders Granite) in the centre. According to Bonin (1986), the radius of a ring intrusion may be directly proportional to the depth of the magma chamber in this case a depth of 10 to 15 kilometres is suggested.

4.3. Zonation of Plutons

Compositional zoning is commonly found in many granite intrusions. This zonation may be reflected by compositional or geochemical changes from the margins to the centre of the pluton. Individual zonation patterns and the character of the contacts between the phases comprising a pluton can be used to define the differing types of zonation (ie. mineral and/or cryptic layering, a ghost stratigraphy, palinpsestic structures), and hence the process which initially formed the zonal pattern. It may represent in situ differentiation, contamination of a single magmatic pulse, or multiple intrusion of the pluton by several individual intrusive pulses from a common source. Such multi-zoned plutons are often composed of a number of successively differentiated phases, with the younger phases intruding into the older phases.

The zonal patterns of plutons formed by in situ differentiation or/and contamination (granitization) of the country rocks are usually developed along the roofs and walls of granite intrusions. Therefore they are affected by different rates of erosion. This style of zonation is usually developed within individual magmatic pulses and has no tectonic implications. In contrast, zoned plutons formed by a sequence of differing intrusive phases are not affected by different rates of erosion due to vertical contacts. Hence, this style of zonation may contain the information on crustal kinetics during the act of emplacement of the plutons (Gastil et al., 1991).

Concentric zonation has been identified in the Cullen Batholith by Stuart-Smith et al. (1993) in the Shoobridge, Tabletop, Bonrook, Driffield, Mount Davis and Allamber Springs Granites. Concentric zonation is also described from the Malone Pluton east of the Cullen Batholith. Systematic mineralogical, petrographic, and chemical variances from the margins to the centres of these plutons indicate two different styles of zonation are present within the Cullen Batholith (Fig. 10).

4.4. Cryptic Layering and Ghost Stratigraphy

Subhorizontal cryptic layering and ghost stratigraphy occurs within most of the plutons in the Cullen Batholith (ie. Burnside, Allamber Springs, Tabletop, McMinns Bluff and Minglo Granites). This zonation appears to be the result of magma contamination by chemically contrasting country rocks (mainly Zamu Dolerite) along the horizontal roofs of the plutons. The roof zones of many of these plutons contain megacrysts of K-feldspar which are interpreted to be the result of the metasomatic growth of K-feldspars due to interaction between water saturated country rocks and water undersaturated granitic magma (ie. the Allamber Springs Granite). The flats or shallow depressions at the present granite outcrops and horizontal roofs of plutons are favourable conditions for the preservation of some remnants of this style of zonation in plan. Figures 6, 11 and 12 show how the basic country rocks (Zamu Dolerite) are structurally related to the granitized equivalents within the granite. Examples of the cryptic layering and ghost stratigraphy at the tops of the plutons are shown in Figures 11 and 12.

The cryptic layering in the Burnside Granite (Fig. 11) indicates that the roof zone of the granite is presently exposed. The granite also has a concentric magnetic anomaly in its centre. A shallow arching of the cryptic layering has been also detected by systematic chemical changes of the granite composition from the margins to the centre. The roof zone of the Allamber Springs Granite contains many xenoliths of granitized country rocks as well as hybrid zones with a distinctly higher colour index. The roof zone is tens of metres thick and is underlain by the main facies of the Allamber Springs Granite (PgaC). The cryptic layering and ghost stratigraphy described from these plutons is very common in the outcrops of many of the plutons in the Cullen Batholith.

4.5. Concentric Zonation

Concentric zonation, believed to be the result of the interaction of several magmatic pulses, is best developed in the Allamber Springs and Shoobridge Granites. In the Allamber Springs Granite, the first pulse of the pluton is represented by a porphyritic coarse biotite granite (PgaC). This phase is intruded along its margin by an equigranular coarse biotite granite (PgaA). Finally, both phases are intruded by a medium-fine grained biotite granite (Saunders Granite-Pgg

Figure 9. Circular and oval shapes of the Cullen Batholith plutons.

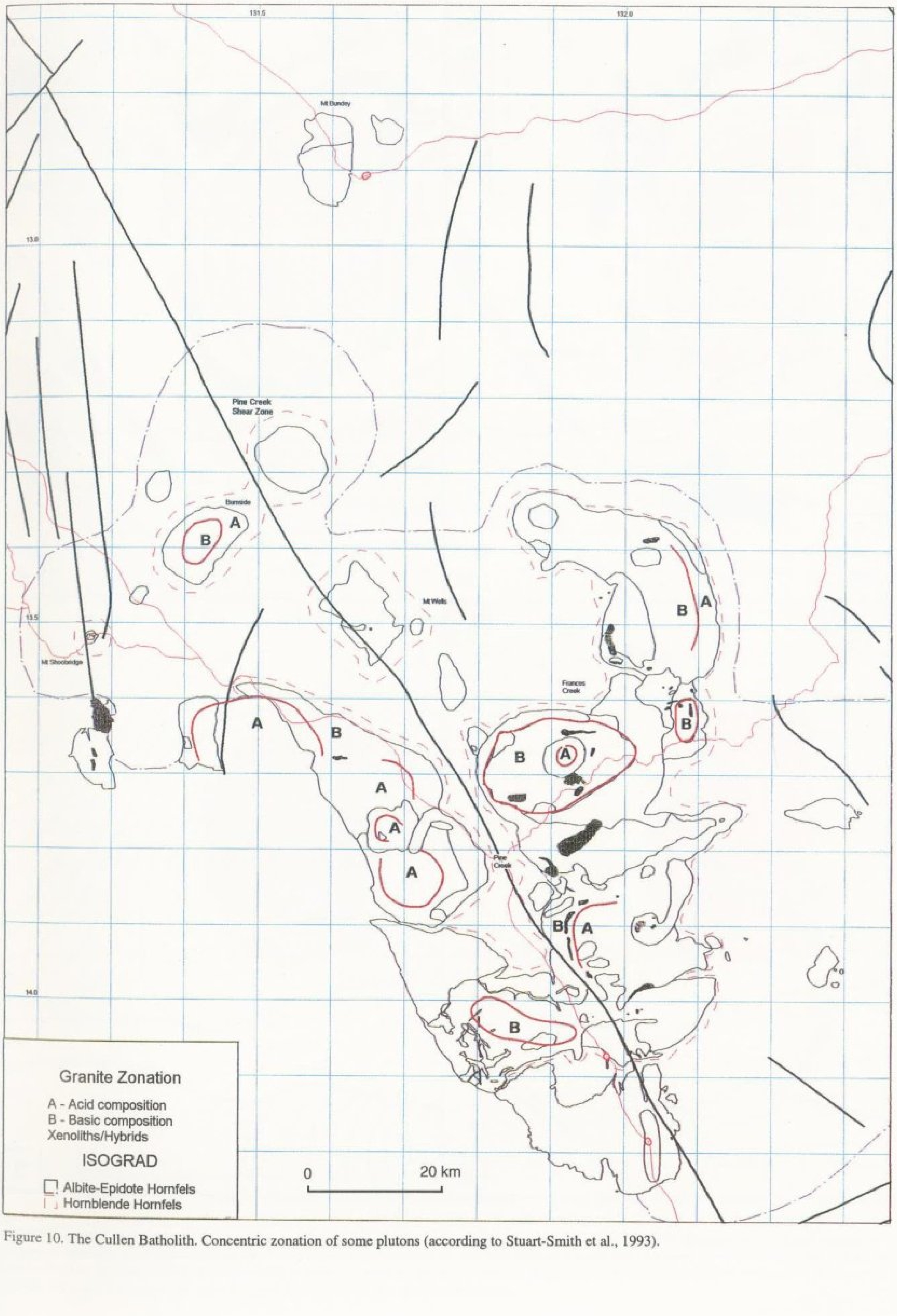

Figure 10. The Cullen Batholith. Concentric zonation of some plutons (according to Stuart-Smith et al., 1993).

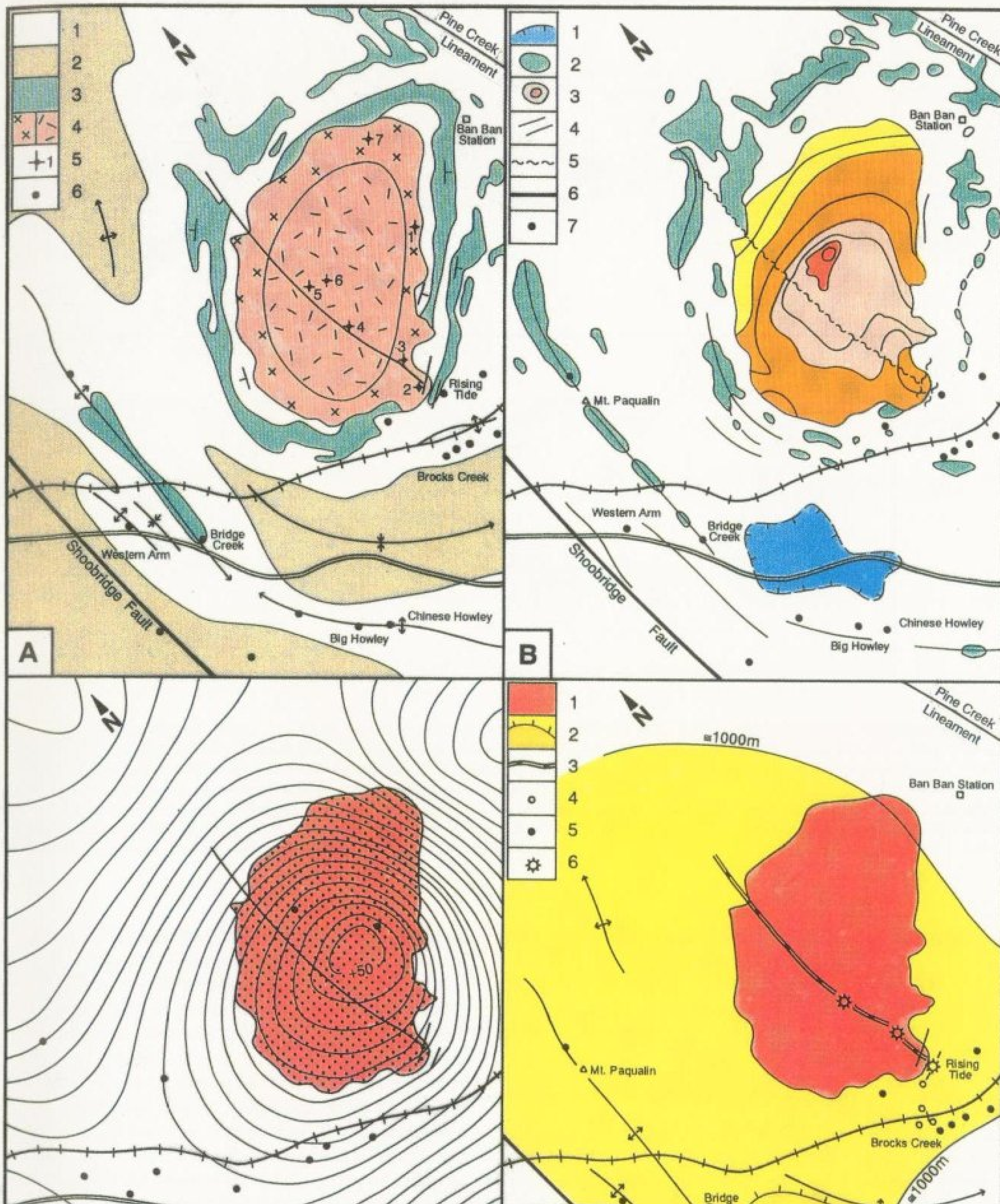

Figure 11. The Burnside granite. A – Surface geology: 1 – South Alligator Group; 2 – Finniss River Group; 3 – Zamu dolerite; 4 – cryptic layering within the Burnside granite, felsic-granite facies at the margin and more mafic at the centre; 5 – granite samples; 6 – gold deposits. B – Airborne magnetics: 1 – negative anomaly; 2 – 3 positive anomaly; 4 – anticline; 5 – quartz vein; 6 – regional fault and lineaments; 7 – gold deposits. C – Gravity – Bouguer anomaly in mGal. D – Roof relief of the Burnside granite. 1 – granite outcrop; 2 – subsurface extent of the granite at –500 m level and –1000 m level; 3 – Stuart highway; 4 – copper deposits; 5 – gold deposits; 6 – epithermal lead prospects.

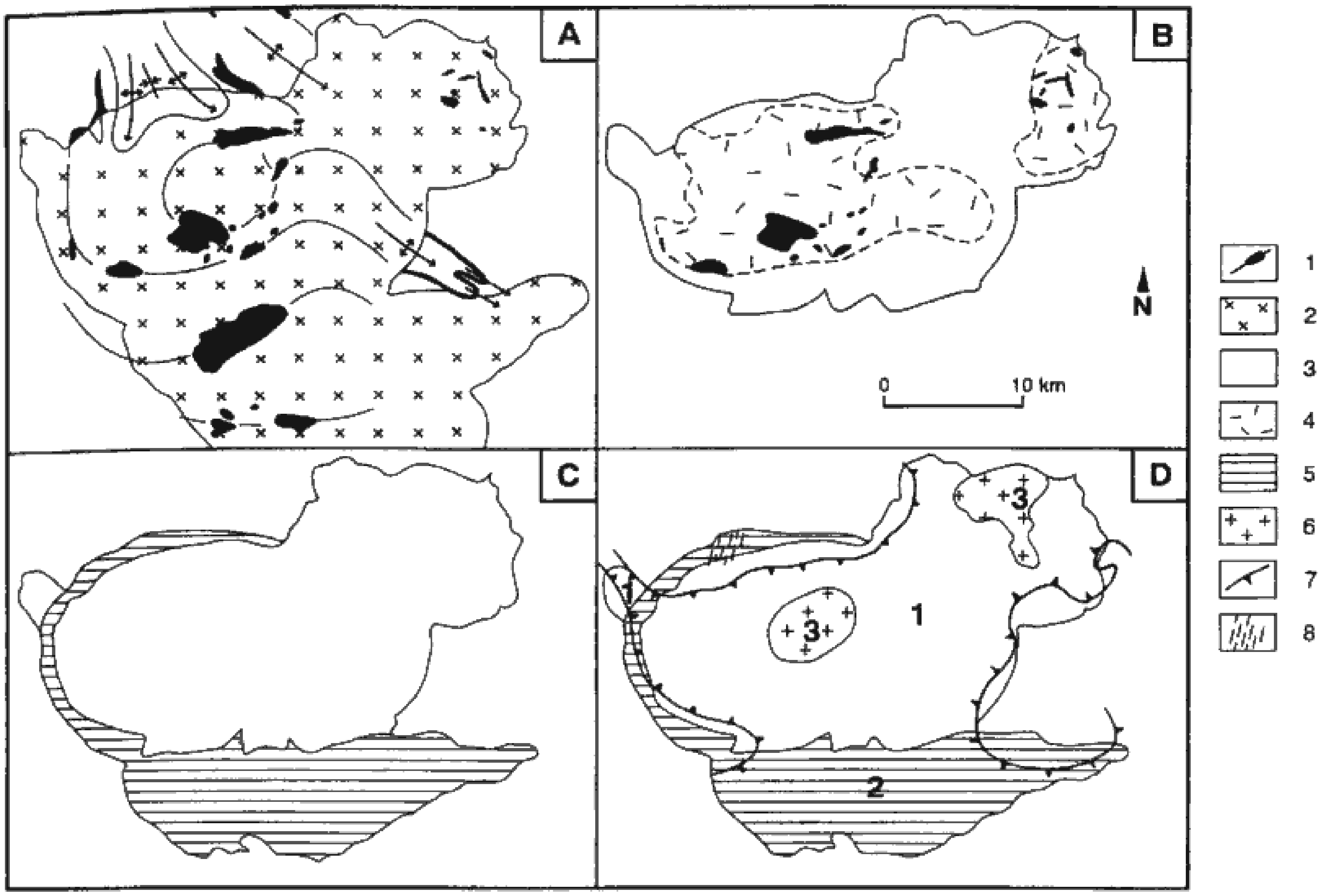

Figure 12. The Allamber Springs Pluton. A – Relationship between country rocks structure and ghost stratigraphy pattern within the granite outcrop. B – Remnants of the original roof of the pluton. (Rafts of Bludells monzonite, PgaC and PgaB phases of the Allamber Springs granite). C – Ring dyke of the Allamber Springs granite (PgaA) intrudes into older Pga B, C & D phases. D – Concentric zonation of the Allamber Springs Pluton. 1 and 2 - The phases of the Allamber Springs and Mount Porter granites; 3 – Saunders and Frances Creek granites.
Legend: 1 – Zamu dolerite and rafts of Bludells monzonite and hornfels. 2 – The Allamber Springs, Mount Porter and McCarthys granite. 3 – Allamber Springs granite phase PgaD in Fig. 12 B. 4 – Allamber Springs granite phase PgaB. 5 – Pga C and A phases of the Allamber Springs granite. 6 – Saunders and Frances Creek granites. 7 – Inward-dipping granite contacts. 8 – Greisenisation.

and Frances Creek Granite-Pgr). The distribution of these phases indicates a two stage development of the pluton (Fig. 12). The reverse zonation of the first and second magmatic pulse may be related to shallow-seated processes in a thin crust, whereas the second pulse may have been derived from a deeper source. Alternatively, the younger granite intrusion in the centre of the pluton has a normal zonation, indicating magma generation from an already preheated and thicker crust. This change of the zonal pattern may result from either a relative movement of the source zone beneath the intruding phases of the pluton or a change of the depth of the source of magmatic pulses with time.

The Shoobridge Granite is a circular granite stock, approximately 1.5 kilometres in diameter, which crops out as a satellite intrusion of the Cullen Batholith west of the Cosmo Howley mine (Fig. 13). The granite has a distinctive concentric zonation and an exceptional variation in mineralogy and chemical composition almost completely covering the range of differentiated granites in the Cullen Batholith. The outer zone comprises mesocratic tonalite with a more porphyritic granodiorite toward the centre, and the core consists of a fine to medium grained leucogranite. The normal concentric zoning indicates two magmatic pulses. The older one more mafic at the periphery and roof, and the younger pulse in the centre.

4.6. Granite Typology and Hierarchy

The granites of the Cullen Batholith have been previously classified into three types by Rattigan & Clarke (1955) and five types by Walpole et al. (1968). More recently Stuart-Smith et al. (1993) distinguished ten major granitoid types on the basis of hand specimen, mineralogy and texture. They include:

granodiorite (type 1)
granite (types 2,3,4)
leucogranite (types 5,6,7,8,9,10) (Table 4)

According to Stuart-Smith et al. (1993) the type 2 granite (Table 4) is the most dominant phase, comprising about 50 % of the batholith. Leucogranites (Table 4) together

Table 4. Granite types of the Cullen Batholith (Stuart-Smith et al., 1993)

1	grey	coarse	porphyritic	biotite	hornblende	granodiorite
2	pink-green	coarse	porphyritic	biotite	hornblende	granite
3	pink-green	medium	porphyritic	biotite	hornblende	granite
4	grey	coarse	porphyritic	biotite	–	granite
5	pink	coarse	porphyritic	biotite	–	granite
6	pink	coarse	equigranular	biotite	–	leucogranite
7	–	medium	equigranular	biotite	–	leucogranite
8	light grey	coarse	porphyritic	biotite	–	leucogranite
9	–	fine/medium	equigranular	–	–	leucogranite
10	–	fine/medium	porphyritic	–	–	leucogranite

make up over 40% of the batholith with types 5, 6, and 8 the most common. The hierarchy of the individual types of Stuart-Smith et al. (1993) is shown in Fig. 14 with the dominant granite types marked by circles. In this study an attempt has been made to simplify this classification while retaining the temporal and compositional relationship between individual granitic plutons as noted by Stuart-Smith et al. (1993). The ten granite types of Stuart-Smith et al. (1993) have been reassigned into three major groups using field relationships, mineralogy and the average geochemical compositions of individual plutons, which were plotted using various standard petrochemical techniques (Figures 16 and 17).

The various granites that comprise the Cullen Batholith have been subdivided as:

1. Early Igneous Suite granites (EIS), which are mesocratic hornblende-biotite bearing, coarse grained, porphyritic, undifferentiated, late-orogenic, tin barren, metaluminous monzogranodiorites. These granites form the main phases of the Minglo, Mount Porter, McCarthys, Fingerpost, McKinlay, Prices Springs, McMinns Bluff, Margaret, Bundey and Allamber Springs plutons.
2. Transitional Igneous Suite granites (TIS), which are biotite bearing, coarse grained, equigranular, poorly differentiated, late-orogenic, stanniferous, peraluminous, monzogranites. These granites form the main phases of the Allamber Springs, Tennysons, Umbrawarra, Tabletop, Mount Davis, Bonrook and Driffield plutons.
3. Young Igneous Suite granites (YIS), which are leucocratic biotite bearing, medium-fine grained, equigranular, moderately differentiated, post-orogenic, stanniferous, peraluminous, monzo-syenogranites. The YIS granites form the main phases of the Burnside, Frances Creek, Fenton, Saunders, Douglas, Yenberrie, Wolfram Hill and Shoobridge plutons. The EIS and TIS granites are the dominant granite types in the Cullen Batholith. The EIS is believed to represent the sub-horizontally stratified roof zone of the batholith and this is usually intruded by the TIS granites. The TIS occurs either as individual plutons (eg, Tabletop, Umbrawarra and Douglas granites) or occupies the internal parts of the batholith usually beneath the EIS granites. The YIS granites mainly occur as separate plutons or stocks that have intruded either the EIS or TIS granites in the south of the Batholith or as satellite bodies in the northern periphery of the batholith.

The marginal zone of many plutons have differing mineralogy, chemical, composition, texture, alteration and style of mineralisation. As discussed previously many of the roof zones of the plutons are usually very flat, showing a high degree of contamination by restites of country rocks. These areas are often greisenized and cut by several stages of pegmatite and aplite dykes. In general the extent of the high temperature alteration in the roof zones of the plutons is limited. Away from the roof zones many of the contact zones of the plutons have distinctive chilled margins (tens metres wide). These margins are generally more felsic, with phenocrystic feldspars, quartz and mafic minerals. Aplite, pegmatite and quartz-tourmaline veins or dykes also occur in this zone.

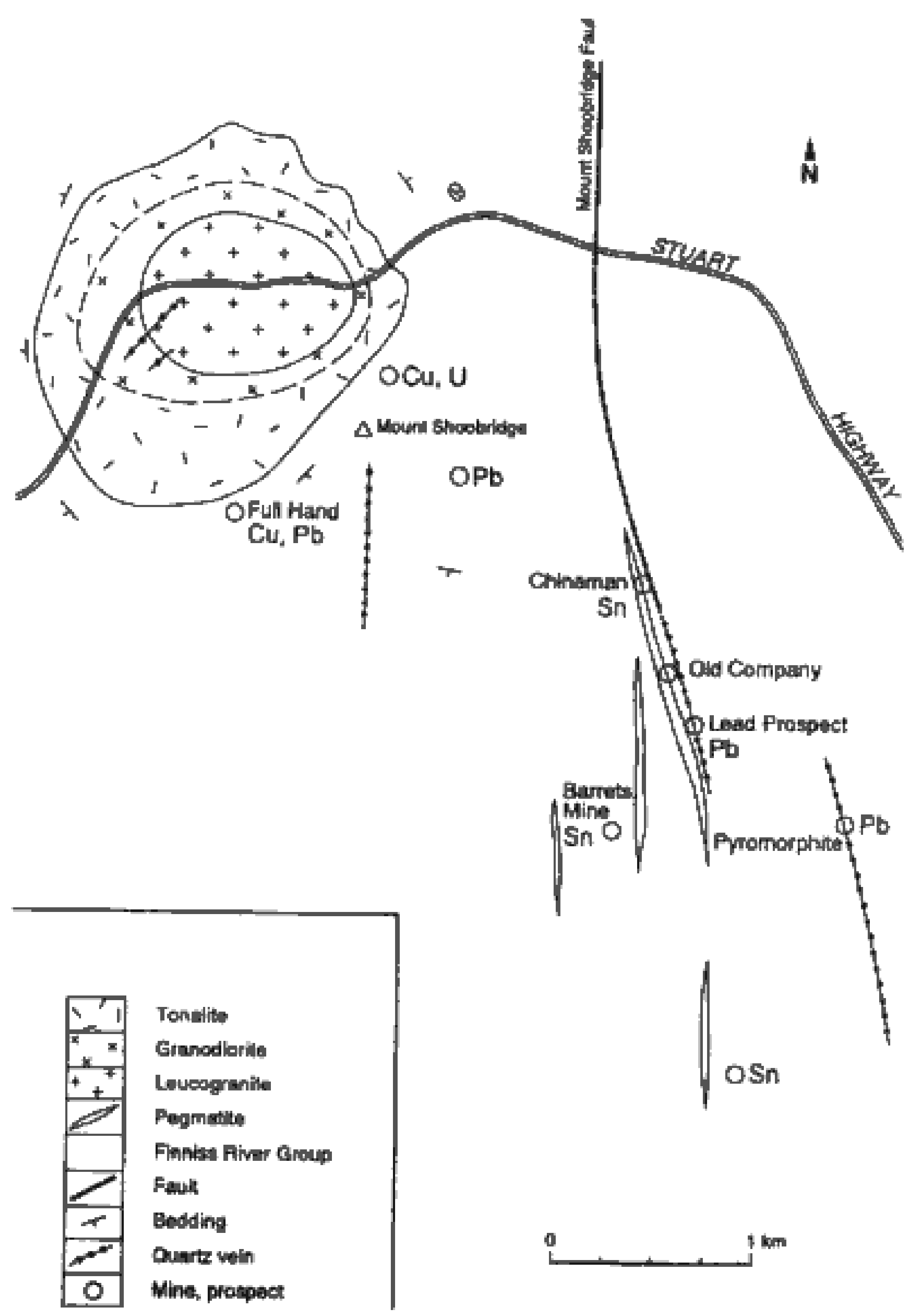

Figure 13. Concentric zonation of the Shoobridge stock and surroundings.

Aplite, pegmatite, tourmaline breccias and quartz-tourmaline veins or dykes up to several metres wide occur in the immediate thermal aureole of most granite plutons. They contain white mica and tourmaline and stockworks with sulphides, cassiterite and/or wolframite. These veins may extend for up to several hundred metres from the pluton or plug (ie. Mount Shoobridge area in Fig. 13). The magmatic-hydrothermal type of tourmaline breccias at the exo-contact of the Allamber Springs Granite indicate that fluid pressures may exeed lithostatic pressure.

Tin ± tungsten mineralisation around the margin of some plutons (ie. Wolfram Hill Granite) is demonstrably related to greisenization, which in turn can be ascribed to veining by reactive fluids from the nearby granite. Ore minerals in the veins are similar to those in the greisens and there is a continuity in mica chemistry between the end stages of granite and pegmatite crystallisation and greisen (ie. the Mount Shoobridge Granite in Fig. 13).

4.7. Granite Isotopic Ages and Geological Chronology

Granitoids of the Pine Creek Geosyncline including the Cullen Batholith, are generally considered (Walpole et al., 1968) to be post-tectonic, intruding the deformed Early Proterozoic lithologies (Page et al., 1988). Their isotopic age dating is based largely on U-Pb zircon, Rb-Sr whole rock and K/Ar mineral data, which is summarised along with the field relationships of the granites by Stuart-Smith et al. (1993). The U-Pb zircon data and the field relationship of plutons are shown in Fig. 14, which generally confirms the threefold subdivision of the granites discussed above.

The isotope age data from some granites also provide information not only on the timing of the magma emplacement, but also the duration of the crystallisation and the cooling of that granite magma (Table 5). The emplacement age of the EIS granites (I) is taken to be about 1830 Ma (Fingerpost granodiorite), the TIS granites (II) is taken to be 1825 Ma, and the Young Igneous Suite (III) is taken to be

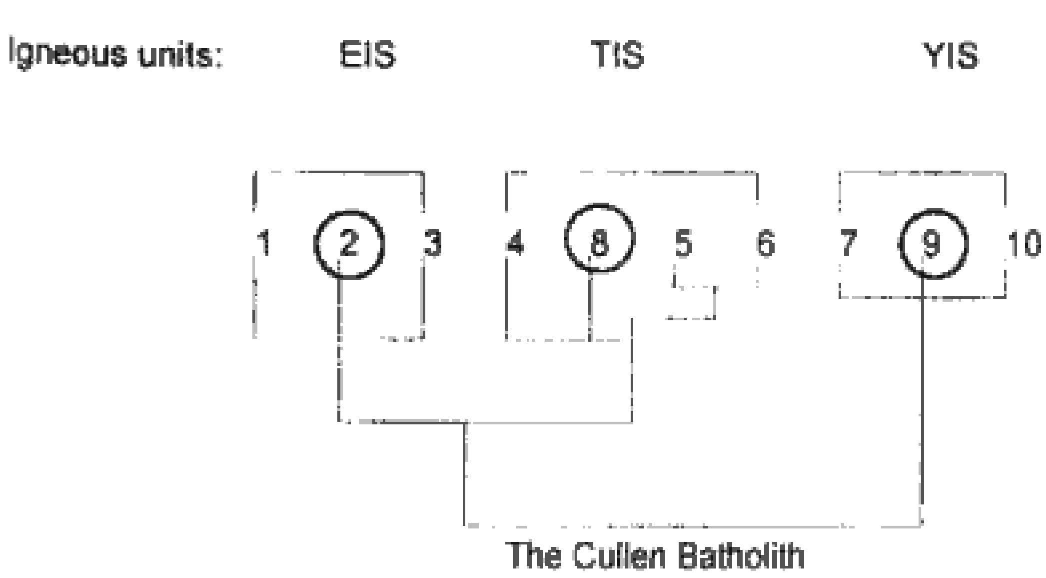

Figure 14. Typological hierarchy of the Cullen Batholith in circles – main types. 1–10 Granite types (after Stuart-Smith et al., 1993).

Table 5. Isotope age data of the Cullen Batholith (Stuart-Smith et al. 1993)

Isotope system	Closing temperature	Mineral	Age (in Ma)	Suite	Time diff. (in Ma)
K-Ar	>300 degC	biotite	1650-1700	I-III	125
Rb-Sr	540 degC	whole rock	1780±20	I-III	40
U-Pb	>800 degC	zircon (Ion micro-probe ages)	1800±5	III	20
			1818-1825	II	15
			1835±6	I	

about 1800 Ma (Stuart-Smith et al. (1993). This represents a 30 Ma time difference between the intrusion of individual suites.

As stated by Stuart-Smith et al. (1993) the pooled Cullen Batholith Rb-Sr age is approximately 40 million years younger than the U-Pb zircon age. This time difference may mark the timing of the final crystallisation or cooling below a threshold temperature of the Cullen Batholith at ca 1770-1780 Ma. The K-Ar biotite ages (Hurley et al., 1961) from some of these granites suggest that the final cooling of the batholith below 250 °C did not occur until some 100 million years later (1650-1700 Ma, Stuart-Smith et al., 1993), see Fig. 15. The extended period suggested by the different closing temperatures of the individual isotope systems indicates that an extended period of cooling from 540 °C to below 300 °C occurred in the batholith. This may have been an important controlling factor on the age and extent of the thermal aureole around the batholith and the timing and distribution of hydrothermal mineralisation spatially related to the Cullen Batholith. The long duration of the elevated temperature regime within and around the Cullen Batholith may be explained by high heat flow as a result of the high heat production of its granites, and this will be discussed in more detail below (Joliet et al., 1989 and Cull, 1991).

4.8. Granite Chemistry and Petrology

Whole rock chemical analyses of the granites used in this study are from the data compiled by Stuart-Smith et al, (1993). This database has been augmented by 35 additional samples, collected during the 1994 field season. The granite samples were classified according to their typology and only the average composition of main granite phases (see Appendix I) have been used in the variation diagrams shown in Figs. 16 and 17. Altered, sheared and hybrid granites were also excluded. The oxides of major elements were recalculated to cationic proportions, to aid determination of the mineralogical significance of the granites. The trace element distributions are discussed individually according to their metallogenic, petrogenetic and tectonic importance. A summary of the geochemical typology of granite types and Igneous suites of the Cullen Batholith is shown in Table 6.

Table 6. Geochemical typology of igneous suites in various schemes

FIGURE		EIS	TIS	YIS
	PETROCHEMICAL			
16A	Rajpoot (1992)	K-normal granite	K-normal granite	K-normal granite
16B	Pecerillo & Taylor (1976)	shoshonitic K-high calc-alkaline	shoshonitic K-high calc-alkaline	shoshonitic K-high calc-alkaline
16E	Bouseily & Sokkary (1975)	undifferentiated-differentiated granite	poorly-moderately differentiated granite	poorly-moderately differentiated granite
	PETROGRAPHICAL NOMENCLATURE			
16D	Rajpoot (1992)	granodiorite-monzogranite	monzogranite monzosyenogranite	monzosyenogranite syenogranite
16C	Debon & Le Fort (1983)	Bi-Hb low-peraluminous Bi-Hb metaluminous granite	Bi-low-peraluminous granite	Bi-low peraluminous-granite
16F	Bouseily & Sokkary (1973)	anomalous granite-granodiorite	differentiated granite	differentiated granite
	METALLOGENIC CLASSIFICATION			
16G	Odale (1980)	barren granite	stanniferous granite	stanniferous granite
	TECTONIC CLASSIFICATION			
16H	Rajpoot (1992)	late-orogenic granite	post-orogenic granite	post-orogenic highly differentiated granite
17 H	Förster & Tischendorf (1994)	syn-collision granite	syn-collision granite	syn-collision granite
	GENETIC CLASSIFICATION			
	Chappel & White (1974) (applied by Stuart-Smith et al., 1993)	I ± S type	I ± S type	I ± S type
	Ishihara (1977)	magnetite series	magnetite-ilmenite series	ilmenite series

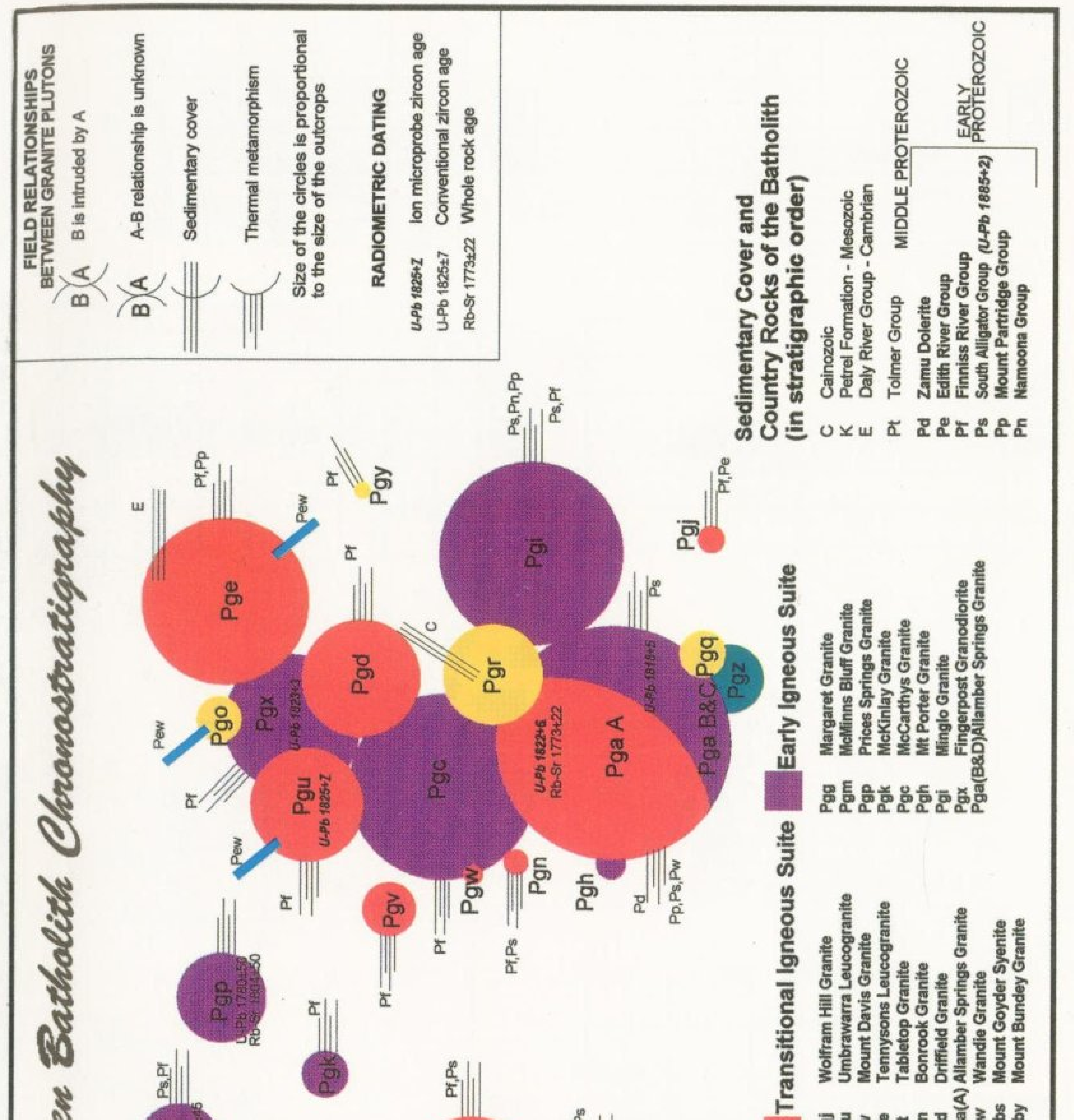

Figure 15. Chronostratigraphy of the Cullen Batholith.

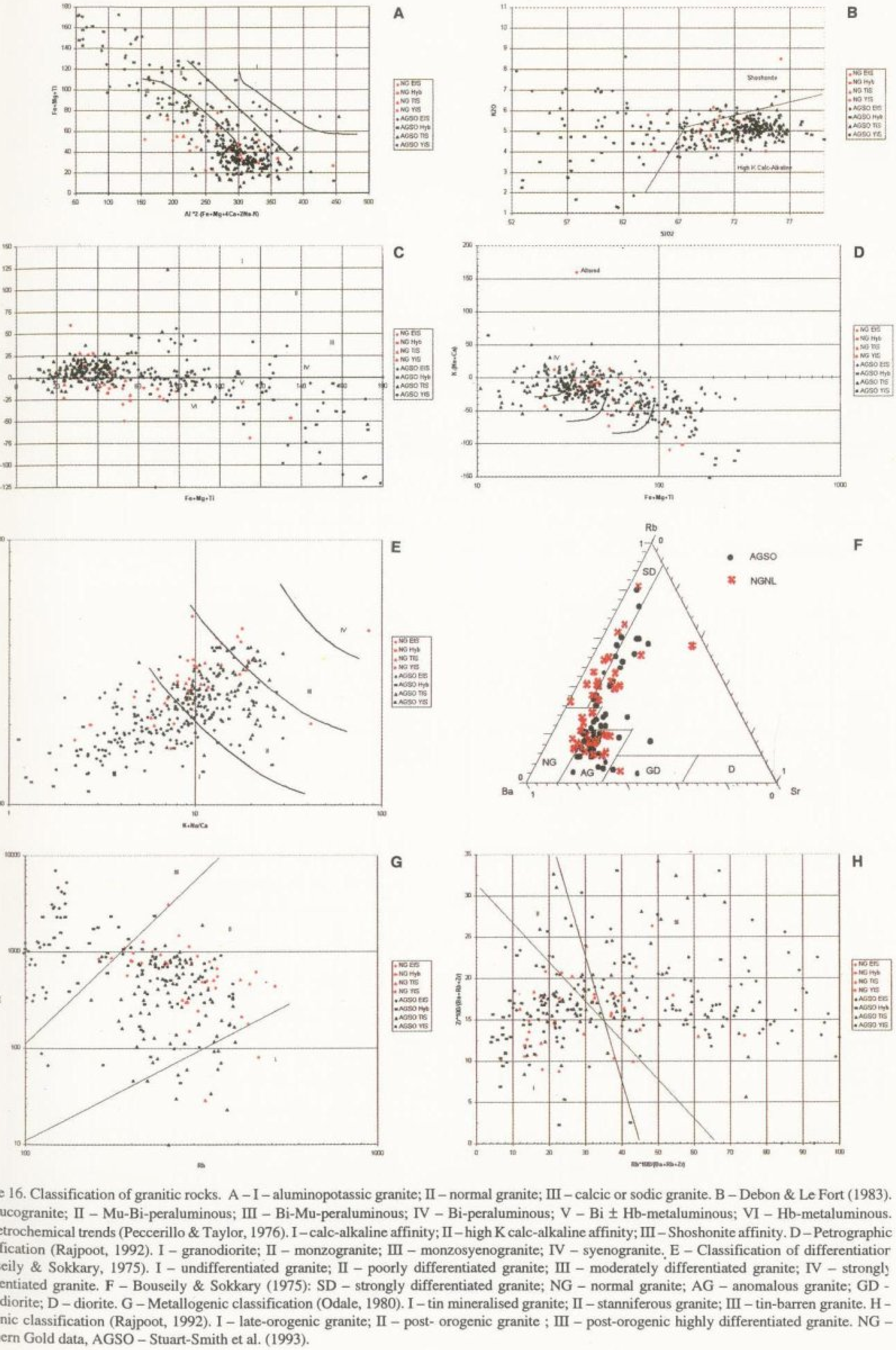

Figure 16. Classification of granitic rocks. A – I – aluminopotassic granite; II – normal granite; III – calcic or sodic granite. B – Debon & Le Fort (1983). I – leucogranite; II – Mu-Bi-peraluminous; III – Bi-Mu-peraluminous; IV – Bi-peraluminous; V – Bi ± Hb-metaluminous; VI – Hb-metaluminous. C – Petrochemical trends (Peccerillo & Taylor, 1976). I – calc-alkaline affinity; II – high K calc-alkaline affinity; III – Shoshonite affinity. D – Petrographic classification (Rajpoot, 1992). I – granodiorite; II – monzogranite; III – monzosyenogranite; IV – syenogranite. E – Classification of differentiation (Bouseily & Sokkary, 1975). I – undifferentiated granite; II – poorly differentiated granite; III – moderately differentiated granite; IV – strongly differentiated granite. F – Bouseily & Sokkary (1975): SD – strongly differentiated granite; NG – normal granite; AG – anomalous granite; GD - granodiorite; D – diorite. G – Metallogenic classification (Odale, 1980). I – tin mineralised granite; II – stanniferous granite; III – tin-barren granite. H – Tectonic classification (Rajpoot, 1992). I – late-orogenic granite; II – post- orogenic granite ; III – post-orogenic highly differentiated granite. NG – Northern Gold data, AGSO – Stuart-Smith et al. (1993).

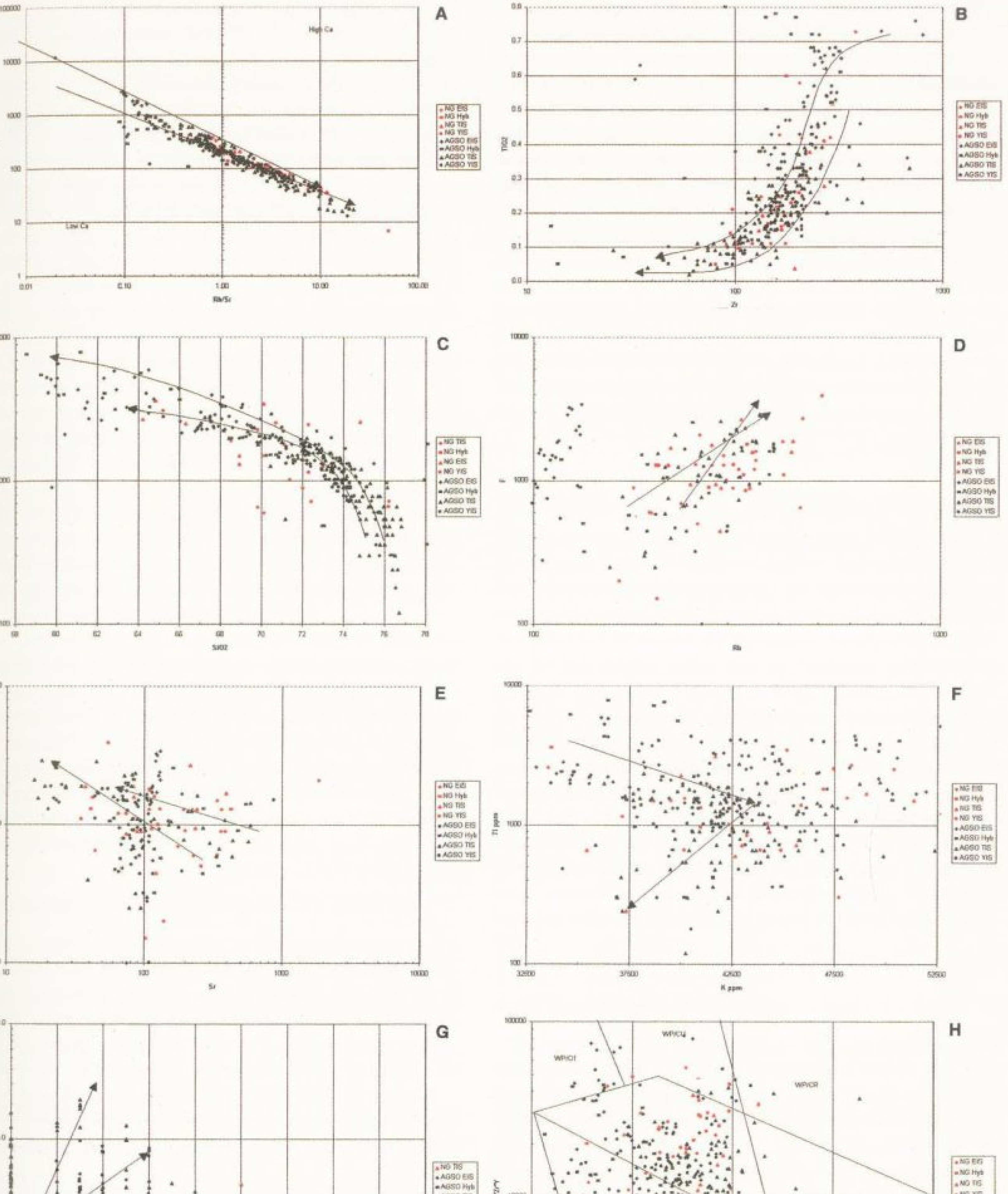

Figure 17. Trace and major elements variation diagrams (A–H) of the Cullen Batholith granites. H – Förster & Tischendorf (1994): ColG – collision granite; SC – syn; LC – late; VAG – volcanic arc; WP – within plate; CR – continental rift; CA – continental arc; CU – continental uplift; OI – ocean island. NG – Northern Gold data, AGSO – Stuart-Smith et al. (1993).

Calculating the Alumina Balance [Al-(Na+K+2Ca)] (Fig. 16A) indicates that most of the granites are" low aluminous " with a few of the EIS granites trending to " metaluminous " (Fig. 16C). All Igneous suites of the Cullen Batholith show high potassium calc-alkaline compositions (Fig. 16B). The Colour Index (Fe+Mg+Ti) (Fig. 16D) indicates that the EIS granites are" mesocratic" and the TIS and YIS granites " leucocratic ".

The Rb/Sr vs Sr variation diagram (Fig. 17A) indicates an increasing order of magmatic differentiation from EIS to YIS granites. The dividing lines for high and low Ca fit well with the classification according to Lehmann & Mahawat (1989), ie. EIS granites plot in the field of high Ca granite and TIS and YIS granites in the field of low Ca granites. The Zr vs TiO_2 variation diagram (Fig. 17B and 17C) indicates a progressive magmatic differentiation from EIS to TIS granites and a broad overlap of the YIS granites. In order to determine the influence of a post-magmatic fluid phase, data are plotted in F vs Rb and F vs Sr variation diagrams (Fig. 17D and 17E). F shows positive and negative correlation with Rb and Sr, respectively. This supports the idea that F enrichment is a consequence of magmatic fractionation. The behaviour of potassium in sequence from EIS to YIS granites indicates the significant influence of metasomatic processes in TIS and YIS granites (Fig. 17F).

Many authors have used geochemical variation diagrams to discriminate tin-bearing from tin-barren granites. These variation diagrams indicate the degree of magmatic differentiation, which is one of the most significant parameters in distinguishing the metalliferous granites. Lehmann (1987) emphasised that granites from various tin provinces show a positive correlation between Sn vs Rb/Sr (Fig. 17G). The granites of the Cullen Batholith show a similar pattern despite wide scatter of data.

4.9. Geochemical Maps of the Cullen Batholith

Regional distribution of major and minor elements in the Cullen Batholith is shown in ten geochemical maps according to individual plutons (see Appendix III). Chemical analyses have been summarised from Stuart-Smith et al. (1993) as mean values of Fe + Mg + Ti (colour index), Al-(Na + K + 2Ca) alumina index, Rb, Li, F, Sr, Rb/Sr, Zr, U and Th of the main phases of the individual plutons.

In general two regional distribution patterns of major and trace elements may be recognised within the Cullen Batholith:

Regional distribution of the igneous suites shows a zonation with the Early Igneous Suite (EIS) in the batholith core, and the Transitional and Young Igneous Suites (TIS and YIS) along its periphery (see Appendix III). This regional arrangement of the igneous suites indicates a deeper source, and/or a thicker crust for the generation of younger plutons. The zonation of the Cullen Batholith also shows asymmetry in the distribution of igneous suites. The young Igneous Suite (YIS) is located in the northern periphery of the batholith, indicating a drift of the zone of anatexis toward north (see Fig. 3).

The Pine Creek Lineament plays a key role in the surface geochemistry of the Cullen Batholith. There is a horizontal displacement of its western segment toward the south-east. Geochemical maps of the plutons west of the lineament overall show higher Rb/Sr ratio, lithium, fluorine, uranium and rubidium contents and lower zirconium, strontium, and thorium than the plutons on the eastern side of the lineament (see Appendix III). It may indicate a difference in the erosion level between the western and eastern segments of the batholith. The western segment is more fractionated and less contaminated (lesser amount of xenoliths and rafts of country rocks) and therefore is more eroded than the eastern segment. It may have some implications for the distribution of the mineralisation around the batholith. There is a similar horizontal displacement of the centres of mineralisation. The less eroded eastern segment shows a larger variety and broader regional distribution of the mineralisation (Fig. 2).

4.10. Magma Generation

The Cullen Batholith has been classified by Wyborn (1988) as part of the suite of dominantly I-type granitoid plutons generated throughout northern Australia during the Early Proterozoic. These granites are believed to have been formed by a process of vertical accretion in an intracratonic environment. Wyborn (1988) suggests mantle-derived sources for this magma rather than an Archaean granitic basement, as proposed by Ferguson et al. (1980). Geophysical, geological, isotopic and geochemical data from the Cullen Batholith indicate an Archaean granitic basement source for magma generation. This may have occurred as a result of underplating during the collision of two Archaean cratons. The high oxidation ratios, reflected in the high magnetic susceptibilities of many of the plutons found by Bajwah (1991) (eg. Tabletop and Mount Bundey granites) may have been caused by interaction between highly magnetised country rocks and granitic magma at the roof of the batholith.

4.11. Two Magmatic Events

The granites of the batholith have been divided into three main suites (EIS, TIS and YIS granites), which generally correspond to the typology proposed by Stuart-Smith et al. (1993). These suites seem to represent two different events of granite magmatism during the waning stages of the Barramundi orogeny. These episodes are presently designated as " first phase of granite magmatism " comprising EIS and TIS granites and "the second phase of granite magmatism" represented by YIS granites. The emplacement of granitic magma probably took place in several pulses. In the Cullen Batholith the EIS granites are underlain by the TIS granites, which may explain the small extent of contamination in TIS granites. Both intrusive suites are intruded by the YIS granites, which follow the feeder pipes within and at the periphery of the main outcrop of the batholith. This suggests that the EIS granites may have prepared the structural foundation for the later intrusions.

A SHRIMP U-Pb zircon age for the Burnside Granite is 1800±5 Ma, which has been interpreted as a minimum age (Stuart-Smith et al., 1993). Lead isotope data from three wholerock samples, their K-feldspars and acid-leachable Pb from the K-feldspars were obtained (Table 7). Regressing all data showed the data scattered well in excess of analytical error. This was due to two outlying data, both from sample CZ251. Omitting these from various data combinations yielded a consistent, although imprecise, age of about 1810 Ma. The best estimate is 1811±47 Ma (see Table 8 and Fig. 18). This age is in accord with the previous zircon result. The Mt Bundey Granite has a U-Pb zircon age of 1831±6 Ma and Pb-Pb isochron age of 1830±39 Ma (Sheppard, 1992). The Mt Bundey and Burnside granites are grouped with the TIS and YIS, respectively, which are in accord with their relative isotopic ages.

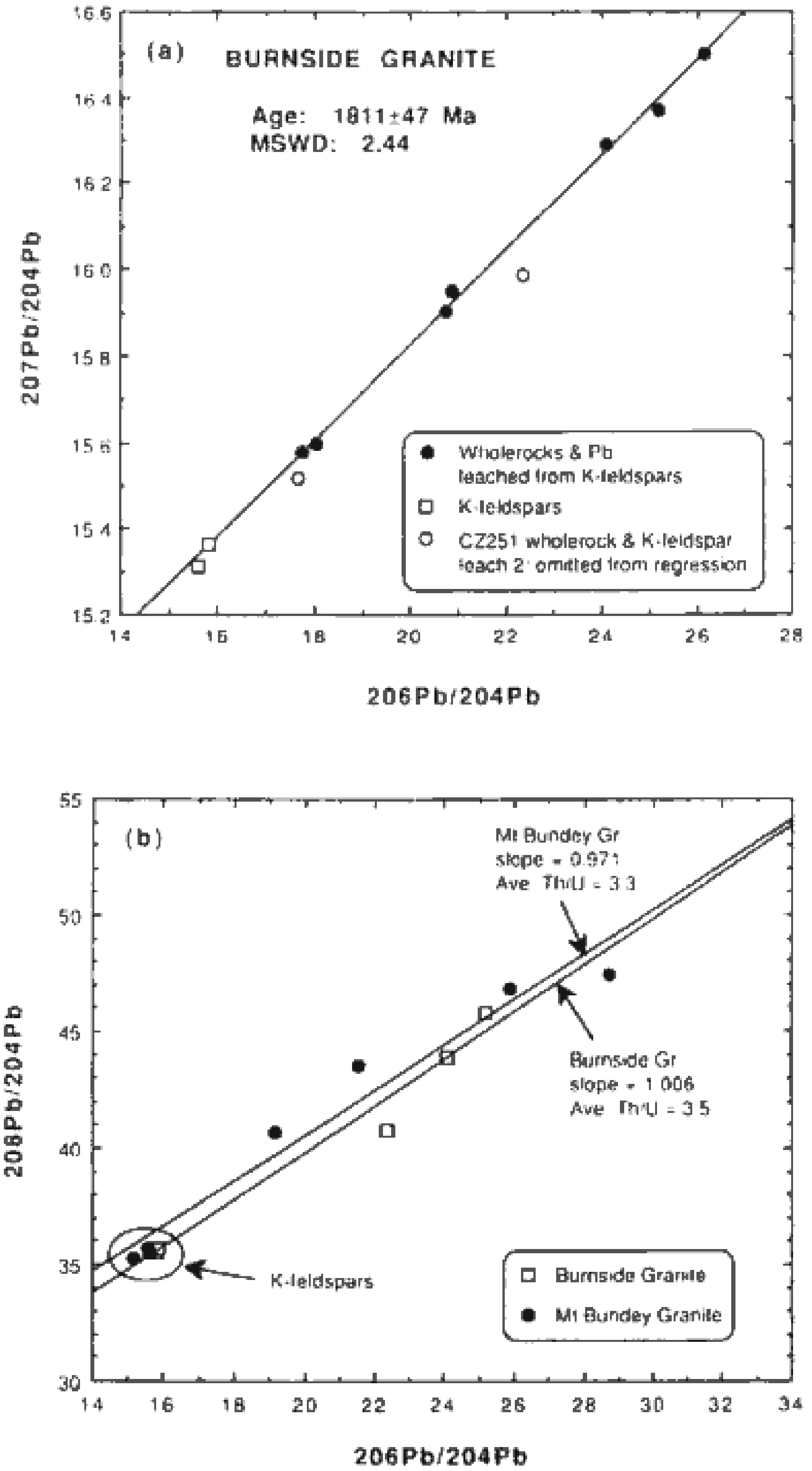

Figure 18. Common Pb isotopic data for the Burnside Granite: (a) $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$, and (b) $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$, also showing data for the Mt Bundey Granite from Sheppard (1992).

For the Burnside Granite, the model source μ ($^{238}U/^{204}Pb$) of 8.17±.02 is indicative of a granite source region which contains older crustal material. The basement to the Pine Creek Geosyncline is the obvious source region. The model source μ for the Mt Bundey Granite is 7.97±.03, which is distinctly different to the Burnside Granite and indicates a different source. However, as these are the only two granites studied so far, further work is needed to test whether all TIS and YIS granites have distinctly different source regions.

The Burnside and Mt Bundey granites initial Pb isotope ratios are significantly different and also imply different source regions for the two granites, which is compatible with the syenite-lamprophyre association at Mt Bundey and the absence of such rocks within the Burnside Granite. Further, as the Mt Bundey and Burnside granites represent the TIS and YIS suites, respectively, it may follow that differences in metallogenic associations and potential may be inherited from their different source regions.

The Th/U of the two granites are similar (Fig. 18) and are similar to average crustal values.

4.12. Heat of the Batholith

Heat from any granite batholith can be generated from two principal sources: 1. the granite magma and 2. the decay of radioactive elements (Stone & Exley, 1982). The combined heat generated by any granite plays an important role in crystallisation processes, development of any thermal aureole in country rocks around the granite and possibly in the origin of hydrothermal mineral deposits. Heat initially derived from a granite magma will have a temperature range between 900 °C to 600 °C that will cool in a relatively short period of time (tens of million years). However, the decay of radioactive elements provides a "permanent heat engine" inside each granite pluton. The amount of heat produced is controlled by the total radioactive element content, particularly the K-U-Th contents. Although the amount of heat produced is small, it is generated continuously and therefore can maintain the temperature of an anomalously hot granite above its surroundings indefinitely. The combination of these two heat sources may create paragenetically, chronologically and structurally complicated and successively superimposed pulses of hydrothermal activity and consequently a wide variety of hydrothermal mineralisation over a considerable period of time (in this case 1800–1350–920 and 100–0 Ma; see Fig. 32).

4.13. Thermal Aureole

The Cullen Batholith is surrounded by an unusually broad thermal metamorphic aureole. At the surface the width of the aureole and its intensity is strictly controlled by the orientation of each particular granite pluton, by the original composition of each granite magma, the depth of intrusion and composition of the host lithologies. The thermal aureole around and outside the Cullen Batholith can be delineated from the contact by a hornblende isograd, followed by a

Table 7. Lead isotope data on the Burnside Granites and Mt Bundey Granite; Mt Bundey data from Sheppard (1992); analytical methods described Mc Naughton et al. (1993); analytical error in all ratios is ±0.15 % (95 % C.L.)

Sample	$^{206}Pb/^{204}Pb$	$207Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Type
Mt Bundey initial Pb	15.131	15.146	35.268	Least radiogenic K-feldspar
Burnside Granite				
CZ250 WR	25.171	16.369	45.735	WR
CZ251 WR	22.359	15.987	40.793	WR
CZ252 WR	24.092	16.290	43.919	WR
CZ250 AWKF	15.604	15.312	35.543	AWKF
CZ251 AWKF	15.826	15.365	35.483	AWKF
CZ252 AWKF	15.833	15.366	35.654	AWKF
CZ250 KFW1	26.157	16.501	46.686	KFW1
CZ251 KFW1	20.763	15.904	38.153	KFW1
CZ252 KFW1	20.882	15.948	40.600	KFW1
CZ250 KFW2	17.753	15.579	37.586	KFW2
CZ251 KFW2	17.677	15.520	36.259	KFW2
CZ252 KFW2	18.048	15.600	37.571	KFW2
Burnside Granite initial Pb	15.604	15.312	35.543	CZ250 AWKF

WR = wholerock; AWKF = acid-washed K-feldspar; KFW1 and KFW2 = Pb leached from K-feldspar

Table 8. Burnside Granite: regression details

Sample group	n	MSWD	Age ± 2σ (Ma)	μ1 ± 2σ
All data (wholerocks, K-feldspars and leaches from K-feldspars)	12	9.83	1796 ± 93	8.15 ± 0.04
All data less two (omit CZ251 wholerock and K-feldspar leach 2)	10	2.44	***1811 ± 47***	8.17 ± 0.02
CZ250: all data	4	2.96	***1810 ± 69***	8.15 ± 0.04
CZ251: all data	4	15.87	1635 ± 333	8.13 ± 0.09
CZ252: all data	4	1.81	***1848 ± 77***	8.18 ± 0.03
CZ250 & CZ252: all data	8	3.20	***1814 ± 58***	8.17 ± 0.03
All wholerocks & K-feldspars	6	15.79	1767 ± 149	8.14 ± 0.07

Best results in bold italics have low MSWD: these omit outlier data from CZ251 biotite isograd and finally the albite-epidote isograd. In contrast to the EIS and TIS granites, the thermal aureole around the YIS plutons is also characterised by widespread tourmalinisation and white mica growth (potash-metasomatism).

Assemblages of garnet-cordierite-andalusite-biotite-quartz-K-feldspar may occur immediately adjacent to some of the granites, suggestive of K-feldspar-cordierite hornfels facies. Inferred temperatures from this facies are approximately = 550 °C. In the outer part of the aureole where biotite-chlorite assemblages occur, temperatures of approximately 300 °C may be inferred.

Because of the variable magmatic history, each pluton would be expected to contribute to the thermal balance of the batholith in different ways. The shape of the roof zone of each pluton appears to have exerted a fundamental control on the distribution and extent of heat transfer to the country rocks and the development of hydrothermal systems associated with granite intrusion and crystallisation. It appears that flat-topped plutons with small irregularities were more likely to concentrate heat on their upper surface than a narrow, steep sided plutons. This combined with the slow cooling of the batholith due to sustained radioactive decay has further influenced the intensity and duration of hydrothermal activity within and around the batholith.

4.14. Heat Production of the Cullen Batholith

The granites of the Pine Creek Plutonic Complex have a concentration of radioactive elements significantly above that of normal granites (Stuart-Smith et al., 1993). As a consequence they are characterised by unusually high heat production and heat flow. The Pine Creek Plutonic Complex lies at the periphery of a major uranium province where uranium deposits such as Ranger, Jabiluka and Naberlek have been formed (Simpson & Plant, 1984). There were no direct heat flow measurements done in the Cullen Batholith, but data from Rum Jungle (83,8 $\mu W/m^2$), Batchelor (79,6 $\mu W/m^2$) and Jabiluka (86.4 $\mu W/m^2$) show linear relationship to the high heat production of the Pine Creek Plutonic Complex (Cull, 1991). The average potassium content is 4 % and contributes to the radioactivity of rocks in approximate proportion 1 % potassium equal to 4 ppm thorium and 2 ppm uranium, respectively. According to Darnley (1982) the Cullen Batholith granites may be classified as uraniferous. The average uranium, thorium and potassium content for the Batholith is 12 ppm U, 40 ppm Th and 4 % K.

The following formula has been used for the calculation of heat production of the granites from the Cullen Batholith:

$$A = 0.081\,(K_2O) + 0.261\,(U) + 0.072\,(Th)$$

(in $\mu W/m^3$; Vigneresse, 1988)

Uranium and thorium contents and heat production values for individual rock types and plutons are summarised in Fig. 19 and Appendix I, respectively. The Cullen Batholith represents the largest volume of the HHP (High Heat Production) granites in the Pine Creek Province. At the surface the weighted mean (by the area of outcrop) of the heat production of the batholith is 5.8 $\mu W/m^3$. It corresponds to the averages for EIS and TIS granites (5.70 and 5.71 $\mu W/m^3$ respectively). The YIS granites show the weighted mean at 6.69 $\mu W/m^3$.

The Cullen Batholith is more radiothermal than many of the high-heat-producing (HHP) granites in Britain, including the Cornubian Batholith (Webb et al, 1985 and Halls, 1994). This compares with radiothermal heat production (pre-weathering) of 4.0–5.7 $\mu W/m^3$ for HHP granites from Britain (Webb et al., 1985 and Lee et al., 1987), 4.2–12.8 $\mu W/m^3$ for radiogenic Bushveld granites (McNaughton et al., 1993), and 5.7–6.3 $\mu W/m^3$ for radiogenic granites from northern Australia invoked by Solomon & Heinrich (1992) as the heat source for the giant Pb-Zn deposits of the Mount Isa and McArthur River areas.

Fehn et al. (1978) emphasised that even under conditions that might have applied in the past, with the presence of thicker cover rocks and a regional thermal event, temperatures in granites such as these would have been restricted to the low end of the hydrothermal range, ie. less than 200 °C. At the present the heat that is generated by these granites would not raise fluid temperatures by more than 50 °C to 100 °C above ambient. Samples of water from the Douglas Hot Springs indicate temperatures of over 60 °C are presently being generated by radiothermal heat from the Cullen Batholith. However, the age (ca 1800 Ma) and state of weathering of the surface outcrops of the granites of the Cullen Batholith indicate that the original uranium and thorium contents of the granites of the Cullen Batholith used to be considerably higher. It was estimated by McNaughton & Goellnicht (1990) that the amount of U-loss during recent weathering of Precambrian granites is 33% of the original U content. Also half-lives of ^{238}U (4.5 . 10^{10} y) and ^{232}Th (1.41 . 10^9 y) indicate that approximately one third of the primary U and Th contents have been lost due to radioactive decay to non-radioactive elements. The higher values of U and Th at the time of the cooling of the granite would have more significantly increased the intensity and extended the life of hydrothermal systems associated with the granite intrusion.

The variation of U and Th with Ti-indexed fractionation for all Igneous Suites of the Cullen Batholith is shown in Figures 20A and 20B. The behaviour of Th is similar to K, generally increasing in EIS granites and decreasing in TIS and YIS granites. Both trends indicate considerable incorporation of Th into the EIS granites, probably due to hybridisation and contamination by country rocks. Whereas U, like Th appears to increase markedly with fractionation in the EIS and TIS granites, in the YIS granites do not. Patterns for the U and Th variation of the EIS and TIS granites are poorly defined possibly due to the surface leaching of U.

The fractionation paths derived from the Ti vs U diagram were superimposed on the variation diagram for Th vs U (Fig. 20C). These paths are calibrated in steps of 250 ppm Ti in Fig. 20C to provide idealised fractionation paths. In

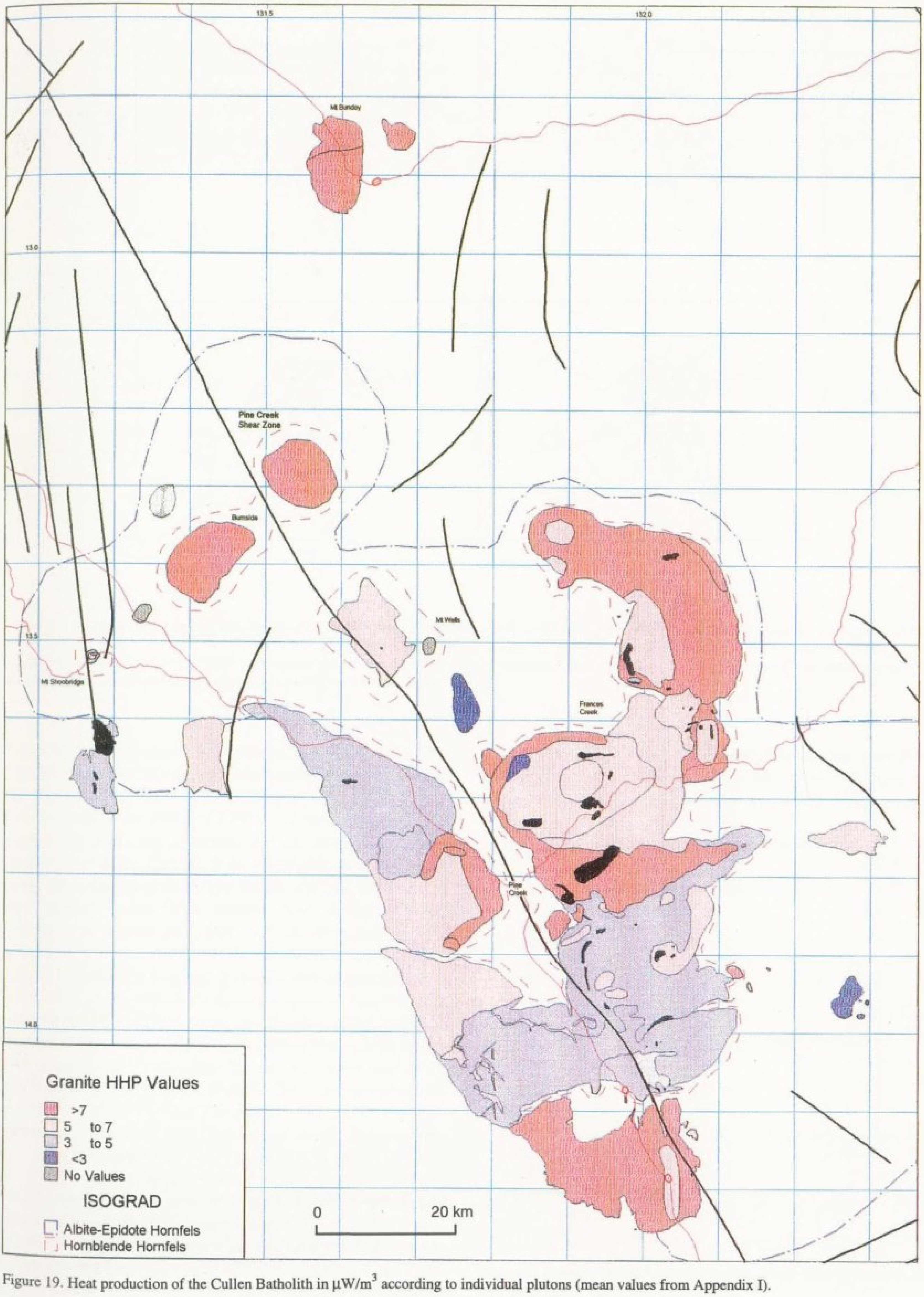

Figure 19. Heat production of the Cullen Batholith in $\mu W/m^3$ according to individual plutons (mean values from Appendix I).

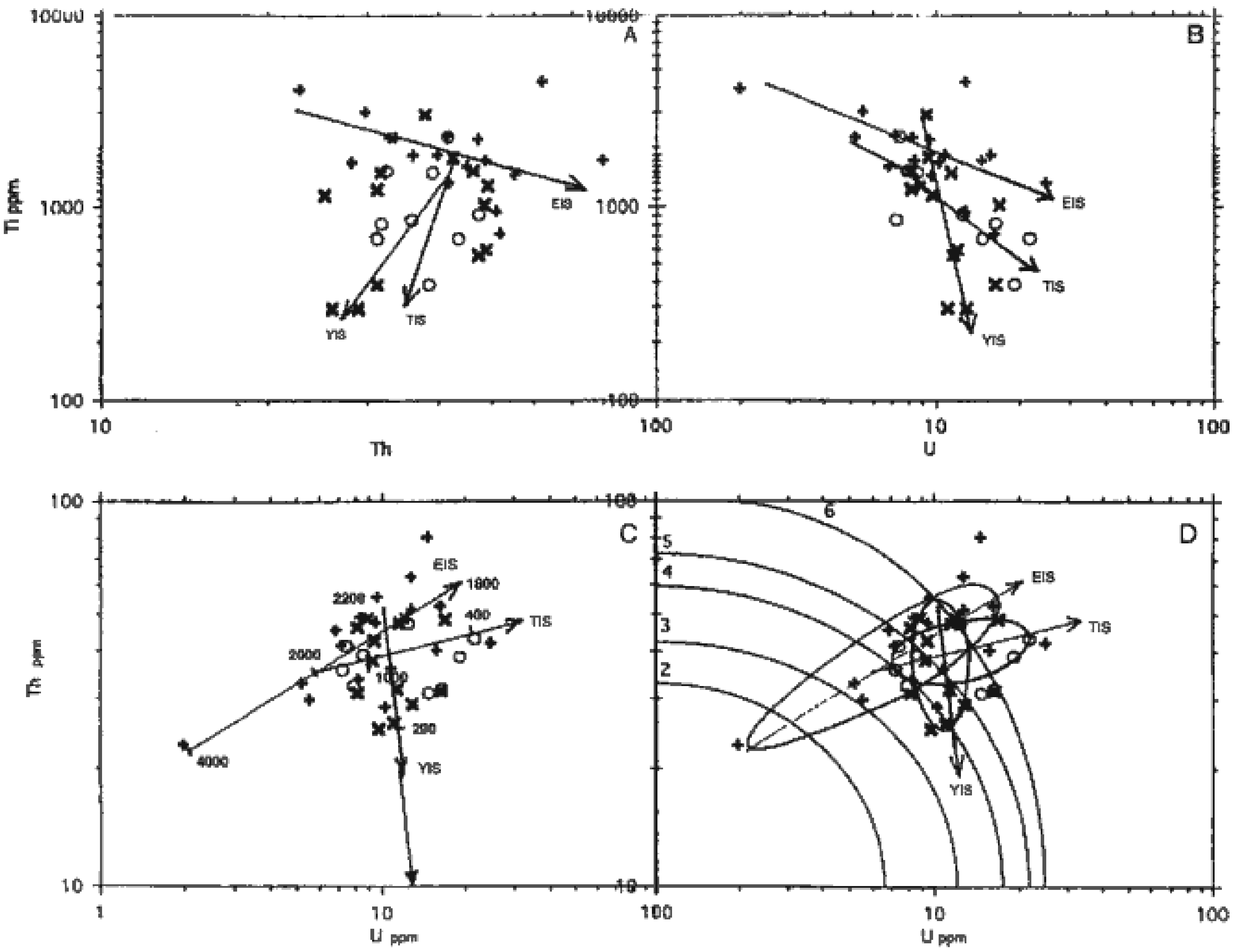

Figure 20. Variation of Th and U with fractionation in the Cullen Batholith. A – Ti vs Th lines show possible fractionation trends of EIS, TIS and YIS granites. B – Ti vs U. C – Th vs U trends are constructed for the fractionation paths in Figs. A and B. Trends are annotated with Ti concentrations in ppm. D – Summary diagram showing fields of presumed surface compositions and fractionation trends from C together with the postulated bulk compositions of the three granite suites. Heat production in $\mu W/m^3$ overlay the entire diagram.

Fig. 20D these fractionation paths are superimposed onto contours representing the total heat production due to U and Th. The fields are shown for the three igneous suites in Fig. 20D. In general the EIS and TIS have a wider range of heat production with higher values for the most fractionated plutons. For these plutons it is reasonable to assume that much of their unexposed root zones are less fractionated than surface rocks. With smaller rates of change of U content with fractionation however, the less-evolved parts of the YIS granites would be more radiothermal.

Fig. 21 shows the implied variation of heat production as a function of fractionation. Extrapolation of fractionation patterns to the different styles of zonation in the batholith suggest a rapid decrease of heat production occurs in the roof zones of the EIS plutons due to magma contamination and hybridisation by the country rocks. The concentrically zoned plutons of TIS and YIS granites may be more fractionated and hence more radioactive at depth. If this is correct, then it is clear from Fig. 21 that a more consistent heat production and a larger volume of radiothermal granite could exist at depth connecting the YIS granite stocks and sheets to the north of the main batholith.

In evaluating the potential of the Cullen Batholith granites as the driving forces for hydrothermal convection the volumetric extent of their radiothermal properties must be considered. In the absence of deep sampling and/or heat flow measurements, a number of properties, including the aspect of zonation, roof relief, gravity anomalies, mineralogy,

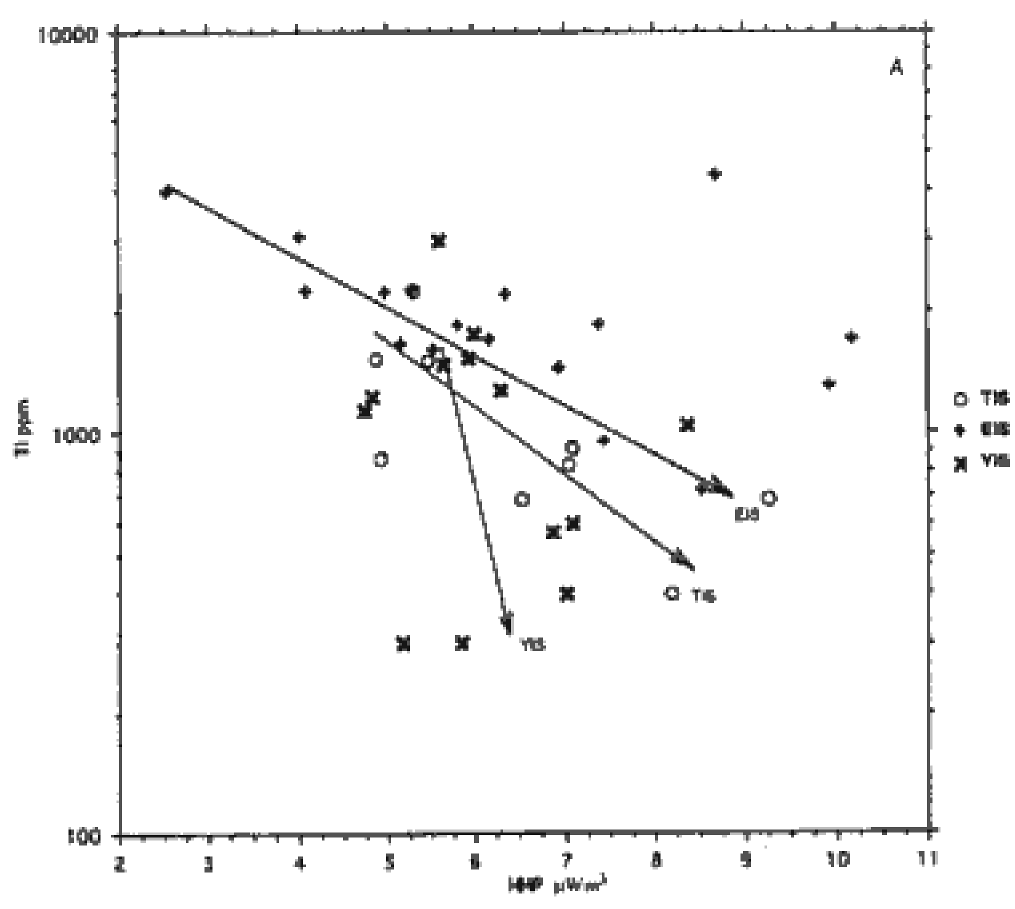

Figure 21. Postulated variation of heat production with fractionation for Igneous Suites of the Cullen Batholith.

geochemistry and tectonic environment may aid this evaluation. Factors such as:

1. The large volumetric extent of the batholith as suggested by negative Bouguer gravity anomalies on a regional scale.
2. The high to low peraluminous rock compositions of the different suites.
3. The presence of primary biotite, but absence of magnetite.
4. The moderately low levels (10–25 ppm) of Nb and Y, and high Th (+ 30 ppm).
5. The high primary contents of U (+ 10 ppm) which show little variation over the observed fractionation range.
6. The concentric normal zonation of many of the plutons.

These all suggest that the "Hot" granites of the Cullen Batholith have influenced the cooling history of the batholith and more importantly the development of hydrothermal systems adjacent to and within the cooling batholith.

4.15. Comparisons with other Granite Batholiths

Granitic rocks occur in most Proterozoic domains of Australia within specific time intervals. They are essentially contemporaneous to major orogenic events between 1850–1800 Ma in a number of terranes.

According to Wyborn et al. (1992) the Cullen Batholith belongs to the group of I-type, Sr-depleted, Y-undepleted, fractionated granites in incompatible elements. Granites of this type include the following: part of the Nicholson granite, the Ewen Batholith (Mount Isa Inlier), possibly the Harverson Suite (Arunta Block), the Lewis granite and Winnecke granophyre (Granites Tanami Block), unnamed intrusive porphyries and the Bernborough Formation (Tennant Creek Block), the Minnie Creek Batholith (Gascoyne Province) the Donnington, the Hiltaba Suites and the Lincoln Complex(Gawler Craton).

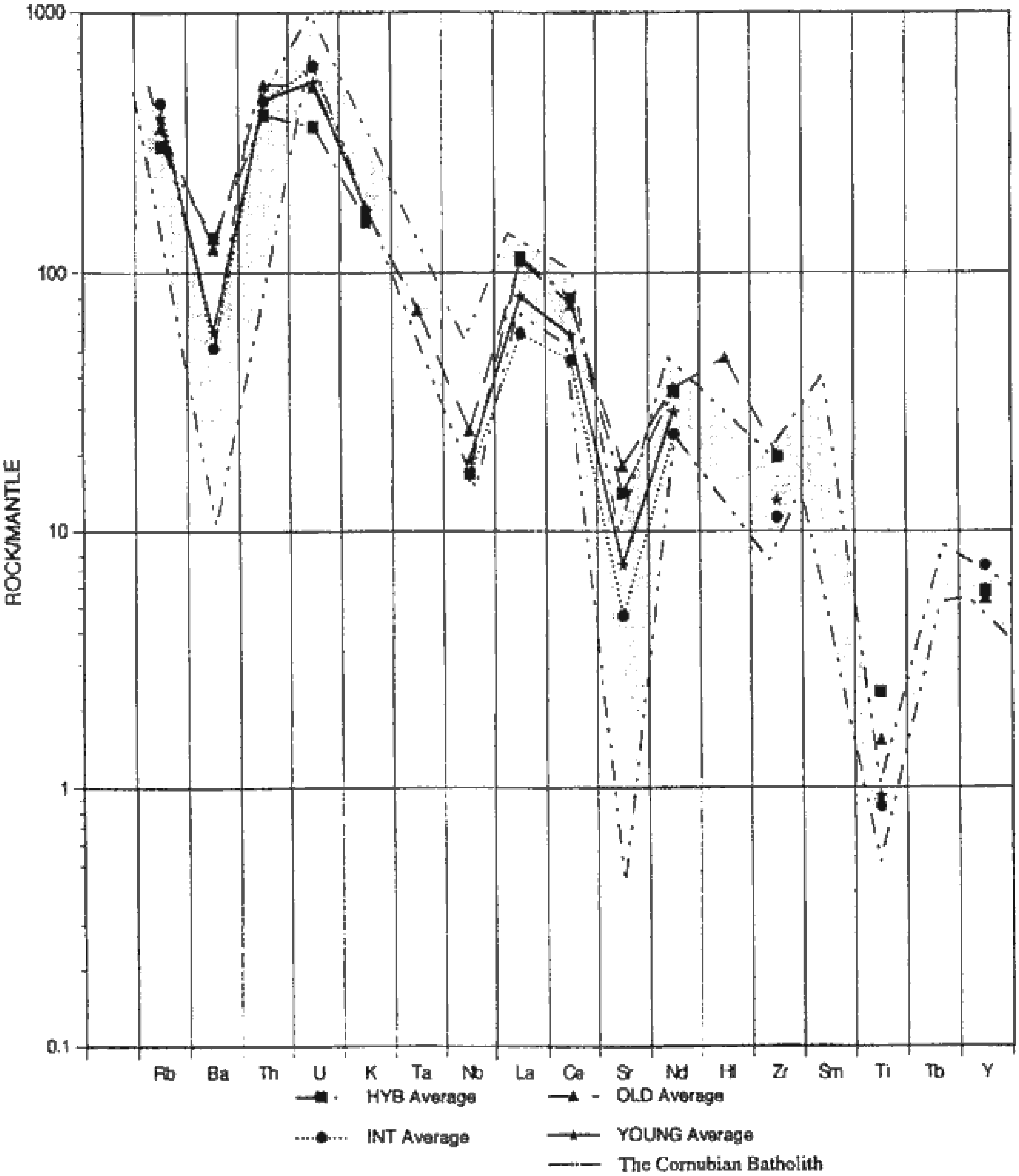

Figure 22. The Cullen Batholith. Primordial/mantle normalized abundance diagram (Sun & McDonough, 1989) for the averages of the main suites.

Granites with similar petrological and chemical characteristics were also emplaced around 700 Ma and include the Mount Crofton Granite Complex (Paterson Province) and even around 300 Ma during the Phanerozoic (Tasmania, N. Queensland).

This group is metallogenically very significant among Australian Proterozoic granitic rocks. Some granites contain vein Sn, W, Cu and U deposits, while Au deposits are located near the contact aureoles (Tanami, The Granites, Tarcoola, Telfer, Cullen Mineral Field). The dominant composition of these granites is monzogranite, containing between 70 to 75 % SiO_2. These felsic magmas have marginal I-S type affinities. The chemical variation within these highly siliceous granites is controlled by fractionation and has high-K calc-alkaline to shoshonitic tendencies. These granites may also be classified as "metalliferous", uraniferous, or as high heat production granites. The Proterozoic "metalliferous" plutons differ from their younger equivalents in having generally lower levels of Sn, which may indicate chemical differences in the source area for the granites.

A multi-element primordial-mantle-normalised abundance diagram, Fig. 22 for the Cullen Batholith granites indicates a similar composition for all the igneous suites, suggesting a similar source composition. This spidergram also indicates that the degree of geochemical evolution of the Cullen Batholith is very similar to some distal Phanerozoic granites (eg. Cairngorm granite in Scottish Caledonides and Cornubian Batholith in south-western England, Halls, 1994).

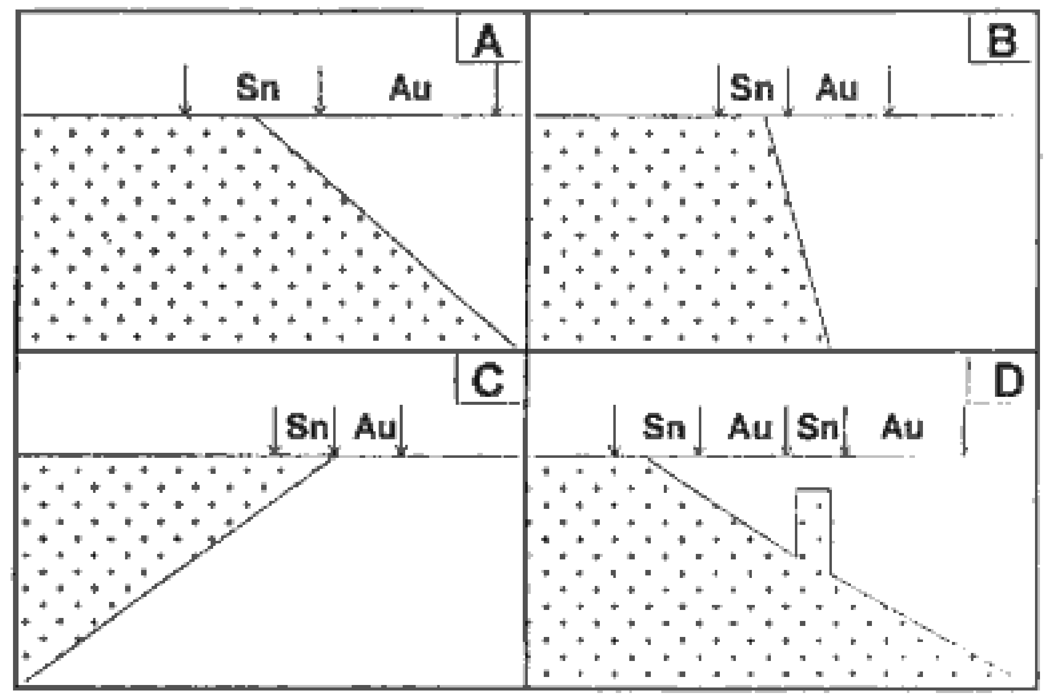

Figure 23. Distribution of the tin and gold mineralisation at the surface according to dip of the granite margin. A – shallow outward-dipping granite contact = broad aureole of the tin and gold mineralisation. B – steep outward-dipping granite contact = narrow aureole of the tin and gold mineralisation. C – shallow inward-dipping granite contact = narrow aureole of the gold mineralisation. D – oscillation of the granite contact produces overlaps of the tin and gold mineralisation.

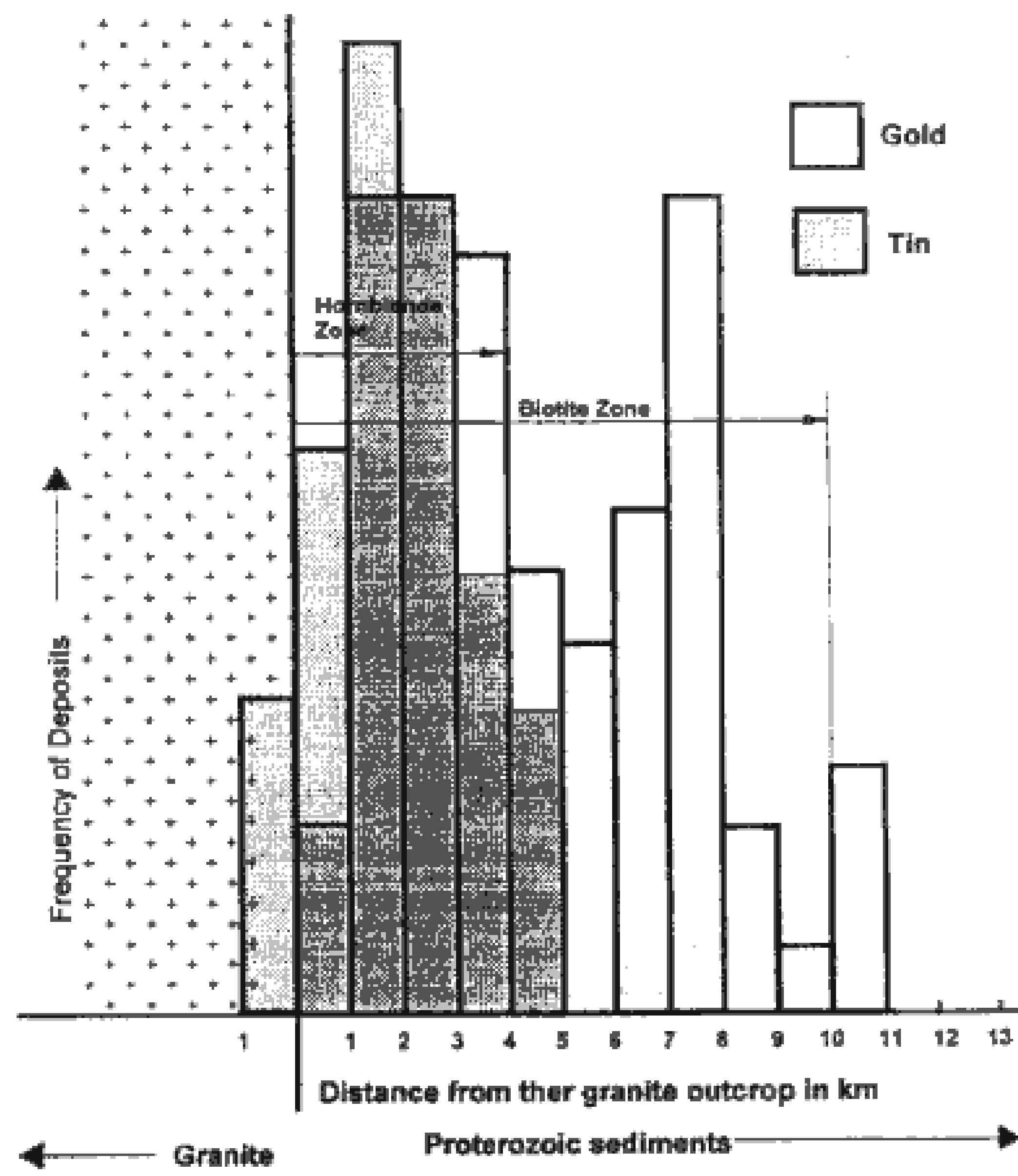

Figure 24. The Cullen Batholith. Lateral distance of gold and tin deposits.

5. Hydrothermal Mineralisation associated with the Cullen Batholith

The geosyncline has been the focus for several phases of mineralisation and contains reserves of gold, base-metals, tin, tantalum, iron, platinum, palladium and uranium (Needham & De Ross, 1990). These resources have been exploited over the past century with periods of major interest during the turn of the century and during the past 20 years. Economically viable resources of predominantly gold, eg., Pine Creek, Cosmo Howley, Goodall and Tom's Gully, and Ag-Pb-Zn, eg., Woodcutters are currently being mined. Gold mineralisation and some base metal mineralisation in the Pine Creek Geosyncline occurs in linear belts up to 20 kilometres in length associated with regional structures eg. the Howley Anticline or the Pine Creek shear zone. No gold mineralisation has been mined to date from the inner thermal aureole of the Batholith. Whereas tin and base-metal mineralisation appear to be exclusively spatially related to the contact aureoles of the Cullen Batholith (Fig. 23 and 24). All of the mineralisation has either a spatial or direct association with D2, D3 or D4 deformation zones, is late in the tectonic sequence mainly related to older reactivated structures. On a regional scale, gold and to some extent base-metal mineralisation has a heterogeneous distribution and is confined to elongate zones associated with regional folds and shear zones suggesting that the dominant control on mineralisation is structural rather than lithological.