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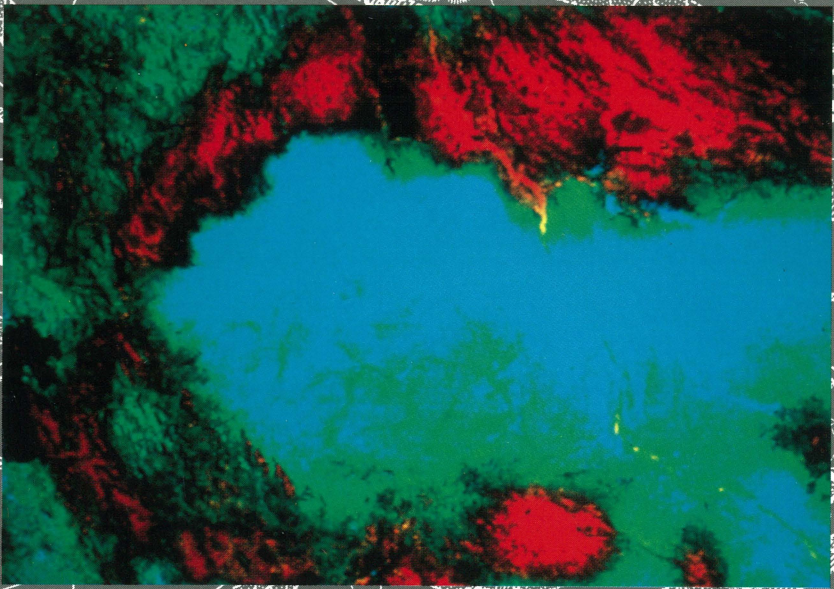
AGSO BULLETIN 229

Geology and Mineral Deposits of the Cullen Mineral Field, Northern Territory



By P.G. Stuart-Smith, R.S. Needham, R.W. Page & L.A.I. Wyborn

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DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION
MINERALS AND LAND USE PROGRAM

BULLETIN 229

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Cover: Composite Landsat/magnetic image of the northeastern lobe of the Cullen Batholith (pale blue and pale green) showing surrounding magnetised contact metamorphic aureole (red). Pelitic rocks within the aureole have common magnetite and pyrrhotite—probably the cause of the enhanced apparent magnetisation. Early Proterozoic metasediments outside the aureole (upper left, dark green) are metamorphosed to lower greenschist facies.

Background: Part of a plan of Union Reefs Goldfield (Shields & others, 1967).

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ABSTRACT

The Cullen Mineral Field, lying in the southern central part of the Pine Creek Geosyncline, contains Early Proterozoic metasediments of the Namoona, Mount Partridge, South Alligator, and Finniss River Groups. The metasediments, originally shale, siltstone, quartz sandstone, conglomerate, greywacke, dolomite, dolarenite, dololutite and tuff, were intruded by pre-orogenic sills of Zamu Dolerite before being deformed and metamorphosed to greenschist facies between 1870 and 1780 Ma. These rocks, together with unconformably overlying felsic volcanics (El Sherana and Edith River Groups), were extensively metamorphosed by syn- to post-orogenic granitoids of the Cullen Batholith emplaced between 1830 and 1780 Ma. The Batholith contains granodiorite, several varieties of granite and leucogranite, bodies of monzonite, and younger syenite dykes.

Largely undeformed Middle Proterozoic, Palaeozoic, and Mesozoic strata rest on Early Proterozoic rocks with marked regional unconformity and form tablelands and plains bordering the mineral field to the southwest and southeast.

The main forms of metal occurrence are: hydrothermal veins and stockworks (Sn, W, Au, Ag, Pb, Zn, Cd, Cu, Bi, As, U, and Mo); volcanogenic stratabound massive sulphide deposits (Au, Ag, Cu, Pb, and Zn); alluvial deposits (Au and Sn); and residual massive oxide deposits (Fe and Mn).

The vast majority of mines have worked hydrothermal deposits which are mostly located in north to northwest-trending faults, shear zones, and associated structures within Early Proterozoic metasediments and granitoids. Pyritic, dolomitic and carbonaceous strata are preferentially mineralised, especially within the Koolpin and Mount Bonnie Formations. The distribution of deposits within the contact aureole defines a zonation of uranium closest to granite, through tungsten, copper, tin, silver-lead, to gold with increasing distance from the granitoid contact. This zonation probably reflects decreasing temperatures within the contact aureole at the time of generation of a variety of metal-bearing fluids, either during granitoid emplacement or later. A magmatic source for some of the metals is indicated, particularly in late-stage, highly fractionated leucogranites which form cusps peripheral to the main body of the Cullen Batholith.

The Cullen Mineral Field has been a major centre of metal production, mainly for gold, silver, lead, copper, tin, tungsten and iron. Minor zinc, cadmium, bismuth, arsenic, molybdenum, uranium and limestone have also been won.

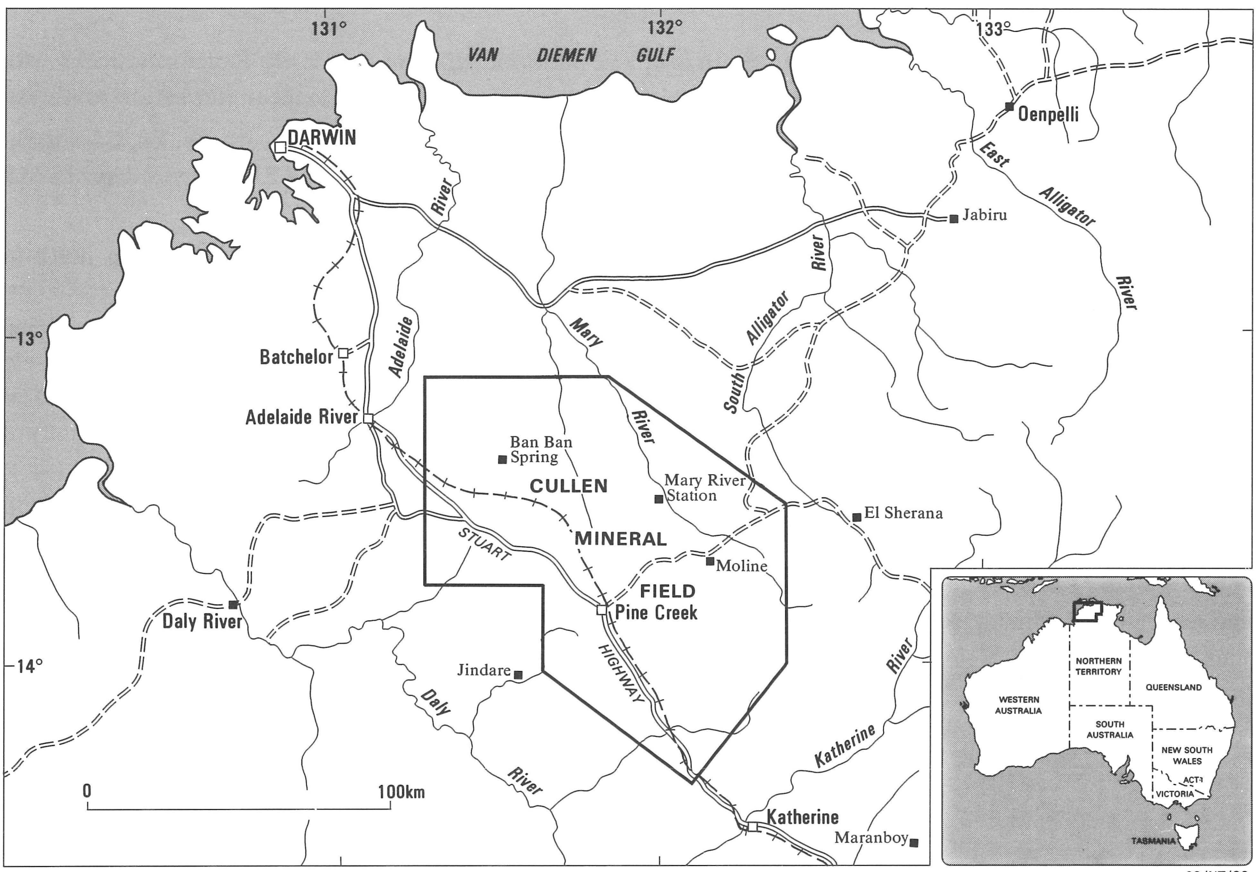

Fig. 1. Locality map.

INTRODUCTION

This Bulletin and accompanying 1:250 000 geological map summarise the results of 1:100 000 scale geological mapping carried out by the Bureau of Mineral Resources (BMR) (now Australian Geological Survey Organisation, AGSO) and the Northern Territory Geological Survey (NTGS) in the Cullen Mineral Field between 1972 and 1982. The geology and mineral occurrences are described and the controls on the distribution and style of mineralisation are examined, with particular emphasis on the geochemistry, geochronology and role of the Cullen Batholith in deposit genesis. The work forms part of the BMR/NTGS regional semi-detailed mapping program of the Pine Creek Geosyncline commenced in 1971 following the discovery of uranium mineralisation in the Alligator Rivers Region in the northeast.

The Cullen Mineral Field lies between latitudes 13°08' and 14°22'S and longitudes 131°14' and 132°25'E, centred about 175 km southeast of Darwin (Fig. 1). The area is sparsely populated with Pine Creek township being the main centre. Access is provided by the sealed Stuart Highway which traverses the region from northwest to south, paralleling the abandoned North Australian Railway, and by the partly sealed Kakadu Highway which runs east from Pine Creek. Mostly unsealed roads to Claravale, Jindare, Frances Creek, Mount Wells, Mount Harris and Mary River station provide access to the remainder of the area.

The term "Cullen Mineral Field", first used by Needham (1981), defines the group of mineral deposits and occurrences located within the Cullen Batholith and its adjacent contact metamorphic aureole. Over 230 mines and prospects occur in the mineral field; their location is shown on the accompanying map.

The Cullen Mineral Field has been a major centre of metal production in the Northern Territory, in particular gold, silver, lead, copper, tin, tungsten and iron. Minor amounts of zinc, cadmium, bismuth, arsenic, molybdenum, uranium and limestone have also been produced. Occurrences of fluorite, topaz and monazite have also been discovered during mining development and exploration surveys.

The mining history of the mineral field began in 1872 with the discovery of gold, soon followed by discoveries of copper, tin, silver and lead with most mineral discoveries made by 1885. Gold has been the main metal produced with over half of the seventy gold mines or prospects in the mineral field recording some production. By December 1989 over 24 t of gold had been won with the *Pine Creek*[135] group of mines (Enterprise) accounting for nearly half the production

Apart from alluvial deposits of gold and tin, most mineral deposits in the region are vein-type deposits in faults and shear zones within the metasediments. Exceptions are the *Frances Creek*[102] hematitic lodes, considered to be the product of supergene enrichment of pyritic carbonaceous shale and siltstone, and the *Iron Blow*[85] and *Mount Bonnie*[86] precious and base metal lodes, which may be of syngenetic origin. Nearly all production has been from the near-surface, oxidised enriched zone, above primary low-grade sulphide ore.

Most of the mineral field lies within the Mount Wells Policy Reserve, which was established by the Northern Territory Administration Mines Branch in 1964 to encourage prospectors to work small tonnage gold, tin and base metal deposits.

Recent Exploration

Work by exploration companies, particularly since the late 1960s, has been concentrated on prospecting principally for gold, tin, base metals, uranium, iron and manganese. Work has included airborne radiometric and magnetic surveys, soil and stream sediment geochemistry, geological mapping and drilling. Reports of these activities are lodged with the Northern Territory Department of Mines and Energy, Darwin.

Several radiometric anomalies have been located by these surveys, but no uranium mineralisation has been discovered. The anomalies were found to be caused by either surficial ferruginous capping or laterite overlying pyritic shale of the Koolpin Formation and Wildman Siltstone, or by outcropping granite, or by sharp changes in topography. A radiometric anomaly located over *McCarthys* mine[152] was attributed to weak uranium mineralisation associated with the silver-lead lodes (Taylor, 1973a).

Detailed geological mapping, and soil and stream sediment geochemical sampling have been carried out over much of the area. Soil and stream sediment samples have been analysed for some or all of the following elements: Cu, Pb, Zn, Ni, Co, Mn, Au, Ag, Sn, As, W, Mo and U. The only significant geochemical anomalies located during these surveys were associated with known mineralisation or associated with small discontinuous ferruginous quartz-filled faults.

Most work since 1980 has centred around testing the

* The locality reference number used on the accompanying map is shown throughout the text as a superscript number attached to the mine or prospect name.

TABLE 1. STANDARD 1:250 000 SCALE GEOLOGICAL MAPS COVERING THE CULLEN MINERAL FIELD AND SURROUNDS

Standard Map Sheet	*Reference*
Fergusson River	Randal (1962a)
Katherine	Randal (1963)
Mount Evelyn	Walpole (1962)
Pine Creek	Malone (1962)

old gold mining developments on the *Howley Anticline*[40-48] and the *Golden Dyke*[83] and *Pine Creek*[135] groups of mines. After major developmental drilling programs, open cut mines have been established at *Pine Creek*[135], *Woolwonga*[34], *Cosmopolitan Howley*[48], *Goodall** and *Moline (Northern Hercules*[157]*)*.

Geological Investigations

Early investigations were mostly reconnaissance trips or reports of mineral occurrences, and are reviewed by Malone (1962), Randal (1963), Walpole (1962) and Walpole & others (1968). Between 1951 and 1959, the area was mapped by BMR surveys as part of a regional evaluation of the Katherine–Darwin region. Geological maps (1:250 000) and accompanying explanatory notes produced during this survey and covering the Cullen Mineral Field are listed in Table 1.

Between 1979 and 1982, the area was mapped by BMR and NTGS, using 1:25 000 colour air photos. Maps and Commentaries covering the BATCHELOR–HAYES CREEK REGION**, EDITH RIVER REGION, McKINLAY RIVER, MUNDOGIE, PINE CREEK AND RANFORD HILL have recently been published, or are in preparation. The index to these maps is given on the accompanying 1:250 000 geological map and shown in Figure 2. Details of the 1:100 000 mapping survey, and the geologists who took part, are given in Table 2. In all eight geologists from BMR, five from NTGS and one from GRDC (Indonesia) were involved.

In conjunction with the mapping, geochronological investigations were undertaken in 1979 and 1983, following up regional geochronological work in the Alligator Rivers Uranium Field reported by Page & others (1980). U-Pb zircon ages were determined to better define magmatic ages, which, together with the known intrusive relationships and geochemical variations within the Cullen Batholith, allows a more definitive model for the

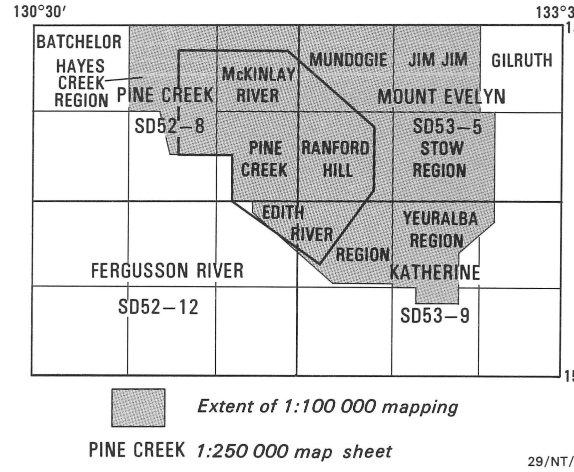

Fig. 2. Index to published geological maps.

tectonic and metallogenic evolution of the Cullen Mineral Field to be determined. Further Rb-Sr whole-rock work was also undertaken on selected granitic rocks in order to confirm previous interpretations and examine the relationship between Rb-Sr ages and post-emplacement, tectonic events.

In the course of mapping, 88 granitoid samples were collected for major and trace element geochemical analysis. These analyses, together with 174 other analyses of the Cullen Batholith (representing all other known analyses) from published and unpublished sources, are tabulated in Appendix 1 and are available as part (ROCKCHEM) of AGSO's NGMA Field and Laboratory databases.

Climate and Physiography

The Cullen Mineral Field lies within the monsoonal climatic zone and has an average annual rainfall of about 1500 mm, most of which falls over four to five months between November and April.

The area straddles the divide between the north-flowing Mary and McKinlay River catchments and the westward-flowing Daly River system. The main physiographic units are the *Lowlands, Dissected Foothills, Tablelands* and *Alluvial Plains* (Fig. 3). The physiography is described by Christian & Stewart (1953), Malone (1962), Randal (1962), Walpole (1962) and Williams (1969).

Marginal to the *Dissected Foothills* and *Tablelands* are undulating low hills and plains of the Lowlands, which are developed over flat-lying Cambrian–Ordovician and late Tertiary sediments and peneplaned deeply weathered

* Goodall mine, discovered and 1981 and located at GL 5739, is not shown on the accompanying map

**Names of 1:100 000 Sheet areas area printed in capitals

TABLE 2. DETAILS OF 1:100 000 SCALE GEOLOGICAL MAPPING, CULLEN MINERAL FIELD AND SURROUNDS

Map Name	*Period of survey*	*Geologists involved in survey*		*References*		
		BMR	*NTGS*	*Map*	*Commentary*	*Data Record*
BATCHELOR-HAYES CREEK REGION	1976	J.M. Rhodes		Crick (1985)		
	1972-1973	K. Johnson				
	1974	J. Ingram K. Johnson I.H. Crick				
	1975-1978	I.H. Crick				
EDITH RIVER REGION	1982	R.S. Needham P.G. Stuart-Smith C. Amri (GRDC)	L. Bagas B.A. Whitehead G. Salas C.A. Mulder	Needham & others (1989)		Needham & others (1986)
McKINLAY RIVER	1978	P.G. Stuart-Smith D.A. Wallace I.H. Crick	M.J. Roarty			
	1979	R.S. Needham P.G. Stuart-Smith D.A. Wallace	M.J. Roarty	Stuart-Smith & others (1985a)	Stuart-Smith & others (1986a)	Wallace & others (1981)
MUNDOGIE	1972	R.S. Needham				
	1976	P.G. Stuart-Smith	M.J. Roarty			
	1977	R.S. Needham P.G. Stuart-Smith I.H. Crick	M.J. Roarty	Stuart-Smith & others (1982)	Stuart-Smith & others (1984a)	Needham & others (1978)
PINE CREEK	1979	D.A. Wallace	M.J. Roarty			
	1980	P.G. Stuart-Smith D.A. Wallace R.S. Needham	L. Bagas	Stuart-Smith & others (1985b)	Stuart-Smith & others (1987)	Stuart-Smith & others (1990)
RANFORD HILL	1980	P.G. Stuart-Smith R.S. Needham D.A. Wallace				
	1981	P.G. Stuart-Smith R.S. Needham R.G. Dodson	L. Bagas	Stuart-Smith & others (1986a)	Stuart-Smith & others (1988)	Stuart-Smith & others (1986c)

Fig. 3. Physiography of the Cullen Mineral Field.

Early Proterozoic granite and minor metasediments. Highly leached skeletal soils and lateritic podsol are common with uniform or gradational gravelly and sandy soils developed over the Daly River Basin sediments. The *Lowlands* are covered by a eucalypt woodland of tall deciduous, mixed or scrubby open forest.

Bouldery granite hills, steep resistant strike ridges and hills of Early Proterozoic metasediments and volcanic rocks, and intervening undulating rubble strewn rises form the *Dissected Foothills*. They rise up to 200 m above the Alluvial Plains and cover about half the area. The rocks are deeply weathered and are covered, in places, by shallow skeletal soils, gradational red and yellow soils, or yellow earth-type soils. Vegetation is mostly a woodland of tall to stunted semi-deciduous eucalypt and tall to midheight perennial grasses.

The most prominent (although least extensive) physiographic unit is the *Tablelands*, developed over peneplaned Proterozoic sandstone and flat-lying Mesozoic sediments. In the west they rise up to 150 m

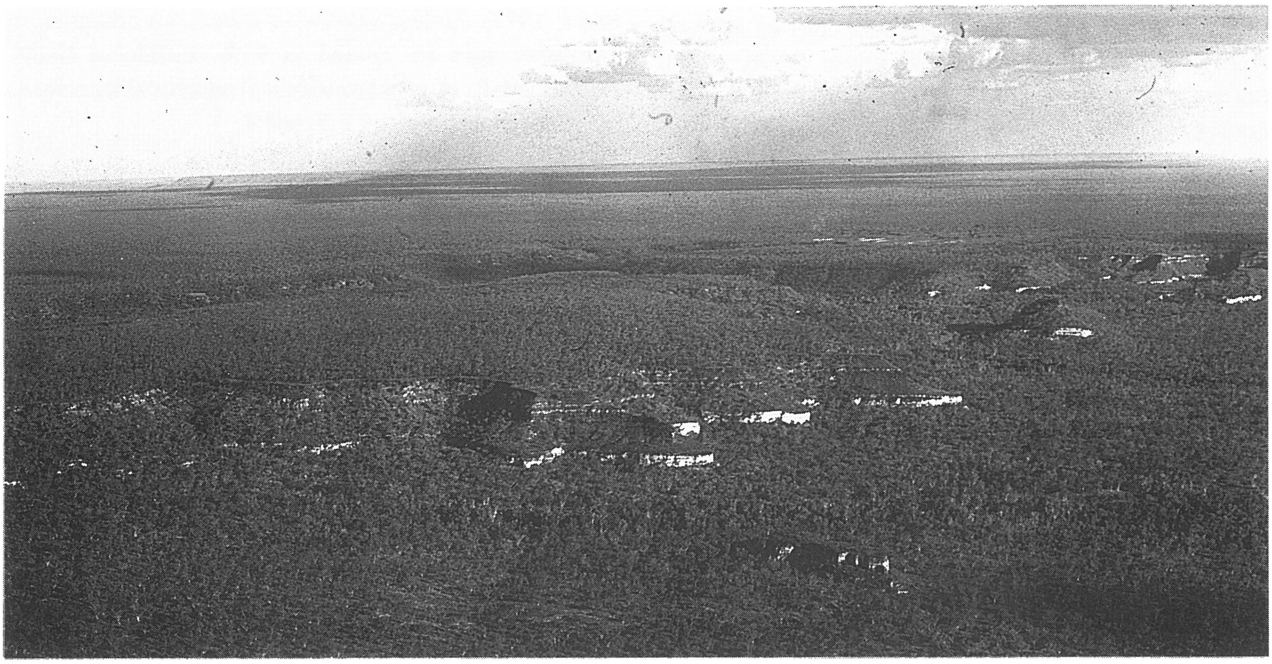

Fig. 4. Aerial view of extensive Tablelands in the southeast. The Tableland is developed on flat-lying Mesozoic sediments which unconformably overlie Early Proterozoic metasediments and volcanics in the foreground.

above adjacent *Lowlands* and are bordered by steep dissected slopes or cliffs. In places, deep gorges have been formed where watercourses are incised along joints and faults. Sparse, tall and open forest, and spinifex grow on a thin veneer of predominantly skeletal soils with patches of bare rock, deep sandy light grey soil, and Tertiary lateritic red earth. In the far north a dissected, jointed and rocky sandstone plateau forms a small area of *Tablelands* at Mount Douglas, covering about 30 km^2. The plateau rises about 200 m above the level of the adjacent *Alluvial Plains* and is surrounded by cliffs and a broad apron of sand and scree.

In the east and southeast, the *Tablelands* form an extensive flat-topped plain, at about 300 m ASL, bordered in places by steep dissected slopes or scarps up to 80 m high (Fig. 4). The plain is developed on poorly consolidated Mesozoic sands, which are rapidly being eroded by streams re-exhuming the underlying irregular topography of the *Dissected Foothills.* The sands are a major aquifer in the region and numerous permanent springs surround the *Tablelands,* feeding the Fergusson and Mary Rivers. Dense, tall open forest, and spinifex grow on a thin veneer of predominantly deep sandy skeletal soils with patches of bare rock, humic silty alluvium, and Tertiary lateritic red earths.

Extensive flood plains, incised channels, levees and billabongs of the Margaret, McKinlay and Mary Rivers constitute the *Alluvial Plains.* They occur mainly in the north, forming the southernmost areas of major flood plains extending 100 km northwards to the coast. Thick Quaternary silty and sandy loamy soils support open savanna, grassland, patches of mixed open forest and galleries of paperbark forest along permanent watercourses.

Rock Terminology and Classification

Sedimentary rock classification follows *sandstone* terminology by Packham (1954) and *limestone* classification by Folk (1959). Where the latter terminology differs from the field term used on the accompanying map reference, the field term is shown in brackets. The term *quartzite* is used for sandstones consisting chiefly of quartz grains that have either been recrystallised by metamorphism or solidly cemented by silica so that the rock breaks through individual grains rather than around them.

Although the Early Proterozoic geosynclinal sediments are metamorphosed to greenschist facies, the prefix *meta-* is only used where the rocks show visible metamorphic mineralogy or fabric in hand specimen. Mineral prefixes used in metamorphic rock terms (e.g. schist) are listed in order of increasing abundance.

Granitoids and *pyroclastic* rocks are classified following the nomenclature recommended by the IUGS Subcommission on the Systematics of Igneous Rocks (Streckeisen, 1973; and Schmidd, 1981; respectively).

Laterite terminology follows that described by Williams (1969).

More detailed petrographic descriptions of all rock types are given by Needham & others (1978, 1986), Stuart-Smith & others (1986, 1990) and Wallace & others (1981).

Classification of Mineral Deposits

On the basis of the dominant style of mineralisation, metal association, and stratigraphic and structural controls, four types of mineral deposits are recognised:

- (1) hydrothermal veins or stockworks associated with granitoid intrusions (Sn, W, Au, Ag, Pb, Zn, Cd, Cu, Bi, As, U, and Mo).
- (2) Stratabound massive sulphide deposits within the South Alligator Group (Au, Ag, Cu, Pb and Zn).
- (3) Residual massive oxide deposits (Fe and Mn).
- (4) Alluvial deposits (Au and Sn).

Non-metallic minerals are not included in this subdivision and are discussed separately.

Analytical methods

Geochronology

Zircon was separated from granite samples collected during 1979 and 1983. Initially, multi-grain U-Pb analyses were made using techniques of Krogh (1973). More recently, a selection of some of the same zircon suites from the Cullen Batholith were analysed using the SHRIMP ion microprobe in the Research School of Earth Sciences, ANU. Detailed descriptions of the techniques for zircon U-Th-Pb analysis using the SHRIMP are given by Compston & others (1984, 1986). Rb-Sr procedures followed those described in Page & others (1976), and isochron regression was adopted from McIntyre & others (1966). Decay constants used are those recommended by the IUGS Subcommission on Geochronology (Steiger & Jdger, 1977). Unless otherwise stated, uncertainties in calculated ages are quoted as 95% confidence limits. Further details of geochronological analytical techniques are given in Appendices 2, 3, and 4.

Geochemistry

Samples were analysed at AGSO: by x-ray fluorescence for SiO_2, Al_2O_3, total Fe, CaO, K_2O, P_2O_5, Ba, Rb, Sr, Pb, Th, U, Zr, Nb, Y, La, and Ce; by atomic absorption spectroscopy after total solution in hydrofluoric acid for MgO, Na_2O, V, Cr, Co, Ni, Cu and Zn; and by wet chemistry for FeO, H_2O^+, H_2O^-, and CO_2.

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This Bulletin is largely based on an MSc thesis by P.G. Stuart-Smith. K. H. Wolf is especially thanked for its conversion to Bulletin standards.

Fieldwork was a team effort by AGSO and NTGS geologists. In this regard, we gratefully acknowledge the contribution by D.A. Wallace, I.H. Crick (AGSO); M.J. Roarty and L. Bagas (NTGS). R.G. Dodson (AGSO), C. Amri (GRDC), L. Mulder, and B.B. Whitehead (NTGS) also assisted in fieldwork.

C. Foudoulis assisted with operations of the SHRIMP ion microprobe and the figures were drawn by H. Apps, Cartographic Services Unit, AGSO.

We wish to thank Noranda Australia Ltd., CRA Exploration Pty Ltd., Peko Exploration Ltd., Pine Creek Goldfields Ltd. and Eupene Exploration Enterprises Pty. Ltd. for freely supplying company information and for many helpful discussions in the field; Mr and Mrs Landsdowne of Katherine, Mr and Mrs G. Walker of 'Goodparla', and Mr Fisher of 'Mary River' for their much appreciated hospitality during the field seasons.

REGIONAL GEOLOGICAL SETTING

The Cullen Mineral Field lies in the southern central part of the Pine Creek Geosyncline (Fig. 5), the geology of which has been described by Needham & others (1980, 1988). The geosyncline contains Early Proterozoic metasedimentary rocks resting on a gneissic and granitic Archaean basement, the latter being exposed to the west and northeast of the mineral field. The metasediments, representing a basinal sequence about 10 km thick (Needham & others, 1988), were folded and metamorphosed at ~1870 Ma to lower to upper greenschist facies and, in places, to amphibolite facies. The 1870 Ma age marked the beginning and peak of the deformation and metamorphic episode (Needham & others, 1988), which began with the intrusion of a large granite—subsequently migmatised—in the northeast of the geosyncline and was interrupted by periods of felsic igneous activity. The precursor sedimentary rocks of the geosyncline were mainly shale (commonly carbonaceous), siltstone, quartz sandstone, conglomerate, greywacke, dolomite (e.g. dolarenite, dololutite) and tuff.

Largely undeformed late Early Proterozoic volcanics (~1860–1850 Ma) and sediments, and Middle Proterozoic, Palaeozoic, and Mesozoic strata rest on the geosynclinal metasediments with marked unconformity. The geosynclinal metasediments are intruded by pre-orogenic dolerite sills and syn-orogenic to post-orogenic granitoid plutons (~1840–1780 Ma), and dolerite lopoliths and dykes.

The geology of the Cullen Mineral Field is shown on the accompanying map. An almost complete sequence of Early Proterozoic geosynclinal strata, metamorphosed to low to upper greenschist facies, is present. Pre-orogenic dolerite sills are common in the middle part of the sequence, and syn-orogenic felsic volcanics and related sediments are exposed in the southern parts. About a third of the field is covered by syn- to post-orogenic granitoids, the effects of which dominate gravity, magnetic and radiometric patterns (Figs 6, 7 and 8). Platform cover, of Middle Proterozoic, Palaeozoic, Mesozoic and Cainozoic strata, mark the perimeters of the field.

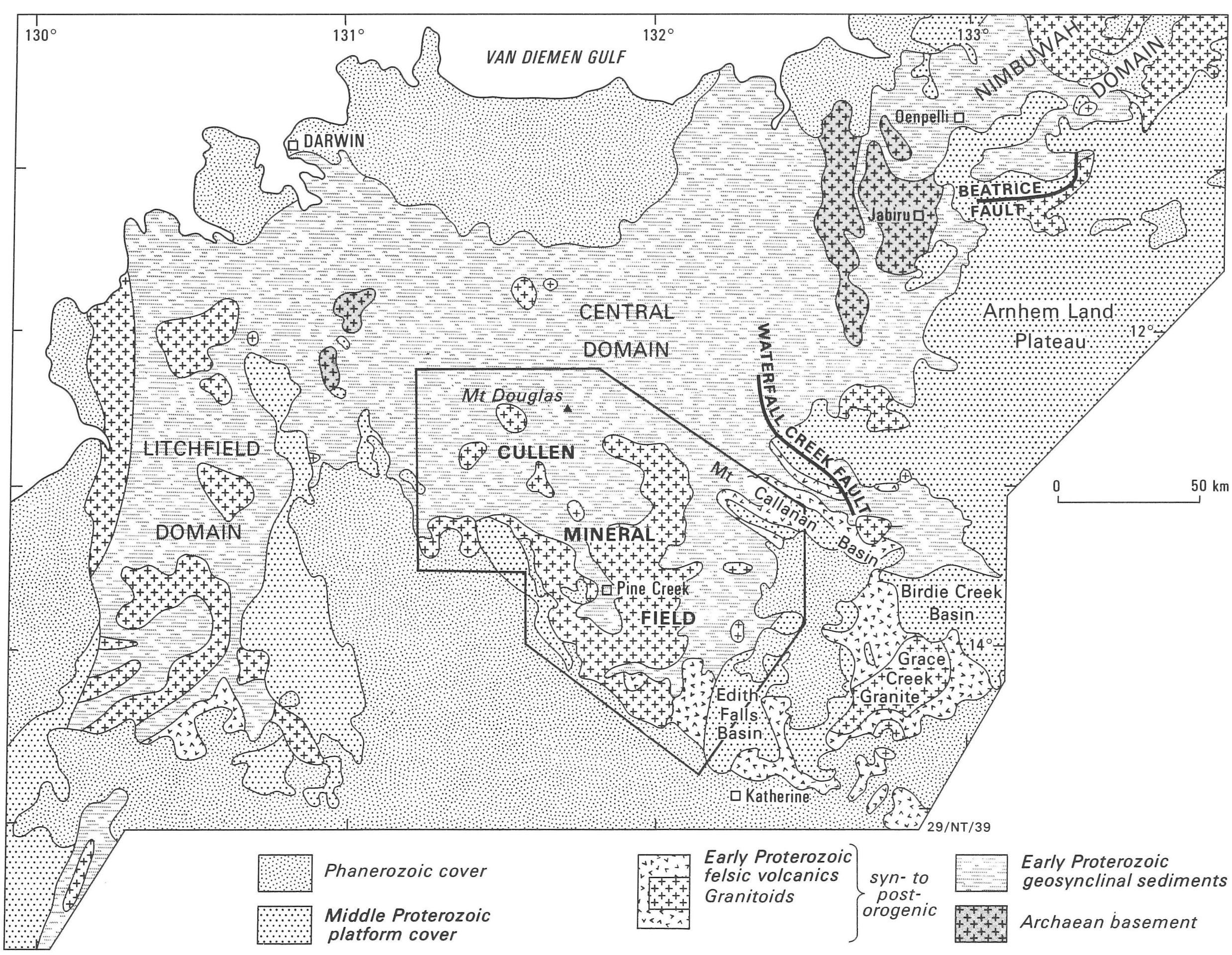


Fig. 5. Regional geological setting of the Cullen Mineral Field.

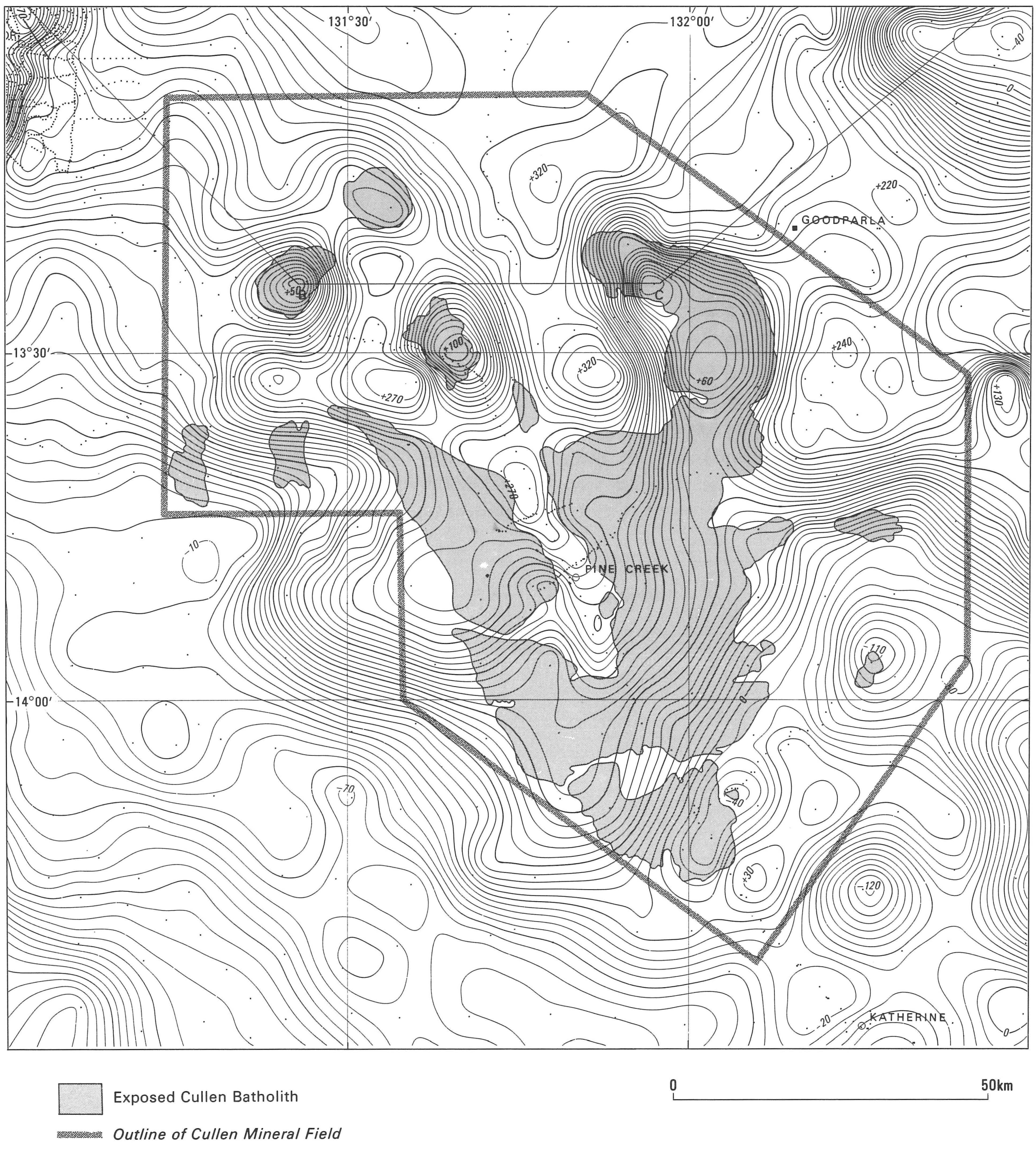


Fig. 6. Bouger gravity map of the Cullen Mineral Field and adjacent areas.

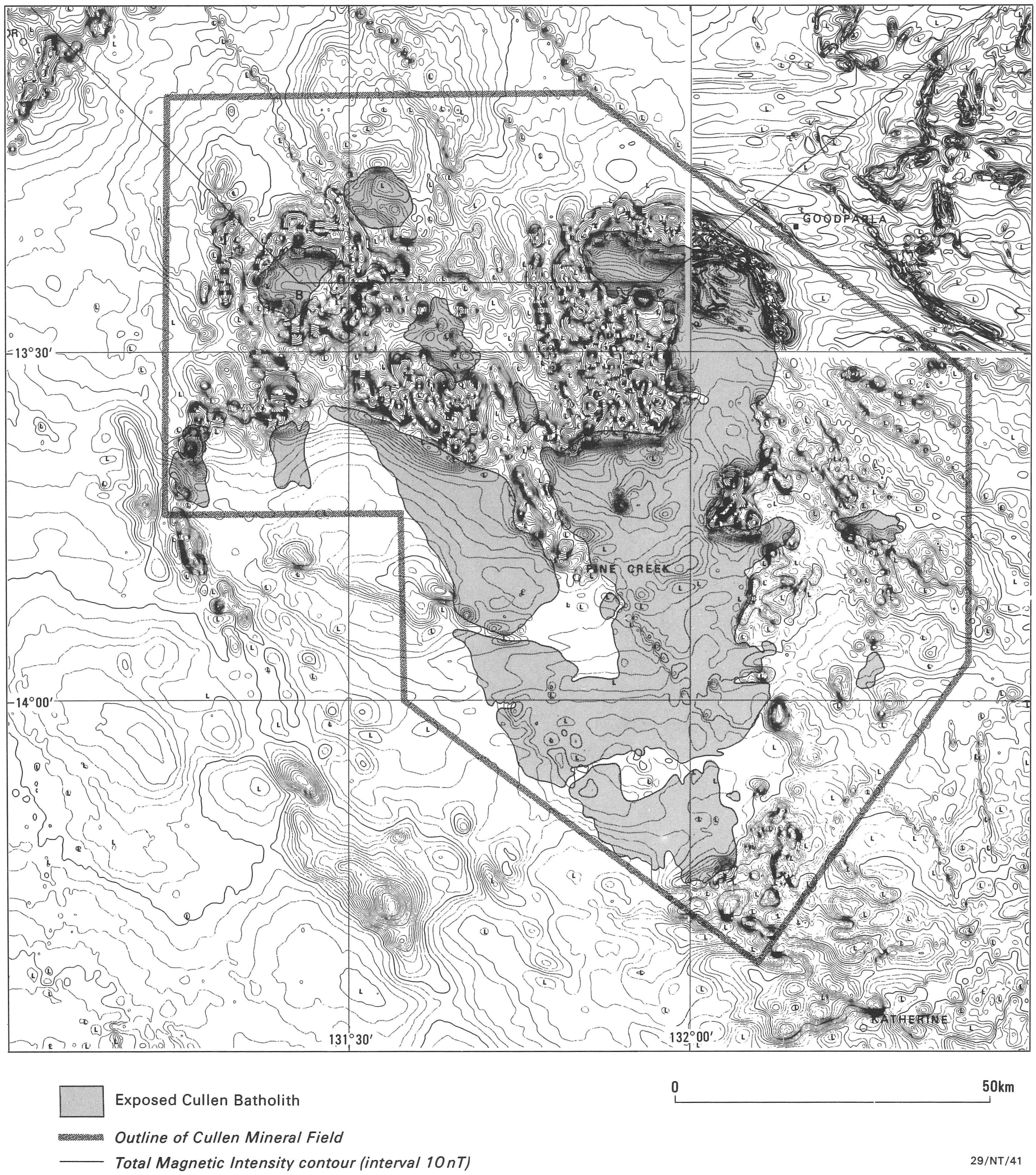


Fig. 7. Airborne total magnetic intensity of the Cullen Mineral Field and adjacent areas.

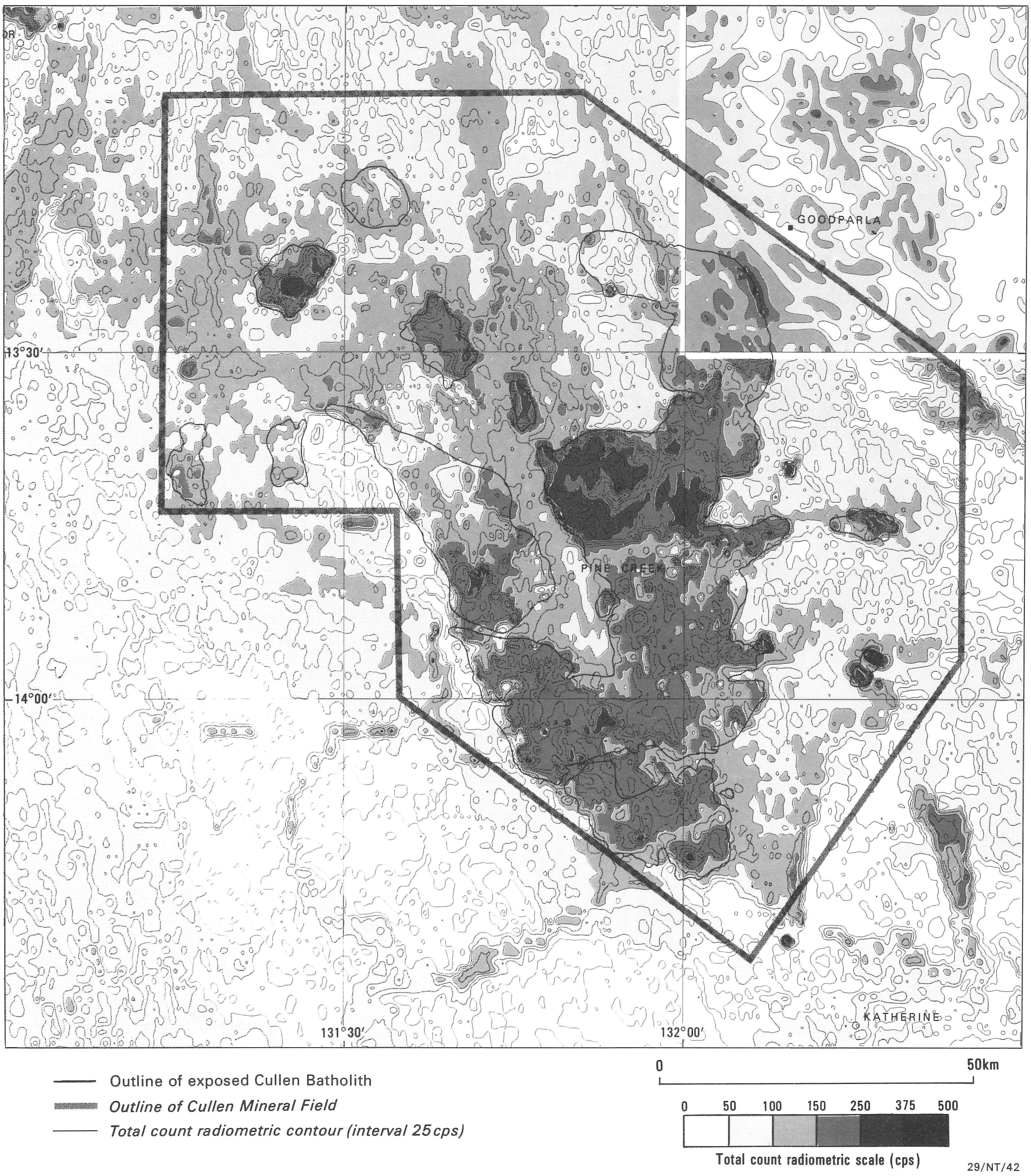


Fig. 8. Total count radiometric anomaly map of the Cullen Mineral Field and adjacent areas.

STRATIGRAPHY

EARLY PROTEROZOIC GEOSYNCLINAL STRATA

The Early Proterozoic geosynclinal stratigraphy is summarised in Table 3. The age of the basement granitoids in the Nanambu Complex and the intrusive Nimbuwah Complex (both northeast of the CMF; Page & others, 1980) confine the depositional age of the strata between 2470 and 1870 Ma. Age determinations (U-Pb zircon analyses) on tuff of the Mount Bonnie Formation (Needham & others, 1988) indicate deposition of the South Alligator Group at about 1885 ± 2 Ma. The older Namoona and Mount Partridge Groups were probably deposited between 2000 and 1890 Ma, given the estimated age of 2000 to 2200 Ma for the Kakadu Group which underlies correlatives of the Namoona Group in the Alligator Rivers Region (Page & others, 1980).

Namoona Group

The Namoona Group is the oldest unit, and contains the Masson Formation and Stag Creek Volcanics. Elsewhere in the Pine Creek Geosyncline, correlatives of the Masson Formation overlie either the basal Early Proterozoic Kakadu Group or the Archaean Rum Jungle and Waterhouse Complexes (Needham & others, 1980). Within this area, the group is unconformably overlain by Early Proterozoic and younger sediments and volcanics.

Masson Formation (Ɛnm)

Distribution. The Masson Formation crops out sporadically as low strike ridges and rubbly rises in the centre of a regional northwesterly plunging antiform surrounding the northeastern lobe of the Cullen Batholith in the northeast. It is mostly covered by a veneer of Cainozoic deposits.

Stratigraphic relations. The formation underlies the Mundogie Sandstone, and has been intruded by several discontinuous sills of Zamu Dolerite and extensively hornfelsed and intruded by the Cullen Batholith. In the east around the margins of the Mount Callanan Basin (see accompanying map), the unit is conformably overlain by the Stag Creek Volcanics and unconformably overlain by, and in places faulted against, the Mount Partridge, South Alligator, El Sherana, Edith River and Katherine River Groups. Tablelands and outlying mesas of flat-lying Cretaceous sediments cover much of the formation. The unconformable contact with the El Sherana Group is exposed at KF 1602*, where near horizontal ignimbrite of the Pul Pul Rhyolite rests on steeply dipping silty phyllite of the Masson Formation. Contacts with the Mundogie Sandstone and Koolpin Formation are not apparent, but unconformable relationships can be inferred from observations elsewhere (Stuart- Smith & others, 1984a, b).

Lithology. In places, a broad twofold stratigraphic sequence can be recognised: a lower unit, about 2500 m thick, of pelites, psammites, and rare dolomitic sediments; and an upper pelitic unit about 300 m thick. *Slate, phyllite, silty phyllite, siltstone* and *sandy siltstone* probably comprise over half of the Masson Formation. They are highly cleaved, brick-red, hematitic, and form flaggy rubble that mantles low rises between sandstone and quartzite ridges. At depth, they are mostly pyritic and carbonaceous. In the metamorphic aureole of the Cullen Batholith, they are metamorphosed to *chiastolite carbonaceous hornfels, spotted grey cordierite-andalusite-muscovite hornfels, grey spotted micaceous hornfels,* and *biotite-muscovite-quartz hornfels.*

Minor laminated thin beds up to 20 cm thick of *grey fine to coarse-grained quartzite, massive coarse to gritty poorly sorted grey feldspathic quartz sandstone* beds up to 2 m thick, and *graded quartz pebble conglomerate* beds up to 1 m thick are interbedded with the pelitic rocks. About a fifth of the formation is sandstone, quartzite or conglomerate, which form well exposed low strike ridges, typically forming intensely jointed and surface silicified blocky outcrops. Cross-bedding, graded beds and ripple-marks are common. Some of the quartz sandstone is friable, limonitic and well bedded. Gamma-ray spectrographic images (K, U & Th) of the area northeast of the Cullen Batholith in MUNDOGIE (BMR, 1989; p 19) indicate that Mundogie Sandstone sandstone and conglomerate, shown on the accompanying map as Masson Formation, form a continuous belt from Chara Chara Hill to near Gertrude Springs below thin Cretaceous cover.

Interbedded dark grey *dolarenite* and laminated to massive crystalline *dolomite* and *dololutite* , forming less than 10% of the formation, are exposed towards the base of the unit. The latter two rock types crop out poorly in creek beds or on low rises between boulders or strike ridges of dolarenite. At the surface, they are commonly brecciated with a distinctive porous brown limonitic crust.

Other rock types are minor massive *hematitic* and *limonitic ironstone,* and rare *muscovite-tremolite marble* and *calc-silicate hornfels,* which form low isolated boulders on the plains northwest and south of Halfway Peak (HL 2209). The distribution and relationships of

* Universal grid reference to the nearest 1000m

TABLE 3. SUMMARY OF EARLY PROTEROZOIC GEOSYNCLINAL STRATIGRAPHY

Unit (map symbol)	*Distribution*	*Lithology*	*Field relations*	*Thickness (m)*	*Depositional environment*	*Remarks*
FINNISS RIVER GROUP						
Burrell Creek Formation	Extensive outcrops on rises and low strike ridges in NW,E, and centre.	Slate,phyllite, siltstone, and sandy siltstone (50-75%); quartz-andalusite-muscovite-biotite-cordierite hornfels near granitoids; fine- to coarse-grained greywacke; minor volcanilithic pebble conglomerate; rare altered felsic to intermediate volcanics and banded chlorite-magnetite ironstone.	Conformably overlies and faulted against Pso. Unconformably overlain by younger units. Intruded by Pdz and Pcg.	1500 +	Deep-water, high-energy.	Flysch deposits derived from up-(Pfb) lifted volcanic source (Needham & others, 1988).
SOUTH ALLIGATOR GROUP						
Mount Bonnie Formation (Pso)	Low rises in N surrounding Pgc.	Slate, mudstone, phyllite and siltstone (>50%); muscovite-biotite-cordierite hornfels and muscovite-microcline-biotite-quartz-andalusite-cordierite hornfels near granitoids; feldspathic greywacke (~25%); minor ferruginous carbonaceous and dolomitic slate and phyllite; banded iron formation; tuffaceous chert, vitric tuff, crystal tuff, lithic crystal tuff and argillite; rare dolomite.	Conformably overlain by Pfb and underlain by Psg. Intruded by Pdz	500-700	Transition between low-energy, shallow-water, reduced environment and deeper water high-energy environment.	
Gerowie Tuff (Psg)	Low rises in N surrounding Pgc.	Green brown or grey siliceous siltstone and phyllite (50%); andalusite-garnet-biotite-muscovite-quartz hornfels near granitoids; argillite (~25%); glassy black crystal tuff, vitric tuff, and tuffaceous chert.	Conformably overlain by Pso and underlain by Psk. Intruded by Pdz and Pgc. Unconformably overlain by Pek, Pep and Phk.	300-400	Low-energy, reduced.	Reworked subaqueous deposits of siliceous ash.
Koolpin Formation (Psk)	Discontinous ridges in N surrounding Pgc.	Ferruginous carbonaceous siltstone and phyllite (~50%) with chert bands lenses and nodules; massive hematitic and goethitic ironstone; minor silicified dolomite and marl; quartz-biotite schist, muscovite-quartz schist, graphitic chiastolite-muscovite-quartz hornfels, dolomitic marble, para-amphibolite and calc-silicate hornfels near granitoids; rare sandy siltstone and limonitic quartz sandstone.	Conformably overlain by Psg. Unconformably overlain by Pep, Phk and Clj, and underlain by Pnm and Ppw. Intruded by Pdz and Pgc.	130-350	Low-energy, reduced, fresh to brackish shallow water (Crick & others, 1980).	

Unit (map symbol)	*Distribution*	*Lithology*	*Field relations*	*Thickness (m)*	*Depositional environment*	*Remarks*
MOUNT PARTRIDGE GROUP						
Wildman Silstone (Ppw)	Strike ridges and low hills N of Frances Ck., and in cores of anti-clines and domes in NW.	Laminated red and white banded pyritic silty carbonaceous phyllite, carbonaceous phyllite with sandy laminae, siltstone (~90%); minor thinly bedded fine to coarse-grained feldspathic sandstone and quartzite, very fine-grained brown quartz sandstone, grey medium-grained quartzite; massive hematitic ironstone lenses (pyritic carbon-aceous shale breccia at depth); rare dolarenite.	Conformably overlies Ppm. Unconformably overlain by Psk and Pbp. Intruded by Pdz and Pgc.	900	Shallow-water transitional with . fluviatile.	Transgressive sub-tidal deposits (Needham & others, 1988).
Mundogie Sandstone (Ppm)	Strike ridges in NE	Coarse-grained feldspathic quartz sandstone and arkose (50%); minor quartz and chert pebble conglomerate, graded bedding and scour structures common; brown, cream, mauve and red banded silty phyllite, silt-stone, sandy siltstone, grey carbonaceous phyllite, phyllite and pyritic grey quartzite; micaceous quartzite, quartz-muscovite hornfels, muscovite-biotite-cordierite-quartz hornfels, biotite-andalusite-quartz-muscovite hornfels and chiastolite-muscovite hornfels near granitoids.	Unconformably or disconform-ably overlies Pnm. Unconform-ably overlain by Psk, Pbp and younger strata. Conformably overlain by Ppw. Intruded by Pdz and Pgc.	1200	Fluviatile (Stuart-Smith& others, 1980, 1984a).	Coalesced fluvial fan deposits.
NAMOONA GROUP						
Stag Creek Volcanics (Pns)	Minor deeply weather-ed outcrops in far NE.	Tuff, tuffaceous greywacke and phyllite, altered intermediate volcanic flow breccia, andesite.	Conformably overlie Pnm.	<1000	Subaqueous.	Intermediate to mafic volcanic deposits(Stuart-Smith & others, 1984a)
Masson Formation (Pnm)	Low strike ridges and rises in NE.	Pyritic carbonaceous slate, phyllite, silty phyllite, siltstone and sandy siltstone (<50%); minor laminated grey fine- to coarse-grained quartzite, massive coarse to gritty grey feldspathic quartz sanstone, quartz pebble conglomerate and dolarenite; rare massive dolomite; and dololutite; chiastolite carbonaceous hornfels, cordierite-andalusite-muscovite hornfels, micaceous hornfels, biotite-muscovite-quartz hornfels, muscovite-tremolite marble and calc-silicate hornfels near granitoids.	Conformably overlain by Pns. Unconformably or disconformably overlain by Ppm. Unconformably overlain by Psk, Pbc, Pbp, Pek and K.	<2800	Dominantly low-energy reducing with periodic high-energy. Subtidal.	Deeper and/or distal equivalents or proximal sandstone deposits else-where (Needham & others, 1988).

these rock types are difficult to ascertain owing to poor exposure and lack of subsurface information; both weather to a deep reddish-brown soil indistinguishable from the soil developed over Zamu Dolerite.

Remarks. The presence of cross-bedded, graded and rippled sandstone in a predominantly pelitic sequence indicates periodic high-energy episodes in probably a low-energy reducing environment (Stuart-Smith & others, 1980). This is consistent with a deeper and/or more distal environment compared to the proximal sandstone sequences of the stratigraphically equivalent Beestons Formation (Rum Jungle area) and the Kakadu Group (Alligators Rivers Region).

Stag Creek Volcanics (Ƥns)

Minor outcrops of *tuff, tuffaceous phyllite* and *greywacke, intermediate volcanic breccia,* and *andesite* of the Stag Creek Volcanics are exposed in the far northeast. The volcanics are poorly exposed, deeply weathered, and are mostly covered by deep skeletal soils. The outcrops form the middle portion of a narrow belt of volcanics up to 1000 m thick, extensive in adjoining MUNDOGIE (Stuart-Smith & others, 1984a) and STOW (Stuart-Smith & others, 1988), where it conformably overlies the Masson Formation.

Mount Partridge Group

Clastic and minor chemical sediments of the Mount Partridge Group either unconformably or disconformably overlie older units in the Pine Creek Geosyncline. The *Mundogie Sandstone*—a fluvial sequence of sandstone, minor conglomerate and pelitic rocks—forms the base and is overlain, probably transitionally, by the *Wildman Siltstone*—a shallow marine possibly subtidal deposit. These are the only members of the group present. They crop out mainly in the northeast where they form a rugged isoclinally folded belt in which shallow-plunging fold axes have axial surfaces dipping steeply to the southwest, and where overturned beds are common.

Mundogie Sandstone (Ƥpm)

Distribution. The Mundogie Sandstone is well exposed in the northeast as fairly continuous northwest-trending strike ridges rising up to 200 m above the intervening valleys.

Stratigraphic relations. The Mundogie Sandstone overlies the Masson Formation with apparent conformity. The contact is either obscured by scree or alluvium or separated by sills of pre-orogenic Zamu Dolerite, but elsewhere in the geosyncline it is either unconformable or disconformable (Stuart-Smith & others, 1984a & b). The upper contact of the sandstone with the Wildman Siltstone is sharp and well defined by the top of the uppermost coarse feldspathic quartzite bed. The contact is also well expressed topographically (subdued relief in the Wildman Siltstone) and is exposed in a road cutting at the Frances Creek iron mines (HK 0997). In places, the Mundogie Sandstone is unconformably overlain by the Koolpin Formation, Pul Pul Rhyolite, and several small thin flat-lying deposits of Cretaceous sandstone and conglomerate.

The sandstone is intruded by the Frances Creek Leucogranite and the Allamber Springs and Minglo Granites, which extensively hornfels the sediments. The contacts are mostly discordant; in places they are very irregular where the strike of the sediments is perpendicular to the contact; such as 4 km east of Allamber Springs where tongues of Allamber Springs Granite penetrate pelitic interbeds. Around the Minglo Granite and the Frances Creek Leucogranite, the contact is concordant and regional northwest-trending fold axes have been deflected parallel to the intrusive contact.

Minor felsite and minette dykes intrude sandstone southeast of Mount Harris (eg. HL 0825, HL 2125, HL 2525).

Lithology. The Mundogie Sandstone, ranging in thickness from less than 300 m east of the Mary River to 1200 m in the Mount Masson area, consists of an interbedded sequence of psammite with minor conglomerate and pelite (the 'lower' and 'middle arenite' units of Hays, 1960). A pelitic lens up to 150 m thick (corresponding to Hay's 'lower lutite unit') extends for over 20 km southwest of Mount Harris. A similar and probably correlative lens crops out 5 km northeast of Halfway Peak, extending for 8 km along the margin of the Cullen Batholith.

Coarse-grained to pebbly feldspathic quartz sandstone and *arkose* comprise over 50% of the formation (comparing with less than 10% in the Wildman Siltstone). The psammitic rocks, cropping out as strike ridges, are pyritic in places and rarely contain shale and siltstone clasts up to 20 cm across. Beds, commonly about 1 m thick and ranging up to 5 m thick, are massive with laminated tops in places. Sedimentary structures include graded-bedding, lenticular cross-bedding and loadcasts. Kaolinisation and sericitisation of feldspar have resulted in a characteristic 'honeycomb' weathering in places. Within the contact aureole of the Cullen Batholith they are recrystallised to *micaceous quartzite.*

Minor lenses and beds of *pebble conglomerate* up to 3 m thick are common in the sandstone, quartzite, and arkose. They contain subangular to well-rounded clasts, up to 4 cm, of quartz, black or white chert, weathered feldspar, and minor shale, phyllite, quartzite, quartz-mica pegmatite, and rare ferruginous volcanic rock, in a coarse, poorly sorted sericitic and hematitic sandy matrix. Graded bedding and scour structures are common.

Thin interbeds of *brown, cream, mauve,* and *red* *banded silty phyllite, siltstone, sandy siltstone, grey carbonaceous phyllite,* and *phyllite* constitute the pelitic lenses and form less than 50% of the formation. They are typically micaceous and pyritic or hematitic, and crop out poorly in creek beds or on low scree-covered rises, between strike ridges of psammitic rocks. Within the contact aureole of the Cullen Batholith, they are tourmalinised, silicified and metamorphosed to *quartz-muscovite hornfels, muscovite-biotite-cordierite-quartz hornfels, biotite-andalusite-quartz-muscovite hornfels,* and *black carbonaceous chiastolite-muscovite hornfels.*

Minor laminated to thinly bedded fine to medium *pyritic grey quartzite* forms interbeds up to 30 cm thick in pelitic sequences.

Wildman Siltstone (Ɐpw)

Distribution. The Wildman Siltstone crops out as strike ridges and rubbly rises in an isoclinally folded belt up to 4 km wide in the central north, flanking the steep ridges of Mundogie Sandstone running northwards from the *Frances Creek iron mines*[102]. Phyllite and siltstone—exposed along the eastern margin of the Burnside Granite and in the cores of the Golden Dyke Dome, Howley Anticline, and two anticlines respectively 11 and 14 km southwest of Burrundie Siding—are probably Wildman Siltstone as they are lithologically similar and also underlie the Koolpin Formation. In many places, the unit is covered by a thin veneer of Cainozoic deposits and less commonly small outliers of Cretaceous sediments.

Stratigraphic relations. The Wildman Siltstone conformably overlies the Mundogie Sandstone and is overlain by the Koolpin Formation. The upper contact is unconformable and is exposed 3 km north of the Frances Creek iron mines where sandstone strike ridges in the Wildman Siltstone are truncated at an acute angle by the Koolpin Formation. In other areas, intense folding has obscured any angularity between the two units and the contact appears disconformable. In several places, discontinuous sills of Zamu Dolerite separate the formation from the overlying Koolpin Formation and intrude the lower parts of the siltstone. The Allamber Springs, Burnside, and Fenton Granites intrude and extensively contact metamorphose the siltstone.

Lithology. The Wildman Siltstone is predominantly pelitic, at least 900 m thick, with up to 10% psammitic rocks. The pelitic rocks comprise *laminated grey, brown, red* and *cream banded silty carbonaceous phyllite,* thinly-bedded bleached white to grey or black *carbonaceous phyllite, grey siliceous phyllite,* and *siltstone* with minor sandy laminae. At depth, most of the pelites are pyritic and carbonaceous (as exposed in the bottom of the Thelma No. 2 open cut, Frances Creek), and within the contact aureole of the Cullen Batholith are metamorphosed to banded *carbonaceous chiastolite-muscovite hornfels* and *spotted micaceous hornfels.*

Ironstone lenses, forming prominent strike ridges up to 50 m high and 1000 m long within carbonaceous phyllite near the base of the unit, were mined at Frances Creek. They consist of massive or brecciated iron and manganese oxides in a siliceous gossanous matrix. At depth, the ironstone grades into pyritic carbonaceous shale breccias which are conformable to bedding and are folded with the enclosing sediments about the northwest-trending isoclinal folds. The origin of the breccias may be related to thrusting within the geosynclinal pile prior to the major folding episode (Needham & others, 1980; Johnston, 1984). The ironstone formed by oxidation and enrichment of the pyritic breccias prior to the Cretaceous, as pebbles of massive hematite are present within overlying basal Cretaceous conglomerates.

Psammitic rocks, more common in the upper part of the formation, include blocky *very fine to fine-grained yellow-brown iron-stained sericitic quartz sandstone, grey medium-grained quartzite, coarse poorly sorted feldspathic quartz sandstone* and *quartzite* and rare *dolarenite.* The quartz sandstones commonly form laminae to thin beds up to 1 m thick, with rare graded pebbly beds, cross-bedding and ripple-marks. Within the contact aureole of the Cullen Batholith, quartz sandstones are silicified and dolarenite is metamorphosed to *biotite-tremolite-quartz hornfels* or *calcite-zoisite-tremolite-quartz hornfels.*

Remarks. Between the McKinlay and Mary Rivers the Wildman Siltstone has been divided by Stuart-Smith & others (1985) into two members corresponding to Hays' (1960) "Upper lutite unit" and "Upper arenite unit", which correlate with the broad two-fold subdivision recognised in MUNDOGIE (Stuart-Smith & others, 1984a) and MARY RIVER and POINT STUART (Stuart-Smith & others, 1984b). These two members, details of which are given in Table 4, are not differentiated on the accompanying 1: 250 000-scale map.

South Alligator Group

The South Alligator Group is a distinctive sequence of iron-rich and tuffaceous strata resting unconformably on older rocks. It is conformably overlain by, and in places faulted against the Finniss River Group and is unconformably overlain by the El Sherana, Edith River, Katherine River and Daly River Groups, and by Cretaceous sediments. The group includes the *Koolpin Formation, Gerowie Tuff,* and *Mount Bonnie Formation,* and crops out as tight to isoclinally folded and faulted belts in the centre and east, and around domal granite contacts in the northwest.

All formations in the group are intruded and

TABLE 4. STRATIGRAPHY OF THE WILDMAN SILTSTONE IN THE MARY–McKINLAY RIVERS AREA

Member	*Thickness (m)*	*Lithology*
upper	150 - 400	Brown phyllite, silty phyllite, grey siliceous phyllite, black carbonaceous phyllite and siltstone (~90%); thinly bedded fine- to coarse-grained quartz sandstone; rare dolarenite.
lower	200 - 500	Laminated grey, brown, red and cream banded silty carbonaceous phyllite and siltstone with minorsandy laminae, grey carbonaceous phyllite with ironstone lenses at base; very minor brown fine-grained quartzite.

extensively hornfelsed by the Cullen Batholith and are also intruded (especially the Koolpin Formation) by discontinuous pre-orogenic sills of Zamu Dolerite. Contact-metamorphic effects of the dolerite are rarely present, owing to overprinting by regional metamorphism.

Koolpin Formation (Ɛsk)

Distribution. Throughout the north, the Koolpin Formation forms a distinctive iron-rich sequence 130 to 350 m thick at the base of the South Alligator Group. It crops out as discontinuous ridges which rise up to 200 m above the floor of adjacent valleys, and are covered by dense tall vegetation and deep reddish-brown soils that contrast markedly with soils on adjacent units.

Stratigraphic relations. The formation overlies the Mount Partridge and Namoona Groups, and is conformably overlain by the Gerowie Tuff. The lower contact is not exposed, but an unconformable relationship is indicated elsewhere in the geosyncline (Stuart-Smith & others, 1984a & b), and by converging structural trends 3 km north of the Frances Creek iron mines and 6 km north-northwest of Mount Masson. In places, the upper contact is faulted or marked by a steep valley formed in a distinctive brown siltstone and shale sequence. This sequence marks the upper part of the Koolpin Formation, and is interbedded with tuff and argillite in the basal few metres of the Gerowie Tuff. In many places, sills of Zamu Dolerite have intruded along the upper and lower contacts.

Lithology. Rock types in the Koolpin Formation are mainly interbedded ferruginous and carbonaceous siltstone and phyllite and carbonaceous claystone, with minor dolomite lenses and rare sandy siltstone and limonitic quartz sandstone. In the Burrundie Dome area, where the formation is thickest, it can be divided into three informal members (Table 5) corresponding to the upper three of the four members described by Nicholson (1980): the lowermost of Nicholson's (1980) members is now placed in the Wildman Siltstone.

Poorly exposed brown, *ferruginous carbonaceous siltstone* and *phyllite* with minor silty laminae are the predominant rock types and are commonly capped by gossanous *ironstone* composed of cellular or massive hematite, limonite, and botryoidal goethite. At depth and within the contact aureoles, they are pyritic and or pyrrhotitic. In the northwest, where the regional metamorphic grade is slightly higher, the rocks are metamorphosed to *carbonaceous quartz-biotite schist*, and *muscovite-quartz schist.* Adjacent to the granitoids, they are commonly tourmalinised and metamorphosed to *grey graphitic chiastolite-muscovite-quartz hornfels.* Bands, lenses and nodules of black to pale grey chert up to 30 cm thick are common, particularly in carbonaceous pelites of the middle member. In the Mount Masson area, pale green, grey or white massive bleached *carbonaceous claystone* forms a discontinuous horizon up to 100 m thick over a strike length of 4 km in the middle part of the formation.

Minor lenses, up to 300 m long and 5 to 10 m thick, of laminated to thinly-bedded or brecciated grey, yellow and pink *silicified dolomite* and *marl* occur within the middle member and crop out as bouldery strike ridges. Within the contact metamorphic aureoles, they form recrystallised *dolomitic marble, para-amphibolite,* and *calc-silicate* rocks with sphene, wollastonite, vesuvianite, diopside and grossular. Silicification of dolomite is apparent only outside the contact aureoles, suggesting that it took place after contact metamorphism, possibly related to supergene processes (Stuart-Smith & others, 1985). This is in contrast to the formation of chert bands, lenses, and nodules in the pelitic rocks which were probably formed by silica replacement of dolomite during diagenesis. Early (at least pre-granitoid intrusion) formation of the chert is indicated by its recrystallised sugary quartzitic appearance within contact aureoles.

Rare *sandy siltstone* and finer-grained laminated porous poorly sorted *limonitic quartz sandstone* form interbeds of up to 15 cm thick within siltstone and shale at the base of the formation in the Mount Harris area, and near Mount Ellison where they are recrystallised to fine-grained limonitic quartzite.

Remarks. The Koolpin Formation represents a basin-wide transgressive sequence deposited under low-energy, reducing conditions in fresh to slightly brackish water (Crick & others, 1980), following uplift, minor warping

TABLE 5. STRATIGRAPHY OF THE KOOLPIN FORMATION IN THE BURRUNDIE DOME AREA

member	*Nicholson's (1980)*	*Thickness(m)*	*Lithology*
upper	Upper Carbonaceous Metapelite Member	80-150	Carbonaceous metapelite with pyrite-rich bands and chert nodules, lenses and bands.
middle	Banded Ferruginous Member	50-100	Interbedded banded quartz-hematite ironstone, para-amphibolite with ferroactinolite and stilpnomelane, silicified dolomite, marl, carbonaceous pelite with chert bands, lenses and nodules.
lower	Lower Carbonaceous Metapelite Member	<50	Carbonaceous metapelite with pyrite-rich bands and chert nodules, lenses and bands.

and peneplanation of the older geosynclinal sediments (Stuart-Smith & others, 1980).

Gerowie Tuff (Ᵽsg)

Distribution. The Gerowie Tuff is well exposed in the north on the flanks of low rubble covered hills and in steep erosion gullies. Characteristically, it has a pale photo-tone, poor skeletal soil, and sparse stunted vegetation.

Stratigraphic relations. The formation is conformable between the Koolpin and Mount Bonnie Formations. The lower contact is at the base of the lowermost tuff or argillite in a 5 to 10 m thick basal zone of interbedded ferruginous shale and siltstone, argillite, and tuff. The upper contact is defined by the base of the lowermost greywacke and is well exposed in a creek bed 5.5 km north of Mount Porter (HK 0696). Minor intrusive sills of Zamu Dolerite in places separate the formation from the underlying or overlying units.

Lithology. The Gerowie Tuff consists of a sequence of interbedded pelitic and tuffaceous rocks, ranging in thickness from 300 m to 400 m. Laminated to thinly bedded green, brown or grey *siliceous siltstone* and phyllite with rare chert nodules, although poorly exposed, probably constitute over 50% of the unit. Both rocks are sericitic and rarely carbonaceous, and within the hornblende hornfels aureole around the Margaret Granite, are totally recrystallised to *andalusite-garnet-biotite-muscovite-quartz hornfels*; in the outer albite-epidote-hornfels aureole muscovite and andalusite are the only contact-metamorphic minerals present.

Well jointed, thinly bedded grey, brown, pink and green *argillite* crops out well and probably comprises about 25% of the formation. Rare angular silt-size crystal fragments of quartz and sericitised or carbonated feldspar indicate a possible tuffaceous origin.

Laminated to massive spotted *glassy black crystal tuff, vitric tuff,* and *tuffaceous chert* form beds up to 10 m thick throughout the unit. Although they constitute less than 25% of the formation, they are prominent in outcrop, and

Fig. 9. Photomicrograph of devitrified glass shards in vitric tuff, Gerowie Tuff (Plane light, scale approx. 1mm across).

their common weathered white appearance is largely responsible for the pale photo-tone for the unit. They contain varying amounts of curved or angular crystal fragments (less than 0.5 mm) of quartz, alkali feldspar, and minor sphene, biotite and zircon in a base of devitrified glass shards and recrystallised alkali feldspar, sericite, chlorite, iron oxides and carbonate. Carbonate occurs as clots comprising up to 5% of the rock (Nicholson, 1980) or less commonly as laminae (Goulevitch, 1978). A weak eutaxitic fabric is present in vitric tuff which consists mostly of devitrified welded glass shards (Fig. 9). Apart from patchy development of microcrystalline quartz, biotite, and chlorite, the tuffs retain their appearance and

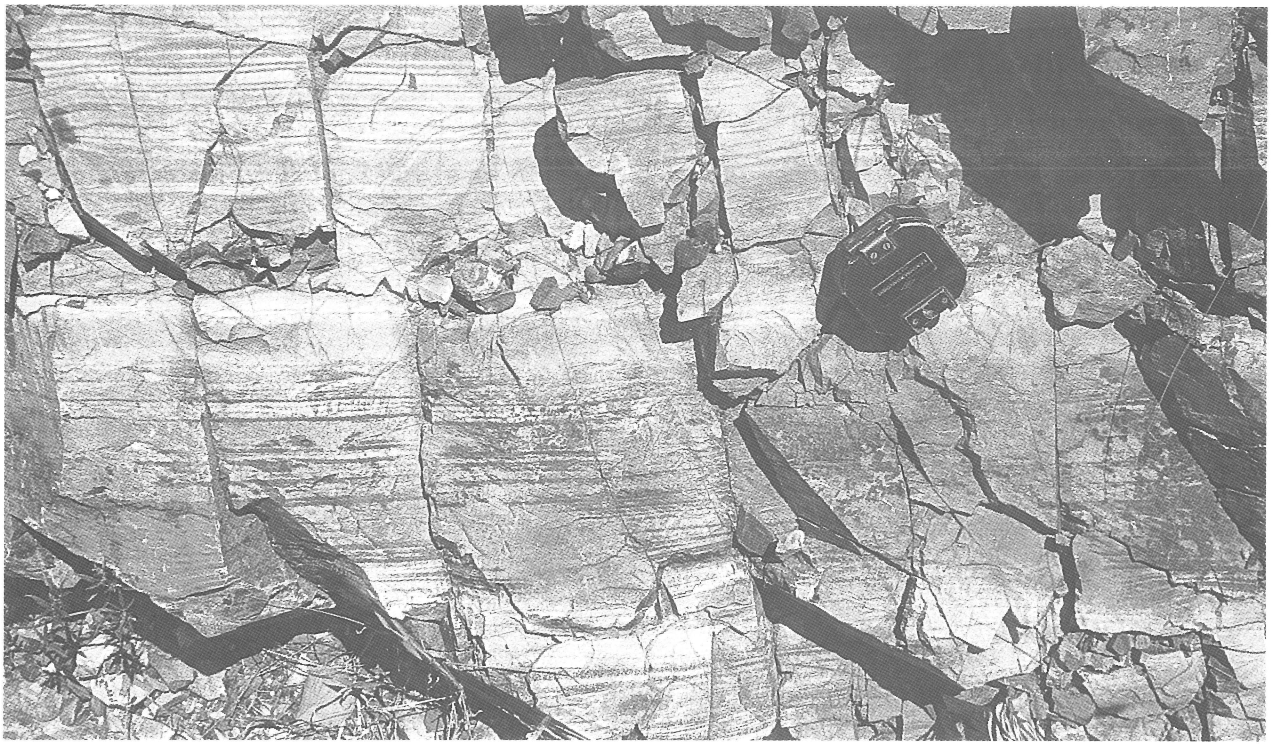


Fig. 10. Jointed, laminated black glassy devitrified crystal and vitric tuff, Gerowrie Tuff.

fragmental fabric within the contact-metamorphic aureole of the granitoids, except within the hornblende-hornfels zone where they are recrystallised to a granuloblastic mosaic of K-feldspar, quartz, biotite, and minor plagioclase.

Many of the tuffs form graded beds, ranging from 30 to 150 cm thick, characterised by massive basal and central sections and a laminated top up to 10 cm thick (Fig. 10). The top few centimetres of the laminated section are typified by flaser bedding and minor soft sediment slumping, and contain sericitic white laminae reflecting a higher pelitic content. A well exposed sequence of graded beds crops out in a creek bed 6.5 km north of Mount Porter (HK 0597). Goulevitch (1980) described a range in composition in one such bed from less than 74% SiO_2 at the base to over 80% SiO_2 at the top. Nicholson (1980) attributed this variation in chemistry within the graded beds to: (a) the alteration of the volcanic material in the sedimentary environment; (b) differences in the chemistry of the original volcanic material; (c) and the rate of silica and clay deposition. The graded beds probably represent ashfall accumulations from a single eruption, or are possibly turbidity current deposits resulting from unstable subaqueous accumulations of volcanic ash.

Remarks. The Gerowie Tuff probably formed as subaqueous accumulations of very fine waterborne siliceous ash in a low-energy environment, where clay deposition was otherwise dominant. Its conformity with the underlying Koolpin Formation and the presence of interbedded pelitic sediments with chert nodules indicate continuation of the restricted fresh-to-slightly brackish-water environment that characterised the Koolpin Formation, throughout the volcanic episode.

Mount Bonnie Formation (Ꞓso)

Distribution. The Mount Bonnie Formation, although extensive, is not as well exposed as other formations in the South Alligator Group. Outcrop is restricted to low rubbly rises, minor strike ridges or incised creek beds. Compared to the underlying Gerowie Tuff the unit has a dark photo-tone, lower relief, more open and taller vegetation cover, and a deeper skeletal soil.

Stratigraphic relations. The formation is conformable between the Gerowie Tuff and the Burrell Creek Formation and in places is faulted against them. The lower contact is the base of the lowermost feldspathic greywacke bed (Stuart-Smith & others, 1984b) and the upper contact is the top of the uppermost chemical, organic or tuffaceous sediment. However, the upper contact is mostly poorly exposed, commonly being obscured by Quaternary cover, and is most places is defined by photo interpretation.

Lithology. Thickness ranges from 500 to 700 m. Within the sequence of interbedded pelite, feldspathic greywacke, minor tuffaceous and dolomitic sediments, and rare banded iron formation, pelitic rocks predominate, consisting of laminated, grey, mauve, brown, and green *slate, mudstone, phyllite* and *siltstone*. They are, in places, pyritic, carbonaceous or dolomitic especially where interbedded with rare beds of *banded iron formation* up to 30 cm thick, the latter composed of alternating magnetite, hematite and pyrite laminae. Chert bands, lenses, and nodules are commonly associated with the banded iron formation, particularly between 100 and 200 m above the base. Within the granite contact aureole, the pelitic rocks are recrystallised to dark grey siliceous *muscovite-biotite-cordierite hornfels* and banded pink *muscovite-microcline-biotite-quartz-andalusite-cordierite hornfels.* Apart from minor laminae associated with the chert bands, carbonaceous sediments within the Mount Bonnie Formation can be distinguished from those in the Koolpin Formation by their lower carbon content (less than 2% compared to about 10% in Koolpin Formation rocks) and their paler grey colour (Goulevitch, 1980).

Deeply weathered and clayey massive fine to coarse (rarely pebbly) *feldspathic greywacke* comprises about 25% of the unit and forms interbeds up to 0.5 m thick within pelitic rocks. Together with these sediments, they form two distinct continuous horizons at the base of the formation, which can be traced over 5 km around the Margaret Syncline (Goulevitch, 1980). Overall the proportion of greywacke increases up sequence to about 50% in the overlying Burrell Creek Formation. Typically, the greywacke is graded, with poorly sorted angular grains of quartz, K-feldspar, plagioclase, microperthite, and volcanic rock fragments in a chloritic and sericitic matrix. The volcanic rock fragments are mostly tuffaceous chert and crystal tuff similar to interbeds in the sequence and the underlying Gerowie Tuff, and minor porphyritic rhyolite. Within the granitoid aureoles, the rocks are recrystallised and crop out as 'tombstone-like' boulders, commonly with epidote nodules several centimetres across, which are prominent on weathered surfaces.

Minor interbeds of laminated to thinly-bedded (less than 10 cm thick) green to black glassy *tuffaceous chert, vitric tuff,* spotted *crystal tuff, lithic crystal tuff,* and grey, brown, pink, pinkish-green, and pale-green *argillite* comprise the remainder of the formation and are common at the base, decreasing up the sequence. The tuffaceous chert, vitric tuff and crystal tuff, are identical to those in the Gerowie Tuff. Lithic crystal tuff, however, only occurs in the Mount Bonnie Formation in the Margaret Syncline, where it has been described as a 'pebble-breccia' by Goulevitch (1980). It occurs as lenses within tuff beds, and consists of rounded to subangular fragments up to 10 cm across of metamudstone, siltstone and tuffaceous chert in a matrix similar to the enclosing tuffs. J.N. Elliston (personal communication, in Goulevitch, 1980) interpreted a mudflow origin for the 'pebble-breccia' on the basis of the delicate fragment shapes, their well-bedded nature, and the presence of symmetrical graded-bedding.

Rare thin lenses of *dolomite* occur near the base of the formation in the McCarthy Hill–Moline area.

Remarks. The Mount Bonnie Formation represents a transition, during the waning stages of Gerowie Tuff volcanism, between the low-energy, shallow-water, reduced environment characteristic of the South Alligator Group, on the one hand, and the turbidite facies of the Finniss River Group, on the other.

Finniss River Group

Burrell Creek Formation (Ꝑfb)

Distribution. The Burrell Creek Formation is the only member of the Finniss River Group, and the youngest Early Proterozoic geosynclinal sedimentary unit. The formation crops out extensively throughout the area on lightly timbered rubble-strewn rises and low strike ridges, which are surrounded by prominent ridges up to 200 m high of hornfels adjacent to the granitoids. Mostly, however, it is present over large areas as subcrop beneath thin Cainozoic skeletal soils or flood-plain deposits. Within the contact aureole bedding trends are difficult to discern on aerial photographs and tree cover is more stunted. Elsewhere, bedding orientations are mostly difficult to determine owing to surficial slumping. However, excellent in situ outcrops are exposed in incised creeks and in numerous cuttings on the Stuart Highway and the abandoned North Australian Railway.

Most rocks within the unit are well cleaved and tightly folded about north to northwest-trending subhorizontal fold axes. Fold hinges are commonly outlined by low strike ridges, particularly where fold axes are steeper. The Pine Creek Shear Zone, about 2 km wide, parallels the northwest trend of the rocks and bisects them immediately east of Pine Creek township .

Stratigraphic relations. The formation conformably overlies or is faulted against the Mount Bonnie Formation and is unconformably overlain by the Early Proterozoic El Sherana Group and younger strata. In the north, Quaternary alluvial deposits of the McKinlay and Margaret River systems cover much of the formation. The unit is intruded and extensively contact-metamorphosed by the Cullen Batholith. It is also intruded by minor sills of Zamu Dolerite, post-orogenic felsite, minette, dolerite and porphyritic syenite dykes. Quartz veins and breccias, either cross-cutting or paralleling the regional northwest trend, are widespread.

Lithology. The formation consists of interbedded pelitic rocks, greywacke, volcanilithic pebble conglomerate, and rare lenses of highly altered felsic to intermediate volcanics. Owing to the lack of continuous exposure or suitable marker horizons, the thickness of the unit is difficult to determine. At least 1500 m can be measured in the Ringwood Range area, probably representing only the basal half of the formation.

Laminated to thinly-bedded, well cleaved, olive green to brown, grey, and red *slate, phyllite, siltstone* and *sandy*

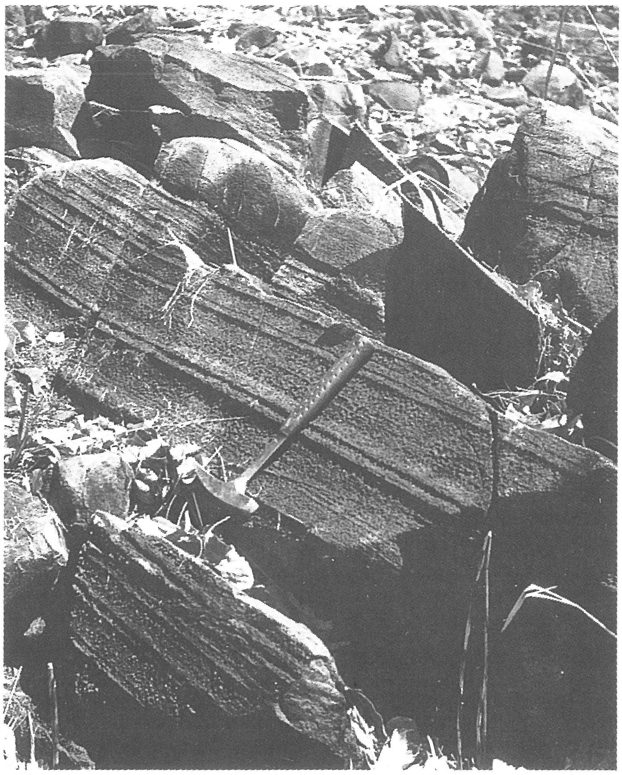


Fig 11. Typical banded quartz–andalusite–muscovite–biotite–cordierite hornfels, Burrell Creek Formation. Banding reflects original compositional differences in a laminated silty shale.

siltstone comprise between 50 and 75% of the formation. They rarely contain pyritic and carbonaceous laminae, and microlenticular cross-bedding and sole-markings are commonly present. Phyllite is mostly a product of shearing of the other pelitic sediments, commonly within fold hinges and the Pine Creek Shear Zone. Within the outer albite-epidote-hornfels facies they are green, and have recrystallised foliated or patchy chlorite and small round porphyroblasts of cordierite and andalusite that are invariably chloritised and sericitised. Near the granitoids, the rocks are totally recrystallised to massive banded dark-grey *quartz-andalusite-muscovite-biotite-cordierite hornfels* (Fig. 11). Their banded appearance is caused by mineralogical differences which reflect compositional variations of the original sediment.

Fine to coarse purple, green or brown *greywacke* occurs throughout the sequence as thin or massive graded beds up to 2 m thick and rarely up to 7 m thick. The beds are commonly pebbly and grade into volcanilithic pebble conglomerate in places. Like greywacke in the underlying Mount Bonnie Formation, 'tombstone-like' outcrops are common and form by a spheroidal weathering process, resulting in outcrops of residual upright elongate boulders of fresh dark grey greywacke surrounded by recessive deeply weathered clayey greywacke. The development of this outcrop style appears to be largely controlled by the presence of a steeply dipping intersection between bedding and cleavage planes. The greywacke is similar in composition to that in the Mount Bonnie Formation, consisting of poorly sorted angular grains of quartz, chert, and feldspar (K-feldspar, sodic plagioclase, microperthite), and lithic clasts of sericitic and chloritic rocks, altered pitchstone, rhyolite and shale in a finer-grained chloritic and sericitic matrix. Secondary epidote, chlorite, muscovite, biotite, and tourmaline are present in places. Adjacent to the granitoids, the original fragmental fabric is preserved, but the matrix is completely recrystallised to granoblastic quartz, biotite, muscovite and feldspar.

Minor discontinuous *volcanilithic pebble conglomerate lenses*, up to 1 m thick and 2 km long, occur within greywacke sequences. The conglomerate typically has a bimodal fabric with pebbles, which comprise up to 70% of the rock, of either angular to subrounded and poorly sorted lithic clasts up to 12 cm across; or rounded well sorted mostly quartz clasts up to 1 cm across, in a greywacke matrix. The pebbles in the first type are mostly volcanic: rhyolite, pitchstone, tuffaceous chert, crystal tuff and vitric tuff; and lesser massive dolomite, silicified dolomite, dolarenite, greywacke, fine arkose, argillite, shale, chert, jasper, quartz and rare muscovite-quartz schist.

Rare bodies of massive dark greenish-grey, medium-grained *altered felsic to intermediate volcanics* form a discontinuous horizon, up to 10 m thick, about 1000 m above the base east of the Margaret Granite (GL 9037, 8830, 8428, 8626 and 8623). Although similar in appearance to weathered greywacke, they consist mostly of carbonate, pale-green chlorite, and quartz. Highly altered plagioclase and K-feldspar laths and phenocrysts up to 1 mm (long) and minor chloritised biotite are commonly present. Quartz and trace amounts of apatite are interstitial to feldspar laths.

Highly altered volcanic rocks, possibly *trachy-andesite*, crop out 1 km south of the *Union Extended*[127] gold mine (HK 0093). The rocks are strongly porphyritic, with phenocrysts of tabular orthoclase up to 2 cm long, and fine-grained oligoclase and clinopyroxene. The phenocrysts, occurring in about equal proportions, are highly altered: feldspars are sericitised and carbonated; and clinopyroxene is mostly altered to chlorite, epidote or actinolite. The groundmass consists mostly of orthoclase crystals with minor interstitial quartz, apatite needles and patchy secondary chlorite, epidote and carbonate. Other probable volcanic rocks include porphyritic *rhyolite* and a dark-green *chloritised mafic rock*, which do not crop out but are found as rubble on the mullock heaps at the Union *Extended*[127] and *Elizabeth*[126] goldmines (GK 9889).

Rare thin beds of banded green *chlorite-magnetite ironstone* form a discontinuous horizon 1 km west of Mount Daniels (JE 9696). They appear to be about 200 to

500 m above the South Alligator Group, but may be part of the Mount Bonnie Formation, as the base of the Burrell Creek Formation is poorly defined owing to complex tight folding and limited exposure.

Remarks. The Burrell Creek Formation represents a turbidite sequence deposited in a subsiding basin in a deep-water, high-energy environment (Needham & others, 1988) following South Alligator Group sedimentation. Sedimentary structures, well expressed on shallow-dipping pavements exposed in creek beds, are inconsistent with the regionally westerly source previously proposed for the formation (Walpole & others, 1968; Johnson, 1974; and Stuart-Smith & others, 1980). Locally, a northerly-trending current direction is indicated by crescent-shaped flute casts 8 km southwest of Pine Creek township (HK 0264) and by ripple- and tool-marks near Stray Creek Gorge (GK 8763) and 9 km northwest of the township (HK 0177).

The composition of greywacke and conglomerate reflects a source area dominated by felsic volcanics, some of which are identical to older rocks within the Early Proterozoic geosynclinal sequence. The tuffaceous chert, crystal tuff, and vitric tuff pebbles are the same as rock types in the South Alligator Group, and the dolarenite pebbles are very similar to dolarenite in the Masson Formation. The pitchstone, an altered dark-brown glassy rock with crystallites up to 2 mm long, is very similar to variolitic andesite of the Shovel Billabong Andesite in MUNDOGIE (Stuart-Smith & others, 1984a).

As the Burrell Creek Formation, here and elsewhere in the Pine Creek Geosyncline, conformably overlies the South Alligator Group, the source area must have been beyond the presently exposed areas of the geosyncline (Stuart-Smith & others, 1987). A source area of high relief and little weathering is indicated by the greywacke compositions (Needham & others, 1988).

EARLY PROTEROZOIC SYN-OROGENIC FELSIC VOLCANIC STRATA

Two groups of Early Proterozoic volcanic rocks and associated sediments are recognised below the Middle Proterozoic Kombolgie Formation (Stuart-Smith & others, 1984a; Needham & Stuart-Smith, 1985a, b). Details of the two groups, the El Sherana and Edith River Groups, are summarised in Table 6.

El Sherana Group

Minor remnants of this group, unconformably overlying tightly folded Early Proterozoic geosynclinal metasediments, occur in the east and south. They form a discontinuous horizon at the base of the Mount Callanan Basin, a small unnamed basin truncated by the northern portion of the Wolfram Hill Granite, and a folded belt west of the Edith Falls Basin. Of the five formations in the Group (Needham & Stuart-Smith, 1985b), only portions of the *Coronation Sandstone, Pul Pul Rhyolite, Big Sunday* and *Tollis Formations* are present. The latter two units are probably correlatives, representing the remnants of a once widespread deposit of interbedded volcanics and volcaniclastic flyschoid sediments in the Katherine–El Sherana area at the close of El Sherana Group deposition (Needham & Stuart-Smith, 1985b).

The age of the El Sherana Group is constrained to about 1870 Ma, as it post-dates the Nimbuwah Event at about 1870 Ma and pre-dates the Edith River Group which formed between 1870 and 1860 Ma (Needham & others, 1988). Preliminary U-Pb zircon data from an andesitic ignimbrite in the Tollis Formation indicates an inherited component, with most zircon grains giving a crystallisation age between 1900 and 1870 Ma (Needham & others, 1988).

Coronation Sandstone (Ᵽbc)

A poorly exposed lens of weathered, white *pebbly coarse-grained quartz sandstone* about 100 m thick and 1.5 km long, crops out 4 km northeast of Gertrude Springs (KE 1798). The sandstone forms a low westerly trending bouldery ridge surrounded by scree and separates rubbly outcrops of Mount Bonnie Formation to the north from weathered volcanics (Pul Pul Rhyolite?) beneath the Kurrundie Sandstone to the south. The attitude of the sandstone lens and its relationships with the surrounding units are not clear. However, its stratigraphic position beneath the Kurrundie Sandstone, and its lithological character indicate that it is probably Coronation Sandstone. Farther to the east in the South Alligator Valley the Coronation Sandstone comprises a valley-fill sequence of sandstone and volcanics, which forms the basal part of the El Sherana Group (Needham & Stuart-Smith, 1985b).

Pul Pul Rhyolite (Ᵽbp)

The Pul Pul Rhyolite forms a semi-continuous horizon around the base of the Mount Callanan Basin. The formation comprises up to 200 m of *massive pale-grey to pink siliceous ignimbrite*, consisting of eutaxitic devitrified glass shards with scattered quartz fragments and layered drusy cavities filled with carbonate and quartz. The ignimbrite rests unconformably on metasediments of the Namoona and Mount Partridge Groups. The contact is well exposed at KF 1602, where subhorizontal massive ignimbrite, underlain by a 0.5 m thick breccia composed of phyllite fragments, rests on steeply dipping silty phyllite of the Masson Formation.

The formation is mostly disconformably overlain by the Kurrundie Sandstone, but the contact is generally obscured by extensive talus deposits shed from the cliff-forming sandstone. Locally, north and immediately south of the El

TABLE 6. SUMMARY OF EARLY PROTEROZOIC SYN–OROGENIC FELSIC VOLCANIC STRATIGRAPHY

Unit (map symbol)	*Distribution*	*Lithology*	*Field relations*	*Thickness (m)*	*Depositional environment*	*Remarks*
EDITH RIVER GROUP						
Plum Tree Creek Volcanics (Pep)	Bouldery hills and ridges at base of Edith Falls and Mount Callanan Basins in E.	Massive rhyodacitic ignimbrite, massive glassy pink rhyolite, flow-banded ignimbrite, thinly bedded felsic tuff, banded siliceous tuff, and crystal tuff (>50%); altered amygdaloidal mafic flows; minor pebbly to coarse-grained lithic quartz sandstone, micaceous sandy siltstone, laminated fine-grained quartz sandstone and tuffaceous siltstone.	Conformably overlies Pek and Pel. Unconformably overlies Early Proterozoic geosynclinal strata. Disconformably overlain by Phk. Intruded by Pgc.	<1300	Subaerial, fluviatile.	Extensive ignimbrite sheets interbedded with fluvial clastics deposited in active half grabens (Needham & Stuart-Smith, 1985a, b; Needham & others, 1988)
Phillips Creek Sandstone (Pel)	Strike ridges along western flank of the Edith Falls Basin in E and isolated outcrop in S.	Labile and tuffaceous, poorly sorted sandstone, purple medium-grained arkose and conglomerate; minor siltstone, phyllite and breccia conglomerate.	Unconformably overlies Pbt. Conformably overlain by Pep. Intruded by Pgc.	<280	Fluviatile	Fan deposits (Needham & Stuart-Smith, 1985b)
Kurrundie Sandstone (Pek)	Rocky ridges along flanks of the Mount Callanan Basin in E.	Thickly bedded to massive, purple to pinkish brown, very coarse-grained to pebbly, lithic quartz sandstone; basal massive polymictic boulder conglomerate; rare brown shale and micaceous siltstone.	Unconformably overlies Pnm, Psk, Pbc, Pbp and Pbb. Conformably overlain by Pep.	<150	Fluviatile.	Coalesced fan deposits. Lenticular and tabular cross-bedding indicates current flow to NW (Needham & Stuart-Smith, 1985b).
EL SHERANA GROUP						
Tollis Formation (Pbt)	Rocky hills and rises in S.	Interbedded fine- to coarse-grained and pebbly volcanilithic greywacke, laminated green or grey siltstone, phyllite, slate, argillite, vitric tuff, crystal vitric tuff and andesitic ignimbrite.	Unconformably overlies Pfb and underlies Pel,Cla and Clj. Intruded by Pgc.	<2200	Deep-water.	Flyschoid sequence derived from volcanic-rich, juvenile and nearby provenance (Needham & others, 1988).
Big Sunday Formation (Pbb)	Minor outcrops along flank of the Mount Callanan Basin in E.	Altered amygdaloidal mafic volcanics; minor tuff, laminated to thinly bedded dark brownish purple ferruginous siltstone, and fine-grained graded feldspathic greywacke.	Conformably overlies Pbp. Unconformably overlies Pnm and underlies Pek and K.	<150	Deep-water.	Flyschoid and volcanic deposits (Needham & Stuart-Smith, 1985b).
Pul Pul Rhyolite (Pbp)	Semi-continuous pavements around the base of the Mount Callanan Basin in the E.	Massive pale-grey to pink siliceous ignimbrite.	Unconformably overlies Pnm, Ppm and Ppw, and underlies Pek and K. Conformably overlain by Pbb.	<200	Subaerial.	Extensive ignimbrite sheets (Needham & Stuart-Smith, 1985b).
Coronation Sandstone (Pbc)	Minor outcrops at base of the Mount Callanan Basin in E.	Pebbly coarse-grained quartz sandstone Overlain by Pek.	.?Unconformably overlies Pso.	<100	Fluviatile.	Valley-fill deposits, elsewhere intercalated with felsic and mafic volcanics (Needham) Stuart-Smith, 1985b).

Sherana road, the Pul Pul Rhyolite is conformably overlain by the Big Sunday Formation. In the same area, it is unconformably overlain by flat-lying Cretaceous sediments forming part of an extensive tableland farther to the west.

Big Sunday Formation (Ᵽbb)

The Big Sunday Formation is represented by a thin lens of interbedded *altered amygdaloidal mafic volcanics,* and minor *tuff, laminated to thinly bedded dark brownish-purple ferruginous siltstone,* and *fine-grained graded feldspathic greywacke.* The formation crops out along the southwestern limb of the Motor Car Creek Syncline in the Mount Callanan Basin. The sequence, up to 150 m thick, conformably overlies the Pul Pul Rhyolite and in the northwest overlaps it to rest unconformably on the Masson Formation. Both lower contacts are covered by thin residual soils or Quaternary alluvium. The unit is deeply weathered and hematised, and is disconformably overlain by the Kurrundie Sandstone and Cretaceous sediments. Mafic volcanics comprise over 90% of the sequence and are typically slightly porphyritic with common quartz, chlorite and carbonate-filled amygdales. Phenocrysts, where present, are mainly crystals or aggregates of carbonated or kaolinised plagioclase with euhedral colourless clinopyroxene or tabular K-feldspar. The groundmass is subtrachytic, mostly of secondary chlorite, carbonate and iron oxides with fine granular chloritised pyroxene, altered plagioclase and K-feldspar.

Tollis Formation (Ᵽbt)

Distribution. The Tollis Formation (Needham & Stuart-Smith, 1985b) crops out in the south, in a small basin truncated by the northern portion of the Wolfram Hill Granite, and in a folded belt west of the Edith Falls Basin.

Stratigraphic relations. The formation is separated from the underlying Burrell Creek Formation by a structural and metamorphic discontinuity, here interpreted as an unconformity. As the basal part of the Tollis Formation is devoid of distinctive volcanic rock types, and is similar lithologically to the Burrell Creek Formation, the boundary between the two formations is, in places, difficult to locate. Recent work has indicated that most of the rocks shown on the accompanying 1:250 000 map as Tollis Formation north and west of Mount Todd are in fact Burrell Creek Formation (K.A.A. Hein, University of Tasmania, personal communication, 1990). However, markedly different fold styles (refolded isoclinal folding in the older rocks, simple upright folding in the Tollis Formation), clearly indicate that these two similar packages of rocks differ in age. The different fold styles also enable approximate demarcation of the boundary by photo-interpretation. Also rocks of the Burrell Creek Formation are of slightly higher metamorphic grade (i.e. low greenschist facies), commonly phyllitic, and in places the cleavage is folded about the same northerly axes defined by folds in the Tollis Formation. The Tollis Formation is contact-metamorphosed by the Cullen Batholith, and unconformably overlain by the Edith River Group and lower Cambrian sediments of the Daly River Basin.

Lithology. The Tollis Formation consists of 2200 m of interbedded greywacke, siltstone, slate, phyllite, argillite, tuff and minor altered mafic to intermediate volcanics. In the south, west of the Edith Falls Basin, the formation can be divided into a lower greywacke-dominant sequence about 900 m thick; a middle argillite and tuff-dominant sequence about 700 m thick; and an upper sequence with roughly equal amounts of phyllite, argillite, greywacke and tuff about 500 m thick. The greywacke-dominant sequence contains an andesite flow about 80 m thick and 13 km long near Edith Falls.

Coarse to fine-grained, and less common gritty or pebbly, *volcanilithic greywacke* is the predominant rock type and forms massive, commonly graded, beds up to 1 m thick. It consists of poorly sorted angular to subrounded clasts of felsic volcanics (pitchstone, rhyolite, and minor vitric tuff), sericitised feldspar, minor quartz (<20%), and secondary chlorite, sericite, epidote, carbonate and iron oxides. Detrital muscovite and zircon are rarely present.

Laminated, green and grey *siltstone, phyllite, slate,* and *argillite* form thin interbeds in greywacke and tuff and consist of foliated sericite, chlorite, and minor quartz and secondary iron oxides. Rare angular crystal fragments of quartz and alkali feldspar may reflect the volcanic-rich nature of the sequence.

Massive, laminated, greyish-green, altered and devitrified *vitric tuff* and *crystal vitric tuff* have a spotted cherty appearance and are common throughout the middle and upper parts of the formation. They consist of varying amounts of recrystallised epidote, chlorite, quartz, carbonate, sericite and iron oxides. Curved devitrified glass shards, and a eutaxitic fabric are commonly preserved. Minor scattered angular crystal fragments of quartz, carbonated feldspar, and chloritised mafic minerals, and felsic volcanic rock fragments (rhyolite, pitchstone) may be present.

Edith River Group

The Edith River Group crops out as a continuous belt of bouldery hills and ridges around the base of the Mount Callanan and Edith Falls Basins, where it unconformably overlies the Namoona, South Alligator, Finniss River, and El Sherana Groups with pronounced angularity. Around the Mount Callanan Basin, the contact with the El Sherana Group is mostly disconformable. The group is also thrown against the South Alligator, Namoona and Katherine River

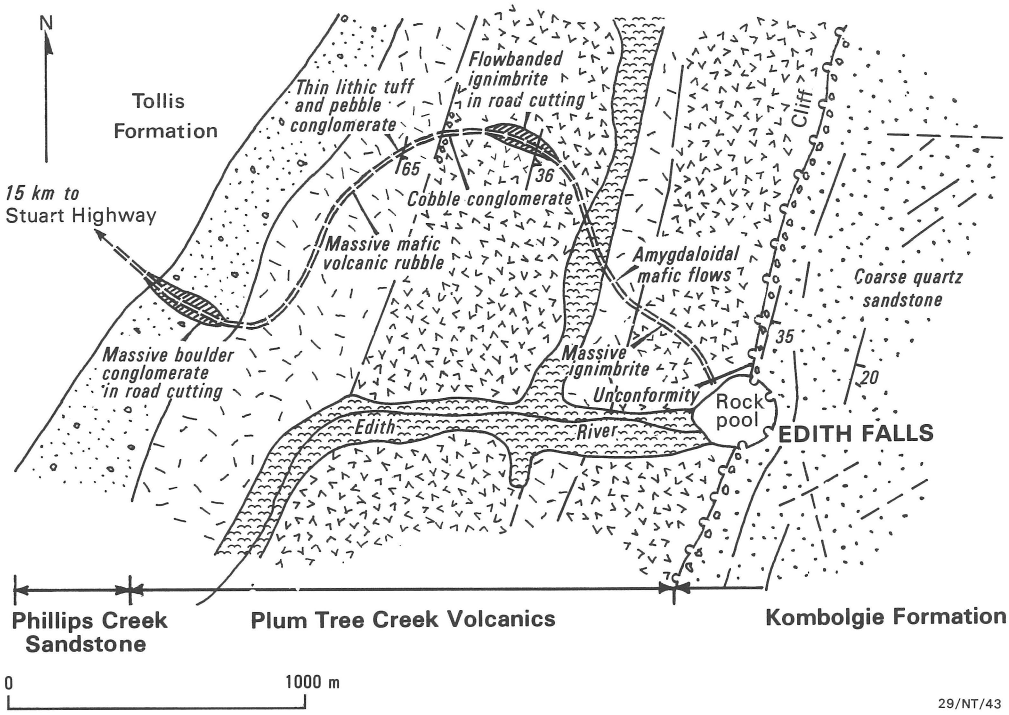


Fig. 12. Section through the Edith River Group at Edith Falls.

Groups by the Mary Fault. Throughout the area, the group is disconformably overlain by the Katherine River Group and in places unconformably by flat-lying Cretaceous sediments. The group is represented by the basal *Kurrundie* and *Phillips Creek Sandstones* and the *Plum Tree Creek Volcanics.*

Total rock ages of ~1750 Ma for the 'Edith River Volcanics' (Compston & Ariens, 1968; Walpole & others, 1968) represent minimum ages. Several rhyodacitic rocks from the comagmatic Plum Tree Creek Volcanics and Grace Creek Granite (east of the Cullen Mineral Field) have igneous crystallisation ages of about 1830 Ma (unpublished data).

A representative section through the group, at the base of the Mount Callanan Basin near Edith Falls, is given in Figure 12.

Kurrundie Sandstone (Ꝑek)

The Kurrundie Sandstone forms the base of the Edith River Group in the Mount Callanan Basin, cropping out as continuous bare rock pavements and rocky strike ridges flanked in places by cliffs up to 100 m high with extensive talus aprons. The unit ranges in thickness from over 150 m in the east, to less than 100 m around the Gertrude Springs Syncline where it eventually pinches out 8 km north-northwest and 6 km southeast of Tent Hill.

The unit consists predominantly of *thickly bedded to massive purplish or pinkish brown, very coarse-grained to pebbly, lithic quartz sandstone.* Grains and pebbles are poorly sorted sub- to well-rounded quartz, chert, tuffaceous chert, ignimbrite, kaolinised feldspar, quartz-tourmaline, and rare foliated arkose. The matrix is clayey and impregnated with iron oxides. Pebble trails are common, and lenticular and tabular cross-beds are present, particularly in the northeast where they indicate a northwesterly current direction.

Massive polymictic boulder conglomerate up to 50 m thick is common at the base. Clasts are sub- to well-rounded, poorly sorted pebbles, cobbles and boulders of brown lithic quartz sandstone, quartz, pink and brown chert, ferruginous quartz sandstone, slate, phyllite, ironstone, and altered felsic volcanics. The felsic volcanic clasts which include ignimbrite, rhyolite, pitchstone, and tuff, predominate in the Motor Car Creek Syncline but are rare in the Gertrude Springs Syncline. They are similar to, and were probably derived from, volcanic rocks in the underlying El Sherana Group.

Rare *brown shale* and *micaceous siltstone* are interbedded with lithic quartz sandstone at the northwestern end of the Gertrude Springs Syncline where the unit pinches out.

Phillips Creek Sandstone (Ꝑel)

The Phillips Creek Sandstone, conformably overlain by the Plum Tree Creek Volcanics, rests with marked angular unconformity on the Tollis Formation in the south. It crops out as a continuous northeast-trending ridge 17 km long on the western margin of the Edith Falls Basin, pinching out northwards, and dipping about 35° to the east-southeast. The southern extent of the unit is terminated by the Phillips Creek Fault and the unconformably overlying Antrim Plateau Volcanics.

The formation consists of up to 280 m of interbedded *labile and tuffaceous poorly sorted sandstone, purple medium-grained arkose, conglomerate,* and minor *siltstone* and *phyllite.*

A small outcrop of *breccia-conglomerate* 6 km west of the Fergusson River Siding is correlated with the Phillips Creek Sandstone. The breccia-conglomerate, composed of blocks of the underlying Burrell Creek Formation metasediments, forms a valley-fill deposit beneath the Plum Tree Creek Volcanics.

Plum Tree Creek Volcanics (Ᵽep)

The Plum Tree Creek Volcanics form the bulk of the Edith River Group and consist of a mixed assemblage, ranging from 400 to 600 m thick in the Mount Callanan Basin up to 1300 m in the Edith Falls Basin, of felsic volcanics, and minor mafic volcanics and clastic sediments. The volcanics conformably overlie the Kurrundie and Phillips Creek Sandstones where present, and elsewhere unconformably overlie Early Proterozoic metasediments. A prominent northwest-trending Fault, the Mary Fault, transects the western margin of the Mount Callanan Basin and throws the volcanics against the metasediments and the disconformably overlying Kombolgie Formation. Outliers of the volcanics west of the Fergusson River Siding unconformably overlie Early Proterozoic metasediments and are intruded by the Tennysons Leucogranite.

Felsic volcanics comprise over 50% of the formation and consist predominantly of *massive rhyodacitic ignimbrite* and lesser *massive glassy pink rhyolite, flow-banded ignimbrite* and minor *crystal tuff.* The rhyodacitic ignimbrite is commonly columnar jointed, rarely flow-banded, and is typically a massive glassy pink porphyritic rock with corroded phenocrysts of andesine, minor microcline, quartz and chloritised hornblende in a brown fluidal microcrystalline groundmass of quartz, alkali feldspar, chlorite and accessory apatite, zircon, sphene and biotite. In outcrop, it commonly has a pitted surface caused by the preferential weathering of the feldspar phenocrysts. Where disconformably overlain by the Kombolgie Formation, it is altered to a mottled purple, brown and green kaolin-hematite-quartz rock, a product of Middle Proterozoic weathering prior to deposition of the Kombolgie Formation (Miller & others, 1992).

Interlayered *mafic flows* with minor *thinly bedded felsic tuff, banded siliceous tuff, fine crystal tuff, lithic tuff, ignimbrite, rhyolite* and *quartz sandstone* are common in the middle of the unit in the Mount Callanan Basin and at the base of the unit in the Edith Falls Basin. The mafic rocks are poorly exposed as rubble, and are deeply weathered and mostly covered by dark reddish-brown skeletal soils. They are highly altered dark-green to greyish-purple massive rocks with rare kaolinised euhedral plagioclase phenocrysts. The rocks mostly consist of secondary hematite, chlorite and epidote with minor primary subidiomorphic andesine laths, augite, and rare interstitial quartz and alkali feldspar are preserved. Rounded to irregular amygdales, up to 1 cm across, filled with calcite, chlorite and quartz, are common.

Minor clastic interbeds of *pebbly to coarse lithic quartz sandstone, micaceous sandy siltstone, laminated fine quartz sandstone,* and *tuffaceous siltstone* are common particularly near the base of the formation.

MIDDLE PROTEROZOIC PLATFORM COVER

Katherine River Group

The Katherine River Group once formed an extensive sheet of sediments and volcanics, resting with marked regional unconformity on Early Proterozoic rocks. Outcrops of the *Kombolgie Formation*, the only formation of the group present, are confined to the Mount Callanan and Edith Falls Basins, and minor northeasterly aligned outliers near Mount Douglas in the north. The stratigraphy of the formation, together with other Middle Proterozoic, Palaeozoic, Mesozoic and Cainozoic platform cover, is summarised in Table 7.

Kombolgie Formation (Ᵽhk)

Distribution. In the north, outliers of Kombolgie Formation sandstone form a 30 km long discontinuous line of prominent ragged rocky hills and tablelands, the largest of which is Mount Douglas. The deeply dissected hills rise up to 200 m above the level of the McKinlay River floodplain, and are covered by stunted trees and scrub. A broad apron of scree and sand surrounds the outliers, particularly along the northern flank of the Mount Douglas outlier. In the east and southeast of the Cullen Mineral Field, the Kombolgie Formation forms a flat-lying deeply dissected plateau bounded by cliffs commonly over 100 m high.

Stratigraphic relations. The Kombolgie Formation disconformably overlies the Plum Tree Creek Volcanics in the Mount Callanan and Edith Falls Basins, and elsewhere unconformably overlies Early Proterozoic metasediments. Along the southern margins of the Mount Callanan Basin and Mount Douglas outlier, it is down-faulted against the metasediments. The Kombolgie Formation is in many areas unconformably overlain by

TABLE 7. SUMMARY OF MIDDLE PROTEROZOIC AND YOUNGER PLATFORM COVER STRATIGRAPHY

Unit (map symbol)	*Distribution*	*Lithology*	*Field relations*	*Thickness (m)*	*Depositional environment*	*Remarks*
CAINOZOIC QUATERNARY						
(Qa)	Along major river systems, particularly in N.	Silt, sand, gravel, clay; black and brown humic soil and clay.	Veneer over older units.	<5	Fluviatile.	Alluvium, outwash and colluvial deposits; minor levee and marsh deposits.
TERTIARY TO QUATERNARY						
(Cz)	Widespread, particulary in lowlands in N.	Sandy to gravelly skeletal soils, gradational red soils and yellow earth soils.	Veneer over Mesozoic and older units.	<2	Continental.	In-situ weathering products.
(Czt)	Flanks tablelands in W.	Coarse sand; granite, metasediment, volcanic, sandstone and quartzite rubble.	Flanks scarps of resistant Mesozoic, Middle and Early Proterozoic rocks.	<10	Continental.	Talus deposits.
(Czg)	Low-lying areas in far N.	Unconsolidated pebble gravels and gravelly skeletal soils.	Remnant aprons flanking steep ridges of Early Proterozoic rocks.	<3	Continental	Older colluvial deposits.
(Czs)	Widespread, particularly over tablelands in SE.	Coarse-grained unconsolidated quartz sand and ferruginous clayey sand.	Veneer on ironstone and older formations.	<10	Continental.	Fan deposits.
(Czl)	Widespread on lowlands and tablelands.	Detrital, pisolitic, and concretionary ironstone.	Flat-lying cappings on older rocks	<3	Continental.	In-situ and reworked remnants of laterite profile.
MESOZOIC						
(K)	Tablelands in E and W.	Massive friable, white fine- to coarse-grained quartz sandstone; yellow to reddish brown quartz sandstone; limonitic and goethitic pebbly quartz sandstone, conglomerate, and breccia at base; minor micaceous siltstone.	Flat-lying veneer unconformable on older formations.	<80	Epicontinental.	Skwarko (1966), Hughes (1978).
CAMBRIAN TO ORDOVICIAN DALY RIVER GROUP						
Jinduckin Formation (€Olj)	Low outcrops along margin of Daly River Basin in SW and S.	Calcareous quartz sandstone, sandy limestone, siltstone and marl; minor fine to coarsely crystalline limestone, oolitic limestone, stromatolitic limestone and fine- to medium grained quartz sandstone.	Conformably overlies €mt.	950	Shallow-marine, probably intertidal.	Forms part of the Daly River basinal sequence (Malone, 1962). Fossiliferous (Öpik, 1968; Jones, 1971).
Tindall Limestone (€mt)	Pavements and craggy outcrops around sink-holes and pavements along margin of Daly River Basin in SW and S.	Laminated to massive crystalline limestone with chert bands and nodules in places.	Unconformably overlies €lj and Early Proterozoic granitoids and metasediments.	<150	Shallow-marine.	Forms part of the Daly River Basin. fossiliferous (Öpik, 1956, Kruse, 1984).

Unit (map symbol)	*Distribution*	*Lithology*	*Field relations*	*Thickness (m)*	*Depositional environment*	*Remarks*
CAMBRIAN						
Jindare Formation (Ꞓlj)	Craggy to rubbly low hills along margin of Daly River Basin in SW and S.	Purple, orange-brown fine- to coarse-grained pebbly quartzite, purplish-brown micaceous siltstone and silty shale, laminated to thinly bedded fine- to medium grained white quartz sandstone; minor basal pebbly arkose, limonitic silicified carbonate breccia, laminated silicified carbonate and silty to sandy porcellanite.	Unconformably overlies Pts and Early Proterozoic metasediments and granitoids. Conformably overlies and interfingers with Ꞓla. Unconformably overlain by Ꞓmt.	200	Continental to shallow-marine.	Forms base of the Daly River Basin. Deposition contemporaneous with mafic volcanism (Ꞓla).
Antrim Plateau Volcanics (Ꞓla)	Deeply weathered exposures in far S.	Purple to black vesicular basalt; minor red ferruginous medium- to coarse-grained sandstone interbeds near base in places, local basal breccia, well-sorted quartz sandstone at top.	Unconformably overlies Pbt, and Pep. Interfingers with and overlain by Ꞓlj.	40	Continental.	Valley-fill deposits of tholeiitic basalt flows and fluviatile clastics.
MIDDLE PROTEROZOIC						
TOLMER GROUP						
Stray Creek Sandstone (Pts)	Tablelands and ridges in W bordering Daly River Basin to west.	Laminated to thinly bedded very fine-grained brown quartzite, limonitic micaceous siltstone, shale, micaceous sandy siltstone; minor fine white quartzite, pisolitic dolomite and brown dolomitic siltstone.	Conformably overlies Ptd. Unconformably overlain by Ꞓlj.	450	Shallow-marine.	Rain prints and dessication cracks (Hossfeld, 1937; Noakes, 1949). *Battenella* (Öpik, 1956).
Depot Creek Sandstone (Ptd)	Tablelands and ridges in W bordering Daly River Basin to west.	Laminated to thickly bedded pink to brown medium to coarse-grained quartz sandstone; minor white coarse to pebbly quartz sandstone and pink quartzite.	Overlian disconformably by Ꞓlj. and conformably by Pts. Unconformably overlies Early Proterozoic rocks.	450	Continental to shallow-marine (Walpole & others, 1968).	
KATHERINE RIVER GROUP						
Kombolgie Formation						
(Phk2)	Tablelands in SE. (Edith Falls Basin).	Massive buff medium- to coarse-grained pebbly quartz sandstone; minor brown ferruginous siltstone.		<375	Continental.	Braided alluvial fan sand deposits intercalated with basalt.
Henwood Creek Volcanic Member (Phh)	Tablelands in SE. (Edith Falls Basin).	Deeply weathered grey massive to amygdaloidal mafic volcanics.		120		
McAddens Creek Volcanic Member (Phm)	Tablelands in SE. (Edith Falls Basin).	Dark-grey massive to amygdaloidal mafic volcanics.	Comprises a conformable sequence, itself unconformable on Early Proterozoic rocks. Unconformably overlain by Mesozoic and Cainozoic sediments.	250		
(Phk1)	Tablelands in E, SE and N. (Edith Falls Basin, Mount Callanan Basin, Mount Douglas outlier).	Massive clayey white to buff poorly sorted coarse- to very coarse-grained pebbly quartz sandstone; massive polymictic boulder conglomerate at base; minor purple quartz sandstone, lithic greywacke and marlstone		<1100		

Fig. 13. Unconformity between basal conglomerate of the Middle Proterozoic Kombolgie Formation and underlying weathered Early Proterozoic Plum Tree Creek Volcanics, near Edith Falls. Note small reverse fault in centre.

flat-lying Mesozoic sediments and a thin veneer of Cainozoic unconsolidated sand and laterite.

Lithology. A near complete sequence of the Kombolgie Formation, about 2000 m thick, is preserved in the Edith Falls Basin. About 1000 m of sandstone (Phk_1) forms the base of the unit, below the 250 m-thick *McAddens Creek Volcanic Member* (Phm), which in turn is overlain by 200 m of sandstone (Phk_2), 120 m of the *Henwood Creek Volcanic Member* (Phh), and then about 175 m of Phk_2 sandstone. The top of the formation is not preserved. North of the Edith Falls Basin, only the lower part of the sequence is preserved and thicknesses are reduced. About 1000 m of the lower unit (Phk_1) is present in the Mount Douglas outlier and the Mount Callanan Basin.

In all areas, the dominant lithology is *massive, clayey white to buff, poorly sorted, coarse to very coarse and pebbly quartz sandstone,* which occurs as jointed beds 1 to 2 m thick. Ripple marks and lenticular and tabular cross-beds are common; limited current measurements on the western margin of the Mount Callanan Basin indicate two prominent directions (110^o and 200^o). Scattered well-rounded quartz pebbles, up to 4 cm across, commonly form thin lenses or pebble trains. *Massive polymictic boulder conglomerate,* up to 20 m thick at the base of the unit, contains well rounded pebbles, cobbles and boulders up to 40 cm across, of vein quartz, pink and white quartzite, hematitic quartzite, argillite, ignimbrite, tuff, chert, agate, and ferruginous pink and purple shale and siltstone in a mauve to dark-brown clayey, hematitic, very coarse quartz sandstone matrix. At Mount Douglas, minor *medium-grained purple quartz sandstone,* and *dark purplish-brown lithic greywacke* and *marlstone* are also interbedded with basal conglomerate. The composition of clasts and the matrix of the lithic greywacke is similar to the conglomerate, but the former also has clasts of sericitised feldspar, altered volcanic rock, and muscovite schist. Many of the clasts are similar to, and were probably derived from, rocks in the underlying Edith River and El Sherana Groups (Fig. 13).

Both volcanic members are poorly exposed and consist of deeply weathered grey, massive to amygdaloidal mafic volcanic flows.

Remarks. The Kombolgie Formation was deposited as a braided alluvial fan sourced from a northwest provenance (Ojakangas, 1979) onto a stable, planated basement.

Tolmer Group

The Tolmer Group includes the *Depot Creek and Stray Creek Sandstones* (Table 7). The group forms a continuous tableland and ridge belt of gently southwest-dipping sandstone and minor siltstone about 5 km wide in the west and southwest. This belt separates Early Proterozoic geosynclinal strata in the east from Cambrian-Ordovician sedimentary rocks of the Daly River Basin to the southwest. The tableland is well jointed and in several places, along the Depot and Stray Creeks and the Douglas River, is cut by gorges up to 100 m deep. Much of the western margin of the tableland is a fault scarp up to 60 m high.

Depot Creek Sandstone (Ꝑtd)

Stratigraphic relations. The Depot Creek Sandstone unconformably overlies, with high angularity, deformed metasediments of the Burrell Creek Formation. At Stray Creek Gorge 20 km west-southwest of Pine Creek township, Walpole & others (1968) described the basal beds filling small gaps and fissures in the underlying rocks. Most of the sandstone unconformably overlies or is faulted against deeply weathered granitoids of the Cullen Batholith. Where exhumed along the eastern margin of the tablelands, the unconformity surface forms a southwesterly-dipping platform towards the top of the slope. However, the surface is mostly obscured by scree or by flat-lying Mesozoic and Cainozoic sediments.

Lithology. The unit forms a 450 m-thick sequence of mostly *pink to brown, laminated to thickly bedded, medium to coarse-grained quartz sandstone* commonly with minor well-rounded quartz pebbles. In places minor, *white, coarse-grained, poorly sorted pebbly quartz sandstone,* silicified to a *pink quartzite* at the surface, is present at the top of the unit, cropping out as a prominent platform (Fig. 14). Clasts up to 15 cm in diameter of quartz, quartzite and sandstone may also be present at the base. Cross-bedding, asymmetrical, symmetrical, and interference ripple marks indicate a southerly current direction ranging between 120° to 200°. North-south current directions are also indicated by less common tool marks and flute casts.

Stray Creek Sandstone (Ꝑts)

Stratigraphic relations. The Stray Creek Sandstone conformably overlies the Depot Creek Sandstone and is either disconformably overlain or faulted against the Jindare Formation.

Lithology. North of Douglas River, where the most complete section is present, the unit is 450 m thick, consisting of interbedded *laminated to thinly bedded, very fine-grained brown quartzite, shale, limonitic micaceous siltstone, micaceous sandy siltstone* and minor *fine white quartzite.* Minor recrystallised, possibly algal, *pisolitic dolomite,* commonly weathered to *chalcedonic limonitic ironstone* at the surface and *brown dolomitic siltstone,* form a continuous horizon about 25 m thick, 340 m above the base of the unit. The dolomitic rocks are poorly exposed and mostly covered by thick reddish-brown residual soils and dense vegetation. Differential weathering of the thinly bedded sequence has produced low cuesta-like ridges flanking the sandstone tableland. The beds are continuous, except where faulted out, and one prominent marker, a purple micaceous sandy siltstone about 10 m thick and 100 m above the base, can be traced from near Hayes Creek in the west to Edna Creek in the southwest.

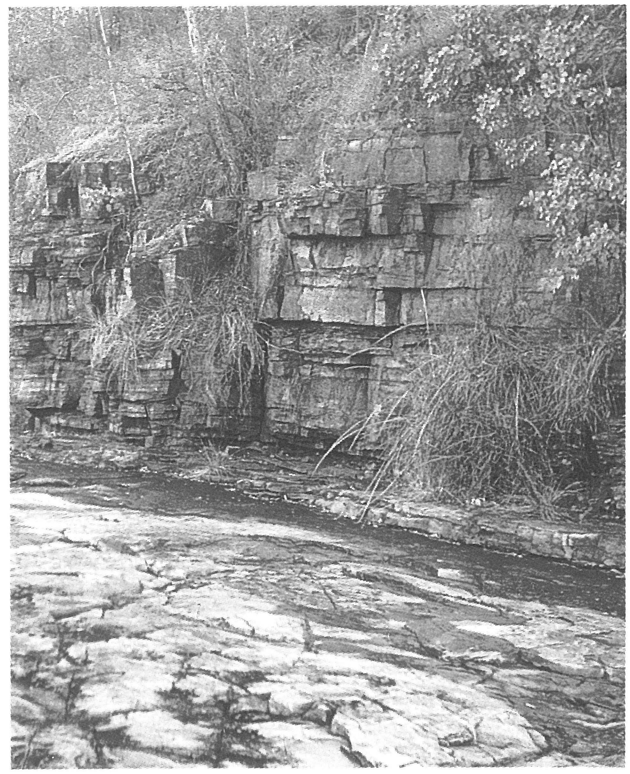


Fig. 14. The contact between the more thinly bedded Stray Creek Sandstone and the underlying thickly bedded Depot Creek Sandstone is commonly expressed as a prominent platform.

Cross-bedding and ripple marks are common and indicate a variable but dominantly southerly current flow, consistent with north-south oriented tool marks. The direction is more variable than in the underlying Depot Creek Sandstone.

Remarks. A shallow-water origin is indicated in several places outside the area by rain prints and desiccation cracks (Hossfeld, 1937; Noakes, 1949). Evidence of marine jellyfish, identified by Öpik (1956) as *Battenella,* and described in several areas outside the area by Noakes (1956), Walpole & others (1968) and Sweet & others (1974), has not been recorded.

CAMBRIAN TO ORDOVICIAN COVER

Lower Palaeozoic tholeiitic basalt flows, carbonate and clastic sediments form the Daly River Basin sequence which conceals the Proterozoic rocks of the Cullen Mineral Field in the south and southwest of the region. The stratigraphy of the basin is summarised in Table 7.

Antrim Plateau Volcanics (∈la)

The lower Cambrian Antrim Plateau Volcanics (Walpole & others, 1968) form a discontinuous base to the Daly River Basin sequence, resting with marked unconformity on the El Sherana and Edith River Groups. The volcanics comprise a 40 m-thick valley-fill sequence of tholeiitic basalt flows intercalated with minor sandstone. A *basal breccia*, with clasts of the underlying lithologies in a sandy matrix, and up to 7 m thick, is locally present. The *basalt* is typically purple to black, deeply weathered and vesicular in places. Minor *red ferruginous medium to coarse-grained sandstone* interbeds, common near the base of the volcanics, are laterally equivalent to the ferruginous, arkosic and cherty lower section of the Jindare Formation. An upper, well-sorted *quartz sandstone*, locally present, rests conformably on top of the basalt flows, dipping regionally about 2° to the south and intertonguing with carbonate rocks of the Jindare Formation.

Jindare Formation (∈lj)

Distribution. Craggy to rubbly low hills of sandstone and silicified carbonate sediments along the northeastern margin of the Daly River Basin comprise the Cambrian Jindare Formation (Stuart-Smith & others, 1987).

Stratigraphic relations. West-northwest of Pine Creek township, the unit is about 200 m thick and forms a gently dipping sequence (less than 12°) which disconformably overlies the Stray Creek Sandstone. Farther south, the unit is either faulted against or unconformably overlies the Stray Creek Sandstone, with dips up to 24° adjacent to some faults. In the far south, the formation overlies and interfingers with the lower Cambrian Antrim Plateau Volcanics, and unconformably overlies Early Proterozoic granitoids and volcanics. The formation in turn is unconformably overlain by or faulted against the Tindall Limestone to the west.

Lithology. The formation consists mostly of interbedded *purple or orange-brown fine to coarse-grained pebbly quartzite, purplish-brown micaceous siltstone* and *silty shale*. The quartzite is poorly sorted and typically has a bimodal fabric. Minor angular to rounded quartz and white chert pebbles (up to 1 cm across) are supported by well-rounded fine to medium quartz grains, and rare zircon cemented by optically continuous and limonitic-stained quartz overgrowths. Many of the quartz grains show abraded secondary quartz rims, indicating they were derived from the reworking of a sandstone. The chert grains commonly contain ghost carbonate rhombs and limonitic pseudomorphs of carbonate crystals, indicating that they are probably silicified carbonate. The base of the unit is marked in the west by *pebbly arkose*, and in the south by minor *limonitic silicified carbonate breccia* and *laminated silicified carbonate*, the latter cropping out as a semi-continuous low strike ridge. *Silty to sandy porcellanite* also occurs near the base of the unit at GK 8458. It consists of poorly sorted silty to coarse well-rounded quartz grains and angular fragments and minor detrital muscovite supported in a brown amorphous matrix. The matrix shows broken wavy laminae, polygonal cracking and possible algal columns, and is probably silicified carbonate.

In the west, an 8 m thick sequence of *laminated to thinly bedded, fine to medium white quartz sandstone* forms a prominent bed at the top of the unit. Tabular cross-bedding and ripple-marks are common and indicate a southerly current direction. In the far south, similar friable quartz sandstone, about 20 m thick, forms the top of the unit which overlaps the Antrim Plateau Volcanics.

Remarks. The Jindare Formation forms the base and eastern margin of the Cambrian to Ordovician Daly River Basin sequence, overlying and interfingering with Lower Cambrian Antrim Plateau Volcanics. The presence of second-cycle quartz grains in sandstone indicates that much of the formation was derived from the reworking of older quartzite—probably from the underlying Depot Creek and Stray Creek Sandstones which may have been exposed as a marginal palaeo-tableland much as they are today.

Shallow-water conditions are indicated by the presence of carbonate, and possibly algal sediments. Ferruginous silicified and brecciated carbonate rocks at the base indicate a hiatus during which stable subaerial conditions persisted for some time prior to Cambrian shallow-marine sedimentation, possibly contemporaneous with extrusion of the early Cambrian Antrim Plateau Volcanics elsewhere.

Daly River Group

The Daly River Group is a sedimentary carbonate sequence cropping out along the margin of the Daly River Basin in the west and southwest of the Cullen Mineral Field. It is mostly covered by Cainozoic sediments, mainly ironstone and gravelly sandy soil. Low dips, vague bedding trends, and strong aerial-photo lineaments suggestive of faulting, render interpretation of the formation boundaries and correlation between units difficult. Two of the three formations in the group are present.

Tindall Limestone (∈mt)

The basal unit of the Daly River Group is the Tindall Limestone, which in places unconformably overlies the Jindare Formation. Elsewhere it unconformably overlies the Cullen Batholith or Early Proterozoic metasediments. The unit is poorly exposed as craggy outcrops surrounding sinkholes or cockpits, and as low-lying pavements with well-developed clints and grikes. The unit consists of *pale-pink, yellow, white and grey, laminated to massive, finely crystalline limestone* which in places has patches of coarsely recrystallised carbonate, and cryptocrystalline chert bands (<5mm thick) and nodules up to 15 cm thick and 30 cm long.

The unit is much more aerially restricted than previously mapped (Malone, 1962), as calcareous quartz sandstone and sandy pellet limestone (sandy pelsparite), previously included in the Tindall Limestone are now placed in the overlying Jinduckin Formation. Bedding plane dips range from 0° to 6° and indicate a probable thickness of between 100 and 150 m. A narrower outcrop width in the south may be caused by steeper dips or southward thinning.

Abundant Middle Cambrian marine fossils are present (Voisey, 1943; Öpik, 1956). Öpik (1956) listed the following genera: *Girvanella, Biconulites hardmani, Lingulella, Obolus, Raterina, Acrotreta, Chancelloria, Helcionella, Hyolithes, Ridlichia, Xystriduna* and unidentified ptychopariids. Kruse (1984) in a review of unpublished work, listed additional molluscan genera (*Acrothele, Westonia, Latouchella*), the younger ptychopariaecean trilobites (*Gunnia, Probowmania?, Ellotia, Piaziella*), eocystids, archaeocyaths, paraconodonts and ?*Porifera*. More recently, Kruse (1990) described an assemblage of trilobites, brachiopods and hyoliths including several new species. Two faunas were differentiated by Kruse (1990): a lower, late Ordian fauna characterised by *Redlichia*, and an upper, early Templetonian fauna characterised by *Xystridura* and ptychopariid trilobites. Most fossils have been collected from relatively thin beds of marine "two-tone" limestone, which does not crop out. Possible stromatolites occur 6 km southwest of Stray Creek Gorge.

Jinduckin Formation (∈Olj)

The Jinduckin Formation conformably overlies the Tindall Limestone (Malone, 1962), but contacts are not exposed. The formation comprises a three-part sequence with: a basal 300 m-thick unit of thinly-bedded salmon-pink and white to *yellowish-brown calcareous quartz sandstone*, and minor *fine to medium-grained quartz sandstone* and *silicified limestone*; a 600 m-thick middle sequence of thinly bedded *calcareous quartz sandstone, sandy pelsparite (sandy limestone), red brown siltstone, marl* and minor *micrite (fine-grained limestone)*, and an upper 50 m-thick unit of interbedded pink to grey *fine to coarsely crystalline limestone* (commonly with chert bands), *siltstone*, and minor *sandy pelsparite (sandy limestone), oosparite (oolitic limestone)* and *biolithite (stromatolitic limestone)*. The total thickness of about 950 m is greater than that reported by Walpole & others (1968), as it includes sediments previously mapped as Tindall Limestone and Ooloo Limestone (Stuart-Smith & others, 1987).

Asymmetric and interference ripple marks are common in sandy units and indicate either easterly (075-110°) or southerly (160-180°) current directions. The ripple marks, oolitic limestone and bulbous stromatolites suggest an intertidal environment. Marine fossils have been found only at one locality near Claravale homestead southwest of the area (Öpik, 1968). Probable *Asaphacea* or *Dikelocephalacea* indicate an upper Cambrian to earliest Ordovician age, supported by late Tremadocian to basal Arenig conodont Assemblage Zones (Jones, 1971).

MESOZOIC COVER

Undivided flat-lying Mesozoic sediments (K, Table 7), up to 80 m thick, form remnant mesas capping older rocks mainly on the sandstone tablelands of the Tolmer and Katherine River Groups in the west and east, respectively. They were previously mapped as Mullaman Beds by Skwarko (1966), but were later interpreted as partly Petrel Formation (Jurassic to Lower Cretaceous) and partly as the Darwin Member of the Bathurst Island Formation (Lower to Upper Cretaceous) by Hughes (1978).

Only a few small remnants of the Mesozoic sequence are preserved northeast of the Stuart Highway and north of the Kakadu Highway. They consist of a 2 m-thick *pebbly to very coarse-grained porous, poorly sorted limonitic and goethitic quartz sandstone* which overlies a discontinuous poorly consolidated *basal breccia* and *cobble conglomerate* mostly of clasts of vein quartz and Early Proterozoic metasediments. Abraded quartz overgrowths on quartz grains indicate derivation from pre-existing sandstone. The sequence is very similar to that farther north in MARY RIVER–POINT STUART REGION (Stuart-Smith & others, 1984b), and probably forms part of Hughes' Petrel Formation (i.e. the 'Coastal Belt' of Skwarko's Mullaman Beds).

Southwest of the highway, the preserved sequence is thicker and is composed mostly of *massive to thickly bedded, poorly to well-sorted medium-grained quartz sandstone, fine-grained quartz sandstone* and minor basal *pebble conglomerate*. Southwest of Pine Creek township, the basal conglomerate is absent and only 2 to 3 m of highly *ferruginous coarse to gritty quartz sandstone* and minor *white medium quartz sandstone* overlie the sediments of the Daly River Basin. The lensing out of the basal pebble conglomerate may reflect the change from Skwarko's 'Coastal Belt' to the 'Inland Belt'. The Mesozoic rocks southwest of the Stuart Highway therefore probably form part of the Bathurst Island Formation. However, the coarse grain size is atypical of the Darwin Member as described by Hughes, and may, in this area, represent equivalents of the poorly sorted sandstone facies of the Marligur Member, which interfingers with the Darwin Member in EAST ALLIGATOR (Needham, 1982) and is extensive below Mesozoic marine mudstone, sandstone and siltstone in the southern part of the Coburg Peninsula (Hughes, 1978; Needham, 1984).

In the east, about 60 m of massive *friable white fine to coarse quartz sandstone*, with minor thin beds of *micaceous siltstone* up to 1 m thick, are capped by 10 to 20 m of *yellow to reddish-brown quartz sandstone* sand overlie the basal *ferruginous quartz sandstone* the latter being exposed farther to the north. Probably both the Petrel and Bathurst Island Formations are represented here, but cannot be separated owing to the lack of palaeontological data.

The basal plane of the sequence represents a palaeo-landsurface on Early Proterozoic metasediments, dipping northeasterly from 265 m ASL southwest of Pine Creek township to 220 m ASL near Douglas Springs, to 180 m ASL north of the Kakadu Highway in the northeast. Over Middle Proterozoic sediments, the surface is highly irregular and the basal limonitic sandstone is mostly absent. Over the Daly River Basin, the base is about 100 to 120 m ASL. The presence of massive hematite pebbles in Mesozoic strata overlying the Frances Creek iron lodes, and deep weathering in the underlying rocks indicates a pre-Mesozoic period of prolonged weathering. This pre-Mesozoic landsurface has largely been re-exhumed and superimposed in most places upon the Tennant Creek Surface, which is associated with widespread lateritisation of the Mesozoic and older rocks (Hays in Walpole & others, 1968). A thin veneer up to 5 m thick of Tertiary ironstone and unconsolidated sand commonly overlies the Mesozoic rocks. The change in base level in the extreme southwest results from faulting or warping along the northeastern margin of the Daly River Basin.

CAINOZOIC COVER

Cainozoic sediments (Table 7) form an alluvial or colluvial veneer over most areas and in more rugged parts grade into talus slopes. They have been divided into the following units: ironstone (Czl), sand (Czs), gravel (Czg), talus (Czt), skeletal soils (Cz), and Quaternary alluvial sediments (Qa). Areas of undivided Cainozoic sediments are grouped with the skeletal soils as Cz.

Tertiary to Quaternary

Ironstone (Czl)

Remnant *ironstone* cappings occur on Mesozoic and Middle Proterozoic strata at about 285-360 m ASL, and on undulating Lowlands plains, in creek flats between rocky ridges and on the Daly River Basin plains. Ironstone is only developed on the tablelands where a thin veneer of Mesozoic rocks covers the Middle Proterozoic sequence, or where iron-rich pelitic rocks of the Stray Creek Sandstone are present. The ironstone is mostly *pedogenic*, forming gravelly soils or concretionary pavements beneath 1 to 2 m of Cainozoic or Quaternary gravelly or sandy soils. The pavements have been re-exhumed by present-day streams, particularly at their headwaters. Generally the ironstone is either detrital or the truncated remnant of the standard laterite profile described by Whitehouse (1940). Of the laterite types discussed by Williams (1969) in the Adelaide River--Alligator River area, the following types have been recognised: *detrital, pisolitic, concretionary ironstone*, and *mottled remnants* of the laterite profile.

Talus (Czt)

Talus slopes are commonly developed around mesas of Mesozoic rocks and on the Middle Proterozoic sandstone tablelands in the west and east, and at the foot of steep strike ridges of Early Proterozoic rocks near Chara Chara Hill (JF 7723). In the west, talus deposits form extensive aprons of mainly *coarse sand* extending up to 2 km from the escarpment onto lowlands of the Daly River Basin. Around the mesas, the talus consists mostly of Cretaceous sediments and weathered granite or metasediment *rubble*. In the east, at the foot of the escarpment bordering the Mount Callanan Basin, the talus consists mostly of sandstone blocks, weathered rubble of Early Proterozoic metasediments, and volcanics.

Gravel (Czg)

Unconsolidated pebble gravels made up of fragments of Early Proterozoic metasediments, together with *gravelly skeletal soils*, occur as semi-continuous aprons over the northern margin of the Allamber Springs Granite and part of the alluvial plains around Mount Douglas. The gravels, several metres thick in places, originated as fan deposits shed from steep ridges of Early Proterozoic metasediments surrounding the low-lying granite plains. Locally, these deposits were lateritised and are currently being eroded by streams.

Sand (Czs)

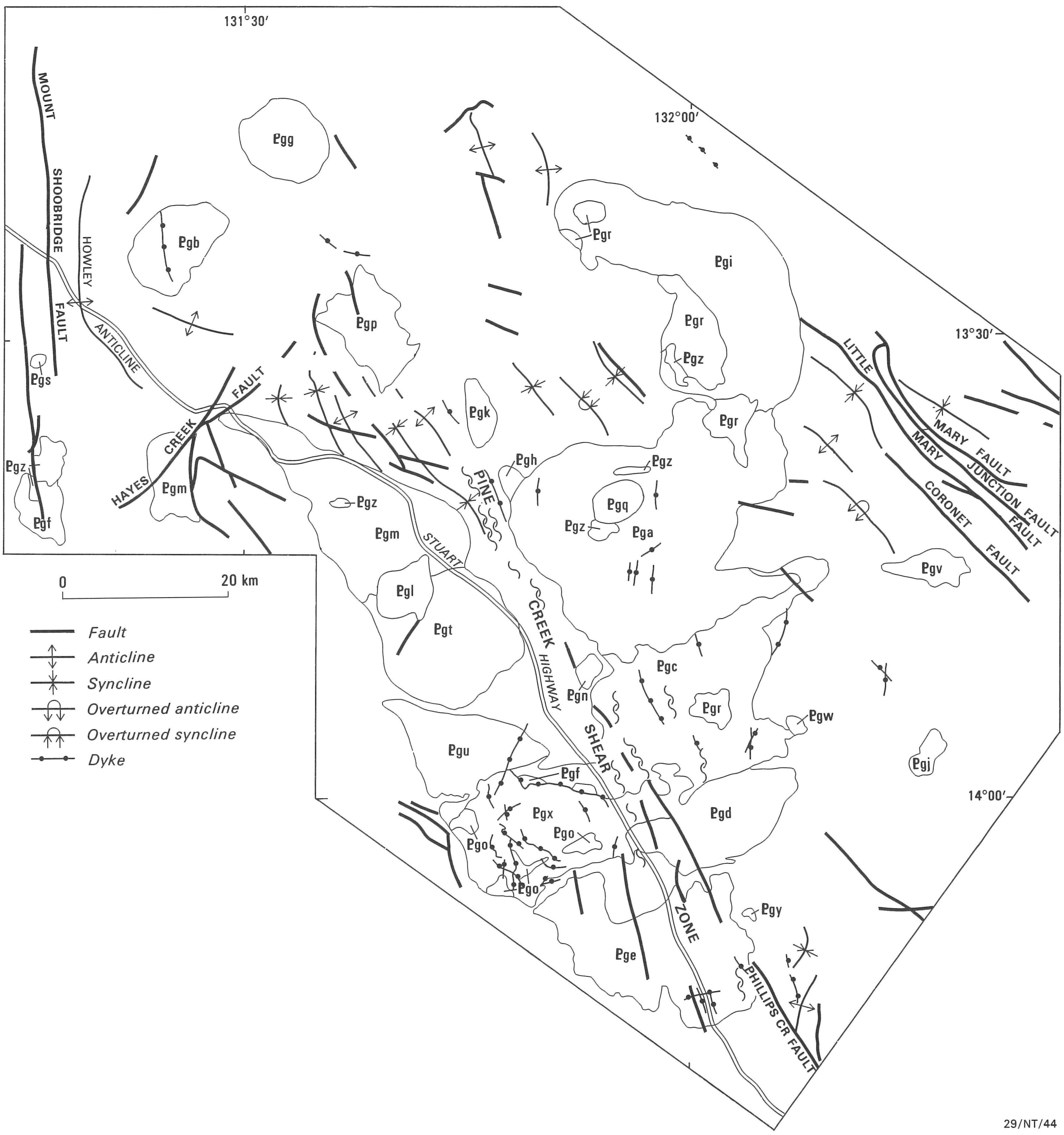
Coarse unconsolidated quartz sand and *ferruginous clayey sand* comprise remnants of the 'Koolpinyah Surface' of Story & others (1969), and together with ironstone cover much of the lowlands and parts of the tablelands. The sands are fan deposits (Story & others, 1969) derived from Mesozoic sand, silt, and claystone, Middle Proterozoic sandstone, and Early Proterozoic rocks. Clean quartz sand, developed on the tablelands from the Depot Creek Sandstone, Kombolgie Formation and Mesozoic sediments, has probably formed continually in an erosional environment since the early Tertiary.

Skeletal soil (Cz)

Sandy to gravelly skeletal soils, gradational red soils and yellow earth soils are widespread, mostly developed in situ in the north over areas of Early Proterozoic metasediments, granite and Palaeozoic sediments, where they cover intervening areas between exposures. Where the soils are thin, structures in the underlying bedrock, such as bedding traces and faults, are recognisable on aerial photographs. In granitoids, sharp colour changes (visible in the field and on aerial photographs) mainly reflect the mafic content of the bedrock, which in some cases enables delineation of phase contacts. The soils represent loose material formed by aggradation of a colluvial plain at a higher level than the current erosional grade, and thus are at present subject to widespread erosion.

Quaternary

Deposition in a continental environment during the Quaternary is represented by a variety of alluvial units (Qa). *Alluvial silt, sand, gravel* and *clay* occur in the courses and flood plains of the Edith, Fergusson, Margaret, McKinlay and Mary River systems. Large bodies of *unconsolidated quartz sand* are also found within the channels of the major creeks and rivers. Minor *silty levee deposits* are developed along the lower reaches of the Mary River in the east. *Black and brown humic soil and clay are commonly developed in poorly drained depressions at the headwaters of streams, particularly in low-lying granite areas, and upon and around the base of Mesozoic tablelands where springs support perennial growth to produce organic-rich marshy deposits.*



DOMINANTLY LEUCOGRANITE PLUTONS

- Ᵽgb Burnside Granite
- Ᵽgf Fenton Granite
- Ᵽgl Douglas Leucogranite
- Ᵽgu Umbrawarra Leucogranite
- Ᵽgo Foelsche Leucogranite
- Ᵽgw Wandie Granite
- Ᵽgr Frances Creek Leucogranite
- Ᵽgq Saunders Leucogranite
- Ᵽgv Mount Davis Granite
- Ᵽgj Wolfram Hill Granite
- Ᵽgy Yenberrie Leucogranite
- Ᵽge Tennysons Leucogranite

CONCENTRICALLY ZONED TRANSITIONAL GRANITE AND LEUCOGRANITE PLUTONS

- Ᵽgs Shoobridge Granite
- Ᵽgt Tabletop Granite
- Ᵽgn Bonrook Granite
- Ᵽgd Driffield Granite
- Ᵽga Allamber Springs Granite

FRACTIONATED ALKALINE SUITES

- Ᵽgz Bludells Monzonite

DOMINANTLY GRANITE PLUTONS

- Ᵽgg Margaret Granite
- Ᵽgm McMinns Bluff Granite
- Ᵽgp Prices Springs Granite
- Ᵽgk McKinlay Granite
- Ᵽgx Fingerpost Granodiorite
- Ᵽgc McCarthys Granite
- Ᵽgh Mount Porter Granite
- Ᵽgi Minglo Granite

Fig. 15. Plutons of the Cullen Batholith.

INTRUSIVE IGNEOUS ROCKS

EARLY PROTEROZOIC PRE–OROGENIC INTRUSIONS

Zamu Dolerite (Ᵽdz)

Pre-orogenic *quartz dolerite* sills of Zamu Dolerite (Bryan, 1962; Ferguson & Needham, 1978) intrude Early Proterozoic sediments in the northern half of the area. The age of intrusion is confined between deposition of the South Alligator Group (1880 Ma) and regional deformation and metamorphism at 1870 Ma (Page & others, 1980). The sills intrude pelitic-rich units, in particular the Koolpin Formation. The centre of intrusion appears to be in the Burrundie Dome area where three major sills, intruding the South Alligator Group, range up to 170 m thick and extend for over 20 km. Elsewhere they are less continuous and also intrude the Namoona, Mount Partridge and Finniss River Groups. Contact effects are mostly absent owing to poor exposure and the effects of post-intrusion regional and contact metamorphism; however, spotted hornfels in the Wildman Siltstone crops out adjacent to a dolerite sill at HL 0900. Compared to the ridge-forming Early Proterozoic metasediments, the dolerite is poorly exposed in valleys as rounded boulders and rubble. However, its subsurface presence is readily distinguished by a characteristic deep reddish-brown soil, and dense vegetation. For the most part, the dolerite is extensively contact-metamorphosed by the Cullen Batholith granitoids to either *altered quartz dolerite* or *amphibolite*.

EARLY PROTEROZOIC SYN– TO POST–OROGENIC GRANITOIDS

Syn- to post-orogenic granitoid intrusions dominate the geology of the mineral field and cover about half of the area. Twenty three plutons form the Cullen Batholith (Fig. 15). Sixteen of these are coalesced or joined at shallow depths and were previously included in the 'Cullen Granite' by Noakes (1949), and form a broad V-shaped mass covering about 2800 km^2 centred on Pine Creek township. The other plutons of the batholith surround the main body and are probably interconnected at depths of less than 3 km (Fig. 16). Details of individual plutons are given in Table 8.

The granitoids intrude the Early Proterozoic metasediments and Zamu Dolerite, and display differing levels of contact metamorphism. Rugged ridges of hornfels rise up to 200 m above the level of the granitoids and topographically define their margins. The contacts are mostly smooth and discordant with minor faulting, except in places around outlying cupolas where they are highly irregular. A major north-northwest-trending shear zone, the *Pine Creek Shear Zone*, follows an embayment of Early Proterozoic metasediments separating the two major lobes of the batholith (Fig. 15). The batholith is overlain by Middle Proterozoic to Cambrian sediments in the west and by scattered residual cappings of Mesozoic sediments.

Batholith components

Until the present survey, the granitoids had not been studied systematically. In the south, Rattigan & Clarke (1955) distinguished three types of granite in the Mount Todd and Lewin Springs 1-mile Sheets. Walpole & others (1968) subsequently extended the subdivision to five phases, which were adopted by Ewers & Scott (1977) in their geochemical study of the 'Cullen Granite'; however, neither study attempted to map out the granite types. The current investigation has distinguished, on the basis of hand-specimen mineralogy and texture, ten major granitoid types. These are described in Table 9 and include: granodiorite (type 1); three types of granite (types 2, 3, 4); and six types of leucogranite (types 5, 6, 7, 8, 9, 10). Their distribution and areal extent are shown in Figure 17 and Table 10. Type 2 granite (Fig. 18) is the dominant phase, comprising ~50% of the batholith. Leucogranites together make up over 40% with types 5, 6 and 8 the most common. As well as the ten granitoid phases, rafts and xenoliths of monzonite and dolerite intrusive net-veined complexes (both shown as Bludells Monzonite on the accompanying map), Early Proterozoic hornfels rafts, and post-granitoid dykes (Lewin Springs Syenite) have been distinguished in areas previously mapped as 'Cullen Granite'. The relationship of all components of the Cullen Batholith is shown diagrammatically in Figure 19.

Minor *greisen* bodies are associated with leucogranite phases, in particular with leucogranite-dominated plutons, such as the Umbrawarra and Tennysons Leucogranites, and the Mount Davis, Wolfram Hill, and Bonrook Granites (Fig. 20). The greisen occurs either as elongate bodies along the pluton margins (Fig. 21) or as stockworks parallelling major joint trends. They probably represent both late differentiates and alteration products of the enclosing leucogranites. Tin, tungsten and copper mineralisation is closely associated with greisen in places.

Bludells Dolerite (Ᵽgz)

The Bludells Dolerite is shown on the accompanying map as 'Bludells Monzonite', where it is described as containing monzonites, syenites and rare olivine dolerite.

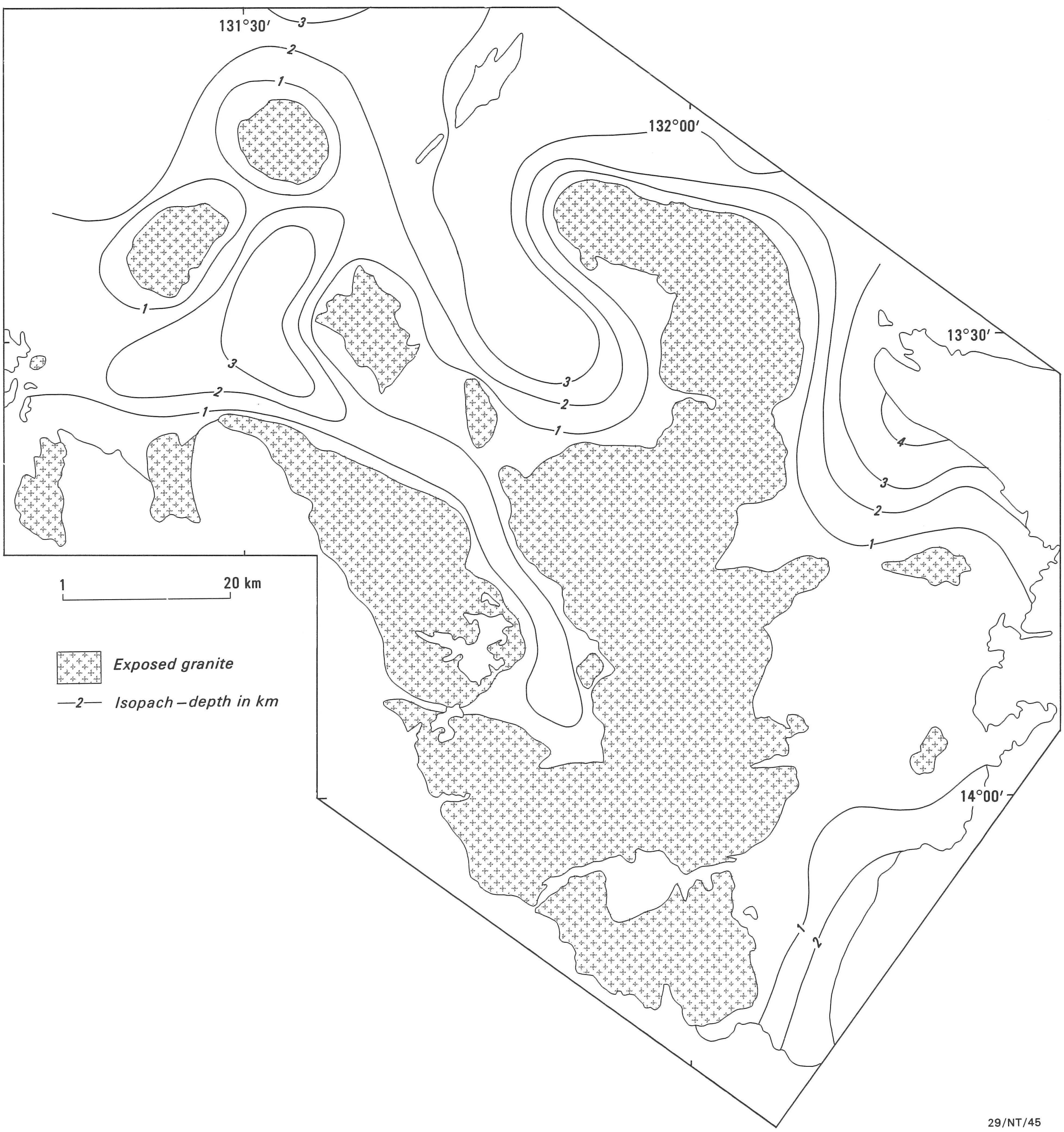


Fig. 16. Granitic basement form lines; based on residual gravity data with a contrast of 0.18 t.m^{-3} between Early Proterozoic metasediments and granitoids (after Tucker & others, 1980).

On the basis of chemistry and petrography, this study suggests that in most plutons where the 'Bludells Monzonite' has been distinguished, rocks defined as monzonites, monzodiorites and quartz syenites are equivalent to the most mafic end-members of the host pluton. These rocks are therefore now included as part of the host pluton. However, doleritic rocks, which are compositionally distinct from their granite host, are redefined as the Bludells Dolerite. The dolerite occurs as irregular-shaped bodies up to 5 km across in the McCarthys Granite in the Bludells Creek area (HK 1659), the southwestern part of the Frances Creek Leucogranite (HL 2302), in the central portion of the Allamber Springs Granite and also as dykes in the northeastern Allamber Springs Granite (JE 8593).

The dolerite is rarely fresh, consisting of primary clinopyroxene, orthopyroxene, olivine, biotite, opaques, plagioclase with minor interstitial quartz and K-feldspar. Widespread alteration is characterised by complete replacement of pyroxenes with colourless to pale-green

TABLE 8. SUMMARY OF EARLY PROTEROZOIC SYN- TO POST–OROGENIC GRANITOIDS

Unit (map symbol)	*Derivation of name*	*Distribution*	*Description*	*Field relations*	*Age (Ma) (see Table 11)*	*Remarks*
LEUCOGRANITE-DOMINATED PLUTONS						
Tennysons Leucogranite (Pge)	Tennysons uranium prospects (Lat. 14°13'S, Long. 132°00'E).	Flanks Stuart Highway south of Fergusson River. Small (3 km^2) body on southern margin of Pgx. Area ~ 300 km^2.	Predominantly Type 8 with marginal phases of Types 5, 6, 7, 9 & 10. All types have common muscovite (~1%) with gradational contacts. Minor greisen. Joints 080°-090° and 160°-170°. Cross-cutting NW-trending quartz veins; fault, breccia and shear zones. Alteration common with fluorite, topaz & sphene.	Intrudes Pfb, Pbt and Pep with shallow-dipping discordant contact. Intrudes Pgx Intruded by Pew. Unconformably overlain by Ꞓlj and Ꞓmt.		Asssociated U & W mineralisation
Yenberrie Leucogranite (Pgy)	Yenberrie Hill (Lat. 14°06'S, Long. 132°03'E).	Two small stocks 1 km apart about 2 to 4 km south of Yenberrie Hill. Area ~ 2 km^2.	Transitional between Types 6 & 9, greisen and topaz-bearing silexite. dykes. Probably connected at depth to Pge.	Intrudes Pfb. Intruded by numerous N-NW-trending quartz and aplite		Associated W, Mo & Bi mineralisation.
Wolfram Hill Granite (Pgj)	Wolfram Hill (Walpole & others, 1968).	Subrectangular pluton and several smaller apophyses ~10 km NE of Black Mountain in SE. Crops out as rugged hills. Area 16.5 km^2.	Mostly Type 6, transitional with Type 9, the latter forming pluton margins and apophyses. Extensively altered with common fluorite and carbonate. Quartz veins and muscovite-quartz greisen zones.	Intrudes Pfb and Pbt. Shallow-dipping contacts.		Associated Sn, W & Cu mineralisationisation. Monazite occurrences
Mount Davis Granite (Pgv)	Mount Davis (Jensen, 1919).	Rocky pavements and bouldery hills in E between Mt Gardiner and Mt. Davis. Elliptical-shaped pluton ~12x4 km. Area ~ 30 km^2.	Predominantly Type 6, transitional with minor Types 5 & 3. Contacts not exposed. Locally altered with quartz and greisen veins and stockworks.	Intrudes Pfb with irregular discordant and shallow-dipping contacts. Joined in subsurface to Pgc. Intruded by Pew dykes.		Associated Cu, Ag, Pb, Au & Bi mineralisation.
Frances Creek Leucogranite (Pgr)	Frances Creek (Lat. 13° 30'S, Long. 132°00'E).	Five separate bodies, up to 5 km across, between Mt. Masson in N and Wandie Ck. in SE. Crops out as bouldery hills. Area ~113 km^2.	Type 9. Common biotite clots (<2cm) and rare K-feldspar phenocrysts (<1 cm). Abundant xenoliths and rafts of Pgz, Pgx and Pga.	Intrudes Pgi, Pga and Pgc. Highly irregular contacts mostly covered by Cz. Contact with Pgi exposed at JF 0578. Intruded by quartz veins and pegmatite, aplite and Pew dykes.		
Saunders Leucogranite (Pgq)	Mt. Saunders (Lat. 13° 35', Long. 131°55'E).	Oval-shaped pluton centered 10 km south of Mt. Saunders. Crops out as rugged bouldery hills. Area ~27 km^2.	Type 7. Microcline (<1cm) & quartz phenocrysts. Biotite aggregates (cm) present in places. Rectilinear and concentic joint patterns prominent on aerial photographs and Landsat images.	Intrudes Pga and Pgz. Forms small stock and ring dyke complex. Margins of main body intruded by dykes and irregular-shaped bodies of aplite and Type 9.		Associated alluvial Sn

Unit (map symbol)	*Derivation of name*	*Distribution*	*Description*	*Field relations*	*Age (Ma) (see Table 11)*	*Remarks*
Wandie Granite (Pgw)	Wandie Creek (Lat. 13° 55'S, Long. 132°05'E).	Oval-shaped pluton centered 10 km NW of Black Mountain in SE. Crops out as jointed pavements and rugged bouldery hills. Area ~3 km^2.	Type 7.	Intrudes Pfb and Pgc? Subhorizontal contacts with Pfb indicated by extensive metamorphic aureole.		Forms a cupola. Associated vein Cu & alluvial Sn.
Foelsche Leucogranite (Pgo)	Foelsche Headland (Lat. 14°05'S, Long. 131°47' E).	Strongly jointed outcrops forming numerous small (<3 km) irregular-shaped bodies between Foelsche Headland and Cullen Siding in SW. Area ~23 km^2.	Type 9. Characteristically pyritic. Quartz and pegmatite veins common.	Intrudes Pgx. Intruded by Pew and Pgu? Unconformably overlain by Ptd and Ꞓlj.		
Umbrawarra Leucogranite (Pgu)	Umbrawarra Gorge (Lat. 13°50'S, Long. 131°40'E).	Rugged bouldery hills and deeply weathered outcrops. Rough triangular-shaped pluton centered 15 km SW of Pine Creek township. Area ~140 km^2.	Type 8. Numerous N-trending quartz breccias, N to NE- and E to SE-trending quartz, aplite and greisen veins and stockworks.	Intrudes Pfb, Pgc, Pgx and Pew? Unconformably overlain by Ptd, K and Cainozoic deposits.	1825 ± 7 (U-Pb zircon, ion microprobe)	Minor associated Sn mineralisation.
Douglas Leucogranite (Pgl)	Douglas River (Lat. 13° 44'S, Long. 131°36'E).	Poorly exposed low outcrops. Subsurface presence indicated by quartz-rich skeletal soils and pale phototone. Circular pluton (~6 km across) centred 17 km NW of Pine Creek township. Area ~39 km^2.	Type 8, minor Type 9. Contact between phases ill-defined and probably transitional.	?Intrudes Pgm and Pgt. Contacts not exposed but appears discordant. Includes raft of Pgm near pluton centre.		
Fenton Granite (Pgf)	Fenton airstrip (Joplin, 1957).	Poorly exposed scattered outcrop west of Fenton airstrip and south of Plateau Point in far W. Area ~32 km^2.	Type 9. Garnet present in marginal phases. Widespread weakly developed N-trending foliation and shear zones.	Intrudes Ppw, Psk, Psg and Pso with broadly concordant contacts. Rafts and xenoliths of Pgz common. Unconformably overlain by Cmt.		

Unit (map symbol)	*Derivation of name*	*Distribution*	*Description*	*Field relations*	*Age (Ma) (see Table 11)*	*Remarks*
Burnside Granite (Pgb)	Burnside homestead (Malone, 1962).	Rocky outcrops in a subrectangular mass southwest of Mt. Ellison in the NE. Area ~89 km^2.	Type 6, slightly porphyritic and foliated in places. Rare xenoliths. Common quartz, aplite, pegmatite and greisen veins.	Intrudes Ppw, Psk and Pdz with mostly concordant contacts. Rim syncline developed around southern and western margins.	1800 ± 5 (U-Pb zircon, ion microprobe).	Mo-bearing quartz veins 5 km NW of Ban Ban Springs.
CONCENTRICALLY ZONED TRANSITIONAL GRANITE AND LEUCOGRANITE PLUTONS						
Allamber Springs Granite (Pga)	Allamber Springs (Lat. 13°37'S, Long. 131°56' E).	Scattered boulders on low lying plains, and rugged bouldery ridges at headwaters of the Nellie and Harriet Creeks in the centre. Area ~618 km^2.	Mostly Type 2 with common xenoliths and rafts of Px and Pgz. Lesser Type 5 forms discontinous bodies internal to an outer marginal zone of Type 6. Minor Types 9 & 4. Veins of aplite, quartz and greisen near pluton margins. Mostly gradational contacts between main phases. Sheared, fractured and silicified near McCarthy Hill in east.	Intrudes Early Proterozoic metasediments with mostly smooth, lobate and discordant contacts. Intrudes Pgh and Pgc and intruded by Pgg, Pgr, Pew and unnamed dolerite dykes. Cainozoic cover of humic soil flats, sandy alluium and unconsolidated gravel fans particularly in northern half. Relationship to Pgi unknown.	1822 ± 6 (U-Pb zircon, ion microprobe).	Minor associated alluvial Sn
Driffield Granite (Pgd)	Driffield Creek (Lat. 14°03'S, Long. 132°05' E).	Crops out east of Cullen Siding along the lower reaches of Driffield Ck. Poorly exposed scattered tors in centre and west, pavements and bouldery hills along southern, eastern and northern margins. Area ~156 km^2.	Central core of Type 2 with common rafts and xenoliths of Pgz, surrounded by outer zone of Types 5, 6 & 9. Minor bodies of greisen, pegmatite, quartz and Px xenoliths in southern marginal phases. Sheared and altered in west within Pine Creek Shear Zone.	Intrudes Pfb with smooth discordant contact. Where exposed (e.g. JE 8444) dips outwards at 60°. Intrudes Pgc and Pgx with lobate, irregular or faulted contacts. Contact with Pgx exposed at HK 1846.		Associated U & Cu mineralisation.
Bonrook Granite (Pgn)	Bonrook Creek (Lat. 13°52'S, Long. 131°53' E)	Poorly exposed, scattered tors and pavements in headwaters of Bonrook Ck. Square-shaped pluton centered 7.5 km southeast of Pine Creek township. Area ~ 7.5 km^2.	Types 4 & 6. Minor Type 9 and greisen. Aplite and pegmatite veins and Px xenoliths common near pluton margins.	Intrudes Pfb and Pso. Probably connected in subsurface to Pgc.		
Tabletop Granite (Pgt)	Tabletop homestead (Lat. 13°49'S, Long. 131°48'E)	Forms roughly circular-shaped pluton centred 10 km west of Pine Creek township. Exposed as jointed pavements, rocky	Types 2, 6, 5, 9, 3 & 4. Three concentric zones arranged from oldest at margin and youngest in centre comprising: an outer zone (Types 2, 3, 4, & 5); an inner zone (Type 6); and a central zone (Type 2).	Intrudes Pfb & Pso with lobate discordant contacts. Intruded by Pgl. Encloses ?raft of Pgm indicating the pluton probably intrudes Pgm but contacts not		Associated vein/stockwork Cu mineralisation & alluvial Sn.

Unit (map symbol)	*Derivation of name*	*Distribution*	*Description*	*Field relations*	*Age (Ma) (see Table 11)*	*Remarks*
		hills and scattered boulders. Deeply weathered beneath overlying K and Ptd. Area ~198 km^2.	Minor late-stage pyritic Type 9 along SE margin. Contacts between phases in outer zone are probably transitional. The presence of chilled margins and dykes indicate intrusive contacts between zones. Minor NE-trending quartz breccia, mylonite and greisen zones in west; pegmatite, aplite and dolerite dykes in centre and south.	exposed. Unconformably overlain by Ptd and K.		
Shoobridge Granite (Pgs)	Mount Shoobridge (Malone, 1962).	Small circular pluton about 21 km WNW of Hayes Creek. Bouldery outcrops ringed by a semi-continuous hornfels ridge. Area ~2 km^2.	Type 2. Three varieties with a leucocratic variety forming a central intrusive core. Minor quartz-muscovite, quartz-barytes, quartz-muscovite-tourmaline, and pegmatite veins.	Intrudes Pfb with concordant and domal contact.	1775±16	Associated Cu, Ag & Pb (U-Pb zircon) mineralisation.
GRANITE DOMINATED PLUTONS						
Minglo Granite (Pgi)	Minglo Creek (Lat. 13° 25'S, Long. 132°00'E).	Crops out in NE as rugged hills along eastern side of Minglo Ck. Elsewhere as low bouldery hills on residual sand plains. Area ~384 km^2.	Type 2. Minor Type 9 along southeastern margin. Aplite, lamprophyre and porphyritic microgranite dykes. Xenoliths and rafts of Pgz common in south and metasediment xenoliths present near pluton margins.	Intrudes Pnm, Ppm, Ppw, Psk & Pso with smooth, mostly discordant contacts. Intruded by Pgr: contact exposed at JF 7805. Relationship with Pga to south unknown.		Associated Sn mineralisation
Mount Porter Granite (Pgh)	Mount Porter (Lat. 13° 38'S, Long. 131°49'E).	Forms small triangular-shaped pluton centred 7 km north of Pine Creek township. Crops out as bouldery hills. Area ~9 km2.	Type 2.Dykes & veinlets of microgranite & tourmaline-bearing pegmatite.	Intrudes Psg, Pso and Pfb with discordant contacts. Contact with Pfb exposed in railway cutting at HK 0387. Intruded by Pga.		
McCarthys Granite (Pgc)	McCarthys silver mine (Lat. 13°45'S, Long. 132°05'E).	Poorly exposed, minor pavements and boulders E and SE of Pine Creek township between Cullen Siding and McCarthy Hill. Area ~392 km^2.	Composite pluton and apophyses comprising: dominantly Type 2 in centre and north; mixed Types 2, 4, 5, 6, & 9 in west; Type 9 along pluton margin north of Wandie Ck; minor Types 4 & 8 in SE. Numerous xenoliths and rafts of Pgz. In W where cut by N to NE-trending shear zones quartz-chlorite-hematite alteration	Intrudes Pfb with smooth, lobate and discordant contacts. Intruded by Pga, Pgw, Pgd, Pgr, Pgu and Pew. Occurs as rafts within Pgu.		Minor associated vein Au mineralisation.

Unit (map symbol)	*Derivation of name*	*Distribution*	*Description*	*Field relations*	*Age (Ma) (see Table 11)*	*Remarks*
			widespread and mylonite and quartz breccia zones common. Minor aplite and pegmatite veins.			
Fingerpost Granodiorite (Pgx)	Fingerpost Creek (Lat. 14°05'S, Long. 131°41' E).	Scattered boulders and pavements in sandy plain flanking Claravale Road between Cullen Siding and Foelsche Headland in the SW. Area ~210 km^2.	Dominantly type 1, grading southwards into Type 3. Minor aplite, greisen and pegmatite. Very minor Type 9 along southern margin. Quartz veins, breccias and mylonite common in E within the Pine Creek Shear Zone. Deeply weathered beneath overlying Ptd and K.	Intrudes Pfb with discordant contact. Intruded by Pgu, Pgo, Pgd, Pge and Pew. Relationship to adjacent Pgc unknown. Unconformably overlain by Ptd and K in W.	1823 ± 3 (U-Pb zircon, ion microprobe).	Associated Cu mineralisation.
McKinlay Granite (Pgk)	McKinlay River (Malone, 1962).	Forms oval-shaped pluton, 9 km across, centred 22 km NW of Mt. Porter in centre. Crops out as rugged bouldery hills. Area 22 km^2.	Type 2.	Intrudes Pfb with smooth concordant contact.		
Prices Springs Granite (Pgp)	Prices Springs homestead (Hasan, 1958).	Subrectangular-shaped pluton, cropping out as bouldery hills and pavements flanking the North Australian Railway between Burrundie and Grove Hill Sidings in N. Area ~89 km^2.	Type 2: two textural varieties: 1) with numerous K-feldspar phenocrysts. 2) with minor phenocrysts in a finer groundmass. Minor greisen.	Intrudes Psk, Psg, Pso, Pfb & Pdz with irregular discordant contacts. Extensive Cainozoic cover in S.	1804 ± 50 (U-Pb zircon)	Described by Hasan (1958)
McMinns Bluff Granite Pgm)	McMinns Bluff (Lat. 13° 45'S, Long. 131°44'E).	Scattered tors and pavements on lowlands mostly south of the Stuart Highway between Hayes Creek and McMinns Bluff.Two main areas of outcrop separated by Ptd. Area ~305 km^2.	Type 2. Minor aplite dykes and Pgz xenoliths and rafts. NE-trending quartz breccia zones. Lower greenschist facies & locally strongly foliated, faulted and albitised in W.	Intrudes Ppw, Psk, Psg, Pso, Pfb and Pdz with smooth, lobate and mostly concordant contacts. Intruded by Pgl forming rafts within the latter. Relationship with adjacent Pgt unknown. Unconformably overlain by Ptd, Clj, Cmt and K. Extensive Cainozoic sand cover.	1835 ± 6 (U-Pb zircon, ion microprobe).	Minor associated Cu mineralisation & alluvial Sn.

Unit (map symbol)	*Derivation of name*	*Distribution*	*Description*	*Field relations*	*Age (Ma) (see Table 11)*	*Remarks*
Margaret Granite (Pgg)	Margaret River (Malone, 1962).	Isolated boulders and pavements on sandy lowlands in N. Forms circular pluton centred 11 km NNE of Ban Ban Springs. Area ~83 km^2.	Type 2. Metasediment xenoliths common near margins. Weakly foliated in places.	Intrudes Psg, Pso & Pfb with subconcordant contacts. Contact exposed at GL 7826.		
FRACTIONATED ALKALINE SUITES						
(Pgz)		Low bouldery rises and scattered rubbly outcrop throughout centre and in S.	Medium-grained greyish green equigranular biotite-hornblende-quartz monzonite, biotite-pyroxene monzonite, biotite-hornblende-quartz syenite; minor biotite-hornblende-quartz monzodiorite and rare coarse-grained porphyritic quartz monzonite.	Occurs as xenoliths and rafts (<5 km across) in Pgm, Pga, Pgi, Pgd, Pgc & Pgr. Distinctive deep reddish-brown residual soils with sparse tree and tall grass cover.	1818+5 (U-Pb zircon, ion microprobe).	Shown as part of the 'Bludells Monzonite' on the accompanying map.
THOLEIITIC SUITES						
Bludells Dolerite (Pgz)	Bludells Creek (Lat. 13° 56'S, Long. 131°57'E).	Low bouldery rises and scattered rubbly outcrop in a 15 km wide belt between Halfway Peak in NE to Edith River Siding in S. Area ~52 km^2	Olivine dolerite.	Forms net-vein complexes in Pgm, Pga, Pgi, Pgd, Pgc & Pgr. Distinctive deep reddish-brown residual soils with sparse tree and tall grass cover		Shown on the accompanying map as 'Bludells Monzonite'.
UNDIVIDED HORNFELS						
(Px)		Low rubbly rises and hills in a semi-continuous belt, up to 15 km wide, between Halfway Peak in NE to Edith River Siding in S. Area ~19 km^2.	Magnetite-biotite-andalusite-cordierite-microcline-quartz hornfels, quartzite, garnet-muscovite quartzite, feldspathic quartzite, micaceous quartzite, chiastolite carbonaceous hornfels, spotted micaceous hornfels, banded pyritic calc-silicate hornfels, amphibolite.	Forms numerous xenoliths and rafts (km across) in Pgr, Pge, Pgi & Pga; and screens separating Pgc from Pga and Pgd.		Probably represent undigested or stoped blocks of adjacent Early Proterozoic strata.

TABLE 9. SUMMARY DESCRIPTION OF SYN- TO POST-OROGENIC GRANITOID TYPES (listed in order of decreasing colour index)

Granitoid type	*Colour*	*Grainsize*	*Texture*	*Megacrysts**	*Major minerals**	*Accessory*	*Mafic minerals*	*Alteration index*	*Occurrence*	*Remarks*
1 Granodiorite	Grey	Coarse	Strongly porphyritic	Pink microcline (<6cm)	Oligoclase, microcline, quartz, hornblende, biotite	Apatite, sphene, zircon, opaques, allanite	10-15	Chlorite, epidote, actinolite carbonate	Pgx	Most mafic phase. Deformed: undulose extinction and recrystallised grain boundaries common.
2 Granite	Pink and green	Coarse	Strongly porphyritic	Pink microperthite microcline (<6 cm)	K-feldspar (microcline, orthoclase) albite/oligoclase quartz, biotite, hornblende, rare muscovite, garnet (Pgc only)	Zircon, apatite, opaques rare allanite, sphene, fluorite (Pgp & Pgg only)	5-15	Chlorite, epidote, sericite, carbonate, muscovite	Pgg, Pgm, Pgt, Pgc, Pga, Pgi, Pgh, Pgk, Pgp, Pgd, Pgs	Most widespread phase (~50%). Deformed locally in major shear zones. Weak foliation, paralleling contacts present locally in marginal phases.
3 Granite	Pink and green	Medium	Porphyritic	Pink orthoclase (<1 cm)	Orthoclase, oligoclase, quartz, hornblende, biotite	Zircon, rare apatite, allanite (Pgv only)	5	Chlorite epidote, sericite	Pgt, Pgv, Pgx	Minor phase.Transitional with Type 1 in Pgx.
4 Granite	Grey	Coarse	Strongly porphyritic	White micro-perthitic micro-cline, pale-green albite/oligoclase, minor quartz	Microcline, albite/oligoclase, quartz, biotite, minor orthoclase, rare hornblende, muscovite	Apatite, zircon garnet (Pgc only)	5-10	Chlorite, sericite, calcite, epidote, muscovite	Pgt, Pgn, Pga, Pgd, Pgc	Minor marginal phase in concen-trically zoned plutons.
5 Leucogranite	Pink	Coarse	Porphyritic	Pink perthitic microcline (<2 cm)	Microcline, quartz, albite/oligoclase, biotite, rare muscovite, hornblende	Apatite, zircon, allanite, opaques, sphene	<5	Sericite, epidote, calcite, chlorite, K-feldspar	Pgt, Pgd, Pga, Pgc, Pge, Pgv	Major phase, commonly forming zones transitional with Types 2 and/or 6.

Granitoid type	*Colour*	*Grainsize*	*Texture*	*Megacrysts**	*Major minerals**	*Accessory*	*Mafic minerals*	*Alteration index*	*Occurrence*	*Remarks*
6 Leucogranite	Pink	Coarse	Equigranular	nil	K-feldspar (microperthite, orthoclase), quartz, albite/oligoclase, biotite, rare hornblende, muscovite	Zircon, apatite, rare allanite, fluorite	<4	Sericite, chlorite, epidote, Fe oxides, carbonate	Pgt, Pgn, Pgd, Pgc, Pga, Pgj, Pgv, Pgb, Pge, Pgy	Major phase, commonly forming zones transitional with Type 5 in concentrically zoned pluton. Minor or major phase in leucogranite-dominated plutons. Locally deformed within the Pine Creek Shear Zone. Differs from Type 5 only in texture.
7 Leucogranite	Pink	Medium	Equigranular	nil	K-feldspar (microcline, orthoclase) quartz, albite/oligoclase, biotite, rare muscovite	Apatite, zircon, rare allanite	2-5	Sericite, epidote, calcite, chlorite, Fe oxides	Pgw, Pgq Pge	Minor phase in leucogranite-dominated plutons. Extensively deformed: recrystallised polygonal quartz grain boundaries, undulose extinction, swapped feldspar rims.
8 Leucogranite	Grey	Coarse	Strongly porphyritic	Russet perthitic microcline (<2cm) grey albite/oligoclase, quartz, minor biotite	Quartz, microcline, albite/oligoclase, biotite, minor muscovite	Apatite, zircon, rare sphene	1-5	Chlorite, epidote, rutile	Pgu, Pgl, Pge, Pgc	Major phase in leucogranite-dominated plutons.
9 Leucogranite and alkali feldspar granite	Pink to grey	Fine to medium	Equigranular	nil	Microcline, quartz, albite/oligoclase, minor biotite, rare hornblende, muscovite	Zircon, apatite, pyrite (Pgo only), rare allanite	<5	Chlorite, epidote, Fe oxides muscovite, calcite	Pge, Pgn, Pgl, Pgr, Pgo, Pgf, Pgj, Pgy, Pgt, Pg,d Pgc	Minor constituent, representing the youngest and most felsic phase within most plutons. Commonly present as dykes or marginal irregular-shaped bodies.
10 Leucogranite	Pale grey to pink	Fine to medium	Slightly porphyritic	Embayed quartz (<1 cm), perthitic microcline, biotite, albite/oligoclase	Microcline quartz albite/oligoclase muscovite, biotite	Apatite, zircon	1	Sericite, chlorite	Pge	Transitional with Type 8: distinguished from Type 8 by fewer megacrysts, the predominance of quartz as a megacryst phase, and by lower biotite and plagioclase contents.

* Listed in order of decreasing abundance.

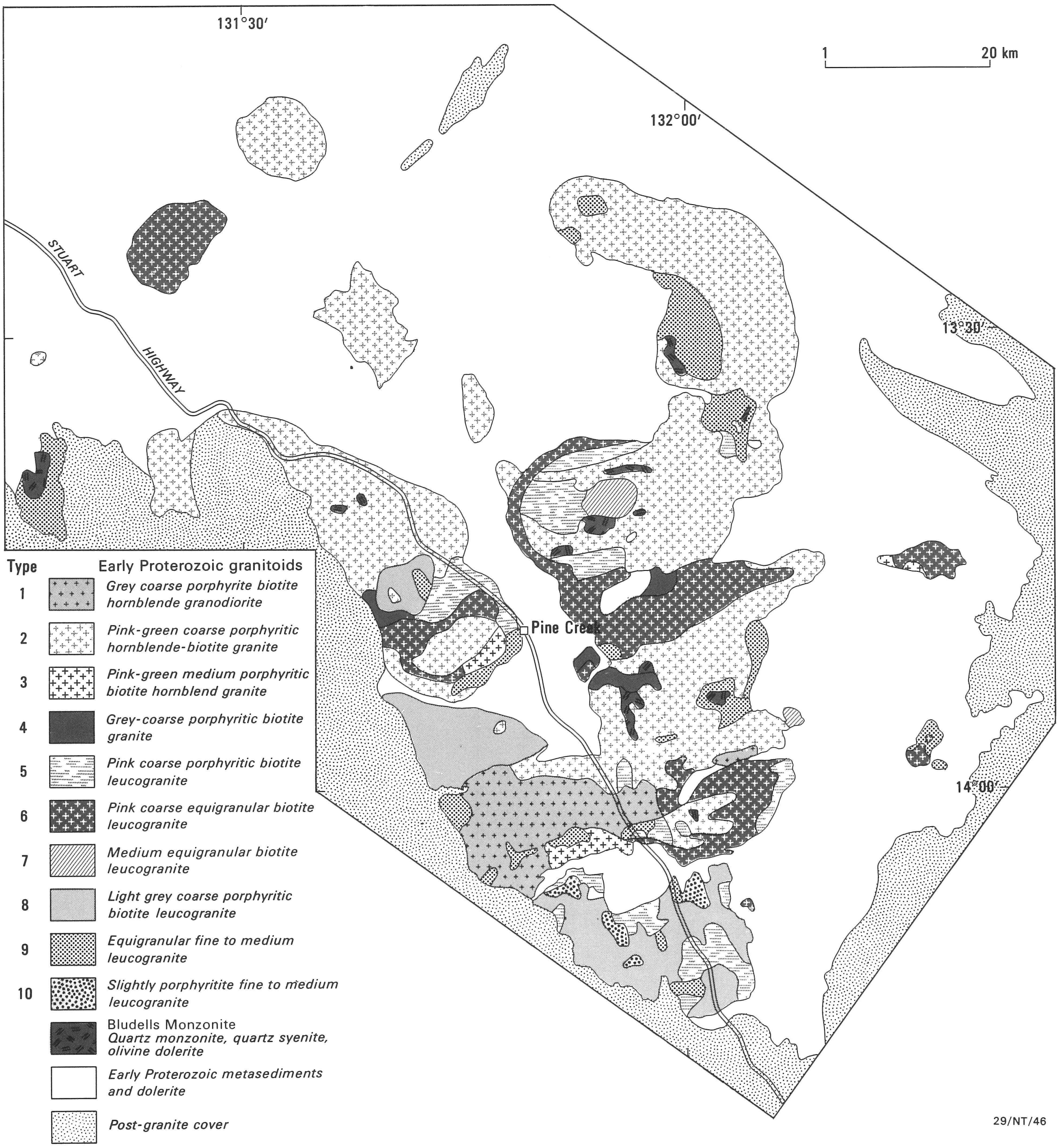


Fig. 17. Distribution of granitoid types in the Cullen Batholith.

actinolite. Chemically, the dolerite is distinguished from more mafic phases of the Cullen Batholith by high Ni (165 ppm) and Cr (up to 2781 ppm), and much lower Ba and Sr values (Appendix 1).

The Bludells Dolerite is probably coeval with the intrusion of the Cullen Batholith as late-stage pegmatite and aplite veins cutting both the dolerite bodies and the enclosing granite are common at contacts. Many of the dolerite bodies are also enclosed by Frances Creek Leucogranite suggesting a possible genetic relationship: the leucogranite representing a localised melt formed by intrusion of the dolerite into a granitic intrusion in a manner analogous to the formation of net-veined complexes (Blake, 1981).

Undivided hornfels (Ex)

Undivided hornfels occurs as numerous bodies, up to 1 km across, within the granitoid plutons and as screens, up to 4 km long and 1 km wide, separating some of the major plutons. It consists predominantly of metasediments

TABLE 10. AREAL EXTENT OF SYN- TO POST–OROGENIC GRANITOIDS (km^2)

	Granitoid type										
Pluton	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*Total*
LEUCOGRANITE-DOMINATED PLUTONS											
Tennysons Leucogranite					61.0	3.9	0.1	203.0	11.9	22.0	301.9
Yenberrie Leucogranite						1.0			1.0		2.0
Wolfram Hill Granite						9.6			6.9		16.5
Mount Davis Granite			1.0		14.7	14.7					30.4
Frances Creek Leucogranite									113.4		113.4
Saunders Granite						26.7				26.7	
Wandie Granite							3.3				3.3
Foelsche Leucogranite									22.6		22.6
Umbrawarra Leucogranite								140.2			140.2
Douglas Leucogranite								32.2	6.3		38.5
Fenton Granite									32.3		32.3
Burnside Granite						88.6					88.6
CONCENTRICALLY ZONED TRANSITIONAL GRANITE/ LEUCOGRANITE PLUTONS											
Allamber Springs Granite		315.6		7.3	180.3	114.9					618.1
Driffield Granite		27.7		0.9	51.7	64.8			10.5		155.6
Bonrook Granite				3.0		4.1			0.4		7.5
Tabletop Granite		94.7	9.6	9.0	20.9	48.6			14.7		197.5
Shoobridge Granite			2.2								2.2
GRANITE-DOMINATED PLUTONS											
Minglo Granite			384.1								384.1
Mount Porter Granite			8.5								8.5
McCarthys Granite			302.0		22.9	41.4			0.4	25.4	392.1
Fingerpost Granodiorite		191.6		18.5							210.1
McKinlay Granite			22.1								22.1
Prices Springs Granite			88.6								88.6
McMinns Bluff Granite			305.0								305.0
Margaret Granite			82.5								82.5
Subtotal	196.6	1633.0	29.1	43.1	370.0	350.2	30.1	375.8	245.4	22.0	**3290.3**
(%)		(6)	(50)	(1)	(1)	(11)	(11)	(1)	(11)	(7)	(1) (100)
FRACTIONATED ALKALI AND THOLEIITIC SUITES											
Rafts and xenoliths (including Bludells Dolerite)											51.8
UNDIVIDED HORNFELS											19.0
								Total area of Cullen Batholith			**3361.1**

lithologically similar to contact-metamorphosed Early Proterozoic rocks surrounding the Cullen Batholith, probably representing 'undigested' or stoped blocks of sediment carried within the intruding granitoids. Rare coarse amphibolite crops out with metasediments within the batholith at HK 1882 and may be Zamu Dolerite. The bodies are probably not roof pendants, as no ghost stratigraphy or structure is preserved. The presence of K-feldspar-cordierite mineral assemblages also indicates temperatures higher than would normally be reached at the roof of a granitoid intrusion.

Alteration and deformation

All the granitoids show evidence of pervasive alteration (Table 9). This alteration may be associated with:

- (1) hydrothermal activity associated with the magmatic process,
- (2) deformation post-dating granitoid intrusion, and
- (3) younger regional metamorphism.

Textures indicate mostly post-intrusion re-equilibration to lower greenschist facies assemblages and are analogous to those described by Wyborn & Page (1983) formed during progressive regional metamorphism of granites from the Kalkadoon Batholith of the Mount Isa Inlier. Plagioclase and mafic minerals (biotite and hornblende) are the main minerals affected. Plagioclase (albite, oligoclase, andesine) is mostly altered to sericite, epidote and calcite; mafic minerals are altered to chlorite, epidote and iron oxide. Chlorite and epidote commonly replace biotite along grain boundaries and cleavage planes and also form lensoidal growths with K-feldspar parallel to cleavage planes. Rarely secondary skeletal growths of biotite are present. Hornblende mostly shows marginal alteration to chlorite and epidote and is less commonly replaced by pale to dark-green amphibole. Swapped optically continuous rims of albite and K-feldspar where the two minerals are in contact are rarely present, are probably the result of the interaction of a low temperature, late-stage, intergranular fluid with meteoric water. Apart from the addition of water, the mineralogical changes indicate little addition or removal of elements.

Deformation textures are also widespread, but are more intense in the west in the Mount Shoobridge Fault system, in the centre where the batholith is cut by the Pine Creek Shear Zone (Fig. 22), and along pluton margins where a weak foliation, parallelling the contact, is common. Undulose extinction, bent biotite crystals, tapered feldspar twins and recrystallised unstrained polygonal mosaics along grain boundaries are common features.

In the west, the Fenton Granite is cut by a 3 km-wide north-trending shear zone, bordered to the east in part by the Mount Shoobridge Fault. The granite within the shear zone is weakly to strongly foliated, and is characterised by recrystallised polygonal quartz foliae which wrap around strained and fractured feldspar crystals. In places, the foliae also contain recrystallised biotite or epidote and sphene.

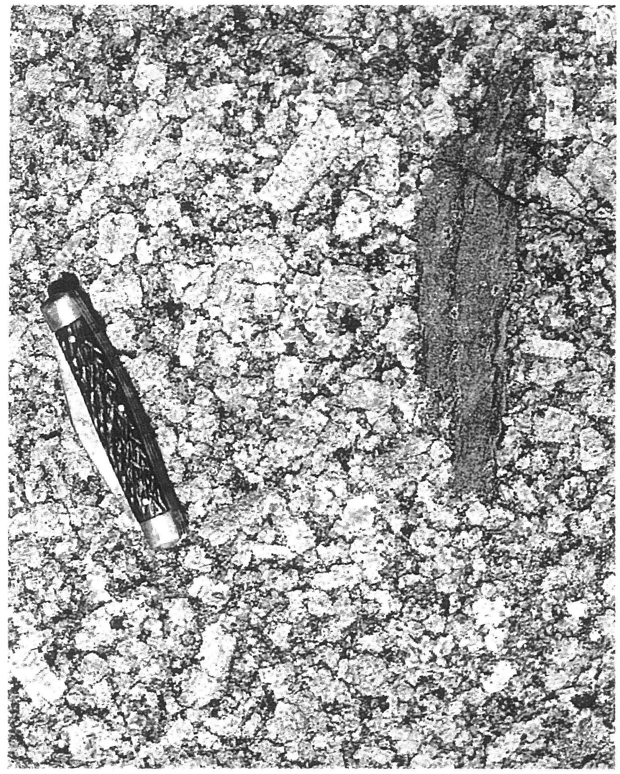


Fig. 18. Pink and green coarse porphyritic hornblende-biotite granite (type 2), with microperthite and microcline megacrysts, is the dominant phase of the Allamber Springs Granite. This phase makes up about 50% of the Cullen Batholith.

Within the Pine Creek Shear Zone, the granitoids have a chlorite grade metamorphic overprint and are commonly foliated, highly strained and extensively altered. Quartz and feldspar grains are fractured and strained; recrystallised, unstrained granular mosaics occur along grain boundaries. K-feldspar is mostly altered to sericite, and patchy quartz and plagioclase are sericitised or replaced by scapolite. Mafic minerals are totally replaced by either chlorite or aggregates of colourless to pale green amphibole, sphene and clinozoisite. Calcite, chlorite and quartz form secondary patchy growths or micro-veinlets, filling fractures and cleavage partings in feldspars. In zones of extreme shearing, the granites form a foliated micro-breccia, ultracataclasite or mylonite, which may be cut by veinlets of scapolite (Fig. 23). Quartz is the only recognisable primary mineral fragment within these zones; secondary muscovite, sphene, topaz and fluorite are present in places.

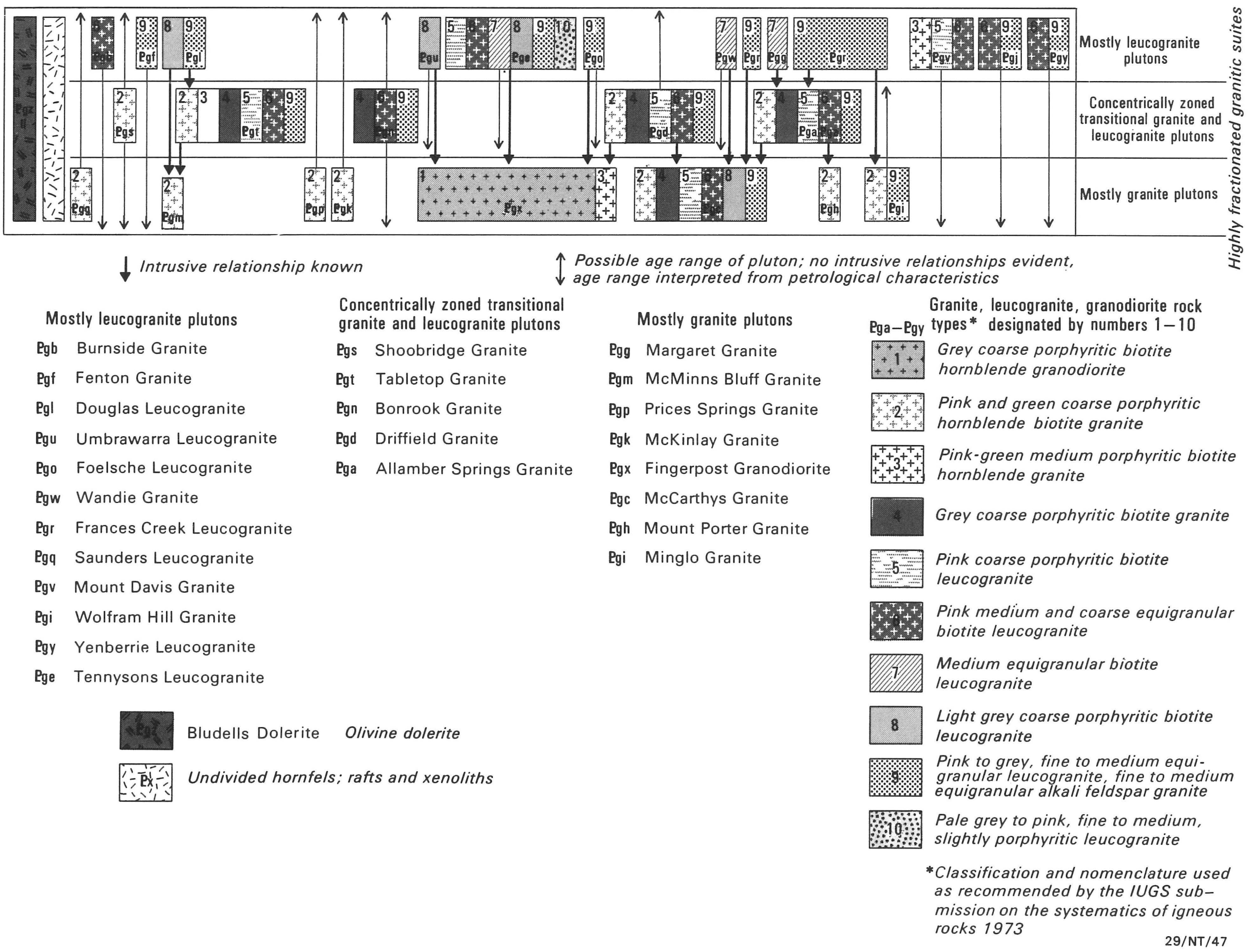


Fig. 19. Diagrammatic relationship of Cullen Batholith plutons and phases.

Other zones of more intense deformation and alteration up to 10 m wide are associated with linear, mostly northwest and northeast to north-trending, quartz breccias and veins throughout the Cullen Batholith. Within these zones quartz and feldspar grains are cracked and strained. Plagioclase is replaced by fine cloudy iron oxide granules, muscovite and chlorite; and biotite is replaced by white mica, chlorite, epidote, limonite and hematite. These zones are also extensively veined by unstrained quartz, chlorite, epidote and rare fluorite. In the McMinns Bluff Granite, several east and northeast-trending siliceous and ferruginous breccias up to 2 km long occur within the granite. The breccias consist of angular blocks of chloritised, hematised and silicified granite in a hematitic quartz-veined matrix and form zones, up to 2 m wide surrounded by 10 m wide zones of sheared and altered granite. Secondary copper mineralisation occurs in one such breccia 14 km north of McMinns Bluff (GK 8586). In the west, within localised shear zones, such as 3 km northwest of Douglas Homestead, granite is fractured and altered to quartz-albite-K-feldspar-epidote-sphene (Joplin, 1957; Walpole & others, 1968).

Geochronology

Previous geochronological work in the Pine Creek Geosyncline, based largely on U-Pb zircon and Rb-Sr whole-rock data, showed the existence of ~2500 Ma granitic basement (Nanambu Complex, akin to the Rum Jungle Complex), and younger 1860 to 1880 Ma granitoids intruding the Early Proterozoic sequence (Page & others, 1980). Additionally, a number of metamorphic rocks in the Alligator Rivers Uranium Field gave whole-rock Rb-Sr ages, and biotite Rb-Sr and K-Ar ages of close to 1800 Ma. This was interpreted as the timing of the main regional metamorphic event in that part of the Pine Creek Geosyncline.

Granitoids of the Cullen Batholith, as well as other so-called 'Carpentarian' granites of the Pine Creek Geosyncline, had generally been considered (Walpole & others, 1968) as post-tectonic in their timing and origin, and hence younger than 1800 Ma. A group of Rb-Sr whole-rock and biotite measurements from some of the plutons comprising the batholith gave a pooled age of 1780 ± 20 Ma (Riley, 1980), appearing to confirm their pre-1800

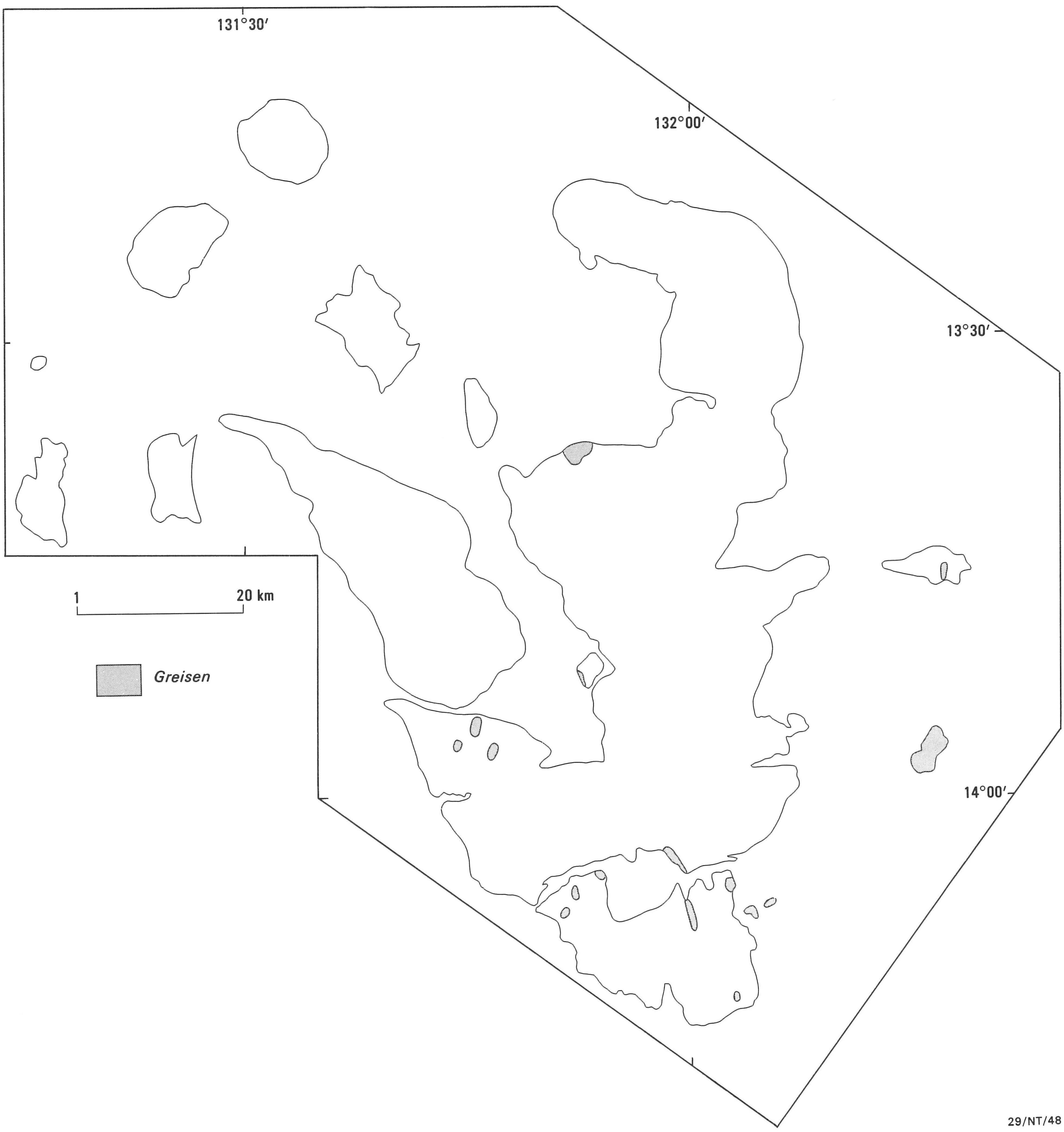


Fig. 20. Distribution of greisen zones, Cullen Batholith.

Ma age constraint. An earlier review of reconnaissance Rb-Sr data from some of these bodies by Compston and Arriens (1968) also indicated ages (including the Cullen Batholith) of 1780 to 1790 Ma, but younger, updated ages (1650-1700 Ma) had been found from K-Ar biotite dating of these rocks (Hurley & others, 1961).

Relationships between plutons of the Cullen Batholith indicate a broad three-fold subdivision in both composition and age:

- (1) the oldest group of plutons is dominated by the more mafic granitoid phases (types 1 and 2), and includes the Margaret, McMinns Bluff, Prices Springs, McKinlay, McCarthys, Mount Porter, and Minglo Granites, and the Fingerpost Granodiorite;
- (2) characteristically concentrically zoned granite and leucogranite (types 2 to 6, and 9) commonly showing transitional contacts, including the

Fig. 21. Compositionally banded quartz-rich greisen (white) intruding muscovite-quartz greisen (dark), Wolfram Hill Granite.

Shoobridge, Tabletop, Bonrook, Driffield and Allamber Springs Granites;

- (3) the youngest most felsic plutons (types 7 to 10) dominated by one leucogranite phase (including the Burnside, Fenton, Wandie, Mount Davis and Wolfram Hill Granites, and the Douglas, Umbrawarra, Tennysons, Yenberrie, Foelsche and Frances Creek Leucogranites). This group often contains xenoliths, rafts or pendants of adjacent granitoids or metasediments, and probably represents high-level intrusions peripheral (except for the Frances Creek Leucogranite) to the main body of the batholith.

This threefold age relationship is in agreement with but is unconfirmed by geochronological studies, in which five plutons representative of the three groups indicated by field relationships have been studied in some detail using U-Pb zircon methods. Initial work on these, and an additional four plutons, using multi-grain, conventional U-Pb zircon techniques, yielded discordant imprecise results, so the ion microprobe technique was subsequently used. All geochronological data, including early Rb-Sr total rock and mineral data and K-Ar data are given in Appendices 2, 3 & 4 and results are summarised in Table 11.

U-Pb zircon data

All U-Pb zircon data from nine plutons are given in Appendices 2 and 3 and plotted in Figure 24. Thorium and uranium plots for the analysed zircons are shown in Figure 25. The ion microprobe and conventionally determined ages listed in Table 11 are closely comparable, however, the ion-microprobe results are generally far more precise than the discordant data obtained from multi-grain analyses. This discordance and poorer precision is due to the presence of non-zircon inclusions in the multi-grain populations, higher common Pb corrections, and a component of inherited zircon. The last could only be detected in the ion-microprobe analyses.

The internal precision and consistent pattern of the ion-microprobe ages strongly suggest that they represent ages of magmatic crystallisation, and hence approximate the magmatic ages of the individual plutons. There is no statistical difference between the ages (ranging from 1818 to 1825 Ma) of the Fingerpost Granodiorite, Allamber Springs Granite, and the Umbrawarra Leucogranite, suggesting that these phases are coeval.

The only part of the batholith with a significantly different age is the McMinns Bluff Granite (1835 ± 6 Ma), which is older than the other plutons and consistent with the field observation that it is part of the oldest pluton group (granite-dominated) and is intruded by the Douglas Leucogranite and Tabletop Granite. The 1800 ± 5 Ma age for the Burnside Granite, indicated by nine near concordant analyses, is unlikely to define the magmatic crystallisation age.

Rb-Sr whole-rock data

Rb-Sr data for 14 whole-rock samples from five plutons are listed in Appendix 4 and plotted in Figure 26. These data represent only the broadest regional coverage of the Batholith, except for the Allamber Springs Granite. In this case, six samples define a model 1 Rb-Sr isochron of 1773 ± 22 Ma (0.7060 ± 19). The validity of this result is strengthened by the isotopically coherent data from the other four plutons (including data from Riley, 1980), which also lie on a model 1 isochron. The pooled regional age for the 14 samples is 1784 ± 8 Ma (initial $^{87}Sr/^{86}Sr$ 0.7057 ± 3). This age and initial $^{87}Sr/^{86}Sr$ is identical to the regional result reported for nine other Pine Creek Geosyncline granitoids by Riley (1980) summarised in Table 11.

The pooled Cullen Batholith Rb-Sr age is 40 million years younger than the U-Pb zircon ages, and is close to the Rb-Sr age obtained for the McMinns Bluff Granite samples. P.J. Leggo's Rb-Sr data of 25 years ago (see Appendix 2, Walpole & others, 1968; summary by Compston & Arriens, 1968), are based on only a few samples, but also indicated ~1780 Ma ages. The

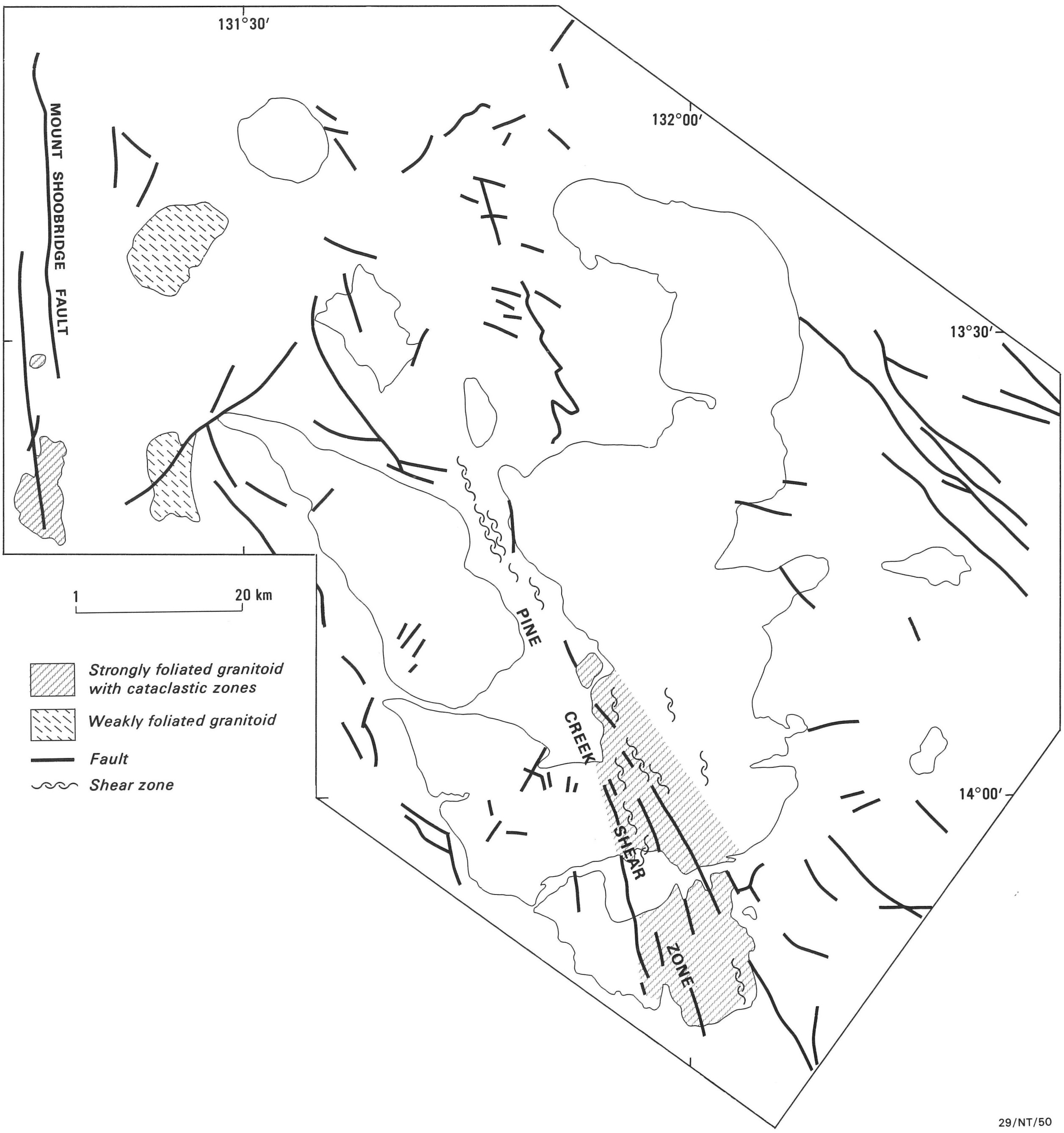


Fig. 22. Deformation zones in the Cullen Batholith.

coherence of this result over such a wide region has to be geologically significant. Unlike parts of the McMinns Bluff Granite, the other granites are not foliated, and hence it is difficult to correlate any petrographic evidence with their young Rb-Sr age. However, all the plutons of the batholith show some degree of alteration and re-crystallisation. The 1770-1780 Ma Rb-Sr age is interpreted here as reflecting the timing of mild hydrothermal activity associated with the Shoobridge Event. In the area of the McMinns Bluff Granite, this included or was accompanied by faulting and shearing that imposed a strong secondary fabric on the granitic rocks. The K-Ar biotite ages (1650-1700 Ma – Hurley & others, 1961) on some of these rocks suggest that final cooling to below 250°C was not attained until some 100 m.y. later.

Geochemistry

Although useful in defining phases of individual plutons, the ten petrographic types, distinguished in the field on the basis of hand-specimen texture and mineralogy, are too broad to be chemically significant, as considerable

Fig. 23. Granite micro-breccia with ultracataclasite veinlets; typical of deformation within the Pine Creek Shear Zone.

mineralogical variation within each type means that each is not chemically unique. The bulk-rock chemical composition of each sample is controlled by the mineral phases present, particularly hornblende, biotite, muscovite, apatite, zircon and allanite. As the abundance of these minerals changes systematically with progressive fractionation, both within and between plutons, the chemical features are unique to each pluton.

The chemistry of individual phases and plutons is affected by the following:

- (1) the degree of fractionation in the felsic phases (>74 wt % SiO_2),
- (2) the abundance of hornblende as opposed to biotite in the mafic phases (<74 wt % SiO_2), and
- (3) the dominant accessory phases present.

The alteration of the rocks makes it difficult to determine whether oxide/sulphide phases present are primary, and to chemically distinguish late overprints associated with deformation and/or metamorphism from any primary hydrothermal alteration. Regardless of the cause of alteration, its presence is probably responsible for most of the scatter on geochemical plots.

A summary of geochemical characteristics with relevant petrographic data is given for the plutons in Table 12 and selected Harker diagrams are given in Figure 28. The locations of all chemically analysed samples, and brief petrographic descriptions are listed in Appendix 1.

Leucogranite-dominated plutons can be subdivided, on the basis of chemistry, into three distinct chemical suites (Fig. 27). However, such subdivision is not possible for the concentrically zoned transitional granite and leucogranite-dominated plutons and the granite-dominated plutons as they are extremely variable in composition. Mafic end-members of these two groups can only be divided into two broad suites based on the dominance of either hornblende or biotite, whilst the felsic end members are similar to one or more of the three leucogranite suites of the leucogranite-dominated plutons. Thus each zoned or granite-dominated pluton has its own chemical characteristics, which in some cases is strikingly dissimilar from any other pluton in the Batholith. Consequently, the chemistry of each pluton is described separately, with individual plutons grouped into suites where possible.

Granite-dominated plutons

The more mafic granite-dominated plutons can be subdivided depending on whether the dominant mafic mineral in the more mafic samples is hornblende or biotite; and the wt% at which hornblende disappears with increasing SiO_2. There are two distinct chemical end-members represented by the hornblende-dominated Fingerpost Granodiorite, which has hornblende present up to 69.24 wt%, and the biotite-dominated McMinns Bluff Granite, with hornblende only up to 64 wt% SiO_2.

Hornblende-dominated suites, including the Fingerpost Granodiorite, McCarthys Granite and the Minglo Granite are high in CaO, Sr and V, and low in TiO_2. K/Rb values are high and show little variation with SiO_2 content, and ASI values are some of the lowest in the batholith.

Biotite-dominated suites: The McMinns Bluff Granite forms two chemically and petrographically distinct bodies, here designated as the McMinns Bluff Granite (west) and the McMinns Bluff Granite (east) separated by unconformably overlying Middle Proterozoic cover. The western part is characterised by hornblende up to 72 wt% SiO_2, whereas in the east hornblende is only present in samples with <64 wt% SiO_2. The granite in the west is strongly deformed, foliated and recrystallised with a metamorphic imprint of up to biotite grade, whereas in the east it is massive except near the margins where a weak foliation is developed parallel to the contact with the metasediments. The northwestern parts of the eastern pluton, particularly close to the Hayes Creek Fault Zone, are also metamorphosed to upper greenschist facies. Relative to other plutons of the Cullen Batholith both parts are high in TiO_2, K_2O, P_2O_5 and Nb.

Mixed biotite-hornblende suites: The Margaret, Prices Springs, Mount Porter Granite and McKinlay Granites

TABLE 11. SUMMARY OF U-Pb ZIRCON AGES (MA) AND Rb-Sr AGE INFORMATION FOR THE CULLEN BATHOLITH

Sample number, Geological unit	*Ion microprobe zircon age*	*Conventional U-Pb zircon age (lower intercept age)*	*Rb-Sr whole-rock age (this study)*	*Rb-Sr age (previous studies)*
79125013	1835±6	1818±3	1767±23 (19 samples)	
(McMinns Bluff Granite)		(193±10)	(0.7061±13)	
83126026	1818±5	1826±18		
(Allamber Springs Granite – mafic phase)		(380±90)		
79125012	1823±3	1843±22		
(Fingerpost Granodiorite)		(395±40)		
83126032	1822±6	1826±32	1773±22 (6 samples)	
(Allamber Springs Granite)		(283±40)	(0.7060±19)	
83126025	1825±7	1805±12		
(Umbrawarra Leucogranite)		(219±42)		
79125023	1800±5	1750±56		1780-1790 Ma[2]
(Burnside Granite)		(426±160)		
79125025		1775±16		
(Shoobridge Granite)		(286±34)		
79125005		1804±50		1780-1790 Ma[2]
(Prices Springs Granite)		(353±48)		
79125024		1860±45		
(Margaret Granite)		(363±108)	Pooling of 5 Cullen Batholith plutons (14 samples) 1784±8 (0.7057±3)	Pooling of all PCG granites (9 samples) 1780±20 (0.7057±10)[1]
				Single biotite age, Cullen Batholith, 1782 Ma[1]

References: [1] - Riley (1980); [2] - Compston & Arriens (1968).

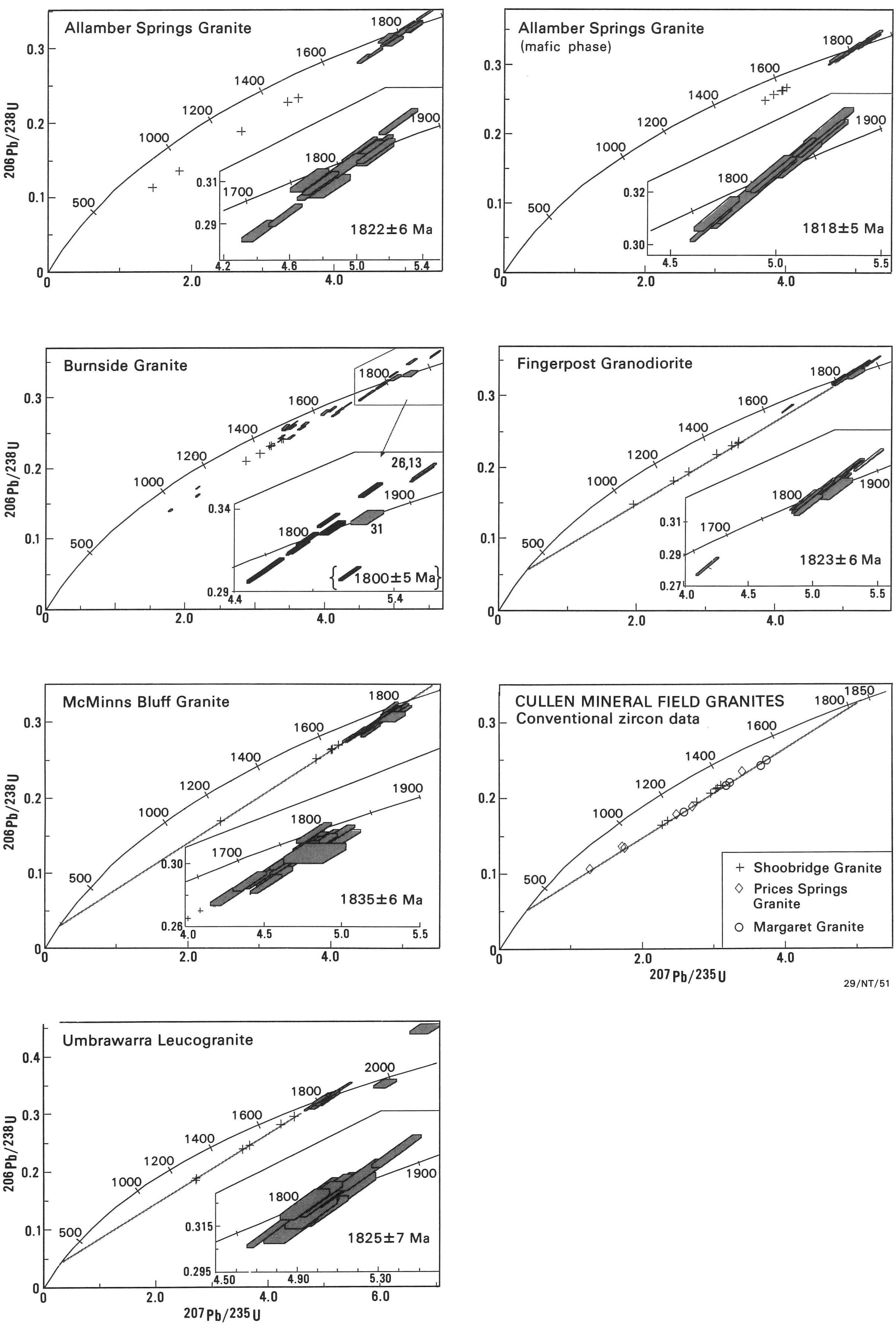


Fig. 24. U-Pb concordia diagrams.

(a) *Allamber Springs Granite* : The zircon population within this granite, like those from the Fingerpost Granodiorite, is dominated by strongly zoned brown euhedra-bearing minute inclusions, but has lower U (200-800 ppm - Appendix 2) and higher Th/U. The ion microprobe data straddle the concordia curve giving a weighted mean $^{207}Pb/^{206}Pb$ age of 1822±6 Ma, clearly indicating the age of igneous crystallisation and emplacement.The conventional data on five bulk fractions (Appendix 3) are relatively inferior because of high common Pb and extensive variable Pb loss from the zircons. The fitted regression (MSWD 56.4) indicates an age of 1826±32 Ma (lower intercept 284±40 Ma). Although the interpreted Pb loss trajectory from conventional work is approximately correct, the resultant age is far less precise than the microprobe result.

(b) *Allamber Springs Granite (mafic phase):* Zircons are light brown to colourless, euhedral, and exhibit strong magmatic zoning. Ion microprobe analyses of 14 grains indicate overlapping to somewhat higher U, Th and Th/U than in the McMinns Bluff Granite zircons (Appendix 2; Fig. 27). Analyses plot on the $^{206}Pb/^{238}U$ - $^{207}Pb/^{235}U$ concordia curve, and lie within analytical error of the weighted mean $^{207}Pb/^{206}Pb$ age, 1818±5 Ma. The five conventional zircon analyses (Appendix 3) are discordant presumably because of inclusions and areas of enhanced Pb loss in the bulk population. Regression of the conventional data indicates Palaeozoic Pb loss (lower intercept 380±90 Ma) and a magmatic age of 1826±18 Ma, in good agreement with the ion microprobe result. The latter can therefore be confidently interpreted as the magmatic and emplacement age.

(c) *Burnside Granite:* Zircons are squat, euhedral, and zoned. High U contents (Appendices 2 and 3) are reflected by the altered and deteriorated nature of most grains. Ion microprobe data (Appendix 2) are scattered with apparent $^{207}Pb/^{206}Pb$ ages between 1469 and 1864 Ma. This scatter is not meaningful, reflecting more than one stage of Pb loss from high U domains. Three graphically distinct groups are discernible: a relatively coherent possibly magmatic group, an older xenocryst group and a younger incoherent, discordant group. This grouping is not apparent morphologically. It is possible that the set of nine near-concordant analyses with a $^{207}Pb/^{206}Pb$ age of 1800±5 Ma define a magmatic crystallisation age. However, considering the older ages (1820 -- 1835 Ma) of other Cullen Batholith plutons and the chemical similarity of the Burnside Granite to some of the other leucogranite-dominated plutons in the batholith, it is unlikely that this age defines the magmatic crystallisation age. Four grains (20, 26, 31, 33) between 1830 and 1860 Ma old may be in part magmatic and/or xenocrystic. Most analyses are discordant and much younger indicating early and multi-stage Pb loss or U gain. The conventional, multi-grain data form a non-linear discordant array (MSWD 11.9) with concordia intersections at 1750±56 Ma and 462±160 Ma. Given the complexities and degree of discordance, these have no geological significance other than being in broad agreement with the ion microprobe results.

(d) *Fingerpost Granodiorite:* Zircons are euhedral, magmatically zoned and dark-brown, with high U contents, mostly between 1000 and 1500 ppm (Appendix 2 and 3). Except for grain 30, the ion microprobe data for the 16 grains analysed form a close population in $^{207}Pb/^{206}Pb$. There is a scatter slightly in excess of experimental error and the data are effectively concordant, at a pooled age of 1823±6 Ma. The much lower U (335 ppm) content of grain 31 decreases the counting statistics for this analysis, leading to a significantly larger error assignment, but exclusion of the analysis makes no difference to the determined age. The seven conventionally determined, multi-grain analyses, having large common Pb corrections, are variably discordant on a trajectory (MSWD 15.8) giving an upper intercept age of 1843±22 Ma (lower intercept 395±40 Ma). This upper intercept age concurs with the ion microprobe result, but the concordancy and better precision of the latter are preferred as defining emplacement age.

(e) *McMinns Bluff Granite*: The granite contains clear, zoned euhedral zircons. Ion microprobe analyses of 21 grains (Appendix 2) show a slightly discordant population on the $^{206}Pb/^{238}U$ versus $^{207}Pb/^{235}U$ discordia plot. However, there are no xenocrystic outliers, and a close coherency in $^{207}Pb/^{206}Pb$ (21 data points within experimental uncertainties) indicates a magmatic age of 1835±6 Ma. Five conventionally analysed, multi-grain zircon fractions (Appendix 3) have the same range of U content as the ion probe analyses but are more discordant, having substantially higher common Pb corrections. The highest-U (-45) fraction is very discordant, suggesting non-zero Pb loss. The conventional array is nevertheless approximately linear (MSWD 1.5), and the extrapolated U-Pb age is 1818±3 Ma (lower intercept 193±10 Ma). This is younger than the indicated ion microprobe age, but is consistent given the gross discordance of one of the bulk fractions and the undue influence this point has on the slope of the discordia trajectory.

(f) *Conventional zircon data of other Cullen Mineral field granites:*

Limited zircon analysis of the *Margaret Granite* shows that the zircons contain a high proportion of common Pb (Appendix 3) and low U. The data are discordant and the regression has a large uncertainty (MSWD 32.4), indicating ages of 1863±45 Ma and 363±110 Ma.

Seven zircon U-Pb measurements from the *Prices Springs Granite* are discordant. Indicated upper and lower intercept ages of 1804±50 Ma and 353±50 Ma are relatively imprecise owing to the presence of high common Pb, high U (1027-2577 ppm), and probable inheritance (MSWD of the discordia regression is 85.1).

Zircons from the *Shoobridge Granite* are squat, translucent and euhedral. The seven measured fractions have moderately high U contents (1244-1516 ppm), high common Pb corrections (Appendix 3), and discordant $^{206}Pb/^{238}U$ versus $^{207}Pb/^{235}U$ data. The discordia regression does not fit within experimental error (MSWD 5.3), and indicates upper and lower intercept ages of 1775±16 Ma and 286±34 Ma.

(g) *Umbrawarra Leucogranite*: Zircons are generally weakly zoned clear grains of igneous aspect with low U and Th contents (Appendix 2), although bulk conventional analyses have high U contents owing to the presence of small inclusions. Apart from the obvious xenocryst analysis (grain 4, $^{207}Pb/^{206}Pb$ age 2036±41 Ma), the data from nineteen analytical points are concordant and coherent to within experimental uncertainties. A magmatic zircon crystallisation age is indicated by the weighted mean $^{207}Pb/^{206}Pb$ age of 1825±7 Ma. Owing to the presence of common P the conventional data are variably discordant on a regression line (MSWD 14.7) with apparent concordia intercept ages at 1805±12 Ma and 219±42 Ma.

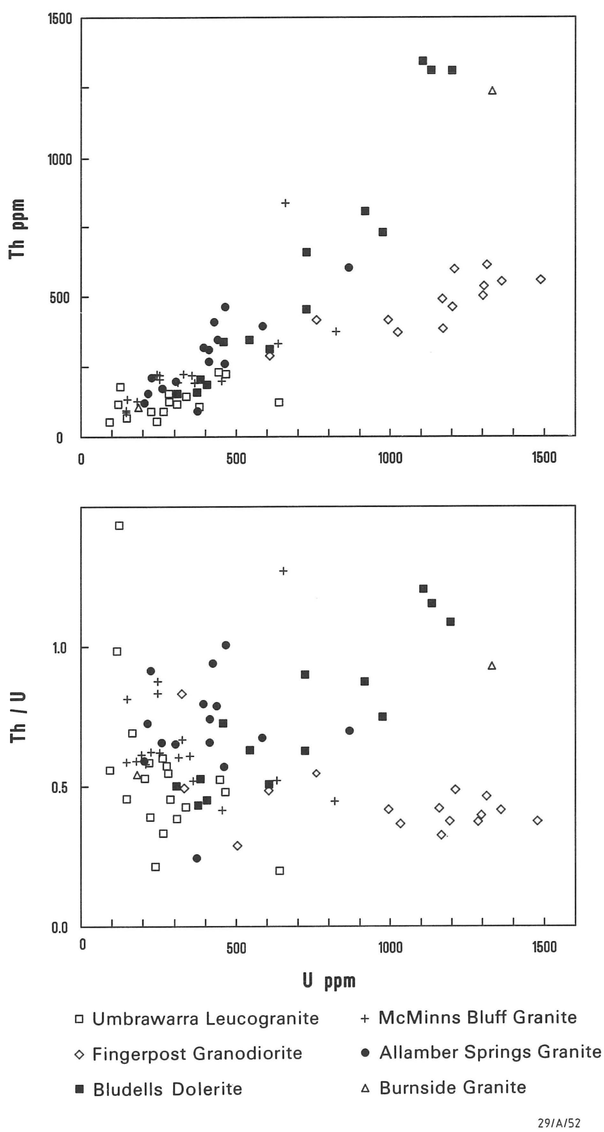


Fig. 25. Th vs. U and Th/U vs. U plots for zircons from the Cullen Batholith.

show characteristics that are intermediate between those of the hornblende- and biotite-dominated groups. However, these intermediate characteristics may be the result of insufficient sampling over an adequate SiO_2 range.

Concentrically zoned transitional granite and leucogranite-dominated plutons

Concentrically zoned transitional granite and leucogranite-dominated plutons have a wide range of SiO_2 contents with mafic end members showing similarities to either the hornblende- or biotite-dominated granite suites, and the more felsic end-members showing characteristics of at least one of the leucogranite suites. Hornblende-dominated suites include the Driffield, Tabletop, Mount Davis and Shoobridge Granites, and biotite-dominated suites comprise the Allamber Springs and Bonrook Granites. The plutons are divided on differences within the more mafic end-members.

Leucogranite-dominated plutons

The leucogranite-dominated plutons, chemically characterised by >70 wt% SiO_2, are divided into three suites on the basis of degree of fractionation with increasing SiO_2. The degree of fractionation is largely determined by changes in:

- (a) Rb, Li, U, and Y content;
- (b) the alumina saturation index [ASI; Zen, 1986: molecular $Al_2O_3/(Na_2O + K_2O + CaO - 3.3 P_2O_5)$];
- (c) $Fe_2O_3/(FeO + Fe_2O_3)$; and
- (d) K/Rb.

Saunders suite: The Saunders suite, comprising the Saunders and Foelsche Leucogranites, shows little variation in K/Rb values, or Rb, Li, U, and Y contents with increasing SiO_2. Both plutons have an ASI <1.1 and $Fe_2O_3/(FeO + Fe_2O_3)$ values >0.24.

Burnside suite: Plutons of the Burnside suite include the Burnside Granite, the Douglas Leucogranite, the Frances Creek Leucogranite and the Wandie Granite. These plutons show increasing Rb, Li, U, and Y and decreasing K/Rb values with increasing SiO_2, with ASI <1.1 and $Fe_2O_3/(FeO + Fe_2O_3)$ values ranging from 0.3 to 0.1. The suite is associated with numerous vein Au, Cu, Sn, Ag-Pb and minor Mo occurrences and deposits.

Tennysons suite: The Tennysons suite is characterised by increasing Rb, U, Y and decreasing K/Rb values with increasing SiO_2. The ASI is >1.1 and $Fe_2O_3/(FeO + Fe_2O_3)$ values are <0.24. The suite, associated with numerous vein U, Sn, W, topaz, fluorite and monazite occurrences, contains some of the most reduced plutons, including the Tennysons Leucogranite, Yenberrie Leucogranite, Wolfram Hill Granite, Fenton Granite and Umbrawarra Leucogranite.

Processes and mechanisms of crystallisation

The chemical and petrographic variability between and within plutons of the Cullen Batholith can be explained by assuming that the batholith crystallised by a process of convective fractionation (Sparks & others, 1984). In this process, magma initially crystallises by accretion of the more mafic mineral phases on the walls of the magma chamber. The derivative interstitial liquid, being less dense than the primary magma, ascends to the top of the magma chamber. Here, because of the large density difference between the primary liquid and the derivative liquid, the two remain segregated and cannot mix, and a compositionally stratified magma chamber is produced.

As crystallisation progresses, the chamber will contain at least three components: the initial magma; the more mafic material that has crystallised on the walls of the chamber; and the lighter derivative liquid, which is more felsic in composition, ponding at the top. Because sidewall crystallisation progresses inwards, cooling by this process produces concentrically zoned plutons becoming progressively more felsic towards the centre.

Periodically, the lighter derivative liquid may move away from the magma chamber and either intrude as leucogranites or extrude as volcanics; the latter usually as flow-banded, crystal-poor rhyolites (Wyborn & Chappell, 1986). However, the composition of both the more felsic derivative liquids, and the original màgma may evolve to the point where the density difference between the two is insufficient to maintain two stratified layers and the layers tend to backmix (Mahood, 1991), producing a pluton of more homogeneous granodiorite to adamellite composition. The end-product of a granitic magma crystallising in this manner is a heterogeneous suite of plutons of three types: leucocratic granites, concentrically zones plutons, and homogeneous plutons of granodioritic to adamellite composition. Each individual pluton usually has distinct chemical composition. A well-documented example of this style of crystallisation is the Boggy Plain Suite of the Lachlan Fold Belt described by Wyborn & others (1987).

Thus, the Cullen Batholith, with groups of leucocratic granites, concentrically zoned plutons and homogeneous plutons, is interpreted as having evolved from a single magma (with the possible exception of the McMinns Bluff Granite) by the process of convective fractionation at or around 1825 Ma (see preceding section on geochronology). Each pluton represents distinct intrusive pulses of magma into the crust derived from either the main parent magma as it progressively evolved in chemical composition, or from fractional crystallisation processes within individual plutons.

Examples of concentrically zoned plutons which become progressively more felsic towards the centre include the Allamber Springs, Shoobridge and Tabletop Granites, whilst examples of plutons of more homogeneous granodiorite to adamellite composition are the eastern part of the McMinns Bluff Granite and Margaret Granite; the abundant leucogranites would be derived from the more felsic liquids.

As the indicated crystallisation age of the McMinns Bluff Granite is 1835 Ma., somewhat older than other components of the batholith, it may be the product of an earlier magmatic event, and not part of the main fractionating system. It is possible, however, that the zircon population which dominates the sample of McMinns Bluff Granite may be an inherited group. Zircons from the granite are distinctly low in U relative to

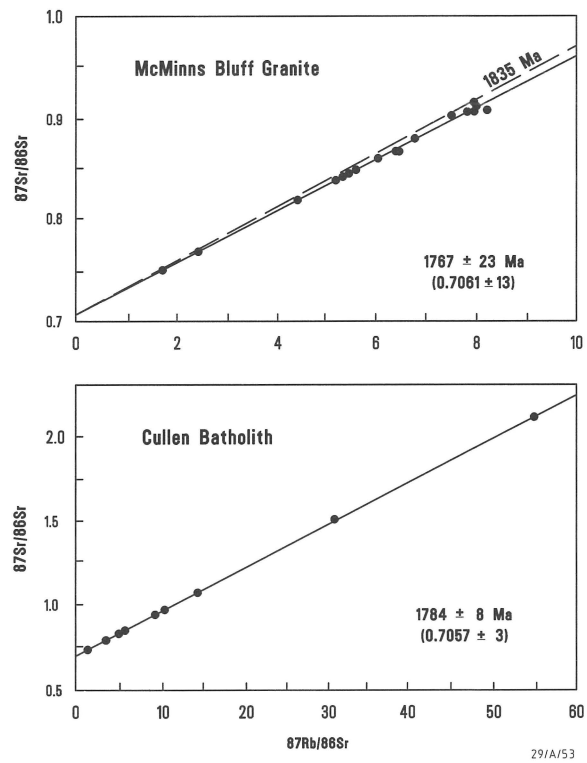


Fig. 26. $^{87}Sr/^{86}Sr$ vs. $^{87}Sr/^{86}Sr$ plots for the McMinns Bluff Granite and undivided Cullen Batholith.

other zircon samples from the Cullen Batholith, and may be inherited from another source.

Relationship of the bulk–rock geochemistry of individual plutons to the fractionation process

For batholiths that have crystallised by a process of convective fractionation, the bulk rock chemistry of each individual pluton is controlled by the composition of the crystallising minerals which change with both progressive cooling and evolution of the magma system. With the possible exception of the McMinns Bluff Granite, the earliest pluton to crystallise would have been the Fingerpost Granodiorite, forming at a time when hornblende was the main mafic mineral to crystallise. As the relative amount of hornblende decreased, biotite increased in proportion within the more mafic plutons: some of the younger, more leucocratic plutons were always dominated by biotite (e.g. Allamber Springs Granite). The dominance of either biotite or hornblende has a profound effect on the chemistry of the more mafic plutons. At similar SiO_2 values, the hornblende-dominated plutons (e.g. Fingerpost Granodiorite) are enriched in MgO, CaO, Na_2O, Ni, and Cu, and depleted in K_2O, total Fe, TiO_2 and Al_2O_3, Li, Zn, and F relative to the more biotite-enriched plutons (e.g. Allamber Springs Granite).

Fig. 27. Distribution of granitoid suites, Cullen Batholith.

Accessory minerals also affect the compositions of the plutons. The early hornblende-rich plutons are low in Zr and P_2O_5, presumably because of a late crystallisation of zircon and apatite respectively from the melt. La and Ce are high in those samples that have allanite, such as biotite-rich coarse granite samples which have ASI <1.1. Monazite is more common in plutons that have higher ASI values and vein monazite occurs in association with the Tennysons suite.

The abundance of Ba, Sr, Pb and Rb is controlled primarily by the crystallisation of feldspar. Barium is highest in the biotite-dominated McMinns Granite and tends to decrease with increasing fractionation, whilst Rb increases and the K/Rb value decreases.

The ASI increases with fractionation: the rate of increase is accelerated by the crystallisation of hornblende, which has a low ASI. Thus, the hornblende-rich Fingerpost Granodiorite has the lowest ASI; and the Tennysons suite, the most fractionated leucogranite suite, has the highest ASI.

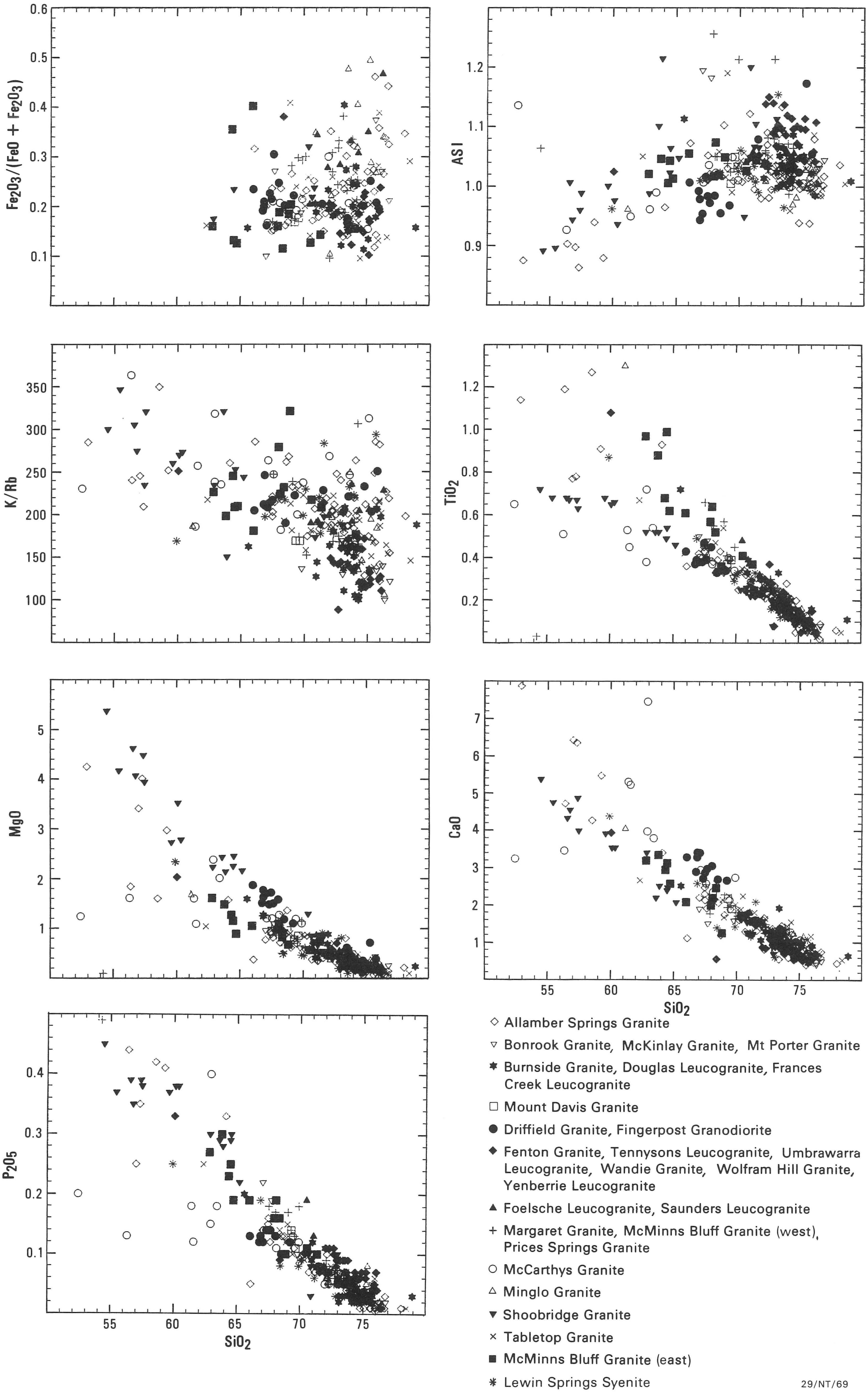


Fig. 28. Selected Harker diagrams for the Cullen Batholith.

TABLE 12. SUMMARY OF GEOCHEMICAL CHARACTERISTICS OF THE CULLEN BATHOLITH

Unit	*Nº of samples*	*Description of analysed samples*	*Accessory minerals*	*Alteration*	*SiO_2 range (wt%)*	*K/Rb**	*ASI*	*FeO/ (FeO + Fe2O3)**	*Remarks**
LEUCOGRANITE - DOMINATED PLUTONS									
Saunders suite									
Saunders Leucogranite	8	Fine or medium grained biotite leucogranites: some with rounded quartz phenocrysts and all with olive brown biotite, microcline, and sericitised plagioclase.	Allanite, zircon, opaques and apatite.	Sericite, chlorite and epidote.	70.51 - 75.15	High and flat with increasing SiO_2	<1.1	High, most samples >0.28.	High TiO_2, Al_2O_3, MgO, Ba, Sr, Th, Zr, Nb, La, Ce, V, Cr and low Na_2O and Y contents. U, Rb, Y and Li contents remain constant with increasing SiO_2.
Foelsche Leucogranite	1	Fine to medium-grained leucogranite characterised by granophyric intergrowths of quartz and K-feldspar.	Common pyrite.	Chlorite, calcite, epidote and sericite.	76.31	High.	<1.1	High.	Low Li, Rb, U and Y.
Burnside suite									
Burnside Granite	11	Biotite granite with olive brown biotite and microcline.	Muscovite, allanite, fluorite and apatite.	Plagioclase grains are sericitised with cores altered to clays	71.96- 74.80	Very low.	<1.1	0.28 - 0.05 (3 samples only).	With increasing SiO_2 Rb, Li, U, and Y rapidly increase exponentially to very high values. High Al_2O_3, Na_2O, Pb, Th, Zr, La, Ce, and Zn values, and low TiO_2, MgO, CaO, K_2O, P_2O_5, Ba, and Sr values. The analyses form a tight grouping, with the exception of D52/8/1 which is anomalous in most major elements.
Douglas Leucogranite	7	Mostly coarse porphyritic biotite leucogranite. Two samples (80120040 and 80120042) are fine-grained biotite leucogranite. Most samples have microcline, red brown biotite and opaque phases, similar to those in the adjacent McMinns Bluff Granite (east.)	Muscovite, microcline apatite.	Largely unaltered Three samples were more highly altered (80120089, 80120040, and 80120084) with common chlorite. Plagioclase is sericitised.	65.58 - 78.94	Very low.	<1.1		High total Fe, Pb, V, Ni and low Al_2O_3, Th, Zr, Nb, Ga, La and Ce with the Na_2O and Ba values. The one unaltered fine-grainedsample (80120042), having high Li, Y, Rb, and U and a low K/Rb value, is typically found in the more fraction-ated leucogranites of the batholith. The altered samples have high TiO_2 and variably anomalous K_2O and CaO values.
Frances Cr Leucogranite	10	Fine-grained biotite granite, with the exception of one coarse grained sample (75470094) with red-brown biotite, coarse allanite and altered plagioclase. The amount of muscovite increases and biotite decreases with increasing SiO_2.	Allanite and apatite.	Clay- and sericite-altered plagioclase. Green chlorite, epidote, sericite and coarse muscovite.	70.93 - 76.08	Low.	<1.1	>0.24	High in Li, Rb, U and Y. Enriched in TiO_2, Al_2O_3, Na_2O, Pb, Th, Zr, Nb, La Ce, V and low in MgO and Sr. The coarser-gained sample is 2 to 3 times enriched in La and Ce relative to the other samples.

Unit	*N° of samples*	*Description of analysed samples*	*Accessory minerals*	*Alteration*	*SiO_2 range (wt%)*	*K/Rb**	*ASI*	*FeO/ (FeO + Fe2O3)**	*Remarks**
Wandie *Granite*	1	Highly altered coarse-grained biotite granite.		Biotite partly altered to chlorite. Muscovite forms vein-like growths particularly on K-feldspar. Plagioclase is partially sericitised, particularly in the cores.	74.77	Low.	<1.1		Chemically the granite is similar to other fractionated leucogranites of the Burnside suite.
Tennysons suite									
Tennysons Leucogranite	12	Coarse, fine and medium-grained biotite granites and leucogranites, with olive brown biotite as the main mafic mineral. Coarser grained samples have 74 wt % SiO_2 with only traces of muscovite (mainly as sericite in plagioclase grains), whilst finer-grained samples (74 wt % SiO_2) are characterised by coarse muscovite and in some cases rounded quartz grains and granophyric intergrowths of quartz and feldspar. K-feldspar is microcline.	Apatite.	Chlorite. Plagioclase is sericitised.	72.08 - 75.94	Low (more fraction-ated samples).	>1.1 (more fraction-ated samples).	Low (more fraction-ated samples).	High values of TiO2, total Fe, K2O, P_2O_5, V, Ni, and Sn and low values for CaO, Na_2O, Ba, Sr, Th, Zr, Nb, La, and Ce. High Rb, U, and Y. Sample (75470058), which is altered, is distinctively low in Rb, Li and Y relative to other samples.
Yenberrie Leucogranite	1	Fine-grained biotite muscovite granite. Coarse muscovite, olive brown biotite, sericitised plagioclase, and microperthite .	Apatite.	Biotite altered to chlorite and epidote. Plagioclase cores sericitised.	75.23	Low.	<1.1	Low.	Similar to fine-grained, more fractionated samples of the Tennysons Leucogranite. High Rb and Y contents. Relative to the Tennysons Leucogranite it does not have high Li or U contents and has low Pb, Zr, and Nb contents.
Wolfram Hill Granite	1	Porphyritic adamellite			68.41		1.58	High.	Very depleted in CaO (0.56 wt %) and enriched in Al_2O_3 (17.26 wt %) hence the ASI value is unrealistically high). No petrographic description or trace element analysis is available for this sample.

Unit	*N° of samples*	*Description of analysed samples*	*Accessory minerals*	*Alteration*	*SiO_2 range (wt%)*	*K/Rb**	*ASI*	*FeO/ (FeO + Fe2O3)**	*Remarks**
Fenton *Granite*	8	Fine-grained adamellites ranging from 71.57 to 74.30wt % SiO_2 with one a medium grained hornblende granodiorite with 60.04 wt % SiO2 (76870143). They comprise mostly red brown to olive brown biotite, microcline, altered plagioclase and quartz.	Allanite, muscovite, sphene and rare garnet.		60.04 - 74.30	Low.	~1.1	Low.	Low TiO_2, MgO, P_2O_5, Th and high Na_2O, Sr, Pb, Ba, Zr, La, and Ce with the more fractionated parts showing a trend towards high Rb, U and Y.
Umbrawarra Leucogranite	4	Perthitic K-feldspar, olive to red brown biotite, and muscovite (increases in abundance with increasing with SiO_2).	Apatite.	Plagioclase is usually sericitised, particularly in the cores.	74.59 - 76.13	Low.	≤1.1	Low.	Low CaO, Na_2O, Ba, Sr, Pb, Th, Zr, Nb, La, Ce, V, Cr and high K_2O, P_2O_5, As and Sn. Like all fractionated plutons it has high Rb, U, Y & Li.

CONCENTRICALLY ZONED TRANSITIONAL GRANITE AND LEUCOGRANITE DOMINATED PLUTONS

Hornblende-dominated suites

Unit	*N° of samples*	*Description of analysed samples*	*Accessory minerals*	*Alteration*	*SiO_2 range (wt%)*	*K/Rb**	*ASI*	*FeO/ (FeO + Fe2O3)**	*Remarks**
Shoobridge Granite	23	Granite with pale blue-green amphibole in the more mafic specimens, surrounded by brown biotite.		Plagioclase is partially altered to sericite and chlorite is common	54.45 - 72.98	High.	Mostly <1.1	Moderate, mostly <0.24.	Most of the analyses are from Rhodes (1969) and full trace element data is only available for three of the samples. The granite is chemically distinct from other plutons of the batholith with higher Al_2O_3, Na_2O, K_2O, P_2O_5, Ba, Sr and Pb, and lower CaO and total Fe. The more mafic end-members are also high in Th, U and Nb. This pluton shows no sign of chemical fractionation in the more felsic end members.
Tabletop Granite	26	Granite types present form two broad groups. The first group granites characterised by large platy biotite: hornblende is present in rocks with <70 wt % SiO_2. The second group contains needle-shaped biotite and hornblende, and is more porphyritic: hornblende is present up to 76 wt % SiO_2. Samples from the latter group have rounded quartz phenocrysts, hornblende, olive brown biotite, perthite, and sericitised plagioclase.	Apatite, allanite and opaques.	Chlorite and sericite, with sphene, calcite and epidote common in deformed samples.	62.33 - 78.46	Moderate (decreases with increasing SiO_2).	Mostly <1.1	Low.	High CaO, MgO, and Sr, and low TiO_2, K_2O Pb, Th, Zr, Nb, Y, La, Ce, V, Ga and F. Mafic end members are chemically most similar to the Fingerpost suite, whilst some of the more felsic samples show increase in Y, U and Rb and decrease in K/Rb values similar to the Burnside suite. These more felsic phases are not restricted to a particular leucogranite type(s), but are distributed more around the northern, eastern and southern margins. Some of the more deformed samples have modified K_2O and Ba contents.

Unit	*N° of samples*	*Description of analysed samples*	*Accessory minerals*	*Alteration*	*SiO_2 range (wt%)*	*K/Rb**	*ASI*	*FeO/ (FeO + Fe2O3)**	*Remarks**
Driffield Granite	4	Coarse-grained biotite granite. Three samples are from close to the Pine Creek Shear Zone and are extensively altered. Where fresh, the granite has olive-brown biotite, muscovite, sericitised plagioclase, perthitic K-feldspar.	Allanite.	Chlorite, muscovite and epidote.	71.49-75.81	Flat and high (in the more SiO_2 enriched granites).	Mostly <1.1	Moderate.	High MgO, CaO, and V and low Sr, Pb, Th, U, Zr, Nb, La and Ce contents. Rb, U, Y and Li increase with increasing SiO_2.
Mount Davis Granite	2	Coarse grained granite. Sample 75470090 is fresh and has hornblende and brown biotite, whilst 75470091 has biotite mostly altered to chlorite.	Allanite, apatite and opaques.	Plagioclase is sericitised in both samples. Chlorite	69.31 - 69.64	Low.	<1.1	Low.	Low TiO_2, Al_2O_3, K_2O and high total Fe, CaO, Na_2O, and V, Sn and Cu contents. The samples are too mafic to indicate fractionation style.
Biotite-dominated suites									
Allamber Springs Granite	65	Although, overall biotite is the dominant mafic mineral, most of the more mafic phases are dominated by hornblende which is present in some samples up to 76.00 wt % SiO_2, generally becomes less common after 71 wt % SiO_2.	Allanite, apatite and zircon.	Plagioclase is mostly sericitised and more deformed samples have chlorite and epidote. Samples near the Saunders Leucogranite are recrystallised and in some cases metasomatically altered with minor muscovite.	56.39 - 80.03	High.	<1.1	High.	Low TiO_2 Al_2O_3, MgO, and CaO, and high Na_2O, Sr, Th, Zr, La, Ce, and V content. Some leucogranites resemble leucogranites of the Tennysons suite, showing an increase in Rb, U, and Y and a decrease in K/Rb value with increasing SiO_2, a low Fe_2O_3/(FeO + Fe_2O_3) value and an ASI of 1.1.
Bonrook Granite	4	Coarse biotite granite and leucogranite.	Fluorite, apatite, and allanite	All samples are altered, and most are deformed with brown biotite altered to chlorite, and sericite replacing feldspar and coarse muscovite.	73.02-76.80	(decreas-ing with increasing SiO_2).	<1.1	Low	Low Al_2O_3, Ba, Th, Zr La, and Ce and high Rb, U and Y. The more fractionated samples are most similar to the Burnside suite leucogranites.
GRANITE-DOMINATED PLUTONS									
Hornblende-dominated suites									
Fingerpost Granodiorite	12	Coarse porphyritic granites, all with hornblende with the exception of the most felsic sample (75470101).	Zircon and apatite.	Plagioclase is sericitised and biotite is altered to chlorite and epidote.	66.03 - 73.51	High.	<1.1	Moderate.	High MgO, CaO, Sr, V, Cr, Ni, Cu, Sn and low TiO_2, Al_2O_3, K_2O, P_2O_5, Li, Rb, Zr (very low), Nb, Y, La, Ce, Zn, and Ga. The pluton is one of the least fractionated plutons in the batholith with the lowest ASI.

Unit	*N° of samples*	*Description of analysed samples*	*Accessory minerals*	*Alteration*	*SiO_2 range (wt%)*	*K/Rb**	*ASI*	*FeO/ (FeO + Fe2O3)**	*Remarks**
McCarthys Granite	16	Coarse-grained porphyritic granite with no samples representative of the fine-grained leucogranite phases. Includes seven samples shown on the accompanying map as Bludells Monzonite. Biotite is brown to brown-green and hornblende is present in the more mafic samples (up to 67.58 wt % SiO_2).	Muscovite and rare garnet in the more felsic samples.	Plagioclase is strongly sericitised and epidote, chlorite and calcite are present in the more highly altered rocks.	52.41 - 75.12	Flat and high.		Low.	Low TiO_2, K_2O, Nb, and high MgO, CaO, Na_2O, Ba, Sr, Zr, V, Cr and Ni. Low Li, Rb, U, Y at high SiO_2 contents. With the exception of 75470052, the samples analysed from this granite show little evidence of fractionation.
Minglo Granite	14	A wide variety of samples were analysed ranging from monzonite through coarse hornblende-biotite granite to fine-grained leucogranite Characteristic brown biotite, with hornblende present in granites with <72.20 wt % SiO_2. K-feldspar is mostly microperthite. Some of the more felsic samples have rounded quartz grains and granophyric intergrowths of quartz and feldspar.	Coarse allanite (particularly in coarse hornblende-poor varieties).	Epidote and chlorite. Plagioclase cores are sericitised.	61.16 - 76.37	Flat and high.	<1.1	Low.	Mafic samples have high Al_2O_3, CaO Na_2O, K_2O, P_2O_5, Sr, Pb, Th, U, Zr, Nb, La, Ce, V, low TiO_2, and MgO and moderate Ba. Felsic varieties are either similar to the Saunders suite, having high $Fe_2O_3/(FeO + Fe_2O_3)$ (0.24) values, flat and high K/Rb values and low ASI, or are quite fractionated and are more similar to the Burnside suite with high Li, U, Rb and Y, low $Fe_2O_3/(FeO + Fe_2O_3)$ (<0.24) values, decreasing K/Rb values and ASI.
Biotite-dominated suites									
McMinns Bluff Granite (west)	19	Fine to coarse-grained granite with common hornblende in rocks up to 72 wt % SiO_2	Apatite, allanite and sphene.	Epidote and muscovite. Strongly deformed, foliated and recrystallised with a metamorphic imprint of up to biotite grade. All samples are located adjacent to the Hayes Creek Fault Zone, and are weakly foliated to mylonitic.	54.23 - 74.31	Low.	<1.1	Moderate.	High TiO_2, MgO, Na_2O, K_2O, P_2O_5, Rb, Sr, Ba, Nb, Zr, Th, and U. Chemically, finer-grained samples closely resemble those of the Tennysons suite with l ow K/Rb values and high Rb, Li, and Y contents. In some samples very high ASI values, low Pb contents and high $Fe_2O_3/(FeO + Fe_2O_3)$ (0.24) values reflect deformation/metamorphic modification. The most chemically altered samples occur near the outcrops of quartz breccia and quartz veining. Zinc is notably higher in the deformed specimens, particularly those with green biotite, and Nb is also high in one of the sheared localities. Of all samples analysed, zircons from this pluton have some of the lowest U contents of the samples analysed.

Unit	Nº of samples	Description of analysed samples	Accessory minerals	Alteration	SiO_2 range (wt%)	K/Rb*	ASI	FeO/ (FeO + Fe2O3)*	Remarks*
McMinns Bluff Granite (east)	13	Coarse porphyritic biotite granite, typically with tabular pale-pink zone K-feldspar megacrysts up to 6 cm across with up to 15% biotite. Hornblende is only present in samples with <64 wt % SiO_2.	Apatite, allanite, zircon and sphene.	Chlorite and sericite. Massive except near the margins where a weak foliation is developed parallel to the contact with the metasediments. The northwestern parts, particularly close to the Hayes Creek Fault Zone, are also metamorphosed to upper greenschist facies with greenish decussate biotite present.	62.81 - 74.10	High.	<1.1	Decreases with increasing SiO_2.	High TiO_2, total Fe, K_2O, P_2O_5, Pb, Zr, Nb, Y, La, Ce, Zn, Ga and F and low MgO, CaO, Na_2O, Sr, Th, U, V and Ni.
Mixed biotite-hornblende suites									
Margaret Granite	1	Coarse porphyritic adamellite with white to pale pink microcline in a medium groundmass of altered plagioclase, biotite and quartz.	Apatite, fluorite and sphene	Chlorite	73.90	Moderate.	<1.1	High.	Poorly defined chemically. Similar to the McMinns Bluff Granite, although it does have distinctly high U (25 ppm) and Nb (24 ppm).
Prices Springs Granite	8	Brown biotite, with hornblende present in the more mafic phases up to 74 wt % SiO_2. Microcline is the dominant K-feldspar and green (?metamorphic) biotite is present in some samples.	Allanite, epidote and muscovite	Plagioclase is highly altered, particularly in the age determination sample	67.90 - 73.98	Moderate.	Mostly <1.1	Moderate.	High TiO_2, Al_2O_3, K_2O, P_2O_5, Sr, Pb, Th, Zr, Nb, and Bi and low CaO, MgO, and Na_2O. Chemically similar to the McMinns Bluff Granite, although it has high Al_2O_3 and Sr as in the Shoobridge Granite.
Mount Porter Granite	3	The most mafic sample has hornblende, whilst secondary muscovite is present in the more felsic samples. K-feldspar is mainly microperthite.		Plagioclase is altered to sericite.	69.78 - 75.74	Low.	<1.1	<0.24	Low TiO_2, MgO, CaO, Ba, Zr, La, Ce, V and high Pb, Nb, and Ga.
McKinlay Granite	2	Biotite granodiorite.			67.04 - 67.72		>1.1	Moderate.	High TiO_2, Al_2O_3, K_2O & P_2O_5 and low MgO and CaO. Although no trace elements or thin sections are available, on major elements, these samples resemble the biotite dominated McMinns Bluff Granite (east).

* *Values are expressed relative to other plutons within the Cullen Batholith*

The decrease in $Fe_2O_3/(FeO + Fe_2O_3)$ values with progressive crystallisation can have at least two possible causes. Firstly, some plutons intrude reduced, carbonaceous metasediments and interaction with these reduced metasediments may lead to a decrease in $Fe_2O_3/(FeO + Fe_2O_3)$ value. However, this seems unlikely as the plutons with the lowest $Fe_2O_3/(FeO + Fe_2O_3)$ value are also those with some of the highest ASI values. Secondly, Dickenson & Hess (1986) argued that the ratio of FeO/Fe_2O_3 increases with increasing K_2O/Al_2O_3, and thus the transition to more reduced compositions with increasing fractionation may depend on the chemistry of the crystallising phases, rather than on interaction with reduced country rock. This decrease in the whole-rock $Fe_2O_3/(FeO + Fe_2O_3)$ value with increasing fractionation does not support the predicted increase in the whole-rock $Fe_2O_3/(FeO + Fe_2O_3)$ value by Bajwah (1991) based on the fact that the fO_2 of biotites and hornblendes increased with increasing fractionation in the Cullen Batholith.

The composition of the leucogranites evolves with progressive crystallisation of the magma. Initially, the leucogranites will be high in Ba and low in Rb, U, Y and other incompatible elements, and will also have a low ASI and high K/Rb (as is observed in the Saunders suite). As crystallisation progresses, Ba and K/Rb values will decrease, and Rb, U, Y and ASI will increase, (e.g. Burnside suite), with the maximum Rb, U, Y and Li, the highest ASI, and lowest K/Rb value being found in the last and most fractionated leucogranites (e.g. Tennysons suite).

Magma generation

The Cullen Batholith is one of a suite of dominantly I-type granitoid plutons generated throughout northern Australia during the Early Proterozoic by a process of vertical accretion, in an intracratonic environment (Wyborn, 1988). Compared with Archaean and Phanerozoic granites, the batholith has distinctively elevated levels in K, Rb, Zr, La, Ce, Th, U, and low Mg and Ca contents. Chemical and isotopic modelling of the granitoids suggest that they formed from 2300-2000 Ma old mantle-derived sources (Wyborn, 1988) rather than an Archaean granitic basement as proposed by Ferguson & others (1980). The sources are interpreted to have formed as a result of mantle convection, which led to extensive underplating of Archaean crust. During this underplating event, large volumes of incompatible element-enriched mantle-derived material accreted to the lower crust, and fractionated significantly. Locally, the more fractionated part of this source was remelted between 1835-1820 Ma to produce the Cullen Batholith.

POST–OROGENIC INTRUSIONS

Numerous bodies of *Lewin Springs Syenite*, *Oenpelli Dolerite*, and unnamed dykes of *dolerite*, *felsite*, *greisen*, *aplite*, *lamprophyre* and *syenite* intrude the Early Proterozoic metasediments and granitoids. They are mostly poorly exposed and contact relationships are obscure. The relative ages of the dykes cannot be determined owing to a lack of cross-cutting relationships. They are most probably late Early Proterozoic, as they are not seen to intrude the Middle Proterozoic or younger sediments. Details of the post-orogenic intrusions are summarised in Table 13.

Lewin Springs Syenite (Ꝑew)

Numerous dykes of *porphyritic quartz syenite*, *quartz microsyenite*, *syenite*, *microgranite*, *microleucogranite*, *quartz micromonzonite*, *and microleucomonzonite* of the Lewin Springs Syenite intrude the Cullen Batholith and Early Proterozoic metasediments and volcanics. The dykes are concentrated in the Fingerpost Granodiorite and also intrude parts of the Tabletop, Allamber Springs, McCarthys and Mount Davis Granites, and the Tennysons Leucogranite. Minor dykes intrude the Plum Tree Creek Volcanics near the Woolngi gold mine, and the Burrell Creek Formation near Mount Davis and 3 km northeast of Wolfram Hill. The age of the dykes is not known: there is no contact between the dykes and Middle Proterozoic or younger strata.

The dykes are either rectilinear north-northwest and northeast-trending or curvilinear. Most trend northwest parallel to pegmatite, aplite and dolerite dykes and the major direction of faulting and shearing within the granitoids. One major dyke, up to 250 m across and 20 km long, trends west to northwest in the Fingerpost Granodiorite, and locally separates it from the adjacent McCarthys Granite. In several places, the dyke is cut and displaced by faults and shear zones within the Pine Creek Shear Zone.

The Lewin Springs Syenite is typically strongly porphyritic, containing K-feldspar phenocrysts, with quartz becoming prominent after 68 wt% SiO_2. Hornblende is present in rocks with up to 74 wt% SiO_2. Chemically, it is similar in most elements to the Fingerpost Granodiorite, although relative to it and to other plutons of the Cullen Batholith the Lewin Springs Syenite has high K_2O, Zr, Th, Rb, and very low Li (Appendix 1).

Oenpelli Dolerite (Ꝑdo)

Scattered spheroidal boulders of pale pinkish-grey *porphyritic olivine dolerite* are exposed within deep reddish-brown soils in the northeast. The dolerite occurs as several dyke-like bodies, up to 3 km long and 300 m

TABLE 13. SUMMARY DESCRIPTION OF POST–OROGENIC INTRUSIONS

Unit (map symbol)	*Lithology*	*Distribution*	*Brief petrographic description*	*Field relations*	*Remarks*
Lewin Springs Syenite (Pew)	Quartz syenite, quartz microsyenite, syenite, microgranite, microleucogranite, quartz micromonzonite, microleucomonzonite.	Within 30 km of Pine Creek township, particularly in S.	Strongly porphyritic; megacrysts of oligoclase, microperthite, orthoclase, embayed quartz, rare biotite and hornblende in a fine-grained groundmass of quartz, K-feldspar, biotite, hornblende and plagioclase. Accessory apatite, zircon and rare allanite. Alteration: sericite, epidote, chlorite, muscovite, carbonate, sphene, prehnite, hematite and actinolite.	Intrudes Early Proterozoic metasediments, volcanics and granitoids.	Forms N-NW- & NE-trending dykes (<250 m wide, <20k m long).
Unnamed dykes	Syenite, micromonzonite, diorite.	Snaddens Ck. (GK 9389) and Jimmy's Knob area (GK 9299).	Recrystallised mosaic of fibrous chlorite aggregates, quartz, K-feldspar; minor muscovite, epidote and apatite.	Intrudes Early Proterozoic metasediments. Contact-metamorphosed by Pgm	Forms dykes and irregular-shaped intrusive bodies. Associated Sn mineralisation. May be related to Pgz.
	Quartz microsyenite	3 km south of Mount Porter.	Fine-grained microcline and graphically intergrown microcline and quartz; minor biotite. Marginal phases with up to 50% quartz, plagioclase and microperthite xenocrysts.	Intrudes Pga.	Forms 10 m wide 4 km-long dyke.
	Fine-grained dolerite	Between Union Hill and Burrundie Siding and at HK 1651 and GK 9672.	Flow-banded, fine-grained subophitic augite, sericitised andesine/labradorite; minor apatite, magnetite, K-feldspar; rare quartz and biotite. *Alteration:* chlorite, actinolite, epidote, sericite and Fe oxides.	Intrudes Pfb, Pgc & Pgt.	Form dykes up to 20 km long.
	Porphyritic dolerite	Mount Daniels and Ranford Hill areas in E.	Andesine phenocrysts (<1cm), ophitic augite mostly relaced by fibrous actinolite, sericite and Fe oxides.	Intrudes Pgc & Pfb.	Form N-NW-trending, 3 m wide and 1300 m long, dykes.
	Massive felsite	Two areas: N and NW of Chara Chara Hill in NE; Between Aston Hill and Two Sisters in E.	Sericitised feldspar and minor embayed quartz phenocrysts (<2 mm) in a fine-grained groundmass of sericite, quartz and granular Fe oxides.	Intrudes Pfb, Pnm & Ppm.	Form NW-trending dyke swarms, individual dykes ranging up to 20 m wide and 5 km long.

Unit (map symbol)	*Lithology*	*Distribution*	*Brief petrographic description*	*Field relations*	*Remarks*
	Greisen	Widespread throughout the Cullen Batholith and adjacent areas.	Coarse- to medium-grained polygonal quartz and muscovite with patchy fine-grained sericite, trace zircon and secondary iron oxides.	Intrude Early Proterozoic meta-sediments and granitoids.	Late-stage differentiates of granitoid intrusions, spatially related to the Cullen Batholith.
	Aplite	ditto	Fine-grained equigranular anhedral quartz, microcline and albite/oligoclase, minor biotite, muscovite and secondary carbonate. Accessory zircon and apatite.	ditto	ditto
	Syenite	ditto	Medium-grained equigranular anhedral microcline, hematised feldspar, quartz biotite and trace apatite and zircon. Porphyritic in places with scattered microcline phenocrysts.	ditto	ditto
	Pegmatite	ditto	Very coarse-grained micrographically intergrown microcline and quartz with minor subhedral oligoclase and biotite.	ditto	ditto
	Lamprophyre	NW of Mt. Daniels in NE at JE 9397 and JF 8805.	Dark pinkish-grey, very fine-grained, slightly porphyritic, with oligoclase and clinopyroxene phenocrysts (<5mm) in a groundmass of K-feldspar, quartz, plagio-clase, granular clinopyroxene; secondary chlorite, epidote, carbonate and actinolite.	Intrudes Pgi & Pfb.	Minor dykes up to 500 m long.
	Minette	Near Chara Chara Hill in NE at HL 2525.	Medium-grained biotite, K-feldspar, plagioclase and minor quartz.	Intrudes Ppm.	Minor dyke about 300 m long.
	Dolerite picrite	NE of Mt. Douglas in far N.		Intrude Early Proterozoic meta-sediments.	Regionally extensive NW trending dykes corresponding to negative magnetic lineaments. Not exposed. K-Ar mineral age ~400 Ma (Newton, pers. com).

wide, intruding the Namoona Group. Contacts with the group are not exposed.

The dolerite, with unaltered clinopyroxene and partly chloritised olivine, is petrographically similar to the Oenpelli Dolerite described in detail farther to the east and northeast of the area by Smart & others (1976) and Stuart-Smith & Ferguson (1978). Elsewhere in the Pine Creek Geosyncline, the unit forms symmetrically differentiated layered lopoliths and dykes, and yields a concordant Rb-Sr total-rock and mineral age of about 1690 Ma. (i.e. earliest Middle Proterozoic (Page & others, 1980; & Page, 1981).

Unnamed dykes

Dykes and irregular-shaped bodies of highly altered *syenite, micromonzonite* and *diorite* intrude the Early Proterozoic metasediments and are associated with tin mineralisation at *Snaddens Creek*[122] (GK 9389) and *Jimmys Knob*[111] (GK 9299). At Snaddens Creek, a syenite dyke is contact-metamorphosed by the 1835 Ma McMinns Bluff Granite.

A sinuous northwest-trending 20 km-long *fine-grained flow-banded dolerite* dyke intrudes Early Proterozoic metasediments from 3 km northwest of Union Hill to Burrundie Siding. A similar-trending dolerite dyke invades the McCarthys Granite 1 km east of the Stuart Highway and about 22 km south-southeast of Pine Creek township. Dolerite rubble at GK 9672 may also be from a dyke intruding the Tabletop Granite.

Porphyritic dolerite dykes, up to 3 m wide and 1300 m long, intrude the McCarthys Granite, the Burrell Creek Formation near Mount Daniels, and the Burrell Creek Formation between Wolfram Hill and Mount Gardiner. They mostly trend north to northwest, parallel to other dykes in the region.

Swarms of massive pale-green *felsite* dykes intrude Early Proterozoic metasediments between Mount Masson and the *Namoona*[12] Ag-Pb prospect, and near the *Crest of the Wave*[181] tin mine. The dykes, ranging from 1 to 20 m wide, extend discontinuously up to 5 km long. They parallel the regional northwest trend and cleavage of the Early Proterozoic metasediments in most places, but cross-cutting contacts are commonly exposed. The felsite is well exposed as blocky strike ridges, and has characteristic high total count radioactivity of times two to four the regional background.

Dykes of *greisen, aplite, syenite* and *pegmatite* occur mostly within the Cullen Batholith, except for minor dykes of greisen which extend into the surrounding hornfels. These dykes are spatially and genetically associated with the batholith and probably represent late-stage differentiates of the granitoid intrusions.

Present also are minor *minette* and *lamprophyre* dykes intruding Early Proterozoic metasediments east of the Minglo Granite and a 10 m wide, 4 km long, north-trending *quartz microsyenite* dyke 3 km south of Mount Porter. The latter is poorly exposed, except for the dyke margins showing considerable contamination from the surrounding Allamber Springs Granite. It is possibly part of the Lewin Springs Syenite, in which case it represents the northernmost exposure. The marginal contamination is, however, a feature not displayed by other dykes of this formation.

Three northwest-trending negative magnetic lineaments cross the northern part of the area, through Early and Middle Proterozoic rocks (Fig. 7). Drilling by NTGS in NOONAMAH on a continuation of the easternmost one, intersected altered *dolerite* and *picrite* at depth (W. Newton, personal communication, 1980). The dykes have a preliminary minimum Palaeozoic K/Ar mineral age of about 400 Ma (Amdel determination for NTGS).

Numerous *quartz reefs and veins* are common throughout the Early Proterozoic metasediments and granitoids and trend mostly northwesterly or north-easterly. The northeasterly trending ones are longer (up to 6 km) and follow major fault and shear zones. Both sets probably represent several generations of veining associated with granite intrusion and deformation between 1870 and 1780 Ma.

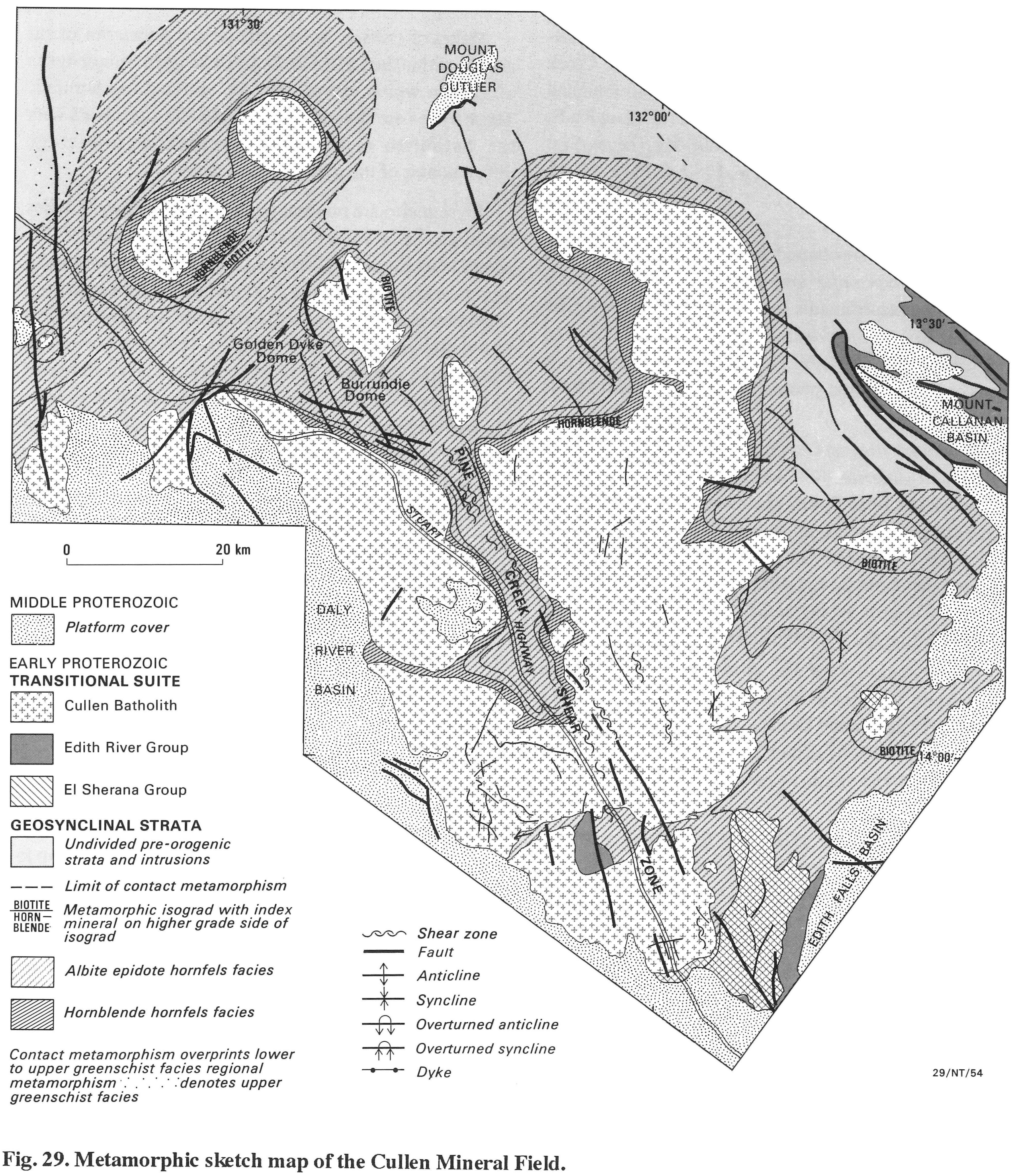


Fig. 29. Metamorphic sketch map of the Cullen Mineral Field.

METAMORPHISM

The Early Proterozoic rocks have been regionally metamorphosed to greenschist facies and contact-metamorphosed by syn- to post-orogenic granitoids (Fig. 29). Regional metamorphism and deformation associated with the *Nimbuwah Event*, at about 1870 Ma, was followed by intrusion of the Cullen Batholith between 1835 and 1820 Ma. Throughout most of the area contact-metamorphic effects associated with intrusion of the batholith overprint regional metamorphic assemblages. However, in the northwest where the regional metamorphic grade is highest, contact- metamorphic minerals are deformed and show late syn-tectonic textures with foliated micas which form the S_1 cleavage (Fig. 30). This feature, and the extensive alteration and deformation of the granitoids, indicates a later, more localised deformation and metamorphic event post-granitoid emplacement. This deformation and metamorphic episode, known as the *Shoobridge Event*, is reflected in isotopic systematics by the ubiquitous 1800–1780 Ma Rb/Sr age (Page & others, 1980) throughout the Pine Creek Geosyncline.

Characteristic mineral assemblages of the major metamorphic lithologies are given in Table 14.

REGIONAL METAMORPHISM

The effects of regional metamorphism are largely obliterated by contact metamorphism except in albite-epidote hornfels facies, where clastic sedimentary rocks show relatively minor contact effects. The regional metamorphic grade ranges from lower greenschist facies in the east and south, to upper greenschist facies in the northwest (Fig. 29).

Throughout most of the area, pelitic rocks are composed of fine-grained, weakly foliated sericite, chlorite and microcrystalline quartz. Psammitic rocks usually exhibit fractured and strained quartz grains with recrystallised optically continuous quartz overgrowths, although relict grain boundaries are preserved in places; minor metamorphic sericite, chlorite, epidote or muscovite may be present. Eutaxitic textures (e.g. devitrified shards) are preserved in tuffaceous sediments of the South Alligator Group, devitrified and recrystallised to chlorite, sericite and quartz. Feldspar, where present in tuffaceous or clastic sediments, is commonly sericitised, carbonated or kaolinised. Carbonate rocks within the Masson and Koolpin Formations are recrystallised fine-grained dolomite. Quartz dolerite sills of the Zamu Dolerite are largely unaltered with minor chloritisation of clinopyroxene, and patchy sericite, carbonate, chlorite, epidote and zeolites.

In the northwest around the Burnside and Shoobridge Granites, the metamorphic grade is slightly higher. Similar regional metamorphic mineralogy is present, with the addition of foliated biotite in pelitic and tuffaceous rocks. Carbonate rocks within the Koolpin Formation are totally altered to banded amphibolite consisting of tremolite, garnet, quartz and biotite.

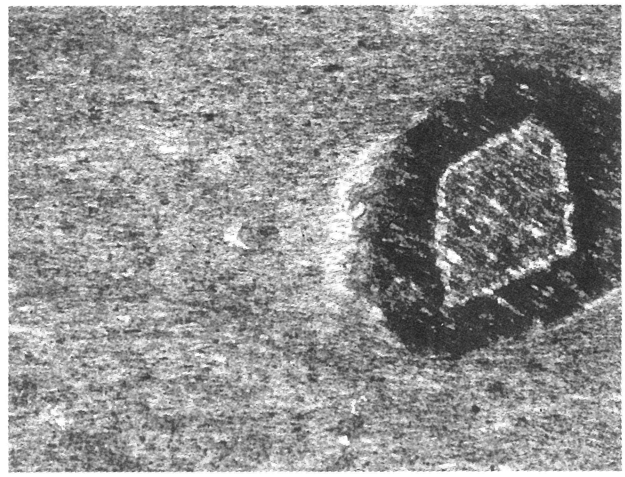


Fig. 30. Round porphyroblasts of cordierite (about 1mm across) within phyllite in the outer albite-epidote hornfels zone show rotational textures indicative of late syn-tectonic growth. The cordierite has been entirely replaced by chlorite (dark mineral) and andalusite (pale cores of porphyroblasts); the latter being mostly altered to white mica. These replacements probably occurred during cooling of the aureole.

CONTACT METAMORPHISM

Most of the contact aureole around the Cullen Batholith is of the albite-epidote hornfels facies with a narrower, inner continuous zone of hornblende hornfels facies (Fig. 29). The boundary between the facies is marked by the hornblende isograd, which at the surface lies mostly within 0.5 km, ranging up to 5 km, of the batholith margin. Rare K-feldspar--cordierite hornfels facies is also present in places adjacent to the McMinns Bluff, Allamber Springs and McCarthys Granites.

The presence of K-feldspar-cordierite-hornfels facies and the size of the granitoid bodies suggest that the granitoids intruded at depths less than 6 km. At such depths, the contact-metamorphic aureole should extend up to 2.5 km from the intrusions with the hornblende and biotite isograds at about 250 m and 750 m, respectively (Winkler, 1976). The width of the aureole indicates that the granitoids have mostly shallow-dipping margins and that all of the outlying plutons are joined at shallow depths to the main body of the batholith. This is consistent with estimates by Tucker & others (1980) of less than 3 km to

TABLE 14. CHARACTERISTIC METAMORPHIC MINERAL ASSEMBLAGES

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	Muscovite ± biotite ± cordierite ± quartz Muscovite + chiastolite + graphite Muscovite + cordierite ± graphite	Muscovite + biotite ± cordierite ± albite ± quartz 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	
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	

granitic basement over the aureole (Fig. 16). The spacing of the biotite and hornblende isograds demonstrate that the batholith surface ranges in dip from subhorizontal northeast of the Wandie Granite to near vertical along the western margin of the McCarthys Granite. The steeply dipping contact here is marginal to the Pine Creek Shear Zone: post-emplacement vertical movement probably steepened the contact and produced shear zones and mylonite in the granitoids southeast of Pine Creek township.

Albite-epidote hornfels facies

The albite-epidote hornfels facies is divided into two parts by the biotite isograd, at the surface extending up to 10 km from the granitoid contact. The inner higher-grade part, together with the hornblende hornfels facies, has readily visible metamorphic minerals and original bedding represented by mineralogical banding. Both these facies are marked by rugged ridges characterised by the lack of bedding trends on aerial photographs, and enhanced apparent magnetisation. The latter feature, illustrated in the frontispiece, is caused by the common presence of magnetite and pyrrhotite in pelitic rocks. The extent of the biotite isograd around the Fenton, Burnside, Prices Springs and McMinns Bluff Granites is less well defined than around other granitoids owing to the higher regional metamorphic grade and possible deformation after contact metamorphism.

The outer part of the albite-epidote hornfels facies zone covers about 75% of the Early Proterozoic metasediments. The outer limit of this zone is poorly defined, as psammitic and tuffaceous sediments show no change from their regionally metamorphosed counterparts. Mafic minerals in the Zamu Dolerite, and in volcanic flows and pebbles in the Burrell Creek Formation, are altered to actinolite, epidote and chlorite. Clinopyroxene is rarely preserved as remnants in actinolite grains in the Zamu Dolerite, whereas outside the aureole it is commonly present mostly as coarse ophitic crystals with only marginal chloritic alteration. Pelitic rocks are also generally more chloritic than in non-hornfelsed areas. Within the aureole, pyritic and carbonaceous pelites are resistant to weathering and are grey to black, whereas outside they are bleached and heavily ferruginised. They are also locally tourmalinised, and commonly spotted owing to small ovoid growths of chlorite (0.5 mm) after cordierite and andalusite (Fig. 30).

All rocks within the inner part of the albite--epidote hornfels facies (i.e. between the biotite and hornblende isograds) are recrystallised, usually with unstrained polygonal mosaic fabrics. Fragmental textures are preserved in greywacke and tuff, and relict grain boundaries, defined by rings of iron oxide inclusions in psammitic rocks, are present in places. The original subophitic texture of the Zamu Dolerite is well preserved, although all clinopyroxene is entirely replaced. Muscovite is ubiquitous in clastic sediments and characteristically forms coarse poikilitic grains. Cordierite is common in pelitic rocks, but is invariably altered to aggregates of fine white mica. Tourmalinisation, particularly of pelitic rocks, is also widespread.

Hornblende hornfels facies

The hornblende hornfels zone is difficult to recognise in the field as the mineralogical changes which define it are restricted to carbonate and mafic rocks. The mineralogy of pelites and sandstones, greywacke and tuff is the same as in the inner albite-epidote hornfels zone. However, most rocks are extensively recrystallised to unstrained granoblastic mosaics.

Pelitic rocks are totally recrystallised to dark-grey conchoidally fracturing rocks similar in appearance to crystal tuff in the South Alligator Group. Sedimentary structures, such as laminae and graded bedding, are preserved by mineralogical changes which reflect original compositional differences. Characteristically, muscovite and cordierite form poikilitic porphyroblasts, and cordierite forms ovoid to irregular crystals up to 2 cm across.

K-Feldspar cordierite hornfels facies

Mineral assemblages diagnostic of the K-feldspar-cordierite-hornfels facies are confined to hornfels rafts and xenoliths within the batholith and in some pelitic rocks adjacent to the McMinns Bluff, Allamber Springs, and McCarthys Granites. The hornfels are typically massive, finely spotted, grey and pink. Cordierite and andalusite both form irregular poikilitic porphyroblasts up to 1 cm across; andalusite also occurs as subidiomorphic colourless to pale pink crystals. Magnetite and tourmaline are also common. The K-feldspar and cordierite together define the facies. The presence of muscovite and its coexistence with biotite and quartz indicates instability, probably involving the following reactions (Winkler, 1976):

muscovite + quartz → K-feldspar + andalusite + H_2O

muscovite + biotite + quartz → cordierite + K-feldspar + H_2O.

Marginal alteration of muscovite and biotite is consistent with these reactions and indicates that the transition from hornblende hornfels facies was incomplete.

STRUCTURE

Between 1870 and 1780 Ma, Early Proterozoic geosynclinal rocks underwent a major period of deformation known as the 'Top End Orogeny' (Needham & others, 1988). The *Nimbuwah Event* (Needham & others, 1988), at ~1870 Ma (Page & others, 1980), marked the beginning and peak of deformation and regional metamorphism: strata were tightly to isoclinally folded, extensively faulted and metamorphosed to greenschist facies. Following a second period of localised folding during the *Maud Creek Event*, at ~1850 Ma (Needham & others, 1988), these structures were modified by granitoid intrusion and development of a major shear zone—the Pine Creek Shear Zone. This shear zone formed during the ~1780 Ma *Shoobridge Event*, the last regional metamorphic and deformation event of the Top End Orogeny (Needham & others, 1988). Apart from periods of uplift and erosion and fault reactivation during the Middle Proterozoic, Palaeozoic and possibly Mesozoic, the area has remained tectonically stable since Early Proterozoic time.

There is no noticeable difference in the folding history between the various Early Proterozoic geosynclinal units. This is consistent with the nature of unconformities within the Early Proterozoic sequence (i.e. at the base of the South Alligator and Mount Partridge Groups), which are either disconformable or show slight angularity indicative of warping, tilting or minor open folding in older units.

Airphoto and Landsat lineaments are common (Fig. 31), particularly as seen in exposed bedrock. The airphoto lineaments range between 1 and 10 km in length, whereas the Landsat lineaments are between 5 and 50 km long. Most correspond to either fault or joint orientations in both the sediments and granitoids, commonly defining extensions.

Major fold axes and bedding trends are shown in Figure 32, faults in Figure 33, and all major structural elements are summarised in Table 15.

Nimbuwah Event (~1870 Ma)

Thrusting

The earliest structures are exemplified by semi-continuous lenses of hematitic ironstones cropping out between Mount Harris and Frances Creek, in the lower part of the Wildman Siltstone. The ironstones are fault breccias, within pyritic carbonaceous strata, forming conformable bodies folded by upright NW-trending F_1 folds. Although there is no stratigraphic repetition, observable displacement or other deformation associated with them, the breccias probably outline post-depositional bedding-parallel thrust faults, developed in the early stages of orogenesis. Other similar conformable mylonite zones and thrust faults have been observed farther to the east in MUNDOGIE (Etheridge & others, 1981; Stuart-Smith & others, 1984a; Johnston, 1984), where they indicate movement of several kilometres from the northeast which resulted in stratigraphic thickening in places. In these areas, an associated bedding-parallel cleavage and west-verging recumbent folds may be present.

Upright NW Folding

The oldest and most prominent folds (F_1) have north to northwest-trending subhorizontal axes (Figs 32 and 34). The folds are symmetrical and either upright or inclined to the southwest, commonly with overturned limbs. The style is a composite of parallel folding in competent psammitic beds and similar folding in pelitic units: a penetrative slaty to phyllitic cleavage (S_1) is present in pelitic rocks and a less-prominent spaced cleavage in psammitic rocks. Both cleavages are the axial plane surfaces to the F_1 folds and are either near vertical or dip steeply to the southwest. The F_1 folds are either truncated or rotated and steepened by later intrusion of the Cullen Batholith.

Faulting

Several long vertical north to northwest-trending faults, commonly showing a history of reactivation, cut Early Proterozoic sediments throughout the area. Juxtaposition of the Namoona and Finniss River Groups indicates that the apparent displacement of Early Proterozoic metasediments on the Little Mary, Junction, and Mary Faults prior to later post-Middle Proterozoic reactivation is at least 1 km vertical, with unknown horizontal movements. The age of the faulting is poorly constrained. The faults parallel the regional trend and axial plane cleavage (S_1) of the Early Proterozoic metasediments and were possibly active during or after F_1 folding as they are displaced and rotated by later structures. However, movement on some of the faults possibly occurred earlier during Early Proterozoic geosynclinal sedimentation, accounting for the absence of the Mount Partridge Group in the northeast beneath the South Alligator Group (e.g. 4 to 20 km north of Mt. Daniels).

Maud Creek Event (1850 Ma)

The second generation of folds (F_2) is confined to south of Wolfram Hill (Fig. 32). The folds are developed in the geosynclinal and younger Early Proterozoic strata of the El Sherana Group (i.e. Tollis Formation), and are typically open to tight and north to northeast-trending. Within the geosynclinal strata, they fold the S_1 cleavage and are associated with a spaced cleavage (S_2). In the Tollis

Fig. 31. Lineament sketch.

Formation, they are the only folds present, forming centroclines in places (Fig. 35), with an axial spaced or slaty cleavage. The folds pre-date the unconformably-overlying ~1870-1860 Ma Edith River Group and are truncated by the Tennysons Leucogranite.

Deformation associated with emplacement of the Cullen Batholith (1835—1820 Ma)

A third generation of folds (F_3) in geosynclinal strata, associated with batholith emplacement (~1835–1820 Ma), is not obvious in outcrop owing to the regional dimensions of the folds. The folds are open and spaced several kilometres apart. They mostly trend east-west and may be associated with poorly developed similar-trending kink or crenulation cleavages. Locally, the F_1 and F_2 fold axes are either steepened and plunge away from the batholith margins, forming rim synclines, or are rotated parallel to the contact (Fig. 32). In places, shallow-dipping joints parallel to the batholith margin are developed in the hornfels aureoles. The interference of the F_1 and F_3 folds has formed the elongate basin and dome structures, such as the Golden Dyke Dome in the northwest (Fig. 32).

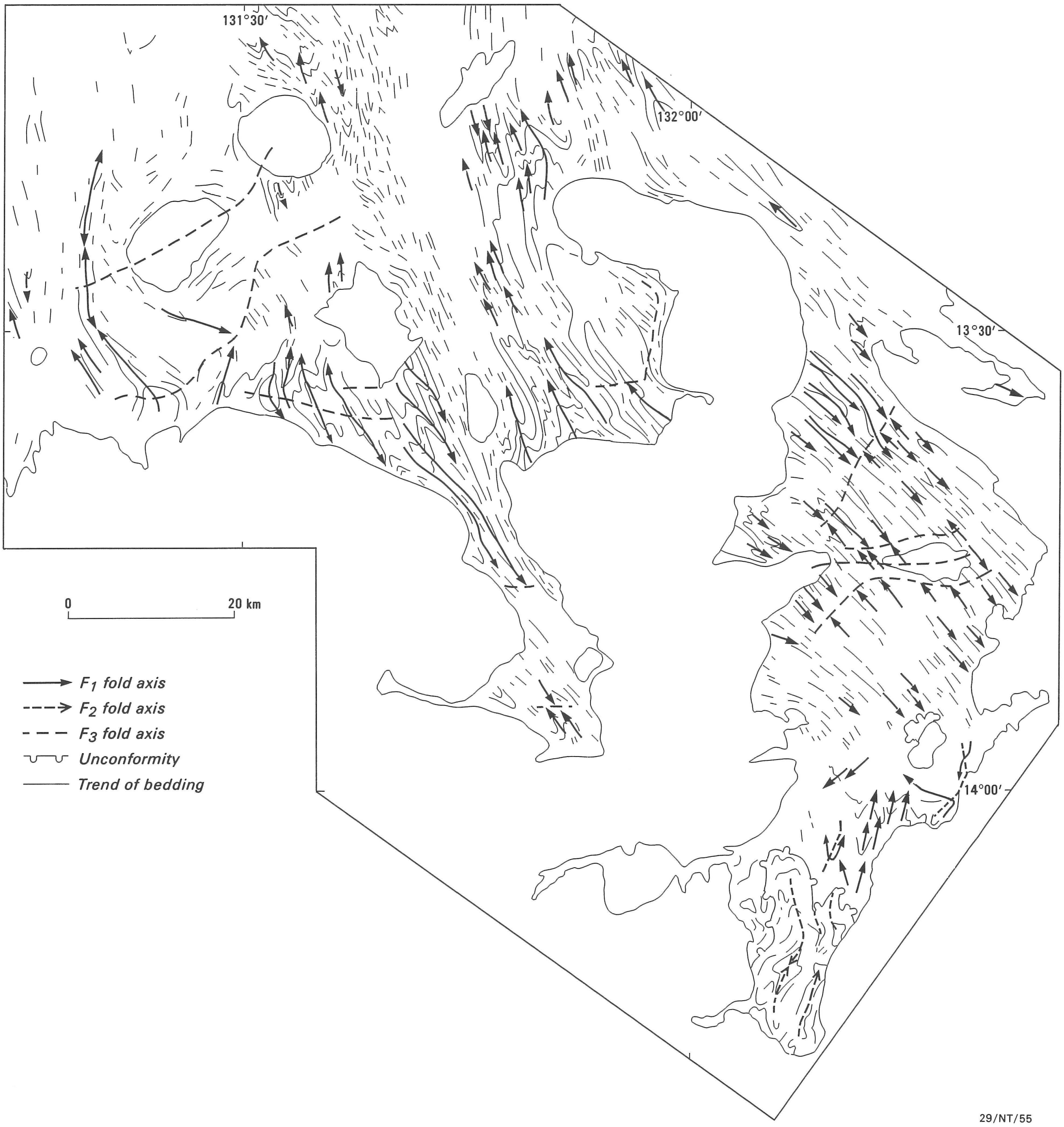


Fig. 32. Fold trends in Early Proterozoic rocks.

Shoobridge Event (~1780 Ma)

Deformation accompanying the *Shoobridge Event* is characterised by the development or reactivation of linear shear zones (such as the Mount Shoobridge Fault and Pine Creek Shear Zone) parallel to the regional N-S to NW-SE strike within the Early Proterozoic metasediments, volcanics and granitoids. The deformation was accompanied by widespread retrogressive metamorphism, which is particularly noticeable in the Cullen Batholith, and localised prograde, biotite-grade regional metamorphism in the northwest adjacent to the Mount Shoobridge Fault.

The age of the deformation event is probably reflected by the ubiquitous Rb-Sr total-rock ages of 1770 to 1780 Ma for the granitoid plutons of the Cullen Batholith, and possibly by the 1800 ± 24 Ma ages recorded in the K-Ar and Rb-Sr systematics of metamorphic rocks of the Alligator Rivers Region to the northeast of the area (Page & others, 1980).

The Pine Creek Shear Zone forms part of a major northwest-trending wrench fault system extending from Darwin to Katherine and includes the Noonamah and Phillips Creek Faults (Needham & Stuart-Smith, 1984a). The zone is well-defined by Landsat and magnetic lineaments passing through Pine Creek township and by

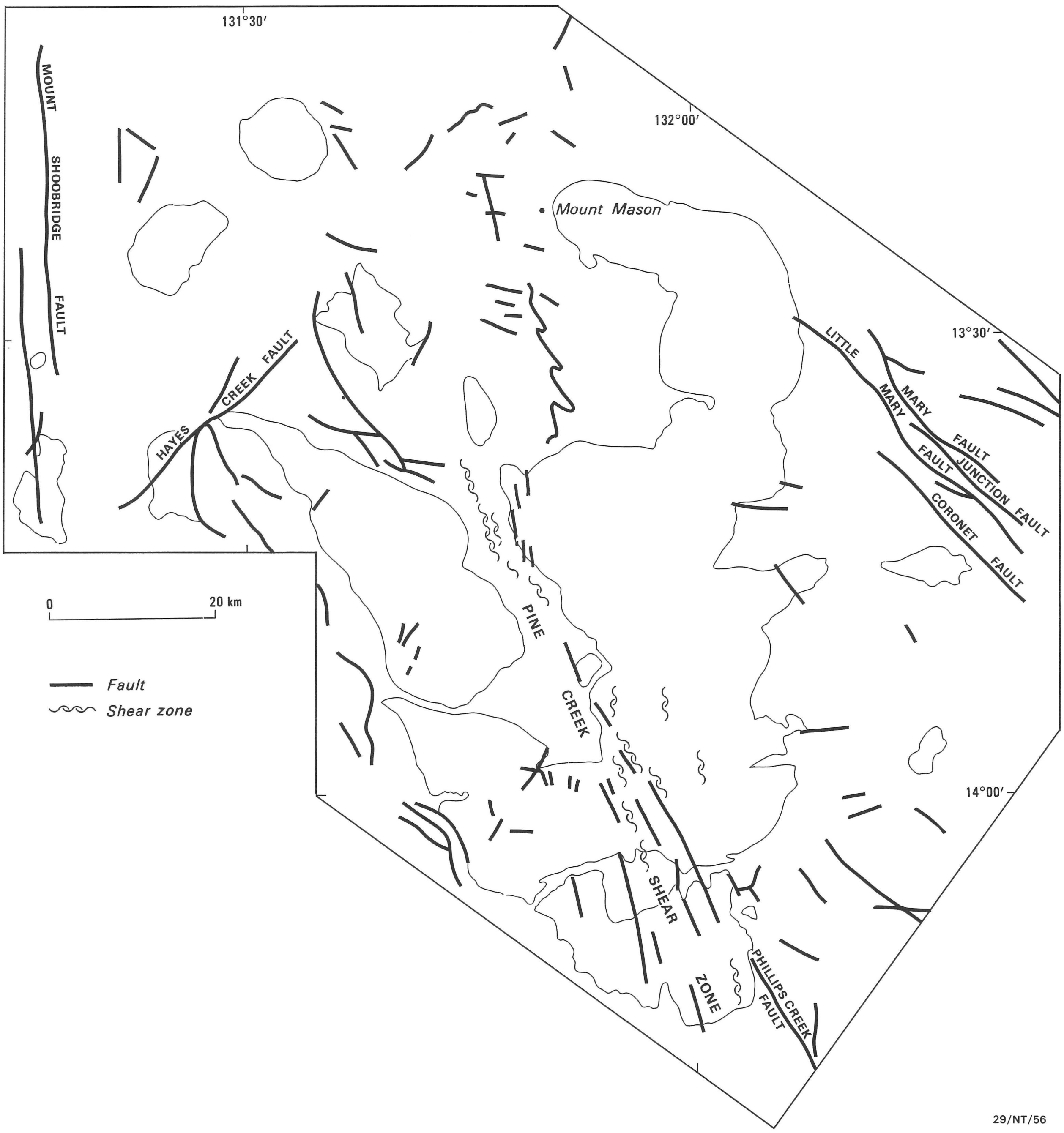


Fig. 33. Fault distribution.

concentrations of northwest-trending airphoto lineaments in the far southeast (Fig. 31). The shear zone follows the embayment of Early Proterozoic metasediments which separates the two major lobes of the Cullen Batholith. It extends from the southern end of the McKinlay Granite, about 2 to 3 km wide, to the southeast where it is about 7 km wide and breaks up into a number of discrete faults, such as the Phillips Creek Fault (Fig. 33). Metasediments within the zone are schistose and chloritic, and bedding and cleavage are parallel and vertical. Where the zone bisects the batholith southeast of Pine Creek township, it splays out into more discrete breccia or mylonite zones. Granitoids within the zone are foliated, strained and extensively altered.

As the Pine Creek Shear Zone parallels the strike of the metasediments, the nature and amount of displacement are indeterminate. However, movement on the faults in the southern part of the zone within the Tollis Formation are sinistral with displacements in the order of 1 to 2 km. These displacements are greater than those observed along the batholith margins suggesting that the zone was active before, as well as after, granitoid intrusion. The restricted development of the shear zone between the two lobes is possibly a result of localised high strain caused by granitoid diapirism during intrusion. Diapirism is also indicated by displacements on a series of north to north-northwest-trending faults on the western margin of

TABLE 15. SUMMARY OF MAJOR STRUCTURAL ELEMENTS AND HISTORY

Event	*Age*	*Folding*	*Faulting*	*Remarks*
	Post-Middle Proterozoic	NW-trending regional open folds in M. Prot. strata. Mesozoic locally drag folded.	Reactivation of N-NW-trending faults. Mostly normal and/or dextral strike-slip displacement. NE-trending reverse faulting. Minor WNW-trending faults.	nil
Shoobridge	~1800 - 1780 Ma	nil	Major NW-trending shear zones and wrench faults.	Widespread retrogressive, and locally prograde, lower greenschist-facies metamorphism.
	~1835 - 1820 Ma	Regional E-W folds (F_3) in Early Proterozoic strata. Formation of rim synclines and domes adjacent to granitoid plutons.	nil	Associated with diapirism accompanying granitoid emplacement.
Maud Creek	~1850 Ma	Open to tight N to NE-trending upright folding south of Wolfram Hill: F_2 in Early Proterozoic geosynclinal strata; F_1 in felsic volcanic strata. Spaced or slaty axial-cleavage.	nil	nil
Nimbuwah	~1870 Ma	N to NW-trending, tight to isoclinal, mostly upright folds (F_1) in Early Proterozoic geosynclinal strata. Inclined to SW in places. Penetrative axial-plane slaty cleavage (S_1).	NW-trending faulting?	Regional greenschist-facies metamorphism.
			SW-directed thrusting.	

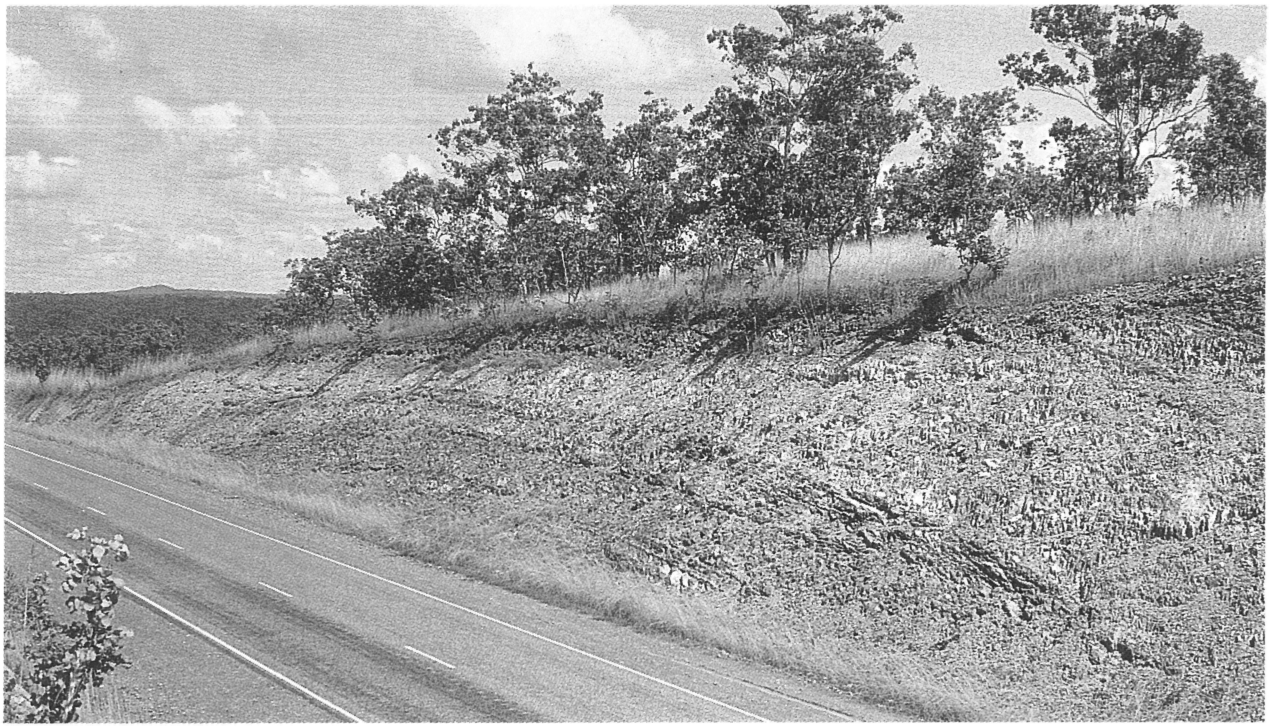


Fig. 34. Road cutting exposure of the Howley Anticline (Stuart Highway 34.6 km southeast of Adelaide River) typical of F_1 folds in the mineral field. This anticline, and others like it, are important exploration targets being the locus of stratabound auriferous quartz vein mineralisation within the South Alligator Group.

the Allamber Springs Granite, which indicate relative uplift of the pluton.

Post–Middle Proterozoic deformation

Folding

Late Early to Middle Proterozoic strata of the Edith River and Katherine River Groups form the mildly deformed Mount Callanan and Edith Falls Basins in the east and southeast, respectively. Post-Middle Proterozoic movement on bounding faults of the Mount Callanan Basin has formed broad open northwest-trending synclines with limbs dipping up to 70° adjacent to faults. The folding of Mesozoic strata at JF 9505 may similarly be related to recent movement of the Little Mary Fault.

Faulting

In the west, a number of north to northwest-trending faults along the western margin of the tablelands form the northeastern margin of the Daly River Basin. These faults are steep normal faults which were active during the Middle Proterozoic, Palaeozoic and possibly Mesozoic, down-faulting sediments to the southwest and locally drag folding them. North of Mount Masson, a series of north to north-northwest-trending faults is arranged en echelon on the limbs of tight to isoclinal folds. Displacements on the faults invariably indicate relative uplift of the eastern block.

In the east, reactivation of vertical north to northwest-trending faults resulted in minor displacement (mostly less than 100 m) of Middle Proterozoic sediments. However, where the Kombolgie Formation is cut by the Mary Fault north of Mount Daniels, relative vertical displacements of about 250 m and dextral horizontal displacements of 1300 m are indicated. Extensions of Landsat lineaments, coincident with or parallel to these faults, indicate southerly extensions of the Mary, Little Mary, Junction, and Coronet Fault systems in the northeast beneath Mesozoic cover; and a southern extension of the Little Mary Fault is suggested by a magnetic lineament. A northerly continuation of the Coronet Fault into the Cullen Batholith is indicated by a coincident Landsat lineament.

The majority of other faults trend west-northwesterly or northeasterly. They clearly postdate F_1 and F_2 folds, earlier north to northwest faults, and displace Middle Proterozoic and older strata. Where the faults cut the Cullen Batholith, they are commonly quartz-filled. The Mount Douglas Fault is a major northeasterly reverse fault, probably extending for over 30 km, which has down-faulted the Kombolgie Formation against Early Proterozoic rocks. Movement on the fault has locally overturned beds on both sides, and in places has reversed fold plunges and rotated fold axes in the older rocks. A similar-trending reverse fault, the Hayes Creek Fault, shows a dextral displacement of about 1 km in the Early Proterozoic metasediments. However, the reverse movement of the fault is opposite to that of the Mount Douglas Fault, as the Depot Creek Sandstone on the southwest side of the fault is downthrown against the McMinns Bluff Granite and Early Proterozoic metasediments. Both faults form part of the 'Grove Hill Cross Flexure' (Walpole & others, 1968), a regional

Fig. 35. Aerial photograph of the Edith Falls area.

northeast-trending structure about which the pitch changes and the trend of F_1 fold axes in the Early Proterozoic metasediments is rotated from northwest to north.

Although west-northwesterly faults are mostly short with little apparent displacement they coincide in places with regionally extensive lineaments. One such Landsat lineament, passing through the northern boundary of the Mount Davis Granite, parallels a cluster of airphoto lineaments and coincides with an 8 km long fault 5 km west of Moline.

ECONOMIC GEOLOGY

MINING HISTORY AND PRODUCTION

The production history and total recorded production of all metals in the Cullen Mineral Field are given in Figure 36 and Table 16.

The mining history of the mineral field began in 1872 with the discovery of gold-bearing quartz in the Golden Dyke Dome and alluvial gold in the Margaret River. Apart from an earlier production peak between 1894 and 1898 when most mines were working, most recorded gold production has been in the last few years (since 1984). Historically, elevated gold prices and modern bulk mining techniques have enabled recent larger-scale open-cut mining development of the previously worked vein lode deposits. Except for the *Moline Dam** and *Goodall** mines, discovered in 1981, all the major gold discoveries had been made by 1885. At least seventy gold mines or prospects are located in the mineral field, with less than half having any record of production. Over 24 t of gold have been won with the *Pine Creek*[135] group of mines (*Enterprise*) accounting for 44% of production. Other significant producers were (are) the *Zappopan*[69] group of mines, the *Union Reefs*[131] mines, the currently reopened *Northern Hercules*[157] and *Cosmopolitan Howley*[48] mines, and the recently discovered *Moline Dam** and *Goodall** mines.

A significant amount of gold production pre-1890 was unrecorded. Up until 1885, there was an export tax on gold and it is probable that every opportunity was taken to smuggle gold out of the country (Sullivan & Iten, 1952). In addition, much of the mining was unsystematic and was undertaken by Chinese on tribute, who did not always report the gold won. Other contributing factors were the small size of deposits, isolation, lack of transport facilities, unfavourable climate, stock exchange gambling and optimistic claims.

In the same year that gold was first discovered in the area, copper was found at *Copperfield*[141] which became the only copper producer until 1900. Although copper was noted in the *Northern Hercules*[157] and *Iron Blow*[85] gold mines, and the *Mount Wells*[94] tin mine, there is no record of copper production from them during this period.

Over 26,000 t of copper concentrate has been produced from sixteen mines, with *Iron Blow*[85] the major producer (58%) and the *Mount Diamond*[167], *Mount Ellison*[39] and *Copperfield*[141] mines as other significant producers. Except for the *Mount Diamond*[167] mine, most copper mines were short-lived, with the bulk of production between 1900 and 1920 peaking between 1904 and 1907 (Fig. 36). The only significant production since 1920 was from the *Mount Diamond*[167] mine in 1973.

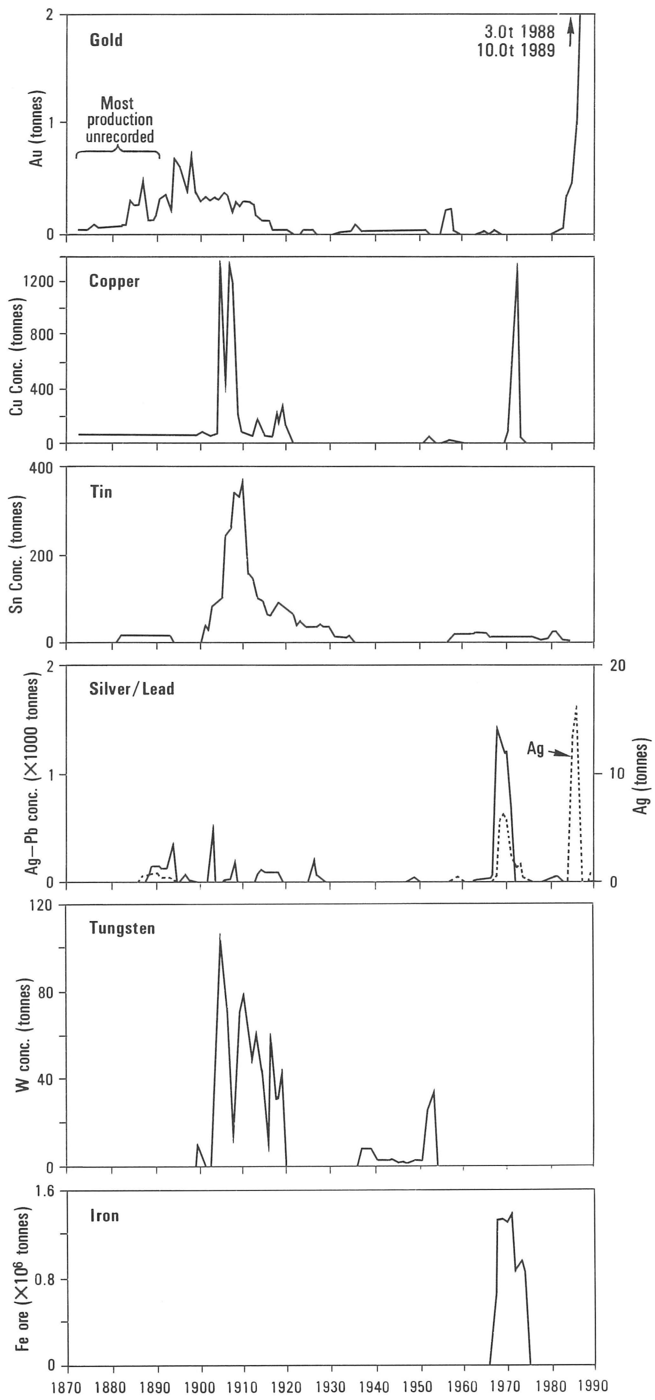


Fig. 36. Precious and base-metal production history of the Cullen Mineral Field. Where annual production is not known, total production has been averaged over the known production period.

* Not shown on the accompanying map (see Appendix 5 for details).

TABLE 16. RECORDED MINE PRODUCTION TO JUNE 1989, CULLEN MINERAL FIELD (tonnes)*

Bismuth	46
Cadmium	54
Copper conc.	26,190
Gold	24.8
Iron ore	7,979,202
Manganese ore	250
Molybdenum conc	0.1
Silver	61.6
Silver/lead conc.	7,476
Tin Conc.	4,288
Uranium (lb U_3O_8)	440
Wolfram conc.	905
Zinc conc.	6,077

* All figures are in metric tonnes except for uranium which is given in emperial pounds of U_3O_8.

The production of tin has been intermittent since its discovery at *Mount Wells*[94] in 1879. Total recorded production from twenty-eight mines is over 4,288 t tin concentrate with *Mount Wells* the major producer, accounting for about 40% of production. Apart from the total production figures for the *Old Company*[53] mine there are no pre-1900 records of tin production. Most production was between 1900 and 1934; production peaked at over 200 t Sn concentrate p.a. between 1906 and 1910 (Fig. 36), when up to eight mines were operating following a spate of discoveries including the *Horseshoe group of mines*[207] and the *Umbrawarra*[150] alluvial deposits. Production from *Mount Wells*[94] was also at its height during this time. After a twenty year hiatus of very low or nil production, a number of new tin discoveries in the Mount Masson area resulted in minor tin production between 1956 and 1965. Since 1965, production has remained at a low level, with a small increase in production in 1980-81 mainly from the *Horners Creek*[93] alluvial workings.

The history of silver and lead production is characterised by short periods of production separated by longer periods of inactivity (Fig. 36). A total of 7,476 t of Ag-Pb concentrate and 61.6 t of silver has been produced from eighteen mines, commonly as a by product of gold or copper ores. The *Evelyn*[156] mine, first discovered in 1886, has dominated production and accounts for 75% of the concentrate and 38% of the silver produced. The mine was last worked in 1973 following a major period of production between 1967 and 1971.

Over 905 t of tungsten concentrate have been produced since 1900 from three mines, the *Wolfram Hill*[186], *Yenberrie*[215] and *Mountain View*[192] mines. The Wolfram Hill mine accounts for 82% of production and has been the only mine worked since 1920. Eighty-eight percent of production was between 1904 and 1919, with production peaking in 1906 and dropping off until 1920. The Wolfram Hill mine was later worked intermittently from 1937 to 1953 (Fig. 36).

A concerted exploration effort in the early 1950s resulted in the location of several radiometric anomalies and minor uranium mineralisation. However, the only production was 440 lb of U_3O_8 from the *Fleur de Lys*[47] mine in 1953-4.

Several iron prospects were located between 1961 and 1972, and the only production was 7,979,202 t of iron ore from the *Frances Creek*[102] group of mines between 1967 and 1974 (Fig. 36).

Other metals produced in the mineral field as by-products of precious or base metal ores are: 6077 t of zinc concentrate and 54 t of cadmium from the *Evelyn*[156] mine; 46 t of bismuth from the *Mount Diamond*[167], *Mount Ellison*[39] and *Yenberrie*[215] mines; and 0.1 t of molybdenum concentrate from the *Yenberrie*[215] mine.

Minor amounts of limestone were mined in the Burrundie area during the late 19th century for local consumption in ore treatment plants.

DEPOSIT DESCRIPTIONS

Detailed descriptions of most of the deposits are included in reports accompanying the 1: 100 000 geological maps (Stuart-Smith & others, 1984a, 1986a, 1987, 1988; Bagas, 1981, 1983). Crohn (1968) provided the first comprehensive summary of the economic geology of the region and aspects of mineralisation have been reviewed by Needham & Roarty (1980), Goulevitch (1980), Nicholson (1980), Nicholson & Eupene (1984, 1990), Stuart-Smith & Needham (1984), Stuart-Smith (1985), and Needham & De Ross (1990). Details of the major gold deposits are included in BMR's Mindep database (Mock, 1992). All mines, prospects and mineral occurrences are shown on the accompanying map and individual deposit descriptions and production are summarised in Appendix 5.

Crohn (1968) recognised a variety of deposit types within the Cullen Mineral Field and classified them as either:

- (1) hydrothermal precious and base metal deposits associated with granitoids;
- (2) iron deposits formed by supergene enrichment of iron-rich sediment; or
- (3) alluvial deposits.

Stratigraphic control of gold deposits within rocks of the "Golden Dyke Formation" (name no longer used and rocks now included in the South Alligator Group) was recognised by Crohn (1968) who suggested that, although most disseminated pyrite was probably syngenetic, "the gold mineralisation was probably younger and controlled by the favourable physical and chemical characteristics of the beds". Needham & Roarty (1980), Goulevitch (1980), and Nicholson & Eupene (1984) interpreted many of these deposits to be syngenetic in origin and representative of a "stratiform" type. However, most of the deposits included in this category are associated with late-stage faulting and quartz-veining, and a replacement origin could also be argued. Most of these deposits are therefore included in a broad 'hydrothermal' category; exceptions are the stratabound Au-Ag-Cu-Pb-Zn lodes of the *Mount Bonnie*[86], *Iron Blow*[85] and *Heatleys*[88] mines. These deposits are differentiated from others by their polymetallic character, the presence of stratified ores and the absence of major late-stage structures. Goulevitch (1980), Nicholson (1980), and Donnelly & Crick (personal communication, 1984) suggest that they are syngenetic deposits probably associated with exhalative activity during the waning stages of felsic volcanism in the South Alligator Group.

On the basis of the dominant style of mineralisation, metal association, and stratigraphic and structural controls, a fourfold classification of mineral deposits is indicated:

- hydrothermal veins or stockworks associated with granitoid intrusions (Sn, W, Au, Ag, Pb, Zn, Cd, Cu, Bi, As, U, and Mo);
- stratabound massive sulphide deposits within the South Alligator Group (Au, Ag, Cu, Pb and Zn);
- residual massive oxide deposits (Fe and Mn); and
- alluvial deposits (Au and Sn).

Non-metallic minerals are not included in this subdivision and are discussed separately.

General features of the deposit types are given below together with discussion of mineralisation controls and genesis.

Hydrothermal deposits

The hydrothermal deposits comprise over 90% of mines and prospects, and production, within the Cullen Mineral Field (Fig. 37). They can be classified into six major types, dependent on metal association, and to a lesser extent gangue mineralogy and structural and host rock association. The six types (minor metals, some or all of which may be present, are shown in brackets) are:

[1] gold (± silver, copper, lead, zinc);

[2] tin (± copper lead, tungsten);

[3] silver-lead (± zinc, cadmium, gold);

[4] copper (± silver, lead, gold, bismuth);

[5] tungsten (± copper, molybdenum, bismuth); and

[6] uranium (± copper).

The geological setting and major characteristics of these deposits are shown in Figure 38 a-f.

Hydrothermal *gold* occurrences are widespread and form quartz reefs in a variety of structural settings (Fig. 38a). The reefs, mostly ranging up to 2 m wide and 100 m long, fill near-vertical north to northwest-trending shear zones which are conformable with the regional axial plane S_1 cleavage of the Early Proterozoic metasediments. Irregular and discontinuous veins, filling tension openings at high angles to shear zones, are commonly associated. Other, less common, forms of quartz reefs include saddle reefs and en echelon veins within shear zones. The gold occurs in disseminated sulphides within the primary zone with grades mostly less than 10 g/t Au. Pyrite and arsenopyrite are the most common sulphides, and minor or trace amounts of chalcopyrite, galena, pyrrhotite, marcasite, sphalerite, tetrahedrite and native bismuth occur in places. Wallrocks are typically sericitised and silicified and less commonly carbonated, chloritised and sulphidised (Nicholson & Eupene, 1990; Sanger-von Oepen & others, 1988). The lodes were originally worked mainly in the oxidised zone within 30 m of the surface where the gold is free-milling, enriched (25 to 35 g/t Au), and associated with limonite, kaolin and quartz. More recent open-cut developments operate mostly in the primary sulphide ore with grades of 1.9-3.8 g/t Au (Nicholson & Eupene, 1990).

Most *tin* deposits occur within massive or brecciated quartz lodes either filling faults where they range up to 2 m wide and 2 km long, or within thin quartz veins and stockworks either adjacent to or within major shear zones (Fig. 38b). Finely disseminated or aggregated cassiterite crystals are associated with pyrite and commonly minor arsenopyrite and chalcopyrite. Chalcocite, wolframite, scheelite, bismuth minerals, galena, sphalerite, gold, silver and tourmaline may also be present.

Between the Prices Springs and McMinns Bluff Granites, several tin deposits are associated with dykes or small irregular-shaped intrusive bodies of syenite, micromonzonite and diorite. Cassiterite is associated with either minor sulphides in steeply-dipping muscovite-tourmaline-quartz lodes or quartz-chlorite veins filling shear zones within or along the contacts of the intrusions.

Other minor forms of tin mineralisation include cassiterite-tourmaline-muscovite-quartz vein stockworks adjacent to the Minglo and Shoobridge Granites, plus disseminated cassiterite within the Wolfram Hill Granite.

Most tin production has been from cassiterite-kaolin-hematite-limonite-quartz lodes, with grades up to 12% Sn

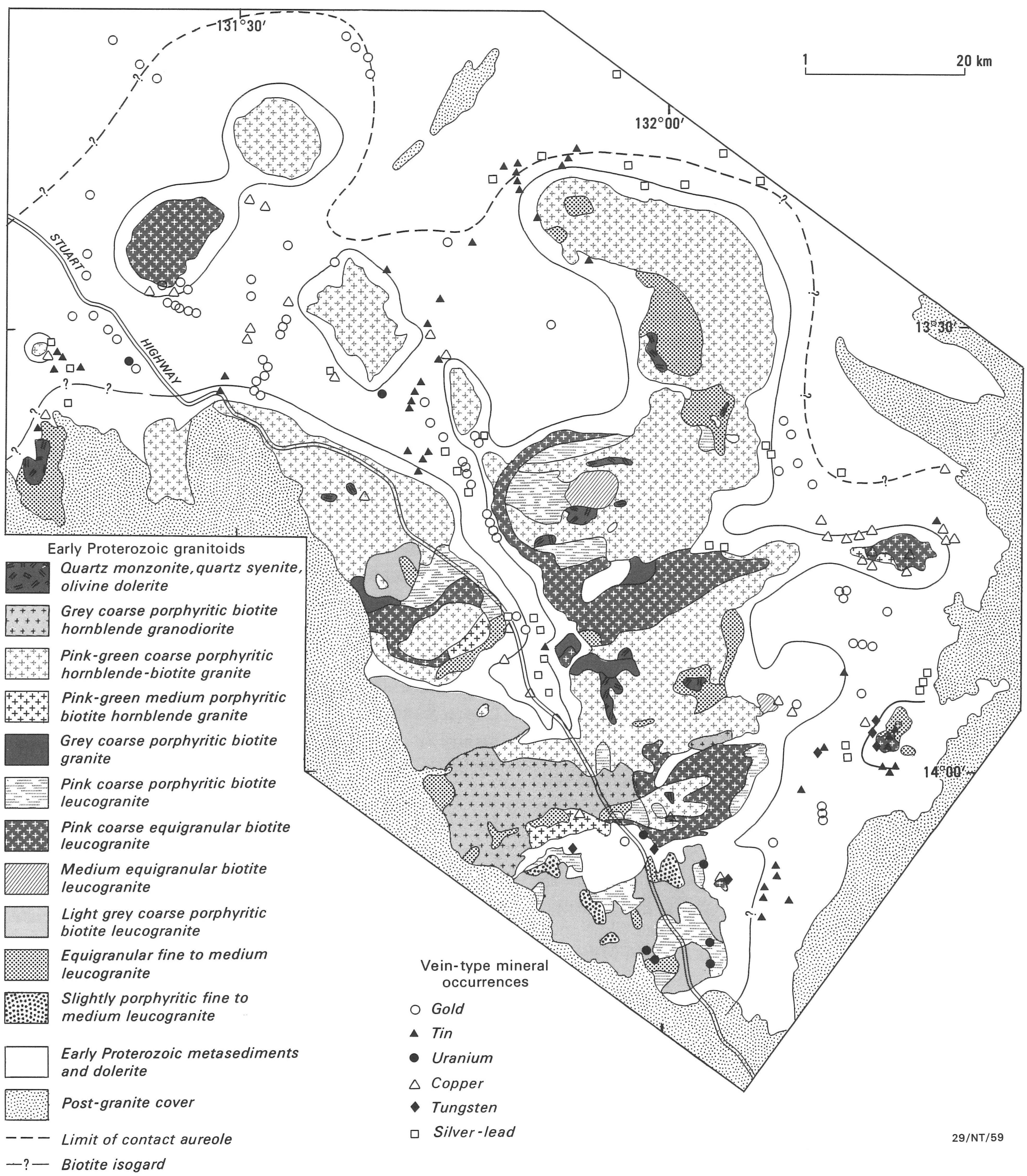


Fig. 37. Distribution of hydrothermal mineral occurrences and granitoid phases of the Cullen Batholith.

in the near-surface oxidised zone. The primary sulphide lodes generally have grades between 1.0-1.2% Sn.

Minor *silver-lead* mineralisation throughout the region is associated with veins, breccias, and stringers of carbonate and quartz mostly in carbonaceous and dolomitic metasediments (Fig. 38c). Like most of the auriferous reefs, the silver-lead lodes are localised within northwest-trending shear zones conformable with the regional axial plane S_1 cleavage of the host Early Proterozoic metasediments. They are up to 1 m wide and discontinuously up to 5 km long. Most silver-lead production has been from the oxidised enriched zone where the main ore minerals are galena, cerussite, and pyrargyrite, with grades 30-70% Pb and up to 113 kg/t Ag. The primary ores are lower grade (2-3% Pb) and consist of argentiferous galena, sphalerite, and pyrite with minor marcasite, arsenopyrite and chalcopyrite in places.

Most production has been from the *Evelyn mine*[156], a skarn deposit, where massive limestone has been altered to marble with tremolite/actinolite, anthophyllite,

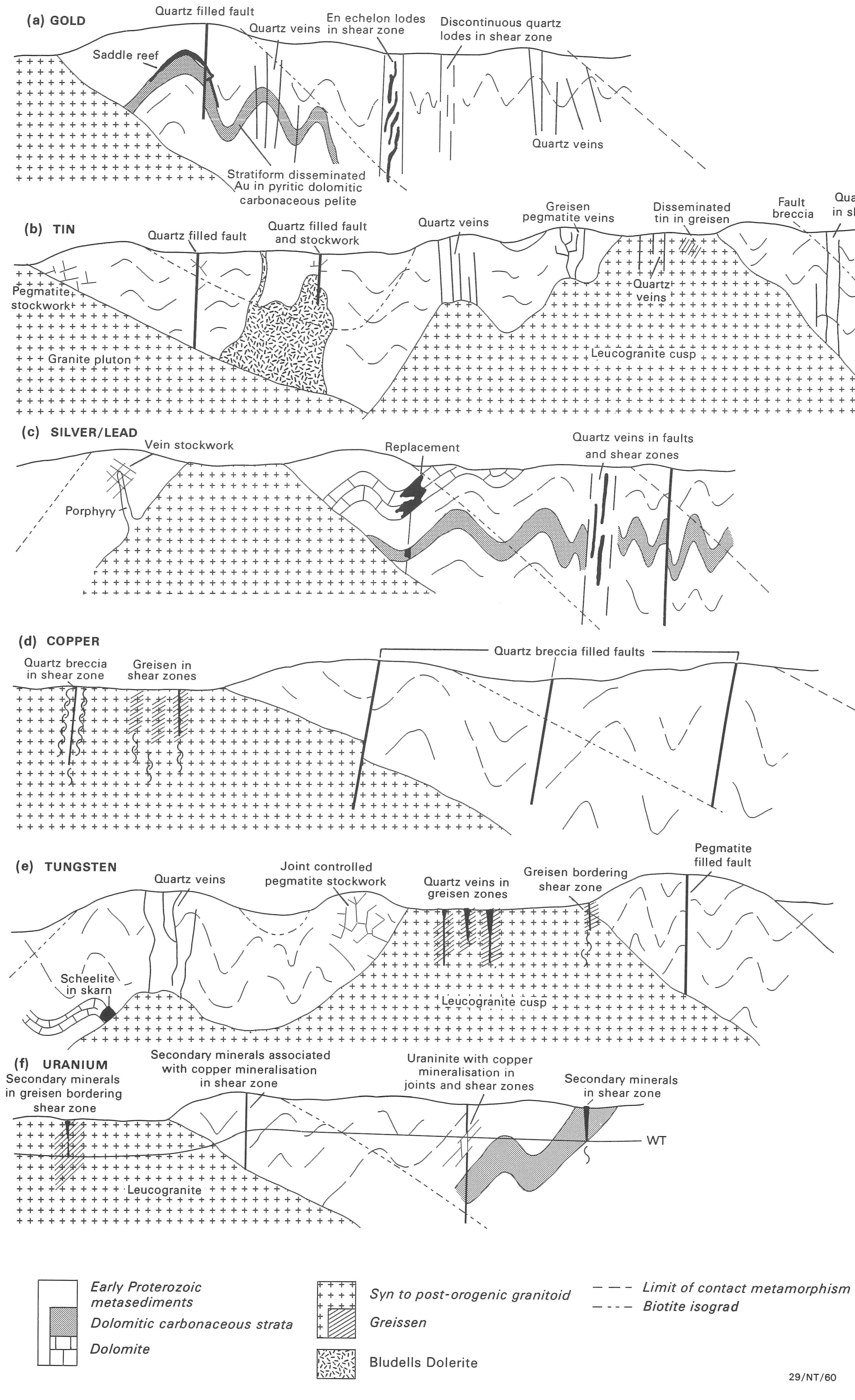


Fig. 38. Schematic sketch showing setting and major characteristics of hydrothermal deposits.

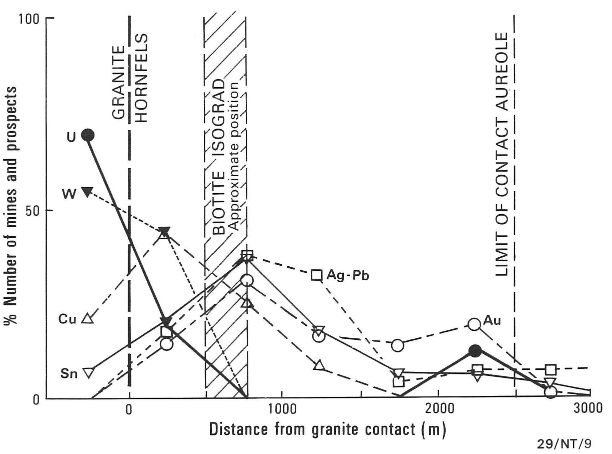


Fig. 39. Zonation of hydrothermal mineral occurrences.

diopside, garnet and serpentine adjacent to ore. The orebodies are small, irregular, tabular to lens-shaped lodes up to 1.6m wide arranged en echelon within a northwest-trending shear zone. Zinc, gold and cadmium, as well as silver and lead, have been produced from an ore of sphalerite, galena, pyrite and pyrrhotite, with minor chalcopyrite and arsenopyrite and rare pentlandite, argentite and electrum (Garth, 1970).

The major *copper* occurrences are located in quartz breccias which fill north to northwest-trending shear zones (Fig. 38d). The mineralised breccias, up to 3 m wide and 2600 m long, are localised within both granitoids and adjacent hornfels. The hornfels is commonly sheared and sericitised. Nearly all production has been from the oxidised zone from ores averaging 10-20% Cu and consisting of malachite, azurite, chalcopyrite, arsenopyrite, cuprite, scorodite, covellite and chalcocite, in a limonite-hematite-quartz gangue.

At depth, the primary sulphide ores are lower grade (less than 5% Cu) and consist typically of chalcopyrite and pyrite; with minor arsenopyrite, galena, cuprite, tetrahedrite, pyrrhotite, molybdenite, and sulphides of bismuth, antimony and silver. Magnetite is commonly present.

A few small copper mines are located in north or east-trending shear zones within the McMinns Bluff, Tabletop and Driffield Granites, and the Fingerpost Granodiorite. The ore consists of secondary copper minerals, including malachite, azurite, chalcocite, cuprite, and chrysocolla, in quartz veins up to 1 m wide which are surrounded by intensely sheared, chloritised and hematised granite. In places, koechlinite (a greenish-yellow bismuth molybdenum oxide, Bi_2MoO_6) is present. In the Mount Davis Granite, copper mineralisation is associated with arsenopyrite-quartz-sericite-chlorite greisens which occupy north-trending shear zones.

A few *tungsten* mines are located in the south, on the margins of the Tennysons and Yenberrie Leucogranites and around the Wolfram Hill Granite. Within the granitoids, mineralisation is wolframite associated with pyrite, arsenopyrite, molybdenite, copper sulphides, plus bismuth and uranium minerals in quartz veins within greisen zones (Fig. 38e). Around the Wolfram Hill Granite, wolframite—together with chalcopyrite, arsenopyrite and pyrite—occurs in quartz veins or biotite-feldspar-quartz pegmatite. The lodes lie against or within 200 m of the granite, and follow joints and shear planes within the hornfels. Grades range up to 4% W and 5% Cu. Minor tungsten mineralisation as scheelite is present in hornfels at the *Mount Wells tin mine*[94] and near the *Evelyn mine*[156].

Several small *uranium* prospects lie within or adjacent to the Tennysons Leucogranite and Driffield Granite in the south. They consist of thin (<45 cm wide) gossanous quartz veins and disseminations with secondary uranium minerals, apatite and iron oxides in sheared, silicified and greisenised granite (Fig. 38f). Three uranium occurrences, including the *Fleur de Lys*[47], mine lie in shear zones within Early Proterozoic metasediments in the northwest. One of these, located near the Shoobridge Granite, has minor uraninite mineralisation with pyrite, chalcopyrite, and chalcocite .

Metal zonation

Using the mapped metamorphic zones (Fig. 29) and the estimates of depth to "granite basement" from gravity data (Fig. 16), Stuart-Smith & Needham (1984) estimated the perpendicular distance from the concealed granitoid contact for each of the deposits. The data for the six major classes of vein deposits are summarised in Figure 39. A zonation of metals is indicated, is not readily apparent from the surface distribution of the deposits owing to the uneven depth to granitoid basement. Difference in the timing of granitoid intrusion, and the effects of structure and host rock composition probably affected deposit distribution on the local scale, accounting for deviation from the overall zoning pattern by individual deposits or local deposit groups (Stuart-Smith & Needham, 1984).

Only ten *uranium* occurrences are known in the region; of these, seven are within granite and the remainder in the contact aureole—two less than 500 m and one over 2000 m from granite.

Tungsten occurrences are similarly distributed. More than half are in granite, where they are commonly associated with molybdenite, bismuth and uranium minerals. The remainder are less than 500 m from granite and are mostly accompanied by copper mineralisation. Tin may be associated with tungsten in all deposits.

Copper deposits are confined to either within granite (21%) or less than 1500 m from the granite contact. Over 40% are within 500 m of granite and are commonly associated with bismuth minerals, and minor silver and gold mineralisation. Those farther from granite are generally monometallic. Copper also occurs as a minor constituent in silver-lead and tin deposits up to 2000 m from the granite contact.

Tin, silver-lead and *gold* deposits show very similar distribution to one another with over 90% of the deposits within the contact aureole, although minor tin deposits also lie within granite. The deposits are concentrated between 500 and 1000 m from granite and decrease in number towards the outer limit of the contact aureole. Only silver-lead and gold mineralisation extends farther than 3000 m from granite.

Relationship to granitoids

The zonation of hydrothermal mineral deposits around the Cullen Batholith and the general spatial association supports a genetic relationship, as proposed by Ewers & Scott (1977). They concluded that the main role of the granitoids was as a heat source for the mobilisation of ore solutions, which were driven by the imposed geothermal gradient, but the source of the metals and hydrothermal solutions was left open to conjecture. However, they did suggest a relationship between uranium, copper and tungsten mineralisation and higher than normal metal values in adjacent granitoids. This was supported by Stuart-Smith & Needham (1984) who evaluated Ewers & Scotts' geochemical data and additional geochemical data in relation to the newly defined granitoid phases and plutons.

Abundance levels of metals in granites have long been cited as evidence for or against a magmatic source for metals in hydrothermal deposits (Krauskopf, 1967). For metallogenic purposes, it is more important to distinguish granitoids that crystallise by convective fractionation from those that are restite-rich. Whalen & others (1982) argued that restite-rich granites cannot give a greater concentration of any element than that in the initial melt or restite. In contrast, mechanisms of crystal fractionation (e.g. convective fractionation) provide a better mechanism whereby metals can be concentrated. White & others (1991) defined a granite classification emphasising that high-temperature K-rich granite liquids, particularly those rich in volatiles (such as F, B, and Li), will crystallise over a wide temperature range and have a greater capacity to concentrate economically important metals. On these criteria, the K-rich Cullen Batholith has high metallogenic potential. The batholith has a wide, high-temperature contact aureole, indicating relatively high initial emplacement temperatures. The SiO_2 range of crystallisation for the batholith is fairly large, ranging from 53 to 78 wt% (Fig. 40), implying a substantial density difference between the primary and derivative liquids.

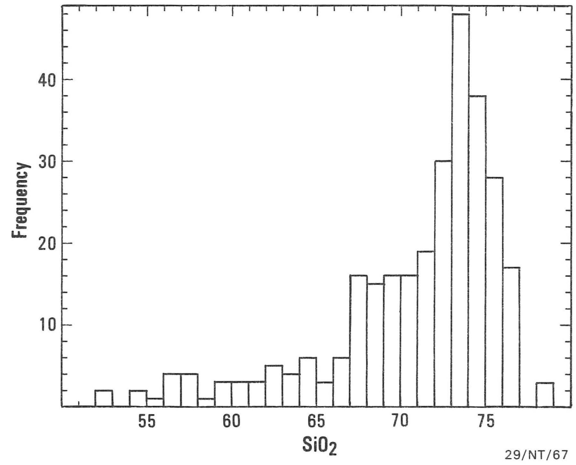


Fig. 40. Frequency vs. SiO_2 plot for the Cullen Batholith.

These factors make the Cullen Batholith ideal for progressive metal enrichment.

There appears to be an association of mineral deposit types with particular granitoid chemical suites (Fig. 41). The interpreted association of the various metals with fractionation is illustrated in Figure 42. The degree of fractionation within the leucogranite suites largely controls the associated metal(s). The Burnside suite, showing significant signs of fractionation, has the greatest range of mineralisation types in its contact aureoles, whilst the most fractionated Tennysons suite has vein mineralisation either in the contact aureole or within the granite, particularly Sn, W and U. In contrast, the unmineralised Saunders suite shows virtually no sign of fractionation.

Small Cu deposits are associated with the concentrically zoned granite and leucogranite plutons, particularly those rich in hornblende. As Au, Pb and Zn do not concentrate within the individual granite plutons but are located some distance from the granite, it is difficult to define which particular plutons they are associated with. Their distribution appears to be more controlled by interaction between specific host rocks within the contact aureole and hydrothermal fluids.

Comparison of the metallogenic potential of the Cullen Batholith with other Australian Proterozoic granites: Compared with many 1880-1800 Ma old granitic batholiths in Australia (Wyborn, 1988), the Cullen Batholith is distinctive in having a greater range of petrological and chemical variability—its association with mineralisation is also unusual. For example, Wyborn & Page (1983) showed that there is very little chemical variation over about 4500 km^2 of the Kalkadoon Batholith and its comagmatic volcanics in the Mount Isa Inlier; similar uniform granites are found throughout northern Australia (Wyborn, 1988) and include the Nimbuwah

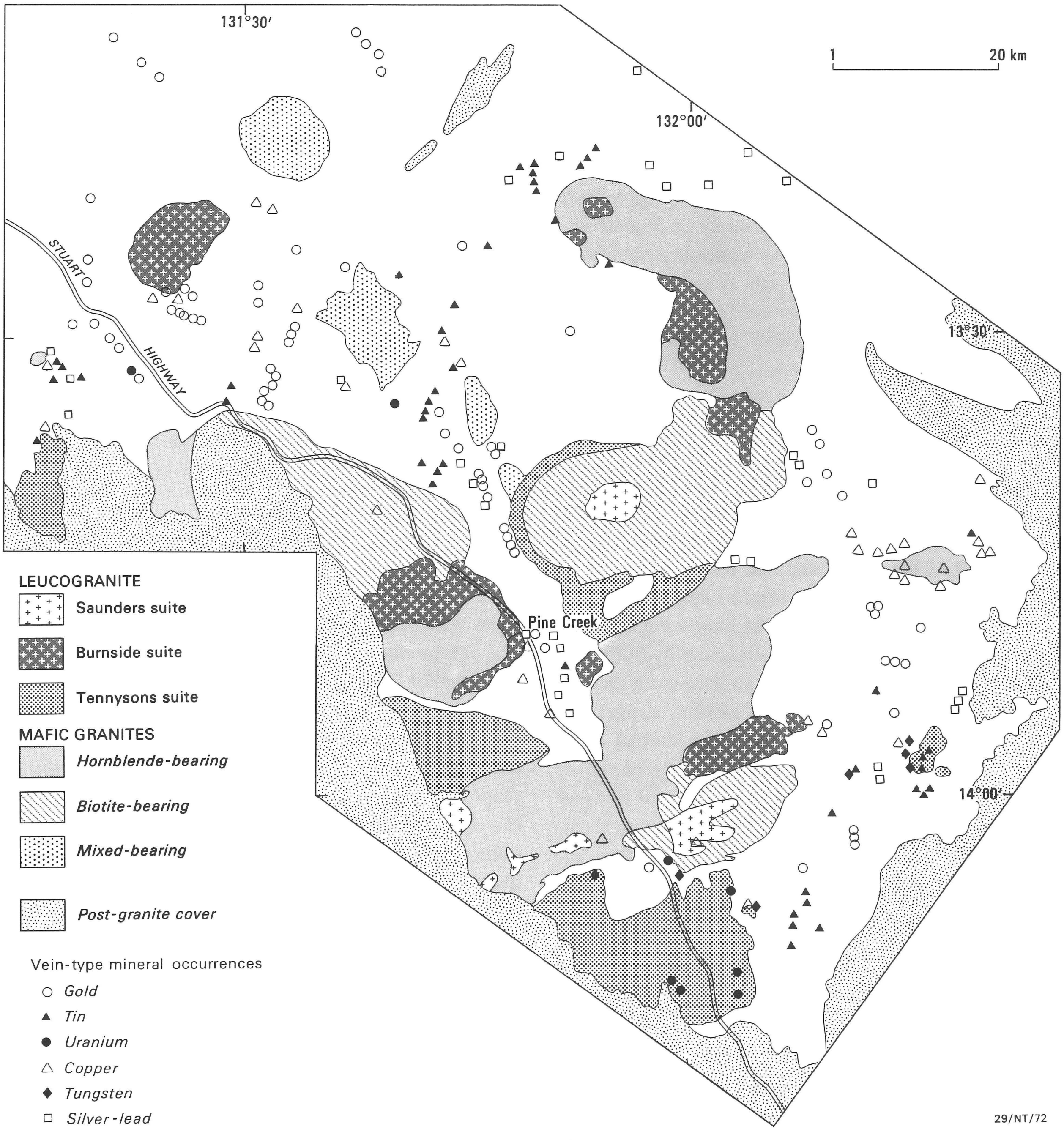


Fig. 41. The distribution of hydrothermal mineral occurrences and granitoid suites.

Granite in the Alligator Rivers Region, the Tennant Creek Granite of the Tennant Creek Block, and the Bow River Granite of the Halls Creek Province. In these bodies, it is difficult to identify petrologically distinct plutons (e.g. leucogranites, zoned plutons) and where exposed, comagmatic volcanics are identical in composition to the intrusives. None of these granites is associated with any significant mineralisation, and unlike the Cullen Batholith they are dominated by abundant xenocrysts or restite (Chappell & others, 1987) and the crystallisation process is one of restite (hornblende, biotite, calcic plagioclase) unmixing from a minimum melt component dominated by quartz, K-feldspar and albite.

There are some granites of similar age (i.e. 1820-1840 Ma) with chemical characteristics similar to the Cullen Batholith [i.e. increasing U, Rb, (Li) and Y, decreasing K/Rb values, and increasing ASI with increasing SiO_2], and several have associated Sn, W, and Cu vein mineralisation (Table 17). In some, leucogranite phases have also been distinguished and pegmatites and are present. However, Au mineralisation is only present where reduced or iron-rich host rocks—such as those within the Koolpin Formation—are present (e.g. Granites--Tanami Block) in addition to the fractionated granitic suites. Some of the features of the Cullen Batholith also typify the 700 Ma old Mount Crofton

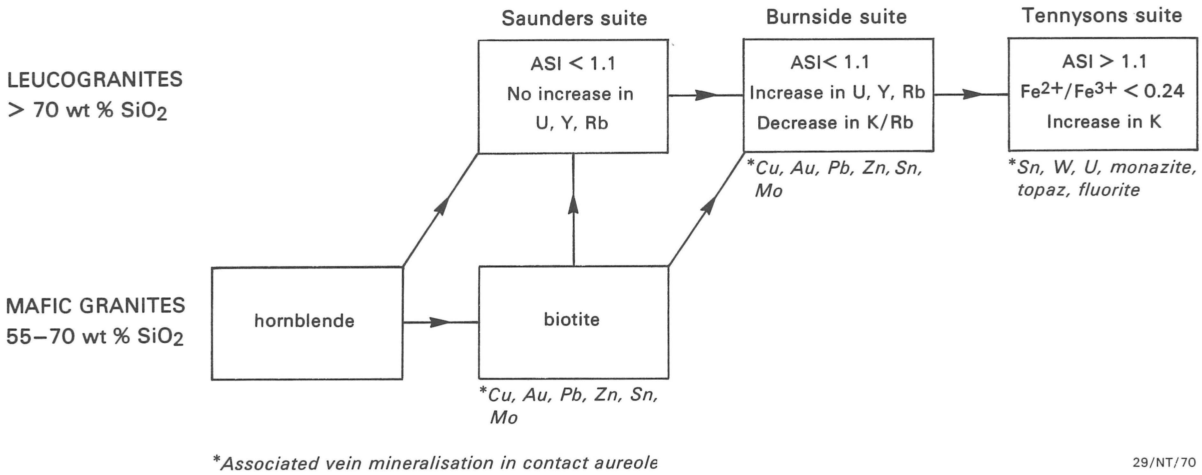


Fig. 42. Granite fractionation trends and associated mineralisation.

Granite and other granites near the Telfer deposit of the Paterson Province (Goellnicht & others, 1991).

Stratigraphic controls

The relative distribution of hydrothermal deposits and amount of produced metal from mineralised stratigraphic units in the mineral field are shown in Figure 43 together with major lithological components. The number of mines and total tonnages from each unit are compared on a per square kilometre basis to remove bias inherent in the differing areal extent of units. A comparison of this nature is limited by the small number of mines and prospects and by the dominance of one or two producers. However, broad stratigraphic controls can be recognised for the distribution of some metals.

Gold vein deposits are widespread in the South Alligator and Finniss River Groups, and the Tollis Formation, with the greatest density of mines and highest average tonnage in the Mount Bonnie and Koolpin Formations. The association of gold deposits with these formations is particularly marked along the Howley Anticline, in the Golden Dyke Dome area, and along the southern margin of the Burnside Granite, and has been noted and discussed by Nicholson (1980), Nicholson & Eupene (1984, 1990), Needham (1981) and Needham & Roarty (1980). Within these units, gold mineralisation is concentrated in either carbonaceous mudstone or pyritic chert-banded dolomitic siltstone ("ironstone") horizons (Nicholson, 1980; Nicholson & Eupene, 1984) and may reflect a preferred replacement horizon for gold-bearing fluids (Crohn, 1968) or synsedimentary concentrations of gold, possibly related to exhalative activity during deposition of the South Alligator Group (Nicholson, 1980; Nicholson & Eupene, 1984, 1990; Cyprus Minerals Australia Company, 1988). Noticeably the average gold content of the Koolpin Formation, geosyncline wide, is above average (Fig. 43), and in places with concentrations of almost 1 g/t Au over strike lengths of at least 3 km (Hossfeld, 1936a; Blanchard, 1937).

Tin deposits occur in all units except the Koolpin and Masson Formations, with a marked higher density in the Tollis Formation (Fig. 43). Differences in average tonnage between units are slight and reflect an inverse relationship with pelitic content, that is, tin deposits appear to be preferentially located in psammite-rich units. This may reflect greater development of open fractures in psammitic units, which are the preferred sites of cassiterite-bearing quartz veins and stockworks. There is no relationship between mineralisation and the average tin content of a unit (Fig. 43). The Gerowie Tuff has anomalous tin, but is one of the least mineralised units and it is unlikely that it was a significant source of tin.

Silver-lead deposits occur in all units except the Tollis Formation and are concentrated in the Wildman Siltstone and the Koolpin and Mount Bonnie Formations, with the Koolpin Formation containing by far the most tonnage (mostly *Evelyn mine*[156] production). There is no relationship with average lead content of the units, however, the main mineralised units are also the carbonate-bearing units (Fig. 43) and as such, they would be the favoured sites for replacement and the precipitation of sulphides from hydrothermal fluids, as is demonstrated by alteration assemblages at the *Evelyn mine*[156].

Copper vein deposits, although not spatially related to gold deposits, show a similar distribution, with the Koolpin and Mount Bonnie Formations having the highest density of mines. The Koolpin Formation also has the highest average tonnage, owing to it hosting the *Ellison*[39] mine. It also contains above average copper concentrations (Fig. 43). Numerous copper geochemical anomalies associated with pyritic beds were located in the Koolpin Formation by Sullivan & Iten (1952) around the Burnside Granite and along the Howley Anticline. This concentration may reflect syngenetic concentration or the suitability of pyritic dolomitic strata to replacement by

TABLE 17. SUMMARY OF SOME AUSTRALIAN EARLY PROTEROZOIC GRANITE SUITES AND ASSOCIATED MINERALISATION

Province	*Granite*	*Mineralisation*
Mount Isa Inlier	Ewen Batholith	nil
Murphy Inlier	Nicholson Granite/ Cliffdale Volcanics	Sn, W, Cu
Davenport Province	Elkedra Granite	W
Tennant Creek Block	unnamed porphyries, Warrego Granite	Au, Cu, Bi
Granites-Tanami Block	Lewis Granite, Winnecke Granophyre, the Granites Granite	Au
Arunta Block	Harveson Granite	nil

metal-bearing fluids. It is noticeable, however, that other carbonate-bearing units (i.e. the Masson Formation and Wildman Siltstone) do not host any copper mineralisation but do have above average copper concentrations (Fig. 43).

There are too few tungsten or uranium occurrences to obtain any indication of stratigraphic control, and both metals are mostly hosted by granitoids. It may be significant, however, that two of the three uranium occurrences (*Fleur de Lys*[47], and *Burrundie*[107]) not in granitoids, are hosted by sediments (the Gerowie Tuff and Koolpin Formation respectively) with above average uranium contents (Needham & Stuart-Smith, 1984b). The Koolpin Formation is the preferred host to uranium mineralisation in other areas of the Pine Creek Geosyncline, such as the South Alligator Valley Uranium Field. Although an epigenetic model is proposed by Wyborn & others (1990) for the South Alligator uranium deposits, mineralisation is of a different style and is probably not associated with deep hydrothermal systems, such as those generated by granitic intrusions as proposed for the Cullen uranium deposits.

Structural controls

Structural controls have been significant in the formation of all the hydrothermal deposits by either providing suitable deposition sites, or by localising replacement mineralisation in carbonate strata. The major forms of structural control are shown schematically in Figure 44.

By far the most common structural controls are steeply dipping faults and shear zones, paralleling the S_1 slaty cleavage which is axial plane to the dominant tight to isoclinal F_1 folds in the Early Proterozoic metasediments. As the folds plunge subhorizontally, the cleavage commonly strikes parallel to bedding, which trends mostly northwesterly except in the north where it swings more northerly. This cleavage, owing to its penetrative nature, provided the major zones of weakness for developing faults and shear zones during later or successive deformations. Displacements on the Pine Creek Shear Zone indicate movements before, during and after granitoid emplacement. These zones were therefore active and suitable sites for the deposition of metal sulphides, quartz, and pegmatite at a time of high fluid movement and induced thermal gradient which accompanied granitoid intrusion.

Several periods of veining, developed during a single (or successive) progressive deformation contemporaneous with granitoid intrusion, are common in many deposits (e.g. Dann & Delaney, 1984; Sanger-von Oepen & others, 1988). At the Enterprise mine (*Pine Creek group of mines*[135]), Arnold (1986; referred to in Cannard & Pease, 1990) recognised three main categories of veins: (1) weakly mineralised bedding-concordant veins (e.g. saddle reefs) and subvertical, S1 parallel, "spur and hinge-zone veins" concentrated in the anticlinal hinge; (2) mineralised stratabound "ladder and sheeted veins" developed late in the folding on the anticline limbs; and (3) sphalerite and galena-rich late-stage veins and breccias in "post-tectonic" faults. The main gold mineralisation is associated with the second period of veining, which is characterised by massive quartz reef development and altered wall rocks (Dann & Delaney, 1984). Commonly, the last movements on fault zones are characterised by brittle deformation features, such as brecciation and the development of tension gashes. Metal sulphides are commonly concentrated by these last movements.

Within the faults and shear zones, veins have a variety of forms: either as discrete lenses within a fault; or as a series of parallel or *en echelon* lodes within a shear zone (Fig 44). Commonly, the richest, and/or the widest, part of the vein is where the main fault or shear is offset by another surface, such as a joint, a competent bed, or a pre-existing quartz vein, resulting in the formation of a series of steeply plunging "pipes", "swells" or en echelon lodes. The *Wolfram Hill*[186] tungsten mine and the *Horseshoe Creek group of tin mines*[207] are good examples of such structures.

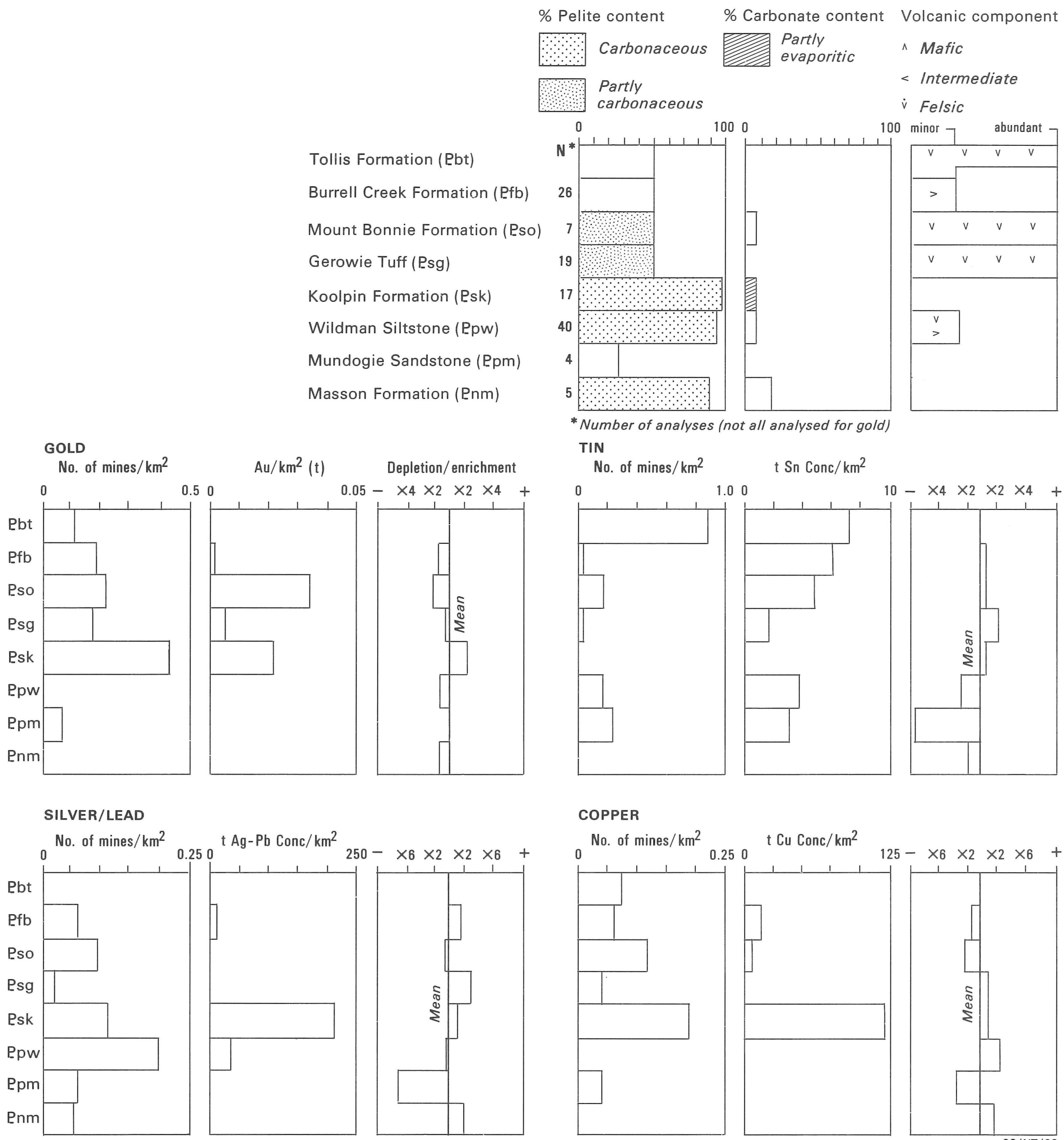


Fig. 43. Stratigraphic control of hydrothermal mineral deposits, shown by variations in lithological composition (after Needham & Stuart-Smith, 1984b), metal content (after Ewers & others, 1985), mineral production, and number of mines. The mean is calculated from all Pine Creek Geosyncline metasediment analyses (after Ewers & others, 1985).

There is a marked coincidence of auriferous lodes with anticlines (see accompanying map), which possibly resulted from the focussing of upward fluid movement into anticlinal hinges during a regime of continuing external stress (Cannard & Pease, 1990). Quartz saddle reefs are associated with some of these anticlines (for example, *Cosmopolitan Howley*[48], *Enterprise*[135] and *Woolngi*[220]). However, they contain low-grade mineralisation, and most mineralisation is in later-stage quartz-filled steeply-dipping faults and shear zones, which are concentrated in the hinge or adjacent limbs of the anticlines. This may reflect the ability of massive saddle reefs to either 'localise' later deformation, and/or that pre-concentration of stratiform gold in saddle reefs is a major precondition for the later development of cross-cutting auriferous reefs, as suggested by Nicholson & Eupene (1984).

Other minor structures controlling mineralisation are bedding plane partings and joints, which control tin and tungsten-bearing pegmatite stockworks and the distribution of some uranium mineralisation.

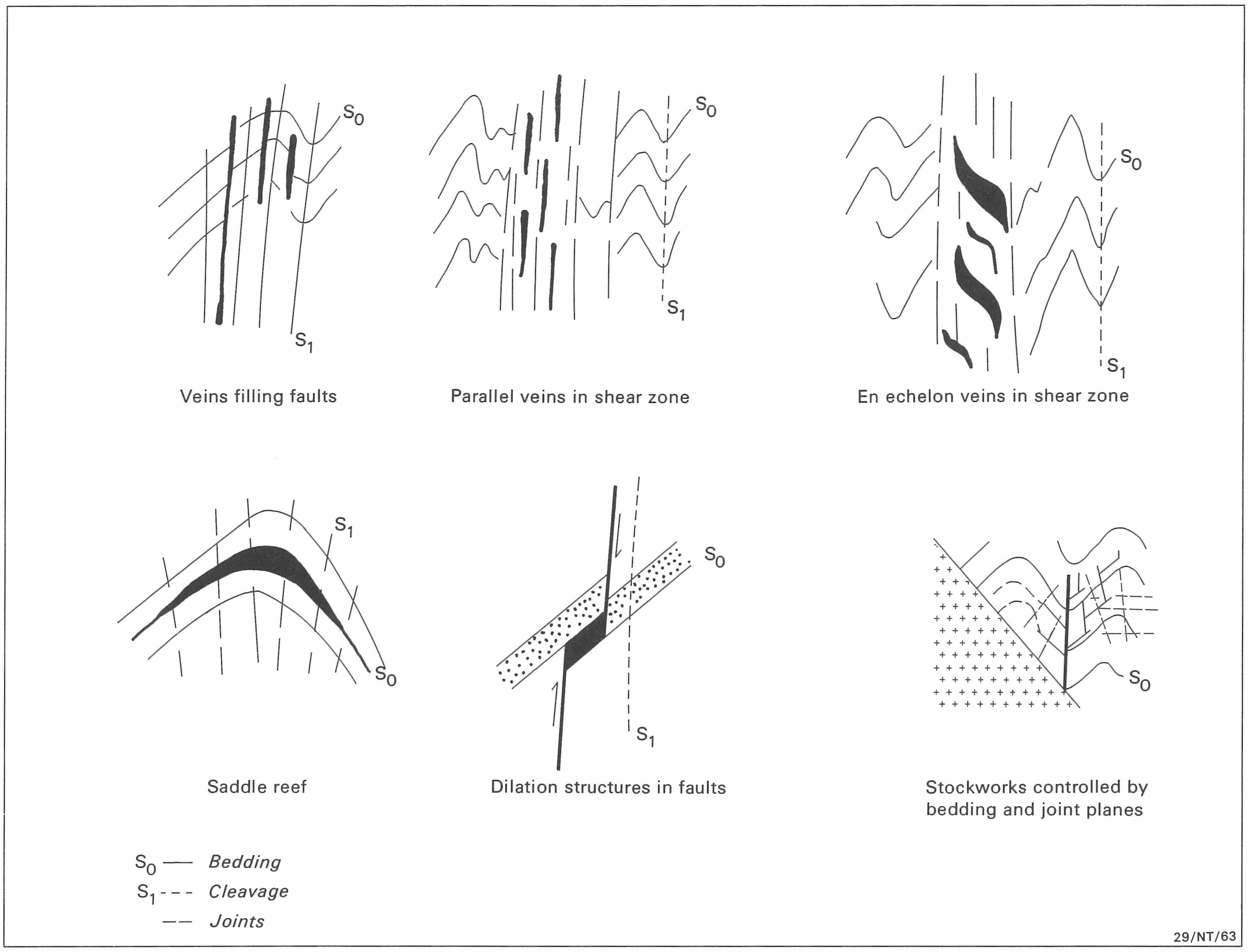


Fig. 44. Major structural controls and forms of hydrothermal mineral deposits.

Summary and discussion of hydrothermal deposits

The hydrothermal deposits comprise over 90% of mines and prospects within the Cullen Mineral Field, and contain gold, silver-lead, tin, tungsten, copper, and uranium. They are dominantly sulphidic and in north to northwest-trending faults, shear zones and associated minor structures. Saddle reefs are also associated with some gold mineralisation, while tin and tungsten minerals may be associated with pegmatite stockworks adjacent to the batholith. Although most deposits are located within the Early Proterozoic sediments, some tin, tungsten and copper and nearly all uranium occurrences are located within the batholith. The shear zones, conformable with the regional penetrative axial plane S_1 cleavage within the metasediments, were active during and after emplacement of the syn- to post-orogenic granitoids. Wall & Taylor (1990) suggested that a key factor in the localisation of thermal aureole gold deposits was reactivation of pre-existing structures during granitoid emplacement by roof lifting and lateral expansion contemporaneous with regional deformation.

The Koolpin and Mount Bonnie Formations are preferentially mineralised; gold and copper occurrences are located in pyritic carbonaceous sediments, whilst silver, lead and zinc mineralisation is in dolomitic strata. This stratigraphic control probably reflects the suitability of the rocks for replacement by mineralising fluids and/or syngenetic concentrations of metals. Some gold in saddle reefs indicates at least some early concentration of gold before granitoid emplacement, possibly from disseminated stratiform accumulations (Nicholson & Eupene, 1984; 1990).

The mineral deposits are zoned from U closest to granitoid through W, Cu, Sn, Ag-Pb to Au with increasing distance from the granitoid contact. This zonation is similar to other district-wide metal zonation patterns in hydrothermal deposits associated with granitoid intrusions and their adjacent extensive contact aureoles (e.g. Cornwall, Great Britain; Herberton, Qld; northwest and northeast Tasmania; and Middle Bothnia, Finland). At Herberton (Blake, 1972) and northeast Tasmania (Groves, 1972) spatial zoning from W to Sn to Cu to Ag-Pb-Zn is associated with highly fractionated Palaeozoic granitoids; in Middle Bothnia the zoning is from Mo-Cu to W-Au to Ag-Pb-Zn and is associated with fractionated syn-orogenic Early Proterozoic (1.93-1.86 Ga) I-type granitoid plutons (Makela & others, 1988). The presence of metal zonation in the Cullen Mineral Field, as in the other districts, indicates that mineralising fluids were generated during granitoid emplacement, and that temperature, decreasing with distance from the intrusive contact, was an important control on metal precipitation. In detail, distribution of the quartz-metal sulphide veins is far more complex, being dependent on the interaction of the ore-bearing fluids and the host rock; physiochemical changes which took place in the fluids; structure; and the number of individual mineralising events. Chemical interaction with the host rock has been important in the emplacement of silver-lead sulphide veins in dolomitic sediments, and the preferential location of auriferous veins within pyritic carbonaceous strata. Wall-rock alteration is also common, particularly in association with uranium, copper, tin and tungsten vein deposits.

Fluid inclusion studies on several of the gold deposits indicate a contribution of both magmatic and metamorphic sources (Dann & Delaney, 1984; Wygralak & Ahmad, 1990). Wygralak & Ahmad found that $\delta^{34}S$ values for sulphides ranged from +4‰ to +10‰, suggesting a magmatic source; δD values in fluid inclusion water ranged from +27‰ to -57‰, and the calculated value of $\delta^{18}O$ ranges from +5.5‰ o to +10.3‰, implying a mixed magmatic and metamorphic source. Magmatic and organic carbon sources are also indicated by $\delta^{13}C$ values of -31.1‰ to +1.2‰. Indicated pressures of less than 2 kb (Wygralak & Ahmad, 1990) and temperatures of 250° to 330°C (Sanger-von Oepen & others, 1988) are consistent with contact-metamorphic mineral equilibria.

In a regional study (away from known mineralisation) of sulphides in carbonaceous strata of the Pine Creek Geosyncline, Donnelly & Crick (1992) found that within contact-metamorphic aureoles magmatically-derived sulphide dominates over country rock sulphide and that abundant disseminated, coarse-grained and vein pyrite and pyrrhotite, in roughly equal amounts, have $\delta^{34}S$ values averaging about +2‰. Outside the contact aureole, disseminated pyrite is present, having enriched $\delta^{34}S$ values, indicative of the presence of sulphate in the Early Proterozoic depositional environment.

These studies confirm a dominantly magmatic S source for metal sulphides within the contact aureole. A magmatic source for some metals may also be interpreted by the trace element distribution in the granitoids; this distribution shows a spatial relationship between uranium, tungsten, and copper deposits, on one hand, and granitoids enriched in those metals, on the other. There is little evidence for any such relationship involving lead, zinc and tin, and no data available to establish any such relationship with gold.

The trace element distribution within the various granitoids reflects a normal fractionation trend of increasing U, Rb, (Li) and Y, decreasing K/Rb values, and increasing ASI with increasing SiO_2. There appears to be an association between mineral deposit types and particular granitoid chemical suites, with the degree of fractionation within the leucogranite suites largely controlling the associated metal(s). Most of the metal-associated granitoids are late-stage, highly fractionated leucogranites, such as the Fenton and Wolfram Hill Granites, and the Tennysons and Yenberrie Leucogranites. These plutons, part of the Tennysons suite, are peripheral to the main mass of the Cullen Batholith and probably represent cusps. They have irregular contacts and their aureoles are wider than those of other plutons, indicating shallow-dipping contacts and a present-day erosional surface probably close to the roof of the intrusions. The plutons also intruded late in the history of the batholith and were favoured sites for metal enrichment.

Stratabound massive sulphide deposits

Two complex precious and base-metal sulphide lodes, the *Iron Blow* [85] and *Mount Bonnie* [86] mines, occur within the Mount Bonnie Formation on the opposite limbs of a shallow north-plunging syncline known as the Margaret Syncline, on the western flank of the Golden Dyke Dome. Both deposits are stratiform within interbedded pyritic shale, siltstone, tuff, mudstone, greywacke and minor banded iron formation. The deposits are stratabound between two major greywacke-mudstone sequences at the base of the formation (Fig. 45), in association with lenses of 'pebble breccia' interpreted as debris flow deposits (Eupene & Nicholson, 1990).

All recorded production from the *Iron Blow mine* [85] is from a lode occupying a steep easterly-dipping, north-trending shear zone. Three types of ore were mined: a siliceous capping; a gossan with gold, silver, lead and zinc; and a quartz-sulphide ore containing pyrite with minor chalcopyrite, sphalerite and galena. A second pyrrhotite-rich lode, up to 30 m thick, occurs at depth within a parallel shear zone, cropping out 50 m west of the main lode (Crohn, 1968).

At the *Mount Bonnie Mine* [86] enriched oxidised ores, averaging 8-9 g/t Au and 300 g/t Ag lie beneath a silicified hematitic and limonitic gossan with secondary arsenic and lead minerals. The main lode is about 20 m thick, and is conformable with bedding, striking about 020° and dipping 40° to the west (Fig. 45). In places, thrust faulting parallel to the lode has resulted in pinch-and-swell structures, and high angle cross-faulting and shearing have caused minor displacements. The primary lode is sulphide-rich, with pyrrhotite, pyrite, arsenopyrite,

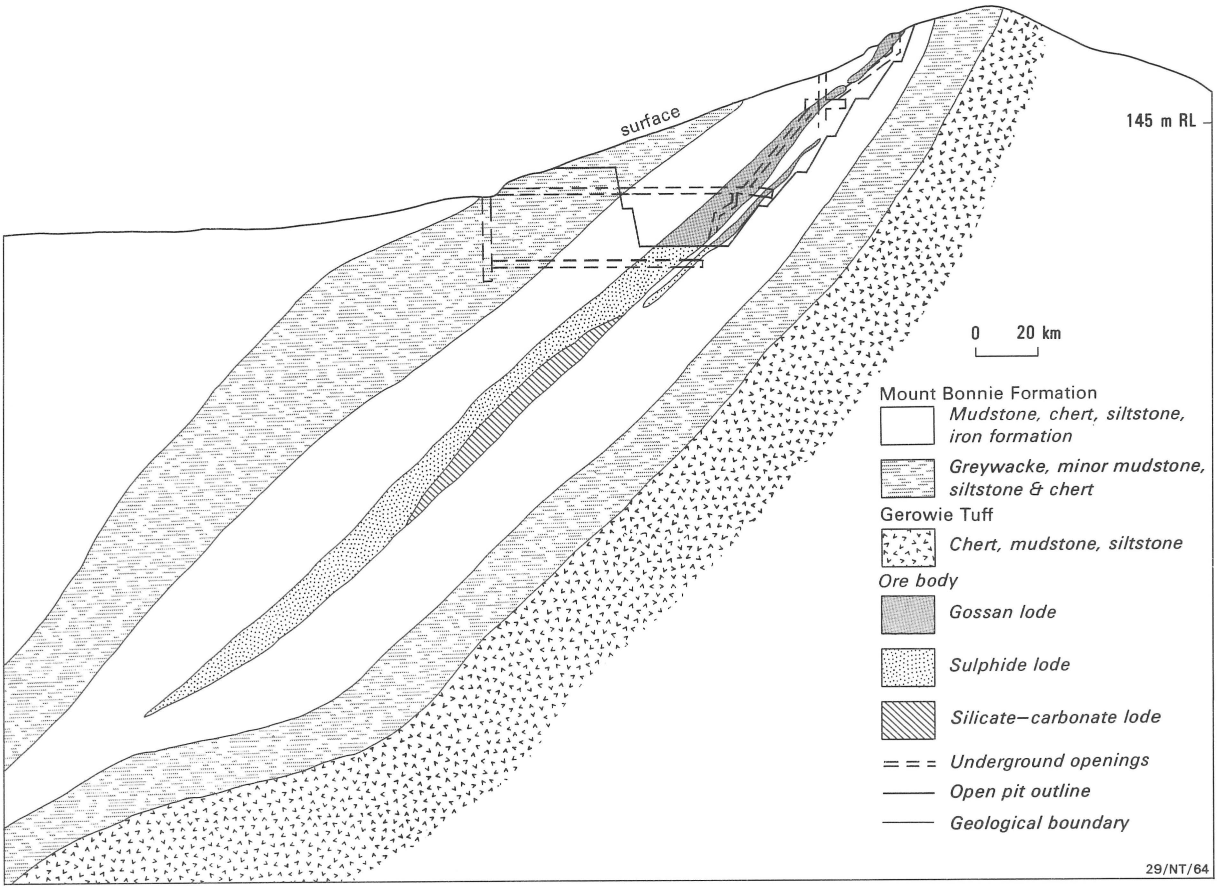


Fig. 45. Generalised cross-section of Mount Bonnie mine (modified from Rich & others, 1984).

chalcopyrite, galena, sphalerite, tetrahedrite, gold and silver, and rare boulangerite, stannite, freibergite, and marcasite in a gangue of quartz, dolomite, calcite, actinolite, chlorite, talc, phlogopite, and minor garnet. Primary ore grades average 1-5 g/t Au and 12-15% combined Pb/Zn.

Apart from minor narrow lodes located within shear zones, the main lodes of these two deposits are roughly lens-shaped, up to 30 m thick, and 150 m across, with the bulk of the sulphides concentrated in tabular zones. Within these zones a weak banding or foliation is present which parallels bedding in the host rocks (Goulevitch, 1980; Eupene & Nicholson, 1990). The stratabound, stratified and stratiform features of the deposits are consistent with a syngenetic origin, and their association with interbedded tuffs may indicate a volcanogenic source.

Goulevitch (1980) proposed a genetic model whereby the metals were derived from saline solutions released during dewatering of underlying tuffaceous strata after their deposition within a restricted sea-floor depression. The combination of the resultant increased sea water salinity, heat, a drop in pH, and the liberation of metals during devitrification may have produced conditions favourable for the transportation of metals precipitating as sulphides in localised reducing environments which characterised early Mount Bonnie Formation deposition. However, sulphur isotope studies indicate that predominantly mantle-derived sulphur, rather than seawater sulphate, was involved and that a restricted low sulphate lacustrine environment is indicated (T.H. Donnelly, CSIRO Canberra, personal communication, 1990).

Other occurrences of stratabound massive sulphide deposits are at *Heatley's Prospect*[88], where base metal sulphides (galena, sphalerite and chalcopyrite) together with 2-5% iron sulphide (either pyrite or pyrrhotite) form discordant veins and as conformable lenses within carbonaceous rocks of the Koolpin Formation. These features, and the presence of soft-sediment deformation structures in the sulphides, indicate that they are probably syngenetic or diagenetic (Nicholson, 1980).

Residual massive oxide deposits

Several ironstone bodies occur in the Frances Creek area and near Mount Shoobridge. The ironstones developed by oxidation and enrichment of either Early Proterozoic pyritic metasediments, or Cretaceous strata.

Massive hematitic ironstone lodes in the Frances Creek area crop out as prominent discontinuous strike ridges up to 50 m high, over a strike length of about 25 km. The most important individual lenses are those in the *Frances Creek group of mines*[102], which include from south to north: Helene, Thelma 2, Ochre Hill and Saddle; others are Elizabeth Marion, Jasmine, Rosemary, Rosemary 2, Thelma-Frances, and Beryl (Fig. 46). The largest tonnages were produced from the Helene Leases, where a group of ironstone lenses appear to thicken within fold hinges. Farther to the north, prominent outcrops about 8-12 km southwest of Mount George have also been prospected for iron and manganese (Friesen, 1972). From the north, they are known as *Big Hill*[28], *Bowerbird*[27], *Millers*[26] and *Saddle Extended*[96].

The ironstone lenses, ranging up to 600 m long and 20 m wide, occur within carbonaceous phyllite and siltstone near the base of the Wildman Siltstone. They are conformable with the enclosing sediments and are folded with them about northwest-trending F_1 isoclinal folds. At depth, the ironstones grade into pyritic carbonaceous shale breccias, probably developed during thrust faulting of the geosynclinal pile prior to the major folding episode (Fig. 47; Needham & others, 1980; Johnston, 1984). The ironstone cappings formed by oxidation and enrichment of the pyritic breccias prior to the deposition of flat-lying Cretaceous sediments which unconformably overlie the ironstone, and locally contain pebbles of massive hematite in basal conglomerates.

The ironstones, averaging 59% Fe, consist of massive or brecciated iron and manganese oxides in a siliceous gossanous matrix. The proportion of hematite to limonite was noted to generally increase from north to south towards the contact with the Allamber Springs Granite (Crohn, 1968). This may possibly reflect the effects of differing degrees of burial beneath the Cretaceous sediments; the greater degree of erosion of ironstones in the north; or a difference of iron-sulphide composition or content of the primary breccia caused by contact metamorphism.

Massive ironstones consisting of hematite, limonite and pyrolusite outline the hinge of a shallow northwest-plunging anticline within the Koolpin Formation about 2 km southeast of the Rosemary tin mine (HL 0115) and include the *Lewis prospect*[29]. The largest body, about 5 x 500 m, yielded values ranging from 39.5% Fe + 3.9% Mn to 24% Fe + 31.2% Mn (Newton, 1977b). At depth, beneath the oxidation zone, the ironstone grades into chloritised and silicified shale and siltstone with narrow pyritic beds.

Near Mount Shoobridge, at *McClean*[58] (also known as *Green Ant Creek)* about 250 t of manganese ore (Needham, 1981) was produced during the late 1950s for use in the treatment of the uranium ores at Rum Jungle. The ore, grading about 60% MnO_2, was produced by breaking and hand-picking boulders of Cretaceous siltstone, which were partly replaced by manganese oxides (McLeod, 1965). The boulders formed part of a talus deposit around a small outlier of Cretaceous sediment.

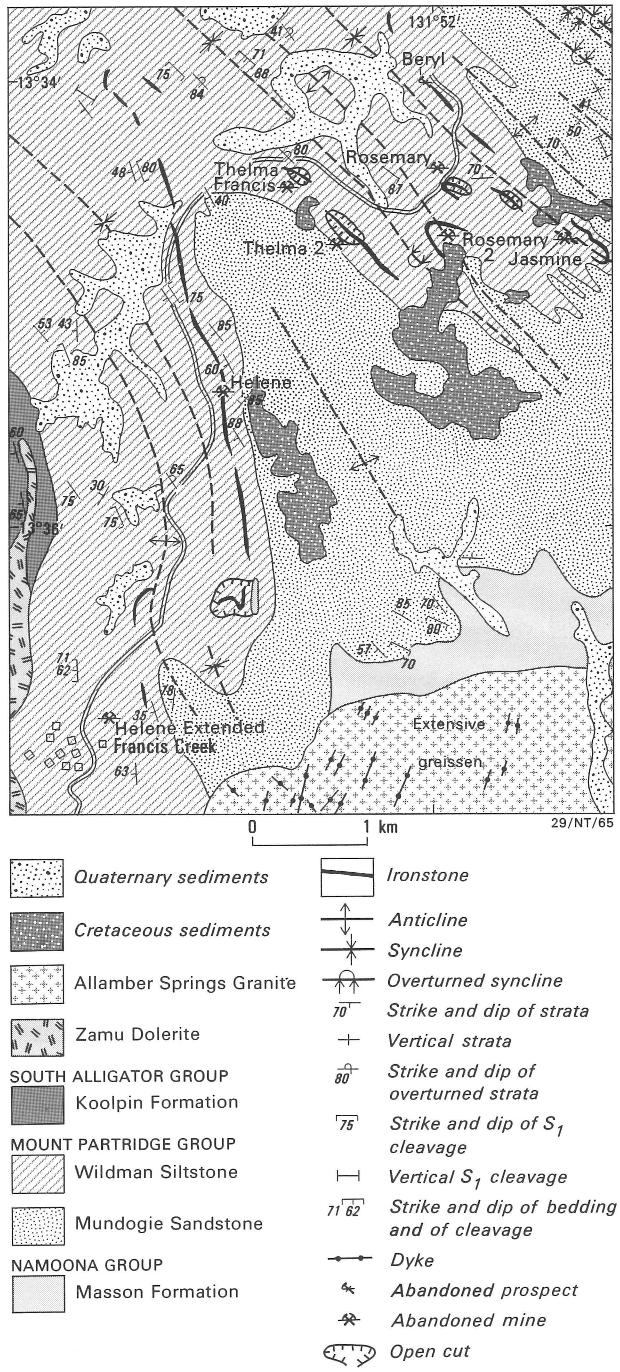


Fig. 46. Generalised geological setting of the Frances Creek iron mines.

Alluvial deposits

Most of the lode gold mines have adjacent eluvial and alluvial workings within surficial Cainozoic deposits. Some of the major workings were at *North Ringwood*[4], *Driffield*[205], *Wandie*[178], *Fountain Head*[74], and along the *Howley line of lodes*[41, 42 & 46]. Alluvial workings at *Sandy*

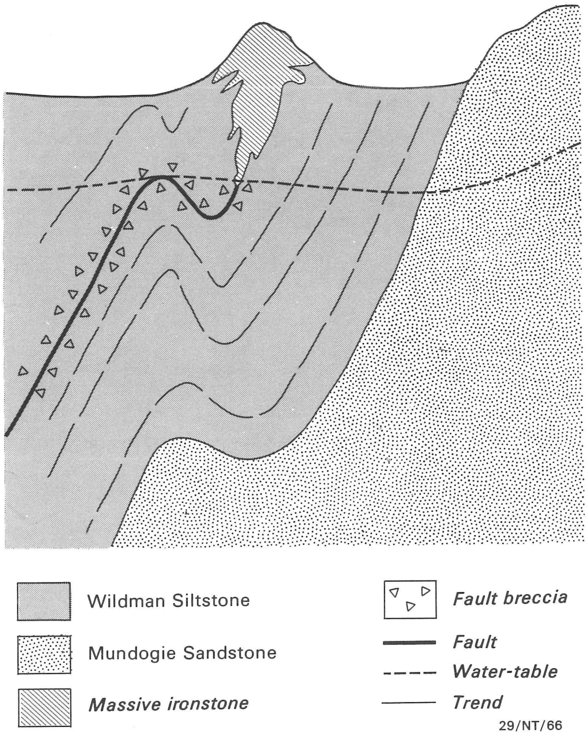


Fig. 47. Schematic diagram showing characteristics of the Frances Creek lodes. The ironstones formed by oxidation and enrichment of pyritic carbonaceous shale breccias within the Wildman Siltstone. The breccias are probably associated with thrust faults which predate the tight to isoclinal folds (F^1).

Creek [82] and *Port Darwin* [81] were probably associated with the nearby *Priscilla Line of Reefs* [80]. Other alluvial workings not associated with lode deposits were worked at *Margaret* [90], *Watts Creek* [101], *Frances Creek* [103], *McKeddies* [25], *Caledonia* [133], *Saunders Rush* [179], and at unnamed diggings on *Bowerbird Creek* [154] about 3 km northeast of the Evelyn mine.

The Cullen Mineral Field has also been a centre of alluvial tin production. Alluvial tin associated with lode tin includes *Barrets* [59], *Snaddens Creek* [122], *Jimmy's Knob* [111], *Mundic* [109], *Emerald Creek* [204], *Morris* [208 & 212], *Shamrock* [213], *Mary River Camp* [176], and the *Mount Wells* [92] area where more recently the *Horners Creek* [93] deposit has been worked. Other occurrences not associated with lode tin deposits include the *Umbrawarra* [150], *Stray Creek* [149], *Douglas River* [124] and *Nellie Creek* [105] mines, and an unnamed prospect [203] on the Wandie Granite. These mines are located within the granitoid terranes where the tin source is probably small zones of disseminated cassiterite within greisen zones.

Non-metallic mineral occurrences

Crystalline limestone is the only non-metallic produced. It was extracted at two localities [91 & 106] from lenses within the contact-metamorphosed Koolpin Formation adjacent to the Prices Springs Granite. The limestone was used in cyanidation and probably as a flux during smelting of metallic ores in the region late last century. No records of production are available (Jensen & others, 1916).

Other non-metallic mineral occurrences include monazite in ferruginous quartz veins within the Wolfram Hill Granite (*Bells prospect* [187]), topaz in silexite (an igneous rock composed essentially of primary quartz) on the eastern margin of the Yenberrie Leucogranite [215], and fluorite a few hundred metres south of the Burnside Granite [66], near the Rising Tide copper mine. The fluorite occurs with sellaite (MgF_2) and muscovite in a pegmatite which forms narrow pods within amphibolite of the Zamu Dolerite.

GEOLOGICAL HISTORY

The Cullen Mineral Field lies in the southern central part of the Pine Creek Geosyncline. Most sedimentary-volcanic deposition, and nearly all the tectonism, metamorphism and igneous intrusion is associated with development of the Early Proterozoic geosyncline. Apart from Middle Proterozoic, Mesozoic and Cainozoic continental to shallow-marine deposition, and minor tectonism, the area has been relatively stable since the late Early Proterozoic. Various interpretations of aspects of the tectonic evolution of the geosyncline have been given by Stuart-Smith & others (1980), Needham & Stuart-Smith (1984b & 1985b), and Needham & others (1988).

Geosynclinal sedimentation and dolerite intrusion (~2000–1870 Ma)

Geosynclinal sedimentation took place during the later part of the Early Proterozoic, probably between 2000 and 1870 Ma ago, in an intracratonic basin; alternating continental and shallow-marine conditions gave way to deeper water at later stages. Marginal arenaceous sequences, resting on Archaean basement (Needham & others, 1980), are not exposed in the mineral field. Interbedded carbonaceous and carbonate rocks accumulated over these sequences at the margins of the basin while in deeper parts, including this area, a thicker sequence of fine clastic and chemical sediments of the *Masson Formation* was deposited. Minor intermediate flows and volcaniclastic sediments (*Stag Creek Volcanics*) were deposited in the northeast at the end of this stage of sedimentation. Uplift and minor warping of these strata followed and a sequence of clastic and minor chemical sediments of the *Mount Partridge Group* formed as alluvial fans (*Mundogie Sandstone*), which were overlain by and were transitional with shallow-marine, possibly subtidal, deposits (*Wildman Siltstone*). A shallow-marine transgression followed minor block faulting, uplift and peneplanation, and the *South Alligator Group*, a sequence of chemical and organic-rich sediments, was deposited. Felsic subaerial volcanism outside the area during this stage, at about 1880 Ma ago, resulted in the origin of intercalated ashfall tuffs. Locally, hydrothermal-exhalative, disseminated and massive, precious and base-metal sulphide deposits (e.g. Mount Bonnie) formed in restricted and reduced environments during the waning stages of this volcanism and coincided with an influx of flysch-type sediment of the *Finniss River Group*, possibly related to deepening of the basin. Later, during this influx, minor felsic to intermediate volcanics were extruded. A source area to the south, composed dominantly of volcanic and minor Early Proterozoic sediments, is indicated. Sills of *Zamu Dolerite* intruded probably near the close of geosynclinal deposition between 1880 and 1870 Ma.

Deformation, felsic volcanism and intrusion (1870–1780 Ma)

Tight folding, faulting and associated low-grade regional metamorphism of the geosynclinal strata and doleritic intrusions possibly took place throughout the Pine Creek Geosyncline at about 1870 Ma (the *Nimbuwah Event*). This deformation was closely followed by extensional block faulting, resulting in a shallow half graben in the east, which was filled by felsic volcanics and sediments of the *El Sherana and Edith River Groups* at about 1870–1830 Ma. Both the Nimbuwah Event and a localised deformation (the *Maud Creek Event*) which separated the El Sherana and Edith River Groups, formed prominent north to northwest-trending tight to isoclinal and mostly upright folds.

Several granitoid plutons, and associated minor alkaline intrusions, were emplaced between 1835 and 1820 Ma, extensively contact-metamorphosing older rocks mostly to albite-epidote and hornblende hornfels facies. K-feldspar-cordierite hornfels facies was reached in some areas. Regional open east-west folding and fault reactivation along axial plane orientations of earlier folds accompanied diapiric emplacement of the granitoids (the *Shoobridge Event*). Most of the plutons, comprising highly fractionated and, in places, metal-enriched leucogranites, coalesced to form the *Cullen Batholith*. Above the irregular-shaped roof of the batholith the introduction of magmatic sulphur and the generation of a variety of fluids resulted in the structurally controlled emplacement of precious and base metal-bearing quartz veins and stockworks within the contact aureole at this time. Pyritic, carbonaceous and dolomitic strata, especially within the Koolpin and Mount Bonnie Formations (South Alligator Group), were preferentially mineralised. The granitoid intrusions were later cut by minor aplite, felsite, syenite and dolerite dykes.

Middle Proterozoic and younger platform sedimentation (1650 Ma–present)

A very long stable period followed peneplanation, broken only by fault reactivation in the northeast and southwest, intrusion of the Oenpelli Dolerite at about 1690 Ma, and the deposition of the relatively flat-lying Middle Proterozoic strata of the Katherine River and Tolmer Groups, and Palaeozoic sedimentation of the Daly River Basin. Deep chemical weathering, producing the massive ironstones at Frances Creek, preceded Mesozoic deposition of a thin veneer of epicontinental to terrestial sediments, the remnants of which form scattered mesas and tablelands. Since the Mesozoic, the area has remained above sea level and has been subjected to continued fault movement and chemical weathering which has produced laterites, and sheet washing of sand and minor gravels derived from older strata. These later, Tertiary, deposits have been continually modified during the Quaternary by repeated erosional and aggradational cycles in a variety of alluvial environments. Alluvial and colluvial concentrations of gold and tin, most probably derived from hydrothermal veins or disseminated concentrations associated with the Early Proterozoic granitoid intrusions, are mostly associated with the Quaternary deposits.

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APPENDIX 1. GEOCHEMICAL ANALYSES OF THE CULLEN BATHOLITH

Chemical analyses (see microfiche)

Analytical methods

All analyses were carried out in the BMR laboratories. Major and most trace elements were determined by X-ray fluorescence spectrometry (XRFS) on Philips PW-1404 or PW-1450 equipment. Major elements were measured on glass fusion discs using the method of Norrish and Hutton (1969). Calibration was against international and secondary rock standards, using SiO_2 and CaO blanks. Matrix corrections, with alpha factors for the rhodium tube, were applied to all major oxides (as well as S) . Ferrous iron (FeO) was determined separately by titration with standard potassium dichromate solution and Fe_2O_3 estimated by difference. Loss on ignition (LOI) was measured by igniting about 5 g of sample at 1050°C. Quoted LOI values are corrected for the FeO contents of the samples. Combined (H_2O^+), moisture (H_2O^-), and total carbon (carbonate and carbon, quoted as CO_2) were determined gravimetrically.

Most trace elements (Ba, Rb, Sr, Pb, Th, U, Zr, Nb, Y, La, Ce, Nd. Pr, Sc, V, Cr, Sn, W, Mo, Ga, As, Cl and Bi) were analysed by XRFS on powder pellets using the techniques of Norrish & Chappell (1977). Molybdenum, rhodium and gold target X-ray tubes were used to give optimum excitation for different groups of elements. Synthetic standards were employed for calibration, except for Rb (NBS-70A and MA-N), Sr (AGV-1, V (AGV-1, BCR-1, and W-1), and Cr (PCC-1 and DTS-1). Mass absorption corrections utilised the Compton scatter method for wavelengths less than 1.74 Å (Fe absorption edge), and coefficients calculated from major element compositions for longer wavelengths. Empirical interfering element corrections were made where necessary. Li, Co, Ni, Cu and Zn were determined with a Varian AA-975 spectrophotometer, Li being analysed by the method of standard dilution. F was measured by specific ion electrode.

Estimated detection limits are given in Table 1. Those for elements determined by XRFS were calculated at the 95% confidence level for detection of peak above background, using the relation given by Jenkins and de Vries (1967):

$$\text{detection limit} = \frac{3c}{(Rp-Rb)} \sqrt{\frac{Rb}{t}}$$

where

Rp = peak count rate (counts/sec)

Rb = background count rate (count/sec)

t = background counting time (secs)

c = element concentration

Note: More realistic detection limits are probably twice the calculated theoretical values with even higher limits for elements that involve significant inter-element corrections (e.g. Ba, Ce, Sc, Y).

Detection limits (in weight percent for major oxides and ppm for trace elements).

SiO_2	0.006
TiO_2	0.008
Al_2O_3	0.007
Fe_2O_3	0.005
MnO	0.004
MgO	0.006
CaO	0.0014
Na_2O	0.02
K_2O	0.0004
P_2O_5	0.003

Ba	5
Li	2
Rb	1
Sr	1
Pb	2
Th	2
U	0.5
Zr	2
Nb	2
Y	1
La	3
Ce	4
Nd	2
Pr	3
Sc	2
V	2
Cr	2
Ni	2
Cu	2
Zn	1
Sn	2
Ga	1
As	0.5
S	12
F	200
Cl	4

Precision and accuracy

Precision of the XRFS technique is generally good, as the effects of all but very short-term drift in machine conditions are practically eliminated by ratioing each measurement to a monitor standard. The precision (1s level) for trace element analyses is typically ±3% at the 30 to 100 ppm level. The corresponding precision for AAS analyses is between ±4 and ±6%.

Accuracy was assessed by analysing international rock standards. Comparisons of XRFS and AAS results for two standard rocks (GSP-1 and BCR-1) are given below.

Comparison of analyses of standard rocks with the recommended values of Abbey (1983).

	GSP-1		BCR-1	
	BMR	Recomm.	BMR	Recomm.
SiO_2	67.97 (0.29) *	67.32	54.42 (0.16)	54.53
TiO_2	0.67 (0.004)	0.66	2.26 (0.015)	2.26
Al_2O_3	15.16 (0.08)	15.28	13.51 (0.06)	13.72
Fe_2O_3(t)	4.26 (0.016)	4.28	13.39 (0.03)	13.44
FeO	2.25	2.32	8.89	8.96
MnO	0.04	0.04	0.17	0.18
MgO	0.99 (0.015)	0.97	3.53 (0.012)	3.48
CaO	1.97 (0.006)	2.03	6.97 (0.06)	6.97
Na_2O	2.74	2.81	3.27 (0.05)	3.30
K_2O	5.56 (0.012)	5.51	1.71 (0.010)	1.70
P_2O_5	0.28	0.28	0.36	0.36
Ba	1300	1300	702	680
Li	25	30	11	14
Rb	253	250	46	47
Sr	237	240	329	330
Pb	54	54	14	14
Th	104	105	6	6
U	2.0	2.1	1.5	1.7
Zr	507	500	187	185
Nb	25	?23	13	?19
Y	28	29	37	40
La	165	195	29	27
Ce	391	360	55	53
Nd	187	?190	32	?26
Pr	46	?50	4	?7
Sc	8	7	31	33
V	49	54	416	420
Cr	11	2	6	15
Ni	7	9	7	10
Cu	30	33	17	16
Zn	91	105	117	125
Sn	8	?5	2	3
Ga	24	23	21	22
As	<0.5	<0.5	1.0	?0.8
S	400	?300	400	?400
F			500	500

*Standard deviation

Location and brief description of geochemical analysis samples of the Cullen Batholith

Note: analytical data for the Cullen Batholith and surrounding regions are provided in the PINE CREEK GEOSYNCLINE subset of the "ROCKCHEM" data base, available from the AGSO Sales Centre.

Pluton	Sample number	Map sheet	Grid ref.	Lith. type*	Lithology
Unknown (see footnote)	75470008	5270	unknown		altered dolerite dyke
	75470013	5270			coarse-grained porphyritic biotite granite
	75470026	5270			porphyritic biotite granite
	75470027	5270			dolerite
	75470028	5270			porphyritic biotite granite
	75470030	5270			porphyritic biotite granite
	75470035	5270			sheared and altered granite
	75470046	5369			greisen
	75470089	5370			fine-grained porphyritic hornblende biotite granite
	D52/8/5	5269			
	D53/9/1	5269			
	D53/9/10	5269			
Allamber Springs Granite	75470001	5270	031857	6	coarse-grained biotite leucogranite
Allamber Springs Granite	75470006	5270	058852	5	coarse-grained hornblende-biotite granite
Allamber Springs Granite	75470007	5270	058852	5	coarse-grained biotite granite
Allamber Springs Granite	75470009	5270	062810	2	coarse-grained porphyritic hornblende-biotite granite
Allamber Springs Granite	75470010	5270	071784	6	coarse-grained biotite granite
Allamber Springs Granite	75470023	5270	113757	2	coarse-grained porphyritic hornblende-biotite granite
Allamber Springs Granite	75470024	5270	130778	5	coarse-grained biotite granite
Allamber Springs Granite	75470025	5270	131783		altered hornblende diorite
Allamber Springs Granite	75470029	5270	204849	6	coarse-grained leucogranite
Allamber Springs Granite	75470031A	5370	785850	2	coarse-grained biotite granite
Allamber Springs Granite	75470031B	5370	795860	2	coarse-grained porphyritic biotite granite
Allamber Springs Granite	75470032	5370	828884	2	coarse-grained porphyritic hornblende-biotite granite
Allamber Springs Granite	75470033	5370	859888	2	coarse-grained porphyritic hornblende-biotite granite
Allamber Springs Granite	75470059	5270	159755	2	coarse-grained hornblende-biotite granite
Allamber Springs Granite	75470060	5270	209753	4	coarse-grained biotite granite
Allamber Springs Granite	75470061	5370	764757	4	coarse-grained biotite granite
Allamber Springs Granite	75470062	5370	826764	6	coarse-grained biotite granite
Allamber Springs Granite	75470070	5270	140796	2	coarse-grained hornblende-biotite granite
Allamber Springs Granite	75470071	5270	239884	2	coarse-grained porphyritic biotite granite
Allamber Springs Granite	75470072	5270	225913	2	coarse-grained hornblende-biotite granite
Allamber Springs Granite	75470073	5270	188917	9	fine/even-grained biotite granite
Allamber Springs Granite	75470074	5270	193918	2	coarse-grained hornblende-biotite granite
Allamber Springs Granite	75470075	5270	110898	2	coarse-grained hornblende-biotite granite
Allamber Springs Granite	75470076	5270	067912	6	coarse-grained hornblende-biotite leucogranite
Allamber Springs Granite	75470077	5270	060889	5	altered coarse-grained biotite granite
Allamber Springs Granite	75470078	5270	074874	2	coarse-grained hornblende-biotite granite
Allamber Springs Granite	75470079	5270	045823	2	coarse-grained hornblende-biotite granite
Allamber Springs Granite	75470092	5370	852921	2	coarse-grained hornblende-biotite granite
Allamber Springs Granite	75470093	5370	837950	2	coarse-grained porphyritic hornblende-biotite granite
Allamber Springs Granite	75470116	5270	188877	6	coarse-grained biotite leucogranite
Allamber Springs Granite	75470117	5270	220814	2	coarse-grained porphyritic biotite granite
Allamber Springs Granite	75470118	5270	229814	2	coarse-grained porphyritic biotite granite
Allamber Springs Granite	75470120	5270	151828		monzodiorite
Allamber Springs Granite	80120006	5270	181904	2	pink-green,coarse-grained,porphyritic hornblende-biotitegranite
Allamber Springs Granite	80120010	5370	793858	2	pink-green,coarse-grained,porphyritic hornblende-biotitegranite
Allamber Springs Granite	80120016	5270	178756	6	pink, coarse-grained, equigranular biotite leucogranite
Allamber Springs Granite	80120017	5270	206743	6	pink, coarse-grained, equigranular biotite leucogranite

Pluton	Sample number	Map sheet	Grid ref.	Lith. type*	Lithology
Allamber Springs Granite	80120020	5270	125769	6	pink, coarse-grained, equigranular biotite hornblende granite
Allamber Springs Granite	80120022	5270	210710	6	pink, coarse-grained, equigranular biotite leucogranite
Allamber Springs Granite	80120023	5270	133757	6	pink, coarse-grained, equigranular biotite leucogranite
Allamber Springs Granite	80120025	5270	125769	6	pink, coarse-grained, equigranular biotite leucogranite
Allamber Springs Granite	80120026	5270	067906	6	pink, coarse-grained, equigranular biotite leucogranite
Allamber Springs Granite	80120027	5370	792752	6	pink, coarse-grained, equigranular biotite leucogranite
Allamber Springs Granite	80120029	5270	141832	9	pink-grey, fine/medium-grained, equigranular leucogranite
Allamber Springs Granite	80120030	5270	193843	9	pink-grey, fine/medium-grained, equigranular leucogranite
Allamber Springs Granite	80120031	5270	200875	9	pink-grey, fine/medium-grained, equigranular leucogranite
Allamber Springs Granite	80120037	5370	781609	9	pink-grey, fine/medium-grained, equigranular leucogranite
Allamber Springs Granite	80120038	5270	244893	9	pink-grey, fine/medium-grained, equigranular leucogranite
Allamber Springs Granite	80120039	5270	151667	9	pink-grey, fine/medium-grained, equigranular leucogranite
Allamber Springs Granite	80120041	5270	203870	9	pink-grey, fine/medium-grained, equigranular leucogranite
Allamber Springs Granite	80120044	5270	154671	9	altered pink-grey, fine/medium-grained, equigranular leucogranite
Allamber Springs Granite	80120045	5270	133757	9	pink-grey, fine/medium-grained, equigranular leucogranite
Allamber Springs Granite	80120050	5270	123696		pegmatite
Allamber Springs Granite	80120057	5270	155673		biotite-hornblende quartz monzonite
Allamber Springs Granite	80120061	5270	142828		biotite-hornblende quartz syenite
Allamber Springs Granite	80120062	5270	188900		biotite-hornblende quartz monzodiorite
Allamber Springs Granite	80120074	5270	174759	9	pink-grey, fine/medium-grained, equigranular leucogranite
Allamber Springs Granite	80120081	5270	188900	9	pink-grey, fine/medium-grained, equigranular leucogranite
Allamber Springs Granite	80120085	5270	128913	5	pink, coarse-grained, porphyritic biotite-hornblende granite
Allamber Springs Granite	80120086	5270	123875	5	pink, coarse-grained, porphyritic biotite-hornblende granite
Allamber Springs Granite	80120087	5270	113757	5	pink, coarse-grained, porphyritic biotite leucogranite
Allamber Springs Granite	80120088	5270	183840	6	pink, coarse-grained, equigranular biotite leucogranite
Allamber Springs Granite	80120097	5270	198928	5	pink/green coarse-grained porphyritic biotite granite
Allamber Springs Granite	83126026	5270	153828		coarse grained hornblende biotite granite
Allamber Springs Granite	83126029	5270	128770	5	biotite granite
Allamber Springs Granite	83126030	5270	033866	6	biotite granite
Allamber Springs Granite	83126031	5270	062842	5	coarse hornblende biotite granite
Allamber Springs Granite	83126032	5270	063838	5	coarse biotite granite
Allamber Springs Granite	83126033	5270	050817		very altered biotite monzodiorite
Allamber Springs Granite	83126034	5270	061801	2	coarse hornblende-biotite granite
Bludells Dolerite	80120065	5270	160582		altered dolerite
Bludells Dolerite	80120066	5270	162830		altered dolerite
Bludells Dolerite	80120067	5270	225028		altered dolerite
Bludells Dolerite	80120068	5270	188900		altered dolerite
Bludells Dolerite	80120069	5270	224053		altered dolerite
Bludells Dolerite	80120070	5370	850926		dolerite
Bludells Dolerite	89126024	5371	783185		fine-grained dolerite
Bonrook Granite	80120013	5270	120667	4	altered grey,coarse-grained,porphyritic biotite-hornblende granite
Bonrook Granite	80120028	5270	127657	9	pink, fine-grained, equigranular biotite leucogranite
Bonrook Granite	80120034	5270	120658	9	pink-grey, fine/medium-grained, equigranular leucogranite
Bonrook Granite	80120035	5270	133656	9	pink-grey, fine/medium-grained, equigranular leucogranite
Burnside Granite	76870150	5171	621117	6	biotite granite
Burnside Granite	76870151	5171	422210	6	fine grained biotite granite
Burnside Granite	76870152	5171	585154	6	biotite muscovite granite
Burnside Granite	76870153	5171	567154	6	biotite muscovite granite
Burnside Granite	76870154	5171	621154	6	altered biotite granite
Burnside Granite	76870155	5171	675172	6	biotite granite
Burnside Granite	76870156	5171	639228	6	biotite granite
Burnside Granite	79125023	5171	661213	6	biotite granite
Burnside Granite	D52/8/1	5171	603154	6	biotite adamellite
Burnside Granite	D52/8/25	5171	621154	6	biotite adamellite

Pluton	Sample number	Map sheet	Grid ref.	Lith. type*	Lithology
Burnside Granite	D52/8/26	5171	549154	6	biotite adamellite
Douglas Leucogranite	75470114	5270	872781	8	porphyritic biotite granite
Douglas Leucogranite	80120040	5270	922748	9	pink-grey, fine/medium-grained, equigranular leucogranite
Douglas Leucogranite	80120042	5270	929769	9	pink-grey, fine/medium-grained, equigranular leucogranite
Douglas Leucogranite	80120064	5270	915762	8	light-grey coarse-grained porphyritic leucogranite
Douglas Leucogranite	80120089	5270	932782	8	light-grey coarse-grained porphyritic leucogranite
Douglas Leucogranite	80120092	5270	916737	8	light-grey coarse-grained porphyritic leucogranite
Douglas Leucogranite	80120094	5270	921799		light-grey coarse-grained porphyritic leucogranite
Driffield Granite	75470040	5269	191452	2	altered coarse-grained biotite granite
Driffield Granite	75470041	5269	191452	4	altered sheared granite
Driffield Granite	75470042	5269	191452	9	altered sheared granite
Driffield Granite	75470103	5269	216482	6	altered coarse-grained biotite granite
Fenton Granite	76870134	5170	510952	2	medium-grained biotite granite
Fenton Granite	76870137	5170	457897	9	fine-grained biotite granite
Fenton Granite	76870138	5170	461893	9	altered biotite muscovite granite
Fenton Granite	76870139	5170	472885	9	fine-grained foliated biotite granite
Fenton Granite	76870140	5170	463878	9	foliated fine- to medium-grained biotite granite
Fenton Granite	76870141	5170	472834	9	fine-grained biotite granite
Fenton Granite	76870142	5170	476827	9	fine-grained biotite granite
Fenton Granite	76870143	5170	447905		medium-grained foliated biotite-hornblende granite
Fingerpost Granodiorite	75470039	5269	171493	1	porphyritic hornblende-biotite granite
Fingerpost Granodiorite	75470063	5269	096492	1	coarse-grained porphyritic hornblende-biotite granite
Fingerpost Granodiorite	75470064	5269	055477	1	coarse-grained porphyritic hornblende-biotite granite
Fingerpost Granodiorite	75470065	5269	016385	1	altered coarse-grained porphyritic hornblende-biotite granite
Fingerpost Granodiorite	75470066	5269	047450	1	coarse-grained hornblende-biotite granite
Fingerpost Granodiorite	75470068	5269	151491	1	coarse-grained porphyritic hornblende-biotite granite
Fingerpost Granodiorite	75470097	5269	099429	1	altered coarse-grained porphyritic hornblende-biotite granite
Fingerpost Granodiorite	75470098	5269	041429 ‘		coarse-grained porphyritic hornblende-biotite granite
Fingerpost Granodiorite	75470099	5269	014499	1	coarse-grained hornblende-biotite metagranite
Fingerpost Granodiorite	75470101	5269	220475	1	altered coarse-grained biotite granite
Fingerpost Granodiorite	79125012	5269	053455	1	altered porphyritic hornblende-biotite granite
Fingerpost Granodiorite	80120095	5270	029525	1	grey, coarse-grained, porphyritic biotite-hornblende granodiorite
Foelsche Leucogranite	75470096	5269	132452	9	fine/medium-grained equigranular leucogranite
Frances Creek Leucogranite	75470080	5271	225120	9	fine/even-grained biotite granite
Frances Creek Leucogranite	75470081	5271	225082	9	fine/even-grained biotite granite
Frances Creek Leucogranite	75470082	5271	244078	9	fine/even-grained biotite granite
Frances Creek Leucogranite	75470083	5370	755040	9	fine/even-grained biotite granite
Frances Creek Leucogranite	75470084	5370	790037	9	fine/even-grained biotite granite
Frances Creek Leucogranite	75470085	5270	243015	9	fine/even-grained biotite granite
Frances Creek Leucogranite	75470094	5370	808981	7	coarse-grained hornblende-biotite granite
Frances Creek Leucogranite	75470108	5271	093188	9	fine/even-grained biotite granite
Frances Creek Leucogranite	80120036	5270	244015	9	pink-grey, fine/medium-grained, equigranular leucogranite
Frances Creek Leucogranite	80120096	5370	822978	9	pink-grey, fine/medium-grained, equigranular leucogranite
Lewin Springs Syenite	75470036	5270			syenite
Lewin Springs Syenite	75470038	5270	156525		syenite
Lewin Springs Syenite	75470054	5270	201559		syenite
Lewin Springs Syenite	75470067	5269	130489		syenite
Lewin Springs Syenite	75470102	5269	221472		syenite
Lewin Springs Syenite	80120051	5370	791698		syenite
Lewin Springs Syenite	80120052	5270	144517		syenite
Lewin Springs Syenite	80120053	5270	241763		syenite
Lewin Springs Syenite	80120054	5370	781751		syenite
Lewin Springs Syenite	80120055	5270	183685		syenite
Lewin Springs Syenite	80120056	5270	169758		syenite

Pluton	Sample number	Map sheet	Grid ref.	Lith. type*	Lithology
Lewin Springs Syenite	80120075	5270	170521		syenite
Lewin Springs Syenite	80120076	5270	952659		syenite
Margaret Granite	79125024	5271	795305	2	biotite granite
McCarthys Granite	75470034	5270	104588	2	coarse-grained porphyritic biotite-hornblende granite
McCarthys Granite	75470037	5270	154530	5	sheared and altered biotite granite
McCarthys Granite	75470052	5270	127630	3	deformed and altered fine-grained porphyriticbiotite granite
McCarthys Granite	75470053	5270	185574	2	fine-grained porphyritic biotite-hornblende granite
McCarthys Granite	75470055	5270	197545	5	coarse-grained leucogranite
McCarthys Granite	79125007	5270	158528	5	highly deformed and altered granite
McCarthys Granite	80120004	5270	207670	2	pink-green, coarse-grained, porphyritic biotite granite
McCarthys Granite	80120012	5270	161650	2	pink-green, coarse-grained, porphyritic biotite garnetiferous granite
McCarthys Granite	80120047	5370	769639		altered coarse-grained porphyritic quartz monzonite
McCarthys Granite	80120018	5270	167517	6	pink, coarse-grained, equigranular biotite-hornblende granite
McCarthys Granite	80120046	5270	189648		altered coarse-grained porphyritic quartz monzonite
McCarthys Granite	80120048	5270	232658		altered, coarse-grained, porphyritic, quartz monzonite
McCarthys Granite	80120049	5270	189648		altered, coarse-grained, porphyritic, quartz monzonite
McCarthys Granite	80120058	5270	218675		biotite-hornblende quartz monzonite
McCarthys Granite	80120059	5270	159592		altered medium-grained quartz monzonite
McCarthys Granite	80120071	5270	161650		pink-grey, fine/medium-grained, equigranular leucogranite
McKinlay Granite	B3968	5270	970020	2?	biotite granodiorite
McKinlay Granite	B3970	5270	970020	2?	biotite granodiorite
McMinns Bluff Granite (W)	76810127	5170		2	coarse foliated hornblende biotite granite
McMinns Bluff Granite (W)	76870128	5170	618873	2	deformed biotite granite
McMinns Bluff Granite (W)	76870129	5170	600875	2	sheared granite
McMinns Bluff Granite (W)	76870130	5170	599879	2	medium-grained porphyritic hornblende-biotite granite
McMinns Bluff Granite (W)	76870132	5170	617934	2	sheared granite
McMinns Bluff Granite (W)	79125013	5170	600886	2	highly deformed hornblende-biotite granite
McMinns Bluff Granite (W)	83126022A	5170	602867	2	sheared biotite gneiss
McMinns Bluff Granite (W)	83126022B	5170	602867	2	sheared biotite gneiss
McMinns Bluff Granite (W)	83126022C	5170	602867	2	sheared biotite gneiss
McMinns Bluff Granite (W)	83126022D	5170	602867	2	sheared biotite gneiss
McMinns Bluff Granite (W)	83126022E	5170	602867	2	sheared biotite gneiss
McMinns Bluff Granite (W)	83126022F	5170	602867	2	sheared biotite gneiss
McMinns Bluff Granite (W)	83126023A	5170	611863	2	sheared fine-grained biotite granite
McMinns Bluff Granite (W)	83126023B	5170	611863	2	sheared fine-grained biotite granite
McMinns Bluff Granite (W)	83126023C	5170	611863	2	sheared fine-grained biotite granite
McMinns Bluff Granite (W)	83126024A	5170	611863	2	sheared granite
McMinns Bluff Granite (W)	83126024B	5170	611863	2	sheared granite
McMinns Bluff Granite (W)	D52/8/4	5170	595933	2	biotite granite
McMinns Bluff Granite (W)	II/1	5170	620874		contaminated albitite (feldspathic rock)
McMinns Bluff Granite (E)	75470014A	5270	724960	4	coarse-grained porphyritic biotite granite
McMinns Bluff Granite (E)	75470014B	5270	724960	4	coarse-grained porphyritic biotite granite
McMinns Bluff Granite (E)	75470015	5270	809919	3	altered coarse-grained porphyritic biotite-hornblende
McMinns Bluff Granite (E)	75470016	5270	838867	3	coarse-grained porphyritic biotite granite
McMinns Bluff Granite (E)	75470018	5270	890887	9	fine/medium-grained biotite granite
McMinns Bluff Granite (E)	75470019	5270	902890	2	coarse-grained hornblende-biotite granite
McMinns Bluff Granite (E)	75470020	5270	901881	4	coarse-grained biotite granite
McMinns Bluff Granite (E)	75470021	5270	902814	4	altered coarse-grained porphyritic biotite metagranite
McMinns Bluff Granite (E)	75470113	5270	899789	4	coarse-grained porphyritic biotite granite
McMinns Bluff Granite (E)	75470115	5270	770912	2	coarse-grained porphyritic hornblende-biotite granite
McMinns Bluff Granite (E)	80120008	5270	851861	4	pink-green, coarse-grained, porphyritic biotite granite
McMinns Bluff Granite (E)	80120014	5270	929795	4	grey, coarse-grained, porphyritic biotite granite
McMinns Bluff Granite (E)	80120063	5270	789927	4	pink-green, coarse-grained, porphyritic biotite granite
Minglo Granite	75470086	5371	851109	5	coarse-grained porphyritic biotite granite

Pluton	Sample number	Map sheet	Grid ref.	Lith. type*	Lithology
Minglo Granite	75470087	5371	776157	2	porphyritic biotite granite
Minglo Granite	75470088	5371	787175	7	coarse-grained biotite granite
Minglo Granite	75470105	5271	096237	2	coarse-grained biotite granite
Minglo Granite	75470106	5271	211095	2	coarse-grained biotite granite
Minglo Granite	75470107	5271	093188	1	porphyritic biotite granite
Minglo Granite	80120060	5270	238002		medium-grained quartz monzonite
Minglo Granite	89126022	5371	782186	5	coarse-grained biotite granite
Minglo Granite	89126023	5371	783186	9	fine-grained granite
Minglo Granite	89126025	5371	803199	2	coarse-grained hornblende-biotite granite
Minglo Granite	89126026A	5371	807206	9	fine-grained granite
Minglo Granite	89126026B	5371	807206	2	coarse-grained pink hornblende biotite granite
Minglo Granite	89126027	5371	857122		coarse-grained pink biotite granite
Minglo Granite	89126028	5371	865141	9	granite with large quartz phenocrysts
Mount Davis Granite	75470090	5370	005790	3	coarse-grained hornblende-biotite granite
Mount Davis Granite	75470091	5370	013780	3	altered porphyritic biotite granite
Mount Porter Granite	75470002A	5270	023865	2	coarse-grained biotite-hornblende granite
Mount Porter Granite	75470002B	5270	023865	2	coarse-grained biotite granite
Mount Porter Granite	75470003	5270	023865	9	coarse-grained leucogranite
Prices Springs Granite	75470127	5270		2?	coarse biotite-hornblende granite
Prices Springs Granite	75470128	5271		2?	coarse biotite-hornblende granite
Prices Springs Granite	75470129	5271		2?	fine biotite granite
Prices Springs Granite	79125005	5270	861055	2?	altered fine grained biotite granite
Prices Springs Granite	B3975	5270	880040	2?	biotite adamellite
Prices Springs Granite	D52/8/20	5271	815601	2?	hornblende-biotite adamellite
Prices Springs Granite	D52/8/21	5271	833060	2?	biotite adamellite
Prices Springs Granite	D52/8/3	5271	833060	2?	biotite adamellite
Saunders Leucogranite	75470119	5270	132860	7	fine/even-grained biotite granite
Saunders Leucogranite	80120033	5270	184874	9	pink-grey, fine/medium-grained, equigranular leucogranite
Saunders Leucogranite	80120077	5270	133871	7	medium-grained, equigranular, biotite leucogranite
Saunders Leucogranite	80120078	5270	162830	7	medium-grained, equigranular, biotite leucogranite
Saunders Leucogranite	80120079	5270	148870	7	medium-grained, equigranular, biotite leucogranite
Saunders Leucogranite	80120080	5270	165874	7	medium-grained, equigranular, biotite leucogranite
Saunders Leucogranite	83126027	5270	153849	7	granite
Saunders Leucogranite	83126028	5270	156837	7	granite
Shoobridge Granite	11	5170	463046		leucocratic adamellite
Shoobridge Granite	12	5170	454040		porphyritic granodiorite
Shoobridge Granite	2	5170	469044		granodiorite
Shoobridge Granite	21	5170	453047		porphyritic granodiorite
Shoobridge Granite	22	5170	454046		porphyritic granodiorite
Shoobridge Granite	25	5170	463037		porphyritic granodiorite
Shoobridge Granite	29	5170	468046		granodiorite
Shoobridge Granite	30	5170	458034		granodiorite
Shoobridge Granite	31	5170	461036		porphyritic granodiorite
Shoobridge Granite	32	5170	454037		granodiorite
Shoobridge Granite	33	5170	458045		leucocratic adamellite
Shoobridge Granite	34	5170	461042		porphyritic granodiorite
Shoobridge Granite	35	5170	459046		eucocratic adamellite
Shoobridge Granite	75080350	5170	451043		hornblende granodiorite
Shoobridge Granite	76870145	5170			fine-grained biotite granite
Shoobridge Granite	79125025	5170	467046		fine-grained biotite granite
Shoobridge Granite	9	5170	466045		granodiorite
Shoobridge Granite	B3999	5170	451025		leucocratic granite
Shoobridge Granite	B4325	5170	451025		leucocratic adamellite
Shoobridge Granite	D52/8/22	5170	469025		leucocratic granite

Pluton	Sample number	Map sheet	Grid ref.	Lith. type*	Lithology
Shoobridge Granite	D52/8/24	5170	451025		porphyritic granite
Tabletop Granite	75470011	5270	016738	5	coarse-grained biotite granite
Tabletop Granite	75470012	5270	960759	5	coarse-grained biotite granite
Tabletop Granite	75470022	5270	987753	2	coarse-grained porphyritic hornblende-biotite granite
Tabletop Granite	75470109	5270	010683	3	porphyritic biotite-hornblende granite
Tabletop Granite	75470110	5270	018685	9	fine-grained porphyritic biotite leucogranite
Tabletop Granite	75470111	5270	030683	3	coarse-grained porphyritic biotite-hornblende granite
Tabletop Granite	75470112	5270	943739	6	coarse-grained biotite granite
Tabletop Granite	80120001	5270	976648	2	pink-green, coarse-grained, porphyritic biotite granite
Tabletop Granite	80120002	5270	952659	2	pink-green, coarse-grained, porphyritic hornblende-biotite granite
Tabletop Granite	80120003	5270	919621	2	pink-green, coarse-grained, porphyritic hornblende-biotite granite
Tabletop Granite	80120005	5270	886649	2	medium-grained biotite granite
Tabletop Granite	80120007	5270	990771	2	pink-green, coarse-grained, porphyritic hornblende-biotite granite
Tabletop Granite	80120009	5270	965785	2	pink-green, coarse-grained, porphyritic hornblende-biotite granite
Tabletop Granite	80120011	5270	900722	2	pink-green, coarse-grained, porphyritic hornblende-biotite granite
Tabletop Granite	80120015	5270	032722	4	grey, coarse-grained, porphyritic biotite-hornblende granite
Tabletop Granite	80120019	5270	968630	6	pink, coarse-grained, equigranular biotite leucogranite
Tabletop Granite	80120021	5270	988758	6	altered pink, coarse-grained, equigranular biotite leucogranite
Tabletop Granite	80120024	5270	961762	6	pink, coarse-grained, equigranular biotite leucogranite
Tabletop Granite	80120032	5270	989758	9	pink-grey, fine/medium-grained, equigranular leucogranite
Tabletop Granite	80120043	5270	037700	9	pink-grey, fine-grained, equigranular leucogranite
Tabletop Granite	80120072	5270	018683	3	pink-green, medium-grained, porphyritic hornblende-biotite granite
Tabletop Granite	80120073	5270	997690	3	pink-green, medium-grained, porphyritic hornblende-biotite granite
Tabletop Granite	80120082	5270	911691	5	altered pink, coarse-grained, porphyritic biotite leucogranite
Tabletop Granite	80120083	5270	955780	5	pink, coarse-grained, porphyritic biotite leucogranite
Tabletop Granite	80120084	5270	923711	5	pink, coarse-grained, porphyritic biotite leucogranite
Tabletop Granite	80120090	5270	906713	8	light-grey coarse-grained porphyritic leucogranite
Tennysons Leucogranite	75470043	5269	232363	8	fine-grained muscovite biotite leucogranite
Tennysons Leucogranite	75470044	5369	776324	8	fine-grained porphyritic biotite granite
Tennysons Leucogranite	75470047	5369	809345	7	fine-grained biotite granite
Tennysons Leucogranite	75470048	5369	792334	5	altered coarse-grained porphyritic biotite granite
Tennysons Leucogranite	75470049	5369	801286	5	coarse-grained porphyritic biotite granite
Tennysons Leucogranite	75470050	5369	805245	2	coarse-grained porphyriticbiotite granite
Tennysons Leucogranite	75470051	5369	784307	8	fine-grained porphyritic biotite-muscovite granite
Tennysons Leucogranite	75470056	5369	764276	8	fine to medium-grained biotite granite
Tennysons Leucogranite	75470057	5269	232277	2	coarse-grained biotite granite
Tennysons Leucogranite	75470058	5369	823297	9	altered fine/even-grained biotite-muscovite granite
Tennysons Leucogranite	75470100A	5369	802263	2	coarse-grained porphyritic biotite granite
Tennysons Leucogranite	75470100B	5369	802263	2	coarse-grained porphyritic biotite granite
Umbrawarra Leucogranite	75470069	5270	976596	8	coarse-grained biotite-muscovite granite
Umbrawarra Leucogranite	80120091	5270	960570	8	light-grey fine-grained leucogranite
Umbrawarra Leucogranite	80120093	5270	986528	8	light-grey coarse-grained porphyritic leucogranite
Umbrawarra Leucogranite	83126025	5270	953565	8	biotite-muscovite granite
Wandie Granite	75470095	5370	872583	7	altered coarse-grained biotite granite
Wolfram Hill Granite	B4009	5370	059674		porphyritic adamellite
Yenberrie Leucogranite	75470045	5369	827364	6	fine-grained biotite-muscovite granite

* Lith type refers to granitoid type as shown on the accompanying geological map. A summary description of the types is given in Table 9.

Note: Where analyses are from earlier work details of some samples are incomplete.

APPENDIX 2. ION MICROPROBE ANALYTICAL DATA FOR ZIRCONS FROM THE CULLEN BATHOLITH

Grainspot	U ppm	Th/U	$^{206}Pb/^{204}Pb$	f206% *	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U \pm 1\sigma$	$^{207}Pb/^{235}U \pm 1\sigma$	$^{207}Pb/^{206}Pb \pm 1\sigma$	Age (Ma)
Allamber Springs Granite (83126032)									
74.1	583	0.68	1617	0.96	0.1978	0.3291±68	5.054±114	0.1114±8	1822±13
75.1	307	0.65	105263	0.01	0.1833	0.3310±69	5.112±112	0.1120±6	1832±9
76.1	462	0.57	632	2.44	0.1879	0.3097±64	4.833±131	0.1132±17	1851±27
77.1	414	0.74	11787	0.13	0.2161	0.3153±65	4.847±107	0.1115±6	1824±10
78.1	217	0.72	1096	1.41	0.2123	0.3278±69	5.090±139	0.1126±17	1842±28
79.1	864	0.70	26103	0.06	0.1924	0.3300±68	5.019±107	0.1103±4	1804±7
80.1	373	0.25	1437	1.08	0.0724	0.2856±59	4.415±108	0.1121±12	1834±20
81.1	394	0.80	1393	1.11	0.2350	0.3131±65	4.720±115	0.1093±11	1788±19
82.1	430	0.94	7671	0.20	0.2882	0.2939±61	4.572±104	0.1128±8	1845±13
83.1	439	0.79	50125	0.03	0.2230	0.3201±66	4.925±107	0.1116±5	1825±8
84.1	207	0.59	8351	0.18	0.1629	0.3208±67	4.936±120	0.1116±11	1826±18
85.1	228	0.91	354610	0.00	0.2531	0.3290±69	5.117±116	0.1128±7	1845±12
86.1	464	1.01	20028	0.08	0.2824	0.3451±71	5.254±116	0.1104±6	1807±10
87.1	414	0.65	3652	0.42	0.1920	0.3084±64	4.753±108	0.1118±8	1828±13
88.1	262	0.66	20064	0.08	0.1965	0.3114±65	4.785±108	0.1115±8	1823±12
Allamber Springs Granite – mafic phase (83126026)									
37.1	1202	1.09	13721	0.11	0.2940	0.3390±70	5.227±115	0.1118±6	1829±10
38.1	613	0.51	9585	0.16	0.1394	0.3312±69	5.097±118	0.1116±9	1826±14
39.1	978	0.75	19920	0.08	0.1919	0.3435±71	5.248±117	0.1108±7	1813±11
40.1	6868	1.30	48733	0.03	0.3130	0.2855±59	4.189±96	0.1064±8	1739±13
41.1	312	0.50	14343	0.11	0.1370	0.3204±67	4.912±112	0.1112±8	1819±13
42.1	730	0.90	22763	0.07	0.2473	0.3304±68	5.046±108	0.1108±4	1812±7
43.1	1137	1.15	75930	0.02	0.3180	0.3324±68	5.082±107	0.1109±3	1814±5
44.1	375	0.44	5074	0.30	0.1261	0.3256±67	4.984±114	0.1110±8	1816±14
45.1	460	0.73	4127	0.38	0.1999	0.3121±65	4.785±109	0.1112±8	1819±13
46.1	1110	1.21	66667	0.02	0.3336	0.3389±69	5.216±109	0.1116±3	1826±5
47.1	384	0.53	2926	0.53	0.1558	0.3137±65	4.805±112	0.1111±10	1817±16
48.1	920	0.87	22989	0.07	0.2544	0.3069±63	4.694±100	0.1109±4	1814±7
49.1	408	0.45	10913	0.14	0.1390	0.3260±67	4.968±111	0.1105±7	1808±11
50.1	729	0.63	23240	0.07	0.1740	0.3254±67	4.987±106	0.1112±4	1818±7
51.1	549	0.63	4052	0.38	0.1787	0.3108±64	4.720±107	0.1101±8	1801±13

* Denotes the percentage of common ^{206}Pb in the total measured ^{206}Pb.

Note: The analysis of grain 40.1 encounted technical problems in the measurement of U+/Zr+ with respect to U+/Zr+ of the standard and has not been used in age determination calculations.

Grainspot	U ppm	Th/U	$^{206}Pb/^{204}Pb$	f206% *	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U \pm 1\sigma$	$^{207}Pb/^{235}U \pm 1\sigma$	$^{207}Pb/^{206}Pb \pm 1\sigma$	Age (Ma) $\pm 1\sigma$
Burnside Granite (79125023)									
1.1	1572	0.32	868	1.78	0.1407	0.3163±41	4.811±71	0.1103±6	1805±10
2.1	2063	0.23	1947	0.80	0.0802	0.2444±32	3.388±48	0.1005±4	1634±7
3.1	5018	0.71	2232	0.69	0.1367	0.2396±31	3.377±46	0.1022±2	1665±5
4.1	1354	0.40	830	1.87	0.1382	0.3502±46	5.251±76	0.1087±5	1778±9
5.1	2294	0.20	860	1.80	0.0828	0.2319±30	3.239±47	0.1013±5	1648±9
6.1	1758	0.31	274	5.66	0.0950	0.2563±34	3.449±63	0.0976±11	1579±21
7.1	2511	0.25	591	2.62	0.0842	0.3209±42	4.863±71	0.1099±6	1798±9
8.1	2316	0.45	510	3.04	0.1150	0.2442±32	3.526±54	0.1047±7	1709±12
9.1	2179	0.24	3046	0.51	0.0763	0.2987±39	4.550±63	0.1105±3	1807±6
9.2	2720	0.24	2609	0.59	0.0776	0.2818±37	4.213±58	0.1084±3	1773±5
10.1	2712	0.34	3070	0.50	0.0867	0.2997±39	4.552±62	0.1101±3	1802±4
17.1	2541	0.93	3484	0.44	0.1926	0.2893±38	4.332±59	0.1086±3	1776±4
18.1	2316	0.23	2191	0.71	0.0762	0.3157±41	4.799±65	0.1102±3	1803±5
19.1	2023	0.23	579	2.67	0.0930	0.2834±37	4.114±61	0.1053±6	1720±10
20.1	2229	0.29	119760	0.01	0.0745	0.4267±56	6.706±89	0.1140±1	1864±2
21.1	1660	0.32	470	3.30	0.1184	0.2580±34	3.444±55	0.0968±8	1563±15
22.1	4392	0.32	1674	0.93	0.0872	0.2397±31	3.377±46	0.1022±3	1664±5
23.1	3102	0.28	519	2.99	0.0915	0.2566±33	3.672±54	0.1038±6	1693±10
24.1	2712	0.37	639	2.42	0.0962	0.2585±34	3.543±52	0.0994±5	1613±10
25.1	3122	0.35	748	2.07	0.0802	0.3323±43	4.993±70	0.1090±4	1782±7
26.1	3007	0.26	4976	0.31	0.1301	0.3598±47	5.568±74	0.1122±2	1836±3
29.1	1584	0.18	492	3.15	0.0826	0.2620±34	3.718±58	0.1029±8	1677±13
30.1	1168	1.20	940	1.65	0.3629	0.1617±21	2.184±35	0.0979±8	1585±15
31.1	578	0.54	354	4.37	0.1586	0.3341±44	5.232±102	0.1136±15	1858±23
32.1	665	0.48	6925	0.22	0.1398	0.3060±40	4.655±68	0.1104±5	1805±9
33.1	3475	0.28	1801	0.86	0.0762	0.3619±47	5.582±76	0.1119±3	1830±4
34.1	3184	0.47	1046	1.48	0.1394	0.1404±18	1.792±27	0.0925±6	1478±11
35.1	3727	0.34	291	5.31	0.0842	0.2785±36	4.007±60	0.1043±6	1703±11
36.1	3738	0.33	2264	0.68	0.0895	0.2634±34	3.573±49	0.0984±3	1594±5
37.1	2646	0.25	749	2.07	0.0756	0.1721±22	2.184±33	0.0921±6	1469±11
38.1	1656	0.19	271	5.71	0.0874	0.3276±43	5.020±79	0.1111±8	1818±13
39.1	571	0.37	2642	0.59	0.1266	0.2763±36	4.156±62	0.1091±6	1785±10

* Denotes the percentage of common ^{206}Pb in the total measured ^{206}Pb.

Grainspot	U ppm	Th/U	$^{206}Pb/^{204}Pb$	f206% *	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U \pm 1\sigma$	$^{207}Pb/^{235}U \pm 1\sigma$	$^{207}Pb/206Pb \pm 1\sigma$	Age (Ma)
Fingerpost Granodiorite (79125012)									
21.1	1165	0.41	23998	0.06	0.1112	0.3241±66	4.926±103	0.1102±3	1803±5
22.1	760	0.54	79114	0.02	0.1533	0.3495±72	5.425±115	0.1126±4	1841±6
23.1	1202	0.38	30506	0.05	0.1064	0.3434±70	5.284±111	0.1116±3	1826±5
24.1	1306	0.40	103734	0.01	0.1135	0.3436±70	5.265±110	0.1112±3	1818±4
25.1	1359	0.40	14896	0.10	0.1129	0.3360±69	5.176±109	0.1117±3	1827±5
26.1	1317	0.46	54915	0.03	0.1295	0.3344±68	5.187±109	0.1125±3	1840±5
27.1	991	0.41	37147	0.04	0.1175	0.3220±66	4.938±104	0.1112±3	1819±5
28.1	1167	0.32	64226	0.02	0.0899	0.3315±68	5.103±107	0.1117±3	1827±5
29.2	1482	0.36	50226	0.03	0.1003	0.3264±67	4.997±105	0.1111±3	1817±5
30.1	1212	0.49	8375	0.18	0.1354	0.2822±58	4.186±89	0.1076±4	1759±6
31.1	335	0.49	1333	1.16	0.1508	0.3310±69	5.172±130	0.1133±14	1853±22
32.1	609	0.49	17431	0.09	0.1342	0.3318±68	5.107±110	0.1116±5	1826±8
33.1	1032	0.36	89366	0.02	0.0992	0.3312±68	5.066±107	0.1109±3	1815±5
34.1	1301	0.39	30506	0.05	0.1098	0.3294±68	5.059±106	0.1114±3	1822±5
35.1	507	0.28	27739	0.06	0.0765	0.3247±67	4.968±107	0.1110±5	1815±7
36.1	320	0.82	7238	0.21	0.2389	0.3208±66	4.962±112	0.1122±7	1835±12
McMinns Bluff Granite (79125013)									
57.1	152	0.81	23674	0.06	0.2213	0.3137±66	4.805±119	0.1111±12	1817±20
58.1	250	0.82	12509	0.12	0.2335	0.2972±62	4.562±106	0.1113±9	1821±15
59.1	148	0.58	5876	0.26	0.1636	0.3106±66	4.794±123	0.1119±13	1831±22
60.1	178	0.68	37341	0.04	0.1883	0.3016±63	4.681±122	0.1126±14	1841±23
61.1	351	0.60	1272	1.22	0.1876	0.2917±61	4.568±118	0.1136±14	1857±23
62.1	197	0.61	8977	0.17	0.1669	0.3195±67	4.822±111	0.1095±8	1791±14
63.1	330	0.65	49407	0.03	0.1940	0.2995±62	4.628±102	0.1121±6	1833±9
64.1	177	0.58	11265	0.14	0.1614	0.3149±66	4.883±115	0.1125±9	1840±15
65.1	270	0.59	3148	0.49	0.1719	0.3152±66	4.999±119	0.1150±11	1880±17
66.1	248	0.87	22401	0.07	0.2436	0.3107±65	4.796±109	0.1120±8	1831±12
67.1	388	0.77	3963	0.39	0.2197	0.3182±66	4.969±113	0.1133±8	1852±13
68.1	362	0.51	6466	0.24	0.1505	0.2900±60	4.472±102	0.1119±8	1830±13
69.1	230	0.61	21973	0.07	0.1730	0.3098±65	4.820±110	0.1129±8	1846±13
70.1	211	0.57	14620	0.11	0.1625	0.3126+65	4.859±113	0.1127±9	1844±14
71.1	453	0.41	1913	0.81	0.1454	0.2870±59	4.515±104	0.1141±9	1866±14
73.1	656	1.26	37369	0.04	0.3546	0.2991±62	4.643±101	0.1126±5	1841±9
92.1	823	0.44	2825	0.55	0.1266	0.3024±62	4.642±103	0.1113±7	1822±12
93.1	258	0.61	1428	1.08	0.1884	0.2793±58	4.265±107	0.1107±13	1812±22
94.1	633	0.51	1415	1.09	0.1469	0.3078±63	4.746±111	0.1118±10	1829±16
95.1	314	0.60	10361	0.15	0.1528	0.2887±60	4.410±107	0.1108±11	1812±18
96.1	218	0.73	357	4.33	0.2186	0.3065±66	4.825±200	0.1142±38	1867±61

* Denotes the percentage of common ^{206}Pb in the total measured ^{206}Pb.

Grainspot	U ppm	Th/U	$^{206}Pb/^{204}Pb$	f206% *	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U \pm 1\sigma$	$^{207}Pb/^{235}U \pm 1\sigma$	$^{207}Pb/206Pb \pm 1\sigma$	Age (Ma)
Umbrawarra Leucogranite (83126025)									
1-1	126	1.43	312	4.84	0.1852	0.4470±96	6.792±267	0.1102±33	1803±56
2-1	92	0.56	2438	0.63	0.1555	0.3313±72	5.137±151	0.1125±20	1839±32
3-1	267	0.34	3375	0.46	0.1002	0.3213±67	5.035±118	0.1137±9	1859±15
4-1	226	0.39	299	5.06	0.1237	0.3522±74	6.095±202	0.1255±29	2036±41
5-1	149	0.45	5241	0.29	0.1279	0.3220±68	4.985±122	0.1123±12	1836±19
6-1	122	0.98	3810	0.41	0.2677	0.3235±69	4.950±132	0.1110±15	1816±25
7-1	166	0.69	5771	0.27	0.1928	0.3293±69	5.017±121	0.1105±11	1807±18
8-1	469	0.48	5511	0.28	0.1381	0.3333±69	5.140±115	0.1119±7	1830±11
9-1	310	0.38	11688	0.13	0.1065	0.3230±67	4.972±114	0.1116±9	1826±14
10-1	220	0.58	1699	0.90	0.1605	0.3139±66	4.870±133	0.1125±17	1840±28
11-1	448	0.53	12129	0.13	0.1420	0.3310±68	5.055±112	0.1108±7	1812±11
12-1	341	0.43	21308	0.07	0.1162	0.3271±68	5.044±113	0.1118±7	1829±11
13-1	279	0.57	3199	0.48	0.1486	0.3206±67	4.970±128	0.1125±14	1839±23
14-1	247	0.22	15755	0.10	0.0614	0.3298±69	5.091±115	0.1120±8	1832±12
15-1	643	0.20	19619	0.08	0.0533	0.3119±64	4.758±104	0.1106±6	1810±9
16-1	284	0.55	6239	0.25	0.1528	0.3258±68	5.003±120	0.1114±11	1822±18
17-1	202	0.59	18605	0.08	0.1654	0.3375±71	5.215±121	0.1121±9	1833±14
18-1	287	0.46	14667	0.10	0.1291	0.3479±72	5.389±120	0.1123±7	1837±11
19-1	377	0.29	1963	0.79	0.1019	0.3277±68	5.005±119	0.1108±10	1812±17
20-1	208	0.53	3817	0.41	0.1431	0.3243±68	4.939±123	0.1104±12	1807±20

* Denotes the percentage of common ^{206}Pb in the total measured ^{206}Pb.

Analytical methods

Conventional zircon multi-grain analyses were made using the techniques of Krogh (1973). The average Pb processing blank was 0.25 ng, having a composition: $^{206}Pb/^{204}Pb$ 17.97, $^{207}Pb/^{204}Pb$ 15.55, and $^{208}Pb/^{204}Pb$ 37.71. A modified York (1969) program was used to regress the U-Pb data, and resultant errors are quoted as 2σ. Uncertainties (2σ) in U/Pb and $^{207}Pb/^{206}Pb$ are 1% and 0.2%, respectively .

Techniques of zircon U-Th-Pb analysis using the SHRIMP ion microprobe are described in detail by Compston & others (1984, 1986). In brief, zircons were mounted in epoxy, polished to expose their centres, and gold coated. They were then analysed using a 10 kV primary beam of negative oxygen ions focussed to an area on the crystal ~30 microns in diameter. Positive sputtered secondary ions were extracted normally to the surface, accelerated to 11 kV, and transferred to a double focussing mass spectrometer operated at a mass resolution of 6500. Isotopic ratios were measured directly using an electron multiplier in ion counting mode, and no correction was made for the small amount of mass dependent mass fractionation (~2.5 per mil per mass unit) that may be induced by the sputtering process and ion extraction system. Corrections were made for initial Pb in the zircons, based upon the measured 204Pb/206Pb.

Pb/U was determined by reference to a standard zircon (SL13, whose age is 572 Ma, equivalent to $^{206}Pb^{*}/^{238}U = 0.0928$) using an empirical quadratic relationship between UO^+/U^+ and Pb^+/U^+ established from accumulated analyses of the standard and monitored frequently during each analytical session. During the 72-hour period that the present ion microprobe data were collected, the 25 standard measurements yielded a standard error of 2.04%. Pb/Th was calculated from Th/U determined directly from ThO^+/UO^+using a constant multiplier of 1.11.

Data were collected in a set of seven scans through the species of interest. Analytical uncertainties for isotopic ratios were governed predominantly by counting statistics and differed according to the concentrations of Pb, U, Th and common Pb in each area analysed. Uncertainties in Pb/U and Pb/Th include an additional component derived from uncertainty in the quadratic calibration curve for the standard for each session. This component dominated the uncertainty in these ratios and was 2.04% (1σ).

APPENDIX 3. CONVENTIONAL U-Pb ZIRCON ANALYTICAL DATA FOR THE CULLEN BATHOLITH

Size (μ),	Weight	Concentration		$^{206}Pb/$	Radiogenic Pb (ppm)			Atomic ratios			$^{207}Pb/^{206}Pb$
Mag.	(mg)	U	Pb	^{204}Pb	206	207	208	$^{207}Pb/$	$^{206}Pb/$	$^{207}Pb/$	age(Ma)
Suscb'y		ppm	ppm	meas.				^{206}Pb	^{238}U	^{235}U	
Allamber Springs Granite (83126032)											
-215 NM2	1.19	1831.7	366.2	179.1	212.8	21.0	44.2	0.09825	0.13521	1.8316	1591
-150 NM1	1.52	1216.9	279.5	487.3	196.8	20.6	33.9	0.10392	0.18828	2.6979	1695
-100 NM1	0.86	1314.9	382.3	346.7	257.6	27.6	44.2	0.10653	0.22803	3.3493	1741
-80 NM1	0.36	1350.8	382.2	441.1	270.3	29.6	39.9	0.10901	0.23292	3.5008	1783
-45	0.31	2326.3	327.4	482.2	225.4	21.2	48.9	0.09391	0.11276	1.4601	1506
Allamber Springs Granite –mafic phase (83126026)											
-215 NM0	3.46	656.4	196.1	1932	148.2	16.1	26.8	0.10834	0.26281	3.9258	1772
-150 NM0	3.24	732.7	216.2	1790	161.8	17.5	30.7	0.10775	0.25711	3.8198	1762
-150 M0	5.61	775.3	223.0	1605	165.8	17.9	32.2	0.10765	0.24894	3.6949	1760
-100 NM0	1.99	704.5	215.4	2350	161.7	17.7	31.5	0.10869	0.26723	4.0048	1778
-80 NM0	2.47	708.9	217.5	1331	160.5	17.5	31.2	0.10857	0.26358	3.9457	1776
Burnside Granite (79125023)											
-150 NM3	0.73	3638.7	1028.7	470.0	752.8	77.8	84.4	0.10284	0.24082	3.4146	1676
-100 NM3	1.04	3640.8	986.7	429.4	722.8	73.4	72.5	0.10110	0.23110	3.2213	1644
-100 M3	1.68	3839.9	965.6	388.6	692.7	69.1	77.3	0.09926	0.21000	2.8741	1610
-80 NM3	0.76	3868.5	1077.0	389.9	770.1	78.4	87.0	0.10137	0.23172	3.2386	1649
-80 NM3*	0.56	3136.4	893.8	441.6	651.0	66.6	71.3	0.10187	0.24161	3.3936	1658
-60 M4	1.31	2433.0	636.6	406.3	460.8	46.8	49.7	0.10109	0.22047	3.0731	1644
Fingerpost Granodiorite (79125012)											
-215 NM2	1.84	1138.6	368.2	242.0	231.1	24.8	42.6	0.10696	0.23620	3.4835	1748
-150 NM2	1.67	1029.9	320.7	267.3	206.4	22.4	36.1	0.10796	0.23331	3.4730	1765
-150 M2	0.94	1119.3	274.2	377.3	186.5	19.3	33.5	0.10309	0.19393	2.7566	1681
-100 NM2	1.36	1021.0	310.1	286.9	202.4	21.6	35.2	0.10638	0.23073	3.3841	1738
-100 M2	1.29	1296.6	300.6	333.0	202.2	20.6	34.5	0.10134	0.18149	2.5358	1649
-100 M3	2.48	1511.2	286.8	341.0	192.1	18.5	35.7	0.09597	0.14800	1.9584	1547
-80 NM2	0.91	1085.5	283.0	582.1	204.0	21.5	33.2	0.10490	0.21876	3.1641	1713
Margaret Granite (79125024)											
-150 NM3	3.36	966.3	292.8	221.9	179.1	19.2	35.3	0.10673	0.21579	3.1754	1744
-100 NM3	2.56	896.7	251.9	324.2	169.2	18.1	27.5	0.10647	0.21960	3.2237	1740
-100 M3	4.56	1203.5	283.9	308.9	187.3	19.5	34.1	0.10376	0.18110	2.5910	1693
-80 NM3	2.13	804.6	273.3	255.6	172.3	18.9	33.4	0.10915	0.24919	3.7502	1785
-60 NM3	1.09	759.2	243.1	302.8	158.0	17.5	30.8	0.11006	0.24218	3.6751	1800
McMinns Bluff Granite (79125013)											
-150 NM0	1.25	376.5	113.6	1337	85.8	9.5	14.2	0.10982	0.26520	4.0157	1797
-150 NM0*	1.18	391.0	125.3	732.0	90.8	10.0	16.1	0.10988	0.27027	4.0946	1797
-150 M0	1.89	512.3	159.4	570.3	111.0	12.2	23.0	0.10908	0.25220	3.7933	1784
-75 NM0	1.19	444.0	141.5	620.0	100.8	11.1	19.1	0.10965	0.26417	3.9940	1794
-45 NM2	0.57	966.1	246.3	215.0	140.5	14.9	43.7	0.10532	0.16926	2.4579	1720

* Abraded in the presence of pyrite.

Pb blank corrections ~0.25 ng (206/204 = 17.97; 207/204 = 15.55; 208/204 = 37.7), and Cumming & Richards (1975) composition for initial Pb.

Size (μ), Mag. Suscb'y	Weight (mg)	Concentration U ppm	Pb ppm	$^{206}Pb/^{204}Pb$ meas.	Radiogenic Pb (ppm) 206	207	208	$^{207}Pb/^{206}Pb$	Atomic ratios $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$ age(Ma)
Prices Springs Granite (79125005)											
-150 NM1	0.29	1027.0	220.0	686.8	166.3	17.3	22.0	0.10362	0.18854	2.6936	1690
-100 NM1	0.41	1313.1	278.8	491.0	202.1	20.4	28.0	0.10051	0.17911	2.4823	1634
-100 M1	0.57	1933.1	319.7	384.1	222.7	21.1	35.1	0.09415	0.13411	1.7409	1511
-80 NM1	0.51	1619.3	443.1	654.0	327.0	34.5	47.1	0.10498	0.23508	3.4028	1714
-80 M1	0.43	2149.0	448.7	626.1	332.2	33.3	46.5	0.09982	0.17993	2.4765	1621
-80 M3	0.44	1645.3	288.3	291.7	192.1	17.7	33.1	0.09152	0.13590	1.7149	1458
-45 M3	0.41	2576.7	349.9	324.0	234.9	20.5	42.1	0.08684	0.10609	1.2703	1357
Shoobridge Granite (79125025)											
-150 NM0	1.68	1244.5	306.0	684.0	226.4	23.6	32.9	0.10376	0.21179	3.0299	1693
-150 M0	6.17	1417.8	291.4	395.0	200.8	20.2	34.5	0.10003	0.16488	2.2740	1625
-150 M1	4.22	1305.7	300.9	578.9	218.7	22.5	33.1	0.10258	0.19499	2.7578	1671
-100 NM0	0.65	1250.6	321.2	393.3	221.7	23.1	36.9	0.10384	0.20632	2.9541	1694
-100 M0	1.93	1358.0	340.5	613.8	248.3	26.0	38.0	0.10403	0.21282	3.0527	1697
-100 M1	2.66	1516.4	322.6	401.0	222.5	22.4	38.2	0.10015	0.17080	2.3584	1627
-80 NM1	1.22	1319.1	343.3	536.0	245.6	25.6	39.9	0.10375	0.21676	3.1008	1692
Umbrawarra Leucogranite (83126025)											
-150 NM1	0.63	840.2	274.3	253.8	177.6	19.4	26.9	0.10849	0.24605	3.6807	1774
-150 M1	1.31	1505.6	440.4	161.1	244.1	25.7	56.3	0.10468	0.18869	2.7233	1709
-100 NM1	0.92	862.2	318.1	278.1	209.0	22.9	31.8	0.10893	0.28221	4.2384	1782
-100 M1	0.73	2857.1	949.7	217.2	588.4	63.6	101.2	0.10758	0.23971	3.5557	1759
-80 NM1	0.70	835.2	301.0	387.2	212.0	23.4	26.9	0.10979	0.29554	4.4740	1796
-45 M1	0.42	498.7	194.4	168.2	79.7	8.5	71.3	0.10554	0.18603	2.7069	1724

Pb blank corrections ~0.25 ng (206/204 = 17.97; 207/204 = 15.55; 208/204 = 37.7), and Cumming & Richards (1975) composition for initial Pb.

APPENDIX 4. Rb–Sr WHOLE-ROCK AND BIOTITE DATA FOR THE CULLEN BATHOLITH

Sample No	Pluton	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
83126025	Umbrawarra	393.8	39.3	31.219	1.50530
83126026	Allamber S. G.	160.3	398.1	1.166	0.73541
83126027	Saunders L.	223.2	142.2	4.583	0.82334
83126028	"	229.4	216.0	3.090	0.78545
83126029	Allamber S. G.	206.7	66.6	9.169	0.94046
83126030	"	262.0	15.7	54.843	2.10720
83126031	"	207.1	42.7	14.522	1.07446
83126032	"	233.3	131.8	5.175	0.83783
83126033	"	164.9	420.9	1.134	0.73475
83126034	"	217.2	178.4	3.546	0.79640
79125012	Fingerpost Gd.	158.8	322.3	1.427	0.74249
83126021	McMinns G.	260.0	146.1	5.204	0.84025
83126022-1A	"	250.6	89.0	8.288	0.90868
83126022-1B	"	252.9	92.6	8.041	0.91129
83126022-1C	"	251.5	93.1	7.951	0.90798
83126022-1G	"	263.7	97.3	7.986	0.91389
83126022-1H	"	243.9	95.3	7.531	0.90076
83126022-1J	"	251.6	107.9	6.844	0.87915
83126022-1	"	255.1	95.8	7.836	0.90503
83126022-2	"	244.9	111.7	6.429	0.86804
83126022-3	"	248.8	12.2	6.501	0.86768
83126022-4	"	247.5	128.5	5.641	0.85026
83126022-5	"	230.9	128.2	5.268	0.83850
83126022-6	"	222.7	119.2	5.467	0.84497
83126023A	"	259.1	125.7	6.040	0.86115
83126023B	"	219.4	119.1	5.391	0.84285
83126023C	"	199.5	131.0	4.444	0.81950
83126024A	"	171.0	286.5	1.730	0.74958
83126024B	"	139.8	167.7	2.422	0.76820
79125013	"	159.2	267.3	1.727	0.75006
D53/9/10	Cullen Batholith	323.0	90.3	10.361	0.97280
D52/8/5	" "	253.0	128.0	5.710	0.85420
D53/9/1	" "	144.0	328.0	1.271	0.73820
D53/9/1 biotite	" "	579	16.3	102.64	3.3357 (1782 Ma)

Analyses by isotope dilution after dissolution of 70 mg, and cation exchange following procedures outlined in Page & others (1976). Last four analyses (Fingerpost/Tennysons suite?) by Riley (1980).

APPENDIX 5. SUMMARY DESCRIPTION OF MINERAL DEPOSITS AND OCCURRENCES

LIST OF ABBREVIATIONS

** Mineralogy*

Act	Actinolite
Angt	Anglesite
Ag	Silver
Agt	Argentite
Ap	Apatite
Aphy	Anthophyllite
As	Arsenic
Aspy	Arsenopyrite
Au	Gold
Auric	Aurichalcite
Az	Azurite
Ba	Barite
Bi	Bismuth
Cc	Chalcocite
Cd	Cadmium
Cer	Cerussite
Chrys	Chrysocolla
Clt, clt	Chlorite(ic)
Cpy	Chalcopyrite
Cst	Cassiterite
Cte	Carbonate
Cu	Copper
Cup	Cuprite
Cv	Covellite
Di	Diopside
Fe	Iron
fe Ox	Iron Oxide(s)
Fl	Fluorite
Fs, fs	feldspar(ic)
G	Galena
Grnt	Garnet
Gtht	Goethite
Hem	Hematite
Hydzn	Hydrozincite
Ko	Koechlinite
Lim	Limonite
Marc	Marcasite
Maut	Meta-autunite
Ml	Malachite
Mn	Manganese
Mn Ox	Manganese Oxide(s)
Mnr	Mineral
Mo	Molybdenum
Moly	Molybdenite
Mt	Magnetite
Mus	Muscovite
Pb	Lead
Pent	Pentlandite
Py	Pyrite
Pya	Pyargyrite
Pyl	Pyrolusite
Pym	Pyromorphite
Pyt	Pyrrhotite
Q	Quartz
Sb	Antimony
Sche	Scheelite
Scor	Scoradite
sec	secondary
Ser	Sericite
Selt	Sellaite
Sid	siderite
Smt	Smithsonite
Sn	Tin
Spl	Sphalerite
Tc	Talc
Tet	Tetrahedrite
Torb	Torbernite
Tou	Tourmaline
Trem	Tremolite
Tz	Topaz
U	Uranium
Ur	Uraninite
W	Tungsten
Wolf	Wolframite
Zn	Zinc

 # Lithology

alt	altered
Arg	Argillite
Ampht	Amphibolite
Ark	Arkose
brec	brecciated
carb	carbonaceous
Cgl	Conglomerate
Dolr	Dolarenite
Do	Dolomite
Dr	Diorite
Fest	Ironstone
Gd	Granodiorite
Gr	Granite
Grei	Greisen
Gywk	Greywacke
Hfs	Hornfels
kaol	kaolinised
mc	micro (prefix)
Mnz	Monzonite
Pampht	Para-amphibolite
pel	pelitic
Phy	Phyllite
Pr	Porphyrite
Qt	Quartzite
Sh	Shale
Sl	Slate
Sltst	Siltstone
Sst	Sandstone
Sye	Syenite
Tf	Tuff
Volc	Volcanic
xl	crystalline

$ Investigations

DDH	Diamond drilling
Gchem	Geochemistry
Geol	Geological mapping
Geoph	Geophysics

APPENDIX 5. SUMMARY DESCRIPTION OF MINERAL DEPOSITS AND OCCURRENCES

No.	*Grid reference*	*Mine, prospect name*	*Metal(s)*	*Recorded production and reserves in ( )*	*Ore grade(s)*	*Mineralogy * Ore*	*Mineralogy * Gangue*	*Structure*	*Deposit description*	*Host unit (lithology)#*	*Workings*	*History$*	*References*
1	GL5447	Star of the North	Au	112,000 g Au		Au	Q	Bedding-parallel shear zones.	Steeply-dipping N-trending veins (<2 km long and <4 m wide).	Pfb (Gywk, Phy & Sltst)	To 40 m depth.	Worked 1896-1920.	Crohn (1968).
2	GL6042	Great Northern	Au										
3	GL6339	Great Western	Au										
4	GL8543	North Ringwood	Au	90,000 g Au		Au	Q, Py, Clt		Horizontal to 45° dipping, veins.	Pfb, Qa (Gywk, Sltst & clt Phy).	Shafts (<40 m), eluvial and alluvial diggings.	Worked 1894-1902.	Crohn (1968).
5	GL8541	unnamed mine	Au										
6	GL8739	Ringwood	Au										
7	GL8738	South Ringwood	Au										
8	HL0731	unnamed prospect	Pb, Zn							Ppw			
9	HL1938	unnamed prospect	Ag, Pb		3.2% Pb, 140 g/t Ag		Q	Fracture zone.	Veins. Mineralisation in zone (2.5 x 125 m).	Ppm (fs q Sst).		Investigations: DDH.	Kenneth McMahon & Partners (1971).
10	JF7830	unnamed prospect	Ag, Pb			G, Cer, Pym	Q, Py, Cte, Hem, Gtht	Breccia and shear zones parallel to S_1 cleavage.	Disseminated and massive fissure fillings over strike length of 6.4 km.	Pnm (do carb Sh, Slst & Dolr).	Costeans.	Found in1954. Investigations: Geol; Gchem; DDH.	Debnam (1955a & b), Crohn (1968), Berger & Normand (1972).
11	JF8227	unnamed prospect	Ag, Pb										
12	JF8425	Namoona Prospect	Ag, Pb, Zn		3.8% Pb, 46 g/t Ag								
13	JF7623	Minglo	Ag, Pb	18.7t Ag-Pb ore	58% Pb, 138 g/t Ag	G, Angt	Q	Vertical breccia trending 170°.	Breccia filling (<2 m wide).	Ppw (py carb pel Hfs).	Shaft (<15 m) & drives.	Worked 1964-5.	Crohn (1968).
14	HL2224	Minglo No. 2 prospect	Ag, Pb							Ppw			
15	HL2026	Gubberah Gossan	Pb, Zn		3.1% Pb, 0.13% Zn	G, Spl	Q, Hem, Py, Cte	Fault zone, dipping steeply NW.	Fault-filling vein (<1 m).	Ppm (fs q Sst, Sltst & py carb Sh).		Found in 1966. 1967-1973 investigations: Geol; Gchem; Geoph; DDH.	Shields & Taube (1967) Shields (1969), Duckworth (1969), Watts (1970), Daly (1971, 1975), Williams (1971), Bullock (1975), Michail (1974), Hone & Major (1978)

16	HL1328	unnamed prospect	Sn	62 t Sn Conc.	0.7% Sn tr Au	Cst	Hem, Q, Lim, Py	*En echelon* NNE & NNW-trending fractures.	Fracture-filling veins, breccias (<1 m wide) & stockworks.	Ppm (fs q Sst, Qt, Slst & Sh).	Pits, open cuts minor alluvial diggings.	Worked inter-mittently since 1956.	Hays (1960) Crohn (1968) Stuart-Smith & others (1986)
17	HL1228	Margaret	Sn										
18	HL1126	Nelson No. 2	Sn										
19	HL0526	Jessops (incl. Billy Can)	Sn	231 t Sn Conc.	1% Sn	Cst	Q, Hem	Vertical NNW-trending fault.	Eluvial deposit over Fault breccia (6 x 365 m).	Ppw (kaod Sh & Slst).	Open cut.	Worked inter-mittently since 1957.	Crohn (1968), Hays (1960), Vanderplank (1964), Pietsch (1973).
20	HL0426	unnamed prospect	Sn			Cst	Q		Veins.	Ppw (Sl & fs Qt).	Shaft (<15 m).		
21	HL0326	unnamed prospect	Pb			G, sec Pb Mnr	fe Ox	NW-trending fault.	Vein filling fault.	Psg (Tf, Sh & Arg).	Costeans.	Investigations: DDH.	
22	HL0525	Mount Masson group of mines (inc. Big Drum, & Big Julie)	Sn	34.3 t Sn Conc.	1.1% Sn tr Au & Ag	Cst	Q, Hem	Vertical NNW-trending fault and adjacent *en echelon* fault arrays.	Fault-filling veins & breccias (<1 m wide & 2 km long).	Ppm (Ark, Qt & Sh).	Pits, adits (<80 m), crosscuts & Shaft.	Worked inter-mittently since 1942.	Hays (1960), Crohn (1963, 1968), Newton (1977a), Barclay (1964), Pietsch (1973).
23	HL0820	Mount George	Sn	12 t Sn Conc.		Cst	Q, Tou, Mus, Hem		Vein stockworks.	Ppm (hfs Ark, q Sst, & Slst).	Open cuts & adits.	Worked inter-mittently 1926-1965.	Hays (1960), Crohn (1968).
24	HL1415	Glenys (Lucy's)	Sn	2.347 t Sn Conc.		Cst	Q, Tou, Mus		Vein stockwork & eluvial deposit.	Ppm	Pits.	Worked 1963-70.	
25	HL0911	McKeddies	Au						Alluvial.	Qa			
26	HL0512	Millers prospect	Fe, Mn	(390 000 t)	58.8% Fe + Mn	Hem, Lim, Pyl	Q	Pre-F_1 thrust - related breccias.	Conformable lenses (600 m x 20 m). Residual cappings.	Ppw (py carb Phy).		Discovered 1961. Investigations: Gchem; Geoph; Geol; DDH.	Crohn (1961), Hughes (1962), Hammond (1963), Barrell (1969), Freisen (1972), Balfour (1978).
27	HL0514	Bowerbird Prospect	Fe, Mn										
28	HL0414	Big Hill Prospect	Fe, Mn										
29	HL0115	Lewis Prospect	Fe, Mn		<55.2% Fe + Mn	Hem, Lim, Pyl			Residual oxidised cappings (<40 m thick, 5 x 500 m).	Psk (clt py Sh & Sltst).		Investigations: Gchem; DDH; Geol.	Newton (1977b).
30	HL0016	Rosemary (Touhy's)	Sn	49.5 t Sn Conc. (3864 t @ 0.5% Sn)	1.07% Sn	Cst	Q, Hem, Lim, Clt, Tou, Aspy	NW-trending Shear zone, dipping 75° NE.	Veins within and parallel to main shear zone. <0.5 m thick and discontinuous over 400 m.	Psg (py carb Sh, Sltst & Tf).	Underground workings.	Discovered 1966. Worked until 1980.	Newton & Shields (1977), Newton (1979), Taylor (1967).

31	GL9617	McKinlay	Au	423 g Au	<20 g/t Au	Au	Lim, Py, Q Aspy, Clt, Cpy	Subvertical NNW-trending shear zone in. F_1 hinge.	Fracture-filling veins.	Pso (sd Sltst, clt Phy & py carb Sl).	Open cuts (<4.6 m).	Worked intermittently since 1938.	Hossfeld (1940), Crohn (1968), Newton (1974a).
32	GL8913	Mavis	Sn	3.5 t Sn Conc.		Cst	Q, Hem, Lim.		Conformable veins (<1 m).	Pso (Sl & Gywk)	Open cut, minor underground workings.	Discovered 1958. Worked intermittently to 1972.	Crohn (1968).
33	GL8314	unnamed mine	Au							Pso			
34	GL7616	Woolwonga	Au	231,300 g Au (2.1 Mt @ 2.8 g/t Au)	60 g/t Au	Au	Q, Py, Aspy G, Spl, Cpy	S_1 parallel, steep NE dipping shear zones in SE-plunging F_1 anticline hinge.	Saddle reefs, sheeted veins (<1 m wide) filling shear zones & minor *en echelon* tension. gashes.	Pso (py carb Sl, Gywk & Sltst).	Shafts (<50 m), trenches, eluvial & alluvial diggings.	Worked intermittently since 1873. Main production 1873-1908.	Voisey (1937), McDonald (1901), Crohn (1968), Rayner & Nye (1937), Shields & Pietsch (1971) Kavanagh & Vooys (1990).
35	GL1930	unnamed prospect	Sn				Tou		Shallow W-dipping veins.	Pfb (Gywk Hfs).	Pits.		
36	GL7923	unnamed prospect	Sn				Q, Tou, Lim		Vein.	Pfb (Phy & Gywk).	Pits.		
37	GL7624	unnamed prospect	Sn							Pfb			
38	GL7322	Olive Prospect	Pb			Cer, G				Psk			
39	GL7122	Mount Ellison	Cu, Bi	3,071 t Cu ore, 3 t Bi	20% Cu	Cpy, Cup, Cc, Bi Mnr, Ml, Az	Q, Py	NNW-trending shear zone.	Vein (<1 m wide) filling shear zone.	Psk (hfs carb Phy)	To 69.5 m depth.	Worked 1891-1911.	Murray (1955), Crohn (1968).
40	GL5122	Mount Paqualin	Au							Psk			
41	GL5116	unnamed mine	Au							Qa, Psk			
42	GL5113	Bridge Creek	Au	394,000 g Au (2 M m^3 @ 0.5 g/m^3 Au)		Au	Q, Py, Aspy, Pyt, G Spl, Cpy, Bi Mnr	F_1 anticline hinge.	Veins (< 0.45 m wide).	Qa, Psk, Psg (carb pel Hfs & Tf).	Shafts (< 33.5 m) & alluvial diggings.	Worked 1873-1939, 1987--.	Sullivan & Iten (1952), Crohn (1968).
43	GL4908	unnamed prospect	Cu, Au				Q			Pfb			

44	GL5208	unnamed mine	Au							Pso			
45	GL5406	Big Howley	Au	420,000 g Au	5 g/t Au	Au	Q, Py, Aspy	F_1 anticline hinge.	Saddle reef (<6 m thick).	Pso	Open cuts, adits (<100 m long) & shafts (<58 m).	Worked 1882-1915.	Sullivan & Iten (1952), Crohn (1968).
46	GL5506	Chinese Howley	Au	550,000 g Au		Au	Q	Subvertical NW-trending shears, parallel to S_1, in F_1 anticline hinge.	Fault-filling veins (< 0.3 m wide).	Qa, Psg (Tf, Sh & Sltst Hfs).	Open cuts, pits & alluvial digg-ings.	Worked 1882-1904.	Sullivan & Iten (1952).
47	GL5603	Fleur de Lys	U, Cu	440 lb U_3O_8		Torb,Az Ml, Cup, Cc, Py, Cpy, Ur		Joints & minor shears.	Coatings on joint, shear & bedding surfaces	Psg (Sl, Sltst & Arg).	Shafts (< 30 m).	Worked 1954-5.	Firman (1955a), Crohn (1968).
48	GL5702	Cosmopolitan Howley	Au	4,177,000 g Au (5.4 Mt @ 2.4 g/t Au)		Au	Q, Py, Aspy, Lim, Gtht, Hem, Spl, Cpy, Pyt	F_1 anticline hinge, S_1 fractures.	Disseminated stratabound ore. Stockworks, breccias and veins filling S_1 fractures. Saddle reefs.	Psk (do carb Phy Hfs).	Open cuts, shafts (< 40 m), exploration shaft and drives.	Discovered about 1880. Worked until 1915, 1988---.	Hossfeld (1942), Crohn (1968), Sullivan & Iten (1952), Alexander & others (1990).
49	GL4704	Jacksons	Ag, Pb	2 t Ag-Pb ore	3% Pb	G, Cer			Vein stockwork (15 m x 100 m)	Pfb, Pgs (pel Hfs, fs Pr)			Crohn (1968).
50	GL4603	Full Hand (Dead Finish)	Cu, Ag, Pb, U	14 t Cu Conc.	20-30% Cu	Ml, Az, Cpy, G Torb	Q, Cte	Steeplly dipping NE-trending shear zones.	Veins in shear zones (<3 m wide).	Pfb (pel & Gywk Hfs).	Open cut, shafts (<37 m).	Worked 1903-9. Investigations (1953): Geol; Geoph.	Jensen & others (1916), Rosenhain & Mumme (1953), Crohn (1968).
51	GL4704	unnamed prospect	Cu			Ml, Az, Cpy, G	Q, Cte	Steeplly dipping NE-trending shear zones.	Veins in shear zones (<3 m wide).	Pfb (pel & Gywk Hfs).	Open cut, shafts	Worked 1903-9.	Jensen & others (1916), Crohn (1968).
52	GL4803	unnamed prospect	Sn			Cst	Q, Mus	Steeply dipping NW-trending faults.	Fault-filling pegmatite & greisen veins in a zone 30 x 400 m.	Pfb	Shafts (<50 m), drives.	Worked 1882-93.	Jensen & others (1916), Crohn (1968).
53	GL4803	Old Company	Sn	147 t Sn Conc.									
54	Gl4902	Pyromorphite Prospect	Pb							Pfb			
55	GL5002	Philip Greets	Cu	362 t Cu Conc.	25-30% Cu		Q	Steeply dipping NW-trending	Fault-filling vein (<1 m wide & 400	Pfb (pel Hfs).	Shafts (<43 m).	Worked 1901-11.	Jensen & others (1916).

								fault.	m long).				
56	GL4802	Halls Creek Prospect	Sn			Cst	Q, Mus		Pegmatite & greisen intrusive veins.	Pfb, Qa	Shallow shafts & open cuts.		Crohn (1968).
57	GL4802	Chinamans Hill Prospect	Sn										
58	GL4401	McCleans Prospect	Mn	250 t Mn ore	60% MnO_2	mn Ox			Oxidised talus deposit.	K (Sltst).		Worked in late 1950's.	McLeod (1965), Needham (1981).
59	GL4901	Barrets	Sn	117 t Sn Conc.		Cst	Q, Mus		Pegmatite & greisen stock-work.	Qa, Pfb	Pits (<6 m deep0 over an area 100 x 30 m.	Worked ?1890-1911.	Jensen & others (1916).
60	GK4597	Carruthers Prospect	Sn							Pfb			
61	GK4697	unnamed prospect	Cu							Psk			
62	GK4998	Whatleys Prospect	Pb							Pso			
63	GL5912	Mackay and Francis Prospect	Cu, Au		36% Cu, 20 g/t Au	Cc	Q, Cte, Ba	Steeply dipping NE-trending fault.	Fault-filling vein (<0.2 m wide).	Psk	Shaft (<10 m).	Worked in 1915.	Jensen & others (1916).
64	GL6012	unnamed mine	Au							Psg			
65	GL6211	unnamed prospect	Cu							Pdz			
66	GL6212	unnamed prospect	Fl			Fl, Selt	Mus		Pegmatite	Pdz (Ampht)			
67	GL6312	Rising Tide	Cu			Cpy, G, Spl	Q, Lim, Py	Vertical NW-trending fault.	Fault-filling breccias & veins.	Psk (carb Sl).	Shafts (<30 m).	Investigations: Geoph; DDH; Gchem.	Sullivan & Iten (1952), Hays (1959), Shields (1965c), Crohn (1968).
68	GL6511	Brittania	Au	26,220 g Au	117 g/t Au	Au	Q	Vertical NW-trending faults.	Fault-filling veins (<1 m wide & 100 m long).	Psg (Tf, pel Hfs)	Open cuts & shafts (<20 m).	Discovered 1875. Worked 1884-93.	Cottle (1937a).
69	GL6409	Zappopan group of mines	Au, Ag, Pb	1,207,000 g Au, 12.8 t Ag-Pb Conc.	20 g/t Au	Au, G	Q, Py, Cte, Aspy	Faults parallel to steep N-dipping axial plane of ESE-plunging F_1 anticline.	Fault-filling veins (<4 m wide).	Qa, Psk, Psg, Pso	To 69 m depth.	Main production 1885-1915.	Brown & Basedow (1906), Brown (1908), Woolnough (1912), Jensen (1914, 1915), Jensen & others (1916), Cottle (1937a),

													Crohn (1968).
70	GL6708	unnamed mine	Au			Au				Pso			
71	GL7012	unnamed mine	Au			Au			Alluvial deposits	Qa	Alluvial diggings.		
72	GL7013	unnamed mine	Au			Au			Alluvial deposits	Qa	Alluvial diggings.		
73	GL7113	Glencoe	Au	(1 Mt @ 1.8 g/t Au)		Au	Q		vein stockwork.	Pso	Open cut.		
74	GL7110	Fountain Head	Au	450,000 g Au (1.6 Mm^3 @ 0.5 g/m^3 Au)	<22.4 g/t Au	Au	Q	S_1 parallel NW-trending faults in F_1 anticline hinge.	Fault-filling veins (<1.5 m wide & <100 m long).	Pfb (Sl, Gywk)	Open cuts, shafts (<33 m) & alluvial diggings.	Worked intermittently 1883-1951, 1988--.	Cottle (1937b), Crohn (1968), Rayner & Nye (1937), Sullivan & Iten (1952).
75	GL7609	Maria Prospect	Cu							Pso			
76	GL7205	unnamed prospect	Cu							Pfb			
77	GL7205	unnamed prospect	Cu							Pfb			
78 79	GL6801 GK6799	Hayes Creek	Sn	160 t Sn Conc.		Cst	Q, fe Ox	Fractured F_1 anticlinal hinge	Fracture-filling veins & breccias (<2 m wide).	Pso, Qa (Sl & Gywk).	Open cuts, adits & alluvial diggings.	Worked 1914-34, intermittent since 1962.	Dunn (1963), Crohn (1968).
80	GL7606	Priscilla Line of Reefs	Au	357,870 g Au		Au	Q, Py, Aspy, Cpy	Steep E-dipping faults on limb of F_1 anticline.	Fault-filling veins (<2 m wide).	Psg, Pso (Gywk, Sl & Phy).	Open cuts, shafts (<57 m) & costeans.	Worked 1872-1907.	Cottle (1937c), Shields & Daly (1967), Shields & Pietsch (1971), Balfour (1978).
81	GL7402	Port Darwin	Au			Au			Alluvial deposits	Qa	Alluvial diggings.		
82	GL7402	Sandy Creek	Au	(2 Mm^3 @ 0.4 g/t Au)		Au			Alluvial deposits	Qa	Alluvial diggings.		Ormsby (1988)
83	GK7298	Golden Dyke group of mines (incl. Fishers, Langleys, Davis Camp & Afghan Gulley)	Au	640,300 g Au 1.6 t Ag	<3.0 g/t Au	Au	Q, Py, Aspy, Cpy, Sid, Clt	F_1/F_3 interference dome.	Stratabound conformable veins and disseminations.	Psk (carb Pel, Do, Pampht & q hem Fest).	Open cuts & alluvial diggings.	Worked 1872-1938, 1987-9.	Hossfeld (1936a), Balfour (1978), Nicholson (1980).
84	GL7502	unnamed prospect	Au			Au				Pfb			
85	GL7604	Iron Blow	Au, Ag, Cu, Pb, Zn	329,000 g Au 15,100 t Cu Conc.	<7.7 g/t Au	Au, G, Cpy, Spl	Q, py, Pyt	Steep E-dipping shear zones.	Stratabound massive sulphide deposits and veins in cross-	Pso (Sh, Sltst, Tf, Gywk & bnd Fest).	Open cut, shafts (<65.5 m).	Worked 1873-1906, 1985.	McDonald (1901), Hossfeld (1937), King & Thompson (1949),

				6-14% Zn)					cutting shear zones.				Kitto (1968), Crohn (1968), Danielson (1970), Shields & Pietsch (1971), Goulevitch (1980), Eupene & Nicholson (1990), Dunn (1961).
86	GL7601	Mount Bonnie	Au, Ag, Cu, Pb, Zn	770,000 g Au 25.3 t Ag (45,000 t @ 9.6 g/t Au)	7.0 g/t Au 230 g/t Ag	Au, Ag, Cpy, G, Spl, Tet	Q, Do, Act, Tc, Clt, Py, Pyt, Aspy	S_1 cleavage.	Stratabound massive sulphide deposit (<30 m thick & 150 across). Ore remobilised into S_1 surfaces.	Pso (Sh, Sltst, Tf, Gywk & bnd Fest).	Open cut, shafts & adits.	Worked 1903-16, 1983-5.	Jensen & others (1916), King & Thompson (1949), Shields & Pietsch (1971), Ivanac (1974), Goulevitch (1980), Rich & others (1984), Eupene & Nicholson (1990).
87	GL7701	unnamed mine	Au			Au	Q			Psk			
88	GK7498	Heatleys Prospect	Pb, Zn		0.1% Cu, 0.1% Pb, 0.2% Zn	G, Spl, Cpy	Py, Pyt		Discordant veins & conformable lenses.	Psk (carb Pel)		Found in 1970. Investigations: Gchem; DDH.	Shields & Pietsch (1971), Baarda (1972), Nicholson (1980).
89	GL8201	Pickfords (Bonnie Jean)	Pb			Cer, sec Cu Mnr	Q	N-NNW shear zones.	Fracture-filling veins	Psg (Tf)	Open cuts & shafts (< 18 m).	Worked 1900-15.	Campbell & Thomas (1956), Crohn (1968).
90	GK7995	Margaret	Au	40,654 g Au (6 Mm^3 @ 0.3 g/m^3 Au)		Au			Alluvial deposit.	Qa, Psk	Alluvial diggings.		
91	GL8800	unnamed mine	Ls			xl Ls				Psk (xl ls Hfs).			Jensen & others (1916).
92	GL9308	unnamed mine	Sn			Cst			Alluvial deposit.	Qa			
93	GL9307	Horners Creek	Sn	33 t Sn Conc, 175 g Au		Cst,Au			Alluvial deposit.	Qa			
94	GL9406	Mount Wells	Sn, Cu	1,690 t Sn Conc, 7.1 t Cu ore, (800,000 t @ 1.2% Sn)	1% Sn 37% Cu	Cst, Wolf, Cpy, Cc, tr Sche	Q, Py	*En echelon* shear zones dipping 45° - 75° E.	Veins, stockworks & wallrock replacement.	Pfb (Sl, Sltst, Gywk & Hfs).	Extensive underground workings.	Worked 1879-1929.	Crohn (1968), Mookhey (1971).
95	GL9603	Lewis Prospect	Sn, Cu, Pb				Q, lim	Shear zone.	Veins filling shear zone.	Pfb (Gywk & Sh).			

96	HL0706	Saddle Extended	Fe			Hem, Lim, Pyl	Q	Pre-F_1 thrust - related breccias.	Conformable lenses (600 m x 20 m). Residual oxidised cappings.	Ppw (py carb Phy).		Discovered 1961. Investigations: Gchem; Geoph; Geol; DDH.	Crohn (1961), Hughes (1962), Hammond (1963), Barrell (1969), Freisen (1972), Balfour (1978).
97	HL1106	unnamed prospect	Au			Au	Q, Hem	Shear zones.	Veins filling shear zones.	Ppm			
98	HL1004	Frances Creek	Au	4,890 g Au	10 g/t Au	Au	Q, Hem	Shear zones on limb of F_1 anticline.	Veins & breccias filling shear zones.	Ppm (Sh, fs Sst & Cgl).	Shaft, adit & alluvial diggings.	Discovered 1926. Lode worked 1936-7.	Shields (1965a), Newton (1974b).
99 100	HL0803 HL0902	Saddle Ochre Hill	Fe			Hem, Lim, Pyl	Q	Pre-F_1 thrust - related breccias.	Conformable lenses (600 m x 20 m). Residual oxidised cappings.	Ppw (py carb Phy).		Discovered 1961. Investigations: Gchem; Geoph; Geol; DDH.	Crohn (1961), Hughes (1962), Hammond (1963), Barrell (1969), Freisen (1972), Balfour (1978).
101	HK0699	Watts Creek	Au	653 g Au		Au			Alluvial deposit.	Qa			
102	HK0994	Frances Creek group of mines	Fe	7,979,202 t Fe ore	59% Fe	Hem, Lim, Pyl	Q	Pre-F_1 thrust - related breccias.	Conformable lenses (600 m x 20 m). Residual oxidised cappings.	Ppw (py carb Phy).		Discovered 1961. Investigations: Gchem; Geoph; Geol; DDH.	Crohn (1961), Hughes (1962), Hammond (1963), Barrell (1969), Freisen (1972), Balfour (1978).
103	HL1402	Frances Creek	Au	4,043 g Au		Au			Alluvial deposit.	Qa			
104	HK2198	unnamed prospect	Fe						Residual oxidised capping.	Pnm			
105	HK1689	Nellie Creek	Sn	3 t Sn Conc.		Cst			Alluvial deposit.	Qa			
106	GL8800	unnamed mine	Ls			xl Ls				Psk (xl Ls).			
107	GK8899	Burrundie Prospect	U			U sec Mnr	fe Ox	Bedding parallel shear zones.	Surficial oxidised capping.	Psk (carb py Sltst).		Found 1954. Investigations: Geoph; DDH.	Stewart (1954), Rade & others (1954), Firman (1955b).
108	GL9300	unnamed mine	Sn			Cst			Alluvial deposit.	Qa			
109	GK9399	Mundic	Sn			Cst	Q, Py		Conformable vein (<1 m wide).	Pso, Pfb		Worked late 1800's-1909.	
110	GK9399	Final Finn	Sn, Cu		1.0% Sn		Q, Hem	Faults &	Fracture-filling	Pso		Investigations:	Newton (1974c).

		Prospect			0.05% Cu			fractures.	veins.	(Tf, tf Sltst, fe Sltst & py Sl).		Geol; Geoph; Gchem.	
111	GK9299	Jimmys Knob	Sn	7.1 t Sn Conc.		Cst	Q, Clt, Lim	Shear zones and faults.	Veins filling faults & shear zones.	Pgz, Pso (Phy, Gywk, Tf, Sye & mc Mnz).	Adits, drives & shafts (<61 m).	Worked intermittently. Most production late 1800's - 1909.	
112	GK9197	Horseshoe	Sn			Cst		Shear zone at or near Psk/Pdz contact.	Disseminations in Pgz and veins filling shears.	Pgz (mc Mnz & Dr).	Shafts (<18 m).		Stuart-Smith & others (1987).
113	GK9397	Teacup	Sn			Cst	Q, Mus, Tou		Steeply dipping NE-trending veins.	Pfb, Pgz (Sltst, Gywk & Dr).	Pit		Stuart-Smith & others (1987).
114	GK9494	Spring Hill	Au, Ag, Sn	658,500 g Au, 0.01 t Sn Conc. 900 g Ag	31 g/t Au	Au G	Q, Py, Lim	Steep E-dipping shear zones in hinge of S-plunging F_1 anticline.	Shear-filling veins (<1.5 m wide).	Pso	Extensive underground workings.	Worked intermittently since 1870's.	Gray (1951), Taube (1966).
115	GK9493	unnamed mine	Au			Au				Pfb			
116	GK9493	unnamed mine	Au			Au				Pfb			
117	GK9692	unnamed mine	Au			Au				Pfb			
118	GK9691	McKinlay	Ag, Pb Au	747 t Ag-Pb Conc., 1.244 t Ag	30% Pb, 1,439 g/t Ag, 63 g/t Au	G, Spl, Cpy, Cc, Pyra	Q, Sid, Py, Marc, Aspy	Subvertical NW-trending shear zone.	Shear-filling vein (<1 m wide).	Pfb (clt Phy & Gywk).	Shafts (<38 m).	Worked intermittently since late 1880's.	Dodson (1969), Crohn (1968), Balfour (1978).
119	GK9491	unnamed mine	Sn							Pso			
120	GK9391	unnamed mine	Sn							Pso			
121	GK9191	unnamed mine	Sn	320 t Sn Conc.						Pso			
122	GK9388	Snaddens Creek group of mines	Sn			Cst	Q, Py G		Vein stockwork.	Qa, Pgz (Sye).	Shallow pits & alluvial diggings.		Crohn (1968).
123	GK8586	unnamed mine	Cu			Ml, Az	Q, Clt, Hem	Subvertical NE-trending fault	Veins filling fractures within breccia & altered wallrock.	Pgm (brec Gr).	Shallow pits.		Stuart-Smith & others (1987).
124	GK8181	Douglas River	Sn	2 t Sn Conc.		Cst			Alluvial deposit.	Qa			
125	GK9888	Flora Belle	Ag, Pb Au	195 t Ag-Pb Conc		G, Spl, Cpy, Cc, Pyra	Q, Sid, Py, Marc, Aspy	Subvertical NW-trending shear zone.	Shear-filling vein (<1 m wide).	Pfb (clt Phy & Gywk).	Shafts (<38 m).	Worked intermittently since late 1880's.	Dodson (1969), Crohn (1968), Balfour (1978), Forbes & Sturm (1967).

126	GK9889	Elizabeth	Au	107,000 g Au	30 g/t Au	Au	Q	Subvertical NW-trending shear zones.	Shear-filling veins (<1 m wide).	Pfb (Gywk & clt Phy).	Small open pits, & shafts (<24 m).	Worked 1875-97.	Crohn (1968), Balfour (1978).
127	HK0093	Union Extended	Au	165,000 g Au		Au	Q, Py, Aspy, G Do		Vein stockwork.	Pfb (Phy, Sltst, alt Volc & Gywk).	Open cut & shafts (<40 m).	Worked 1875-1908.	Crohn (1968), Stuart-Smith & others (1987).
128	HK0192	Union Extended	Ag, Pb	18 t Ag-Pb Conc.		G, Angt	Q	Vertical N-trending joints.	Veins filling joints.	Pfb (Phy).	Shafts (<10 m).		
129	GK9986	unnamed mine	Au			Au	Q	Subvertical NW-trending shear zones.	Shear-filling veins (<1 m wide).	Pfb (Gywk & clt Phy).	Small open pits.		
130	GK9986	unnamed mine	Ag, Pb			G, Spl,	Q, Sid, Py,	Subvertical NW-trending shear zone	Shear-filling vein (<1 m wide).	Pfb (clt Phy & Gywk).	Shafts.	Worked intermittently since late 1880's.	Dodson (1969), Crohn (1968), Balfour (1978).
131	HK0183	Union Reefs group of mines	Au	1,513,500 g Au (3.1 Mt @ 1.7 g/t Au)		Au	Q, Py, Aspy, tr Cpy, G, Spl, Pyt, Marc, Cte	Subvertical NW-trending shear zones.	*En echelon* veins & breccias within shear zones over a 5 x 0.45 km area.	Pfb (Phy & Gywk).	Open cuts, shafts (<61 m) & adits.	Worked 1873-1906. Subsequent investigations: DDH; Geoph.	Brown (1908), Jensen (1915), Hossfeld (1936b), Shields & others (1967) White & others (1967), Marlatt (1968), Shields (1970), Turner (1990).
132	HK0677	Basin 6 Prospect	Ag, Pb			G	Q	NW-trending shear zone.	Shear-filling veins.	Pso (Phy & Gywk).	Costeans.	Investigations: Gchem; Geoph.	Smith & Goudie (1971).
133	HK1174	Caledonia	Au	14,300 g Au		Au			Alluvial deposit.	Qa			
134	HK0670	unnamed prospect	Ag, Pb			G	Q		Veins.	Pfb (Phy & Gywk).			
135	HK0570	Pine Creek group of mines (Enterprise)	Au	10,946,000 g Au 4,000 g Ag (22.7 M t @ 1.9 g/t Au 8.4 Mt @ 3.1 g/t Au).		Au	Q, Py, Aspy, Cpy, G, Spl, Pyt, Tet, Bi Mnr	SE-plunging F_1 anticline cut by NW-trending sub-vertical faults parallel to S_1.	Saddle reefs & veins filling faults. Disseminated wallrock replacement.	Pso, Pfb (Phy & Gywk Hfs, carb Sh Hfs).	Open cut, extensive underground workings to 80 m depth.	Main production 1870's-1915, 1985	Hossfeld (1936c), Shields (1965b), VanderPlank (1965), Crohn (1968), Dann & Delaney (1984) Cannard & Pease (1990).
136	HK0468	Enterprise No. 2	Cu			Cc, Ml, Cup, Az, Ko, Chrys	Q, Clt, Hem	Subvertical NE-trending shear zone.	Veins filling shear (<1 m wide).	Pgt (leuco Gr: Type 9).	Shallow pits.	Investigations: DDH.	Newton (1975), Stuart-Smith & others (1987).
137	HK0967	Kellys	Sn	2.0 t Sn Conc.		Cst	Q, fe Ox		Veins.	Pfb (Phy & Gywk).		Worked 1908-9.	Brown (1908).

138	HK1067	unnamed mine	Sn			Cst			Veins & breccia.	Pfb			
139	HK0866	unnamed prospect	Ag, Pb			G	Q	N-trending shear.	Shear-filling vein.	Pfb (Phy, Gywk)			
140	HK0766	Lucknows	Ag, Pb	152 t Ag-Pb Conc.		G	Q	NW-trending shear.	Shear-filling vein.	Pfb (Phy & Gywk).			
141	HK0465	Copperfield	Cu	2357 t Cu ore	12% Cu	sec Cu Mnr	Q	Shear zone dipping 60° WSW.	Breccia (<1.5 m wide) within shear zone.	Pfb (Gywk & Phy Hfs)	Pits & shafts (<4 m).	Worked 1872-1917. Investigations: Gchem, Geoph, DDH (1971).	Jensen (1919), Crohn (1968), Smith & Goudie (1971).
142	HK0763	Mount Wigley	Ag,Pb	61 t Ag-Pb Conc.		G	Q	N-trending shear.	Shear-filling vein.	Pfb (Phy & Gywk).	Shaft (<8 m).	Worked 1907.	Crohn (1968).
143	HK0662	unnamed prospect	Cu				Q	NNW-trending shears.	Shear-filling vein.	Pfb (Phy & Gywk).			Stuart-Smith & others (1987).
144	HK0762	unnamed prospect	Cu				Q	NNW-trending shears.	Shear-filling vein.	Pfb (Phy & Gywk).			Stuart-Smith & others (1987).
145	HK0962	ML426A	Ag, Pb	23.3 t Ag-Pb Conc.		G	Q	N-trending shear.	Shear-filling vein & breccia.	Pfb (Phy & Gywk).	Shallow pit.	Worked 1978-9.	
146	HK1262	unnamed prospect	Au			Au	Q, Aspy	NNW-trending fault.	Fault-filling vein.	Pgc (Gr).			
147	HK1361	unnamed prospect	Au			Au	Q, Aspy	NNW-trending fault.	Fault-filling vein.	Pgc (Gr).			
148	GK8966	unnamed prospect	Cu			Cc, Ml, Cup, Az, Ko, Chrys	Q, Clt, Hem	Subvertical NE-trending shear zone.	Veins filling shear (<1 m wide).	Pgt (leuco Gr: Type 6).			Stuart-Smith & others (1987).
149	GK9066	Stray Creek	Sn	18 t Sn Conc.		Cst			Alluvial deposit.	Qa			
150	GK9756	Umbrawarra	Sn	273 t Sn Conc.		Cst			Alluvial deposit.	Qa			
151	JE8378	unnamed mine	Ag, Pb							Ppw	Shaft.		
152	JE8578	McCarthys	Ag, Pb	580 t Ag-Pb Conc.	308 g/t Ag, 69% Pb	Cer, G, Angt, Pym		Shear zone dipping 70° - 80°W.	Veins (<1m wide) within shear zone.	Ppw (carb Sltst Hfs).	Shafts (<24 m).	Worked 1912-7.	Weber (1968), Crohn (1968), Balfour (1978).
153	JE9193	unnamed mine	Au			Au, Ml	Q, Lim, Clt, Py	NE-trending fault.	Vein.	Pfb (Gywk & Phy).	Pits.		

154	JE9192	unnamed mine	Au			Au			Alluvial deposit.	Qa	Alluvial diggings.		
155 156	JE8890 JE8889	Evelyn	Ag, Pb Zn, Cd, Au	56,813 g Au, 22.55 t Ag, 5,591 t Ag-Pb Conc., 54 t Cd, 6,077 t Zn Conc.	0.6 g/t Au, 275 g/t Ag, 6.3% Pb, 7% Zn	G, Spl, Cpy, Agt, Pent, Smt, Hydzn, Angt, Cer, Auric	Q, Hem, Cte, Py, Pyt, Aspy	NW-trending shear zone.	*En echelon* tabular lens-like lodes (<1.6 m wide & 60 m long) within shear zone. Brecciated & altered wallrock (Act, Trem, Di, Grnt, Aphy).	Psk (Ls Hfs, Do Hfs & Sltst Hfs).	Shafts, drives & open cut.	Worked 1886-9, 1903-12, 1924-6 1966-70.	Hossfeld & others (1937), Rowston (1957), Crohn (1968), Garth (1970), McCulloch (1972), Balfour (1978).
157	JE9287	Northern Hercules	Au, Ag, Cu	1,145,788 g Au, 0.36 t Ag, 23 t Cu Conc. (1 Mt @ 3.7 g/t Au)	57 g/t Au, 0.4 g/t Ag	Au, Cpy, Cc, G, Tet, Spl, Cv	Q, Py, Aspy, Ser, Fs	Shear zones dipping 65°-70° ENE.	Vein & breccia fillings in tension fractures within shear zones.	Pfb (Gywk, Sltst & Phy).	Shafts (<134 m) & crosscuts.	Worked 1882-1900, 1954-7. Investigations: Geol; Gchem; Geoph; DDH.	Sullivan (1940), Summers (1957), Miller (1990).
158	JE9086	Stockyard Prospect	Au, Ag, Cu		3.7 g/t Au, 300 g/t Ag, 0.85% Cu	Au, Cpy, Spl	Py, Q Aspy, Pyt, Lim, Hem		Vein.	Pso (Sltst & Tf).	Costeans.	Investigations: Geol; Gchem; Geoph; DDH.	Cox (1969 & 1970), Veit (1969).
159	JE9485	Eureka Creek Prospect	Au, Ag		1.7 g/t Au	Au Scor	Q, Py, Aspy	NW-trending shear zone.	Fracture-filling vein.	Pfb (Sltst).		Investigations: Gchem.	McCulloch (1972).
160	JE9887	Bowerbird	Ag, Pb	13 t Ag-Pb Conc.		G				Pfb	Shafts & drives.	Worked prior to 1908, 1913.	Crohn (1968), Balfour (1978).
161	JE9682	unnamed prospect	Cu, Ag, Pb							Pso			
162	JE9680	unnamed prospect	Cu						Vein	Pfb			
163	JE9979	Lakeside Prospect	Cu			Ml, tr Cpy, Spl, Moly	Q, Clt, Cte, Py, fe Ox	Shear zone dipping 70° SW.	Breccia filling shear zone.	Pfb (pel & Gywk Hfs).	Shaft & pits.	Investigations: Geol; Geoph, Gchem; DDH.	Taylor (1973b).
164	KE0179	Mount Gardiner	Cu, Pb, Ag	77 t Cu Conc. 7 t Ag-Pb Conc.		Ml, Az, G	Q, Hem, Mt	N to NE-trending faults.	Greisen veins & breccia filling faults.	Pfb (pel & Gywk Hfs)		Worked 1907, 1930.	Jensen (1919), Crohn (1968).
165	KE0280	IXL	Cu	10 t Cu Conc.	10% Cu	Ml, Az	Q, fe Ox	Vertical NW-trending shear zone.	Veins within shear zone.	Pfb (Sltst & Gywk Hfs).		Worked 1900-8. Investigations: Gchem; Geoph.	Sturm (1966), Balfour (1978). Jensen (1919).

166	KE0077	Waldens No. 2 Prospect	Cu			sec Cu Mnr	Q	Steeply dipping NW-trending shear zone.	Veins within shear zone.	Pfb (pel & Gywk Hfs).	Shallow pits & trenches.		
167	KE0277	Mount Diamond	Cu, Ag, Au, Bi	3,151 t Cu Conc. 111,476 g Au, 3.7 t Ag, 43 t Bi	4.7% Cu, 0.21 g/t Au, 75 g/t Ag, 0.07% Bi	Cpy, G, Bi Mnr, Cc, Ml, Az, Cv, Cup, Spl, Sb	Q, Py, Aspy, Lim, Mt, Fs, Clt	Steeply dipping NW-trending shear zone.	Veins within shear zone.	Pfb (pel & Gywk Hfs).	Shafts (<63 m), inclined adit & extensive underground workings.	Worked 1898-1920, 1970-3.	Gray & Winter (1915), Taylor & Cox (1969), Crohn (1975), Balfour (1978).
168	KE0277	Waldens	Cu	628 t Cu Conc.	10% Cu	Ml, Az, Cpy, Scor	Q, Lim, Hem, Aspy, Py	Steeply dipping NW-trending shear zone.	Veins & breccia within shear zone.	Pfb (pel & Gywk Hfs).	Shafts (<31 m).	Worked 1904-19.	Crohn (1968), Balfour (1978).
169	KE0278	unnamed mine	Cu							Pgv (Grei).			
170	KE0377	unnamed mine											
171	KE0477	unnamed mine											
172	KE0778	Mount Davis	Cu, Ag, Pb	792 t Cu Conc.	12.3% Cu, 312 g/t Ag	Cpy, Cc, Ml, G, Scor	Q, Clt, Ser	N-trending shear zones.	Greisen alteration zones (<0.6 m wide) within shear zones.	Pgv (Grei).	Shafts (<17 m) & drives.	Worked 1907-17. Investigations: Geoph.	McPhar Geophysics (1971).
173	KE0776	Hamiltons	Cu	12 t Cu Conc.		Ml, Cc, Scor	Q, Lim	Subvertical NW-trending fault.	Breccia (<0.8 m wide) filling fault.	Pfb (pel & Gywk Hfs).	Shafts (<18 m).	Worked 1907. Investigations: Gchem; Geol; Geoph; DDH.	Herrmann (1971), Balfour (1978).
174	KE1180	Coronet Hill	Cu, Ag, Pb	2,893 g Ag, 252 t Cu Conc.	550 g/t Ag, 22% Cu, 10% Pb,	Cpy, Cv, G, Cup, Tet, Spl, tr Au, Bi , Sb	Q, Py Aspy, Pyt	Steep SW-dipping faults.	SE-plunging lenses within veins filling faults.	Pso, Pfb (Tf, Cht & Sltst).	Adits, drives & shafts (<37 m).	Worked 1887-1918.	Ruxton & Shields (1962), Crohn (1968), Nicholson (1981).
175	KE1181	Ross	Sn, Cu			Cst, Cpy	Q, Tour, Aspy	Steeply SW-dipping fault.	Veins (<0.3 m wide) filling fault.	Pso, Pfb (Tf, Cht & Sltst).	Shafts & crosscuts.		Ruxton & Shields (1962).
176	KE0685	Mary River Camp	Sn	46 t Sn Conc.		Cst	Q		Vein & associated alluvial deposit.	Qa, Pfb	Shafts (<24 m) & alluvial diggings.	Worked 1910-3.	Balfour (1978). Crohn (1968).
177	KE1290	Mary River Junction	Cu	70 t Cu Conc.		Ml, Cc	Q, fe Ox	Fault dipping 30° - 40° SW.	Breccia filling fault.	Pnm (Sh & Qt).	Pits & shafts.	Worked 1913, 1917-8.	Rix (1964), Crohn (1968).
178	JE9772	Wandie group of mines	Au	225,833 g Au (1,240,500 m^3 @ 0.07 g/t Au)	41 g/t Au	Au, G	Q, Py	Bedding-parallel fractures.	Steep WSW-dipping veins (<1 m wide). Associated	Pfb, Qa (Phy, Gywk).	Shafts (<21 m), alluvial diggings	Worked 1895-1906.	Balfour (1978), Jensen (1919), Thomas (1966),

									eluvial & alluvial deposits.				Balde (1979), Balfour (1978).
179	KE0469	Saunders Rush	Au			Au			Alluvial deposit.	Qa			
180	KE0265	Brilliant	Au			Au	Q		N-trending veins.	Pfb (Phy, Sltst & Gywk).	Shallow pits.		Balfour (1978).
181	JE9963	Crest of the Wave	Sn	155 t Sn Conc.	15% Sn	Cst	Q, Py, Aspy	Bedding parallel faults dipping 60° W.	Fault-filling veins (~0.2 m wide).	Pfb (Phy & Gywk Hfs).	Shafts (<40 m) & drives.	Worked intermittently since 1907.	Kleeman (1938), Sturm (1966).
182	KE0263	unnamed prospect	Ag, Pb			G	Q	NW-trending faults.	Veins (<1 m wide) filling faults.	Pfb (Phy & Gywk).			Ellis (1928), Kleeman (1938), Patterson (1958).
183	KE0962	Tableland	Ag, Pb			G	Q	NW-trending faults.	Veins (<1 m wide) filling faults.	Pfb (Phy & Gywk).	Shallow open cuts.		Ellis (1928), Kleeman (1938), Patterson (1958).
184	KE0960	Silver spray	Ag, Pb	19 t Ag-Pb Conc.		G, Cer	Q, Lim	NW-trending faults.	Veins (<0.6 m wide) filling faults.	Pfb (Phy & Gywk).	Shallow open cuts.	Worked 1905-7.	Crohn (1968), Kleeman (1938).
185	KE0159	Last Hope	Au	569 g Au	28 g/t Au	Au	Q	E-trending fractures.	Fracture-filling veins.	Pfb (Gywk, Sltst & Phy).	Shafts (<4 m).	Worked 1910.	Kleeman (1938).
186	KE0357	Wolfram Hill (incl. Irwins)	W, Cu	264 t Cu Conc., 740 t W Conc.	5% Cu, 4% W	Wolf, Cpy	Q, Fs, Biot, Aspy, Py	Bedding parallel shear zones dipping 60°-80° NE. W-dipping (50°) joints.	Pegmatite veins filling shears. Ore concentrated as stacked lenses within pipes developed at shear/joint intersections.	Pfb (Gywk & Sltst Hfs).	Open cuts, adits & shafts (<43 m).	Worked 1900-19, 1937-53.	Kleeman (1938).
187	KE0556	Bells Prospect	Mz			Mz	Q, fe Ox		Veins.	Pgj (leuco Gr: Type 9).			Brown (1908).
188	KE0555	Connells	Sn	0.6 t Sn Conc.	14% Sn	Cst			Disseminations.	Pgj (leuco Gr: Type 6).			Brown (1908).
189	KE0555	Martins	Sn, Cu	1.3 t Sn Conc.		Cst			Disseminations.	Pgj (leuco Gr: Type 6).			Brown (1908).
190	KE0554	Kellys	Sn, W			Cst, Wolf	Q, fe Ox		Veins (<1.8 m wide).	Pgj (leuco Gr: Type			Brown (1908).

										6).			
191	KE0554	unnamed mine	Sn			Cst	Q		Veins.	Pgj (leuco Gr: Type 6).			
192	KE0453	Mountain View	W	1.5 t W Conc.	<60% W	Wolf	Q, Fs	Joints trending 320°-350°, dipping 30°-80° NE.	Pegmatite veins (<15 cm) filling joints.	Pfb (pel & Gywk Hfs).		Worked 1918-20.	Jensen (1919), AGGSNA (1937), Kleeman (1938).
193	KE0253	unnamed prospect	Cu, Ag, Pb			Ml		Shear zones.	Veins and surface coatings in shears & fractures.	Pfb (Sltst & Gywk Hfs).			Stuart-Smith & others (1988).
194	KE0451	Hidden Valley group of mines	Sn	19 t Sn Conc.	2.5% Sn	Cst	Lim	Steeply dipping N to NE-trending faults.	Fault-filling breccias.	Pfb (clt fe Phy).	Open cuts, adits & shafts (<20 m).	Worked 1905-30.	Woolnough (1912), Jensen (1919), Kleeman (1938).
195	KE0551	Wests	Ag, Pb	36 t Ag-Pb Conc.	1010 g/t Ag, 65% Pb	G, Cer	Q, Lim	WNW-trending faults dipping 43°E.	Veins (<1 m wide) filling faults.	Pfb (Phy & Gywk).	Shallow open cuts.	Worked 1927 & 1936.	Ellis (1928), Kleeman (1938), Patterson (1958), Jensen (1919).
196	KE0351	unnamed prospect	Ag, Pb			G	Q	NW-trending faults.	Veins (<1 m wide) filling faults.	Pfb (Phy & Gywk).			Ellis (1928), Kleeman (1938), Patterson (1958).
197	KE0050	unnamed mine	Sn			Cst			Alluvial deposit.	Qa			
198	JE9951	Crocodile Billabong	Ag, Pb			G, Cer	Q	NW-trending faults.	Veins (<1 m wide) filling faults& bedding parallel fractures.	Pfb (Phy & Gywk).	Costeans.	Investigations (1958): DDH.	Patterson (1958).
199	JE9953	unnamed prospect	Ag, Pb			G	Q	NW-trending faults.	Veins (<1 m wide) filling faults.	Pfb (Phy & Gywk).			Ellis (1928), Kleeman (1938), Patterson (1958).
200	JE9753	Black Hill	Sn, W	0.1 t Sn Conc.		Cst, Wolf	Clt, Q		Veins.	Pfb (Phy & Gywk Hfs).			Jensen (1919), Prichard & others (1956), Balfour (1978).
201 202	JE9357 JE9159	Fergusson Prospects	Cu			Ml		Shear zones.	Veins and surface coatings in shears & fractures.	Pfb (Sltst & Gywk Hfs).			Stuart-Smith & others (1988).
203	JE8960	unnamed mine	Sn	(1.814 t Sn)	0.05% Sn	Cst			Alluvial deposit.	Qa, Pgw			Daly (1971).

204	JE9450	Emerald Creek	Sn	56 t Sn Conc.		Cst, sec Pb Mnr	Q, Hem	Faults trending 170° & dipping 70° W.	Veins (<1 m wide) filling faults.	Pfb, Qa (Gywk & Phy).	Pits & shafts (<20 m). Associated eluvial & alluvial diggings.	Worked 1908-13, 1978.	(Crohn (1968).
205	JE9746	Driffield group of mines	Au	164,800 g Au	14 g/t Au	Au, G	Q, Py fe Ox, Aspy		Vein stockwork.	Pfb, Qa (Gywk, Sltst & Phy).	Open cuts, shafts (<40 m) & alluvial diggings.	Worked 1882-1912.	Hossfeld (1941), (Crohn (1968).
206	JE8943	unnamed mine	Au			Au			Vein.	Pfb			
207	JE9041	Horshoe Creek group of mines	Sn	660 t Sn Conc. (207–208)		Cst, sec Cu Mnr	Q	NNW-trending, steeply dipping faults & shears. Associated *en echelon* fractures.	Veins filling faults, shears & fractures.	Pbt, Qa (Gywk & Sl)	Pits & shafts (<50 m) & alluvial diggings.	Worked intermittently. Main production 1908-1910.	Jensen (1919), AGGSNA (1937).
208	JE9138	unnamed mine	Sn			Cst			Alluvial deposit.	Qa			
209	JE9038	unnamed prospect	Sn							Pbt			
210	JE9039	Quigleys Reef	Au		20 g/t Au	Au	Q, Lim	NE-trending faults.	Veins (<2 m wide) filling faults.	Pbt (Gywk, Sltst, Tf & Phy)	Open cuts, shafts (<24 m) & adits.	Worked ~1889-1919.	Woolnough (1912), Jensen (1919), Hossfeld (1941).
211	JE8837	Jones Brothers	Au	28,460 g Au	24 g/t Au	Au, G Cpy	Q, Lim, Hem, Aspy, Py	NNE-trending fault.	Vein (<1 m wide) filling fault.	Pbt	Open cuts, shafts (<40 m) & drives.	Worked prior to 1911 & 1937-1940.	Cottle (1937d), Hossfeld & Nye (1941).
212	JE9235	Morris	Sn	183 t Sn Conc. (212–213)		Cst, sec Cu Mnr	Q	NNW-trending, steeply dipping faults & shears. Associated *en echelon* fractures.	Veins filling faults, shears & fractures.	Pbt, Qa (Gywk & Sl).	Pits, shafts (<50 m) & alluvial diggings.	Worked intermittently. Main production 1908-1910.	Jensen (1919), AGGSNA (1937).
213	JE8833	Shamrock	Sn										
214	JE8835	Tollis Reef	Au		7 - 21 g/t Au	Au	Q	Faults dipping 50°-70° WSW conformable with bedding.	Veins (<1.2 m wide) filling faults.	Pbt	Shafts (<11 m).	Worked ~1908-1919.	Jensen (1919), Cottle (1937d).
215	JE8336	Yenberrie group of mines	W, Mo, Bi, U, Cu, Tz	163 t W Conc., 0.1 t Mo Conc., minor Bi		Wolf, Moly Bi Mnr Cu Mnr	Q, Py, Aspy		Veins (<1 m wide) within NNW-trending greisen & aplite dykes.	Pgy (leuco Gr & Grei).	Pits & shafts (<10 m).		Gray & Winters (1916), Rattigan & Clarke (1955), Crohn (1968).

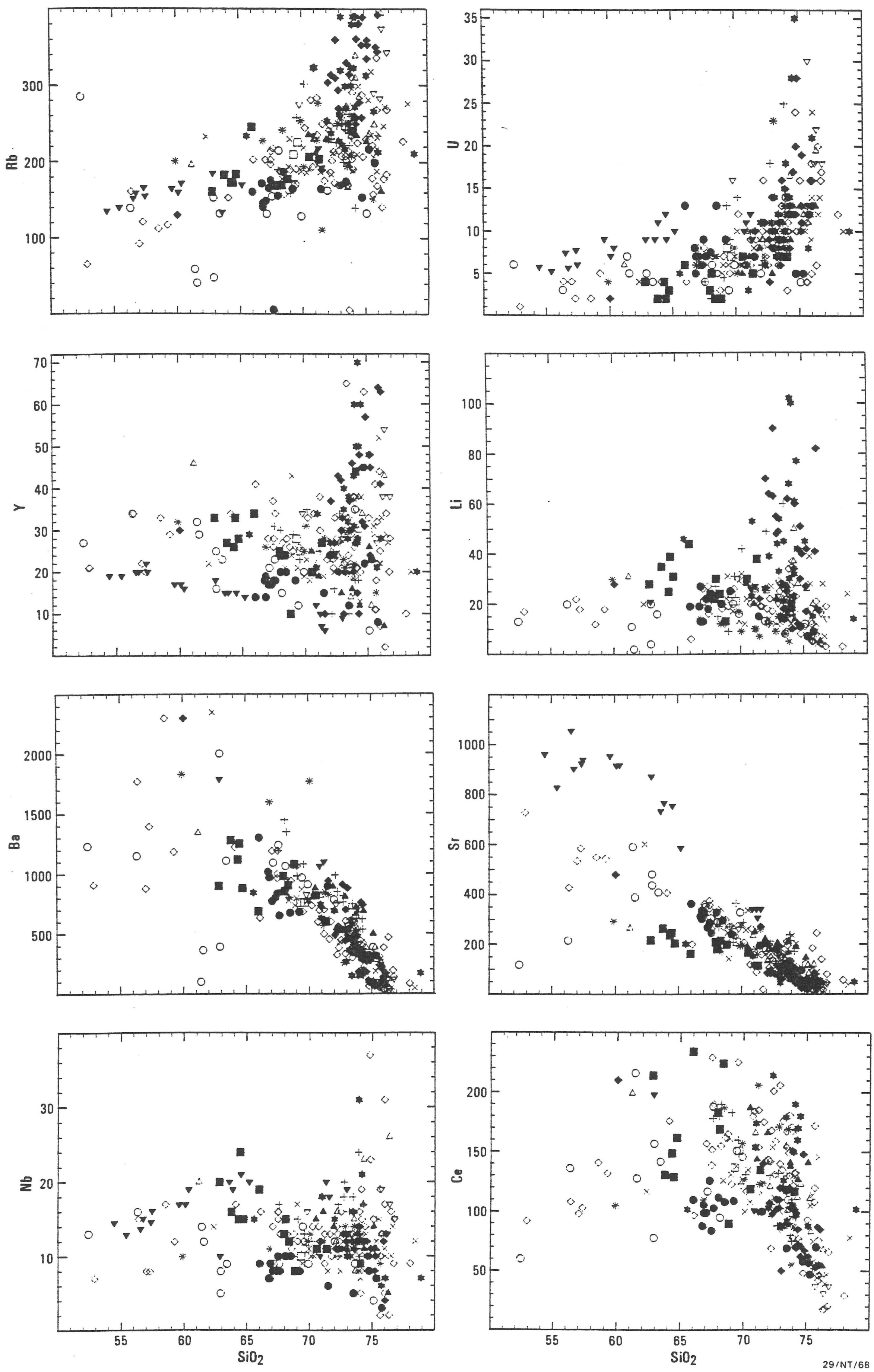
216	JE8137	Yenberrie Prospect	U		0.1-0.2% U_3O_8	Torb, Maut	Q, Lim, Hem, Ap	Steeply dipping N to NW-trending shear zones.	Disseminations & veins (<0.45 m wide) within shear zones.	Pge (leuco Gr: Type 8 & Grei).			Fisher (1952), Gardner (1953a, b, c), Crohn (1968).
217	HK2341	unnamed prospect	W			Wolf	Q, Fs		ENE-trending pegmatite dyke.	Pfb (pel & Gywk Hfs).			
218	JE7744	unnamed prospect	Cu			sec Cu Mnr		NW-trending shears & fractures	Coatings on shear & fracture surfaces.	Pgd (altd Gr: Type 2)	Shallow pits.		
219	HK2243	Fergusson River Prospect	U		0.1-0.2% U_3O_8	Torb, Maut	Q, Lim, Hem, Ap	Steeply dipping N to NW-trending shear zones.	Disseminations & veins (<0.45 m wide) within shear zones.	Pge (leuco Gr: Type 8 & Grei).			Fisher (1952), Gardner (1953a, b, c), Crohn (1968).
220	HK2041	Woolngi	Au	143,000 g Au		Au	Q	SE-plunging F1 anticline cut by NNW-trending faults.	'Saddle reefs' & veins filling faults.	Pfb (pel & Gywk Hfs).	Shafts (<30 m) & adits. Associated alluvial diggings.	Worked 1896-1908 & intermittently since 1908.	Jensen (1919), Crohn (1968).
221	HK1645	Expectation Prospect	Cu			Ml, Cc, Cpy	Q, Py	N-trending fault dipping 80° W.	Vein (<1 m wide filling fault.	Pgx (altd Gd: Type 1).	Pits (<10 m).		
222	HK1341	Tennysons	W			Wolf	Q	NNW-trending shear zone.	Veins within shear zone along Pge/Pfb contact.	Pge (Grei & leuco Gr: Type 8).			
223	HK2228	Tennysons No.1 Prospect	U		0.1-0.2% U_3O_8	Torb, Maut	Q, Lim, Hem, Ap	Steeply dipping N to NW-trending shear zones.	Disseminations & veins (<0.45 m wide) within shear zones.	Pge (leuco Gr: Type 8 & Grei).			Fisher (1952), Gardner (1953a, b, c), Crohn (1968).
224	HK2326	Tennysons No.2 Prospect	U		0.1-0.2% U_3O_8	Torb, Maut	Q, Lim, Hem, Ap	Steeply dipping N to NW-trending shear zones.	Disseminations & veins (<0.45 m wide) within shear zones.	Pge (leuco Gr: Type 5 & Grei).			Fisher (1952), Gardner (1953a, b, c), Crohn (1968).
225	JE8229	YMCA No. 1 Prospect	U		0.1-0.2% U_3O_8	Torb, Maut	Q, Lim, Hem, Ap	Steeply dipping N to NW-trending shear zones.	Disseminations & veins (<0.45 m wide) within shear zones.	Pge (leuco Gr: Type 5 &Grei).			Fisher (1952), Gardner (1953a, b, c), Crohn (1968).
226	JE8226	YMCA No. 2 Prospect	U		0.1-0.2% U_3O_8	Torb, Maut	Q, Lim, Hem, Ap	Steeply dipping N to NW-trending shear zones.	Disseminations & veins (<0.45 m wide) within shear zones.	Pge (leuco Gr: Type 8 & Grei).			Fisher (1952), Gardner (1953a, b, c), Crohn (1968).
227	JE8729	unnamed	Cu			sec Cu		Shear zones.	Coatings on	Pbt			

		prospect				Mnr			shear & fracture surfaces.				
228	JE8627	unnamed prospect	Cu			sec Cu Mnr		Shear zones.	Coatings on shear & fracture surfaces.	Pbt			
229	HK2132	Hore & O'Connors	U		0.1-0.2% U_3O_8	Torb, Maut	Q, Lim, Hem, Ap	Steeply dipping N to NW-trending shear zones.	Disseminations & veins (<0.45 m wide) within shear zones.	Pge (leuco Gr: Type 8 & Grei).			Fisher (1952), Gardner (1953a, b, c), Crohn (1968).

Additional mines and prospects not shown on accompanying map

	HL0918	McKeddies	Cu			Ml, Az, Tet, Cup,			Veins (<0.3 m).	Ppm	open cuts.		Brown (1908).
	JE9286	Moline Dam	Au	1,307,000 g Au (2.3 Mt @ 3.1 g/t Au): includes 1989 production & reserves of Northern Hercules.	2.1 g/t Au	Au, G, Spl, Bi Mnr	Q, Py, Pyt, Aspy, Fs, Tou, Ser, Clt, Cte	S_1 parallel shears & fractures within F_1 anticline hinge.	Stratabound disseminations & conformable veins.	Pso (py carb Sltst & Sh).	Open cut.	Worked 1989--.	Miller (1990).
	GL5739	Goodall	Au	2,369,000 g Au (3.7 Mt @ 2.3 g/t Au)		Au	Q, Py, Aspy tr Cpy, G, Tet, Spl, Bi Mnr, Ser	Subvertical N-trending shears parallel to S_1 within F_1 anticline hinge.	Vein stockwork.	Pfb (Gywk & Sh).	Open cut.	Discovered 1981. Worked 1987--.	

Note: All production figures are to June 1989 in the above table and differ for some of the gold mines listed on the accompanying map which include all production up to December 1984.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