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GEOLOGY OF THE BATES 1:100 000 SHEET AREA (4646), MUSGRAVE BLOCK, WESTERN AUSTRALIA

BY

A. J. STEWART

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DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

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Abstract

The Bates 1:100 000 Sheet area exposes some of the deepest crustal rocks known in Australia. The southern three-quarters of the region comprises granulite, granite, and mafic intrusions; these are thrust over schistose granite forming the northern quarter. The granulite was derived from 1580 Ma-old felsic and mafic volcanic rocks with small amounts of intercalated silicic and aluminous sediments. They were multiply deformed and metamorphosed to granulite facies (about 15 km depth) at around 1200 Ma, and synchronously intruded by voluminous rather quartz-poor charnockitic granitoid at about 1185 Ma. Injection of mafic and felsic magmas forming dykes and other small intrusions took place at about 1080 Ma, and was followed by further mafic dyking at about 1000 Ma and again at 800 Ma as downsagging of the Amadeus Basin to the north began. At about 540 Ma, the region underwent east-northeast-directed under- and overthrusting along the Woodroffe Thrust, which brought transitional granulite–eclogite-facies rocks from 40 km depth up over amphibolite-facies rocks. The southern portion of the overthrust block (south of the Bates region) subsequently collapsed along normal and reverse faults, and left the subeclogitic rocks as a wedge or 'popout' forming the highest part of the region. Erosion of the highlands provided early Cambrian coarse clastic detritus to the Amadeus Basin.

Introduction

BATES[1] 1:100 000 Sheet (4646) is situated in the far east of Western Australia, between Wingellina and Giles in the Proterozoic Musgrave Block (see 'Map Locality' and 'Geological Map of Musgrave Block' beside 1:100 000 map). The area was first mapped geologically by J.L. Daniels, R.C. Horwitz and M.K.J. Kriewaldt in 1966 (Daniels 1972, which contains references to earlier work in the general area). The area was mapped at the detailed reconnaissance scale (using 1:80 000 scale black and white aerial photographs) by A.J.Stewart of AGSO in 1991, as part of the Musgrave project of the National Geoscience Mapping Accord (NGMA). The NGMA, endorsed by the Australian (now Australian and New Zealand) Mineral and Energy Council in August 1990, is a joint Commonwealth/State/Territory initiative to produce a new generation of geological maps, data sets, and other information on strategically important regions of Australia over the next 20 years. The aims of the Musgrave project were:

- update and improve the geoscientific knowledge base of the Musgrave Block through systematic multi-disciplinary studies.
- provide the regional framework as a basis for decisions concerning the environment, water and mineral resources, and land management by governments and by the aboriginal communities.

There is no permanent habitation in BATES (Fig. 1). Warlpapuka, in the west, Arnold Creek in the southwest, and Mirturtu in the southeast are concrete shelters with water bores nearby. An unsealed road crosses the area from north to south, and connects Giles weather station 75 km north of the area with Wingellina (Irrunytju) 7 km south of the area, whence it eventually reaches Mulga Park homestead, 270 km to the east. Another unsealed road near the southern edge of the sheet connects Wingellina with Blackstone, 22 km to the west. Graded tracks leave this road at Warlpapuka; one heads northeast to a solar-powered water bore in the centre of the area, another heads southwest to Blackstone. Other tracks connect Wingellina with Mount Gosse and the Mount Daisy Bates area in the east.

Most of BATES is sand dune country between about 570 m and 650 m above sea level (ASL), through which rise isolated hills (inselbergs) and ridges of crystalline rock (Fig. 2) rising to 880 m ASL at Mount Gosse in the southeast. In the southwest, extensive rocky hills reaching 750 m ASL are part of the Mount Aloysius massif (Glikson et al.1996).

Cainozoic deposits cover 90 percent of BATES. Relationships of the units are shown in the diagram of Cainozoic Rock Relationships beside the map. *Ferricrete or laterite* (Tf) and where it is disaggregated, *laterite gravel* (Qg), are most extensive in the north where they form low rises on schistose granitic rocks. Flat-lying bedded *claystone* (Czs) several metres thick crops out around and between claypans in the east, about 5 km northeast of Mount Gosse. *Calcrete* (Czk) rises are exposed in the south along the Wingellina-Blackstone road, and it also forms extensive sheets exposed in the swales between sand dunes in low-lying areas elsewhere. *Red earth* (Qr), characterised by a thick cover of mulga (*Acacia*), floors the valley swales between sand dunes and tends to be concentrated on slightly higher ground next to areas of calcrete. *Colluvium* (Qc) is concentrated on still higher ground around rocky hills and ranges. Soft, powdery *gypsum* (Qy) forms low mounds next to some claypans, and also encrusts the tops of some claypans. *Claypans* (Ql) are concentrated in the east, which is slightly higher than the west of the sheet area, and tend to lie at low points between hilly areas. Red *aeolian sand* (Qs) is the most extensive Cainozoic unit, and forms a network of short irregular fixed dunes 6-12 m high.

[1] Capitalised names refer to standard map sheets.

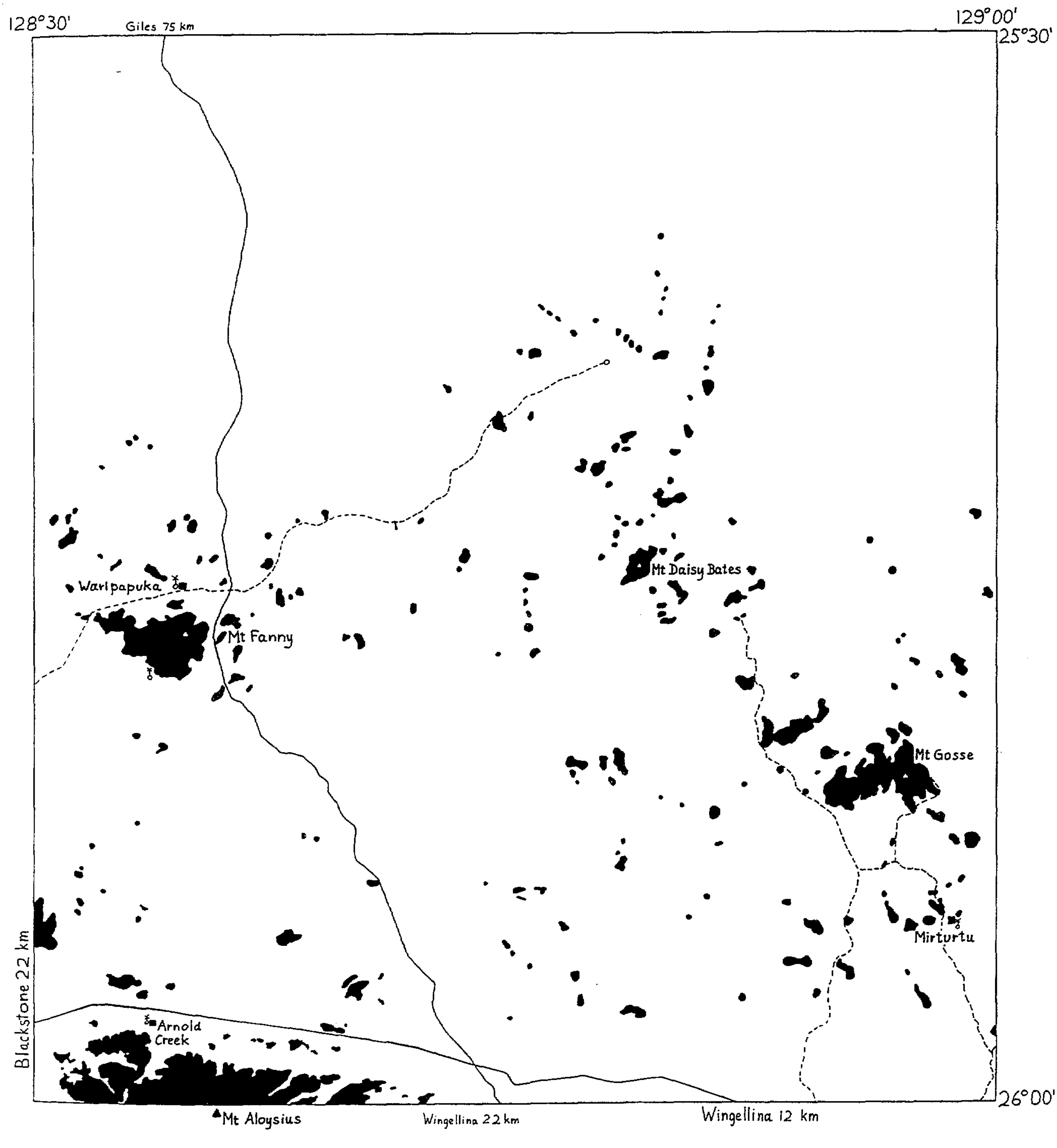

Figure 1. Locality map of BATES showing hills and outcrops in black.

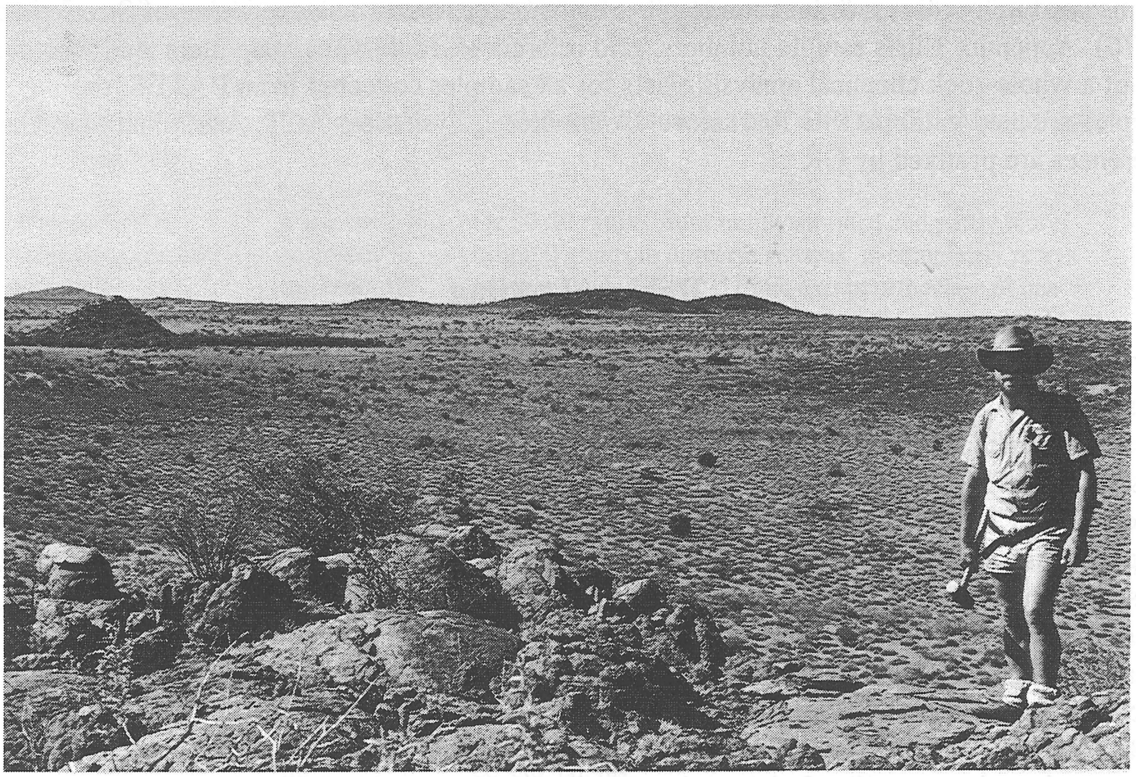

Figure 2. View of typical landscape in BATES, showing inselbergs of granite and granulite above sand plain with dunes. Jeff Windsor for scale.

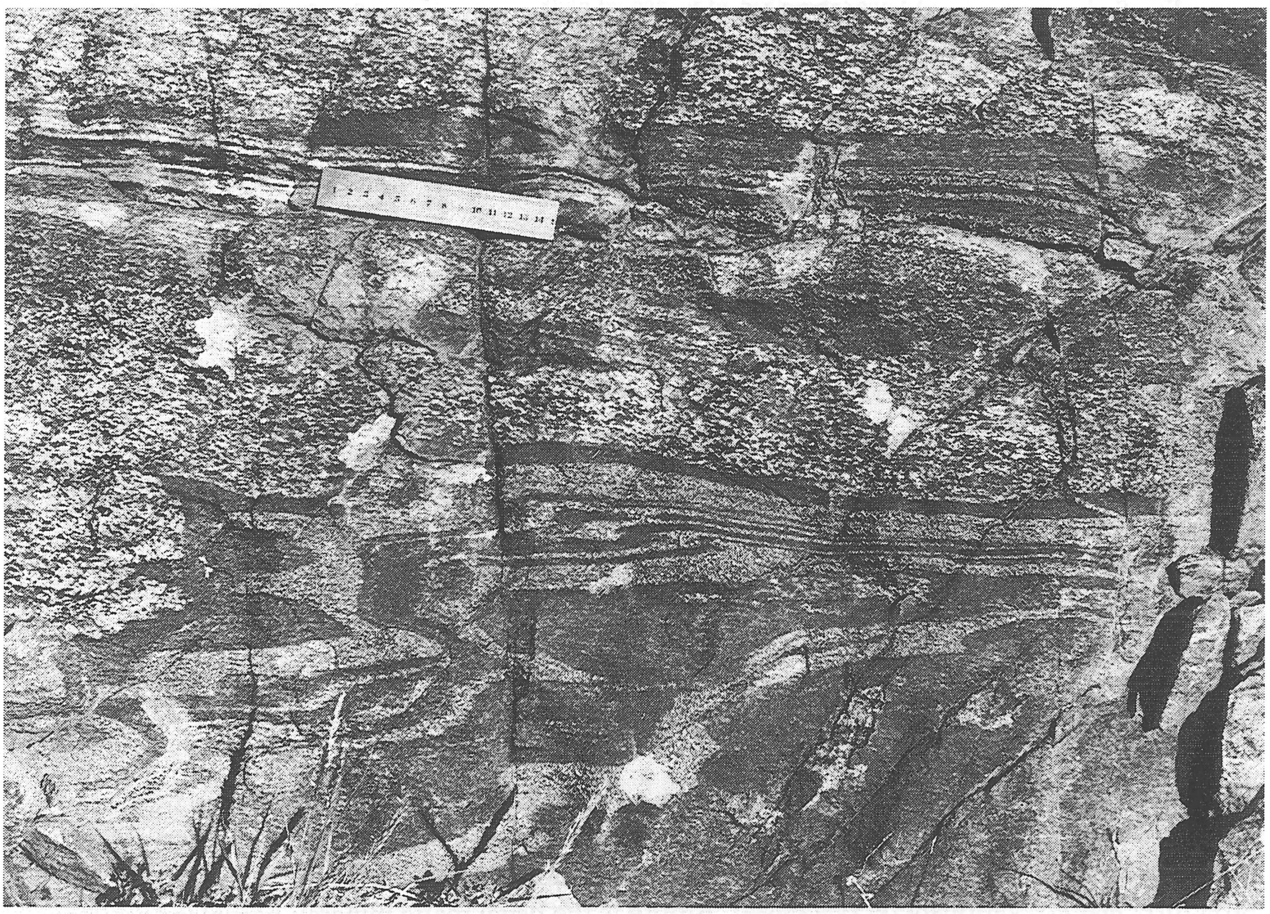

Figure 3. Interlayered felsic (coarse-grained 'clotty' appearance), intermediate (medium-grained pale grey) and mafic (fine-grained dark grey) granulites of unit fn/m. Margins of layers are S_1. Tight F_2 folds at bottom. GR 603463. Scale 15 cm long.

Terms used follow Bates & Jackson (1980). Igneous rock nomenclature is that of Streckeisen (1976). Appendix 1 lists sample numbers, grid references, rock types, map units, and whether or not a whole-rock chemical analysis exists for all samples collected from BATES; the samples are held in the AGSO Rockstore, Collie Street, Fyshwick, ACT. Australian Map Grid references are prefixed by GR.

Regional setting

BATES lies wholly within the western part of the Musgrave Block of central Australia. The Musgrave Block consists chiefly of metaigneous rocks and subordinate metasediments intruded by layered mafic intrusions (Giles Complex; Nesbitt et al. 1970), granites, and mafic dykes; all these crop out in BATES. Metamorphic facies in the block ranges from greenschist to subeclogite (Clarke et al. 1995a). The block is cut by several major fractures (see 'Geological Map of Musgrave Block' in map legend), the most northerly of which, the Woodroffe Thrust, passes through BATES. Felsic rocks north of the Woodroffe Thrust contain amphibolite-facies mineral assemblages, and have given a zircon U-Pb metamorphic age of about 1600 Ma near Amata, 200 km east of BATES (Maboko et al. 1992). Felsic and lesser amounts of mafic volcanics and shallow-water sediments (silicic and aluminous clastics and rare carbonates) south of the Woodroffe Thrust accumulated between about 1550 and 1300 Ma, and were metamorphosed to granulite facies at about 1200 Ma (Gray 1978; Sun & Sheraton 1992; Glikson et al. 1996, p. 135). This time of metamorphism is also found in the western Albany-Fraser Orogen of Western Australia, and in the Bunger Hills of Antarctica (Clarke et al. 1995b). All these areas are characterised by extensive mantle-derived and low to mid-pressure granulite-facies metamorphism (1200 Ma), suggesting the existence of a Gondwana-wide 'Grenvillian' orogen at that time (Clarke et al. 1995b).

An account of the structural evolution of the Mount Aloysius massif in the southwest of BATES appears in Stewart (1995a), and a description of the Woodroffe Thrust in the north in Stewart (1995b).

Proterozoic geology

Descriptions of rock types

Proterozoic rocks underlie the whole of BATES, but because of extensive Cainozoic cover and the scattered distribution of exposures, no stratigraphic sequence is apparent except in the well exposed Mount Aloysius massif in the southwest. The units are described below in the same order as shown in the map legend, which is arranged as far as possible in chronological order. Petrographic descriptions are set out in Table 1.

Schistose granite, granodiorite, tonalite, and leucotonalite (gs)

Schistose (deformed) granitoids crop out north of the Woodroffe Thrust, and range from tonalite through granodiorite and monzogranite to syenogranite (Table 1). The rocks are fine to coarse-grained, range from foliated granitoid to orthogneiss with a strong mylonitic structure, and are variously recrystallised. Biotite is the usual mafic mineral; hornblende is rare and pyroxene absent. Textures range from cataclastic through mylonitic to granoblastic in the most recrystallised variants. There is no discernible gradation evident, in the few exposures that exist, in intensity of deformation and recrystallisation with distance from the main thrust, suggesting that subsidiary shear zones probably exist but are not exposed. Lineation in the

Table 1. Petrography and estimated modal percentages of Proterozoic igneous and metamorphic rocks in BATES

Rock type and mapcode	Texture	Mineral assemblages[2] and modal percentages
Schistose granite, granodiorite, tonalite, leucotonalite, gs	Cataclastic to mylonitic to granoblastic	Qz 20-30 ranges from mildly strained and partly recrys original grains to unrecrys ribbons, to completely recrys polygonal aggs; Kfs 0-57 mic except orthoclase in one sample, strained, broken, in one sample recrys; plag 15-64, adn (An_{36}) in tonalite, olig elsewhere, undeformed to mildly bent; bi 0-8 strongly aligned, in places recrys; hbl 15 in one sample; tit 0-3, opq 0-2, ms 0-2. Acc: zir, all, ep, rut, fluo.
Sillimanite-garnet felsic granulite, fns	Granoblastic	Qz, kfs, gar, sill, ± plag (Gray & Compston 1978)
Garnet felsic granulite, fg	Granoblastic	Qz, kfs, plag, gar ± opx (Gray & Compston 1978)
Felsic granulite, fna	Granulo- to granoblastic, rarely cataclastic	Adn-lab (An_{41-68}) 5-84, mesoperthite 0-64, qz 0-40 as largelobate amoeboid grains, opx 4-20 bright red to bright green, cpx 0-10, gar 0-2, opq 0-2, bi 0-1. Acc: ap, sp. Sec: cc, chl, ep, ms.
Felsic and mafic granulites, fn/m: Felsic component	Granuloblastic	Olig 40 recrys, mesoperthite 26, qz 20, gar 8 as small inclusions in plag and as rims around clusters of cpx 2, bi 3 as rims around opq 1; opq grains elsewhere rimmed by plag then by gar, or by bi then by gar.
Intermediate component	Granuloblastic	Byt (An_{71}) 77-83, opx 3-15, gar 5-10, bi 1-3, opq 1-2
Mafic component	Granoblastic to granuloblastic	Adn (An_{34-50}) 40-65, cpx 0-35 rimmed by plag then by gar, opx 2-14 rimmed by act then by gar, hbl 0-15 packed with opq specks, gar 4-15 as sparry coronas around mafic grains, bi 2-3 as aggs with cpx, opq 2-5 rimmed by plag then by gar, rut 0-<1.
Felsic granulite, fn	Granuloblastic	Mesoperthite 77, qz 20, opq 2, opx, gar rimming opx and opq grains
Leucogranulite, fnk	Granoblastic	Kfs (orthoclase) 84, qz, 10, opx 3, plag 1, bi 1, opq 1. Acc: zirc.
Metabasalt, mb	Granuloblastic	Byt (An_{71}) 39, cpx 30, qz 20, opq 10, tit 1 around opq and dissem. Qz + lab (An_{68}) amygdales
Quartzite, qt		Qz 99, mag 1, GR 783296. Qz 84, kfs 10, mag 5; gar 1 in some layers, GR 810290.
Quartzite, qt_1	Granuloblastic	Qz 95, ms 3, sill 1 intimately assoc w ms, opq 1.
Quartzite, qt_2	Granoblastic	Qz 82, strained frac clasts mic 10, sill 3, yellow-green stau 2 rimmed by ms 2, opq 1 assoc w gold-brown rut.

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[2] **Abbreviations:** Acc, acc–accessory; act–actinolite; agg(s)–aggregate(s); alk–alkali; all–allanite; am–amphibole; An–anorthite (optically estimated from albite twinning); adn–andesine; ap–apatite; assoc–associated; bi–biotite; byt–bytownite; cc–calcite; chl–chlorite; clz–clinozoisite; cpx–clinopyroxene; di–diopside; dissem–disseminated; ep–epidote; Ess–essential; fluo–fluorite; frac–fractured; fs–feldspar; gar–garnet; g'mass–groundmass; hbl–hornblende; kfs–K-feldspar; lab–labradorite; leuc–leucoxene; mag–magnetite; mic–microcline; ms–muscovite; ol–olivine; olig–oligoclase; opq–opaque grains; opx–orthopyroxene; phenos–phenocrysts: phl–phlogopite; plag–plagioclase; pseudom–pseudomorphed; px–pyroxene; qz–quartz; recrys–recrystallised; incl–inclusions; rut–rutile; scap–scapolite; Sec–secondary; serp–serpentine; sill–sillimanite; sp–spinel; stau–staurolite; tit–titanite; Tr–trace; w–with; zir–zircon.

Rock type and mapcode	Texture	Mineral assemblages and modal percentages
Intermediate granulite, in		Plag 80, qz 15, opx 5.
Staurolite-bearing felsic gneiss, vh	Granuloblastic	Zoned olig 35, mesoperthite 34, qz 10, poikiloblastic hbl 10, gar 5, bi 5, round grains yellow stau 0.5. Acc: tit, all, rounded zir, ap.
Charnockite, g_1	Allotriomorphic with granoblastic grain boundaries	Blue qz 25, mesoperthite 72, opx 1, myrmekitic plag 1, opq 1. Acc: ap, zir.
Garnet granite, ga_{1-10}	Allotriomorph-ic to granulo-blastic	Qz 5-25, alk fs 0-75, plag lab-olig (An_{58-25}) 0-68, bi 0-8, hbl 0-20, opx 0-7, cpx 0-5, gar 1-10 (20 in one sample), tit 0-5, ap 0-2. Acc: opq, zirc, all, ilm. Sec: leuc, ms, cc, act, rut, ep, chl.
Dolerite and metadolerite of the Giles Complex; dlg	W exposure: subophitic E exposure: granoblastic	Sodic lab (An_{54}) 70, cpx 12, opx 5, opq 5, interstitial qz 5, bi 3. Cpx 51 recrys, cloudy lab (An_{60}) 40, opq 7, bi 2.
Dolerite, metadolerite dykes; Type A	Blastophitic to granuloblastic to cataclastic	Lab (An_{64}) 70, opx 5, opq 5, bi 3; recrys cpx 0-17 in some samples, ol in one sample. Acc: sp
Mafic dyke, gbc; GR 502343, Type C	Hypidiomorph-ic	Cloudy lab (An_{66}) 40, poikilitic cpx 25, opx 25 as phenocrysts to 1.2 cm around ol 5, bi 2, opq 2, sp acc.
Dolerite, metadolerite dykes; Type B	Blastophitic to granuloblastic to cataclastic	Lab (An_{52-62}) 25-40, cpx 13-33, hbl 4, opq 2-7; opx 0-40 in some samples, bi and ol in one sample each.
Metadolerite, dl; subeclogite facies	Blastophitic or blasto-hypidio-morphic to granuloblastic	Cloudy brown lab-adn ($An_{57-33;}$ 9 samples average An_{45}) 10-50 recrys to polygonal mosaics in some samples, cpx 0-34 commonly recrys at margins to aggs small grains, brown-green hbl 0-70 mantling cpx, brown opx 0-40, gar 1-33, opq 0-12, bi 0-7, dissem rut 0-2. Acc: scap, ap, sp; ol 2-5 in two samples pseudom by px or opq or serp. Sec (retrogressive): cc, chl, ms, clz/ep. Qz 24, 30, occurs in two leucocratic variants.
Metagabbro, gb: lens 16 km W of Mt Gosse (subeclogite facies)	Granoblastic with relict hypidiomorph-ic characterist-ics	Cloudy brown byt (An_{71}) 34, ol 20 pseudo by opq + px, opx 10, cpx 10 packed with inclusions, opq 3 rimmed with bi 1, green hbl 2 as fine aggs; gar 20 rims opq + px aggs, rims opx and cpx, and sits between byt and mafic grains.
Dyke gb 3.5 km N of Mt Fanny (subeclogitic)	Granoblastic	Green hbl 70 as recrys mosaic aggs around coarse relict cpx 14, recrys mosaic adn (An_{49}) 10, gar aggs 5, orange idioblastic rut 1, scap 1.
Porphyritic microgranite, gm	Granuloblastic	Phenos: lab (An_{62}) 40, qz 20. G'mass: plag, qz, alk fs 26, hbl 3, opx 2, cpx 2 with partial rims gar, opq 2 rimmed by gar, bi 2, ap 1.

deformed granitoids is gently plunging and parallels that in the Woodroffe Thrust, indicating that the deformation accompanied the thrusting at about 530 Ma. The absence of pyroxene militates against these granitoids being the deformed equivalents of younger granites (e.g., units gr, g, gh, or ga).

Sillimanite-garnet felsic granulite (fns) crops out only in the Mount Aloysius massif (Table 1). It is fine to medium-grained, and discontinuously thinly layered. Cordierite is absent.

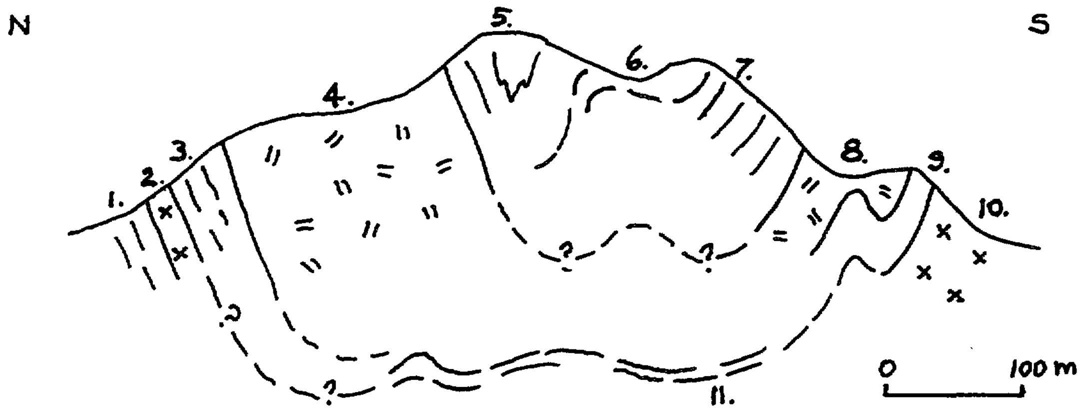
Garnet felsic granulite (fg) forms small well defined bands outlining a tight steeply plunging near-reclined synform in the Mount Aloysius massif (Table 1). It is massive to weakly layered and coarse to very coarse-grained.

Massive to weakly layered felsic granulite (fna) forms four separate outcrops in the Mount Aloysius massif (Table 1). It is coarse to very coarse-grained, and layering is inconspicuous, poorly defined, and commonly interrupted; lithological differences between layers are slight. Composition ranges from felsic to intermediate, and rarely, mafic. South of BATES, in the east of the Mount Aloysius massif, the outcrops widen to form a mass 6 km across, whose boundaries cross-cut layering in the adjoining granulites. The mass ranges in composition from alkali-feldspar granite through leucotonalite and quartz leucomonzogabbro to leuconorite, and is interpreted as a mobilised parautochthonous partly intrusive body (Glikson et al. 1996, p. 27).

Interlayered felsic and mafic granulites (fn/m) are the most abundant rocks in BATES after the granitoids. The unit makes up the major part of the Mount Aloysius massif, the northern and eastern flanks of Mount Fanny, and forms inselbergs at many other places in the area. The unit comprises thin (centimetre-scale) to thick (metre to decametre-scale) layers of alternating felsic and mafic granulite (Table 1); mafic granulite commonly forms metre-scale boudins and lenses also. Intermediate granulite interlayers (Table 1) are present at many localities (Fig. 3). Layering is commonly nebulitic. Contacts between layers range from sharp to gradational. Coarse-grained felsic sweatouts in mafic layers, and 1-2 m layers and patches of coarse-grained granite or pegmatite occur at some localities; where these connect, agmatite results. Garnet rims ortho- and clinopyroxene and opaque grains in both the mafic and felsic layers. Foliation, principally by flattening of quartz grains, is strong, and is axial-plane to steeply plunging intrafolial folds ranging from open to isoclinal.

The hill at GR 910420 shows a typical sequence in the unit; the inward dips suggest a synformal klippe lying on a folded subhorizontal fault (Fig. 4), but exposure to the north and east is lacking.

At GR 905333, interlayered felsic and mafic granulites pass through a transition over some 50 m into garnet granite, massive for some metres near the granulites, but with vague diffuse nebulitic layers farther away. On the eastern side of the hill, a mass of mafic granulite tens of metres across has an irregular contact with the granitoid, which contains a train of angular mafic granulite fragments (Fig. 5). These observations suggest the granitoid formed by melting of the felsic granulite, and contains fragments of originally interlayered mafic granulite. A similar transition into coarse-grained felsic partial melt is exposed at GR 744324.



1. Felsic granulite, m-f.gr, lam, swirly, agmatitic, dark and light layers
2. Metagranite or metapegmatite, m.gr, very flattened, sharp contacts
3. Felsic granulite with abundant garnet and mafic grains (?biotite)
4. Mafic granulite, c.gr, cpx rimmed with garnet, feld. recryst; metagab.
5. Felsic granulite, f.gr, as for 1., gar + pyrox, numerous small tight folds
6. Felsic granulite, lam, c̄ thin pegmatite lenses
7. Felsic granulite, leucocratic, 2% pyrox c̄ gar rims, lam cut by foliation
8. Mafic granulite, m.gr, diss. gar, pyrox, plag (no gar rims); drag-folded contact with 9. below, upright axial plane; may connect with 4. above
9. Felsic granulite, leucocratic, mylonitic, c̄ gar; passes transitionally over few m into 10. below
10. Granite, c.gr, gar, massive with mylonite zones
11. Mylonite at W end of hill, approx. horizontal, c̄ broad open folds and warps; may connect with 2. above

Figure 4. Typical sequence in interlayered felsic and mafic granulites of unit fn/m. Sequence underlain by subhorizontal mylonite and may be a synformal klippe. GR 910420.

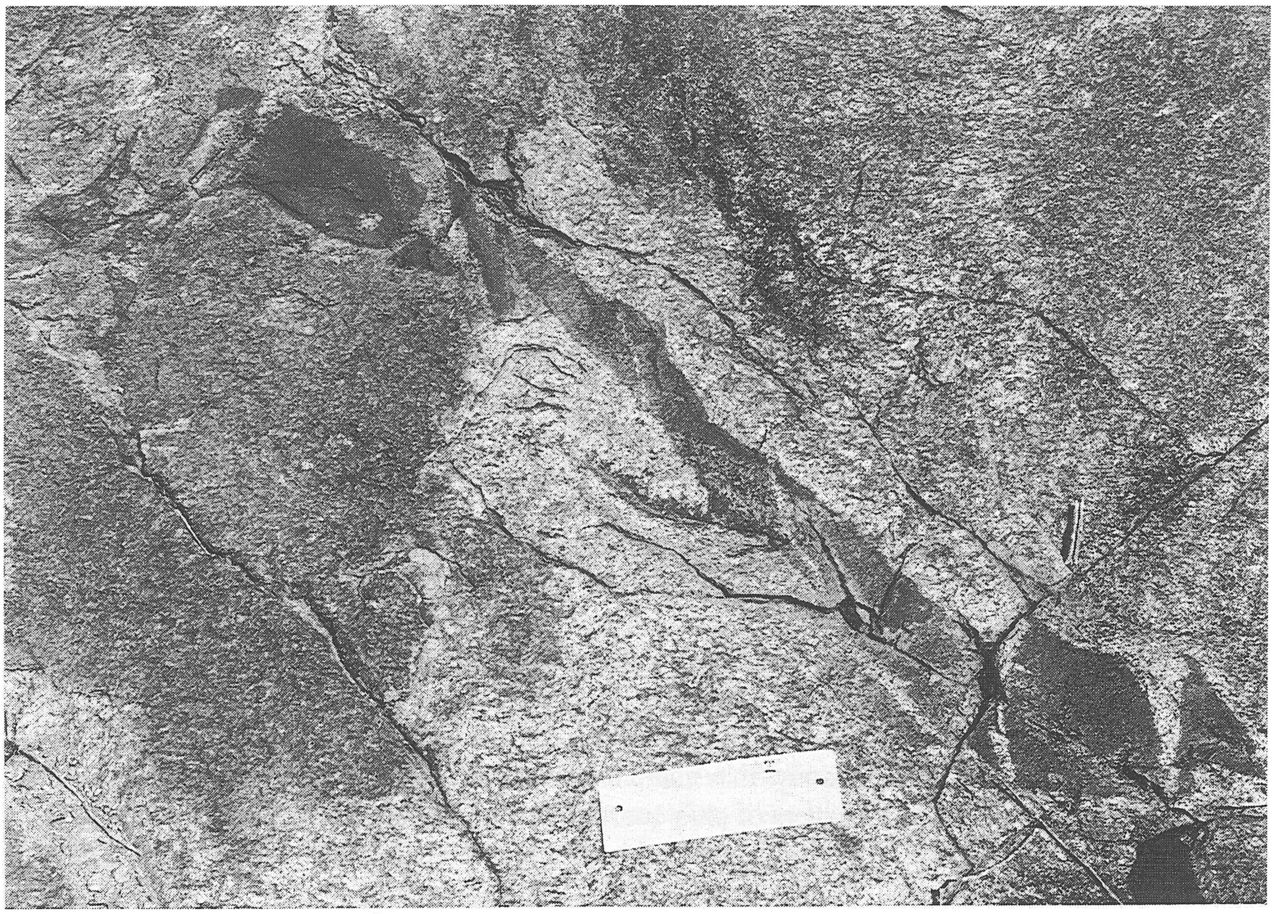


Figure 5. Fragmented mafic dyke or layer, now granulite, in garnet granite (ga type). GR 905333. Protractor 15 cm long.

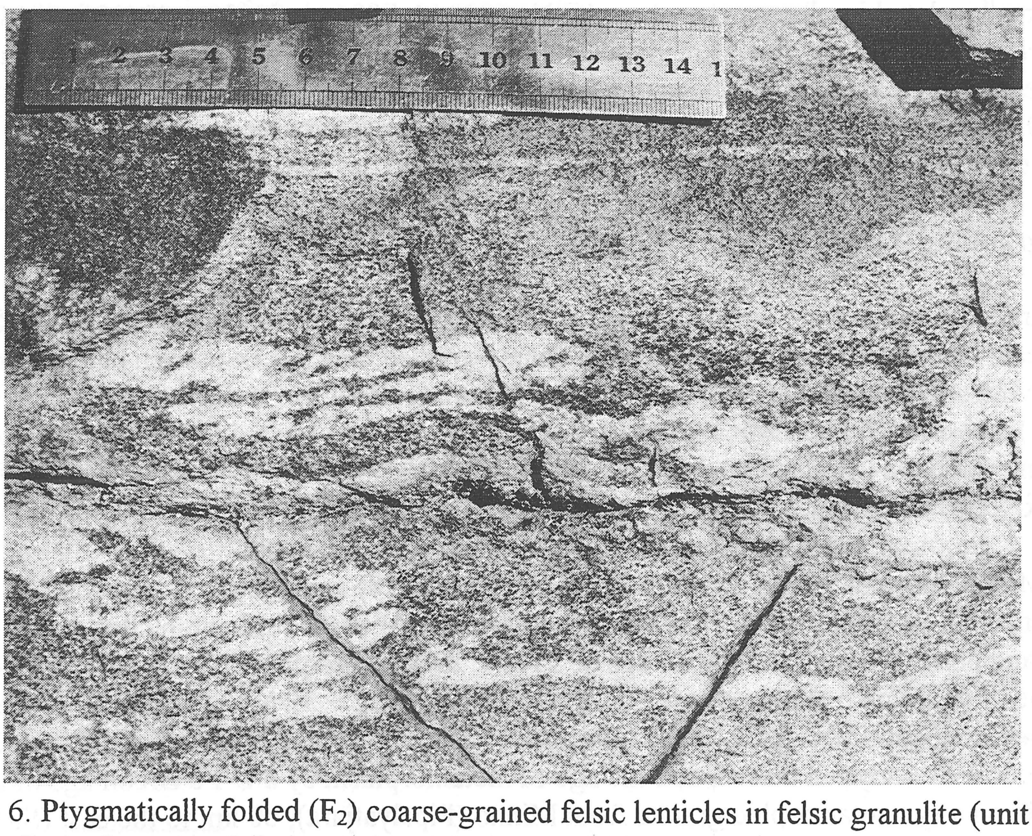


Figure 6. Ptygmatically folded (F_2) coarse-grained felsic lenticles in felsic granulite (unit fn). Grain-flattening foliation S_2 is axial-plane to folds. Lenticle margins are slightly more mafic than lenticle or host rock. GR 754503. Scale 15 cm long.

Felsic granulite (fn)

Felsic granulite (Table 1) forms inselbergs about 5 km west of Mount Gosse, 6 km west of Mount Daisy Bates, 3-6 km east, northeast and north of Mount Fanny, and near Mirturtu in the southeast; it also forms a layer in the Mount Aloysius massif in the south. The rock is generally grey-brown with blue quartz, equigranular to rarely feldspar-phyric, medium to coarse-grained, and thinly and discontinuously layered due to variations in felsic mineral proportions and grainsize. Coarse to very coarse-grained felsic pegmatitic metre-scale lenticles and masses (partial melt? Fig. 6) are common, and the rock grades into migmatite as these become more abundant. Mafic minerals make up about 3 percent of the rock, and garnet rims around the mafic grains are characteristic. The rock is massive to strongly foliated, the foliation arising principally from flattening of quartz. Tight to isoclinal folds are present in places, with the grain-flattening foliation defining the axial plane (Fig. 7a, b).

Southwest of Mount Daisy Bates, the granulite is fine-grained, and felsic lenticles have thin mafic selvedges. Migmatitic layers are ptygmatically folded.

West of Mount Gosse, the granulite is medium to fine-grained, and rare mafic boudins are present.

North and northeast of Mount Fanny, thin mafic layers and boudins make up about 10 percent of the rock, and rare 2 m-thick layers of blue quartz (metamorphosed siliceous sediments or quartz veins) are present. Migmatitic layers in this area are tightly folded.

Mafic granulite (mn)

Mafic granulite crops out extensively at the western end of the Mount Aloysius massif, and forms small isolated inselbergs elsewhere (GR's 522340, 700544, 780308, 836395, 941349). The rock is grey to black, fine to medium-grained, and massive to weakly foliated. It is usually homogeneous, but in places includes thin lenses of felsic and/or intermediate granulite, and at GR 780307 it contains coarse-grained centimetre-scale felsic lenticles (sweat-outs?).

Leucogranulite (fnk)

Leucogranulite forms three large bodies at the western end of the Mount Aloysius massif. It is very weakly layered to massive, medium to coarse-grained, and has an uneven blue-green colour. The only thin-sectioned sample is quartz alkali-feldspar syenite in composition (Table1). Layering in the adjoining fn/m granulite unit diverges around the easternmost body, which may be a pre- or syntectonic intrusion; its intrusive origin is supported by an occurrence of a dyke of similar syenite 500 m to the south of BATES, at GR 578249.

In the Mount Aloysius massif south of BATES, Gray (1978) and Gray & Compston (1978) determined Rb-Sr whole-rock isochron ages on samples from the felsic granulites described above, and pooled these to obtain an age of 1578 ± 20 Ma, interpreted as the protolith age. The time of granulite metamorphism was determined at 1222 ± 39 Ma. The protolith age was confirmed by slightly younger U-Pb zircon ages of about 1530 Ma on a banded felsic granulite from the Mount Aloysius massif, and the age of metamorphism by a U-Pb zircon age of about 1200 Ma on a synmetamorphic granite from Minno (Pipalyatjara), 60 km to the east (Sun & Sheraton 1992; Glikson et al.1996).

Metabasalt (mb)

Metabasalt forms several low hills in the southwest. It is undeformed, contains quartz + plagioclase amygdales, and is completely recrystallised to granulite facies (Table 1). The metabasalt adjoins strongly deformed quartzite. The lack of deformation of the basalt is relatively unusual for this region[3] ; the body may be a large competent boudin surrounded by ductile metasediments, which took all the strain.

Quartzite and metasandstone (qt)

Quartzite and metasandstone form isolated outcrops in the south and southwest. The rocks are fine to medium-grained, and preserve relict bedding. Mineral assemblages are set out in Table 1.

Quartzite (qt_1) at GR 675355 on the Giles – Mulga Park Road is fine-grained, sillimanite-bearing (Table 1), strongly foliated and lineated, and shows two generations of folds. The earlier are tight reclined F_1 folds with axial planes parallel to the prevailing foliation and axes parallel to the lineation, and the later (F_{1b}? F_2?) are gently south-plunging upright folds which fold the foliation but plunge parallel to the prevailing lineation. On the northern side of the outcrop, fine to medium-grained metasandstone or meta-arkose is exposed, and carries ovoid megacrysts of K-feldspar concentrated in thin conglomerate-like layers (Fig. 8); relict cross-bedding is visible in places.

In the southwest (qt_2), the quartzite contains sillimanite and staurolite (Table 1), and is separated from metabasalt to the south by an antiformal mylonite zone.

Intermediate granulite (in)

Intermediate granulite (Table 1) forms a small hill at only one locality, GR 523346. At the southern end of the hill, very coarse-grained rapakivi granite intrudes the intermediate granulite, and strewed granulite fragments in granite form a 1 m-wide zone between the two rock types.

Staurolite-bearing felsic gneiss (vh)

Staurolite-bearing felsic gneiss (Table 1) interlayered with leucocratic garnet-pyroxene-bearing gneiss form a single exposure at GR 933535 in the east. The staurolitic rock is medium-grained, thinly layered from intermediate to melanocratic compositions, and contains round feldspars and mafic boudins and lenses. Small upright intrafolial early folds have subhorizontal axes, and late southeast-plunging open folds deform layering, foliation and lineation.

Rapakivi granite (gr)

Rapakivi granite forms a large poorly exposed mass in the southwest, and smaller masses 4 km north of Mount Fanny, 1 km south of the Woodroffe Thrust, and 500 m west of the north-

[3] One could speculate that the metabasalt is a correlative of either the Mummawarrawarra Basalt 40 km to the south-southwest, or possibly the Bloods Range beds, which crop out underneath the Dean Quartzite of the Amadeus Basin, 93 km to the north. That this is not so is shown by the schematic cross-sections in Figure 17, where the rocks in the south of BATES are located in a thrust block from deep in the crust.

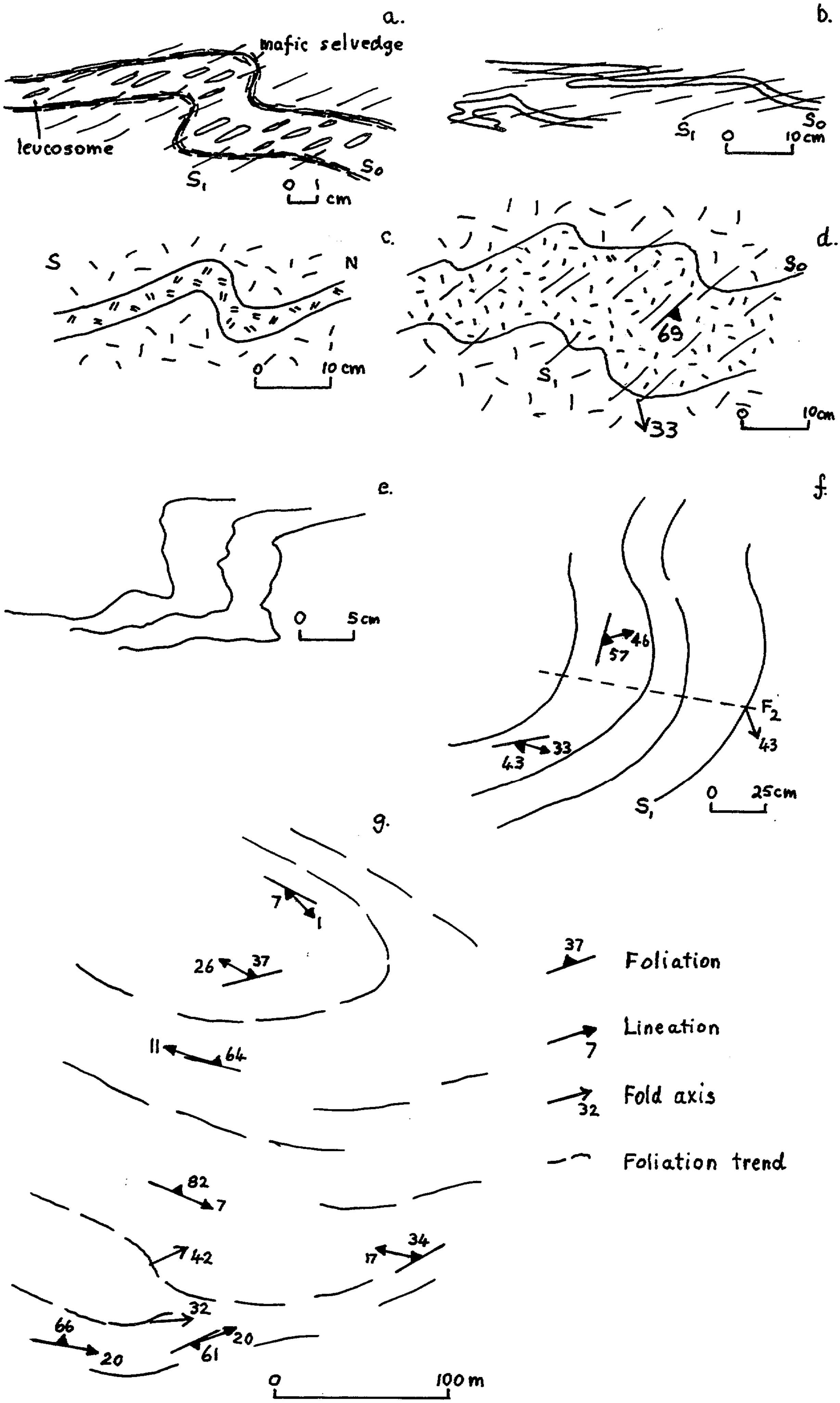

a.
mafic selvedge
leucosome
S_1
S_0
0 1 cm
b.
S_1
S_0
0 10 cm
c.
S
N
0 10 cm
d.
S_0
69
S_1
33
0 10cm
e.
0 5cm
f.
46
57
F_2
43
33
43
S_1
0 25cm
g.
7
1
26
37
11
64
82
7
42
17
34
32
66
20
61
20
0 100 m
37
Foliation
Lineation
7
Fold axis
32
Foliation trend

Figure 7. Sketches of mesoscopic folds, BATES. (a) F_2 fold in coarse-grained leucosome layer with mafic selvedges in fine-grained felsic granulite (fn); foliation S_2 is axial-plane to fold and parallel to long axes of coarse flattened quartz grains (ellipses); GR 636508. (b) F_2 folds in thin mafic layers S_1 in felsic granulite (fn); axial-plane foliation S_2 cuts S_1; same locality as (a). (c) Vertical profile of tight F_2 fold in interlayered felsic and mafic granulites (fn/m), GR 522340. (d) Open F_2 fold with axial-plane foliation in felsic granulite (fn/m) with weak S_1 layers of more and less felsic compositions, GR 590550. (e) Plan view of vertically plunging F_2 folds in thinly interlayered felsic and mafic granulites (fn/m), GR 943340. (f) Open F_3 fold plunging south-southeast in staurolite gneiss (unit vh), GR 933535; S_1 layering and L_2 lineation both folded; limbs of fold display small intrafolial F_2 folds (not shown). (g) Folds in tonalitic mylonite (D_6) with subhorizontal lineation, GR 946520; probable subsidiary fault or splay of Woodroffe Thrust.

Figure 8. Metasandstone with K-feldspar porphyroblasts (metamorphosed clay lumps?) adjoining quartzite, GR 675355. Scale 15 cm long.

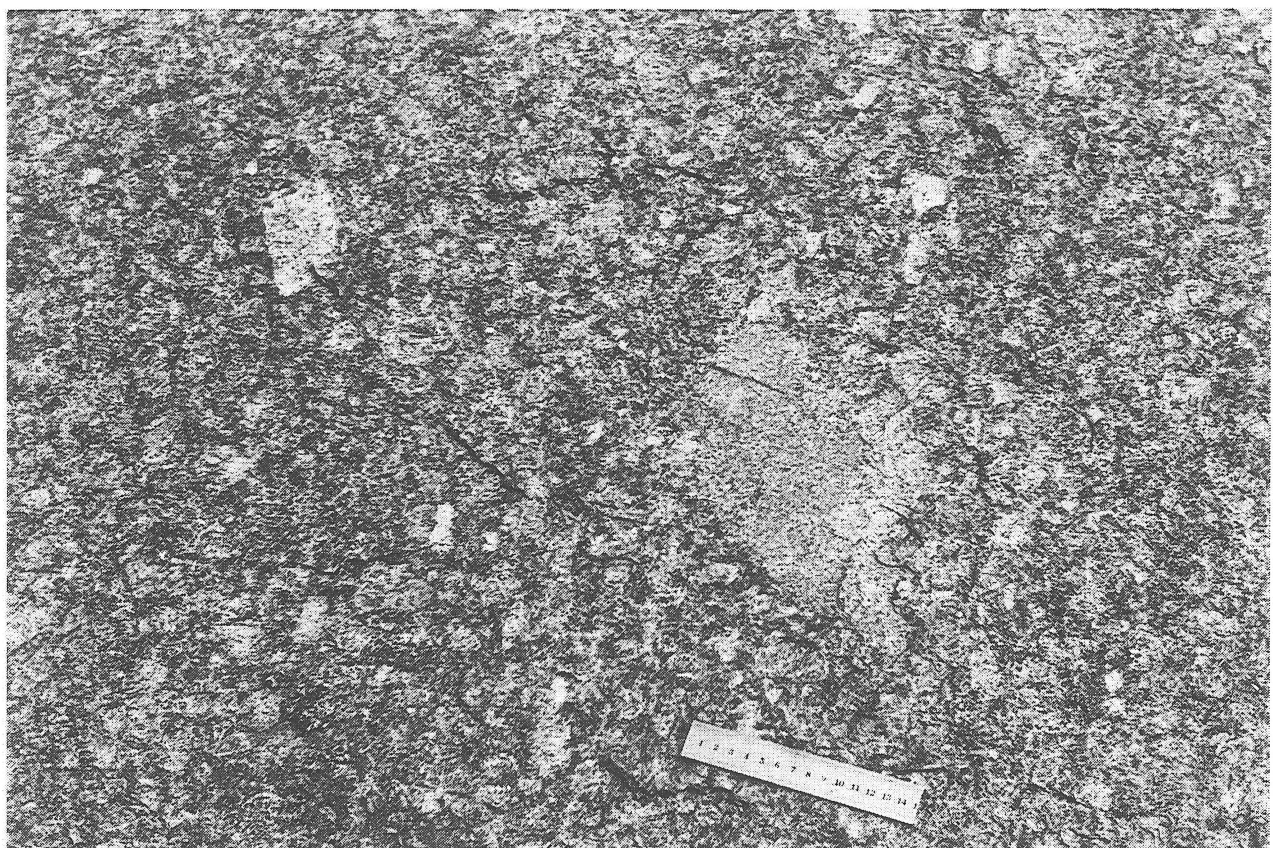


Figure 9. Rapakivi granite with sparse mantled feldspars and xenolith of felsic granulite, GR 524363. Scale 15 cm long.

south tear fault cutting the thrust. The rock is coarse to very coarse-grained, massive to strongly foliated, weathered and friable (which discouraged sampling). Euhedral or round K-feldspars mantled by plagioclase are common. The large southwestern mass includes xenoliths of felsic (Fig. 9) and mafic granulites, quartzite, and coarse-grained granite. At GR 565428 in the north of the mass, a lit-par-lit contact zone of rapakivi granite intruding felsic and mafic granulites is exposed. At GR 553433 in the same area, a dyke of porphyritic granite of the type forming Mount Fanny intrudes the rapakivi granite. At GR 522360, a dyke of quartz alkali-feldspar syenite (ga_{10}) intrudes, and contains mantled K-feldspar xenocrysts from, the rapakivi granite.In contrast, the small body of rapakivi granite 1 km south of the Woodroffe Thrust (at GR 757632) encloses xenoliths of quartz monzonite (ga_1). Hence, it seems that the rapakivi granite is coeval with the garnet granite complex.

The small body of rapakivi granite 3.5 km north of Mount Fanny is intruded by a prominent metagabbro dyke with spectacular garnet coronas around mafic grains.

Granite (g) and charnockite (g_1)

Granite crops out at and near Mount Fanny in the west, in the southwest, and at GR's 640380, 646378, 715611, 748319, and 785575. At Mount Fanny[4], the granite is deformed to strongly foliated medium to coarse-grained leucocratic augen gneiss. Most of it is homogeneous, but in the west of the massif it includes a few thin dark lenticular layers and undulatory schlieren. The foliated granite includes regions of, and appears to be the deformed equivalent of, coarse-grained rapakivi granite (unit gr), which forms a large body to the south. South of the summit of Mount Fanny, xenoliths of felsic and mafic granulites from unit fn/m are common; north of the summit, dykes of porphyritic granite intrude the fn/m unit. At the summit[5], felsic granulite bordering the granite is lineated only, and east-plunging mullions or rods are well developed. The granite contains fine garnet, and is K-feldspar-phyric in places. It is intruded by numerous metadolerite dykes.

The granite at Mount Fanny is mantled to the north and east by interlayered felsic and mafic granulites (unit fn/m). As the granite is approached from the northeast, the felsic component of the granulites becomes more and more granitic in appearance over some 300 m. This suggests that the granite may have formed by melting and separation from the felsic granulite. This notion is supported by the presence of dark layers and schlieren in the west of the massif (described above) that could be the mafic residue from melting, but needs testing by petrological and isotopic studies, as does the relationship of the granite at Mount Fanny to the rapakivi granite to the south.

Charnockite (Table 1) forms an inselberg 2 km east of Mount Fanny, and is a coarse-grained leucocratic foliated orthopyroxene alkali-feldspar granite. Numerous metadolerite dykes with subeclogite facies assemblages cut the charnockite. There are no subeclogite facies minerals or textures in the charnockite, but its leucocratic composition (98% felsic minerals) may have precluded their formation.

[4] Aboriginal law prohibited sampling of the Mount Fanny massif.
[5] The Mount Fanny trig point shown on the map at GR 572479 is not the highest point. The highest point is at GR 578485, marked by a cairn and trig beacon.

Hornblende granite (gh)

Coarse-grained foliated granite containing prominent clots of hornblende forms widely scattered inselbergs at GR 553387 and 835505; the latter is a local garnet-free variant of the garnet granite (ga) described below.

Garnet granite ± biotite ± hornblende ± clinopyroxene ± orthopyroxene (ga, ga_{1-10})

Garnet granite[6] ± various mafic minerals (Table 1) is the most abundant unit in BATES, where it makes up the major part of the hanging wall block above (south of) the Woodroffe Thrust. It forms prominent hills at Mount Gosse, Mount Daisy Bates, another massif 6 km northwest of Mount Gosse, and numerous inselbergs elsewhere. The rock is medium to coarse-grained (fine-grained where recrystallised), equigranular to K-feldspar-phyric, and massive to foliated. Quartz is commonly blue. Orthopyroxene is igneous. Garnet forms conspicuous rims around mafic minerals, and, together with biotite, hornblende and rutile, formed during metamorphism of the granite. Small mafic xenoliths are common, felsic granulite xenoliths less so. Metadolerite dykes with garnet rimming mafic grains are numerous; microgranite dykes with garnet and mafic grains are rarer. Mylonite zones a few metres thick are common. The rock ranges in composition through ten subtypes from quartz gabbro to alkali-feldspar granite, as the proportion of felsic minerals changes (Fig. 10). The boundaries of the ten subtypes shown on the map are notional only, and simply show that the subtype indicated crops out inside that area. Petrographic details of the garnet granite are set out in Table 2.

Table 2: Petrographic details of garnet granite (ga, ga_{1-10})

Quartz 5-25%: flattened recrystallised lenticular aggregates of fine-grained substantially strain-free polygonal grains; relict original grains rare, have serrate margins and strained and/or polygonised interiors.

Alkali feldspar 0-75%: ranges from plagioclase-free orthoclase to plagioclase-rich mesoperthite; in some samples is strained, bent, fractured and/or polygonised microperthite augen with cross-hatched twinning; in other samples recrystallised to fine polygonal aggregates orthoclase; quartz inclusions common.

Plagioclase 0-68%: ranges from labradorite (An_{58}) in quartz monzogabbro, through andesine in quartz leucodiorite, quartz monzonite and granite, to oligoclase (An_{25}) in quartz monzodiorite, granite, melagranite, quartz monzonite and quartz syenite; forms large zoned grains commonly strained, fractured and bent with serrate margins, and as small recrystallised grains forming polygonal mosaic; blade-like garnet forms inclusions parallel to twin lamellae in one sample; calcite forms a fine dust in some large grains; myrmekite rare.

Hornblende 0-20%: forms large dark green – yellow green – pale green grains or small grains in equant to lenticular symplectites associated with garnet, quartz, plagioclase and biotite; also occurs as amoeboid lobate or sieve-like grains with quartz inclusions; has formed between feldspar and orthopyroxene; rimmed by garnet in some samples, by garnet + biotite in one.

Biotite 0-8%: red brown to pale yellow brown randomly oriented to aligned flakes or aggregates in following forms: inclusions in plagioclase parallel to twin lamellae; coronas with garnet around hornblende and opaque grains; as symplectites with quartz inside garnet; replacing orthopyroxene; as aggregates mixed with hornblende and opaque grains; as symplectites with hornblende and opaques rimmed by garnet; mantled by garnet against feldspar; mantling opaque grains.

Clinopyroxene 0-5%: occurs only in quartz monzonite, melagranite, granite, quartz syenite, quartz leucodiorite, quartz leucomonzogabbro and tonalite; large bright pale green grains (jadeitic?) or aggregates of

[6] It is unusual to qualify a granite with a metamorphic mineral that formed long after crystallisation of the original magma, but garnet is the only mafic mineral common to all the rock types included in this map unit.

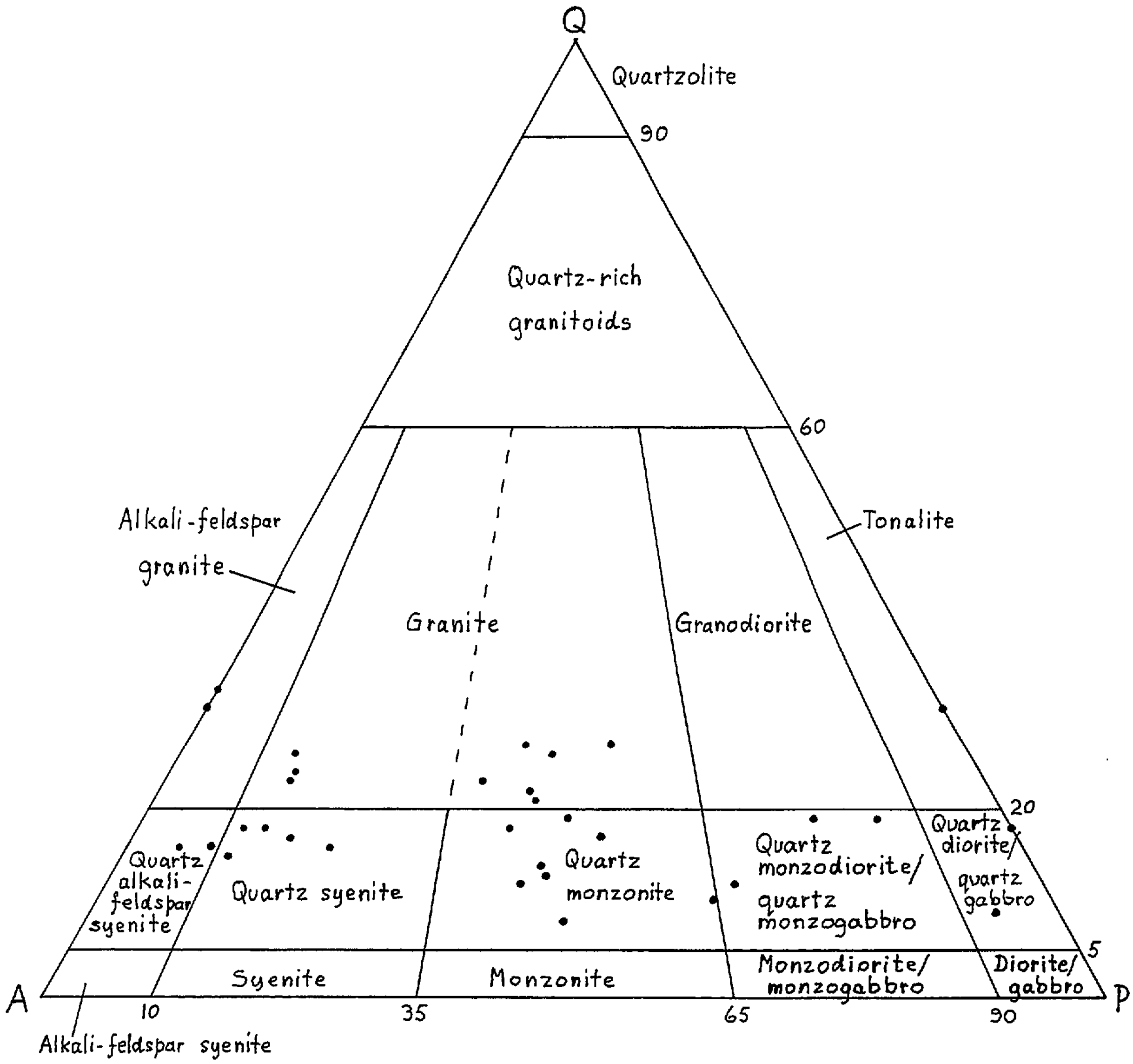


Figure 10. Triangular diagram of modal percentages of quartz (Q), alkali-feldspar (A) and plagioclase (P) recalculated to 100 percent for 31 thin-sectioned samples of garnet granite variants ga_{1-10}. Rock classification boundaries and names from Streckeisen (1976).

small grains generally mixed with biotite, quartz and garnet; large grains rimmed by plagioclase (inner) then by garnet (outer), or by opaque grains; garnet has formed between clinopyroxene and feldspar.

Orthopyroxene 0-7%: in quartz monzonite (some but not all samples), charnockite, quartz leucodiorite, quartz leucomonzogabbro, quartz leucosyenite, and quartz alkali-feldspar syenite; large grains, pleochroic red to green, generally rimmed by: plagioclase (inner) then by garnet (outer) with or without biotite; clinopyroxene (inner) and garnet (outer); blue-green hornblende (one sample); garnet where orthopyroxene formerly touched feldspar.

Garnet 1-10% except 20% in one sample: in all variants except quartz alkali-feldspar syenite; pink to pale orange; in undeformed samples forms small grains as coronas around mafic minerals as detailed above; in a few samples deformation has re-arranged the coronas into small lenticular aggregates spread through the rock or disseminated in recrystallised feldspathic groundmass; rare unstrained amoeboid grains.

Minor minerals: titanite up to 5% with opaque and leucoxene inclusions; apatite up to 2% recrystallized to polygonal mosaics in places and occasionally rimmed by garnet; opaque grains; zircon; orange rutile; orange metamict allanite; muscovite associated with biotite; calcite as xenoblastic aggregates; blue-green amphibole rimming orthopyroxene; epidote in cracks in plagioclase; chlorite in cracks in hornblende.

Dolerite, metadolerite, gabbro and metagabbro

Mafic magma intruded the BATES region at least three times during the Proterozoic, and much of it was subsequently metamorphosed. The intrusions are divided into five groups based on age[7], distribution and metamorphism. Petrographic details are set out in Table 2.

Dolerite and metadolerite of the Giles Complex (dlg) crop out in the southwest, and are intruded by plugs and sheets of microgranite. The western exposure (GR 502323) is unmetamorphosed and subophitic (Table 1). The eastern exposure (GR 652281) is more mafic and recrystallised to a granoblastic texture (Table 1). Sun et al. (1996a, b) have dated the Giles Complex at 1078 ± 3 Ma.

Type A metadolerite dykes (Clarke et al. 1995a) are numerous in the Mount Aloysius massif in the southwest. The dykes strike east-northeast to east, are characterised by original orthopyroxene ± clinopyroxene, are strongly metamorphosed, and are about 1073 Ma old (Sun et al. 1996a, b).

Dolerite (dlc), gabbro (gbc) and Type C mafic dykes (Clarke et al. 1995a) are unmetamorphosed, and form prominent hills at GR's 630325, 665300, 680295 and 747287. A mafic dyke at the northern end (GR 502343) of the western exposure of dolerite of the Giles Complex is an unmetamorphosed porphyritic olivine gabbro. The dykes are characterised by original olivine, and are about 1000 Ma old (Glikson et al. 1996).

Type B mafic dykes strike west-northwest at the western end of the Mount Aloysius massif, are characterised by original clinopyroxene ± orthopyroxene and little or no olivine, are weakly metamorphosed, and are about 800 Ma old (Glikson et al. 1996, p. 135).

Metadolerite (dl) and metagabbro (gb) dykes and plugs crop out at many places south of the Woodroffe Thrust; particularly prominent ones are situated at GR's 559582, 630325, 665300, 760352, and 824560. Virtually all the dolerites have been metamorphosed to subeclogite facies assemblages (Table 1; Clarke et al. 1995a). The rocks are characterised by symplectitic coronas, commonly garnet-bearing, which surround mafic mineral grains in nearly every sample. The most common assemblages are set out in Table 3. Clarke et al. (1995a)

[7] Mafic dykes in the Bell Rock 1:100 000 sheet area were divided by Clarke et al. (1992-3) into petrographic Types A, B, and C before being dated, and when this was done Type C proved to be older than Type B. As the A, B and C terminology is already entrenched in the literature, it has been retained here.

determined pressures of 1000 Mpa and temperatures of 720-750°C on these rocks. Sm/Nd isotopic analyses of mineral pairs (garnet-plagioclase and clinopyroxene-hornblende) indicate the subeclogite facies metamorphism occurred about 535 Ma ago (Clarke et al. 1995b). The emplacement age of the dykes is bracketed between about 1190 Ma and 800 Ma. The older limit assumes that the garnet granite and rapakivi granite which host the dykes in BATES are coeval with porphyritic and rapakivi granites of that age in the Champ de Mars area south of the Hinckley intrusion (Sun et al. 1996a, b). The younger limit assumes that Type B mafic dykes of this age in the Mount Aloysius massif represent the latest episode of mafic intrusion in BATES.

Metagabbro with subeclogite facies assemblages forms a lenticular body 4 km long at GR 785415, a small plug at GR 840337, and a dyke at GR 565515. The rocks are coarse-grained, massive to foliated, and range in texture from granoblastic with relict hypidiomorphic features in massive rocks to completely granoblastic in foliated rocks.

Table 3: Corona assemblages in metadolerite dykes, BATES.
Abbreviations as in Table 1

Core mineral	Corona assemblage (inner to outer)
Cpx	Plag, gar
Cpx	Plag, bt, gar
Cpx	Hbl ± gar
Cpx	Gar where cpx touches plag
Opx	Cpx
Opx	Cpx, hbl
Opq	Bt
Opq	Bt, gar
Opq	Plag, gar
Opq	Assoc with and replaced by rut
Opq	Hbl

Garnet also occurs as idioblasts in plagioclase.

Porphyritic microgranite (gm)

Porphyritic and equigranular microgranite associated with granulites crop out in the southwest at GR 555298, and 5 km southeast of Mount Daisy Bates, at GR 852486. The southwest exposure comprises mafic granulite intruded by pipes and plugs of porphyritic microgranite, which contains swarms of angular xenoliths of the granulite. The inselberg near Mount Daisy Bates comprises a central north-striking septum of felsic granulite bordering very coarse-grained garnet granite, both intruded by dykes of porphyritic microgranite. The microgranite is recrystallised, and the plagioclase is unusually calcic (labradorite; Table 1).

Porphyritic microgranite intrudes the two masses of dolerite of the Giles Complex at GR's 502322 and 655282. The microgranite intrusions are a few tens of metres in extent, have been recrystallised to granuloblastic texture at both exposures, and enclose angular xenoliths of dolerite. Mafic clots (microxenoliths) contain clinopyroxene and hornblende, as does the groundmass of the microgranite.

Vein quartz (q)

Vein quartz forms numerous prominent 'blows' north of the Woodroffe Thrust. The quartz is fine-grained, recrystallised and sugary in appearance, and ranges from massive, to foliated and lineated, to lineated only. Some quartz blows are brecciated, others are sheared to quartz augen wrapped by secondary limonite.

Mylonite (m)

Nine inselbergs of mylonite in the northern part of the sheet area delineate a major easterly-striking fault zone. The mylonite dips gently south, separates granulite to subeclogite facies metamorphic rocks to the south from amphibolite facies rocks to the north, and is located along strike from the Woodroffe Thrust in the Northern Territory to the east (Forman 1972). Hence the mylonites in BATES are interpreted as a continuation of the Woodroffe Thrust (Stewart 1995b; Fig. 11). A tenth isolated hill 10 km to the south at GR 945517 may mark a subsidiary thrust fault. Numerous other mylonite zones a few metres thick cut the granulites and granitic rocks of BATES south of the thrust, but are too small to show at 1:100 000 scale, except for a subhorizontal folded fault at GR 910420.

The mylonite exposures making up the Woodroffe Thrust are mainly derived from the unit of schistose granitoid north of and below the thrust. Garnet-bearing mylonite derived from the garnet granite south of and above the thrust is less common.

The outer less deformed parts of the mylonite zone are fine to very fine-grained, pale, laminated, schistose and friable, and contain small feldspar augen and veinlets of ultramylonite. The mylonite consists of angular bent clasts of K-feldspar, fractured to granulated sericitised plagioclase, broken hornblende (in some samples), and rare garnet augen in a streaky groundmass of either ribbon quartz or recrystallised very fine-grained mosaic quartz, microcrystalline K-feldspar, and elongate aggregates of preferentially oriented biotite

The central most intensely deformed part of the mylonite zone comprises thinly interlayered pale very fine-grained mylonite (as described above) and dark aphanitic ultramylonite. The ultramylonite comprises round nearly strain-free quartz, subrounded plagioclase and hornblende, and fractured garnet in a streaky barely resolvable groundmass of highly flattened and bent lenses of cryptocrystalline quartz and/or feldspar, lenticles of very fine biotite, and opaque grains.

A north-northwest-striking tear fault cuts the Woodroffe Thrust, and is marked by two hills of mylonite. The mylonite is similar to that in the easterly-striking mylonite zone, but includes abundant broken clasts and lenticular aggregates of garnet forming up to 10 percent of the rock.

Metadolerite dykes in the Woodroffe Thrust and tear fault consist of garnet relics partly altered to chlorite and calcite, hornblende segmented by actinolite-filled cracks, bleached biotite, and sericitised plagioclase.

Small mylonite zones a few metres thick that cut the garnet granite and granulites south of the Woodroffe Thrust are essentially similar to those in the Woodroffe Thrust. Garnet ranges from undeformed to fractured to augen with strain lamellae. Clinopyroxene forms small augen in some samples, and quartz is strongly deformed and recrystallised to very flat lenses and ribbons.

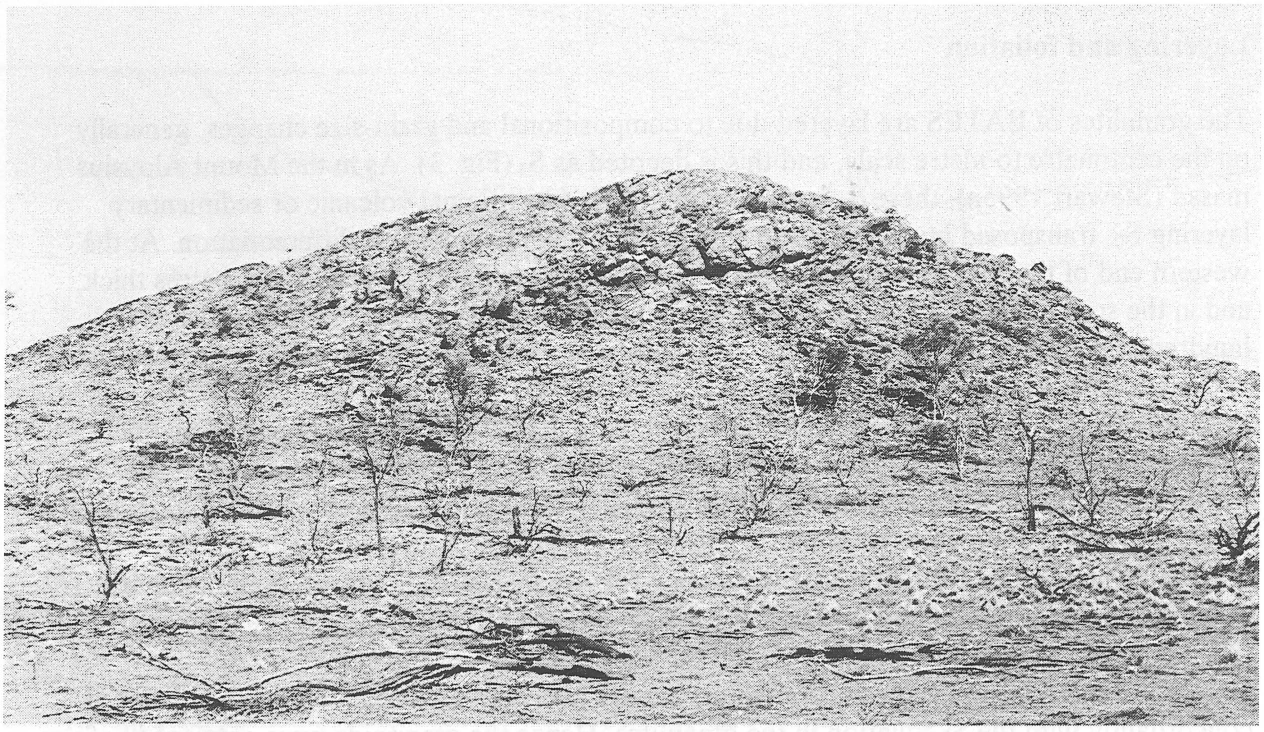


Figure 11. Largest exposure of Woodroffe Thrust in BATES, looking southwest. Entire hill is mylonite, with most intense zone at prominent subhorizontal joint one third of the way down hill from top. GR 827632.

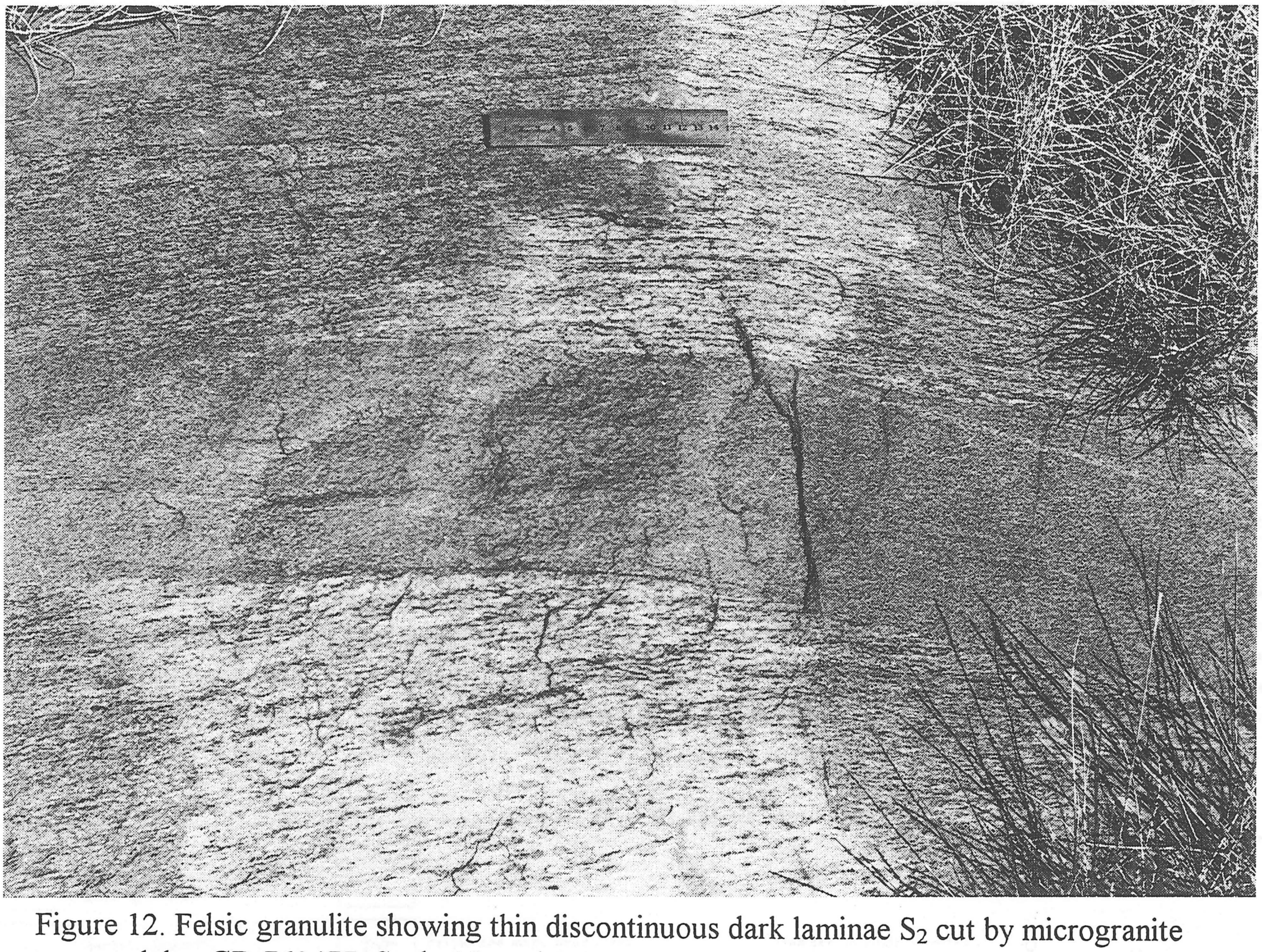


Figure 12. Felsic granulite showing thin discontinuous dark laminae S_2 cut by microgranite dyke, GR 760477. Scale 15 cm long.

Structure[8]

Layering and foliation

The granulites of BATES are layered due to compositional and grain-size changes, generally on the centimetre to metre scale, and this is denoted as S_1 (Fig. 3). As in the Mount Aloysius massif (Stewart 1995a), these S_1 layers are interpreted as original volcanic or sedimentary layering S_0, transposed by deformation and enhanced by metamorphic differentiation. At the western end of the Mount Aloysius massif, mafic layers are tens to hundreds of metres thick, and in the south of BATES three exposures of quartzite can be joined into a layer several hundred metres thick and about 20 km long; these macroscopic layers are S_0, and parallel S_1.

Foliation S_2 in the granulites and granites is mylonitic in character, and is imparted by the flattening of mineral grains. Quartz is lenticular, commonly strongly so; feldspars are bent and fractured, and mafic minerals form elongate aggregates and trains of small grains. Elongation of the grains and aggregates produces a lineation L_2. Felsic non-layered granulite units commonly have a thin discontinuous lamination formed by sparse to abundant dark laminae 1-2 mm thick and tens of centimetres long; this is also assigned to S_2 (Fig. 12).

Granitoids in BATES intrude the granulites, but are almost everywhere foliated and lineated concordantly with the S_2 foliation in the granulites. Hence the granitoids were emplaced before or during D_2 deformation and metamorphism, and their foliation is also denoted as S_2.

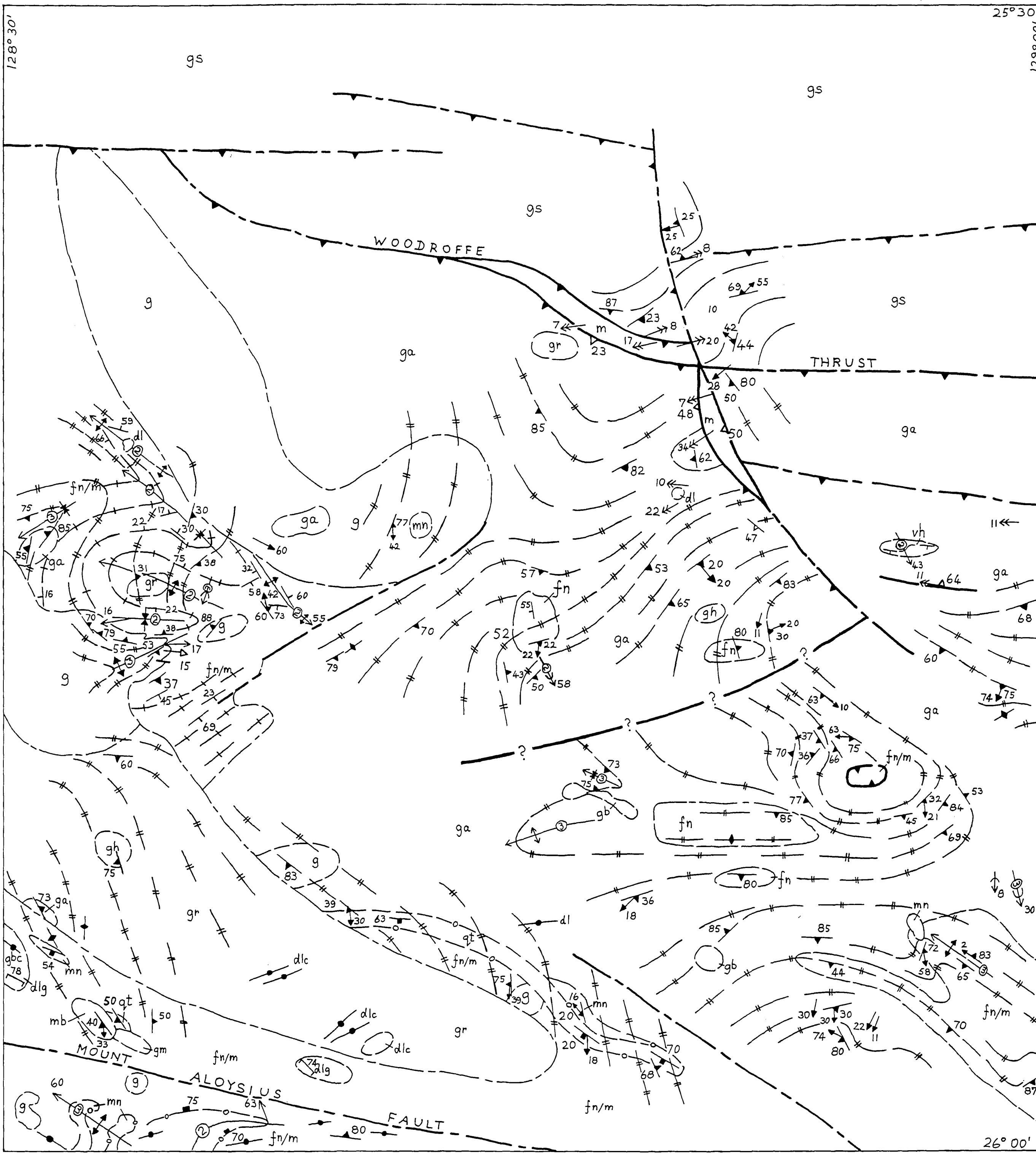
Figure 13 is a solid geology and structural sketch map of BATES, and shows all measurements of S_1, S_2 and S_3 recorded in the area. Form lines showing the trends of S_1 and S_2 were interpolated between measurements as far as practicable.

Folds

The earliest recognised folds are tight to isoclinal mesoscopic intrafolial folds F_2 which deform the S_1 layering in the granulites (Figs. 3, 6, 7a, b, c, d, e). The mylonitic S_2 foliation in the rocks is axial-plane to these folds. Plunges are mostly subhorizontal, but become subvertical on the limbs of later folds. Most examples are centimetres in size, but a subhorizontal fold tens of metres across affects layered felsic granulite at GR 814288. Macroscopic F_2 folds are inferred from strike swings in the S_1 layering in the areas 1 km and 10 km north and 6 km east-northeast of Mount Fanny (Fig. 13).

F_3 folds are upright, and range from gentle to isoclinal. Only two were seen in outcrop, and deform S_1, S_2 and L_2 (Fig. 7f). No axial-plane foliation was observed. On the map, variation in strike and dip of S_2 indicates that several macroscopic F_3 folds exist (Fig. 13), e.g., at Mount Fanny and 8 km north of there, where they trend northeast, and in the southeast and southwest, where F_3 folds trend northwest. A tight dome is inferred in the Mount Gosse area in the east. The gentle and smooth variations in trend of the S_2 foliation and of the F_3 fold traces suggests that strain during that time was markedly inhomogeneous, but no clear F_4 fold generation is apparent.

[8] D, S, and F nomenclature corresponds with that of Clarke et al. (1995a) and Glikson et al. (1996) in the Champ de Mars area, 18 km south of BATES.



m	Mylonite
gm	Porphyritic microgranite
dl	Metadolerite (subeclogitic)
gb	Metagabbro (subeclogitic)
	Metadolerite dykes types A and B; Some subeclogitic dykes
dlc, gbc	Dolerite, gabbro, Type C mafic dykes
dlg	Dolerite and metadolerite of Giles Complex
ga	Garnet granite
gh	Hornblende granite
g	Granite
gr	Rapakivi granite
vh	Staurolite gneiss
qt	Quartzite
mb	Metabasalt
mn	Mafic granulite
fn	Felsic granulite
fn/m	Felsic and mafic granulites
gs	Schistose granitoids

- Geological boundary, approximate
- Geological boundary, magnetic interpretation
- Fault (queried where inferred)
- Thrust fault
- Fault, magnetic interpretation
- Antiform with plunge*
- Synform with plunge*
- S_0 layering trend
- S_1 layering trend
- S_2 foliation trend
- S_0 layering strike and dip
- S_1 layering strike and dip
- S_2 foliation strike and dip
- S_3 foliation strike and dip
- S_6 foliation strike and dip
- L_2 lineation
- L_3 lineation
- L_6 lineation
- Unassigned foliation trend
- Fold axis*

*Number in circle denotes deformation episode

0 5 10 KM

Fig. 13. Solid geology and structural sketch map, BATES

Faults

Major faults in BATES are the Woodroffe Thrust and its coeval tear-fault in the north, and the Mount Aloysius Fault in the southwest (Fig. 13). The latter is inferred from four pieces of evidence:

1. The ridges of the Mount Aloysius massif terminate along a topographic lineament;
2. A magnetic lineament coincides with (1);
3. Pressure estimates by Clarke et al. (1995a) are 300 to 500 MPa south of the topographic/magnetic lineament, and 1000 to 1400 MPa north of the lineament.
4. Inferred trends of S_2 foliation north of the fault are at a large angle to those south of the fault.

Faults striking northeast from the Mount Fanny area and northwest in the southeast of the region are inferred from magnetic data, and their existence is supported by marked differences in inferred trends of foliation on each side of the faults. The fault striking east to east-northeast across the centre of the sheet area is inferred from differences in strike and dip of S_2 trends only.

These faults, together with some magnetic lineaments parallel to the Woodroffe Thrust, are assigned to D_6 in the scheme of Clarke et al. (1995a).

A subhorizontal folded fault underlies a hill of interlayered felsic and mafic granulites (fn/m) at GR 910420 (Fig. 4). Exposure to the north and east is lacking, but the fault is inferred to surround the granulites, which may be an isolated thrust klippe.

Mylonites

Numerous mesoscopic mylonite zones (58 were observed) cut the granulites and granites in BATES (Fig. 14). The zones are 1-20 m wide, several hundred metres long, and are commonly bordered by up to 2 m of less strongly mylonitic host rock on each side (Fig. 15). Lineation is present in most but not all mylonites, the absence of lineation implying pure shear strain at those localities. Sense of shear is commonly indeterminate from outcrop examination, but where visible appears to be dextral, sinistral, reverse, or normal in about equal proportions (at different exposures). The mylonite zones cut and hence post-date layering S_1 and foliation S_2 in the surrounding rocks. Mineral assemblages and hence metamorphic facies in the mylonites are similar to those in the surrounding rocks, implying that mylonitisation took place during the metamorphism.

Poles to mylonite foliations (Fig. 16a) show that many mylonites dip gently to moderately south; the weak girdle spread indicates possible folding of the mylonites around a gently west-plunging axis (9/256). Lineation plunges in the mylonite zones show a weak subhorizontal concentration trending east-northeast (Fig. 16b). These are the same orientations for foliation and lineation noted in the mylonite of the Woodroffe Thrust (Stewart 1995b, Figs. 9c, 9f), suggesting that the mylonites throughout the BATES region were caused by the same faulting event that produced the Woodroffe Thrust. This is supported by subeclogite facies (garnet-clinopyroxene) mineral assemblages in mylonites south of the Woodroffe Thrust investigated by Clarke (1993). The mylonites are probably lower crustal splays of the Woodroffe Thrust.

Many of the mylonites are openly to closely folded around subhorizontal axes, with the mylonitic foliation and lineation both affected. Fold trends show no preferred orientation. At GR 946520, recrystallized mylonite in garnet granite is folded around east-west horizontal axes, and then kink-folded around moderately steep northeast-plunging axes (Fig. 7g).

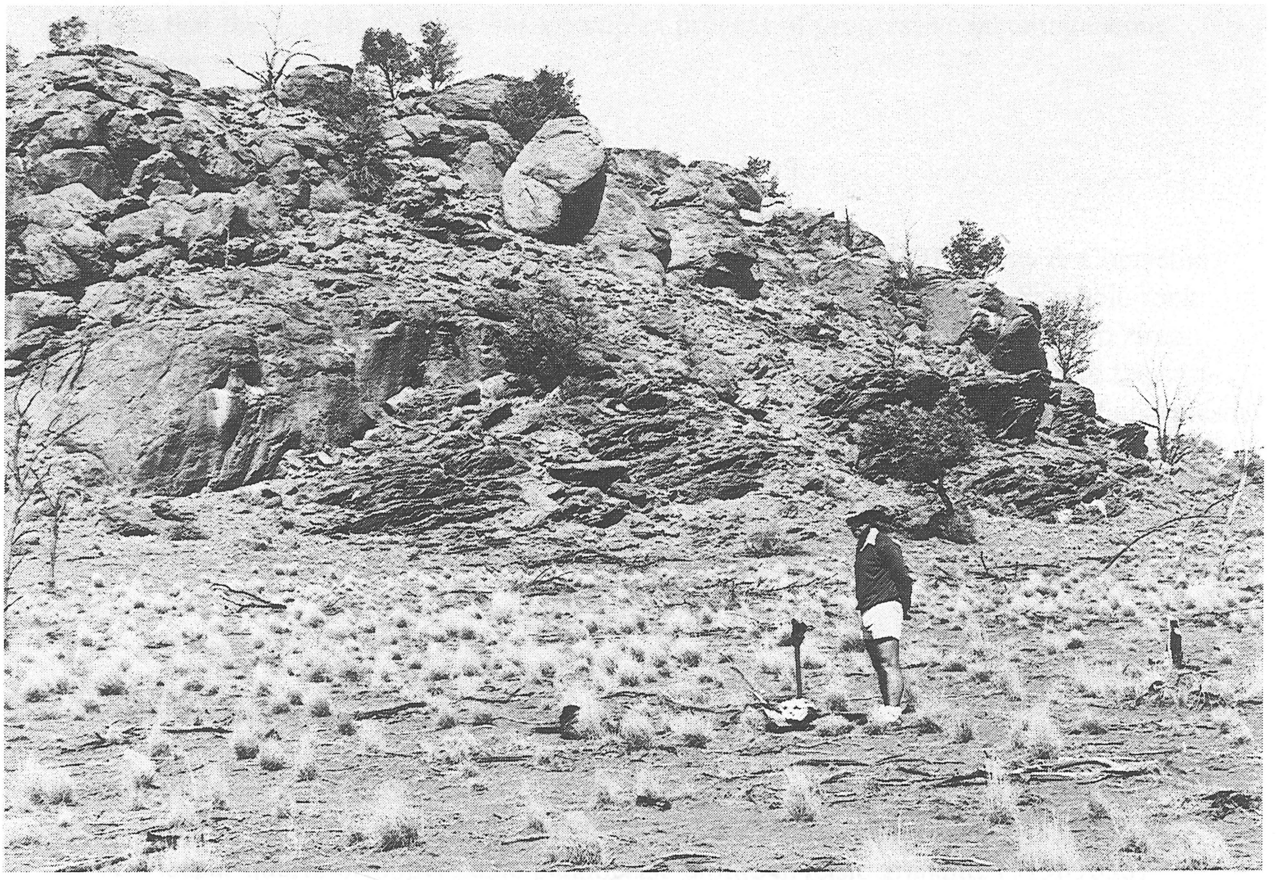


Figure 14. Mylonite zone exposed at base of hill of foliated garnet-hornblende granite (ga_2), GR 868495.

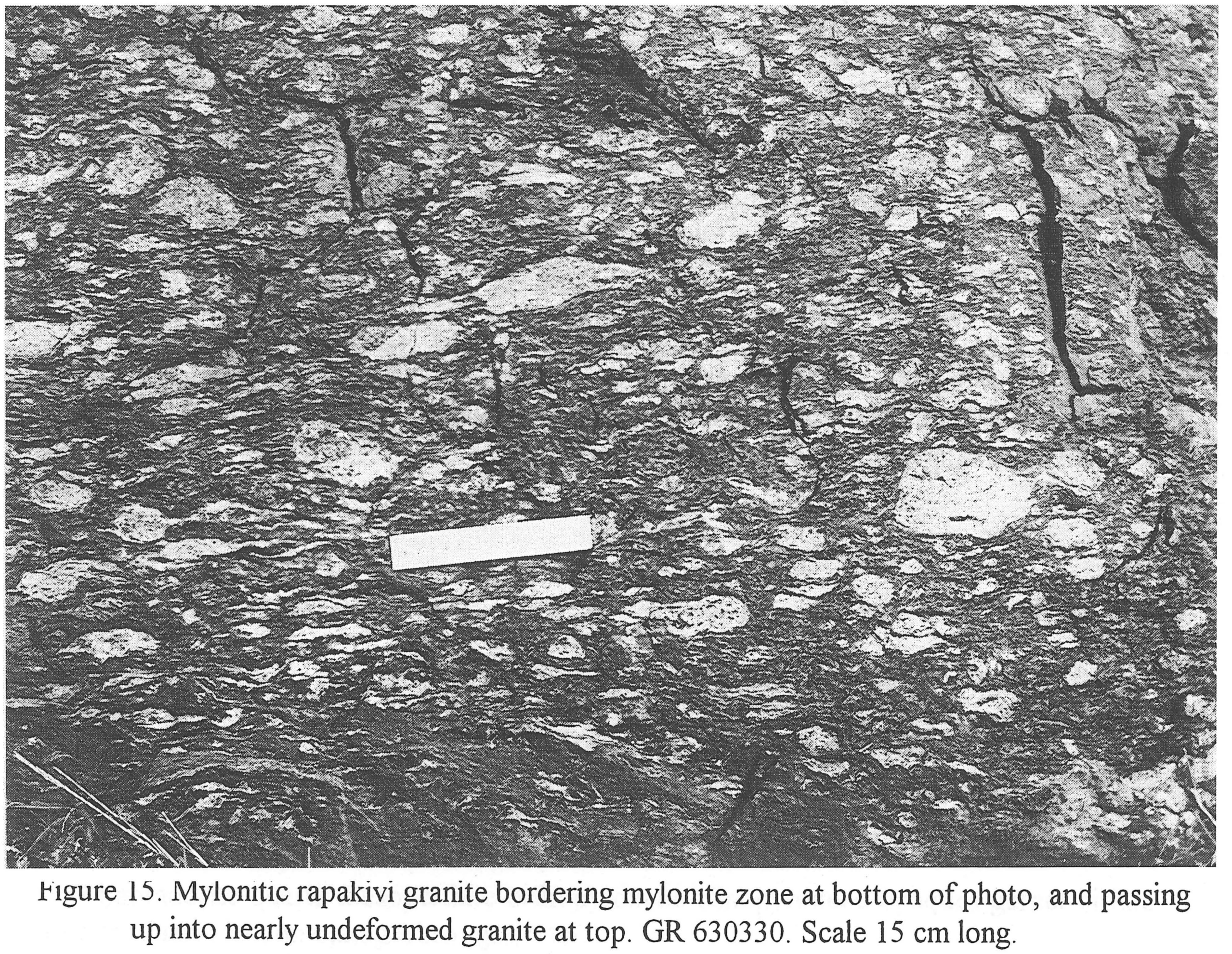
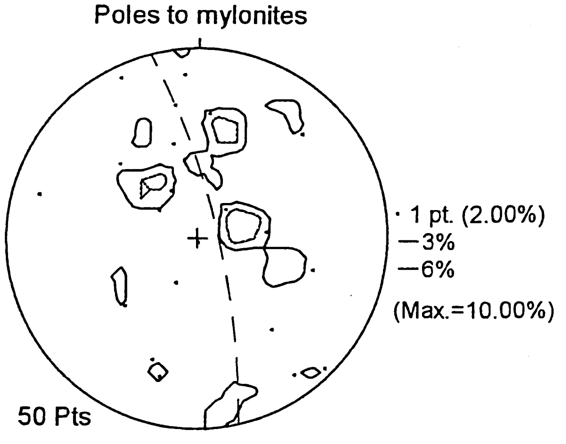


Figure 15. Mylonitic rapakivi granite bordering mylonite zone at bottom of photo, and passing up into nearly undeformed granite at top. GR 630330. Scale 15 cm long.



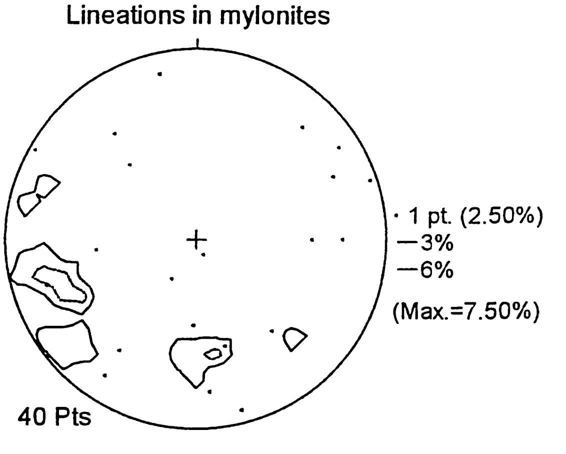


Figure 16. (a) Stereograms of poles to mylonite foliations and (b) lineations in mylonites in BATES. Equal-area plots on lower hemisphere. Plotted using GEORIENT program written by R. Holcombe, University of Queensland.

The marked spread in foliation and lineation measurements and the folds in the mylonites indicates that the 530 Ma faulting was a complex process of progressive inhomogeneous deformation.

Metamorphism

Regional metamorphism occurred twice in the Bates region. Gray (1978; Gray & Compston 1978) determined the time of granulite metamorphism at 1222 ± 39 Ma (Rb-Sr whole-rock isochron) in the Mount Aloysius massif, and this was confirmed by a SHRIMP U-Pb zircon age of 1200 Ma on synmetamorphic augen gneiss at Minno (Pipalyatjara), 60 km to the east-southeast by Sun & Sheraton (1992; Sun et al. 1996a, b) The subeclogite facies metamorphism is dated by Clarke et al. (1995b) with Sm-Nd mineral-pair ages of 536 ± 16 and 533 ± 16 Ma on a metagabbro dyke (91989485a and b, 3.5 km north-northwest of Mount Fanny). This agrees with Rb-Sr and Ar-Ar ages of 550-530 Ma inferred for the Petermann Orogeny which produced the Woodroffe Thrust 250 km to the east (Maboko et al. 1992; Camacho & Fanning 1995).

Granulite facies metamorphism

The granulite facies metamorphism at around 1200 Ma in the Mount Aloysius massif is characterised by such assemblages (in order of decreasing abundance) as:

- K-feldspar-quartz-orthopyroxene-plagioclase-biotite in felsic granulite (91989056)
- Bytownite-orthopyroxene-garnet-opaques-biotite in intermediate granulite (91989117)
- Labradorite-opaques-garnet-biotite-orthopyroxene-hornblende in mafic granulite (91989082)
- Labradorite-clinopyroxene-orthopyroxene-opaques-biotite-spinel in Type A metadolerite (91989053)

The garnet-bearing assemblages have been studied in detail by Clarke et al. (1995a, p.130), who estimated the temperature during D_2 at 750°C for samples 9082 and 9117 in the Mount Aloysius massif, with a corresponding pressure of about 500 MPa. D_3 pressure estimates were 400-600 MPa if T is assumed to be 700°C (9117); a reliable temperature estimate for D_3 was not possible because of uncertainty as to whether garnet used in the calculation was D_3 or relict-D_2 (Clarke et al. 1995a). An additional pressure estimate of 900-1300 MPa for D_3 (sample 9082) is 'possibly unreliable, owing to incomplete chemical equilibration' (Clarke et al. 1995a, p. 139), and another D3 pressure estimate of 1100-1400 Mpa is from sample 9455, 25 km north of the Mount Aloysius massif in the region affected by subeclogite facies metamorphism (see below).

Subeclogite facies metamorphism

The subeclogite facies metamorphism at about 530 Ma in the area between the Woodroffe Thrust south to the latitude of Mount Gosse is characterised by such assemblages as:

- K-feldspar-oligoclase-quartz-hornblende-garnet-orthopyroxene-biotite (melagranite ga_2, 91989455)
- Hornblende-garnet-labradorite-clinopyroxene-scapolite-rutile-orthopyroxene (metadolerite, 9453)
- Labradorite-quartz-mesoperthite-orthopyroxene-clinopyroxene-opaques-garnet-biotite-apatite (quartz leucomonzogabbro, ga_5, 9460)
- Hornblende-clinopyroxene-andesine-garnet-scapolite-rutile (metagabbro, 9485a)

R9700511

Pressure estimates are consistently 1000-1400 MPa, and temperature estimates range from 700-875°C (Clarke et al. 1995a, p. 141).

The southerly extent of the 530 Ma-old subeclogite facies metamorphism is difficult to define, as D_3 and D_6 assemblages can be texturally similar; symplectites with garnet occur in felsic granulite in both the Mount Aloysius massif and in the area to the north as far as the Woodroffe Thrust.

Geological history

The sequence of Proterozoic to Early Cambrian events in BATES is set out in Table 4. The earliest recorded event was formation of the schistose (foliated) granite in the north. Its age has not been determined in BATES. In lithology, metamorphic facies, and structural position below the Woodroffe Thrust it resembles the 1600 Ma-old Olia Gneiss 200 km to the east (Maboko et al. 1992). This may be a reasonable estimate of the age of the foliated granite in BATES, but it is just as likely that the granite could be one of the younger varieties.

The only geochronological data on the parent sediments and igneous rocks of the felsic and mafic granulites, metabasalt and quartzite in the centre and south of BATES is the pooled Rb-Sr isochron age of 1580 Ma determined by Gray (1978; Gray and Compston 1978). They interpreted this age as the protolith age because individual isochrons were precise, described large bodies of rock or entire lithological units, possessed large spreads in Rb/Sr ratio, and initial ratios of felsic layers were significantly different from those of mafic layers. Sun & Sheraton (1992) confirmed the 1580 Ma age with a SHRIMP U-Pb zircon date of about 1530 Ma on a banded felsic granulite from Mount Aloysius. The relationship of these granulites to the foliated granite in the north before they were brought together by 535 Ma-thrusting is unknown.

Deformation in BATES probably began before 1200 Ma, when D_1 transposed original S_0 layering and formed the present S_1 layering. In the Mount Aloysius massif south of BATES, small recumbent folds formed during D_1 (Stewart 1995a), but have not been recognised in BATES. The earliest folds seen in BATES are small tight to isoclinal F_2 folds, which deform the S_1 layering and have an S_2 axial-plane schistosity. These deformations accompanied the granulite metamorphism of the region (Clarke et al. 1995b), which was dated by Gray (1978, Rb-Sr whole-rock; Gray & Compston 1978) and Sun & Sheraton (1992, U-Pb zircon) at about 1200 Ma.

The later part of the D_2 deformation and granulite metamorphism was accompanied by the emplacement of large amounts of syntectonic foliated charnockitic granite containing orthopyroxene as its main mafic igneous mineral. In places (eg, Mount Fanny), the granite appears to have formed by melting of granulite. These granites have not been dated in BATES, but may be coeval with masses of biotite granite dated at about 1190 Ma in the Champ de Mars area 18 km to the south (Sun et al. 1996a, b). Low-angle D_2 faulting formed at least one small thrust-sheet in the east, and placed granulite over granite.

About 100 Ma later, around 1080 Ma, the western Musgrave region south and west of BATES was invaded by huge lopolithic intrusions of mafic magma forming the Giles Complex, and small outliers of the complex encroached into the southern part of BATES. Type A mafic dykes in the Mount Aloysius massif are coeval with and petrologically similar to the Giles Complex (Sun et al. 1996a, b) and both are dated at 1078 Ma (Sun et al. 1996a, b). Sheets and

Table 4. Sequence of Proterozoic to Early Cambrian events in BATES

Event	Age (Ma)	Remarks
Granite emplacement	1600[1]	Protolith of schistose granite (gs) in north; age inferred from Olia Gneiss 200 km to E
Felsic and mafic volcanism, sedimentation	1580[2]	Protoliths of felsic (fns, fg, fna, fn/m, fn, fnk), intermediate (in), mafic (mn), and pelitic granulites (vh), metabasalt (mb), quartzite (qt) with S_0 layering
D_1	>1200	Formation of S_1 layering by transposition and metamorphic differentiation of S_0
D_2	1200[2,3]	S_2 foliation, F_2 folds, L_2 lineation. P = 500 MPa, T = 750°C
Granite emplacement	1190[4]	Synchronous with D_2; folded by F_3; units gr, g, g_1, gh, ga
Mafic intrusion	1080[4]	Type A dykes in Mount Aloysius massif; Giles Complex (dlg)
Microgranite intrusion		Sheets and plugs of porphyritic microgranite (gm)
D_3	1060[5]?	F_3 folds, upright, open to close, gentle to moderate plunge. P = 400-600 MPa, T = 700°C?
Mafic intrusion	1000[6]	Type C dykes throughout area; units dlc, gbc
Mafic intrusion	820[6]	Type B dykes in Mount Aloysius massif and possibly throughout area; units dl, gb
Petermann Orogeny, D_6	550-530[1,5,6]	East-northeast-directed thrusting along Woodroffe Thrust and associated splays and tear-fault; normal faulting on Mount Aloysius Fault; subeclogitic metamorphism P = 1000-1400 MPa, T = 700-875°C

[1]Maboko et al. (1992). [2]Gray (1978). [3]Sun & Sheraton (1992). [4]Sun et al. (1996a, b). [5]Clarke et al. (1995b). [6]Glikson et al. (1996).

plugs of microgranite intrude the Giles Complex bodies in BATES; although undated, their age is bracketed by that of the Giles Complex and by the time of D_3 deformation, which recrystallised the microgranites.

D_3 deformation affected all the granulites, granites and Giles Complex intrusions, and produced upright open to close macroscopic folds. The time of D_3 deformation is later than the 1078 Ma age of the Giles Complex (Sun et al. 1996a, b), and has been tentatively equated by Clarke et al. (1995a), on the basis of the thermal perturbation implied by cordierite + spinel coronas on garnet at Cohn Hill, 70 km west of BATES (Clarke & Powell, 1991) with the last stage of the 1080-1060 Ma magmatism and metamorphism that accompanied the emplacement of the Giles intrusions.

Mafic magma again intruded BATES at about 1000 Ma (Type C dolerite and gabbro bodies) and 800 Ma (Type B; Glikson et al.1996). The latter can be related to tension during initial downwarping of the Amadeus Basin to the north (Shaw et al. 1984, 1991).

The present-day architecture of the Earth's crust in the Musgrave region has been determined by Lambeck & Burgess (1992) from teleseismic travel time studies. Figure 17 shows a possible sequence of events which produced the present structure. Section a shows the crust at 800 Ma after completion of D_{1-3} deformation and mafic dyking. Volcanics of the Tollu Group, dated at 1078 ± 5 Ma (Glikson et al.1996) and coeval with the Giles Complex are shown south of the position of BATES. These volcanics provide a levelling datum, as they have been preserved at or near ground level for a billion years since their eruption. At about 550 Ma, the crust underwent thrusting along the Woodroffe Thrust, involving both under (b) and overthrusting (c) to achieve the displacement of 80 km depicted by Lambeck & Burgess. (The highlands so formed provided detritus for Early Cambrian molasse sediments in the Amadeus Basin to the north.) The thrusting brought lower-crustal granulite (transitional to eclogite) facies rocks from a depth of 40 km up over upper-crustal amphibolite facies rocks, as observed in BATES. Normal or transtensional faulting (c, d) along the Mann Fault and steep reverse fault equivalents of the Lindsay and Wintiginna Lineaments ensued. This took remnants of the Tollu Volcanics down to their present level, and left a crustal wedge or 'popout' as the highest part of the region. Erosion since then has left only the lower-crustal portion of this wedge, the hanging wall of the Woodroffe Thrust in BATES. The Mount Aloysius Fault in BATES is on strike with and is possibly the western extension of the Mann Fault. Downthrow to the south of the Mann/Mount Aloysius Fault is consistent with markedly lower pressure estimates in the Mount Aloysius granulite massif of 300-500 MPa, compared to 1000-1400 MPa north of the massif (Clarke et al. 1995a). Topographic south-block-down 'steps' in the present landscape, noted by Feeken (1992, cross-sections accompanying map), may be the surface expression of the steep reverse faults. If so, they imply longevity of the landscape similar to that noted elsewhere in central and northern Australia (Stewart et al. 1986; Ollier et al. 1988).

Economic geology

Water

Permanent surface water is not present in BATES. A few rockholes are present, and temporarily contain a few cubic metres of water after rain. Underground potable water is obtained from bores at Warlpapuka, Arnold Creek, Mirturtu, and from an unnamed bore near the centre of the area. Details of quality and supply are not available. The large areas of calcrete in the southern half of the sheet area are potential sources of potable water, but have not been tested. The presence of gypsum crusts on claypans in the east of the area indicates saline groundwater there.

Metals

The Musgrave NGMA project did no systematic study of metallic mineralisation, as this was a condition of access into aboriginal reserves. The following notes are compiled from a summary of earlier work by Glikson et al. (1996).

Platinum Group elements

The Giles Complex is a potential source of platinum group elements (PGE), but the high sulphur content of the magmas, the separation of the magmas into discrete bodies rather than forming a single large body, the consequent rapid cooling of the separate intrusions which would therefore have had less time to concentrate any PGE sulphides, and preliminary PGE

Fig. 17

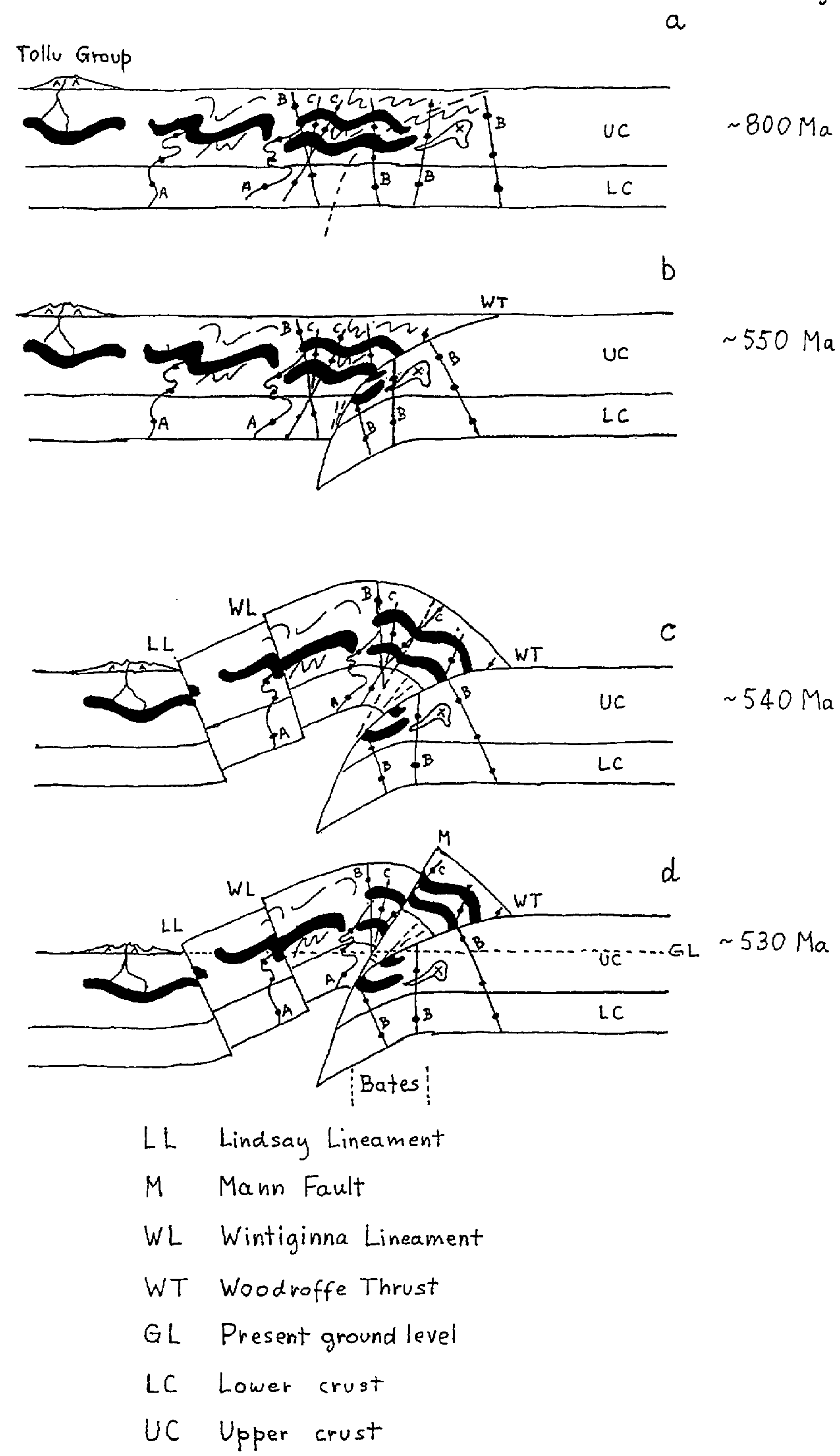


Figure 17. Diagrammatic cross-sections showing possible Neoproterozoic to Cambrian evolution of Musgrave Block. (a) Initial crust showing position of Woodroffe Thrust. (b) Underthrusting and (c) overthrusting along Woodroffe Thrust, with splays in lower crust. (d) Reverse faulting along equivalents of Wintiginna and Lindsay Lineaments. (e) Normal faulting along Mann Fault, and projected location of BATES. Solid black represents intrusions of Giles Complex. Modified from Lambeck & Burgess (1992).

analyses which show no concentration of PGE during crystal fractionation all indicate that the PGE potential of the Giles Complex in BATES is low.

Nickel

Nickeliferous laterites on Giles Complex rocks near Wingellina south of BATES were explored in the 1960s and 70s, and contain some tens of millions of tonnes of subeconomic nickel resources. There are no laterites associated with the Giles Complex intrusions in BATES.

Chromium

Chromite is scarce in the Giles Complex, and not known from BATES. The scarcity is attributed to uptake of Cr in early crystallising clinopyroxene in the mafic/ultramific rocks, leaving little to concentrate in the late melt fractions.

Copper

Daniels (1972) reported chalcopyrite and chalcocite 'in gabbroic rocks from a small dyke-like body 4.5 miles south of Mount Gosse'. This is located in felsic granulite at GR 945335, but the occurrence was not seen during the present survey.

Acknowledgements

I thank Andrew Glikson, manager of the NGMA Musgrave Project, for inviting me to work on the granulites hosting the Giles Complex, Geoff Clarke for discussions on subeclogite facies rocks, Jeff Windsor for willing field assistance, and the Ngganyatjarra Aboriginal tribe and community coordinator Ruth Raintree for accommodation at Wingellina in 1991. Discussions with and reviews by Alfredo Camacho, David Champion, and John Sheraton improved the report considerably.

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Appendix 1: Sample numbers, grid references, rock types, map units and analysis availability for all thin-sectioned samples collected from BATES

Sample number	Grid reference	Rock type	Map unit[9]	Chemical analysis[10]
91989053	550276	Metadolerite (Type A)	Dyke	Y
91989056	575264	Felsic leucogranulite	fnk	Y
91989082	547256	Mafic granulite layer	fnk	-
91989117	586245	Intermediate granulite	fn/m	Y
91989418	751633	Quartz monzonite	ga_1	Y
91989420	779643	Granite mylonite	m	-
91989421	802643	Mylonitic tonalite	gs	Y
91989422	806640	Mylonitic granite	gs	Y
91989423A	813635	Granite mylonite	m	-
91989424C	821631	Granite mylonite	m	-
91989425A	826630	Mylonitic leucogranodiorite	m	Y
91989425D	826630	Metadolerite (subeclogitic)	-	-
91989425E	826630	Granite ultramylonite	m	-
91989426	824692	Mylonitic leucotonalite	gs	-
91989427	823671	Schistose granodiorite	gs	-
91989432	848624	Granite	gs	-
91989435	988549	Mylonitic quartz monzonite	ga_1	Y
91989435A	988549	Tonalitic mylonite	-	-
91989436B	946520	Felsic blastomylonite	m	-
91989436D	933535	Staurolite gneiss	vh	Y
91989437	840608	Granite mylonite	m	-
91989438A	838593	Granite mylonite	m	-
91989438B	838593	Metadolerite (subeclogitic)	-	-
91989440	829566	Melagranite	ga_2	Y
91989442B	824560	Metadolerite (subeclogitic)	dl	Y
91989443B	813544	Quartz monzodiorite	ga_9	Y
91989444	801537	Quartz monzonite	ga_1	Y
91989445B	794526	Quartz monzonite	ga_1	Y
91989448	835527	Granite mylonite	ga_2	Y
91989449	823531	Blastomylonite	-	-
91989451	813520	Quartz syenite	ga_3	Y
91989453	807514	Metadolerite (subeclogitic)	-	Y
91989454	805513	Melagranite	ga_2	Y
91989455	868495	Foliated melagranite	ga_2	Y
91989455B	868495	Granite mylonite	ga_2	-
91989458	723526	Quartz leucodiorite	ga_4	Y
91989460A	758516	Quartz leucomonzogabbro	ga_5	Y
91989460B	758516	Quartz alkali-feldspar syenite	ga_{10}	Y
91989460E	758516	Quartz micromonzonite dyke	ga_1	Y
91989464B	697501	Quartz leucosyenite	ga_7	Y
91989465A	668482	Quartz leucodiorite	ga_4	Y
91989466	668484	Quartz leucomonzogabbro	ga_5	Y
91989469B	740596	Microtonalite dyke	-	-
91989470	757600	Metadolerite (subeclogitic)	-	-
91989471	840590	Quartz diorite mylonite	m	-
91989472C	518510	Olivine metadolerite (subeclog.)	-	-
91989473	514533	Quartz syenite	ga_3	Y
91989474	515535	Mafic granulite raft in qz syenite	ga_3	Y
91989475	520536	Granite	ga_2	Y
91989476B	510547	Metagabbronorite (subeclogitic)	dl (Type A)	Y
91989476C	510547	Metadolerite (subeclogitic)	dl	Y
91989476D	510547	Metagabbronorite (Type B)	-	Y
91989476E	510547	Metadolerite (subeclogitic)	dl	-
91989480A	551588	Metadolerite (subeclogitic)	-	Y
91989485A	566516	Metagabbro (subeclogitic)	gb	Y

[9] A dash means too small to show at 1:100 00 scale on Bates map.
[10] Results available from AGSO ROCKCHEM database.

Appendix 1 (cont.): Sample numbers, grid references, rock types, map units and analysis existence for all thin-sectioned samples collected from BATES

91989487	621523	Mafic granulite	fn/m	Y
91989488B	636508	Mafic granulite	fn/m	Y
91989496B	601494	Metadolerite (subeclogitic)	-	Y
91989497	604491	Metadolerite (subeclogitic)	-	Y
91989498	605490	Alkali-feldspar charnockite	g_1	Y
91989499A	603463	Charnockite	ga_2	Y
91989500C	565428	Metadolerite (Type B)	-	Y
91989504	546490	Metapyroxenite (subeclogitic)	-	Y
91989511	675355	Quartzite	qt_1	-
91989514C	803422	Metadolerite (subeclogitic)	-	-
91989514D	803422	Quartz monzonite	ga_1	-
91989515C	939410	Quartz syenite mylonite	ga_3	-
91989517B	778418	Olivine metagabbro (subeclog.)	gb	Y
91989524	948481	Foliated tonalite	ga_8	-
91989525B	852486	Microgranite	gm	-
91989528C	853392	Quartz syenite	ga_3	Y
91989535B	907450	Granite	ga_2	Y
91989536A	894463	Melagranite blastomylonite	ga_2	Y
91989536C	911423	Mafic granulite	fn/m	Y
91989536F	908423	Leucogranite blastomylonite	fault	-
91989540	911424	Felsic granulite	fn/m	-
91989542	982453	Quartz monzonite	ga_1	Y
91989544A	984376	Alkali-feldspar granite	ga_6	Y
91989546A	978378	Alk-fs granite blastomylonite	ga_6	-
91989550C	839338	Metadolerite (subeclogitic)	-	Y
91989550D	839338	Leucogranodiorite pod in doler.	-	-
91989558C	922309	Granite	ga_2	Y
91989563	963295	Felsic granulite	fn/m	Y
91989567B	815290	Garnet quartzite	qt	-
91989569D	780308	Diop-gar-plag granulite	mn	Y
91989571	746323	Felsic granulite	fn/m	Y
91989574	750352	Metadolerite (subeclogitic)	-	Y
91989578	570302	Quartz monzonite	ga_1	Y
91989580A	549305	Metabasalt	mb	Y
91989580F	549305	Quartzite (metasandstone)	qt_2	-
91989581A	503323	Porphyritic microgranite	-	-
91989581C	503323	Dolerite	dlg	Y
91989583A	502343	Olivine gabbro	gbc	Y
91989585A	522360	Quartz alkali-feldspar syenite	ga_{10}	Y
91989590A	652281	Recrystallised dolerite	dlg	Y