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GUIDEBOOK — ARUNTA BLOCK, CENTRAL AUSTRALIA, IGCP PROJECT 235 — METAMORPHISM AND GEODYNAMICS FIELD CONFERENCE ON GRANULITE FACIES METAMORPHISM JUNE 25 – JULY 1, 1989

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Guidebook - Arunta Block, central Australia, IGCP Project 235 - Metamorphism and Geodynamics Field Conference on Granulite Facies Metamorphism

June 25 - July 1, 1989.

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ABSTRACT

The metamorphic rocks of the Arunta Block, central Australia, formed from Proterozoic protoliths deposited no more than 200 million years before prograde high-T, low-P metamorphism. In the central province this occurred at about 1800 Ma; in the northern province widespread Rb-Sr ages circa 1650 Ma suggest it occurred somewhat later, though Collins & others (1989) report older ages of metamorphism in the central north. Grade of the exposed rocks varies from lowermost amphibolite to granulite. Estimated pressures range from <2kbar to 9 kbars, corresponding temperatures from 600°C to about 900°C. Granulite metamorphism was accompanied by extensive migmatization, the result of water-undersaturated partial melting. As there was virtually no melt extraction, the granulites retained the undepleted chemical signatures typical of their lower-grade lateral equivalents. Models that best explain this segment of the tectonic evolution are those based on vertical accretion, involving intracratonic processes of extension, rift-related sedimentation and a-subduction. Retrograde metamorphism, localized in zones of severe deformation and hydration, occurred after considerable cooling. However, the regional distribution of pressure conditions for the retrograde metamorphism appears to have been little changed from that of the prograde metamorphism.

Localities in the Reynolds Range district, the Strangways Range district, and the Harts Range district provide outcrops that show aspects of the metamorphic history.

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PART 1

OVERVIEW OF THE GEOLOGY OF THE ARUNTA BLOCK

Introduction:- Geological and tectonic framework

RGW, RDS, BJH

The Arunta Block occupies some 200 000 km^2 in central Australia (Fig. 1). It merges northwest into The Granites-Tanami Block and north into the Tennant Creek Block, all of Proterozoic age. It is onlapped by platform covers of Middle Proterozoic, Late Proterozoic to mid Palaeozoic, and Mesozoic ages. Exposures are in part excellent but a major portion of the block is covered by a veneer of Cainozoic sediments and sheet sand.

The Arunta Block is subdivided into northern, central and southern tectonic provinces (Shaw & others, 1984, Stewart & others, 1984). Boundaries between the provinces, where these are exposed, are major faults. The northern and southern provinces have a large proportion of orthogneiss (meta-granite); the central province contains mostly supracrustal rocks.

The supracrustal rocks of the Arunta Block have been classified into broad lithological packages: Division 1 contains principally felsic and mafic rocks, probably the products of bimodal volcanism; Division 2 of pelitic and calcareous sediment; Division 3 of mature quartzite and pelite. Within each tectonic province unconformities separate the Divisions, but stratigraphic correlation of Divisions between tectonic provinces is uncertain; that is, the Divisions may be of different ages in different provinces. Correlations between Division 2 in the northern province and the Warramunga Group in the Tennant Creek Block and bwtween Division 3 and the Hatches Creek Group, also in the northern province have been proposed (e.g., Stewart & others, 1984).

Early, small gabbro-norite-anorthosite intrusions in the central and northern provinces preceded granite intrusion which occurred both before and after folding. Many of the granites are metamorphosed, and,

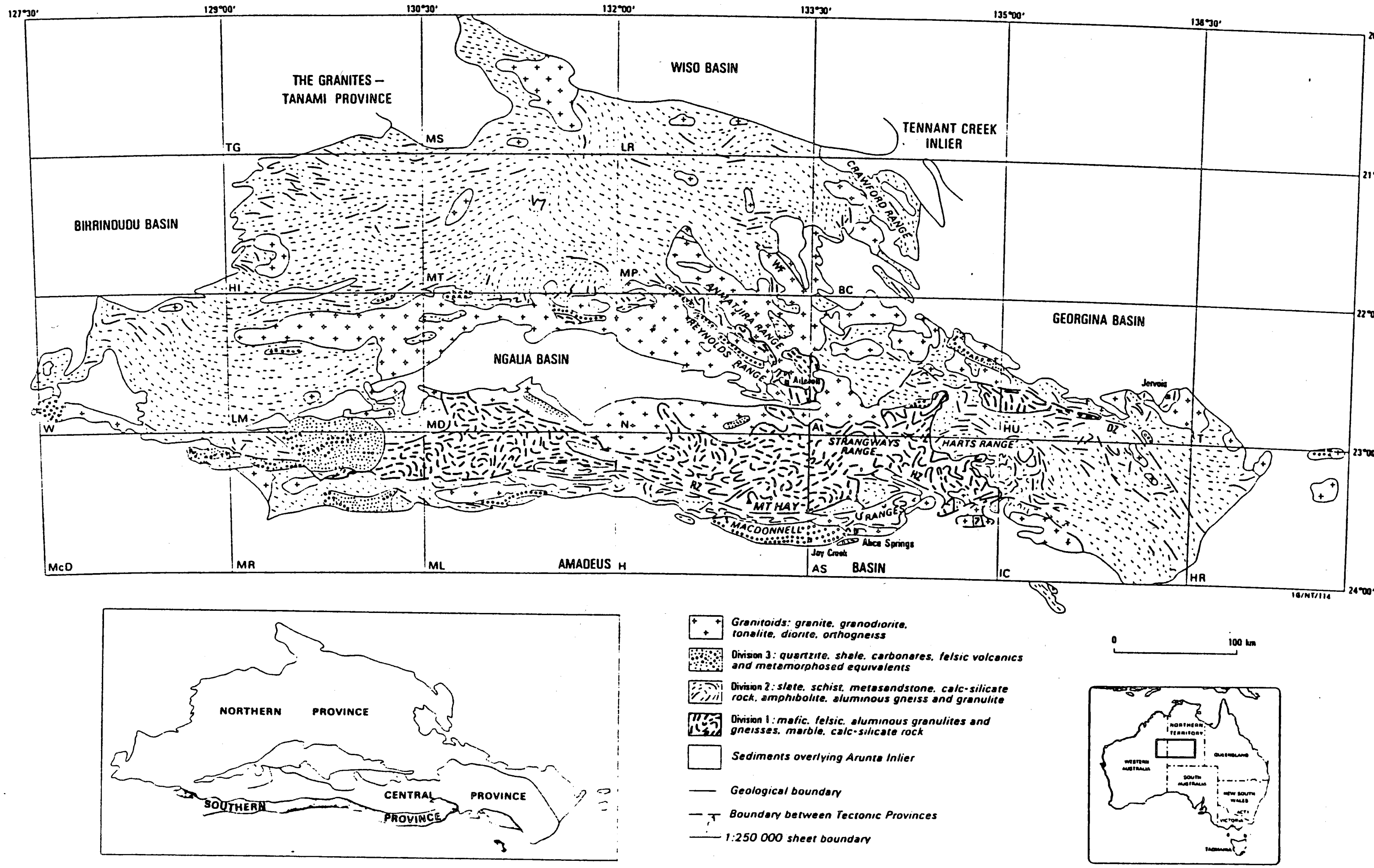


Figure 1.The Arunta Block, showing the provinces and the distribution of the major stratigraphic units (after Stewart & others, 1984)

particularly in the northern province, metamorphism of the granites was preceeded by intrusion of mafic dykes.

Warren & others (in prep) have shown that the majority of felsic igneous rocks in the Arunta Block belong to the Sr-depleted, Y-enriched class of Tarney & others (1987); a small volume belonging to the Sr-enriched, Y-depleted class occurs in the central east of the central province and in the adjacent southern province. The Sr-depleted, Y-enriched magmas are characterized by high levels of incompatible elements (Fig. 2): a preliminary subdivision into an Alarinjela supersuite and a Jinka supersuite has been proposed. Intrusions of the Jinka Suite are locally later, and even more enriched in Rb, Th, U, F, and REE than the Alarinjela Suite in areas where the two occur together. Within the Alarinjela Suite, subtle variations in chemistry (e.g., Sn, Ga/Al, Ba) which initially appear to be controlled by regional factors, may actually have time-tectonic significance,

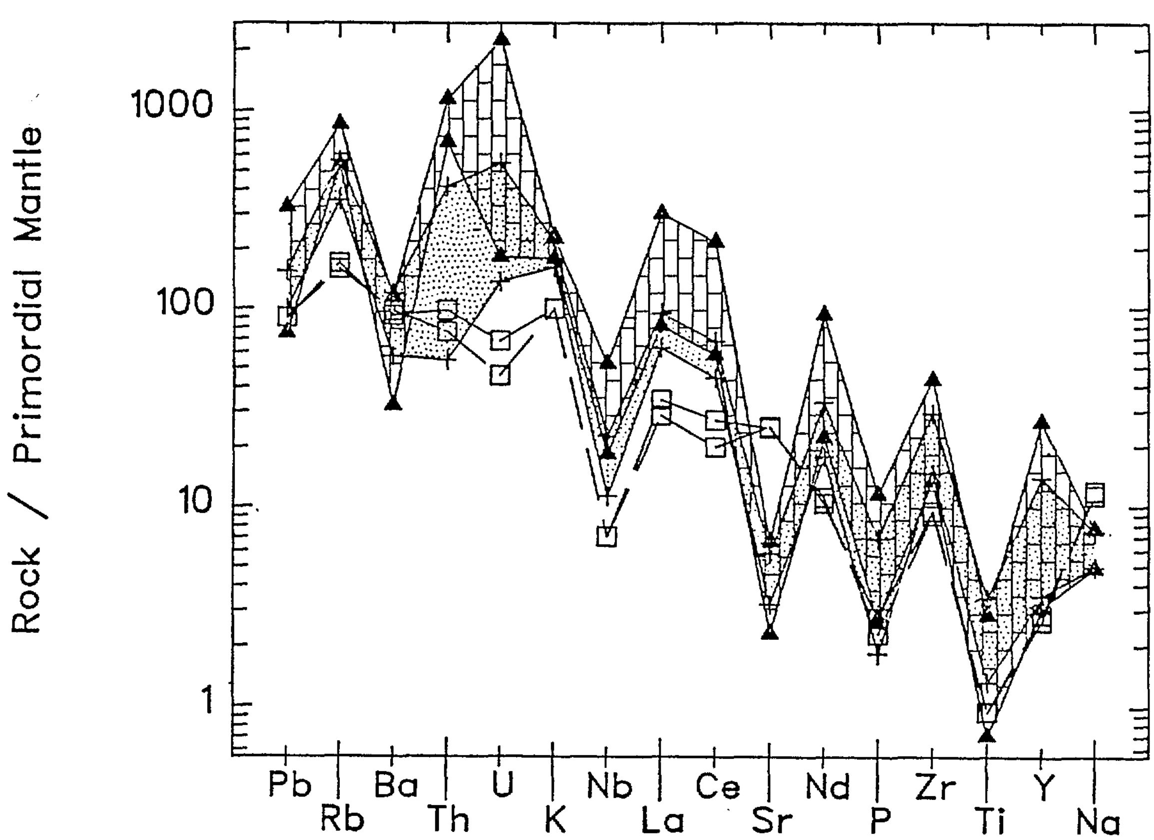


Figure 2 Element distribution envelopes for the Alarinjela suite (dotted pattern) and the Jinka suite (Bricked pattern). The element distribution for the Atnarpa Suite is illustrated by two samples of Alice Springs Granite (open squares).

representing three episodes of felsic igneous activity. The Atnarpa Suite of Sr-enriched, Y-depleted granites (Atnarpa Igneous Complex, Huckitta Granodiorite, Alice Springs Granite) has a less evolved chemical signature (Fig. 2), and represents a change from shallow melting in the earlier felsic activity to magma generation at greater depths.

Folding in the Arunta Block began with early flat-lying folds, and flat-lying thrusts, followed by more obvious upright folds. This sequence of structural events is typical of the Early to Mid Proterozoic history throughout northern Australia (Fig. 3).

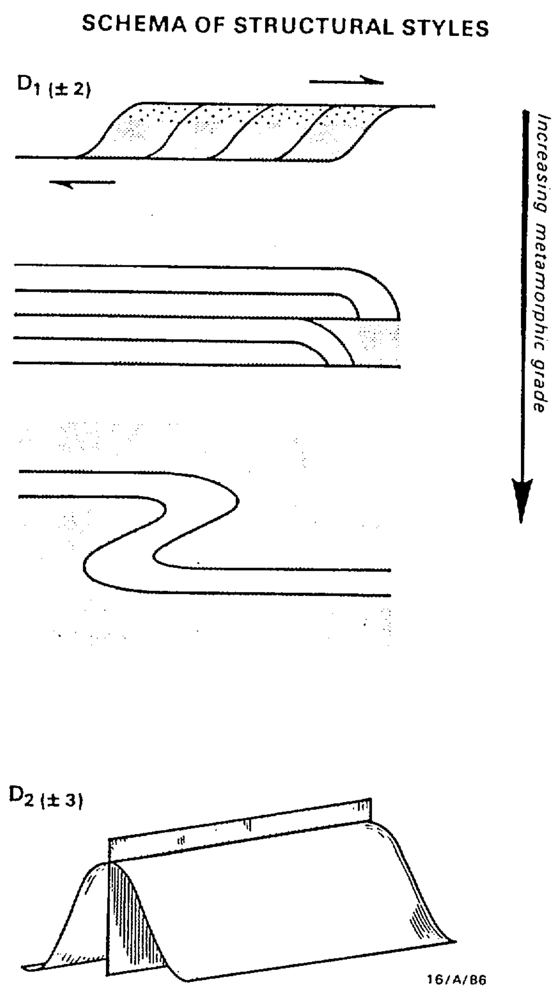


Figure 3. Structural styles in the Australian Proterozoic (after Etheridge & others, 1987).

The Arunta Block is dissected by faults, which in the high-grade areas may be zones up to several kilometres across of hydrous, schistose, retrogressed rocks, others are narrower and/or mylonitic. At higher crustal levels, in the poorly exposed northern Arunta Block, topograpically prominent quartz-filled fractures continue along the same trends as the major shear zones in the high-grade areas. Orientation of the faults ranges from flat-lying north-directed thrusts (extreme east) through upright (Delny-Mount Sainthill and the quartz veins) to shallow south-directed thrusts (southern margin). The Redbank Thrust Zone and other faults in the central west of the Arunta Block dip northwards at 30-45^{o}; seismic sections show that the Redbank Thrust Zone penetrates to the mantle (Goleby & others, 1989). In the Reynolds Range, the shears and faults dip north at the southern margin and fan to south-dipping at the northern margin (cross-section in Stewart, 1981).

Geochronology

The Arunta Block is poorly served by age determinations; many of the published data record deformation and/or metamorphism. Estimates of the age of formation of the rocks within the Arunta Block are based on correlation with the Tennant Creek Province to the north and extrapolation of the sketchy data available within the Block. Some of the extensive granites of the northern province (e.g., Dneiper, Alarinjela, Ali Curung) and possibly some of the deformed granites in the southern province are chemically similar to granites in the Tennant Creek Block dated at 1870$\pm$20 and 1846$\pm$8 Ma and so are correlated on compositional criteria with the extensive Proterozoic felsic igneous rocks emplaced at 1900-1840 Ma in the major episode of crustal growth in northern Australia (Wyborn & others, 1987, Wyborn 1988). A similar correlation for the felsic rocks in the central province is supported by isotopic studies: Sm-Nd studies on material from several localities in the central province show that these bimodal metavolcanics were derived from a source that separated from the mantle 2300-2000 Ma (Black & McCulloch, 1983, Windrim & McCulloch, 1983); by extrapolation, the chemically similar granites were derived from the same source, the age of which is common to the Proterozoic throughout northern Australia (Etheridge & others 1987; Wyborn, 1988).

Rb-Sr ages of high-grade quartzofeldspathic gneisses (metavolcanics of Division 1) in the central province of 1820±60 Ma, IR 0.704, 1800±25 Ma, IR 0.707; and 1790±35 Ma IR 0.708 (Iyer & others, 1976; Windrim and McCulloch, 1983; Black & others, 1983) cluster around 1800 Ma; and are interpreted to record high-grade metamorphism. The low Sr IRs for these Rb-rich rocks indicate a brief crustal residence prior to metamorphism, consistent with the correlation of these with the granites of similar composition with ages of 1870-1850 Ma in the Tennant Creek Block.

Blake and Page (1988) have shown that volcanics of the Hatches Creek Group in the Davenport Province of the Tennant Creek Block to the north are 1820-1810 Ma (preferred age of crystallization from zircon studies). Division 3 in the northern Arunta Block is correlated with the Hatches Creek Group, and there is close chemical similarity between the lopolith of Warimbi Porphryry which intrudes Division 3 in the Reynolds Range and felsic volcanics which occur in the Hatches Creek Group. It follows that the granites which intrude Division 3 are therefore probably younger than 1820 Ma: this applies to some granites in the central and western parts of the northern province.

Shaw & others (1984) give an age of 1750 Ma (Rb-Sr method, with an acceptable IR of 0.701) for the Jervois Granite in the northeast of the northern province. Chemically similar granites form small intrusions in the northern and central provinces west of the Jervois district, extend across much of the southern Arunta and occur in the Casey Bore Inlier. Cooper & others (1988) reported a zircon age of 1745(+9,-7) Ma for the Bruna Gneiss central east of the central province, which appears to be similar in chemistry. Collins & others (1989) have obtained zircon ages from the Reynolds Range region which they relate to metamorphic events at 1820, 1760 and 1730 Ma: the younger two ages appear to have overlap with events in the eastern Harts Range.

Nd-Sm analyses indicate a source age circa 1650 Ma, assuming an ϵ_{Nd}

value of +5 to +6 (M.T. McCulloch, ANU & S.-S. Sun, BMR, pers. comm.) for the Atnarpa Igneous Complex in the southeast of the central province and for the Alice Springs Granite. This is very close to the Rb-Sr whole rock age of 1651$\pm$47 Ma, IR 0.705, given by Black & others (1983) for the Atnarpa Igneous Complex, though the IR nevertheless suggests a metamorphic age. Thus the data suggest that the Atnarpa Suite was emplaced without the cycle of underplating and remelting which characterized most of the Proterozoic felsic activity in northern Australia.

Rb-Sr determinations in the Reynolds Range of 1670$\pm$87 Ma and 1647$\pm$65 Ma record metamorphism and/or resetting and also, possibly, granite intrusion at this time (Aileron event of Black & others, 1983). The Bonya Schist has a Rb-Sr whole rock age of 1625$\pm$50 Ma, IR 0.711 (Black, 1979). Pegmatites and related leucogranite in the northeast give Rb-Sr ages of 1680 to 1642 Ma. Resetting of the Rb-Sr system circa 1660 Ma is also recorded in the Davenport Province to the north. Thus there was a widespread thermal event in the northern Arunta province at about the same time as emplacement of the Atnarpa Suite in the southeast.

Inferrences which can be made from the geochronological data, coupled with the correlations with the Tennant Creek block include (i) Division 2 (except perhaps the Bonya Schists in the Jervois district) in the northern province is older than 1820 Ma; (ii) Division 1 in the central province (the Strangways Metamorphic Complex) is also 1820 Ma or older; (iii) zircon data (Cooper & others, 1988) show the Harts Range Group (Division 2 in the central province) is probably younger than Division 3 in the northern province.

K-Ar systems closed at about 1700 Ma in the extreme east of the Arunta (Warren, 1982). This is the only indication of the age of the rocks in the Arunta Block east of the Tarlton Fault.

K-Ar ages of about 1450 Ma in the northeastern Arunta (Hurley & others, 1961) are co-incident with Rb-Sr ages reported by Iyer & others (1976) in the central province, from sites now recognized as being close to deformation zones. Black & others (1983) reported a number of Rb-Sr determinations in the central north of the Block in the range 1400-1500 Ma. It seems probable that this was a period of deformation and, and at least in the northeast, uplift.

Reactivation of the southern province began at 1200 Ma with intrusion of small alkaline bodies (Langworthy & Black, 1975), followed by migmatites dated at 1100-1000 Ma (Marjoribanks & Black, 1974). Intrusion of mafic dykes at 900 Ma (Black & others, 1980) predates deposition of platform cover across central Australia. The Mud Tank Carbonatite was intruded circa 732 Ma (Black and Gulson, 1978).

Shaw (1987) has proposed a model for deformation and sedimentation in the cover sequence in central Australia that involved extension at mid-crustal levels during the early Palaeozoic: this mainly affected the central east (approximately the Harts Range region). Substantial deformation of cover and basement at the end of the Ordovician, and again in the Mid Devonian to Early Carboniferous, occurred across central Australia. K-Ar ages in parts of all three provinces record these events.

Prograde Metamorphism

Generally, the earliest recognizable episode of metamorphism is of the high-T, low-P type. Throughout much of the northern province the grade is upper greenschist or transitional amphibolite. Metapelites contain two-mica assemblages, andalusite and/or corderite. There was a remarkable lack of penetrative deformation in the low-grade rocks: outcrops that in the field appear to be untouched by metamorphism, for example, mudstone, dolerite or fresh acid porphyry, are found to be completely recrystallized in thin section. Granites and mafic dykes, particularly in the northern province, have been metamorphosed with little or no concurrent deformation. In general, metamorphic fabric is granoblastic, so that metamorphism came after or outlasted major deformation. In the Reynolds Range region, where there is continuous section from low- to high-grade metamorphites, the locus of prograde PT conditions crossed from the andalusite to sillimanite fields within the Crd-Kfs-Qtz-Bt-AS stability field (AS = aluminosilicate mineral): in this area, nearly all dehydration reactions occurred at comparatively low pressure, leaving only amphiboles, cordierite and biotite persisting as hydrous phases to higher grades, marked by the formation of migmatites, and by the incoming of garnet and/or orthopyroxene in pelitic rocks (Warren & Stewart, 1988; Fig. 4a).

In the central province (e.g., Edwards Creek and Mount Milton, Fig. 5), cordierite quartzites (high-grade equivalents of cordierite-anthophyllite rocks) contain cordierite, garnet and/or orthopyroxene with K feldspar. Sapphirine-bearing silica-undersaturated rocks are found in spatial association with these rocks, and also as pods in metasediments in the Reynolds Range region of the northern province.

Granulite-facies assemblages are believed to have formed through dehydration melting. Segregation of water-undersaturated melts varied with rock type, but the melt-fraction was essentially retained within the rocks in which it formed. Thus, the high-grade metamorphism was near-isochemical, reflected, for example, in high K_2O, high Rb, and low K/Rb being maintained in felsic rocks at granulite grade. Moreover fluid composition was locally buffered and fluid flow restricted; as is shown by Cal-Wo-Scp-Grs in areas with Opx-Cpx and Opx-Kfs (Warren & others, 1987). Therefore high heat flow did not result from fluid advection. The extremely high-T, low-P conditions and consequent elimination of muscovite by dehydration reactions below the minimum-melt curve are reflected in the paucity of S-type granites in the Arunta Block.

In the Strangways Range, central province, where Warren (1982) estimated P of 8 ± 1 kbars and T of 850-920 ^{o}C for the Mount Milton area, high temperatures are also indicated by high Al_2O_3 in orthopyroxene. The geobarometer based on Cpx-Pl-Qtz (Ellis, 1980) gives slightly higher values for pressure; but limits of uncertainty overlap at higher temperatures with those for barometers based on Grt-Opx-Pl-Qtz (Harley, 1981, Perkins & others, 1981). The compositions of co-existing Grt and Crd (*mg* Grt 40.5-43.6, *mg* Crd 85.1-89.7) are substantially in agreement with those predicted by Hensen & Green

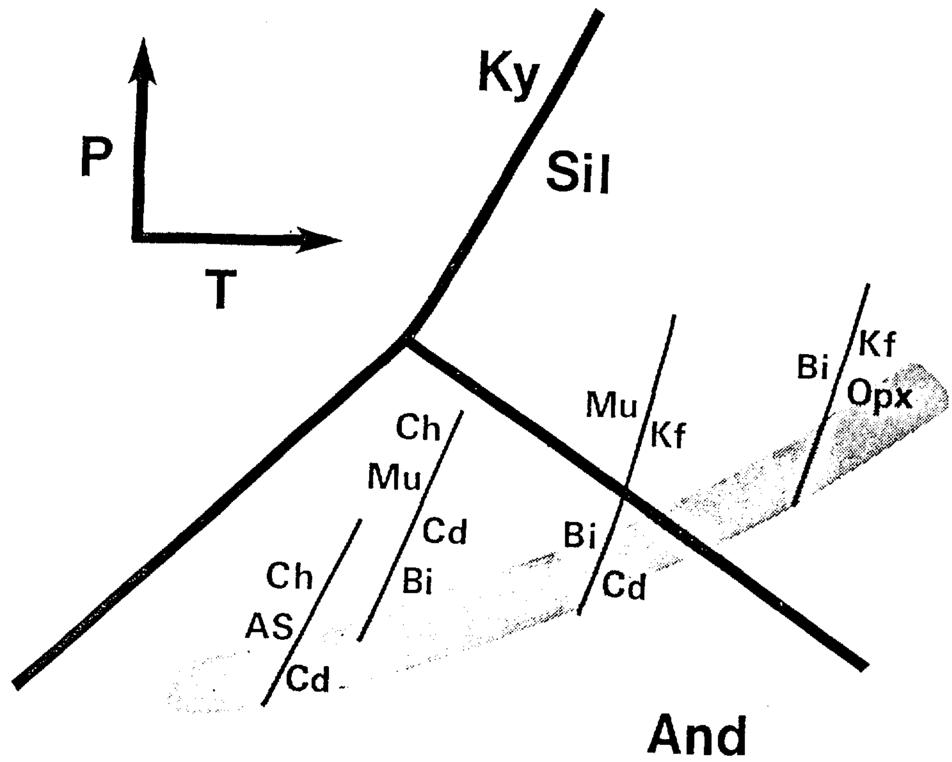


Figure 4a Locus of PT conditions for prograde metamorphism in the Reynolds Range region (after Warren & Stewart, 1988).

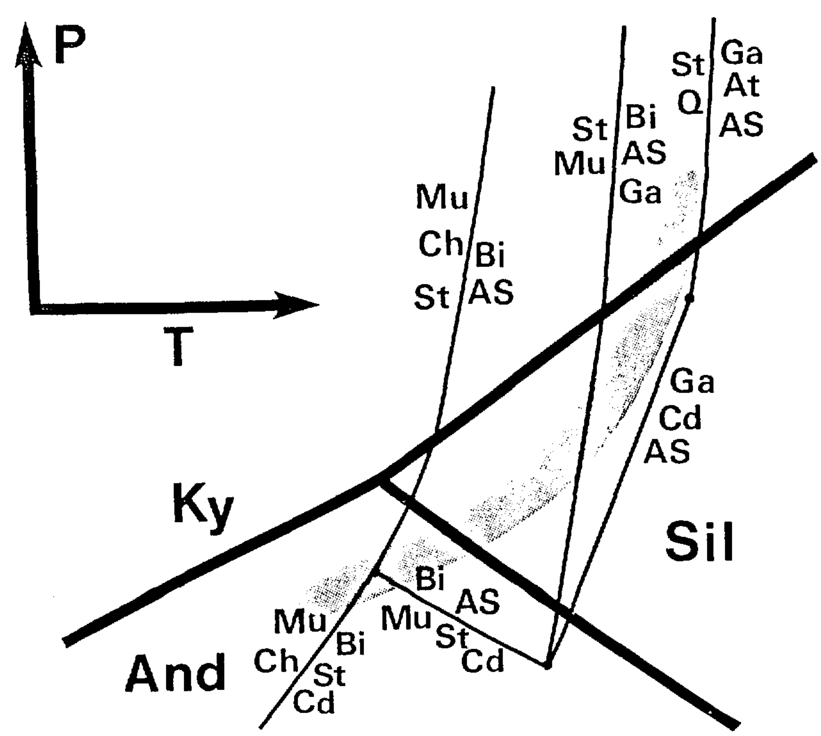


Figure 4b Locus of PT conditions for retrograde metamorphism in the Reynolds Range region (after Warren & Stewart, 1988).

TABLE 1 Localities, assemblages, and mineral data used to determine pressure conditions shown in Figure 4

Locality, *Petrology*	Data
1. Anmatjira Range *Grt-Crd-Sil-Bt* *Some Ga includes* *Sil needles*	Grt core *mg* 15.1, edge 13.0 Crd core 56.6, 57.1 K_D 7.3 Grt with Sil needles 17.3 Crd 67.3, adj. Grt 15.6, K_D 11.2
2a. Reynolds Range *Grt-Sil-Bt-Qtz-Ab* *Grt includes* *Sil needles*	Grt, no Sil, 24.5, 24.9 Grt with Sil 24.2, 25.4 Grt adj Bt 21.8, 19.2
2b. Reynolds Range *Grt-Crd-Sil-Bt-Qtz*	Grt core 17.1, edge 11.5 Crd 60.8 K_D 11.9 Grt 14.7, Crd 64.5, K_D 10.5
3. Reynolds Range *Grt-Sil-Cd-Spl-Kfs-Qtz-Bt*	Grt core 21.4, 23.1 edge 20.8, 18.2 Crd 70.7, 70.8, 70.9, 72.4 K_D cores 8.1, edges 10.8
4. Aileron district *Crd-Grt-Sil-Kfs-Bt* *Grt with Sil needles* *late Crd rims on Grt*	Grt core 15.8, 15.2 Grt with Sil 16.3 Crd 65.1, 70.7, 77.7
5. Rembrandt Rock *Grt-Crd-Spl-Kfs-Qtz*	Grt core 15.8, edge 12.6 Crd 53.7, 53.9 K_D cores 6.2 Crd adj. Grt 65.2, K_D 12.9
6. N Papunya turnoff *Crd-Grt-Sil-Kfs-Qtz-Bt*	Grt core 38.0 Crd 82.5, K_D 7.7 Grt core 34.9, edge 35.1 Crd 83.5 K_D 9.3
7. N Joker Bore *Grt-Crd-Qtz-Bt*	Grt 15 Crd 69.7 K_D 12.8
8. Mount Bleechmore *early Grt-Crd-Sil* *late Grt overgrowths*	early Grt core 19.2, 19.8 Crd core 72.6, K_D 11.2 late Grt, edge 24.3, 22.1 Grt overgrowth 22.1, 20.0 Crd adj. late Grt 70.8, 76.6, 77.6 K_D 10.2.
9. Black Point *Crd-Opx-Phl-Qtz*	Crd core 88.5 Opx 73.8 Al_2O_3 7.55%
10a. Kanandra Dam *Crd-Grt-Qtz*	Grt core 20.5, edge 22.5 Crd 77.1, 77.6 K_D 11.3 Grt euhedra 24.3 Crd 68.8, 70.1 K_D 7.3
10b. Kanandra Dam *Crd-Grt-Qtz*	Grt core 31.6, 30.8 Crd 78.7, 80.5, 79.6 K_D 9.7, 10.0
11. S Dingo Dam *Grt-Spl-Bt-Kfs-Qtz-Sil*	Grt core 29.6, edge 28.3
12. Middle Dam *Grt-Opx-Pl*	P 4±1 kbar[1]
13. Tower Rock *Crd-Opx-Kfs-Qtz-Bt*	Crd 76.4, 76.1 Opx 59.2 Al_2O_3 3.44%
Cpx-Opx-Pl-Qtz	P 4±1 kbar[2]
14. Deep Bore *Grt-Crd-Sil-Bt-Qtz* *Crd rims on Grt*	Grt core 21.5, 21.3 edge 16.4, 16.5 adj. Crd 58.3 K_D 7.08 Grt 12.0, adj Crd 62.8
Cpx-Opx-Pl-Qtz *(2 samples)*	P 5.5±1, 3.1±1, 6.7±1 kbar[2]
15. Oonagalabi *Cpx-Opx-Pl-Qtz*	P 11.5±1 kbar[2]
16. Edwards Creek	P 7.5±1 kbar[3]
17. Mount Milton	P 8±1 kbar, T 850-920°C[3]
18. Phlogopite Mine	P 9 kbar [4]
19. N Old Hamilton Downs HS *Grt-Crd-Opx-Bi-Qtz*	Grt 40.3, 43.6 Crd 87.9, 88.7 Opx 71.1, Al_2O_3 4.31%

1 method of Harley (1982),
2 method of Ellis (1980)
3 Warren (1982)
4 Green & Vernon (1974)

(1973) for P ~ 8 kbar. These values have been used as bench-marks to estimate pressures elsewhere in the Arunta Block where other acceptable geobarometers are not available (Table 1, Fig. 5).

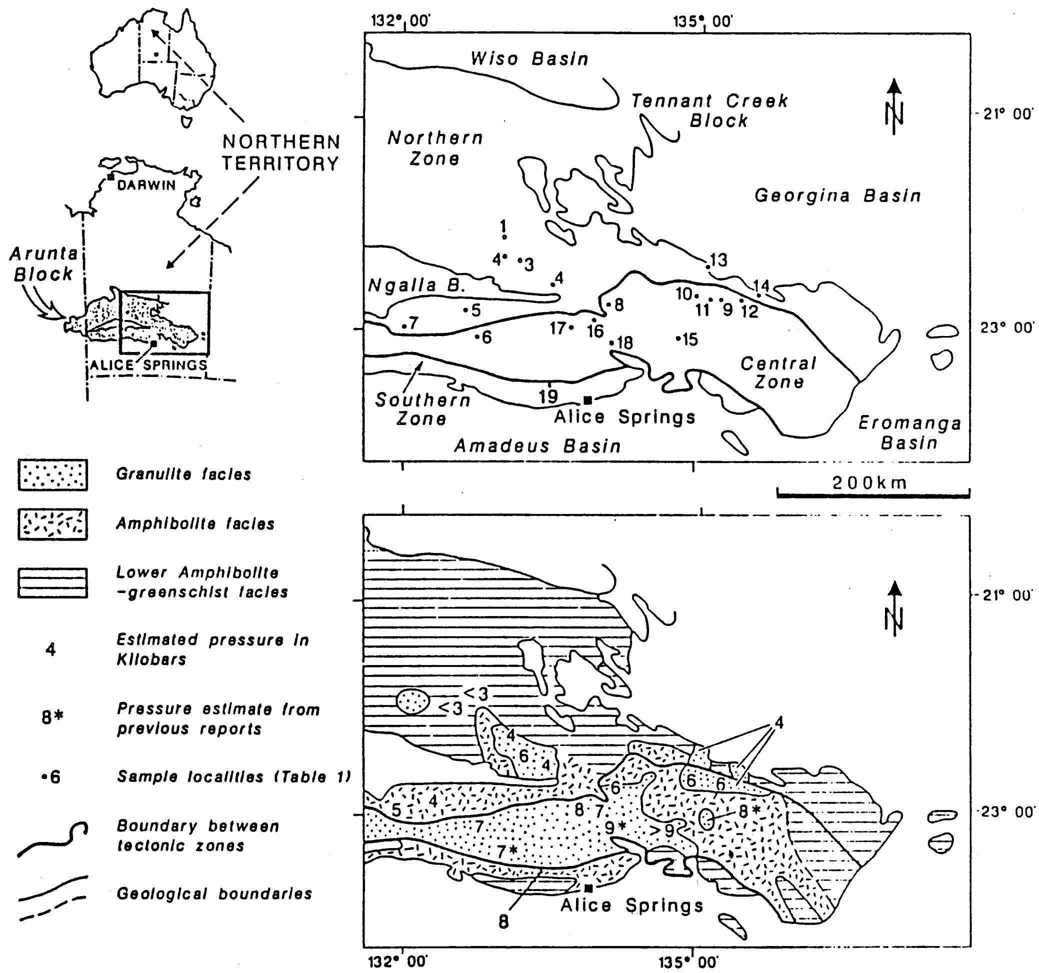


Figure 5a Localities for which PT data are available: Refer Table 1

5b Estimated pressures.

That metamorphism of the high-T, low-P type was widespread in the Arunta Block is indicated by the occurrence of relict quartz-spinel in several locations, south of the Ngalia Basin, in the Reynolds Range region and in the Deep Bore Metamorphics.

In the Reynolds Range, aggregates of sillimanite in the assemblage Crd-Qtz-Kfs-Bt-AS are interpreted as pseudomorphs after poikiloblastic andalusite, consistent with increase in pressure at high temperature. The widespread occurence of needles of sillimanite included in garnet suggests breakdown of precursor cordierite, also through increase in temperature.

Retrograde metamorphism during cooling

The pervasive formation of biotite at the expense of orthopyroxene-orthoclase in the granulites is believed to have involved water from the crystallizing partial melts component. In the mafic granulites, pyroxenes were invaded by retrogressive hornblende. In silica-undersaturated rocks, coronas of sapphirine or cordierite on spinel and of cordierite on sapphirine occur in association with phlogopite invasive into orthopyroxene. These coronas probably formed by reaction between restite spinel or sapphirine and K-rich melt during cooling (Fig. 6). Excess SiO_2 released during phlogopite formation also formed minute quartz grains in these otherwise silica-undersaturated rocks.

In lower grade rocks, cooling from peak conditions produced coarse grained muscovite rimming andalusite, and complex aggregates with andalusite cores zoned outwards through chlorite, muscovite and biotite, presumed to be after cordierite (Warren & Stewart, 1988).

The cooling has been described as near-isobaric. On a regional basis there is a good correspondance between high pressure prograde and retrograde zoning. Many reactions are consistent with near-constant pressure during cooling; cordierite in cordierite quartzites from the central province and part of the Reynolds Range region has fine-grained orthopyroxene-sillimanite$\pm$gedrite at the margins; and in the Mount Milton outcrops cordierite-sapphirine boundaries are overgrown by orthopyroxene-sillimanite. There is evidence of minor vertical adjustments, reflecting warping:- as for example, garnet overgrowths in garnet-cordierite rocks from the central province and the northern Reynolds Range region. In other localities cordierite rims garnet-sillimanite, apparently recording uplift of a few kilometres (i.e., about a kilobar); in these areas fine-grained symplectitic breakdown of garnet to cordierite-orthopyroxene has also been observed.

Retrogression related to the shear zones

Intense later retrogression is localized in and immediately adjacent to shear zones. Textures and mineral assemblages in these rocks

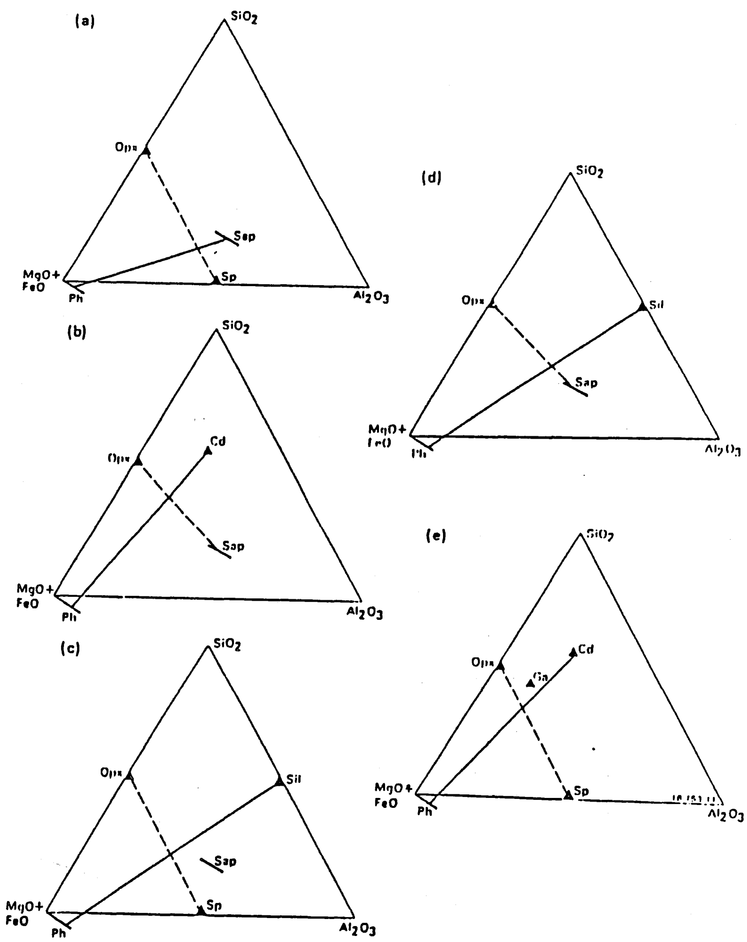


Figure 6. Products of the reactions between K-rich melt and restite minerals, indicated by dotted lines during cooling in silica-undersaturated rocks. Phlogopite projected from K feldspar.

indicate a prolonged and repeated history of deformation and hydration. In the granulite regions the earliest assemblages in the shear zones formed in the kyanite stability field; in the Reynolds Range the retrogression is zoned regionally into And, Sil or Ky bearing assemblages which show the same distribution from low to high pressure as the zoning of the prograde metamorphism. Partial retrogressed rocks close to shear zones are particularly informative, as in these incomplete overprinting reactions are preserved, which allow the construction of a PT locus for the retrogression (Warren & Stewart, 1988). Formation of some shear zones may have involved fluid circulation to great depths, shown by development of high-P hydrous assemblages in granulite areas. Metasomatism related to fluid movement can be demonstrated in some shear zones: orthoschist in the Reynolds Range which has been depleted in sodium and calcium, large nodules of kyanite, biotitite and garnet-biotite rock and quartz veins in the shear zones all demonstrate considerable element-mobility.

Retrogression without hydration in the vicinity of faults has produced garnet overgrowths in two-pyroxene granulites. These are particularly well-developed in the Mount Hay - Mount Chappell massif, but have also been described from the northern and eastern margins of the Strangways Range, where they give PT conditions consistent with the kyanite-gedrite retrogression in near-by hydrated rocks.

Evidence for the PT path during unroofing has been obtained from the shear zones on the edge of the northern Strangways Range. In this area kyanite, gedrite and staurolite are corroded and embayed by cordierite, and some of the kyanite is pseudomorphed by sillimanite. Where this late cordierite co-exists with garnet, K_D Grt-Crd is considerably higher than for the prograde association (K_D>20, compared to 9-10), showing that the late garnet and cordierite equilibrated at considerably lower temperature and after uplift, of a few kilometres (i.e., a change in pressure of about a kbar). This was followed by renewed near-isobaric cooling, during which sillimanite, gedrite and staurolite once more formed as fine grained phases along cordierite grain boundaries. Narrow zones with quartz-chlorite assemblages are the latest phase of the retrogression.

Tectonic Processes

The metamorphic evolution can be subdivided into three major tectonic phases. The first involves deposition, igneous activity, deformation and metamorphism in the Early Proterozoic; the second, reworking of the southern province and deposition of the cover sequence; and the third, formation of the shear zones. The second and third overlap in time.

Etheridge & others (1987) have developed a tectonic model invoking extension to explain the main features in the development of the Early Proterozoic crust in northern Australia. This involves underplating by mantle-derived material, sag and rift phases of sedimentation with bimodal volcanism, emplacement of granites, deformation, and finally metamorphism. Shaw & others (1984) suggested the final stage involved A-subduction, similar to that in the generalized model of Kröner (1983, 1984). (See also Kerr, 1988.) Thus it is proposed that the Arunta Block formed substantially through vertical accretion; with initial extension involving rifting, sedimentation, and addition of new crustal material, followed by a compressional phase, driven by delamination of the lower crust. This reconstruction of the evolution accounts for the rapid downwarping of the felsic volcanics of the central province, compressional folding, metamorphism in a regime of high heat flow and subsequent cooling under near-isostatic conditions (cf Warren, 1983; Wickham & Oxburgh, 1985). A modification to the above interpretation is to suggest that metamorphism occurred in a second cycle of underplating and extension (e.g., following the model of Sandiford & Powell, 1986), without A-subduction and compression. Such a model would permit a time-gap between formation of protolith and metamorphism; and would account for the lack of deformation accompaning peak conditions, especially apparent in the granites of the northern tectonic province, and for the observation that the last event to preceed metamorphism was intrusion of mafic dykes.

Events from 1200 Ma onwards in the southern province suggest renewed underplating (intrusion of the Mordor Complex), heating (development of migmatites) and extension (intrusion of the Stuart Dyke Swarm, deposition of platform cover). These were perhaps related, as suggested by Shaw & others (1984), to development of the Musgrave Block to the south.

Shaw & others (1984) proposed a tectonic model in which the Arunta Block formed in cycles of successive extension, sedimentation, deformation and metamorphism: this remains a valid model: see also James and Ding (1988). In the last cycle the Late Proterozoic to Palaeozoic cover was deposited over the metamorphic rocks of the Arunta Block.

The present distribution of prograde PT conditions (Fig. 5) is the result of differential uplift with relative movement taken up on the shear zones. The questions of the age of the shear zones and time of unroofing of the high-grade regions remain unresolved. The shear zones appear to have had a prolonged history of reactivation, probably originating in the early development of the Block and acting as zones of weakness thereafter, reaching their final form in the Palaeozoic. The faults in the northeast and east of the Arunta Block controlled Late Proterozoic sedimentation (Walter, 1980). High grade rocks along the northeast margin had reached the surface before this time, probably circa 1450 Ma, when the K-Ar system was closed. Elsewhere cover rocks are seen to rest only on low grade basement. Only one example of cover rocks caught in a shear zone cutting high-grade rocks is known, from the northeastern Strangways Range. K-Ar ages show that the shear zones were active during the Mid Palaeozoic Alice Springs Orogeny, so it is possible that the major unroofing of some areas occurred as late as this.

PART 2

THE EXCURSION:- ITINERARY AND LOCALITY DESCRIPTIONS

PROPOSED ITINERARY

June 25 Assemble Alice Springs. Depart approx 1400 hrs, travel to Reynolds Range region.

Camp Mount Stafford district

June 26 Traverse southeast Mount Stafford. Low to high prograde metamorphism in the andalusite-stability field. Metamorphosed post-granite mafic dykes.

Camp Woodforde River

June 27 Woodforde River valley: partial melting, KFMASH silica undersaturated assemblages; Peaked Hill: retrogressive assemblages in pelites; Gas Pipeline: partial melting in pelites

Transfer to Strangways Range, camp north of Mount Milton

June 28 North of Mount Milton: granulite-facies metamorphism of felsic, mafic, silica-undersaturated and calc-silicate rocks; Yambah Schist Zone: retrogression of similar rocks.

Camp near Edwards Creek

June 29 Edwards Creek Prospect: multiple hydrous retrogressions of granulites, mainly KFMASH assemblages; South of Mud Tank: metamorphosed Late Proterozoic cover, dry retrogression of mafic rocks, with late garnet, Mud Tank Carbonatite

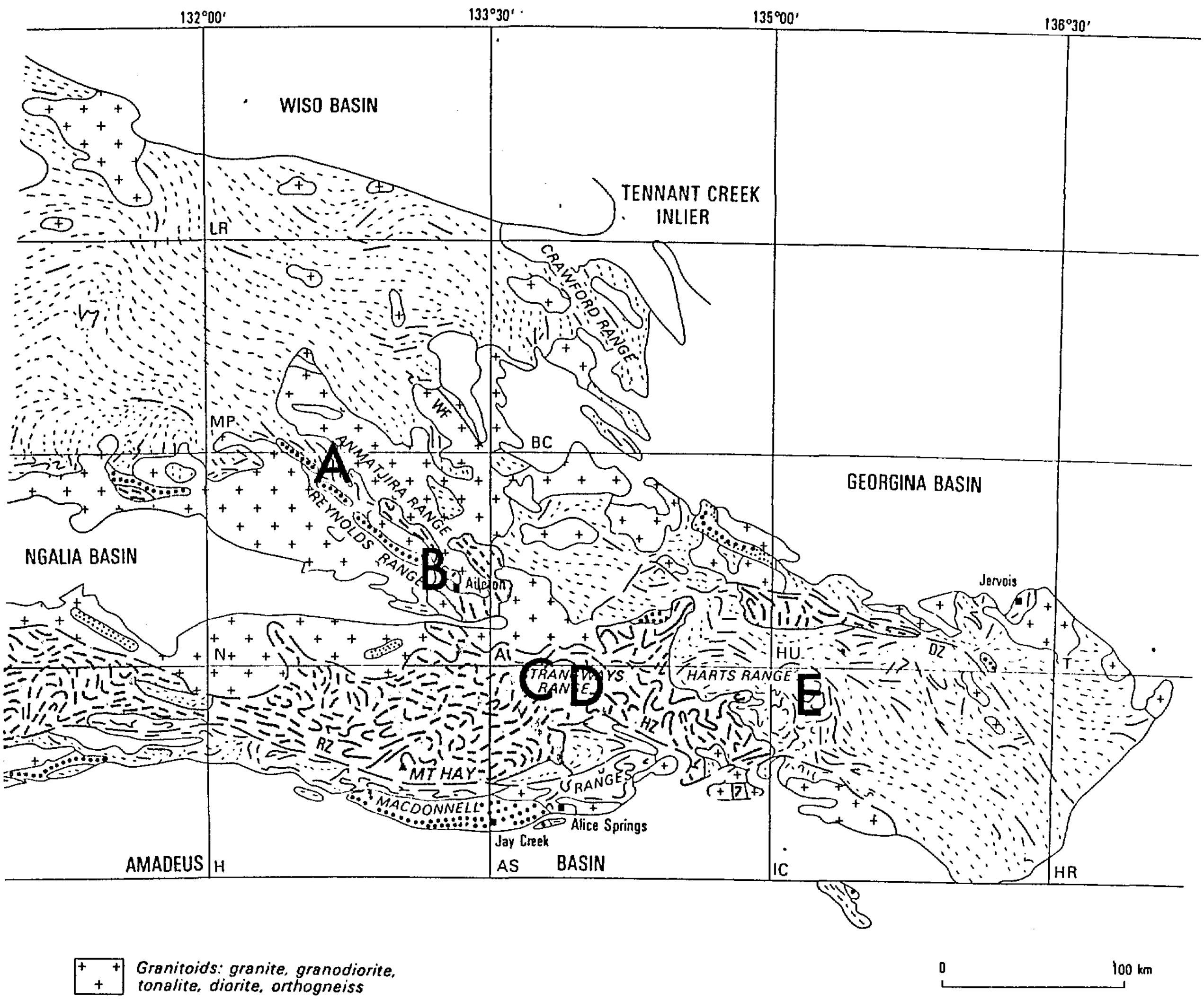
Transfer eastern Harts Range, camp near Valley Bore

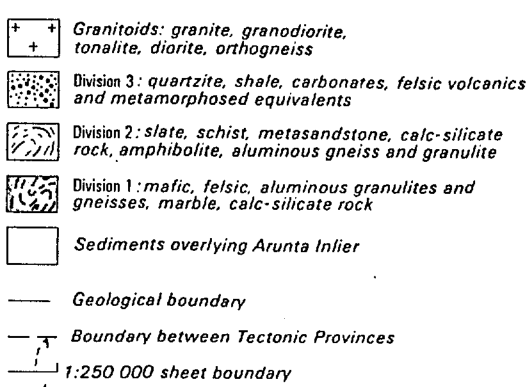
June 30 Metamorphism of pelites and calc-silicates at upper amphibolite to granulite grade, retrogression or upper plate-lower plate relationships involving cordierite-bearing assemblages in the eastern Harts Ranges.

Camp near Arltunga

July 1 *Return to Alice Springs*

Figure 7 Part of figure 1, showing the districts in which the stops are situated.





A Mount Stafford District

B Eastern Reynolds Range

C Northern Strangways Range

D Mud Tank District

E Eastern Harts Range

Roadside Geology, Day 1 Airport - Alice Springs - Reynolds Range

The Alice Springs airport is situated in the Amadeus Basin sequence, south of Alice Springs. The road to town passes through the Blatherskite ridge, a steeply dipping ridge of Heavitree Quartzite, the basal unit of the Amadeus sequence, within the folded thrust slice of the Blatherskite Nappe. After crossing poorly exposed Arunta rocks north of the Heavitree Quartzite ridge, the road passes over the concealed fault and reaches a second ridge of Heavitree Quartzite at Heavitree Gap, on the southern outskirts of Alice Springs. The unconformity, which is somewhat deformed, is exposed in the cutting for the railway, immediately west of the road.

Small hills within the township are Alice Springs Granite, probably intruded at about 1650 Ma. Metamorphic foliation results in elongate bouldery outcrop. The red sandstone used to face several buildings in the town is Arumbra Sandstone from the Amadeus Basin Sequence. This unit, of latest Proterozoic to Cambrian age, is noted for its trace fossils: casts of medusa and other soft bodied organisms.

North from Alice Springs the road climbs through hills of Alice Springs Granite and crosses the Charles River Fault, the same folded thrust as in the Blatherskite Nappe. North of the Charles River Fault the road passes through migmatitic gneiss, megacrystic gneiss, and amphibolite of the southern tectonic province. About 300m south of the Tanami road junction (16 km north of Alice Springs) there is an abrupt change in landscape which is the surface expression of the Redbank Thrust Zone, a major east-west, north-dipping fault extending down to mantle depths (Goleby & others, 1989; refer Fig. 8).

North of the Redbank Thrust Zone, the flat landscape of mulga scrub and spinifex overlies Tertiary sediments. About 40-50 km north of Alice Springs the road passes through low rises of laterite overlying Arunta rocks, and near the junction of the Plenty River road boulders of granulite are exposed in the road verges. The road north continues over Tertiary sediments as far as the Hann Range (Native Gap), where it passes through a ridge of Vaughan Springs Quartzite. This, the lateral equivalent of the Heavitree Quartzite, marks the southern margin of the Ngalia Basin. A short distance north of the Hann Range, the road crosses the concealed overthrust northern margin of the Basin and passes through the low hills of granulite and orthogneiss at the eastern end of the Reynolds Range.

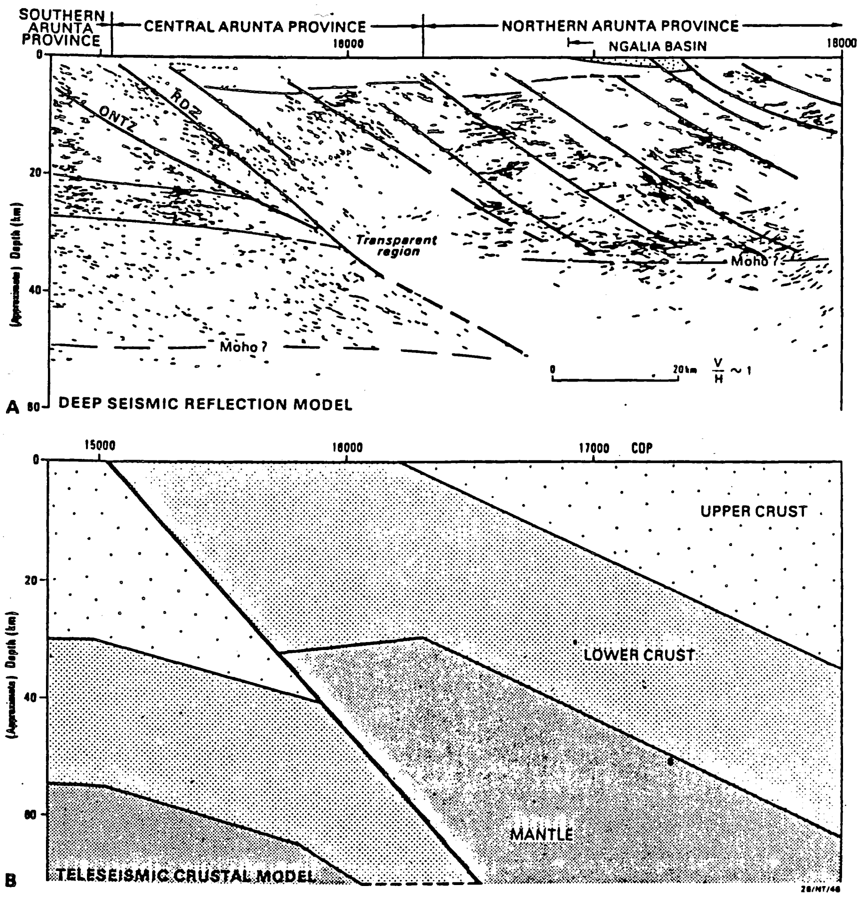


Figure 8 Interpreted crustal structure of the Arunta Block from the deep Seismic data. RDZ refers to the Redbank Thrust Zone, ONTZ to the Ormiston Nappe and Thrust Zone. (a) Deep seismic-reflection model and (b) Teleseismic crustal model, based on the observed teleseismic travel-time data. (after Goleby & others, 1989).

About 20 km north of the settlement of Aileron, the excursion turns off from the Stuart Highway to follow a station access road that runs through the valley between the Reynolds and Anmatjira Ranges, both containing orthogneisses and metamorphic rocks of granulite to greenschist grade. The topography of this district is controlled by the major zones of retrogression that dissect the high-grade rocks. West of Pine Hill homestead, the road crosses a divide between the drainage basins of the Hansen and Lander Rivers through a saddle in orthogneiss. One of the metamorphosed mafic dykes that cut the granites is exposed in this saddle.

A Mount Stafford District RHV, WJC, GLC

General Statement

At about 1820 Ma, amphibolite to granulite facies metamorphism and partial melting occurred at remarkably low pressure (around 2.5-4 kbar) in a small area (260 km^2) of metapelites, metapsammites and less abundant mafic intrusive rocks around Mount Stafford, in the northwest Anmatjira Range (Fig. 1). The rocks belong to the Lander Rock Beds, part of Division 2 (Stewart & others, 1984). They were deposited circa 1870 Ma, on the basis of stratigraphic correlation with units in the Davenport Province of the Tennant Creek Inlier to the north (Blake & Page, 1988).

The metamorphic grade varies from low pressure amphibolite facies in the southwest to low-pressure granulite in the northeast, over a lateral distance of only 10 km (Fig. 9), indicating a local thermal gradient of about 75^{o}/km. Despite the high metamorphic grade, many sedimentary and igneous structures are well preserved and foliations are relatively weak, although strong multiple deformation characterizes metapelitic layers in places. The rocks have been subjected to three episodes of syn-metamorphic folding, involving a layer-parallel foliation locally deformed by recumbent folds that are overprinted by upright folds.

Three episodes of folding occurred during high-grade metamorphism in the Mount Stafford area. High-grade rocks in the Mount Weldon area, immediately southeast of the Mount Stafford area, have been each affected by two or three episodes of folding that have minor or no expression in the Mount Stafford area (Collins & others, 1989a). Moreover, U/Pb dating of zircon grains with the ion microprobe (Collins & others, 1989b) has shown that both the Mount Weldon and the Reynolds Range metamorphisms are temporally distinct from each other and from metamorphism/deformation in the Mount Stafford area. Therefore, the Mount Stafford metamorphism is labeled "M_1" and the accompanying folding episodes are labelled F_{1a}, F_{1b}, and F_{1c} as follows:

Mount Stafford	M_1 (circa 1820 Ma)	F_{1a}, F_{1b}, F_{1c}
Mount Weldron	M_2 (circa 1760 Ma)	F_{2a}, F_{2b}, F_{2c}
SE Reynolds Range	M_3 (circa 1730 Ma)	F_{3a}, F_{3b},

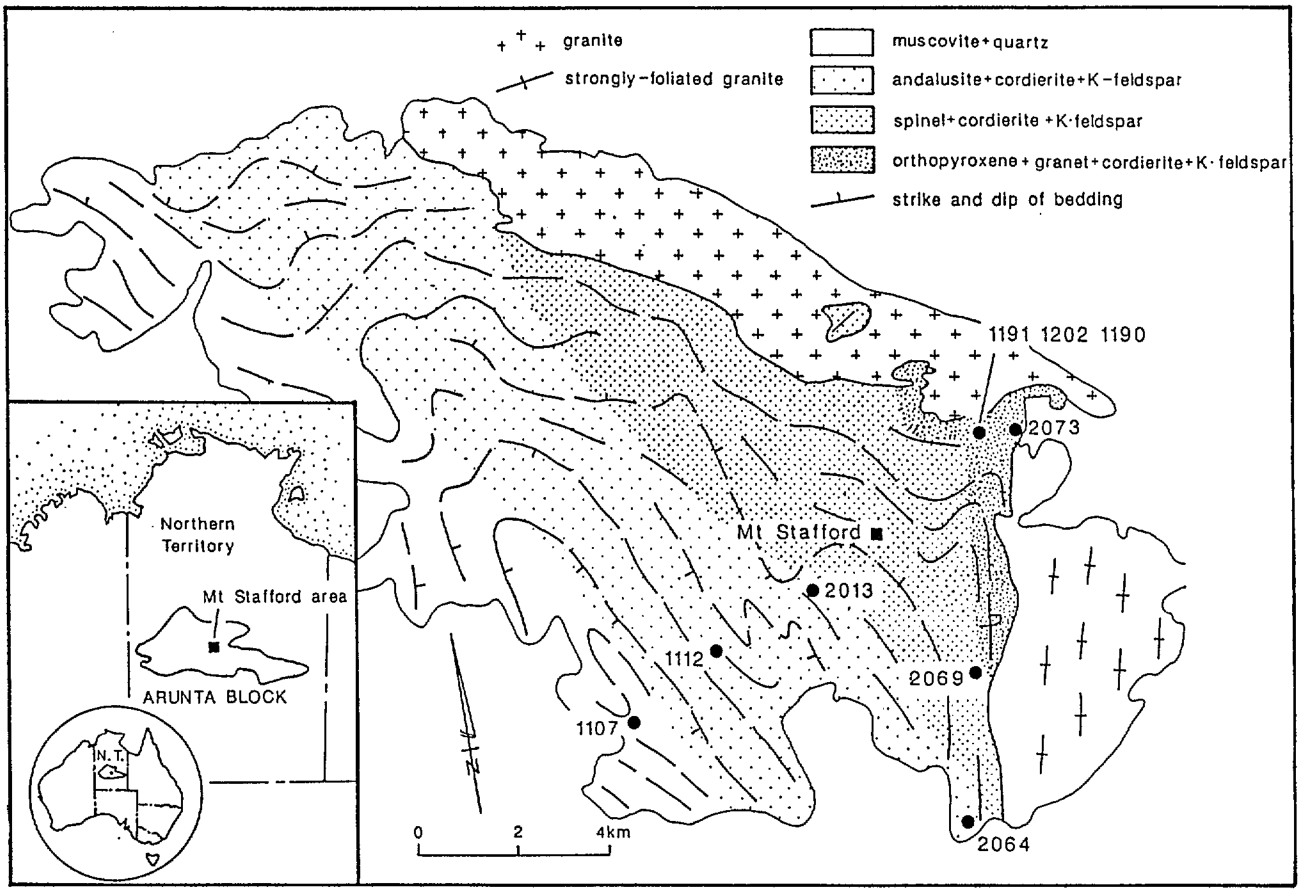


Figure 9 The Mount Stafford district, showing the metamorphic zonation.

Metamorphic zones at Mount Stafford are : (1) muscovite, (2) andalusite-cordierite-K feldspar, (3) spinel-cordierite-K feldspar, and (4) orthopyroxene-cordierite-K feldspar. Peak metamorphic conditions of about 750°C and 2.5 kbar were attained during the second and third episodes of folding (F_{1b} and F_{1c}) in lower-grade rocks, but during the first and second episodes (F_{1a} and F_{1b}) in highest grade rocks, on the basis of rare leucosomes occurring in S_{1a} (Vernon & others, 1989).

Exceptionally low pressure during melting is reflected in the common presence of magmatitic andalusite in leucosomes, which are typically devoid of plagioclase (Vernon & Collins, 1988). This lends support to the relevance of the andalusite-sillimanite equilibrium curve (Richardson & others, 1969), since it appears that insufficient fluorine or boron were available to move the revelant melting curve to low enough temperatures to intersect the relevant melting curve to low enough temperatures to intersect the andalusite-sillimanite curve of Holdaway (1971). Melting was unfocussed so that nebulitic, rather than stromatic migmatites were produced. Igneous microstructures are preserved in leucosomes, owing to the weakness of penetrative deformation and accompanying recrystallization during and after melting (Vernon & Collins, 1988).

The melts did not escape from the source rocks, so that crystallization during cooling released water and probably potassium, which reacted with cordierite and some K feldspar to form unusually abundant, pseudomorphous, symplectitic intergrowths of andalusite, biotite and quartz, probably during an increase in pressure. These intergrowths resemble intergrowths after cordierite in some other low-pressure complexes, such as Cooma (Vernon, 1979, 1982; Vernon & Pooley, 1981) and Wongwibinda (Vernon, 1982). The symplectite is abundant in higher-grade rocks, probably because the water was released while the temperature was high enough to stabilize cordierite + K feldspar.

Continued metamorphism during the third episode of folding (F_{1c}), as well as during later local thrusting of the adjacent Mount Weldon terrane (Colins & others, 1989; Clarke & others, 1989) over the Mount Stafford rocks, produced higher pressure (up to about 4.3 kbar) assemblages while the rocks were cooling. Thus, the Mount Stafford rocks provide good evidence of an anticlockwise PTt path. This is anticipated from the common observation that minerals are known to grow during a folding phase (i.e., during limited crustal thicking) in low-pressure metamorphic terrains.

The unusually high temperature at high crustal levels in the Mount Stafford area requires local upward transfer of heat through intrusion of magma. This was probably granitic magma (Stewart & others, 1980), as all mafic rocks in the area were metamorphosed at the peak of metamorphism. Granitoid intrusions tend to occur in the higher-grade parts of the Mount Stafford area, but trangress metamorphic zones. However, they could have been responsible for local heat transfer, eventually breaking through concentric metamorphic zones, as in the model of den Tex (1963). Such a process can account for the relatively local nature of the regional metamorphism, its unusually low pressure, and the relatively fine grainsize of some of the rocks (reflecting a relatively short period of heating). However, some more regional heating, persumably by unexposed mafic intrusions (cf Shaw & others, 1984), is necessary to explain the the regional nature of the metamorphism, in contrast to more locallized contact around high-level granitoid plutons in areas that have not been regionally heated. The regional heating possibly may be explained by the model of Loosveld & Etheridge (1989), involving asthenospheric rise as a consequence of the detachment of a root of upper mantle due to convective instability produced during lithospheric thickening (cf Kerr, 1988).

The traverse for Day 1 goes from the muscovite zone through the andalusite-cordierite-K feldspar zone almost to the spinel-cordierite-K feldspar zone (Fig. #). The highest-grade rocks occur in the northeast and east of the area: their characteristics are similar to those of the highest grade rocks we will observe. Photomicrographs and field photographs of the highest-grade rocks, as well as photomicrographs of rocks at stops 4, 5 & 6 will be available.

Stop 1 Lander River Muscovite-grade outcrops

Low-grade turbidites of the Lander Rock Beds typically form low outcrops in the Lander and Hansen River valleys. Bedding (S_0) is subvertical and is defined by alternating psammitic and pelitic layers. A strong cleavage (probably S_{1c}) is sub-concordant with S_0, reflecting the upright, southeast-trending, tight to isoclinal folds that are typical of these low-grade rocks. These folds control the outcrop pattern in the Mount Stafford area (Fig. 9)

The relatively low-grade (muscovite zone) schists at this locality consist mainly of muscovite, biotite and quartz, with or without minor tourmaline, ilmenite and apatite. Detrial quartz grains and sedimentary structures (including bedding, graded bedding and ripple cross-laminations) are commonly visible in the muscovite zone. In thin section, the S_{1c} cleavage is seen to be defined by folia of fine-grained white mica that anastomose around detrital rock and mineral fragments. Mafic rocks in this zone have relict igneous microstructures, masked to various degrees by growth of fibrous blue-green amphibole.

Stop 2: Locality 1107, Fig. 9

Here the metapelitic beds are characterized by dark cm-scale clots, orginally cordierite, which give these rocks (and most of the rocks in the Mount Stafford area) a spotted appearance. The rocks are generally coarser-grained than at Stop 1, but graded bedding is apparent, indicating that the rocks are right-way-up. They form the hinge of a shallow, doubly-plunging anticline, but are folded through a synclinal axis 150 m to the north. A weak upright cleavage (S_{1c}) is axial planar to the fold.

In thin section, the metapelites consist of granoblastic microcline-perthite, interspersed with aggregates of red-brown biotite, irregular to subrounded porphyroblasts of cordierite (entirely pseudomorphed by fine-grained symplectic aggregates of andalusite, biotite and quartz), and irregular porphyroblasts of andalusite (locally with symplectic fringes of quartz and andalusite in optical continuity with the porphroblasts). Retrograde muscovite is also present, along with very minor, local, fibrous sillimanite that probably grew during the last stages of metamorphism (syn F_{1c}), after the thermal peak. The biotite and elongate cordierite porphyroblasts outline the main foliation (S_{1c}, which is perpendicular to the bedding (S_0) in the hinge of the fold, and traces of S_{1a} or S_{1b}, slightly oblique to S_0, are also revealed by local weak alignment of biotite and former cordierite.

Stop 3: Locality 1109, Fig 9: Andalusite-cordierite-K feldspar Zone

Here metapelite and psammitic schists are well laminated. The rocks occur on the northern limb of the F_{1c} syncline near stop 2. They dip moderately steeply (55^o) to the southwest. A weak foliation (S_{1a}or S_{1b}) is sub-parallel to bedding and is overprinted by the regional, southeast-trending subvertical foliation (S_{1c}).

At this stop, rocks in the andalusite-cordierite-K feldspar zone have reached temperatures high enough to produce local partial melting. Leucosome patches vary from diffuse to locally aligned in S_{1c}, and a few pegmatitic patches with tourmaline are visible. Most leucosome is confined to the metapelite layers, which also show dark cordierite porphyroblasts which are extensively to completely replaced by fine-grained symplectic intergrowths of andalusite, biotite and quartz. The observation that leucosome material has not escaped from the rocks indicates that water was released from the rocks into the adjacent rocks from the leucosome as it crystallized. This water (possibly with some potassium) could account for the extraordinary abundance of symplectite replacing cordierite and some K feldspar in rocks of the Mount Stafford district.

Stromatic migmatites are rare in the Mount Stafford district where nebulitic types predominate. Possibly this is due to the lack of focussing of water into specific narrow layers, and may reflect the relatively low state of deformation of the rocks when the melting occurred. In turn, this may have prevented the localization and accompanying recrystallization into leucosome layers (as is common in stromatic migmatites), so that igneous microstructures were preserved iin the leucosomes (Vernon & Collins, 1988). Fine bedding laminations are preserved in more psammitic layers.

Late fibrous sillimanite occurs in all these rocks, but it mostly post-dates the symplectic (which is itself random and post-deformational), and so probably formed during M_2. Some foliated sillimanite may have formed during F_{1c}. No prograde sillimanite occurs in the Mount Stafford district, all sillimanite having grown after the thermal peak, during an increase in pressure associated with F_{1c} folding and especially with F_2 thrusting of the Mount Weldon terrain over the Mount Stafford terrain.

Stop 4: Locality 1112

Sedimentary boudinage and slump breccias are common in this area, as shown by rotated metapsammite blocks in metapelite and the converse. In these blocks, $S_{1a/1b}$ is commonly very oblique to S_0, indicating rotation before the earliest tectonic deformation. Neither S_0 nor $S_{1a/1b}$ are regionally consistent; only S_{1c} (trending northwest-southeast) has a constant orientation.

The structural complexity is complicated by the greater degree of melting at this locality, compared to Stop 3. Here, rocks in the andalusite-cordierite-K feldspar zone have reached temperatures high enough to produce extensive partial melting, the leucosomes being diffuse and pervasive, although some have segregated into pegmatitic patches or pods aligned in S_{1c}. Dark porphyroblasts are cordierite that has been replaced, extensively to completely, by fine-grained symplectitic aggregates of andalusite, biotite and quartz. Prismatic pink andalusite occurs in uncommon pegmatitic leucosome patches and patchy leucosomes also contain rare K feldspar megacrysts. Idioblastic andalusite in plagioclase-free melt implies exceptionally low pressure, and so supports the andalusite-sillimanite curve of Richardson & others (1969).

Stop 5

Along the track to the gorge, euhedral pink andalusite occurs in uncommon pegmatitic pods of leucosome in metapelite. Mafic rocks here are two-pyroxene granofelses with brown hornblende, even though adjacent metapelites contain andalusite. This situation in the granulite facies is abnormal, and reflects the abnormally low pressure of the Mount Stafford metamorphism. The mafic rocks here are typical of those co-existing with metapelites in all three of the highest-grade zones.

Stop 6: (Locality 2013: Fig 9)

Excellent exposures at this locality show recumbent isoclinal F_{1b} folds outlined by dark metapsammitic layers (S_0). Metapelitic layers show abundant dark porphyroblasts of altered cordierite, whereas more psammitic layers show a strong foliation (S_{1a}) that has been folded, along with S_0, by the F_{1b} folds, which themselves have been gently folded by upright F_{1c} folds. However, no S_{1c} foliation is apparent. Furthur to the east, F_{1a} are consistently west-verging.

The rocks here are at the high-grade edge of the andalusite-cordierite-K feldspar zone, bordering on the spinel-cordierite-K feldspar zone (Fig. 9); higher-grade rocks look similar in the field. Metapelites are typically nebulitic migmatites with diffuse leucosomes. Metapsammitic rocks tend to be finer-grained and some resemble hornfelsic rocks. Graded bedding is preserved locally. Higher-grade rocks show microstructural evidence of late reations indicating increase of pressure during cooling (Vernon & others, 1989).

B Eastern Reynolds Range RGW BJH

Stop 7: Woodforde River Valley:- Silica-undersaturated assemblages.

Exposures in the hills west of the Woodforde River consist of metapelite with mafic pods of the Lander Rock Beds (Division 2) overlain by quartzites (Mount Thomas Quartzite) and metapelites (Pine Hill Formation) of the Reynolds Range Group (Division 3). These are intruded by granite, now also metamorphosed. The metapelites contain Crd, with Kfs, Qtz and Bi; Sil is common, Grt less so. Opx is rare, occurring in the assemblage Qtz-Kfs-Crd-Opx$\pm$Bi. The mafic rocks are almost everywhere retrogressed, but two-pyroxene assemblages are locally preserved. Partial melting is extensive, and the granites contain garnet-bearing migmatites.

The area lies north of the Woodforde River Shear, a wide (one to several kilometres) zone of anastomosing sheared and deformed rocks. Narrow shears cut through the high-grade rocks, and extensive late hydration affects rocks close to the shears. Altered cordierite in this area contains biotite and kyanite.

Several small outcrops of silica-undersaturated rocks have been found in these hills. These are generally resistant tough dark granofels forming pods with dimensions ranging from less than one metre to several metres, The earliest discoveries were close to the unconformity between Divisions 2 and 3; and several pods have been found at the same position about 10 km to the east. However, other pods have since been discovered both below and above the unconformity. Kornerupine, both in silica-undersaturated and silica-saturated assemblages also occurs about 10 km to the east, in pelites of the Pine Hill Formation.

Prograde temperatures in these rocks have been estimated as being similar to those in the northern Strangways Range on the basis of the Al_2O_3 content of orthopyroxene in the sapphirine-bearing rocks, and on the TiO_2 content of phlogopite-biotite (Warren & Stewart, 1988, see Fig. 10). The pressure estimate of 5-6 kbars is dependant on the Grt-Crd compositions in Qtz-Sp bearing rocks collected a few kilometres to the east of the Woodforde River.

The textural relationships seen in these rocks are typical of silica-undersaturated rocks in the Arunta Block. Spinel forms cores within sapphirine or cordierite, and orthopyroxene is invaded by late biotite. Warren and Stewart (1988) interpreted this texture as the result of reaction between a potassic melt phase and restite spinel during early cooling (Fig. 6). Biotite, wagernite and fluor-apatite in these rocks all contain fluorine; and a single whole-rock analysis shows 0.4 percent F: This may affected the temperature at which partial melting occurred during prograde metamorphism. The large laths and finer-grained anthophyllite which cut across the earlier phases are interpreted as phases related to the later hydration in the shear zones.

Stop 8: Peaked Hill:- Retrogressed metapelites.

Peaked Hill is a small sharp hill to the north of the Pine Hill road: the most prominent outcrops which form the highest part of the hill are a horseshoe-like layer of amphibolite (probably a steeply plunging open fold). On the outer slopes of the hill, outcrops are felsic gneisses (some with sillimanite); within the horseshoe, they are metapelites with cordierite, garnet, orthopyroxene and partial melting. At least two zones of hydration, but without severe dislocation, cut across the outcrops: retrogression is variable, locally reaching back as low as chlorite-grade. These outcrops have provided specimens with retrogressive staurolite, a rare mineral in the northern Arunta Block, with gedrite and sillimanite (Fig. 4b).

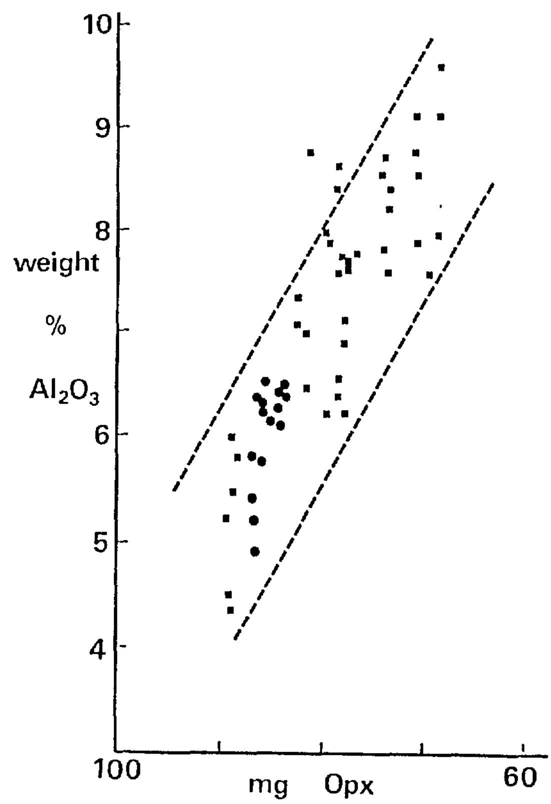


Figure 10 The Al_2O_3 content of orthopyroxene co-existing with sapphirine spinel and phlogopite in silica-undersaturated rocks. Squaress refer to the Mount Milton outcrops, circles to the Reynolds Range outcrops. Though the plot indicates temperatures in the two areas were similar, allowance must be may for the effect of higher pressure in the Strangways Range region (after Warren & Stewart, 1988).

Stop 9: The Gas Pipeline cutting:- Partial melting, early uplift, and late retrogression

A short section of the pipeline carrying natural gas from the Amadeus Basin to Darwin has been buried in a cutting through the hills west of Aileron. This cutting provides excellent exposures of the Nolans Dam Metamorphics and the Aileron Shear Zone.

The Nolans Dam Metamorphics are cordierite-bearing metapelites, probably facies variants of the Lander Rock Beds, with which they appear to interfinger to the northwest. They are more massive and contain less cordierite than the Lander Rock Beds. In the cutting migmatite containing restite crystals of cordierite, garnet and orthopyroxene interpreted as the products of water-absent partial melting. Thin sections from these outcrops show symplectic breakdown of garnet recording uplift.

The shear zone incorporates both the Nolan Dam Metamorphics and orthogneiss (Napperby Gneiss or Boothby Orthogneiss). Chemical differentation (metasomatism *s.l.*) and new fabrics are well developed.

Stop 10: Blue Bush Swamp:- Extreme retrogression.

The low hills immediately to the south of Blue Bush Swamp consist of intensely retrogressed rocks (probably mostly orthogneiss). The main rock type is mica schist. Nodules of coarse pale-blue kyanite are locally abundant in the ridge to the south of the swamp.

Roadside geology, Plenty River Road

From the Reynolds Range, the excursion retraces its route as far as the turn-off from the Stuart Highway eastwards onto the Plenty River Road. The Plenty River Road skirts the high ground of the Strangways and Harts Ranges, utilizing more level terrain over Tertiary sediments, and in places threading through the low foothills of the ranges. The excursion is to leave the Plenty River Road to inspect outcrops at Mount Milton, Edwards Creek, and south of Mud Tank before finally turning off the Plenty River Road east of the Harts Range settlement to follow station access tracks south into the eastern Harts Range.

The first low hill to appear on the left hand side is Coles Hill, containing outcrops of calc-silicate rock. This is typical of outcrops of basement throughout a substantial part of the Arunta Block: the highest points in a buried topography that are emergent in a cover of Tertiary sediments. At about 20 km, Mount Strangways, the westernmost part of the Strangways Range forms a prominent rise south of the road. From here as far east as Mud Tank, the outcrops to the south of the road are granulites of the Strangways Metamorphic Complex, similar to those at Mount Milton, which lies southeast of Mount strangways.

Near the turn off to Bushy Park, the Plenty River Road begins to thread between ridges of deformed rock in the Wallaby Knob Schist Zone, a major zone of retrogressed granulites several kilometres wide. The low hill visible to the north is Mount Bleechmore, also composed of granulites, but apparently stabilized at much lower pressure (See Fig. 5) than the granulites to the south.

East of Mud Tank, almost co-incident with the end of the bitumen surface, the road crosses into the Harts Range Group. The low outcrops adjacent to the road immmediately east of Ongeva Creek are meta-pelites of the Irindina Gneiss, characterized by garnet and sillimanite. The prominent range to the south of the road is Riddock Amphibolite, a thick layer of mafic rocks within the Irindina Gneiss. South of the Harts Range settlement the hills are laced by large pegmatites, and it possble to pick out mine dumps dating from the era of mica mining. These mines produced much of the specimen material by which the Arunta Block is represented in museums. At the Entire Creek crossing the excursion turns south into the "valley country", a wide open region within the domed Harts Range Group.

C Northern Strangways Range RGW BJH RDS

Stop 11 The Mount Milton Sapphirine Lens:- Migmatites, Silica-undersaturated rocks, calc-silicate rocks, Fluid phase relationships.

The Mount Milton Sapphirine lens is about 1.5 km north of Mount Milton and 5 km southeast of New Bullock Bore in the southern rim of an amphitheatre of low hills. The lens and surrounding rocks are part of the Yambah Granulite, within the Strangways Metamorphic Complex (Division 1)

Most of the rocks in the area covered by Figure 11 are migmatitic quartzofeldspathic gneisses. Mafic granulite occurs within the gneisses as folded distorted and boundinaged layers: there are also areas of predominantly mafic rocks. The outcrops include a thick unit of cordierite quartzite which contains several lenses of silica-undersaturated rock, amongst which is the sapphirine-bearing lens, and calc-silicate rock, and also a thin, discontiuous layer of calc-silicate rock, marble, silica-undersaturated rock and BIF. A small, fault bounded block contains fine layered rock, laminated mafic rock, and a 1 metre layer of cordierite quartzite.

The terrain is broken up by a network of faults and small shears. Most shears are poorly exposed features, occurring in stream valleys. No marker layers can be traced across the faults, so estimates of displacement are not possible.

Quartzofeldspathic gneiss includes a range of textural types, all consisting of quartz, orthoclase, plagioclase with variable amounts of ferromagnesian minerals. Though biotite is the common ferromagnesian mineral, garnet and orthopyroxene are present in some outcrops. Migmatites are extensively developed in the more massive exposures (to 30 percent in some exposures). The gneissic fabric is defined by concentration of the ferromagnesian minerals, but boitite is not strongly oriented.

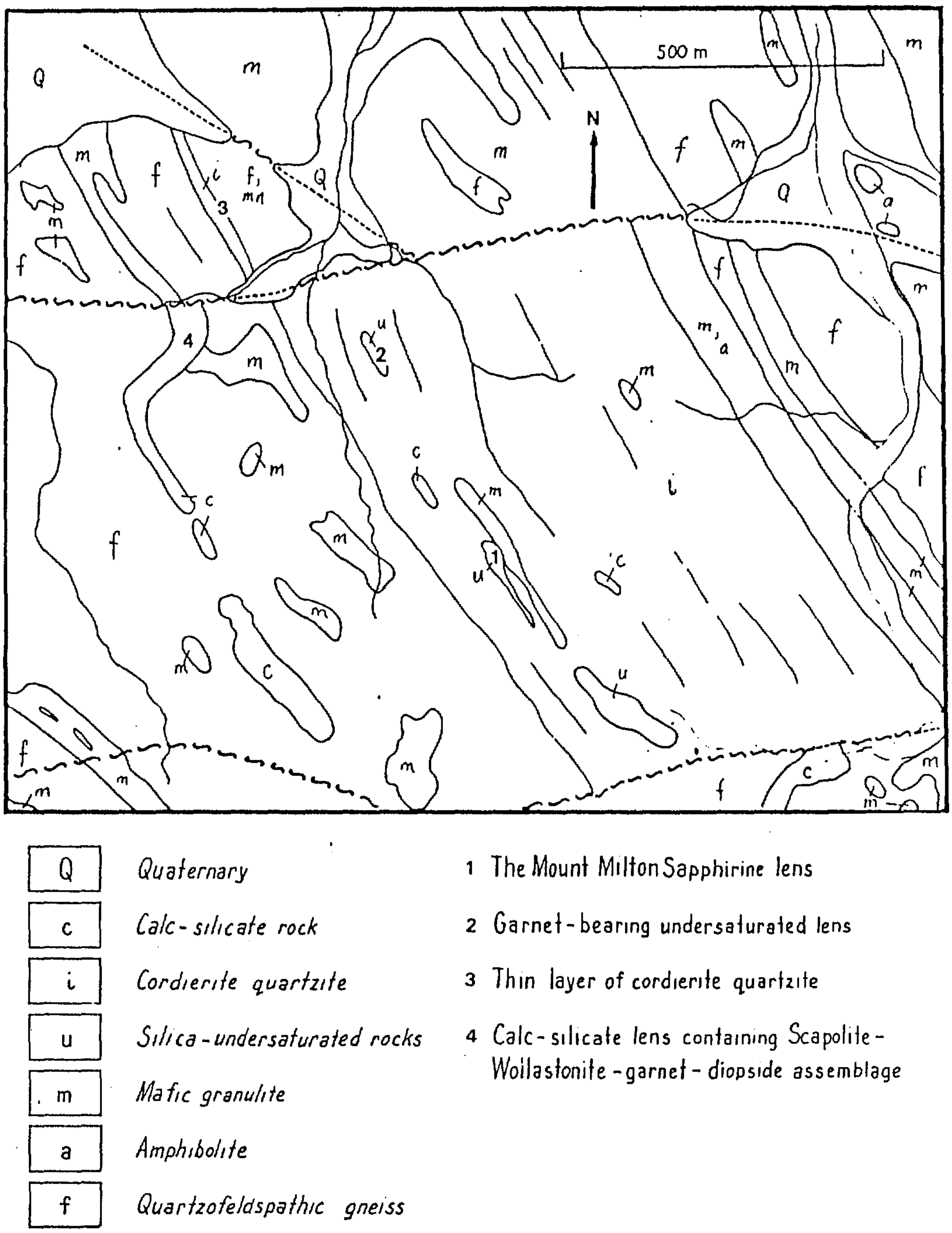


Figure 11 Geological map of the area surrounding the Mount Milton sapphirine lens (after Warren, 1982)..

Mafic granulite consists of plagioclase and two pyroxenes with variable amounts of late hornblende and minor quartz and biotite. The more massive mafic granulite in the outcrops to the north of the sapphirine lens tends to be coarser grained and have more plagioclase than the thinly layered bodies.

Calc-silicate rocks occur as small lenses within the quartzofeldspathic gneisses and cordierite quartzite. These range from finely layered (generally the smallest bodies) to massive. The mineralogy of these outcrops indicates impure dolomite as the protolith. The largest calc-silicate unit can be followed, as part of a complex layer, for about a kilometre. At its north end it contains marble with garnet, scapolite, wollastonite, and calcite; an assemblage requiring high water to CO_2; in contrast to assemblages in other adjacent rock types. Massive marble associated with magnesian silica-undersaturated rocks across the fault to the south of the cordierite quartzite may be part of the same layer.

Cordierite quartzite forms the prominent ridge which contains the main sapphirine lens. This ridge is divided into two by a deeply incised gully. East of the gully, the outcrops are predominantly massive siliceous cordierite-bearing granofels. West of the gully, the outcrops become more diverse: they include garnet-cordierite granofels, and enclose lenses of mafic granulite, calc-silicate rock and several lenses of silica-undersaturated rock. The irregularly shaped bodies of silica-undersaturated rock are elongated parallel to the layering of the cordierite quartzite, but their margins may be locally discordant. These undersaturated rocks form tough, dark outcrops, which tend to be less well exposed than the the surrounding quartzite. A feature of the undersaturated rocks is the existence within the lenses of small, chemically distinct domains. Crystals of sapphirine enclosed within K feldspar have been obtained from these outcrops, though the best specimens come from outcrops in the northern rim of the amphitheatre.

Assemblages within the silica-undersaturated rocks are strongly dependant on bulk composition, particularly Mg/Fe. The southern lens is highly magnesian, shown by light colours of the minerals, including the sky-blue sapphirine. The main sapphirine lens is less magnesian, and sapphirine from here is inky blue-black; spinel in the same outcrops is green-black. There are also silia-undersaturated rocks too iron-rich to stabilize sapphirine, which instead contain spinel-cordierite-orthopyroxene and one outcrop of garnet-spinel-orthopyroxene rock.

Metamorphic conditions have been estimated at 850-920°C, 8±1 kbars from a variety of geotherometers and geobarometers, using Grt-Pl-Opx-Qtz (e.g., from Qtz-Opx[$Mg_{2.26}Fe^{2+}_{1.39}Mn_{0.03}Fe^{3+}_{0.19}Al_{0.48}Si_{3.66}O_{12}$] - Grt[core $Mg_{1.12}Fe^{2+}_{1.62}Mn_{0.11}Ca_{0.11}Fe^{3+}_{0.12}Al_{1.98}Si_{2.95}O_{12}$]-Pl[$Or_{2.2}Ab_{58.2}An_{39.6}$]) and Cpx-Pl-Qtz assemblages. Al_2O_3 contents >10 weight percent occur in the core of orthopyroxene of *mg* 66 included within sapphirine.

Stop 12: Yambah Retrograde Schist Zone

The Yambah Schist Zone is made up of two fault zones, intersecting at right angles in a wide valley south of Mount Strangways. The schist zone are each about 1 km wide, with diffuse margins grading into relatively undeformed granulite of the Strangways Metamorphic Complex (Yambah Granulite).

The major rock type in the schist zones is muscovite-biotite-quartz schist, in places containing garnet, kyanite and/or staurolite porphyroblasts. In composition these rocks resemble the adjacent quartzofeldspathic gneisses and are considered to have formed from them; though Iyer (1974) reported that the schists are more aluminous, with higher Al_2O_3 and lower SiO_2 than the gneisses presumed to have been their protolith. The muscovite schists enclose pods of other rock types: These include mafic schists (cf the mafic granulite in the Yambah Granulite), and pods of chlorite-garnet schist with associated calc-silicate rock, and a pod of gedrite-bearing rock.

Evidence for multiple deformation and polymetamorphism can be found in these rocks. The schistose fabric of the rocks is, in places, complexly refolded. The Yambah Granulite contains sillimanite: but the important aluminosilicate in the schist zone is kyanite. The large blue blades of kyanite commonly have faces corroded and etched by fine white muscovite, as do the staurolite porphyroblasts.

An obvious feature of the schist zone is metamorphic segregation, which has produced large zoned knots of kyanite, biotite and quartz. Mobility of K_2O, at least in the latter stages of formation of the schists seems probable, given the widespread growth of fine muscovite.

Iyer & others (1976) reported a Rb-Sr age of 1820 ± 60, IR 0.704 (corrected for revised decay constant), using a whole rock isochron based on specimens collected west of the schist zone. The age of the Schist Zone itself is not known.

Stop 13: The Edwards Creek prospect

The Edwards Creek prospect is situated in low hills on the northern edge of the Strangways Range, at 23° 01'S, 133° 01'E. Outcrops containing copper, lead and zinc minerals are erratically distributed along the west limb and northern axial zone of an upright south plunging synform, over a strike length of nearly a kilometre (Fig. 12).

The prospect and surrounding rocks are in a small fault block about 4 km east-west by 1.5 km north-south. This block is bounded on the north by the Wallaby Knob Schist Zone, a wide, east-west striking zone of multiply-deformed gneiss and schist; on the south by a second wide schist zone; and on the east and west by north-northwest trending faults. Minor shear zones and faults dissect the block internally. Several shears pass close to or displace the rocks of the prospect. The rocks in these minor shears, like those in the Wallaby Knob Schist Zone, bear the imprints of several episodes of deformation, hydration and retrogression.

The well-exposed cordierite quartzite, which occurs adjacent to the Cu-Pb-Zn-bearing outcrops, persists well beyond the prospect, so that folds can be traced out over several square kilometres, using this unit as a marker.

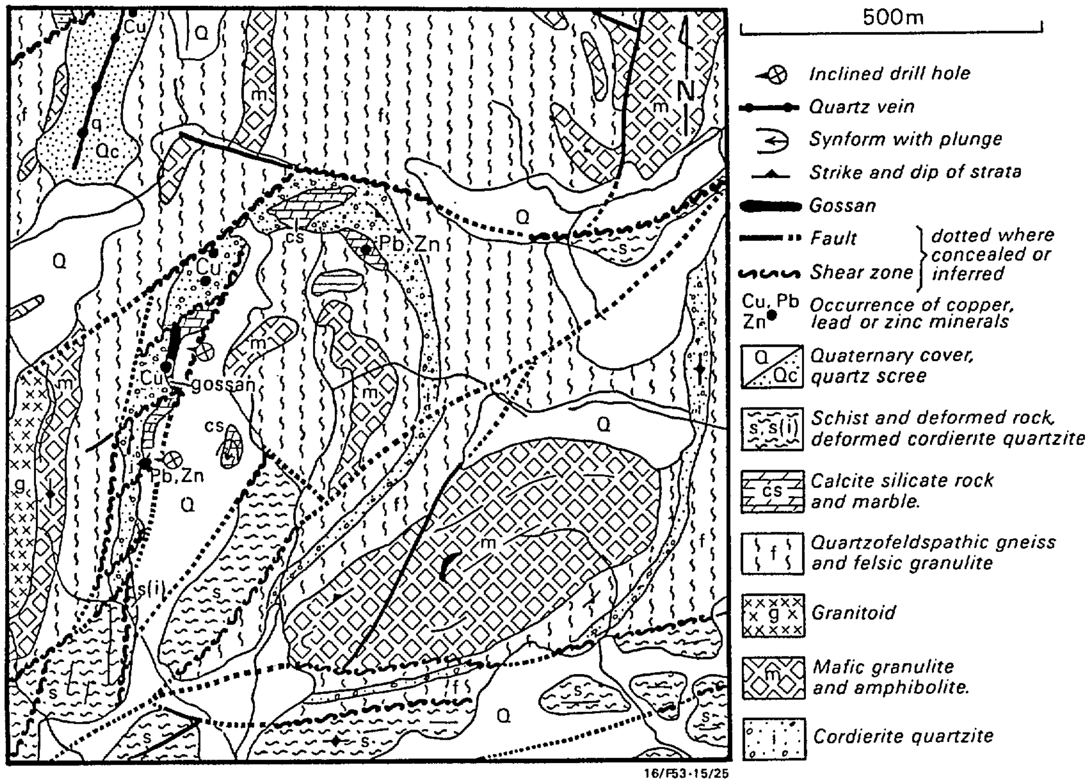


Figure 12 Geological map of the area surrounding the Edwards Creek Prospect (After Warren & Shaw, 1985).

Away from the prospect, individual quartzofeldspathic and mafic units persist for considerable distances with little change in thickness, but close to the prospect, units thicken and thin markedly. Such variations in thickness are not related to the folds and so are considered to be primary features.

Several small bodies of orthogneiss disrupt the well-layered sequence and have margins which are locally discordant. Mesoscopic features (foliation, granoblastic fabric, myrmekite) show that the orthogneiss bodies shared the history of the surrounding layered rocks and so predate the granulite stage.

Rocks carrying ore minerals crop out adjacent to the cordierite quartzite or form pods within it. Sulphides (galena, sphalerite and pyrite) occur in some of the marbles: secondary copper minerals occur in some of the gedrite rocks. The prominent siliceous ironstone, stained by secondary copper minerals may be a true gossan or a ferruginous and siliceous cap over impure marble. Analysed samples show a wide range of metal values and ratios: from these data and field observations, the Edwards Creek prospect is best regarded as a zinc prospect in which copper and lead were partitioned into the gedrite rocks and the marbles respectively.

The wall rocks of the prospect provide excellent material for study of the retrogressions, granulite assemblages are not as well preserved as at the Mount Milton outcrops. Orthopyroxene-K feldspar assemblages occur in felsic rocks north of the prospect, and assemblages developed in the initial cooling, including rare sapphirine, are present in undeformed rocks. Several parameters can be used to show conditions were not as extreme as at the Mount Milton outcrops: the Al_2O_3 of orthopyroxene is lower than in corresponding assemblages, at the same *mg* value, than at Mount Milton; and the TiO_2 content of biotite at similar *mg* values is also lower. Orthopyroxene-chrondodite-spinel, indicating a local high fluorine activity, occurs in the silica-undersaturated rocks.

Gedrite-bearing rocks are common along the shear zones, where retrogressed cordierite quartzite contains gedrite-staurolite-kyanite-quartz$\pm$garnet assemblages with later cordierite. Initial retrogression therefore took place in the kyanite stability field. The earlier retrogressive assemblages in silica-undersaturated rocks contain coarse-grained gedrite and anthophyllite. More hydrated rocks include examples with corundum-staurolite-chlorite assemblages with staurolite of *mg* 40-42. Uplift follwing the gedrite-kyanite retrogression took the rocks back into the sillimanite stability field, so that late cordierite formed from the kyanite, gedrite and staurolite. An episode of cooling then followed, and fine-grained staurolite and sillimanite formed in the cordierite which postdated the kyanite stage. The final retrogression was in the chlorite-quartz stability field.

The marbles are derived from impure dolomites: they contain calcite, dolomite, forsterite, humite, gahnite and sulphides. Forsterite retrogresses to a colourless phyllosilicate, possibly antigorite. Coarse-grained chlorite (to several centimetres) has been collected from weathered calcareous rocks just north of the ironstone ridge, and nodules of chlorite to a centimetre in diameter are present in some marbles.

C Mud Tank district RDS RGW BJH

Stop 14: Heavitree Quartzite south of Mud Tank: Cover Rocks

A ridge of Heavitree Quartzite, the basal unit in the late Proterozoic cover sequence (Amadeus Basin and Ngalia Basins), is caught up in the fault zone at the northern edge of the West Bore Schist Zone. The schist zone which strikes east-west, contains lenses of quartzofeldspathic schist, biotite schist, amphibolite, thin layers of quartzite, Muscovite-biotite schist and quartzofeldspathic gneiss. The outcrops of Heavitree Quartzite have a well-developed fabric and coarse-grained muscovite. The presence of these rocks raises questions about the time at which the surrounding high-grade rocks were unroofed and the schist zones began to evolve.

Stop 15: Garnet-bearing mafic rocks: dry retrogession

The stability field for garnet in rocks of mafic composition shifts to lower pressure at lower temperatures. Thus the near-isobaric cooling from peak conditions took the mafic granulites in the higher pressure terrains within the Arunta Block into the garnet-stability field; though late garnet seems to have formed only in mafic rocks close to major faults. The low hill of mafic rocks 8 km southwest of Mud Tank lies between an unnamed fault trending south-southwest and the Woolanga Lineament. Late garnet is present in the mafic rocks; from which the conditions have been estimated at P 7 ± 1 kbar and T circa $610^{o}C$ (from, e.g.,
Grt[$Mg_{0.65}Fe^{2+}_{1.77}Mn_{0.05}Ti_{0.03}Al_{1.99}Si_{2.95}O_{12}$],
Opx[$Mg_{2.39}Fe^{2+}_{1.62}Mn_{0.01}Ca_{0.02}Al_{0.07}Si_{3.93}O_{12}$],
Cpx[$Mg_{1.48}Fe^{2+}_{0.52}Ca_{1.87}Ti_{0.01}Al_{0.24}Si_{3.86}O_{12}$], Pl [$Or_{0.6}Ab_{49.5}An_{49.9}$]).

Stop 16: The Mud Tank Carbonatite

The Mud Tank Carbonatite is situated near the northern margin of the Strangways Range. Three main outcrops of carbonatite are aligned in a northeastly direction over a distance of about 2 km; a fourth outcrop lies a further 2 km southwest. Crohn & Moore (1984) interpreted the results of auger drilling to show that plug-like bodies of carbonate rock are surrounded by poorly exposed phlogopite-carbonate rock. The carbonatite intrudes garnetiferous, semi-pelitic biotite schist. Contacts are not exposed, but where they have been intersected in drill core they are somewhat sheared. There is no evidence of fenitization. Basic rocks, possible xenoliths, found as lenses within the carbonatite are amphibole-rich rocks that show slight indications of metasomatism. The only alkaline rocks associated with the carbonatite crop out as small bodies of albite pegmatite, generally less than 3 m long, within the carbonatite. Some contain trace amount of sodic pyroxene and amphibole.

Exposures of the carbonatite are deeply weathered. Dipping layering can be seen in some outcrops. Most of the material on the surface is a residual carapace of apatite, magnetite (strictly martite), and zircon, mixed with pisolites of ferruginous laterite. In drill cores, the carbonatite is mainly coarsely crystalline white carbonate rocks, with minor amounts of magnetite, pale green apatite, dark green chlorite, zircon, phlogopite, and zoned sodic amphibole. The carbonates are calcite and dolomite in near-equal proportions. Ilmenite, pyrite, chalcopyrite, quartz and pseudomorphs of possible columbite after pyrochlore have also been reported.

E Eastern Harts Range RLO

Stop 17: 7km east-northeast of Valley Bore.

Lens of pelitic metamorphics approximately 3 m thick by 100 m enclosed in granitic gneiss consists of abundant kyanite and phlogopite with cordierite and sillimanite.

Stop 18: 10 km southwest of Valley Bore.

Strongly deformed Bruna Gneiss

Stop 19: 11 km southwest of Entire Bore

Well layered sequence of pelites and semi-pelites passing northwest into calc-silicate rock, para-amphibolite and marble. The locality is noted for the large euhedral garnets which contain inclusions of sillimanite. These occur in migmatitic segregations with plagioclase within a biotite quartzofeldspathic gneiss of the Harts Range Group. A poorly exposed pelitic layer to the southeastcontains large nodules of sillimanite-magnetite in a matrix of muscovite. Above the garnet-bearing layer there is a layer of gedrite-bearing granofels which carries large crystals of kornerupine.

Roadside Geology, Harts Range - Arltunga - Alice Springs

If time permits, the excursion will follow a different route to return to Alice Springs. From the eastern Harts Range, station access tracks offer a route south to the southern margin of the Arunta Block. This track passes through hills of Harts Range Group, and crosses back into Cadney Gneiss, a calc-silicate unit in the upper part of the Strangways Metamorphic Complex. North of Claraville homestead the track swings to the south to cross the Tertiary sediments of the Hale Basin, and gives a good view of the ridges of Heavitree Quartzite in the nappe complexes along the northern margin of the Amadeus Basin. The planar land-surface preserved in these ridges may date from the late Mesozoic.

South of Claraville, the road winds through ridges of Atnarpa Complex, a suite of mafic to felsic intrusions to which the Alice Springs Granite is related. Near Arltunga, a former gold mining settlement, the road cuts through the deformed thrusts and nappes of Palaeozoic ages: severely deformed basement and cover, including stretched pebbles are exposed in the core of the White Range Nappe. From Arltunga, the road passes through more ridges of Heavitree Quartzite, and then follows Bitter Springs Gorge, cut through the Bitter Springs Formation, the unit of calcareous rocks and evaporites that overlies the Heavitree Quartzite in the Amadeus Basin. Recumbent folds are exposed in the hills that flank the gorge. From Bitter Springs Gorge the road follows valleys between ridge-forming units of the Amadeus Basin sequence, returning close to the basement uncomformity near Emily Gorge.

Acknowledgements

The assistance of the Northern Territory Geological Survey, in particular Dr R Thompson, in the organization of this field conference is gratefully acknowledged. Microprobe analyses used in the text were made at RSES, Australian National University, using the programs of Ware (1981). Figure 5 was drafted by Marianne Kadar (UNSW).

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