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Deformation of the Crust and Mantle in Central Australia

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SUMMARY

Three zones of retrograded crystalline basement rocks have been delineated in central Australia. One, along the southwestern margin of the Amadeus Basin, was deformed about 600 m.y. ago during the Petermann Ranges Orogeny. Two—one north of the Amadeus Basin, the other north of the Ngalia Basin—were deformed during the Carboniferous Alice Springs Orogeny. Each retrograded zone is highly deformed and is flanked on one side by folded and thrust sedimentary rocks and on the other by granulite and amphibolite facies rocks. The high-grade rocks appear to have resulted from several metamorphic episodes in the Precambrian. A major gravity gradient is associated with each retrograded zone; the Bouguer anomaly highs generally occur over the areas of high-grade metamorphic rocks, and the lows over the sedimentary basins and retrograded rocks.

In general, the deformed and retrograded zones are moderately to gently dipping. The gravity gradients are so wide and steep that to explain them the deformed zones must pass through the crust into the mantle beneath. The crust and mantle above each deformed zone have been upthrust, bringing granulite facies rocks to the surface and producing Bouguer gravity anomaly highs over the uplifted lower crust and mantle.

The deformed zones are similar to the subduction zones that may develop on the margins of continents, but there is no evidence of continental collision in central Australia when they were formed, and they are regarded rather as possible examples of intracontinental plate reactions. They may have extended right across the continent or may terminate against strike-slip (transform) faults. A possible site for such a transform fault in Western Australia is discussed, but its existence is speculative.

Fig. 1. Locality map.

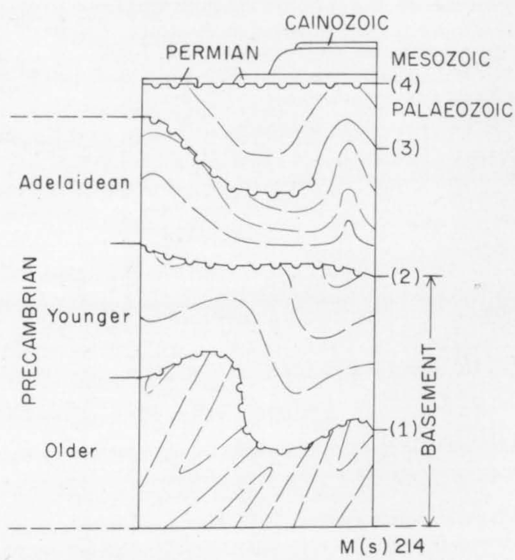

Fig. 2. Diagram showing relationships of rock units. (1) Arunta Orogeny. (2) Unnamed diastrophism. (3) Petermann Ranges Orogeny. (4) Alice Springs Orogeny.

INTRODUCTION

The area studied (Fig. 1; Pl. 1) occupies about 600 000 km^2 in the centre of the Australian continent. It includes the southern part of the Northern Territory and adjacent areas in Western Australia and South Australia. Extensive tracts of Adelaidean and Palaeozoic sedimentary rocks are preserved in the Georgina, Amadeus, Ngalia, and Officer Basins, and the basins are separated by metamorphosed Precambrian basement rocks. The purpose of this Bulletin is to demonstrate that three easterly-trending zones of severe crustal dislocation cross central Australia. Each zone contains retrograded basement rocks and passes through the crust into the mantle beneath. These conclusions have been drawn from a study of the relationships between regional metamorphism, structure, and Bouguer gravity anomalies as summarized on Plate 1. The text that follows is essentially a brief explanatory note to the map.

GENERAL LITHOLOGICAL FEATURES

As the age of the Precambrian rocks is largely unknown they can be only partly subdivided into specific time units such as those used in Australia by Dunn et al. (1966) or in Canada by Stockwell (1964). They are subdivided according to their metamorphism, structure, and stratigraphic position into three groups (Fig. 2).

The oldest are moderately to highly metamorphosed gneiss and schist intruded by igneous rocks (Fig. 2; Pl. 1). They are overlain unconformably by several sequences of little metamorphosed Precambrian sedimentary and volcanic rocks that are intruded by granite.

The third major group consists of up to 500 m of Adelaidean sedimentary rocks preserved conformably and unconformably beneath Palaeozoic sedimentary rocks in the Amadeus, Georgina, Ngalia, and Officer Basins. This group is referred to as the 'Adelaidean sedimentary rocks'. They are not intruded by granite and contain little volcanic material. Two units that will be referred to later in this Bulletin are the Heavitree Quartzite and the Bitter Springs Formation. The Heavitree Quartzite is a thick orthoquartzite at the base of the Amadeus Basin. The orthoquartzite is conformably overlain by a thick unit of carbonate rocks, shale, and evaporites called the Bitter Springs Formation.

Cambrian to Carboniferous? sedimentary rocks are the last in the region to have been extensively deformed.

Another major stratigraphic unit consists of flat-lying continental Permian rocks and marine and continental Mesozoic rocks. They are overlain over much of the area by a thin veneer of continental Tertiary and Quaternary sediments.

The distribution of these rocks is shown on Plate 1.

METAMORPHISM

INTRODUCTION

Compilation of the metamorphic map of central Australia (Pl. 1) was first suggested to D.J.F. by Professor James B. Thompson Jr of Harvard University in 1967. A preliminary metamorphic map that summarized all the information available at that time was produced in 1968 (Forman, 1968). The results of many workers were used in the compilation. The most detailed work had been carried out by: Joklik (1955); Wilson (1947, 1948, 1950, 1952a, b, 1953, 1955, 1958, 1959, 1960); Morgan (1959a, b); McCarthy (Mirams, 1964; Forman, Milligan, & McCarthy 1967; and McCarthy, 1965), and Talbot & Clarke (1917).

A great deal of petrographic information has become available since early 1968: Thomson (1969), Kreig (1968), and Arriens & Lambert (1969, and pers. comm.) on areas in South Australia; Daniels (1969, 1971a, b) on areas in Western Australia, and Evans & Glikson (1969) and Wells, Evans, & Nicholas (1968) on the Ngalia Basin area of the Northern Territory. Since 1968 the authors have collected extensively in the southwestern margin of the Amadeus Basin (Petermann Ranges and Ayers Rock Sheet areas) and in the area north of the Amadeus Basin (Mount Liebig, Hermannsburg, Alice Springs, Alcoota, and Illogwa Creek Sheet areas). In addition representative samples from the Bureau of Mineral Resources rock collection have been sectioned and quickly examined by one of us (D.J.F.); there are now over 3000 thin sections in the collection.

It is beyond the scope of this paper to detail the many other sources—Bureau of Mineral Resources, State Mines Departments, Universities, and private companies—that have willingly contributed petrographic information. The source of the information used for compilation of this metamorphic map may be obtained from the 1 : 250 000 scale working maps, card index, and thin section collection of BMR.

Metamorphic grades ranging from the lower greenschist to granulite mineral facies of mafic rocks are preserved in the older Precambrian basement rocks. The younger Precambrian basement rocks are slightly metamorphosed and the cover of Adelaidean sedimentary rocks is unmetamorphosed in many areas, though locally they reach the staurolite zone of pelitic rocks. The description of metamorphism that follows takes no account of the age of the rocks affected by it or the time at which the metamorphism occurred, which is dealt with in a later chapter. The distribution of characteristic mineral assemblages is shown on Plate 1 together with the distribution of important metamorphic marker minerals such as andalusite, kyanite, staurolite, sillimanite, and cordierite. An approximate correlation of mineral zones in pelitic rocks with characteristic mineral facies developed in associated mafic rocks and with index minerals found in calc-silicate rocks is given by Thompson & Norton (1968).

Granulite Facies

Three east-trending belts of granulite facies rocks cross central Australia (Pl. 1). The largest belt crops out between the Amadeus and Officer Basins, the second between the Amadeus and Ngalia Basins and the Amadeus and Georgina Basins, and the third between the Ngalia and Georgina Basins, extending easterly between the Amadeus and Georgina Basins. At this stage we do not know whether the second and third belts are nearly parallel or whether they cross.

Three facies subdivisions are recognized The typical granulite facies assemblage is plagioclase–clinopyroxene–orthopyroxene, with or without K feldspar, quartz, and minor hornblende and biotite (Fig. 3). In many areas, however, amphibolite facies rocks are intimately admixed with the granulite facies rocks, even on the scale of a thin section, and in these areas hornblende and biotite are commonly associated with hypersthene and clinopyroxene.

The typical pelitic assemblage that occurs within these granulites is quartz–K feldspar–sillimanite–garnet–biotite (Fig. 4), but the belt north of the Ngalia Basin commonly contains both andalusite and sillimanite together with quartz, K feldspar, biotite, and garnet suggesting a high-temperature but low-pressure origin if this is an equilibrium assemblage. However, the presence of prograde greenschist and lower

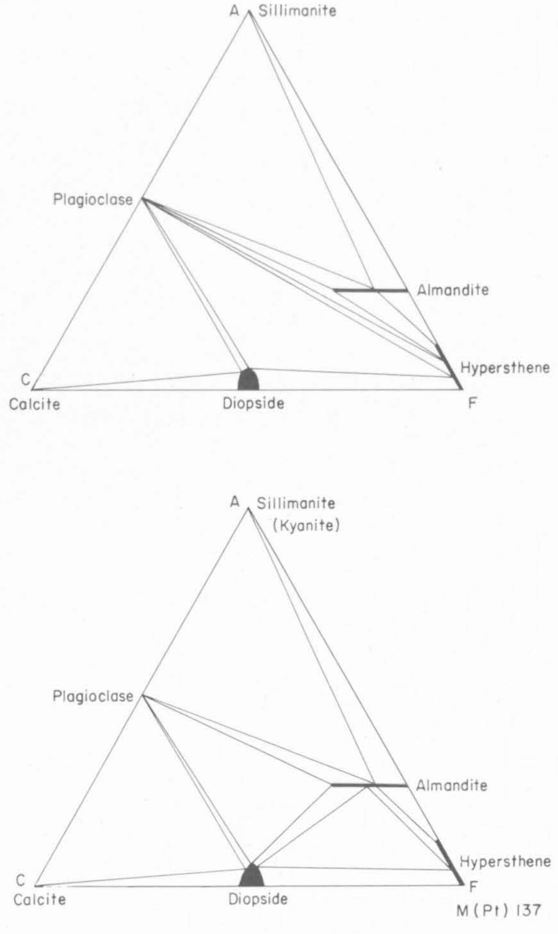

Fig. 3. Two mafic facies diagrams for granulite facies rocks. Pressure, temperature, and activities of H_2O and CO_2 are assumed external variables. Quartz and K feldspar are additional phases. Each diagram represents a subdivision of the granulite facies shown on Plate 1.

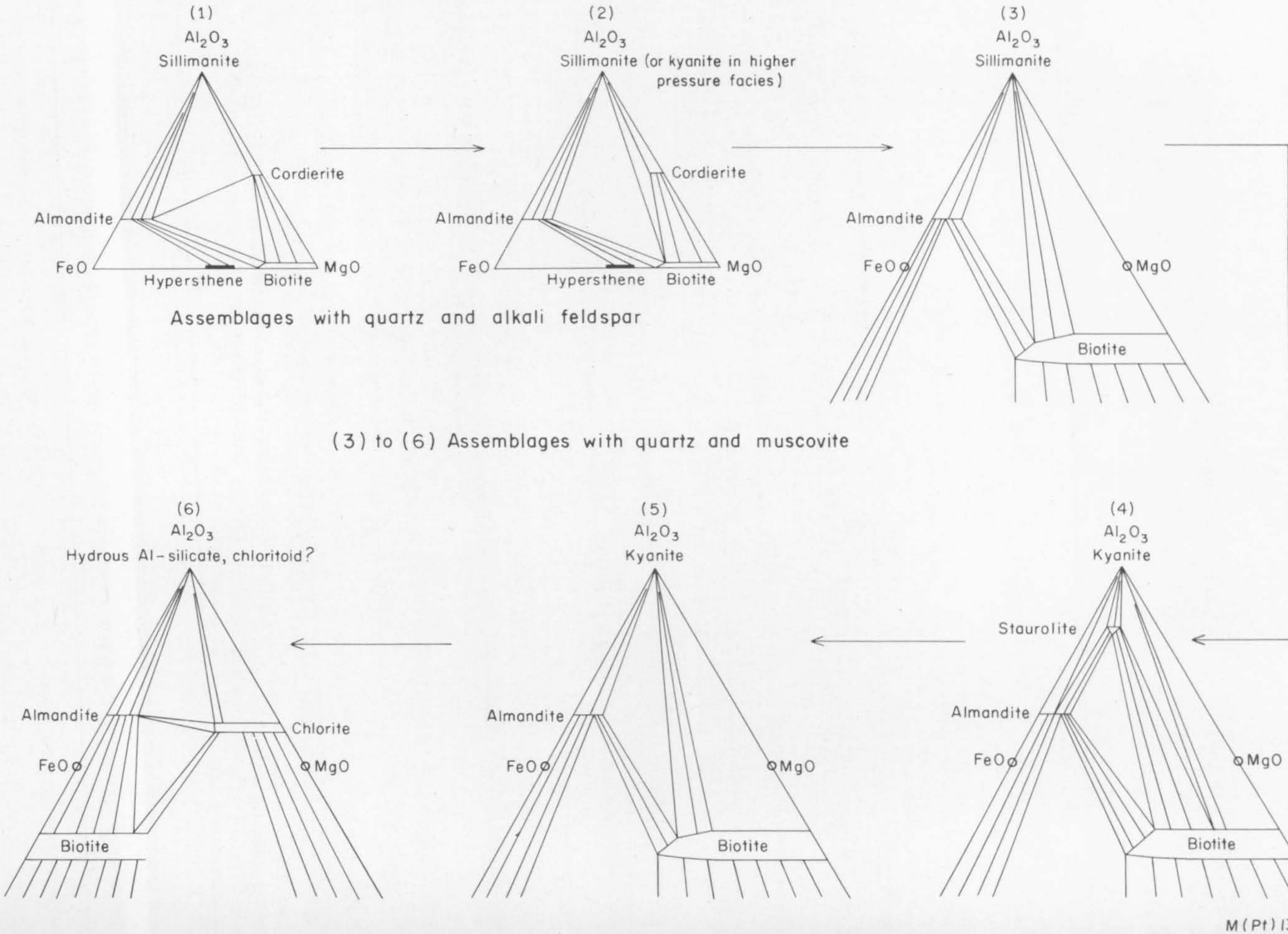

Fig. 4. Metamorphic facies developed in pelitic schists. Arrows suggest decreasing order of metamorphic grade. The sequence is generalized and simplified and intermediate steps are missing. Pressure, temperature, and activity of H_2O are assumed external variables. (1) to (2) occur in granulite facies, (2) to (5) in amphibolite facies. Distribution of lower sillimanite facies rocks (3) and muscovite–kyanite bearing rocks (4 and 5 undifferentiated) is given on Plate 1.

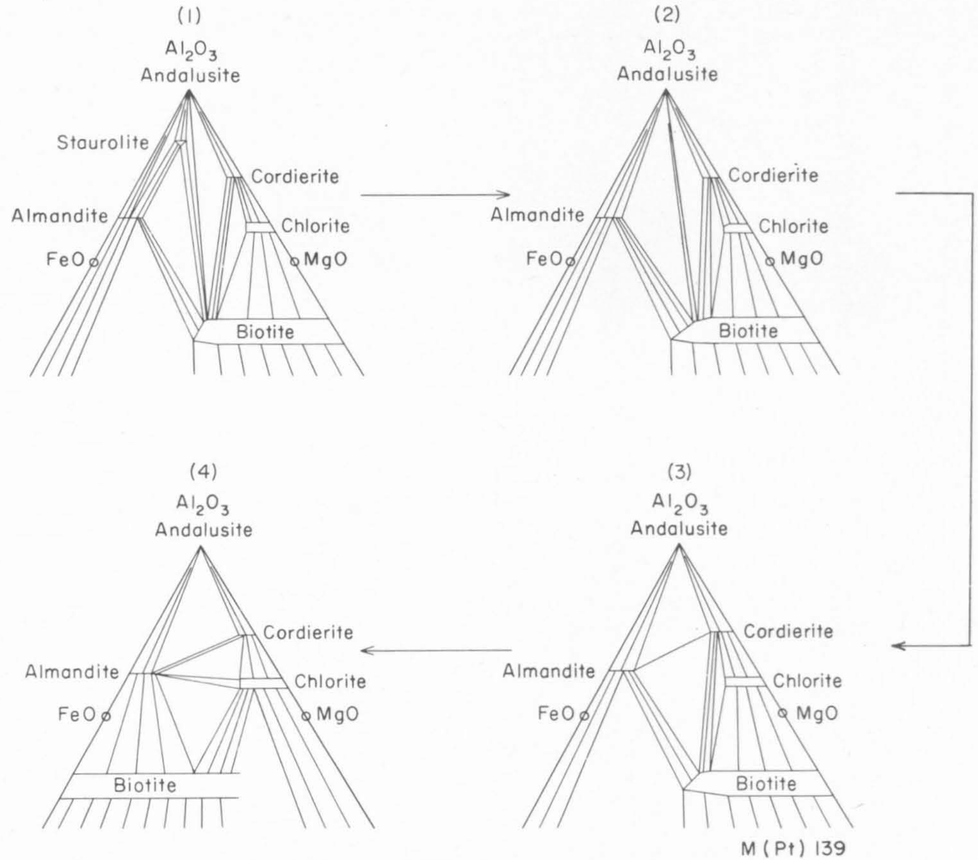

Fig. 5. Four metamorphic facies diagrams for pelitic schists containing andalusite. Quartz and muscovite are additional phases. The arrows suggest decreasing order of metamorphic grade. Pressure, temperature, and activity of H_2O are assumed external variables. All occur in amphibolite mineral facies of mafic rocks. Distribution of andalusite–staurolite bearing rocks (1) and of andalusite bearing rocks (2–4 undifferentiated) is given on Plate 1.

amphibolite facies metamorphic rocks that may be younger than the high-grade rocks in the same area suggests that the assemblage is not in equilibrium and that the andalusite grew during a second metamorphism episode.

A third mineral assemblage, thought to develop at higher pressure, occurs near the Western Australia/Northern Territory/South Australia border junction. In these rocks (Fig. 3) clinopyroxene and garnet occur with plagioclase, quartz, and K feldspar. Some relict hypersthene occurs in most rocks but is almost invariably surrounded by reaction rims demonstrating that the reaction hypersthene + plagioclase $\rightleftarrows$ clinopyroxene + garnet has occurred. The assemblage kyanite–K feldspar–quartz–biotite–garnet (Kreig, 1968) occurs in the southeast part of the granulite zone, suggesting another area also of high-pressure origin.

Amphibolite Facies

Amphibolite facies rocks (Pl. 1) are the most abundant. Mafic and calc-silicate

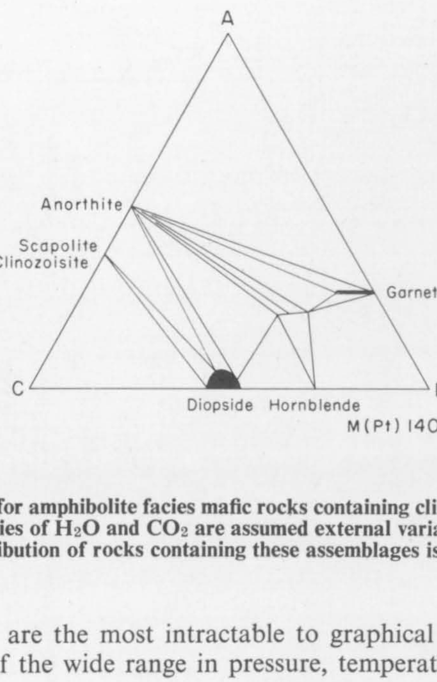

Fig. 6. Facies diagram for amphibolite facies mafic rocks containing clinopyroxene (diopside). Pressure, temperature, and activities of H_2O and CO_2 are assumed external variables. Quartz and K feldspar are additional phases. Distribution of rocks containing these assemblages is given on Plate 1.

rocks of this grade are the most intractable to graphical analysis and comparison, probably because of the wide range in pressure, temperature, and activities of H_2O and CO_2.

The pelitic schists have been graphically analysed and compared by the method set out in Thompson (1957); the results are given in Figures 4 and 5. Unfortunately, the pelitic schists are not sufficiently widely distributed in most areas to serve in subdividing all the amphibolite facies on the metamorphic map. Consequently a large area has been left undifferentiated, and other areas are differentiated on the basis of the mineral assemblages in mafic rocks.

No work has been done on the amphibole or plagioclase minerals; so rocks containing kyanite, sillimanite, andalusite, or viridine in pelitic schists and garnet in mafic rocks are excluded from the greenschist facies and the first appearance of these minerals is taken as the lower boundary of the amphibolite facies.

A transition from greenschist facies to amphibolite facies is seen in the southwestern margin of the Amadeus Basin, where an isograd showing the first appearance of kyanite has been mapped (Pl. 1).

The upper boundary of the amphibolite facies is chosen as the first appearance of hypersthene. Pelitic rocks in the amphibolite facies below this isograd are of upper sillimanite grade (characteristically quartz–K feldspar–sillimanite–garnet–biotite, Fig. 4). Associated mafic rocks commonly contain clinopyroxene, and others the assemblage quartz–feldspar–garnet–hornblende–biotite. Mafic and calc-silicate rocks containing both clinopyroxene and scapolite (Fig. 6) are common. These assemblages developed during metamorphism high in the amphibolite facies.

High-grade (and high-pressure) amphibolite facies rocks occur near the Western Australia/Northern Territory/South Australia border junction adjacent to the high-pressure granulites. They are subdivided into two typical assemblages: (1) quartz–K feldspar–plagioclase–clinopyroxene–garnet–biotite–amphibole with or without rutile, apatite, zircon, scapolite, and clinozoisite, and (2) quartz–K feldspar–plagioclase–hornblende–biotite–garnet–iron oxide, with or without apatite and zircon. Relict hypersthene is found within these rocks at several localities, and reaction rims indicative of high pressure are common within metamorphosed mafic dykes. Two types of reaction rim occur in mafic dykes intruding rocks containing each assemblage: (1) olivine + plagioclase $\rightleftarrows$ hypersthene + clinopyroxene + spinel, and (2) hypersthene + plagioclase $\rightleftarrows$ clinopyroxene + garnet. Crystallites of kyanite? (or sillimanite) occur within the feldspars of the metamorphosed mafic dykes. The hypothesis of a high-pressure origin for these rocks (Kushiro & Yoder, 1966; Green & Ringwood, 1967) is strongly supported by the assemblage quartz–K feldspar–kyanite–biotite–garnet–rutile in associated pelitic rocks.

Further attempts to subdivide the amphibolite facies (except locally by pelitic assemblages, Figures 4 and 5) have failed.

Greenschist Facies

Greenschist facies rocks are largely confined to three east-trending belts (Pl. 1), one south of the Amadeus Basin, one in the northern margin of the Amadeus Basin, and one in the northern margin of the Ngalia Basin. Each is at least 400 km long; they may be up to 80 km wide, but in many areas are less than 15 km wide.

Typical mafic and granitic assemblages in the greenschist facies are represented in Figure 7 using the A (Al_2O_3) – C (CaO) – F ($FeO + MgO$) projection of Barth et al. (1939) and Turner & Verhoogen (1960). Upper greenschist facies is differentiated from lower greenschist facies by the appearance of biotite in higher grade rocks of suitable composition. Quartz, albite, muscovite, biotite, chlorite, and pyrophyllite are minerals typically found in pelitic schists of this grade.

The calc-silicate assemblages may differ from those in Figure 7 according to whether the rock has been progressively or retrogressively metamorphosed into the greenschist facies, and these differences are attributed to differences in the activities of H_2O and CO_2 (activity is defined in Thompson, 1957) as well as the pressure and temperature during metamorphism. Further, the activity of CO_2 is not always externally controlled (J. B. Thompson, Jr, pers. comm.) and it seems from apparent local variation in activities of H_2O and CO_2 that the mobility of CO_2 under metamorphic conditions may lag behind that of H_2O.

In the northeastern margin of the Amadeus Basin the retrograde calc-silicate rocks contain actinolite and epidote, but prograde calcareous rocks in the same area, and in the southwestern margin of the Amadeus Basin, are different; muscovite,

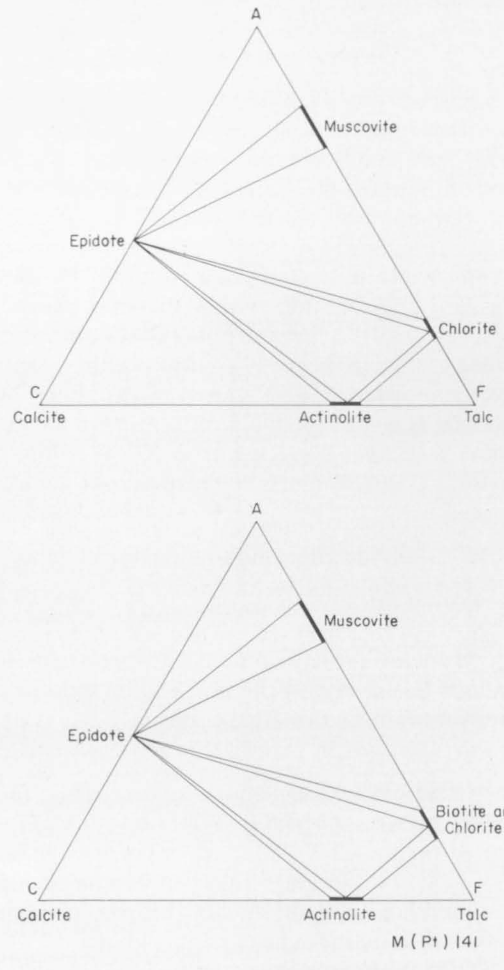

Fig. 7. Facies diagrams for greenschist facies mafic rocks. Pressure, temperature, and activities of H_2O and CO_2 are assumed external variables. Quartz, K feldspar, and albite are possible additional phases. Distribution of rocks containing these assemblages is given on Plate 1.

chlorite, and talc may develop, but actinolite has not been found in them and epidote is rare.

ADELAIDEAN AND PALAEOZOIC STRUCTURE

The following description of the regional structure has been adapted from Forman (1968). The regional structure is shown on Plate 1. Regional 'anticlinoria' separate the Officer and Amadeus Basins, the Amadeus and Ngalia Basins, the Amadeus and Georgina Basins, and the Ngalia and Georgina Basins. The Amadeus and Ngalia Basins are down-warped areas between the 'anticlinoria'.

Nappe structures, involving both basement rocks and Adelaidean cover sedimentary rocks, occur within the low-grade metamorphic rocks in the southwestern, northern, and northeastern margins of the Amadeus Basin. All the nappes front towards the Amadeus Basin. The largest, the Petermann Ranges Nappe (Forman, 1966) on the southwest margin, extends at least 300 km in an easterly direction, and has moved northwards, by overthrusting and overturning, about 50 km. The nappes in the northern and northeastern margin of the Amadeus Basin are smaller. They have moved southwards by overthrusting and overturning for about 13 to 24 km. Two nappes are piled one on the other in the Arltunga Nappe Complex (Forman et al., 1967; Forman, 1971) and the Ormiston Nappe Complex (Forman et al., 1967).

The sedimentary rocks within the Amadeus Basin are strongly folded, and their deformation is of the Jura or Appalachian type. There are two major unconformities in the Amadeus Basin (Fig. 2). A folded unconformity between Adelaidean and Cambrian sedimentary rock proves two periods of folding; one late in the Adelaidean or early in the Cambrian (about 600 m.y.). The other is dated as Carboniferous by an unconformity between folded sedimentary rocks of Devonian to Carboniferous? age and flat-lying Permian and Mesozoic sedimentary rocks.

The Adelaidean or early Cambrian folds in the south of the Amadeus Basin are poorly exposed and therefore their geometry and mutual relations over much of the area are unknown. Generally only closed or tight canoe-shaped synclines with flat plunges are preserved. Dips are steep to overturned in some areas. Many of the folds in Western Australia were formed late in the Adelaidean or early in the Cambrian. Strike-slip faults occur in the sedimentary rocks of this area, but practically no faults have been mapped in the Northern Territory because of the poor outcrop. Forman (1966) gave evidence to suggest that these folds formed over a décollement within the Bitter Springs Formation during northwards tectonic transport while the Petermann Ranges Nappe developed.

The Carboniferous folds are well exposed in the northern part of the Amadeus Basin. There are numerous folds of great regularity and length: several may be traced for 240 km. The folding style ranges from gentle to closed; the folds may be symmetrical, asymmetrical, or overturned. The interlimb angle of the anticlines (Ramsay, 1967, p. 349) is usually more acute than that of the synclines, which are typically gentle or may be of the double hinge type. The structure becomes more complex deeper in the anticlinal cores, where crumpling of strata, faulting, and thrusting are common. Many folds have a core of isoclinally folded Bitter Springs Formation and some have a core of highly sheared or brecciated gypsum (from the Bitter Springs Formation) with large included blocks of carbonate rock. The gypsum mass commonly intrudes the deepest strata in the anticlinal core and at several localities gypsum also intrudes Palaeozoic strata. The Heavitree Quartzite is not exposed in the core of any of the anticlines and it is clear that the folding of the sedimentary rocks above the Bitter Springs Formation does not extend downwards to the Heavitree Quartzite or basement rocks. This conclusion is supported by the results of structural interpretation, seismic profiling, and aeromagnetic and gravity interpretation; so there is little doubt that there is a décollement within the Bitter Springs Formation.

There are two surfaces of décollement, or detachment, in the northeastern part of the Amadeus Basin; one in the Bitter Springs Formation and the other in a Lower Cambrian carbonate and evaporite unit called the Chandler Limestone. The sedimentary strata have been folded over both surfaces and the thrust surface connecting the lower and upper décollements is itself folded and imbricated. The folds over the lower décollement surface have a different amplitude (about 3000 m) from those over the upper surface (about 500–1000 m). This is related to the depth of folding (Billings, 1954, p. 60).

The wavelength of the folds is variable. Near the northern and southern margins of the Amadeus Basin there are large broad synclines, probably of the double hinge type, within which subsidiary folds occur whose wave lengths are about 19 km. In the centre of the Basin the wavelengths range from 10 to 22 km.

There was one major deformation after Devonian rocks were deposited in the Georgina Basin. The structural complexity is greatest in the southwestern margin, where the sedimentary rocks are tilted up against normal (?) northwesterly faults with throws up to about 1000 m, and a large broad syncline (or monocline) has developed in the Dulcie Range. The southwestern limb of the monocline dips moderately to steeply but the northeastern limb is flat-lying.

Two periods of folding affected the sedimentary rocks of the Ngalia Basin. A folded angular unconformity near the base of the Cambrian sedimentary rocks is correlated with the older, Adelaidean or early Cambrian, unconformity within the Amadeus Basin. Gentle to closed folds of Carboniferous? age in the Devonian to Carboniferous sediments of the Ngalia Basin are related to overthrusting of crystalline basement rocks onto the sedimentary cover along the northern margin of the Basin.

Little is known of the structure of the Officer Basin. Palaeozoic sediments are gently folded and unconformably overlie Adelaidean sedimentary rocks whose stronger folding is at least partly related to basement faulting.

Faults occur within the anticlinoria of basement rocks. A thrust of continental proportions (Wilson, 1960; Major, 1970), called the Woodroffe Thrust, trends easterly near the Northern Territory border between the Officer and Amadeus Basins. It has a gentle southerly dip, and the presence of outliers to the north demonstrates that in some areas its regional dip is nearly flat. Beneath the thrust is a zone of more plastic deformation, exemplified by the thrusting and recumbent folding in the Petermann Ranges Nappe to the north.

Other major faults called the 'Davenport Shear Zone' and the 'Mann Fault Zone' are shown south of the Woodroffe Thrust, but not named, on Plate 1. The Davenport Shear Zone is probably older than the Woodroffe Thrust, but the Mann Fault Zone, which faults an outlier of Adelaidean or early Cambrian sedimentary rocks (Pzl? on Plate 1) may be of the same age as the Woodroffe Thrust, or younger.

A thrust zone occurs north of the Amadeus Basin, and thrusts within the Ormiston Nappe Complex and the Arltunga Nappe Complex (Forman, 1971) belong in it.

A third thrust, or thrust zone, occurs to the north of the Ngalia Basin, but its easterly extension between the Amadeus and Georgina Basins cannot be located and its western extension is uncertain. Thrusting in the south of this zone has forced crystalline basement rocks over and onto the sedimentary cover along the northern margin of the Ngalia Basin. A thrust is confidently interpreted on a seismic section across the margin. A displacement of at least 12 km along the thrust and a northerly dip of 35° are indicated (F. J. Moss, BMR, pers. comm.).

STRUCTURAL AND METAMORPHIC HISTORY

A complex record of diastrophism is preserved in the rocks of central Australia (Forman, 1968; Forman *in* Wells et al., 1970), but only diastrophism accompanied by regional metamorphism (orogeny) will be considered in this Bulletin. There have been at least three orogenies (Fig. 2): the Arunta Orogeny and others before the Adelaidean sedimentary rocks were deposited; the Petermann Ranges Orogeny late in the Adelaidean or early in the Cambrian; and the Alice Springs Orogeny in the Carboniferous.

Arunta and Other Orogenies

The areas between the sedimentary basins are underlain by gneiss, schist, quartzite, marble, and mafic and ultramafic rocks that were strongly folded, metamorphosed, and intruded by granite before the younger Precambrian basement rocks were deposited. The older Precambrian basement rocks are called the Arunta Complex (Mawson & Madigan, 1930) north of the Amadeus Basin and the Musgrave–Mann Metamorphics (Thomson, 1969) and Olia Gneiss (Forman, 1966) south of the Basin.

The Arunta Complex was folded and metamorphosed during the Arunta Orogeny (Forman et al., 1967; Forman, 1968). Granites intruding the Arunta Complex in the southern margin of the Georgina Basin were dated by Hurley et al. (1961) using the K/Ar method at 1440 m.y., but one of them was subsequently dated from concordant total rock and mineral Rb/Sr methods at 1690 m.y. by Riley (1961, and pers. comm. *in* Compston & Arriens, 1968). This date is younger than the 1840 m.y. obtained by Wilson et al. (1960) from Rb/Sr determinations on a single muscovite from the same granite, and is preferred because it rests on many more analyses. Six samples of gneiss from the front of the Arltunga Nappe Complex in the northeastern margin of the Amadeus Basin were dated by Miss Rosalind Bennett (pers. comm.) of the Bureau of Mineral Resources at the Australian National University. Rb/Sr measurements by Miss Bennett show that biotite from the gneiss is at least 1500 m.y. old and that whole rock samples show an upper age limit of about 1900 m.y. The true age of formation of the gneiss is somewhere between these extremes. Stewart (1971) dated separates of muscovite, biotite, and hornblende from the Arunta Complex within the Arltunga Nappe Complex using the K/Ar method. A considerable spread of dates was obtained; the oldest date of 2132 m.y. (considered anomalously high) was obtained from a hornblende, all the other dates were below 1700 m.y.

With these isotopic dates it is difficult to know the age of the high-grade metamorphism typical of the Arunta Orogeny, particularly as there is evidence in some areas for several Precambrian metamorphic episodes in addition to that in the Palaeozoic. The preponderance of older dates near 1700 m.y. suggests this as a minimum age for the high-grade metamorphism.

Arriens & Lambert (1969) analysed ten granulite facies gneisses from the Musgrave–Mann Metamorphics in the Musgrave Ranges by the Rb/Sr whole-rock method and obtained an isochron of 1380 ± 120 m.y. with initial Sr^{87}/Sr^{86} of $0{\cdot}7072 \pm {\cdot}0025$. They considered this was the age of the granulite facies metamorphism. They also indicated the possibility of an earlier 1655 ± 110 m.y. isochron with initial Sr^{87}/Sr^{86} of $0{\cdot}708 \pm {\cdot}001$ for some of the gneisses in the Musgrave Ranges. Ten samples from the Ernabella Adamellite, which intrudes the Musgrave–Mann Metamorphics, gave an isochron of $1\,120 \pm 100$ m.y. with initial Sr^{87}/Sr^{86} of $0{\cdot}7106 \pm 0{\cdot}0014$.

There is evidence of at least two metamorphic events in the Mann Ranges of the Petermann Ranges Sheet area (Forman, 1972), where mafic dykes intruding the Musgrave–Mann Metamorphics are comparatively little deformed but have been metamorphosed to amphibolite and granulite facies. Further, a thrust zone that intersects the mafic dykes contains clinopyroxene and garnet, typical minerals of the second, high-grade, metamorphism. It appears therefore that this second high-pressure metamorphism of the Musgrave–Mann Metamorphics is genetically related to thrusting—perhaps the movement expressed farther east as the Davenport Shear Zone.

The Musgrave–Mann Metamorphics therefore have undergone at least two periods of high-grade metamorphism, the younger metamorphism possibly taking place about 1400 m.y. ago, before the latest granites were intruded.

The Olia Gneiss (Forman, 1966, 1972) is abruptly separated from the Musgrave–Mann Metamorphics by the Woodroffe Thrust, and is of much lower metamorphic grade. Two specimens of metamorphosed granite intruding the Olia Gneiss were dated by P. J. Leggo at 1150 and 1190 m.y. using the Rb/Sr whole-rock method (Forman, 1966), but younger Rb/Sr isotopic ages of about 600 m.y. were obtained from biotite and microcline separates. The whole-rock age is considered to be the date of emplacement of the granite, whereas the mineral ages give the date of a subsequent metamorphism that occurred during the Petermann Ranges Orogeny. The early folding and metamorphism of the Olia Gneiss took place at least 1170 m.y. ago and probably earlier, at the same time as the Musgrave–Mann Metamorphics.

Petermann Ranges Orogeny

During the Petermann Ranges Orogeny (Forman, 1966, 1972), 600 m.y. ago, an easterly trending zone of the crust was deformed along the southern margin of the Amadeus Basin. The zone dips to the south. Its top is the Woodroffe Thrust and its base is probably the base of the Petermann Ranges Nappe. Above the deformed zone the granulites of the Musgrave–Mann Metamorphics were uplifted and transported northwards along the Woodroffe Thrust. The Petermann Ranges Nappe, involving Olia Gneiss and Adelaidean cover rocks, developed near the surface within the deformed zone. All the rocks—Olia Gneiss, granite, mafic dykes, and Adelaidean cover—were metamorphosed within the deformed zone. The cover rocks near the base of the zone were progressively metamorphosed up to the staurolite isograd. The Olia Gneiss was deformed and retrogressively metamorphosed under the same conditions within the zone and also beneath it. The intensity of metamorphism diminishes towards the Amadeus Basin, and only lower greenschist facies rocks occur near the southern margin of the Basin. As the Petermann Ranges Nappe developed, the more competent Adelaidean sedimentary rocks were detached from the incompetent Pinyinna Beds (lithological correlative of Bitter Springs Formation) and slid northwards on a décollement surface within the Bitter Springs Formation. This folding, of the Jura or Appalachian type, is preserved in the southwestern Amadeus Basin unconformably beneath the Cambrian sedimentary rocks.

Alice Springs Orogeny

The Arunta Complex was folded, thrust, and retrograded in restricted zones along the northern margins of the Amadeus and Ngalia Basins, and adjacent sedimentary rocks in the basins were folded, during the Alice Springs Orogeny (Forman, 1966, 1968, 1971; Forman et al., 1967) in the Carboniferous.

Deformation during the Alice Springs Orogeny was of similar type to that during the Petermann Range Orogeny; but two zones were deformed during the Alice Springs Orogeny and in each of them the displacements were smaller and southerly rather than northerly. The metamorphism was of lower grade.

The more prominent zone runs easterly along the northern margin of the Amadeus Basin and includes the Ormiston and Arltunga Nappe Complexes. The southern margin of the deformed and retrograded zone coincides approximately with the northern margin of the Amadeus Basin, which is a large monocline; to the north the zone is bounded by high-grade, typically granulite facies, metamorphic rocks. Within the zone the Arunta Complex is retrograded, at least partly, and in the nappes the cover of Heavitree Quartzite and Bitter Springs Formation is progressively metamorphosed. Details of structure and metamorphism within the Arltunga Nappe Complex are given by Forman (1971).

Although the zone of retrograde metamorphism can be traced through the Arunta Complex, thrusts cannot. There is a group of thrusts at the base of the Arltunga Nappe Complex that probably marks the base of the zone, but these cannot be traced very far to the east or west or connected with thrusts at the base of the Ormiston Nappe Complex. In contrast with the deformed zone developed during the Petermann Ranges Orogeny there is no clearly defined thrust contact with the overlying granulites. Detailed mapping by R.D.S. (unpublished), north of the Arltunga Nappe Complex, suggests that the partly to completely retrograded core rocks of the upper nappe pass northwards into the high-grade rocks without major structural discontinuity. This suggests that deformation in these core rocks, above the base of the nappe, is partly penetrative and partly by numerous closely-spaced minor faults.

The deformed zone, north of the Ngalia Basin, is less clearly defined by mapping. Its presence is inferred from thrusting along the northern margin of the Ngalia Basin, the presence of granulites to the north, a few greenschist facies rock specimens collected from within it, and a Bouguer gravity anomaly low adjacent to it.

Further the zone deformed in the Carboniferous does not entirely coincide with the greenschist facies rocks shown north and west of the Ngalia Basin on Plate 1; the greenschist facies rocks near the Western Australian border are younger Precambrian basement rocks overlain unconformably by unmetamorphosed Adelaidean sedimentary rocks. Prograde younger Precambrian basement rocks are also suspected north of the Ngalia Basin in the east (Pl. 1) and their full extent is unknown. The picture is also complicated south of the Georgina Basin, where we know even less of the relationships between high-grade and low-grade rocks, and no attempt is made to interpret this area.

The age of the Alice Springs Orogeny has been deduced as Carboniferous by dating the folding in the basins, and by isotopic dating of metamorphic minerals formed during the orogeny. Stewart (1971) has dated muscovite from four samples of metamorphosed Heavitree Quartzite in the Arltunga Nappe Complex by the K/Ar method. He reports that all the muscovite samples from the Heavitree Quartzite, and one whole-rock sample from the Bitter Springs Formation, are early to middle Carboniferous in age (358–322 m.y.). Walpole & Smith (1961, p. 667) report a 367 m.y. K/Ar age determination on biotite from a gneiss in the Arunta Complex, 3 km southwest of the Harts Range Police Station. If the Devonian–Carboniferous boundary is accepted at 362 m.y. (MacDougall et al., 1967) then the retrograde metamorphism north of the Amadeus Basin must have occurred very late in the Devonian or in the early to middle Carboniferous.

In summary, therefore, the main movements during the Carboniferous Alice Springs Orogeny took place along two northerly dipping zones of deformation that pass through the crust north of the Amadeus and Ngalia Basins. The basement rocks are deformed and retrograded in these zones and the sedimentary rocks in the adjacent basins are folded and thrust.

RELATIONSHIP BETWEEN METAMORPHISM, STRUCTURE, AND BOUGUER GRAVITY ANOMALIES

The metamorphic map (Pl. 1) shows three high-grade belts of granulite and amphibolite facies rocks, one north of the Ngalia Basin, and one north and one south of the Amadeus Basin. These belts are flanked on one side by deformed belts, generally of greenschist facies, that commonly occur on the margins of the sedimentary basins: one passes into the Ngalia Basin, and the Amadeus Basin is flanked on both margins by greenschist facies rocks. Within the low-grade, predominantly greenschist facies, belts the older Precambrian basement rocks are retrogressively metamorphosed but the younger Precambrian basement rocks and the Adelaidean sedimentary cover are progressively metamorphosed.

The Bouguer anomaly map (Pl. 1) shows an easterly zone of positive Bouguer anomalies (up to +50 mgals) over the granulites between the Officer and Amadeus Basins that is flanked to the north by a deep gravity trough (down to −130 mgals) over the retrograde belt. The Woodroffe Thrust crops out within the Bouguer gravity gradient between the high and low.

Another easterly zone of positive Bouguer anomalies (up to +40 mgals) occurs over the Arunta Complex between the Amadeus and Ngalia Basins. It is flanked to the south by a deep gravity trough (down to −145 mgals). The gradient between them parallels the northern margin of the Amadeus Basin and occurs over an area of granulites bounded to the south by retrograde greenschists.

A west-northwesterly trending gradient appears to intersect the easterly gradient to the north of the Amadeus Basin. It passes north of the Ngalia Basin and then trends westerly. It is flanked to the southwest by a deep Bouguer gravity trough, down to −100 mgals north of the Ngalia Basin, and to the northeast by an undulating gravity platform.

The metamorphism, structure, and Bouguer gravity anomalies shown on Plate 1 may be related by postulating three zones of crustal deformation that pass right through the crust into the mantle beneath (see section, Pl. 1). The gravity highs occur over areas where the lower crust and upper mantle have been upthrust and the gravity lows reflect the areas of thickest crust in front of the dislocated zone. No attempt has been made to calculate the anomaly curve that would arise from the distribution of crust and mantle shown on the section (see Wells et al., 1970, p. 139, for example), which is therefore highly diagrammatic. This calculation can best be made after the deep seismic profiling along the section line that is tentatively programmed by BMR for 1973 and 1974.

SIGNIFICANCE OF THE DEFORMED ZONES

The three zones of crustal dislocation are hundreds of kilometres long; they may extend right across the continent, and it may be possible to explain them by an extension of current theories of plate tectonics. Plate tectonics refers to interactions between continental and oceanic crust, between oceanic and oceanic crust, and between continental and continental crust. According to the plate theory interaction between continental crust and oceanic crust is responsible for geosynclinal sedimentation, folding, metamorphism, and magmatism; resulting in continental accretion. It appears that the earlier metamorphisms in central Australia, such as the Arunta Orogeny, may have been the result of interaction of continental and oceanic crust about 1800 m.y. ago or earlier. It is not intended to speculate further on the nature of these early events except to compare and contrast them with the deformations of the continental crust which occurred in central Australia about 600 and 350 m.y. ago during the Petermann Ranges and Alice Springs Orogenies. The deformed zones that developed within the continental crust during these orogenies are similar to the subduction zones that may develop on the margins of continents, and this similarity suggests a similarity in driving mechanism even if not in their tectonic setting. Gilluly (1971, p. 2387) recognizes continent-continent junctions between plates, giving the Himalayan Ranges as an example. However, this appears to be an example of intercontinental reaction, whereas in central Australia we have an example of intracontinental reaction. The nature of this type of intracontinental deformation will clearly be highly influenced by the temperature and degree of plasticity in the deformed part of the crust and upper mantle. Whereas the earlier deformations (Arunta Orogeny and others) were accompanied by comparatively high-temperature metamorphism, typically producing andalusite, sillimanite, and cordierite, the Petermann Ranges and Alice Springs Orogenies clearly occurred when the geothermal gradient was much lower. Viridine and kyanite were produced during the Petermann Ranges Orogeny. The deformed crust was comparatively brittle and because of the low geothermal gradient and a comparative absence of water those parts of the crust carried down into the mantle were not partly melted and there was no magmatic activity. The rather hypothetical section on Plate 1 suggests that only a small quantity of crust was underthrust into the mantle and therefore the process may have halted in its infancy, by comparison with interactions between continental and oceanic plates.

It is quite possible that some of the deformations in central Australia which took place before the Petermann Ranges Orogeny were of the intracontinental deformed zone type. Two narrow zones of kyanite–staurolite rocks transgressing granulite facies Arunta Complex are shown on Plate 1 to the northeast of Alice Springs, and the Strangways Range (suspected) carbonatite occurs close to one of these. Mention has already been made of clinopyroxene and garnet-bearing thrust zones within the granulite facies rocks of the Musgrave–Mann Metamorphics. It is possible that under an appropriate geothermal gradient granitic and mafic magmas could be generated in the vicinity of the deeper parts of the deformed zone, which would account for some of the post-tectonic granite and mafic dykes in the area. Deformation and metamorphism of these mafic dykes suggest a repetition of the process at a later stage.

The continental crust in central Australia may well be very ancient: if so, even the Arunta Orogeny may be the symbol of interaction not between continental and oceanic crust, but within a single continental plate.

It is expected that the concept of complex reworking of continental crust by deformed zones can be tested by detailed mapping, isotopic age determinations, and the deep crustal seismic surveying programmed by BMR for 1973 and 1974. Certainly the model presented in this paper is an oversimplification of a complex reality.

Earlier in this paper we mentioned that the three zones of crustal deformation may have extended right across the continent. The Bouguer gravity map of Australia offers an opportunity to quickly test this hypothesis. It does appear possible that the gravity high associated with the Petermann Ranges zone of crustal dislocation extends westward along the northern margin of the Pilbara Block but this is by no means certain. The westerly-trending gravity highs associated with the Alice Springs Orogeny terminate in Western Australia close to the border in a zone of northerly-trending anomalies. Extensions eastward are difficult to trace as the trends are no longer so pronounced.

However, the plate theory offers the further possibility that the zones of dislocation may terminate against one or more strike-slip (transform) faults. We have speculated that a northerly-trending strike-slip fault may extend right along the eastern side of Western Australia from the Joseph Bonaparte Gulf in the north, south-southwest along the eastern margin of the Kimberley Block (see Rod, 1966), and then southwards to the west of the Arunta and Musgrave Blocks and the east of the Yilgarn Block. This trend can be seen by inspecting both the Bouguer gravity map of Australia (which has not yet been completed but is available for inspection at BMR) and the 1971 Tectonic Map of Australia. There is no proof or even strong evidence, at this stage, to support this speculation.

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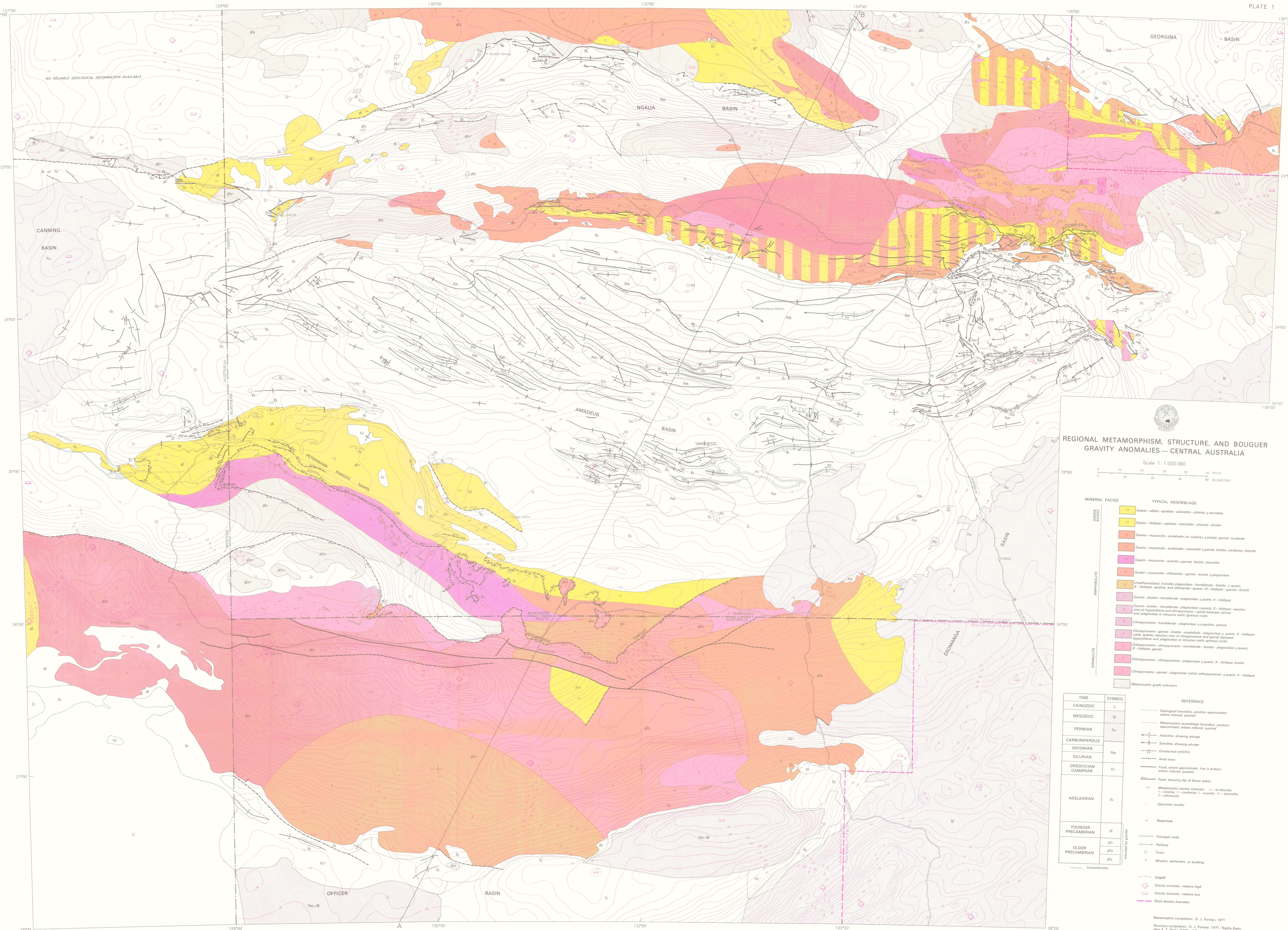
PLATE 1



REGIONAL METAMORPHISM, STRUCTURE, AND BOUGUER GRAVITY ANOMALIES — CENTRAL AUSTRALIA

Scale 1 : 1 000 000

0 10 20 30 40 50 MILES
0 20 40 60 80 KILOMETRES

MINERAL FACIES		TYPICAL ASSEMBLAGE
GREEN SCHIST	14	Quartz—albite—epidote—actinolite—chlorite ±microline
	13	Quartz—feldspar—epidote—actinolite—chlorite—biotite
AMPHIBOLITE	12	Quartz—muscovite—andalusite (or viridine) ±biotite, garnet, cordierite
	11	Quartz—muscovite—andalusite—staurolite ±garnet, biotite, cordierite, chlorite
	10	Quartz—muscovite—kyanite ±garnet, biotite, staurolite
	9	Quartz—muscovite—sillimanite—garnet—biotite ±plagioclase
	8	Undifferentiated; includes plagioclase—hornblende—biotite ± quartz, K—feldspar, epidote, and sillimanite—quartz—K—feldspar—garnet—biotite
	7	Garnet—biotite—hornblende—plagioclase ±quartz, K—feldspar
	6	Garnet—biotite—hornblende—plagioclase ±quartz, K—feldspar; reaction rims of hypersthene and clinopyroxene—spinel between olivine and plagioclase in intrusive mafic igneous rocks
	5	Clinopyroxene—hornblende—plagioclase ±scapolite, sphene
	4	Clinopyroxene—garnet—biotite—amphibole—plagioclase ± quartz, K—feldspar, rutile, apatite; reaction rims of clinopyroxene and garnet between hypersthene and plagioclase in intrusive mafic igneous rocks
GRANULITE	3	Orthopyroxene—clinopyroxene—hornblende—biotite—plagioclase ±quartz, K—feldspar, garnet
	2	Orthopyroxene—clinopyroxene—plagioclase ±quartz, K—feldspar, biotite
	1	Clinopyroxene—garnet—plagioclase (relict orthopyroxene) ±quartz, K—feldspar
		Metamorphic grade unknown

TIME	SYMBOL
CAINOZOIC	Cz
MESOZOIC	M
PERMIAN	Pzu
CARBONIFEROUS	Pzu
DEVONIAN	Pzm
SILURIAN	Pzm
ORDOVICIAN CAMBRIAN	Pzl
ADELAIDEAN	Ꞓu
YOUNGER PRECAMBRIAN	pꞒ
OLDER PRECAMBRIAN	pꞒn
	pꞒm
	pꞒa

Intruded by granite

Unconformity

REFERENCE

Geological boundary, position approximate; where inferred, queried

Metamorphic assemblage boundary, position approximate; where inferred, queried

Anticline, showing plunge

Syncline, showing plunge

Overturned anticline

Axial trace

Fault, where approximate, line is broken; where inferred, queried

Fault, showing dip of thrust plane

Metamorphic marker minerals: A—andalusite, V—viridine, C—cordierite, K—kyanite, St—staurolite, S—sillimanite

Specimen locality

Waterhole

Principal roads

Railway

Town

Mission, settlement, or building

Isogals

Gravity anomaly—relative high

Gravity anomaly—relative low

Rock density boundary

Metamorphic compilation: D. J. Forman, 1971

Structure compilation: D. J. Forman, 1971; Ngalia Basin after A. T. Wells (BMR); Officer Basin after various sources, Geological Survey of Western Australia and Department of Mines, South Australia

Gravity compilation: Northern Territory and Western Australia by Geophysical Branch, BMR; South Australia by Geological Survey of South Australia (71/684D)

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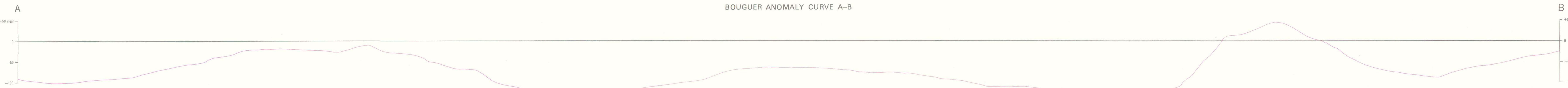
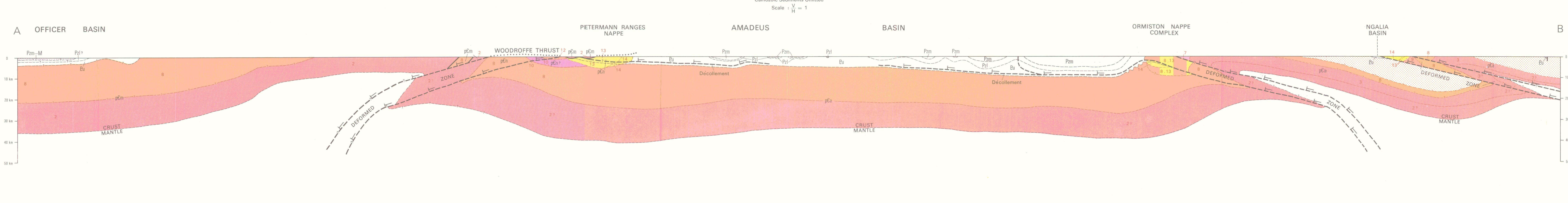
BOUGUER ANOMALY CURVE A–B



DIAGRAMMATIC SECTION

Cainozoic Sediments Omitted



MAP AREA IN RELATION TO 1:250,000 GEOLOGICAL SERIES

Showing Magnetic Declination 1970