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Structure and Tectonic Development of the Mount Doreen 1:250 000 Sheet Area

By R.D. Shaw

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AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

REGIONAL GEOLOGY AND MINERALS

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SUMMARY

The Mount Doreen 1:250 000 map area covers parts of the early to middle Proterozoic Arunta Block and Neoproterozoic to Carboniferous Ngalia Basin. The earliest orogenic event recognised affected the Lander Rock beds and was followed by the intrusion of a cordierite granite, the Ngadarunga Granite, into migmatitic gneiss thought to have been generated locally during peak metamorphic conditions. An 1880 Ma age for this granite, together with regional correlations, suggests that this orogeny may broadly correlate with the early stages of the 1850-1890 Ma Barramundi Orogeny recognised in other parts of northern Australia. In the Mount Doreen Sheet area this tectonism is referred to as the Yuendumu Orogeny. The earliest stage assigned to this event is characterised by tight to isoclinal folds, and a regional slaty cleavage that may be the result of thrusting and crustal shortening.

Several migmatitic and gneissic bodies that are similar to that surrounding the Ngadarunga Granite are aligned east - west to form a weakly defined belt within a region where the recorded metamorphic conditions extend above the regional average to the biotite isograd. Here, continued deformation of the slaty cleavage has resulted in a second generation of upright folds characterised by an axial-planar crenulation-like cleavage. The 1880 Ma Ngadarunga Granite has intruded the largest of these migmatitic gneiss bodies, thereby providing a minimum age for the migmatisation there. Elsewhere along a belt of migmatitic and gneissic bodies, the age of migmatisation is less well constrained.

The unconformably overlying Reynolds Range Group was tightly folded and flattened within narrow high-strain zones during the Wabudali tectonic phase of uncertain age. Tight, boat-like isoclinal synclines, outlined by the Reynolds Range Group, formed during this event and may represent footwall-keels to north-directed reverse faults. Although intrusion of the Carrington Granitic Suite commenced before the Wabudali Tectonic Phase at about 1780 Ma, most granites in the region post-date this deformation, the youngest recorded granite being about 1570 Ma.

After a long period of relative quiescence, subsidence was initiated in the Ngalia Basin at about 830 Ma. Episodic subsidence, punctuated by periods of erosion, continued to about 300-400 Ma when the existing composite basin was inverted in two phases during the Alice Springs Orogeny. The first phase was the Kerridy Movement, which involved faulting, tilting, minor folding and widespread erosion. This phase is thought to have involved the injection of siliceous hydrothermal fluids into the faults to produce widespread ridge-forming quartz veins. It probably took place during the Late Devonian, and is correlated with the Pertnjara Movement in the Amadeus Basin. The second phase occurred during the mid-Late Carboniferous and was more intense. It resulted in thick-skinned, basement-cored overthrusting and reverse faulting. During concurrent thin-skinned detachment, which was localised within a suspected salt unit near the base of the succession, several decollement-related folds were formed.

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INTRODUCTION

Current Investigation

In 1991, a reconnaissance structural study was carried out in the Mount Doreen 1:250 000 Sheet area[1] by R.D. Shaw (Australian Geological Survey Organisation [AGSO]). The study had the objective of elucidating the structural and tectonic evolution of the Sheet area and fitting it into a regional context. This study has been more recently updated in the light of new geochronological information.

The Sheet (ie. map) area studied is bounded by latitudes 22°00'S and 23°00'S and longitudes 130°30'E and 132°00'E. It covers part of the Palaeoproterozoic to Mesoproterozoic Arunta Block and part of the overlying Neoproterozoic to Palaeozoic Ngalia Basin.

The structural study was carried out in conjunction with a 1:100 000 geological mapping program in cooperation with the Northern Territory Geological Survey (NTGS). D H Blake of AGSO (formerly BMR) mapped VAUGHAN (1:100 000 and adjacent sheet areas to the west), C Edgoose (NTGS) covered DOREEN, while D Young (NTGS) was responsible for YUENDUMU. The poorly exposed GURNER, NEWHAVEN and SIDDELEY Sheet areas were mapped by A Camacho (NTGS) in conjunction with D. Young.

This research forms part of the Kimberley-Arunta Project, undertaken jointly by the Australian Geological Survey Organisation, the Northern Territory Geological Survey and the Geological Survey of Western Australia, as part of the National Geoscience Mapping Accord (NGMA).

Previous Investigations

Other outputs to date from this NGMA project include the progress and final reports on VAUGHAN by Blake (1991a, 1993), a BMR Research Newsletter article by Shaw et al. (1992a) and a paper on geochronological results by Young et al. (1995).

As well as incorporating the results of this joint work, the structural study builds on the earlier 1:250 000 geological mapping program summarised by Wells (1972) and takes note of a subsequent synthesis of the stratigraphy and structure of the Ngalia Basin by Wells and Moss (1983), incorporating BMR seismic data.

A model for the Proterozoic stratigraphy of the northern Arunta province has been proposed by Stewart et al. (1984), based on the studies of the Reynold and Anmatjira ranges summarised in Stewart et al. (1980). Immature metasedimentary rocks of turbiditic origin have been assigned to the Lander Rock beds correlate with the Warramunga Formation (previously 'Group') in the Tennant Creek region; the unconformity overlying platform sediments of the Reynolds Range Group correlated with the Hatches Creek Group in the Davenport region (Stewart et al. 1984). These correlations are still regarded as valid, even though the Lander Rock beds may be somewhat older than their correlate, the Warramunga Formation, currently dated at around 1860-1870 Ma (see Young et al. 1995, Donnellan et al. 1995, Compston 1991, 1995). The Hatches Creek Group have been currently placed at 1820-1800 Ma, based on the U-Pb zircon ages of felsic extrusives at the base of the sequence (Blake & Page, 1988). As pointed out by Dirks and Norman (1992), the Reynolds Range Group, like the Hatches Creek Group, may be rift-related.

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[1] Throughout this report 'Sheet area' refers to the 1:250 000 Sheet area, whereas a capitalised map sheet name (e.g., DOREEN) refers to the 1:100 000 Sheet area

The general tectonic framework proposed for the Arunta Block by Black et al. (1983) and Shaw et al. (1984) is still substantially valid, although the precise age and nature of this framework has become much clearer with later work. These syntheses proposed five major tectonic events:

1) the Strangways Event at 1800-1750 Ma,

2) the Aileron Event at 1650-1700 Ma,

3) the Anmatjira Event at about 1400 Ma,

4) the Ormiston Event at about 1050 Ma, and

5) the Alice Springs Orogeny, well-established as an event, at 300-400 Ma.

The current state of knowledge of these and some other events is given in Collins & Shaw (1995). New ages for the tectonic events in the Mount Doreen region have been documented in Young et al. (1995) and the significance of these new ages will be discussed in the interpretative part of this report.

DEFORMATIONS IN THE PROTEROZOIC ARUNTA BLOCK

Geological Outline

Arunta Block

The stratigraphy is outlined in Figure 1. Figure 2 provides the physiographic setting and shows the main topographic features referred to in this report. Figure 3 is a sketch of the solid geology that also shows the distribution of the main structural features. Further information on the structural features is provided in Figure 4a, the legend to which is a separate Figure (4b).

The Arunta Block, both north and south of the Ngalia Basin, consists chiefly of deformed and metamorphosed sedimentary rocks and granite intrusions. The oldest rocks exposed, those of the Lander Rocks beds, were tightly folded and regionally metamorphosed from greenschist to granulite facies before the deposition of the Reynolds Range Group, Patmungala beds and Nicker beds. These three younger units, also tightly folded, are mainly metamorphosed to greenschist facies. The metamorphisms were of high-temperature low-pressure type. The granites belong mainly to two suites:

(1) the Carrington Granitic Suite that is characterised by xenolithic, and locally migmatitic foliated granites which intrude the Lander Rock beds (comprising most of the 'gneissic, xenolithic granite in Fig. 3), and

(2) the post-tectonic Southwark Granitic Suite, typified by non-foliated granites containing tabular-feldspar phenocrysts, which intrudes the Reynolds Range Group, Patmungala beds and Nicker beds. (shown as 'megacrystic granite' in Fig. 3).

North of the Ngalia Basin the Arunta Block is cut by numerous faults, some of which are more than 50 km long (Fig. 4). They are commonly filled with quartz. These faults form branching, but disconnected, networks. Most of the quartz veins and foliations in adjacent schists are sub-vertical. These features suggest that the main episode of fault generation was in a strike-slip, possibly transtensional, regime. The largest fault network, which forms part of the east-west trending Coxes and Treachery schist zones (Fig. 4), is cut by, and hence predates, the 1567 Ma Yarunganyi Granite of the Southwark Granitic Suite. An east-southeast trending splay, the Bundarunganu schist zone, is a belt of metamorphically retrograde two-mica schists. In the northwest, the east-northeasterly trending Weaner Fault Zone and linked faults to the east separate a region of generally high-grade metamorphic rocks to the north from granites of the Southwark suite and low-grade Patmungala and Nicker beds to the south. To the south, the Eva Springs fault zone separates granites of the Southwark suite from the Ngalia Basin succession.

Ngalia Basin

The Ngalia Basin is the preserved remnant of a much more extensive polyphase, intracratonic basin (e.g., Shaw 1991, Shaw et al. 1991b). It is an synformal structure with its steeper northern margin outlined by a combination of a steep homoclinal upturn, a low-angle thrust faults and high-angle reverse faults. Its southern margin is a gently north-dipping basement-cover interface, disrupted by complex faulting; for example the Gurner Fault in the west and a set of horst- and graben-like structures in the Newhaven region (Wells & Moss 1983 p. 53, 60). Depth to basement estimates and seismic interpretation suggest that similar horst and graben-like structures are present to the east and northeast. The sedimentary rocks of the Ngalia Basin have not been regionally metamorphosed.

The main period of thrusting and decollement-related folding in the northern part of the Ngalia Basin dates from the Late Devonian to Carboniferous Alice Springs Orogeny (Wells & Moss 1983), when the Yuendumu and Waite Creek thrusts, the Treuer Fault Zone, and probably also the Weaner and Eva Spring fault zones formed. These thrusts displaced the basement, and point to a 'thick-skinned' tectonic style. Evidence for displacements in excess of 10 km on these faults comes from seismic data (Wells & Moss 1983).

System of Analysis

A structural analysis was carried out to unravel the tectonic complexities of the region. Because of the isolated and disconnected nature of the exposures, it was not possible to erect a simple, definitive deformation chronology. A particular problem concerns the relative ages of a series of migmatite complexes. These migmatites may represent either basement to the more readily mappable stratigraphic sequences or a set of metamorphic and structural complexes that were superimposed after deposition of the stratigraphic sequences. It turns out that the situation may be even more complex, involving more than one age and origin of migmatisation.

Because of these complexities the deformations recognised during he structural analysis are labelled according to which geological unit is affected (ie. Da, Db, Dc) rather than a chronological sequence (ie. D1, D2, D3). These categories (Da, Db, Dc etc.) are referred to as deformational groupings and are summarised in Tables 1, 2 and 3. The actual details of the structural analysis are presented below (in fine print) as an aside to the main report. To simplify the account of the tectonic development, a system of locally defined events is used. The distribution and correlation of these events is then interpreted and discussed. This means that there are two parallel systems of tracking the deformational history that are coincident at the specified reference localities.

CAINOZOIC	Homestead beds (Ta)
	Alice Springs Orogeny (~300-400 Ma)
	NGALLA BASIN
PALAEOZOIC	
LATE DEVONIAN TO CARBONIFEROUS	Mount Eclipse Sandstone (Ce)
	Kerridy Sandstone (Dk)
ORDOVICIAN	Djagamara Formation (Od)
CAMBRIAN	Bloodwood Formation (Cb)
	Walbiri Dolomite (Cw)
	Yuendumu Sandstone (pCy)
	Unconformity
NEOPROTEROZOIC	Mount Doreen Formation (paq)
	Rinkabeena Shale (par)
	Narburula Formation (paa)
	Albinia Formation (paa)
	Vaughan Springs Quartzite:
	Bigrlyi Sandstone Member (pavb)
	Treuer Member (pavt)
	Eva Springs Sandstone Member (pave)
	Major Unconformity
	ARUNTA BLOCK
MESOPROTEROZOIC	*Mafic dykes*
	Southwark Granitic Suite (pgs;+ pgw, pgy) (~1570 Ma)
	Hardy & Wabudali Tectonic Phases
	Andrew Young Igneous Complex (png) (~1635 Ma)
PALAEOPROTEROZOIC	Mafic dykes
	Nicker beds (pls) (*~1770 Ma*)
	Carrington Granitic Suite (pgc; +pgw, pgl) (~1780 Ma)
	Patmungala beds (*~1800 Ma*)
	Reynolds Range Group:
	Pine Hill Formation (prp)
	Mount Thomas Quartzite (prt)
	Yumurrpa Granophyre (pgm) (MOUNT THEO)
	Yuendumu Tectonic Event (~1880 Ma)
	Ngadarunga Granite (pgn) (~1880 Ma)
	Migmatitic gneiss (plm)
	Lander Rock beds (plr)

Fig. 1. Simplified stratigraphic chart.

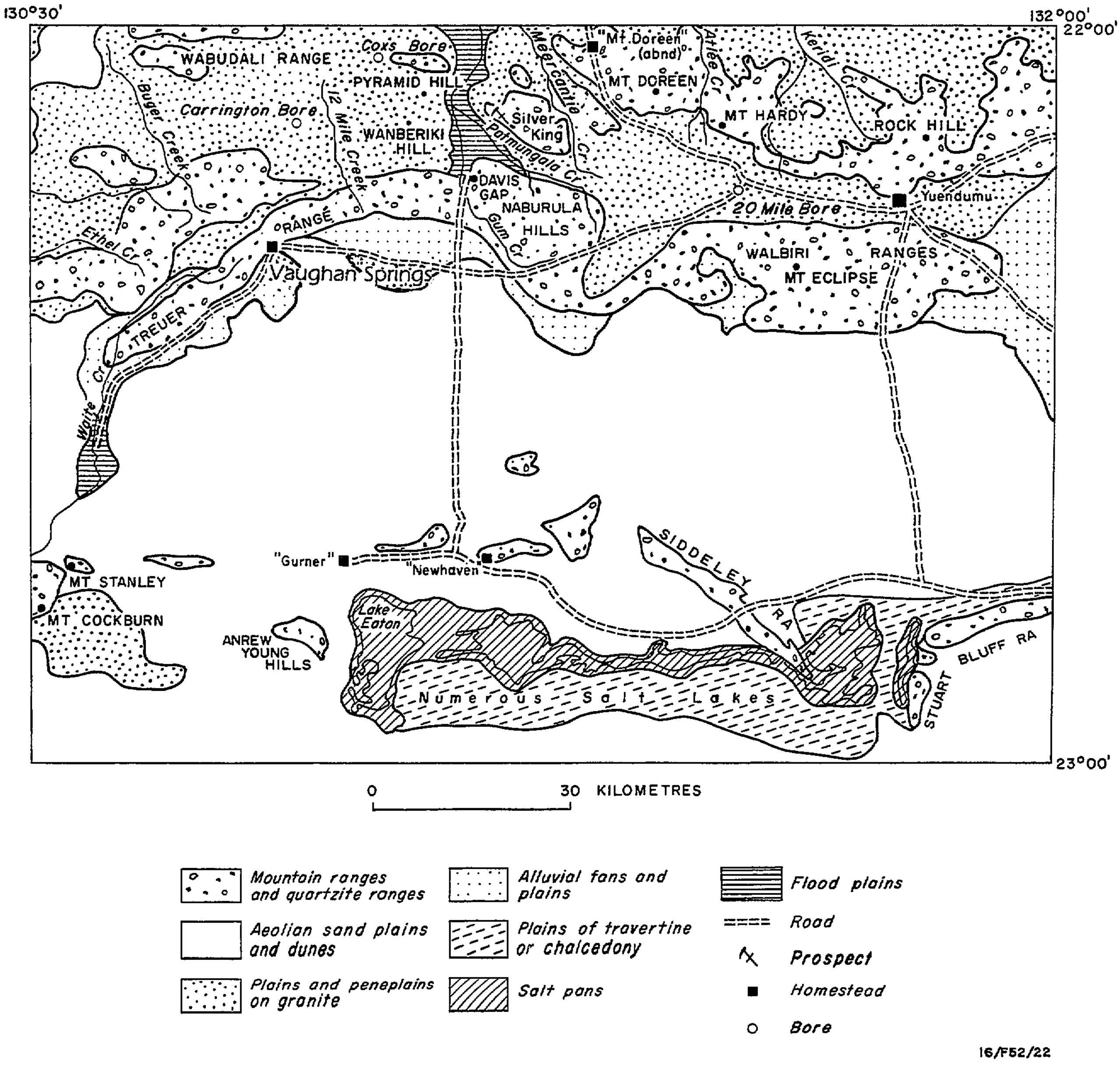

Figure 2. Locality sketch showing physiographic divisions (after Wells 1972)

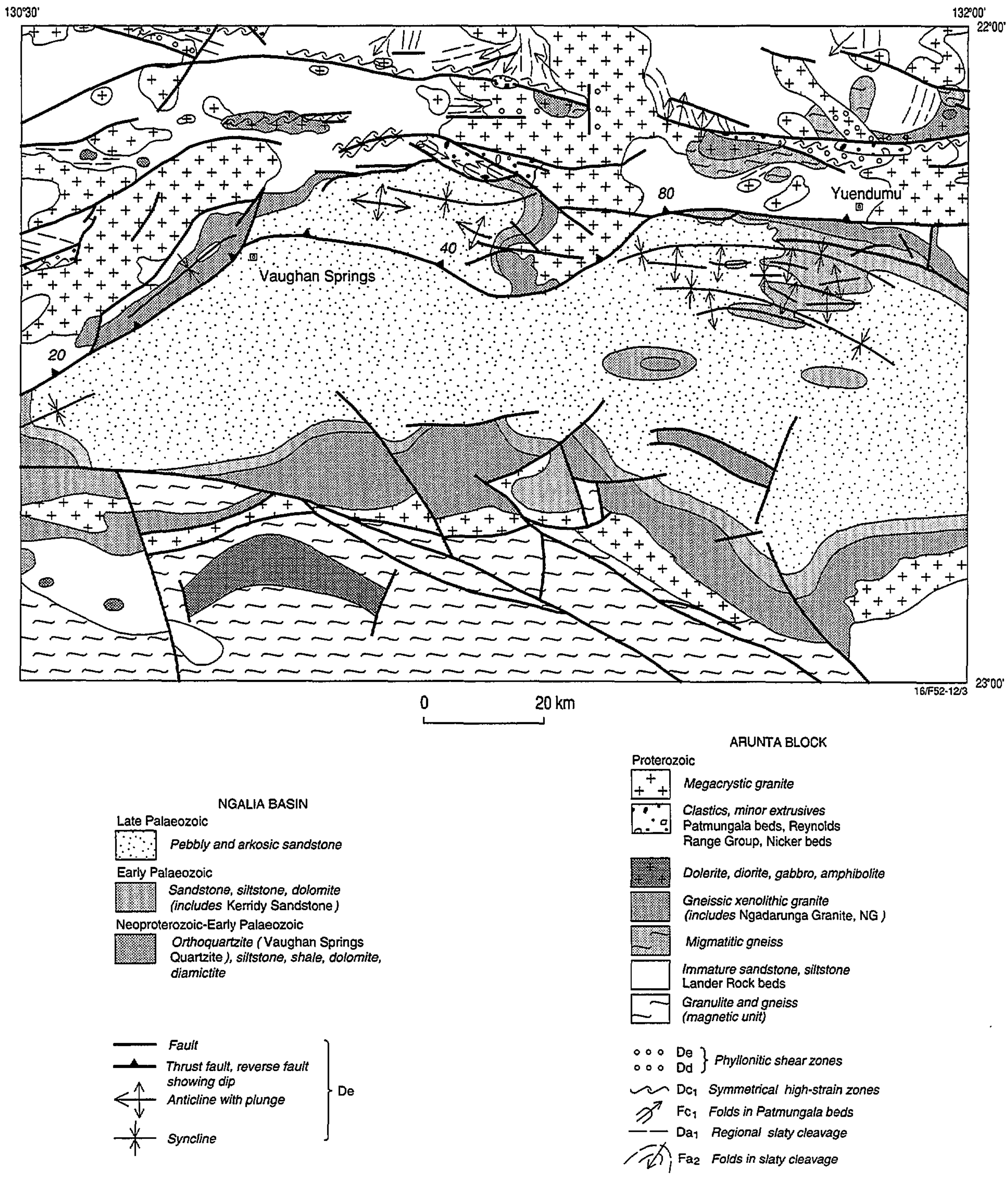

Figure 3. Solid-geology sketch map, Mount Doreen Sheet area

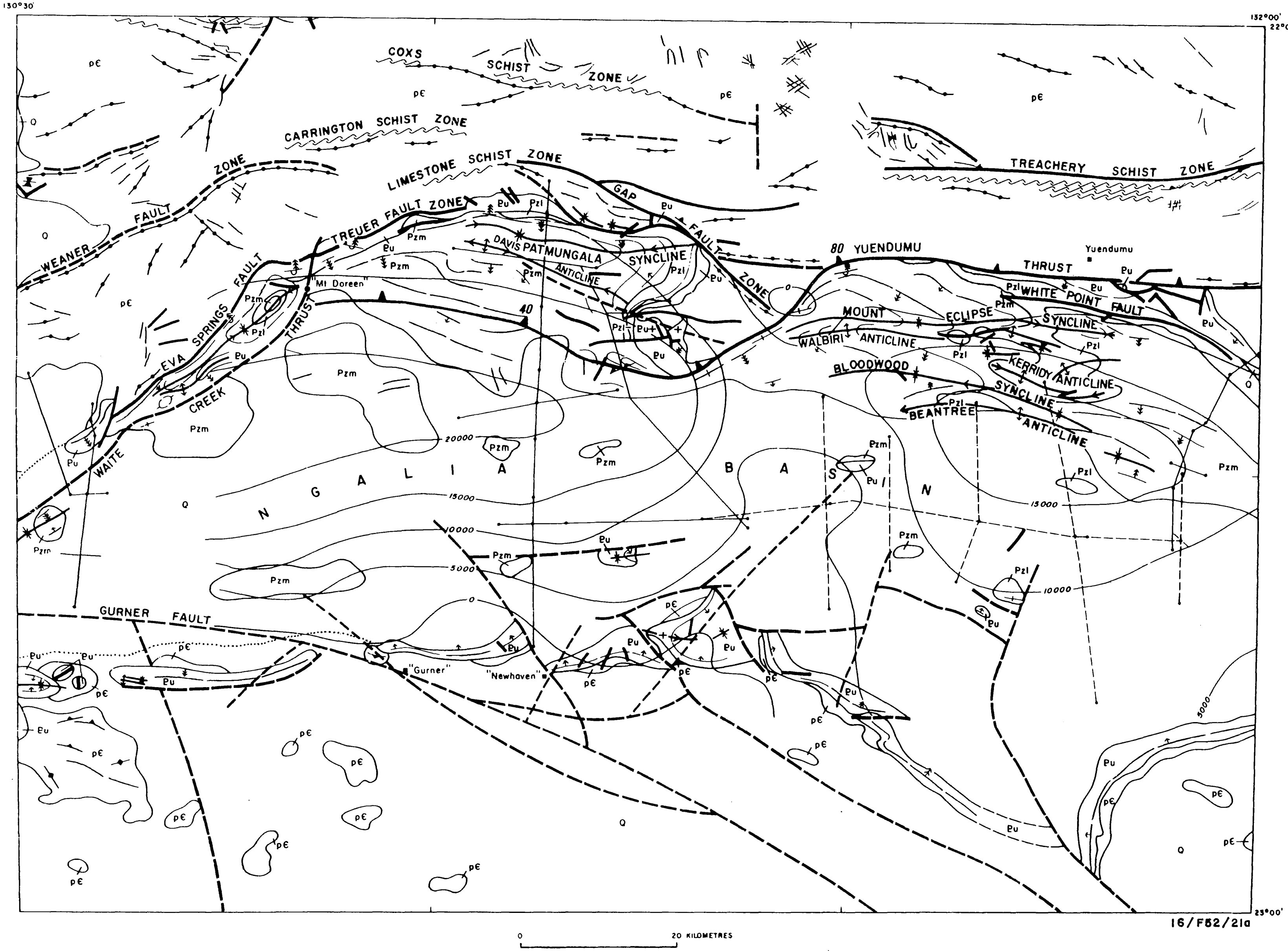

Figure 4a. Structural features in the Mount Doreen Sheet area (see 4b for legend; after Wells, 1972)

AGE		SYMBOL	ROCK UNIT
CAINOZOIC		Q	Sand, sand dunes, alluvium red soils, evaporites
CARBONIFEROUS		Pzm	Mount Eclipse Sandstone
ORDOVICAN		Pzl	Kerridy Sandstone Djagamara Formation
CAMBRIAN		Pzl	Bloodwood Formation Walbiri Dolomite
PROTEROZOIC	NEO-PROTEROZOIC	Pu	Yuendumu Sandstone Mount Doreen Formation Vaughan Springs Quartzite
PROTEROZOIC		p€	Patmungala Beds, unnamed metamorphic and igneous rocks

- *Geological boundary*
- *Fault or thrust, fault zone, showing dip*
- *Fault or thrust, inferred*
- *Anticline, showing plunge*
- *Syncline, showing plunge*
- *Trend lines*
- *Trend of foliation with prevailing dip*
- *Vertical foliation*
- *Foliation trend, dip indeterminate*
- *Dip 15°*
- *Dip 15 - 45°*
- *Dip 45°*
- *Overturned dip*
- *Horizontal strata*
- *Vertical strata*
- *High-strain zone*
- *Dyke or vein*
- *Fault paralleling vein*
- *Concealed margin of basin, position approximate*
- *Joint pattern*
- —1000— *Contours on interpreted depths to magnetic basement in feet below sea level* } *After Hortman, 1963*
- *Interpreted fault* } *After Hortman, 1963*
- *Seismic survey traverse lines, B.M.R.*
- *Seismic survey traverse lines, G.A.I. (Hudson & Campbell, 1965)*

16/F52/21b

Figure 4b. Legend for Figure 4a

Characterising and naming tectonic events

A number of tectonic cycles or 'Events' are recognised, each comprising of a number of complex phases involving several episodes of folding and one or more metamorphisms. Each tectonic event is given a local name and a reference area. This system of characterising events was established after the mapping and is discussed by Young et al. (1995). The defined tectonic events are as follows:

1) The *Yuendumu tectonic event*, characterised by high-grade metamorphism and migmatisation accompanied by complex folding is referred to as the *migmatitic phase of the Yuendumu Orogeny*, and followed by granite intrusion at about 1880 Ma. The two generations of regional folding that appear to precede this migmatisation and granite intrusion are referred to as the *Wolfram tectonic phase*.

2) The deep-seated deformation of the *Hardy tectonic phase* produced a high-grade foliation in some of the Carrington Granitic Suite. One granite from this suite has been dated at about 1780 Ma (Young et al. 1995).

3) The high-level *Wabudali tectonic phase* involved both 2-5 km-wide high strain zones in the Reynolds Range Group and tight regional folding of the Patmungala beds. It preceded intrusion of the Southwark Granitic Suite at about 1570 Ma.

4) The *Jubilee deformation* of unknown age produced a penetrative foliation and retrograde metamorphism in post-tectonic granites, such as the undated Yaloogarrie Granite near the Jubilee Silver King Mine.

5) The *Doreen deformation* produced intense, narrow, greenschist shear zones cutting the Yarunganyi Granite near Mount Doreen, dated by Young et al. (1995) at about 1567 Ma.

Initial field-based structural analysis

This section is concerned with the initial regional structure study based on a structural analysis, aimed at differentiating the various phases of deformation. These relations are very complex and show that the region has been affected by several orogenies. Those readers not concerned with the details of this analysis are advised to skip this section. By keeping track of the locally named tectonic events and how they correlate with the regionally recognised orogenies you should be able to follow the main body of the report. Cross-links between the various levels of analysis and interpretation are provided by the Tables, especially Tables 1, 2 and 4.

As has been explained, an unconventional deformation annotation, D_a-D_b-D_c, is adopted because the order of superposition of structures has been deduced by indirect evidence. Subscripts a, b and c are not necessarily in time sequence. They simply refer to the stratigraphic grouping affected by each deformation, namely the Lander Rock beds, a local unit of migmatitic gneiss, and the Reynolds Range Group. Individual phases of deformation affecting each stratigraphic grouping are labelled D_{a1}, D_{a2}, etc (Table 2).

The deformational groupings are as follows:-

(1) Greenschist facies Lander Rock beds, which is dominated by immature sandstone and siltstone. This unit is cut by foliation of deformational grouping Da.

(2) A migmatitic, granulite-facies metamorphic unit, characterised by pelitic and felsic gneiss. This unit is cut by foliations of deformational grouping of Db.

(3) Early gneissic granites (including the Carrington Granitic Suite and the Yaloogarrie Granite (see Table 1b). This unit is cut by foliations of deformational grouping Dc. This foliations also discordantly cuts foliations assigned to Db.

(4) The unconformably overlying Reynolds Range Group, which consists mainly of mature, shallow-water sediments. This unit is cut by foliation deformational grouping of Dc.

(5) Patmungala and Nicker beds, two spatially separated successions of fine-grained clastics and minor felsic extrusives. These units are cut by foliations tentatively assigned to deformational grouping of Dc.

(6) Granites lacking a high-grade penetrative tectonic foliation (Southwark Granitic Suite and other tabular -feldspar granites, see Table 1b). These granites are cut by foliations of deformational groupings Dd and De. Foliations assigned to Dd cut the tabular-feldspar granites, whereas foliations assigned to De cut the now coarsely porphyritic granites of the Southwark Granitic Suite.

Tentative correlations are made between the deformations recognised in the granite suites and those in the sedimentary rocks. The resulting composite scheme for labelling deformation episodes is outlined in Table 1a, and incorporates relational data from the sedimentary sequences and granite suites. The distributions of the main mappable structural features characterising the tectonic cycles are also shown in Figure 3.

The unconventional annotation sequence D_a, D_b, D_c is designed to be consistent with the stratigraphy shown on the 1:250 000 geological map, the sequence a, b, c also follows the preferred stratigraphy adopted by Young et al. (1995). Thus, the annotation 'a' in D_{a1-2} is adopted for the regional tectonic cycle associated with prograde greenshist metamorphism in the Lander Rock beds. A localised high-strain deformation accompanied by high-grade metamorphism is designated D_{b1-4}, as the migmatisation characterising the unit is thought by Young et al. (1995a) and Young et al. (1995b) to closely follow deformation of the Lander Rocks beds (D_{a1-2}). As will be discussed later, however, this time relationship is not unequivocal. The third deformation grouping, D_{c1-3}, affects the younger Reynolds Range Group.

Some foliations are not so readily labelled. An example of such a complication is the mica foliation developed in the Carrington suite of granites, which is labelled Dcx, as it affects a granite dated at about 1780 Ma, and so is younger than the Reynolds Range Group, the reference unit for the deformation grouping D_{c1-3}.

Ultimately, the local reference name for each deformation cycle or event (Table 2) will become more established as its age is better constrained. Table 2 gives a current estimate of the age of each deformation based largely of the work of Young et al. (1995).

The above scheme is only to avoid confusion: the sequence D_a, D_b, D_c being used rather than D_1, D_2, D_3 so as not to necessarily imply a chronological order. As foreshadowed above, another problem is determining the deformational grouping that has affected a particular granite suite.

The scheme adopted is summarised within Table 1, based on characterising the styles of deformation and taking note of overprinting relationships. For example, most granites are not affected by major deformations and are only cut by younger, relatively narrow shear zones. Using such relationships, the following deformational granite categories are recognised.

1. D_{bx} — Undeformed, metamorphically retrogressed granite associated with large migmatitic bodies. e.g., Ngadarunga Granite.

2. D_{cx} — Xenolithic and gneissic granites that are not clearly associated with large migmatitic bodies. Three sub-categories are identified:

(i) Granite unrelated to migmatitic rocks, showing a gneissic foliation. e.g., Yulyupunyu Granitic Gneiss in northeast YUENDUMU (Table 4).

(ii) Undeformed, xenolithic granite with a thin migmatitic margin. e.g., unnamed granite, *pgc* (Meercantie Creek phase, tentatively assigned to the Carrington Granitic Suite) south of the Wolfram Hill prospect (Table 4).

(iii) Undeformed, xenolithic granite cut by D_c-styled high-strained zones. e.g., Carrington Granitic Suite south of Mount Hardy. The development of the mica foliation cutting this Carrington suite granite is referred to as the *Hardy Tectonic phase* as it overprints a 1780 Ma granite and is itself cut by Dc high-strain zones.

3. D_{dx} — Tabular-feldspar granite overprinted by a weak, diffuse biotite foliation. e.g., the Yaloogarrie Granite east of the Jubilee Silver King prospect.

4. D_{ex} — Coarsely porphyritic granite cut only by intense, narrow, greenschist shear zones. e.g., Yarunganyi Granite.

As with the deformations affecting other units, those affecting the granites are given local tectonic event names that are defined for a particular granite or suite of granites (Table 2). The phases within each deformational group are described in turn and their temporal and regional significance is then interpreted. A regional model is deduced for the correlation of local tectonic events between the units and across local faults, and is compared with deformational histories and orogenic cycles interpreted from elsewhere in the Arunta Block and in the wider region (see below and final Tables 5 & 6).

D_{a1} - D_{a3} Deformations — the Lander Rock beds

(including folding of the Wolfram tectonic phase) [D_{a1} - D_{a2}]))

Deformation D_{a1}. This deformation is expressed as tight to isoclinal upright F_{a1} folds with a penetrative sub-vertical slaty axial-planar cleavage. In western VAUGHAN the folds generally plunge steeply to the east, whereas in DOREEN and YUENDUMU they plunge moderately to shallowly and trend north to northwest (Table 3). The reference area for the *Wolfram Tectonic Phase* is in the region of Wolfram Hill Cu-W mineral deposit where relations between superposed F_{a1} and F_{a1} are well developed.

The axial-planar slaty cleavage (S_{a1}) shows minor homotaxial fanning in fold hinges and is expressed by aligned muscovite and biotite. As illustrated in Figure 5a, the slaty cleavage commonly shows marked refraction across bedding planes (S_0).

Lineation L_{a1} is defined by the S_{b1}/S_0 bedding-cleavage intersection, which is visible on S_{a1} surfaces, and parallels F_{a1} fold hinges.

In the Gintys Bore area bordering the Yarunganyi Granite (previously Mount Doreen Granite) small rounded andalusite porphyroblasts are aligned approximately parallel to L_{a1} in some high-grade rocks. These andalusites are oblate in shape as a result of strain, suggesting that they crystallised late in D_{a1}. This relationship implies that the andalusite formed during the regional metamorphism which may be 1880 Ma or older and, as such, is not simply a product of contact metamorphism by the granite, itself being dated at 1567 ± 6 Ma (Young et al. 1995).

Deformation D_{a2}. This deformation, also developed in the Lander Rock beds, is represented by a crenulation-like cleavage that is axial planar to folds which are slightly more open than those of F_{a1}. The associated folds have a chevron style and the cleavage is not generally accompanied by the metamorphic differentiation that normally a feature of crenulation cleavage. The cleavage varies in trend from 355° to 40° and even to 88°. Northeast trends are common in DOREEN. The S_{a2} cleavage becomes more apparent as the metamorphic grade increases from west to east and reaches above the biotite isograd as is the case in eastern DOREEN and in YUENDUMU. However, it is also evident in lower grade phyllites in the Wolfram Hill area east of Mount Doreen in central-northern DOREEN, where it is expressed as a sub-vertical space-cleavage, as illustrated in Figure. 5b. Farther to the west, in VAUGHAN, S_{a2} cleavage and F_{a2} folds are weakly developed or absent. In places, such as west of Molyes Bore in DOREEN, F_{a2} trends change slightly but abruptly between small fault blocks formed during D_{a2} or later. Here, a syn-D_{a2} age for detachment across the faults is favoured as the separating faults are sub-parallel to F_{a2} axial traces, and these change in strike from one fault block to the next. In YUENDUMU, northerly trending folds have developed under amphibolite facies conditions.

Mesoscopic F_{a2} folds including upright folds, isoclines and also kink-like folds, appear to be preferentially developed in pelitic beds. In places, the axial-planar cleavage fans slightly about F_{a2} fold hinges (e.g. northeast of Mount Hardy). More generally D_{a2} is expressed as weak crenulations. For example south-southeast of Gintys Bore, F_{a2} forms small kinks and weak crenulations with wavelengths of less than 10 cm.

A lineation, L_{a2}, corresponding to the $S_{a1}/_{a2}$ cleavage intersection, is marked in places by dark elongate spots which may represent retrogressed cordierite.

Deformation D_{a3}. D_{a3} is represented by east-trending kink folds. Northeast of Mount Hardy these folds have wavelengths of up to 0.5 km. The lineation L_{a3} corresponds to the intersection of S_{a3} with S_{b2} and/or S_{b1} and these are commonly sub-parallel. Where L_{a3} is strong, the rocks commonly form a phyllitic pencil slate.

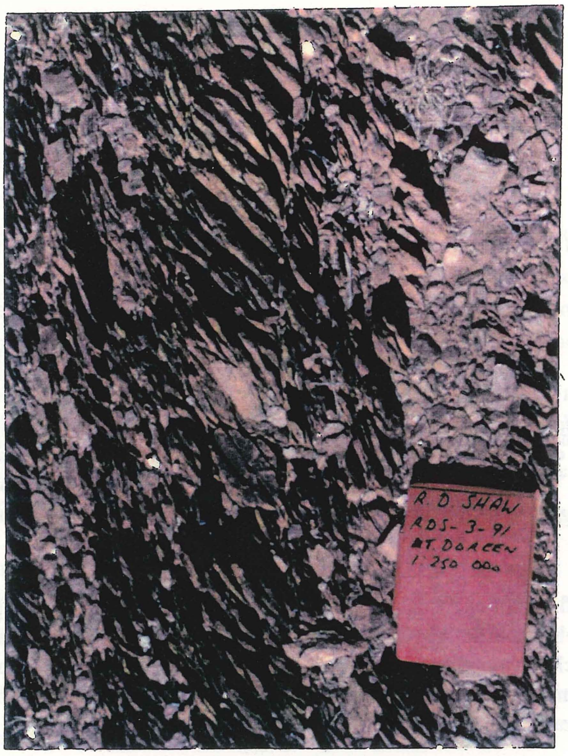

Fig. 5a. Refracted S_{a1} slaty cleavage

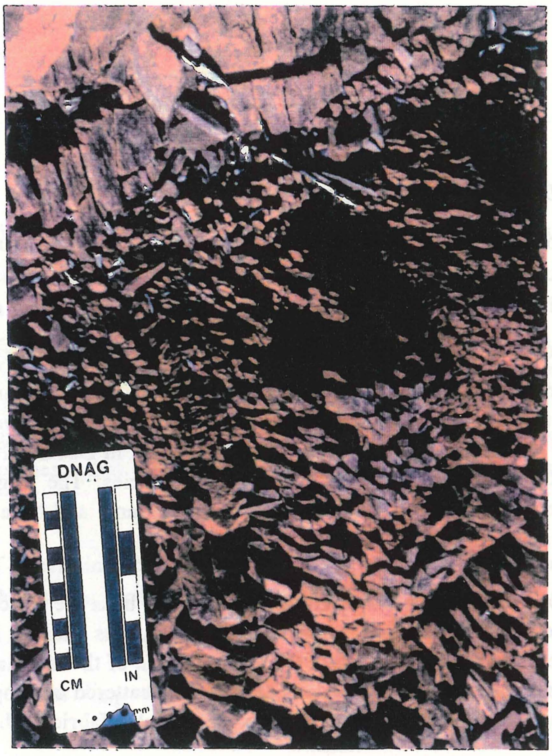

Fig. 5b. Weak S_{a2} crenulation-like cleavage

Fig. 5c. Reclined F_{b2} fold, felsic patches are mobilisate [Up is to the LHS],

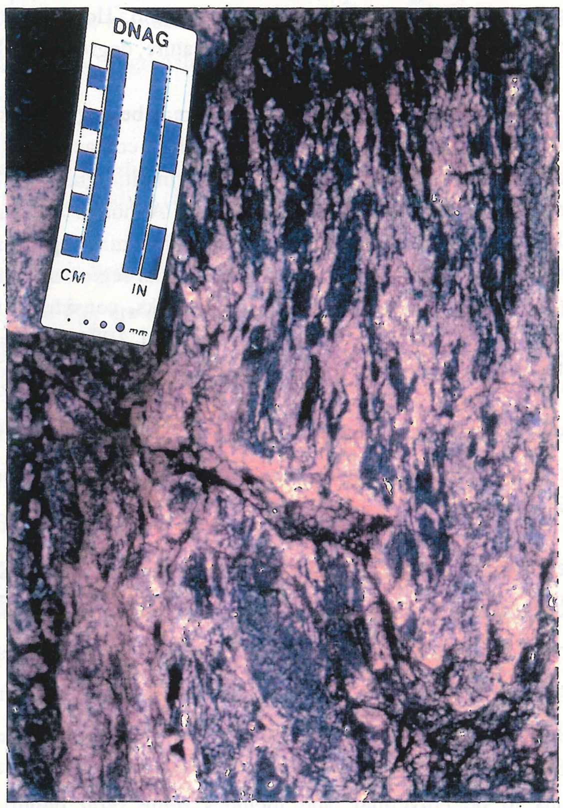

Fig. 5d. Markedly migmatised garnet-biotite [Up is to the LHS]

Fig. 5. Basement structures formed during the Yuendumu Event

D_{b1} - D_{b5}, Deformations — Migmatitic Gneiss Unit

(folding [Db1 - Db4] of the migmatitic phase of the Yuendumu Event) folding [Db1 - Db4] of the migmatitic phase of the Yuendumu Event

Structural complexity, not represented by D_{a1}- D_{a2}, is confined to rocks of the highest metamorphic grade. A representative series of deformations with distinctive styles, developed in migmatitic gneiss, is evident in northeast YUENDUMU, and this area is taken as the reference area for the *migmatitic phase of the Yuendumu events*. Migmatitic gneiss is also exposed 5 km northwest of Rock Hill in northeast YUENDUMU, and in DENISON to the east (Stewart et al. 1980). The gneiss has undergone complex folding and metamorphism to granulite facies. The migmatitic unit is intruded by small bodies of metagabbro containing metamorphic orthopyroxene and clinopyroxene, and by a larger garnet-cordierite granite body containing inclusions of highly strained, migmatitic country rock.

Contacts with the lower grade Lander Rock beds are either faulted or not exposed. There is a sharp jump in metamorphic grade and degree of strain across these contacts, as clearly identifiable Lander Rock beds are metamorphosed to only middle amphibolite grade and lack the intense strain of the migmatitic rock. A weakly strained, retrograde greenschist, schistose contact zone between the two units is exposed as scattered outcrops 20 km northwest of Yuendumu township. This schist zone contains asymmetric fabrics and overprints the complex fabric of the migmatitic unit.

Not all the high-grade rocks are so complexly deformed. An east-west belt of weakly deformed cordierite granulites and related gneiss extends across the mapped region.

The migmatitic fabric in the gneiss from the reference area is superimposed on a foliation formed during a high strain event involving disruption and transposition of an earlier compositional layering. The above structural chronology is largely based on exposures northeast of Yuendumu township. However, the number of fold phases varies from place to place and may be dependent on local variations in temperature, degree of melting and stress variations.

Similar complexly deformed rocks that may belong to the same set of deformations occur in GURNER, to the south of the Ngalia Basin. Here a metamorphically discordant contact is inferred between low-grade pelitic and turbiditic schists of uncertain stratigraphic affinity and high-grade migmatitic gneisses. Here, high-grade migmatitic cordierite-garnet felsic gneiss lies along strike to the northwest and southeast. Although the greenschist facies metasediments most probably correlate with the lithologically similar Lander Rock beds, they may represent a distal pelitic variant of the Reynolds Range Group, (compare with Dirks 1990). BMR aeromagnetic data in this region suggests that the weakly magnetic schistose metasediments are surrounded by a large region of highly magnetic rocks, considered to mainly represent felsic and mafic rocks of the Central Tectonic Province of the Arunta Block (see Shaw et al. 1984, Mutton & Shaw 1979, Mutton et al. 1983), as well as several younger mafic intrusions such as those of the igneous complex in the Andrew Young Hills.

Deformation D_{b1}. A high-strain foliation, S_{b1}, parallels, but disrupts and transposes, a lithological layering which is highlighted by migmatitic leucosomes. This complex foliation is further enhanced locally by additional metamorphic differentiation and later migmatisation.

Deformation D_{b2}. F_{b2} folds deform S_{b1} expressed by a transposed migmatitic layering (note: mobilisate shown in Figure 5c). In places, a strong lineation of aligned sillimanite needles and streaky aggregates of biotite parallels the fold axes. Where D_{b2} strains are high and S_{b1} has been disrupted and transformed into S_{b2}, F_{b2} folds are typically intrafolial. Where the strain is less intense, but still strong, F_{b2} folds are commonly reclined and the strain is partitioned into mesoscopic (outcrop-scale) high-strain zones as illustrated in Figure 5c (site is in the southern flanks of the ranges, 20 km west-northwest of Yuendumu). Where the regional strain is moderate, the folds are disharmonic and change character along the fold profile. In such areas, the F_{b2} folding tends to be polyclinal, and includes some tight doubly-plunging folds. Rare S_{b2} layering is produced by metamorphic differentiation that is axial-planar to F_{b2} folds.

Plunges of F_{b2} folds vary widely, partly as a result of the high D_{b2} strains and partly as a consequence of the interference effects between D_{b2} and later D_{b3} deformations. For example, F_{b2} folds with moderate to shallow plunges are common northeast of Yuendumu township (along Kerridi Creek, known locally as 'Mission Creek'), where superposition of F_{b2} and F_{b3} folding is apparent. In regions where S_{b_1} is the dominant penetrative structural element, F_{b_2} folds tend to be reclined and plunge down-dip within S_{b_1}.

Deformation D_{b_3}. The last coherent phase of deformation which can be recognised in most migmatitic gneisses is represented by mesoscopic, crenulation-like, open, upright folds with rounded hinges and shallow plunges. Formation of these folds appears to have accompanied the final stages of prograde metamorphism within the PT field of partial melting. The folds invariably show mobilisate injected along axial-planar fractures. At the highest grades of metamorphism multiple phases of migmatisation are evident, as is the case in central YUENDUMU, illustrated in Figure 5d, where garnet-biotite ± andalusite selvedges have formed at the margins of quartzofeldspathic leucosome layers (site is a small hill 8 km west-northwest of Rock Hill, near Wakurpa outstation). However, as will be discussed further below, although current evidence suggests that these high-grade metamorphic rocks represent metamorphosed Lander Rock beds: a competing hypothesis that they might represent a pre-existing basement cannot be completely excluded.

Remarkably similar folding occurs in high-grade migmatitic rocks of uncertain metamorphic age and stratigraphic affinity such as those bordering a body of banded cordierite-quartz rock within the Lander Rock beds, 3 km west of 8-Mile bore and in a mixed group of rocks at Pyramid Hill, in both in DOREEN.

Deformation D_{b_4}. At some localities, late steeply-plunging kink folds, F_{b_4}, accompanied the final stages of prograde metamorphism.

Deformation $D_{b_{5'}}$. This deformation accompanied local retrograde metamorphism of the high-grade migmatite. The annotation $5'$ in $b_{5'}$ is used to highlight the fact that it probably belongs to a separate, younger tectonic cycle. The reference locality for this retrogression is at Keridi Creek, 7 km northwest of Yuendumu township. Here, $F_{b_{5'}}$ folds are open, plunge 50-60° to 110-140°, and are accompanied by a pervasive schistosity characterised by the preferred orientation of commonly fine-grained muscovite (Fig. 6a, site is a migmatitic gneiss exposed in Keridi Creek, 7 km northwest of Yuendumu). These $F_{b_{5'}}$ folds are upright and refold F_{b_2} folds. In places a lineation outlined by fine-grained muscovite aggregates parallels the fold axes. Although a retrograde event, the metamorphism remained within amphibolite facies.

West of Yuendumu, in high-grade, partly retrogressed gneisses, an easterly trending zone of deformation has developed that is similar in style, orientation and accompanying metamorphic grade to the $F_{b_{5'}}$ folding (at Keridi Creek).

Whether $D_{b_{5'}}$ correlates with deformations recorded in the Lander Rock beds (D_{a_1} - D_{a_2}) or deformations affecting the Reynolds Range Group (D_{c_1} - D_{c_2}) is a subject of debate. Both $F_{b_{5'}}$ and F_{a_2} are characterised by open folds with moderately steep plunges, and both reached amphibolite metamorphism, indicated by the presence of muscovite and incipient migmatisation. In places, the coexistence of late sillimanite and muscovite in rocks of the Lander Rock beds suggests metamorphism to the lower temperature part of the medium pressure amphibolite facies (see Miyashiro 1973, p. 306).

On the other hand, the axial plane foliation to $F_{b_{5'}}$ folds is similar in orientation and grade to the S_{c1} foliation in infolded segments of Reynolds Range Group within the adjoining Treachery Schist Zone (Fig. 4). Furthermore, $D_{b_{5'}}$ and D_{c1} may also correlate with D_{b_3} and all be part of the Treachery Schist Zone (Fig. 4) as argued below. The time of the $D_{a_{1-3}}$ deformations relative to the $D_{b_{1-3}}$ sequence of deformations is considered further below, while reviewing models for the origin of the migmatitic gneiss units.

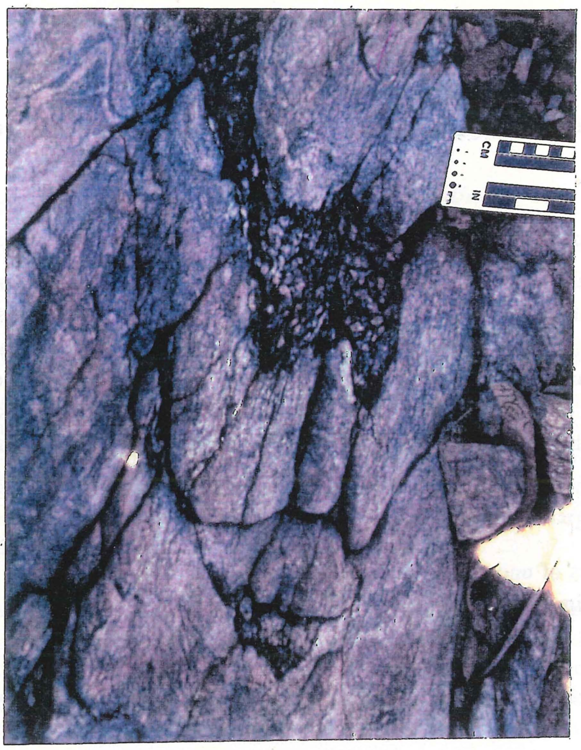

Fig. 6a. $F_{b5'}$ folding of F_{b2} folds [Up is to the RHS]

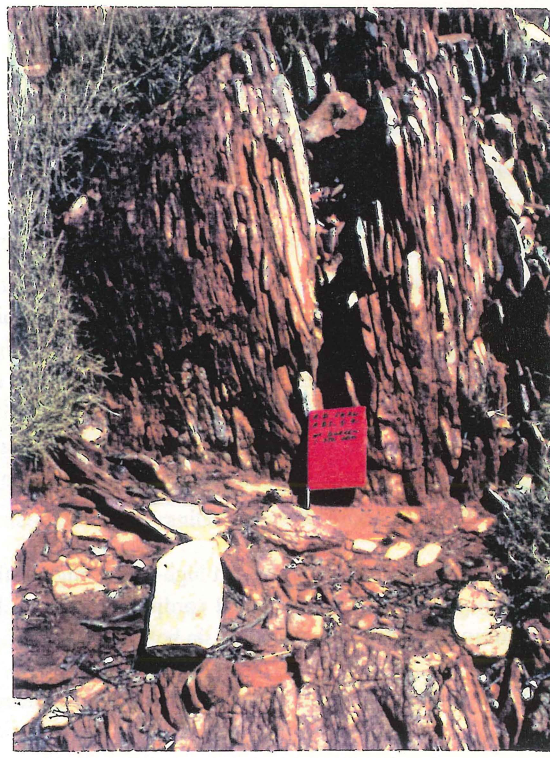

Fig. 6b. Cobble and boulder conglomerate stretched during D_{c2}

Fig. 6c. Zone of late-stage multiple quartz veining [Frame width 20 cm]

Fig. 6d. Tightly folded quartz veins within D_e shear zone

Fig. 6. Basement structures formed during the Hardy and Warbudali tectonic phases, possibly the Anmatjira Uplift, and the Alice Springs Orogeny

D_{c1} - D_{c3} *Deformations — Reynolds Range Group*

(Wabudali tectonic phase)

Deformation D_{c1}. This deformation is characterised by a strong sub-vertical east-trending foliation that affects the Reynolds Range Group and Lander Rock beds. Progressive deformation under predominantly plane-strain conditions is suggested by both the consistently sub-parallel, platy and planar nature of this foliation and the general symmetry of its microstructures. The Wabudali Range is the reference area for the *Wabudali tectonic phase,* incorporating F_{c1} and the subsequent folding generations in this tectonic cycle.

Here, a high degree of oblate strain is postulated, consistent with the low angle of cross-beds in sandstone units and the abundance of foliated, folded and boudinaged quartz veins.

In several places, north of Yuendumu, a high degree of prolate strain is demonstrated by a very strong streaky lineation, outlined by elongated quartz grains. Near the base of the Reynolds Range Group at a locality 9 km north-northeast of Yuendumu township, pebble shapes show that elongation locally exceeds 300%. (Fig. 6b, site is at the base of the Reynolds Range Group, 19 km northeast of Yuendumu). The maximum strain axis is aligned within L_{c1}. In general, S_{c1} is a slaty cleavage outlined by mica orientation and flattened quartz grains.

Zones of high flattening strain are generally 250 m to 2 km across. Well-defined zones extend along the southern part of the Wabudali Range in northern VAUGHAN, where the mainly non-coaxial strain is marked by deformed quartz and feldspar augen within a deformed pebbly silty sandstone, immediately underlying the Reynolds Range Group west of Mount Singleton. A more complex high-strain zone, with multiple bifurcations, extends from south of Mount Hardy eastwards to south of Rock Hill, and may extend farther to the east and west.

Tight, upright, sub-horizontal, boat-like, macroscopic F_{c1} synclines control the preserved distribution of the Reynolds Range Group. These F_{c1} synclines have wavelengths of 100 m to 2 km. In regions where their southern limbs are commonly overturned, slightly asymmetric strain fabrics suggest a component of top-to-the-north (south/north) shear. The best example of such a relationship is on the southwest flank of Wabudali Range, where shortening of the southern fold limb was sufficiently intense for a mylonitic foliation, showing a down-dip stretching lineation, to develop in pebbly sandstone. Parasitic mesoscopic folds in the pelitic upper part of the Reynolds Range Group have been rotated into a down-dip orientation as a result of such high strains.

The high-strain zone in the Wabudali Range affects the Reynolds Range Group and adjacent units, and parallels the axial plane of the syncline. Therefore, it is considered to have formed during the progressive development of the syncline rather than to have been an older strain zone that was subsequently folded about the syncline. Asymmetric and intense fabrics on its southern limb may relate to a shearing dominated by plane strain, but with a minor component of northerly-directed shear.

An east-trending D_{c1} zone of high strain south of Mount Hardy, referred to as the Treachery Schist Zone (Fig. 4), widens eastwards and splits into several narrow zones. This schist zone is characterised by a penetrative two-mica foliation, abundant quartz veining and rare pegmatite veining. South of Rock Hill this zone affects the Lander Rock beds in addition to the Reynolds Range Group, being superimposed on an earlier sequence of structures, including F_{a1} folds, F_{a2} crenulation cleavage and later-stage F_{a3} kink folds. This relationship is such that the S_{a3} affecting the Lander Rock beds appears to be equivalent to the earliest foliation, S_{c1}, recognised in the Reynolds Range Group.

A highly strained zone, referred to as the Coxs schist zone (Fig. 4), which affects the Reynolds Range Group 10 km south-southwest of Wolfram Hill, is considered to be the westward continuation of the above-mentioned Treachery Schist Zone exposed south of Mount Hardy. This westward continuation of the zone is disrupted by a big-feldspar granite, the Yarunganyi Granite.

These D_{c2} high-strain zones formed under lower amphibolite facies conditions involving the crystallisation of fine-grained biotite, fine- to coarse-grained muscovite and, in places, andalusite porphyroblasts that are oriented sub-parallel to F_{c2}, but are deformed by L_{c2} crenulations.

Within the Lander Rock beds, the third phase of folding D_{b3}, parallels and may correlate with the first phase of tight, east-west trending folding, D_{c1},in the Reynolds Range Group. Such a relationship between D_{a3} and D_{c1} cleavage is well illustrated 9 km east-southeast of Mount Hardy where a strong penetrative crenulation cleavage in the Lander Rock beds to the north parallels an exceptionally strong S_{a3} slaty cleavage that is axial-planar to a tight east-west syncline in quartzite of the Reynolds Range Group to the south. This means that S_{a3} is probably equivalent to Dc1.

Deformation D_{c2}. Near Mount Singleton minor F_{c2} folding appears to be coaxial with the large isoclinal F_{c1} syncline outlined by the upstanding quartzite in the Wabudali Range. Tight F_{c2} structures fold the L_{c1} bedding/cleavage lineation on the south side of the syncline where an F_{b2} fold plunges 10° to 132°. In the core of the main syncline D_{c2} is expressed as fine L_{c2} crenulations and mullions.

Deformation D_{c3}. Small mesoscopic F_{c3} kinks in the Wabudali Range are considered to be related to gentle bends in the major D_{c1} syncline.

A similar situation exists 8 km southeast of Mount Hardy, where an intense, steeply-dipping foliation cuts the S_{c1} schistosity at a high angle and is associated with northeast-trending kinks and faults outlined by quartzite of the Reynolds Range Group.

Timing of the deformation sequence D_{c1-c3}. The D_{c1-c3} sequence of deformations are older than those granitic bodies that intrude the Reynolds Range Group, but are younger than the Lander Rock beds. Xenolith-rich granodiorite belonging to the Carrington Granitic Suite is cut by a high-strain zone correlated with D_{c1}. This is assigned to D_c implying that the D_c, sequence of deformations is younger than the Carrington Granitic Suite dated at 1779 ± 9 Ma. The D_c deformations are older than those granites containing tabular K-feldspar that are exposed west of Mount Singleton and west of Mount Hardy. These granites intrude the high-strain D_{c1} zones and cross-cut the D_{c1} syncline in both the Wabudali Range and west of Mount Hardy. One of the porphyritic K-feldspar granites, the Yarunganyi Granite, has been dated at 1567 ± 6 Ma (Young et al. 1995) in MOUNT DOREEN. If these relationships are accepted, then the D_{c1-c3} deformations occurred after Reynolds Range Group sedimentation at about 1800-1820 Ma (see Blake, 1991a; Blake & Page, 1988) but before the ~ 1570 Ma Yarunganyi Granite. The deformation sequence D_{c1-c3} shows some similarities in orientation and style to the Weldon Event in the Reynolds Range (Table 5) and so may correlate with the Strangways Event that peaked at 1760-1750 Ma (see Black & Shaw 1992, Collins & Shaw 1995).

Deformations — Patmungala and Nicker beds (D_{c1-3}?)

Folding of the Patmungala and Nicker beds

A single phase of east-southeast-trending folds (F_1) is evident in the Patmungala beds. Although these folds are generally shallowly plunging, they are locally polyclinal with plunges ranging from sub-horizontal to 60°. Many of the folds are tight and asymmetric in that the anticlines have steep northern limbs.

In places, steep, strike-parallel zones of detachment separate areas of tight, polyclinal folding, as indicated by an abrupt change in fold plunge.

An axial-planar cleavage (S_1) is markedly refracted across lithological boundaries, although it is generally sub-parallel to bedding (S_0) in siltstone. In the more quartzose beds the axial-planar cleavage is expressed as spaced fractures. Thin (1-3 cm) veins of fibrous quartz fill these fractures within tight F_1 folds. In the more pelitic rocks, the axial-planar cleavage is a slaty cleavage outlined by the orientation of mica.

The single phase of folding in the Patmungala beds is correlated with F_{c1} folding in the Reynolds Range Group because of the similarity in style and the generally shallowly plunging nature of the folds. The folding is younger than the protolith age of 1799

± 9 Ma for tuffs within the Patmungala beds (Young et al. 1995). The low metamorphic grade of S_1 is consistent with the folding being relatively late in the deformation history of the region.

D_c Foliation affecting early granite suites*

(Hardy tectonic phase)

Several granites of the Carrington suite are affected by a micaceous foliation. These include a granite of the Carrington Suite mapped as pgc_3 dated by the U-Pb zircon method at 1779 ± 6 Ma (Young et al. 1995), located south of Mount Hardy. This region is taken as the reference area for the *Harding phase of deformation.* The foliation is schistose and generally outlined by biotite and muscovite. Where the foliation cuts amphibolite pods in the granite it is outlined by retrograde biotite. The associated minerals suggest the foliation was formed under amphibolite facies conditions. In the southern and western parts of the granite body, the gneissic foliation strikes northerly, and, as such, is discordant to the easterly strike of a D_{c1} high-strain zone belonging to the Wabudali tectonic phase exposed immediately to the north. In the northwest of the granite the foliation swings to become west-striking. In Figure 3 the distribution of the foliation is represented by pattern for D_c*.

The foliation Dc* can be traced to the west where it overprints the foliations Db1-4 in the migmatitic gneiss surrounding the Ngadarunga Granite. this relationship implies that Dc* is equivalent to Db5'.

In the northeast of YUENDUMU, a northeasterly-trending gneissic foliation that developed in the Yulyupunyu Gneissic Granite (pgl), may have formed during this or an earlier event. Widespread re-melting is recorded in sparsely distributed shear bands in the granite. These have a normal sense of movement and cut the gneissic foliation. This augen-bearing granitic gneiss is very similar in lithology to the Napperby Gneiss that is widespread in the Reynolds Range region. Its zones of re-melting are similar to those in that gneiss which records a 1775 ± 12 U-Pb Ma age for high Th/U overgrowths. The Yulyupunyu Gneissic Granite is also lithologically similar to the Possum Creek Charnockite with a magmatic U-Pb age of 1774 ± 6 Ma (Collins & Williams 1995). So, the migmatised shear bands in the Yulyupunyu Gneissic Granite could be a similar age.

The locally-developed migmatitic fabric that characterises an unnamed granite of the Carrington Granitic Suite (Pgc at Mercantie Creek), which crops out in central-northern DOREEN, may well have formed during the same event. The granite, centred on the region of the Jubilee Silver King Mine, contains numerous rafts of migmatite and schist, as well as biotite-rich clots rimmed by leucosome. It is intruded by a post-tectonic tabular feldspar granite that forms part of the Yalgoogarrie Granite.

D_{cx} High-strain Zones cutting early granite suites

(Part of the Wabudali tectonic phase)

High-strain zones that are similar in character to the D_{c1} zones transect both the Reynolds Range Group and a leucocratic phase of more generally xenolith-rich biotite-bearing Carrington Granitic Suite (near Carrington Bore in VAUGHAN and south of Limestone Bore in DOREEN). This suite includes a foliated xenolith-rich granodioritic phase and a younger, more massive leucocratic phase. Whereas the foliation in the granodioritic phase is magmatic as it does not cut the xenoliths, the high strain zones in the leucocratic phase have relatively symmetrical microfabrics and contain coarse muscovite that crystallised under amphibolite facies conditions. Based on its deformational style and metamorphic grade, this deformation, designated D_{cx}, is considered to correlate with deformation D_{c1}. As with foliation D_c*, it is younger than the ~ 1780 Ma Carrington granites (Young et al. 1995). The foliation D_c* differs from the more gneissic foliation, D_{cx}, in forming narrow, linear zones.

D_{dx} *Penetrative foliations cutting post-tectonic granites*

(Jubilee deformation phase)

This phase is represented by a weak, locally mylonitic, penetrative foliation that forms zones up to 2-3 km wide cutting some members of the tabular-feldspar granite suite is designated D_{dx}. The foliation is characterised by the development of fine-grained biotite.

The tabular feldspar granite in DOREEN west of Mount Hardy and at Rock Hill in YUENDUMU, by contrast, shows a magmatic flow foliation. These granites are younger than the regional slaty cleavage, D_{a1}, affecting the Lander Rock beds.

One D_{dx} zone consists of a complex set of criss-crossing narrow foliated zones outlined by finely recrystallised biotite, within the muscovite-biotite Yaloogarrie Granite, 10-12 km west of 8 Mile Bore (e.g. west of Meercantie Creek). In another zone farther west towards the Jubilee Silver King Prospect, a similar weak tectonic foliation, outlined by fine-grained new biotite, is developed in the tabular K-feldspar Yaloogarrie Granite, and also affects late-stage aplitic dykes. This region is adopted as the reference area for the *Jubilee deformation phase.*

Some of the tabular-feldspar granites, such as the Southwark Granite in VAUGHAN (see Table 1), which are cut by foliation of similar style to D_{dx}, are petrologically grouped with the Yarunganyi Granite dated at 1567 ± 6 Ma. Thus, some foliations designated D_{dx} may be younger than 1570 Ma. These foliations could correlate with either those of the Redbank uplift event at 1400-1500 Ma (Shaw & Black 1991) or the early stages of the Alice Springs Orogeny at 400-300 Ma (Shaw & Black 1991, Shaw et al. 1992b). However, the fine-biotite foliation in the Yaloogarrie Granite does not appear to continue eastwards into the 1570 Ma Yarunganyi Granite.

D_{ex} *Narrow late-stage shear zones*

(Doreen deformation phase)

Several narrow phyllonitic mylonite zones up to 500 m or more across cut the tabular-feldspar granite suite, as well as the other units. These zones have features that set them apart from the D_{dx} zones. The reference set of shear zones are those cutting the otherwise undeformed, post-tectonic, 1567 Ma Yarunganyi Granite. The *Doreen deformation phase* takes its name from Mount Doreen, which is the highest point in the outcropping Yarunganyi Granite and the old, informal name for the granite.

Firstly, several of them have asymmetric microstructures, including S-C fabrics, which indicate a top-to-the-south sense of shear (north/south), or less commonly, a top-to-the-west sense of shear. That is, they are non-coaxial shear zones.

Secondly, they formed under greenschist facies conditions involving the production of white mica, fine-grained biotite and/or chlorite.

Thirdly, they are bordered by more diffuse regions characterised by protomylonite, with fine-grained biotite outlining a platy foliation that has a consistent planar orientation over distances of 1 km or more.

Excellent examples of such zones of phyllonitic mylonite, containing folded and deformed mylonitic quartz veins, cut tabular K-feldspar granite north and northeast of Rock Hill. A steeply plunging lineation and asymmetric fabric indicate a top-to-the-south sense of shear. One of these zones 1 km north of Rock Hill trends west of northwest (320°) and dips 85° north (at 22°08.37', 131°49.64'). Folded and foliated quartz veins indicate multiple phases of shearing together with some plane strain. Both the variable, but consistently down-dip, stretching lineations and asymmetric fabrics are consistent with a north-block-up sense of movement. S-C fabrics outside the quartz-veined part of the zone confirm the top-to-the-south sense of shear (north/south).

A similar phyllonitic or frilled-schist zone cuts an outlier of the tabular-feldspar Wabudali Granite 5 km south of Mount Singleton (e.g. at 22°2.61'S; 130°45.16'E). Here, the foliation is outlined by white mica and chlorite. The schistose granite is locally cut by quartz veins, but in places the vein quartz is foliated, indicating multiple movement. The mylonitic schist zone, marked by the retrograde assemblage muscovite-chlorite-quartz, is folded in places into moderately-plunging folds that range in style from kink-like to tight and appressed (Fig. 6d). A locally developed, oblique, north-striking, steeply-dipping, late cleavage may represent extensional shear bands, and may imply late-stage along-strike elongation. Both the variably plunging, tight folds outlined by quartz veins and the general absence of a stretching lineation suggest that the deformation history was generally dominated by plane strain. Along strike to the northwest, where the schist zone meets a granite, it passes abruptly into a complex zone containing hydrothermally altered quartz-veins and quartz-breccia. This close spatial relationship between the hydrothermal quartz veining and the shearing implies that the unstructured quartz veining has been introduced later during tensional tectonism, thereby overprinting a pre-existing shear zone. A further complication of this particular zone is that it aligns to the east with major schist zones that formed during the D_C deformation cycle, namely the Coxs and Treachery schist zones (Fig. 4). Thus, repeated reactivation is implied.

In a similar zone south of Pyramid Hill, phyllonitic mylonite and mylonitised vein quartz are locally progressively deformed into steeply plunging, sheath-like folds. Another possible example is a quartz-filled fault zone 3 km west of Mount Hardy.

A brief summary of our current understanding of the tectonic history afflicting the Arunta basement in the Mount Doreen Region is outlined further below (see also Table 4). The deformation sequence recognised in the field is related to tectonic events based on geochronological data from the study region and the Arunta region as a whole. To understand the basis for the synthesis presented in Table 4, we must discuss some of the geological problems.

PROBLEMS OF INTERPRETATION

Relative ages of the gneisses

Although there appears to be a general continuum from low to high-grade metamorphism within the Lander Rocks beds, abrupt changes in metamorphism commonly take place at faults, and it cannot be shown conclusively that all rocks assigned to the Lander Rock beds have been through the same tectonic events; some rocks may be older, by an orogenic event, than others. Assemblages in the pelitic rocks progress from muscovite-chlorite, through biotite-muscovite-andalusite and cordierite-andalusite-potassium-feldspar-biotite, to sillimanite-cordierite-garnet-biotite. The cordierite granulite, gneiss and migmatite, assigned to map-units Plrc and Plm of the Lander Rock beds, like that surrounding the syntectonic, cordierite and garnet-bearing Ngadarunga Granite near Yuendumu occur in isolated outcrops elsewhere. Sillimanite is present in the highest-grade gneisses. The cordierite-bearing rocks, which in places preserve bedding and other sedimentary structures that appear to be only weakly deformed, correspond to magnetic highs in a broad belt of high-grade metamorphic rocks traversing the region from east to west, north of the Ngalia Basin, and could represent localised metamorphic 'hot spots'.

Several of these high-grade metamorphic pockets are dominated by weakly deformed cordierite granulite, and, as such, are metamorphically and structurally similar to the Mount Stafford beds from the Reynolds Range Region. The timing of metamorphism of these beds during the Mount Stafford Event (Table 5) is constrained by the preferred 1820 Ma age of Mount Stafford Granite, although ages as old as 1860 Ma cannot be discounted (see Collins & Williams 1995). Significantly, the Ngadarunga Granite is commonly recrystallised and retrogressed to a garnet-sillimanite-biotite assemblage, indicating a second or progressive metamorphism that could represent a younger metamorphic event like the Mount Stafford Event. Given the limits of experimental error and the difficulty in distinguishing igneous zircons from metamorphic or inherited zircons, these cordierite granulites may be part of the *migmatitic phase of the Yuendumu Event* and correlate with the Mount Stafford Event. Alternatively, they are separate events.

These pockets of high-grade gneiss scattered along the east-trending belt, but not everywhere containing cordierite, are expected to fall in the age range 1880 Ma to 1760 Ma, and, given the tectonic events recognised in the Arunta Block (Collins & Shaw 1995), most probably lie at one end of this range or the other, with most probably falling at the older end and being part of the *migmatitic phase of the Yuendumu Orogeny*.

The following gneisses that lie in this belt vary considerably in character.

(i) The body of cordierite gneiss with very planar compositional layering and superimposed schistosity at 'Leopard Rock', (4 km south of Wolfram Hill, 300 m west of the Tanami road) lies alongside a sillimanite-bearing migmatitic gneiss with a structure very similar to that at Pyramid Rock (see next below).

(ii) The migmatitic gneiss at Pyramid Hill is intercalated with a variety of metasedimentary rocks and small amounts of hornblende-rich amphibolite. An early period of high strain is indicated by a complex foliation displaying quartz rodding and preferred hornblende orientation. This early foliation is folded into shallowly plunging crenulation-like folds with rounded hinges that have thin mobilisate layers along their axial-planar structures. Late retrograde metamorphism and an overprinting foliation of white mica probably record actively along an offshoot of the Coxs schist zone formed during the Wabudali tectonic phase (deformation Dc).

(iii) The younger migmatite associated with the 1780 Ma Carrington Granitic Suite.

(iv) The Yulyupunyu Granitic Gneiss northeast of Yuendumu shows a high-grade migmatitic foliation, suggesting an early deformation under high-temperature metamorphic conditions. It is grouped with the Carrington suite of granites and, on the basis of its similar fabric and lithology, may also correlate with the 1760 Ma Napperby Gneiss from the Anmatjira-Reynolds Range region (Collins & Williams 1995). Similar granites (Pgc) also occur in the Yuendumu region where they appear to intrude the Ngadarunga Granite (Pgn).

(v) The granite intruding Lander Rock beds 12 km northeast of Silver King Mine has a marginal weakly-foliated migmatitic phase containing rafts of locally andalusite-rich schists. It is either a deep granite or has incorporated and metasomatised blocks of Lander Rock beds.

Models for the origin of migmatitic gneisses

The $D_{b1\text{-}4}$ group of deformations that characterise the migmatitic phase of the Yuendumu Event developed in the migmatitic gneiss unit differ from those affecting lower grade Lander Rock beds in several aspects. Features associated with the migmatitic gneiss unit which are not present in the Lander Rock beds are:

(i) multiple high-strain and migmatite events;

(ii) concurrent progressive metamorphism up to granulite facies grade that affected small gabbroic bodies, appears to be synchronous with the last regionally developed migmatitic event;

(iii) intrusion of late-stage (post - D_{a2}) deep-level granitic intrusion.

An important consideration in understanding the origin of these migmatites is the regional significance of D_{b5}'. The D_{b5}' deformation took place under retrograde conditions with the formation of a foliation outlined by muscovite. As such, it appears to pass westwards into the foliation characterising the Hardy tectonic phase, Dc*. Alternatively, it may correlate with D_{a3} developed in the Lander Rock beds and also effectively represent D_{c1} identified in the Reynolds Range group, as well as Dcx cutting the early granites. While it affected the migmatitic rocks in Keridi Creek, it is similar in orientation to D_{a3}. (e.g. 20 km northwest of Yuendumu township). Not all the granulite facies rocks were retrogressed during this deformation, perhaps because retrogression took place only in those places where fluids introduced along shear zones changed the kinetics of metamorphic reactions.

Several tectonic models that could account for formation of the migmatitic gneiss unit are shown in Figure 7 , together with their implied PTt paths (pressure-temperature-time paths).

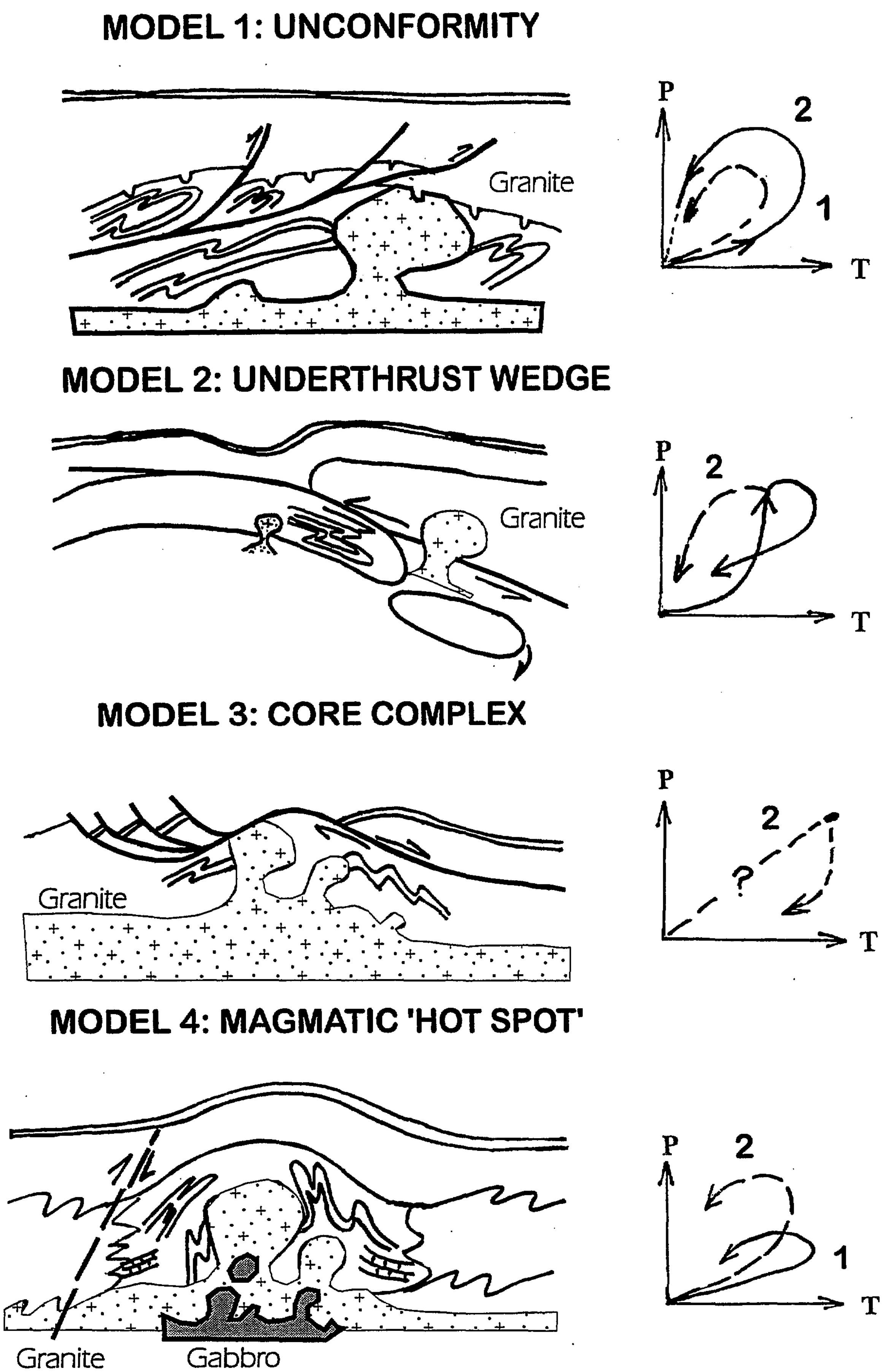

Figure 7. Models for the development of the migmatitic gneiss complexes

Model 1 — that the contact between the migmatitic rocks and the lower grade Lander Rock beds is an unconformity (Fig. 7.1). In this model the migmatites would have been exposed at the surface before the Lander Rock beds were deposited, thus, implying removal of a thick section of the crust. This model would predict that the migmatites should record two metamorphisms, and the Lander Rock beds one metamorphism. If the first metamorphism recorded in the migmatites was of the high temperature - low pressure type accompanying basic or felsic magmatism, it might show an anticlockwise PTt path at mid and upper crustal levels (curves 1 & 2 in Fig. 7.1). If the deformation in the Lander Rock beds records crustal shortening, a clockwise PTt path might be recorded at mid-crustal levels. In addition the migmatites would be expected to record a phase of unloading not recorded in the Lander Rock beds.

Another consequence of this model is that the two units would be very different in age. Consequently, the contact between the two units should be sharp. Although sharp contacts between the units appear to be the norm, this affect is largely a result of subsequent retrogression as part of D_{b5}' and is, most likely, part of a subsequent cycle of deformation: that is part of D_c or D_{cx}. In this hypothesis, the norites and xenolithic garnet-cordierite granite might represent post-migmatite intrusions emplaced in the basement before deposition of the Lander Rock beds. So the D_a group of deformations would be expected to post-date D_b structures in the migmatitic basement at least in the form of localised cross-cutting zones. Thus, in this model the retrograde schistosity overprinting the migmatitic unit S_{b5}' should be equivalent to one or both of the regional cleavage in the Lander Rock beds, S_{a1} or S_{a2}. Such a correlation is in conflict with the preferred correlation of the retrograde event D_{b5}' with either D_{cx}, D_c*, or D_{c1} (or what is labelled D_{a3}). However, an argument against the preferred correlation is that both the D_{c1} and D_{a3} deformations do not appear to be accompanied by incipient migmatisation, as appears to be the case with D_{b5}' and may be the case with S_{a2}.

Model 2 — The migmatites were originally part of an underthrust wedge (Fig. 7.2). Such a wedge may have been emplaced during A-subduction (see Kroner, 1981) or some other mechanism involving crustal thickening with coeval lithosphere thinning, perhaps as a consequence of induced convective instability in the mantle (Houseman et al. 1981, Loosveld & Etheridge 1990). In such an underthrust wedge the boundary between the units is tectonic rather than stratigraphic. In this model the two layered units could be of similar age. Both units could show D_a and D_b folds, but these may be more abundant in the underthrust slab. The predicted anticlockwise PTt path for the metamorphism (Fig. 7.2) in the upper crust has been documented from similar migmatitic complexes in the Arunta Block (Stewart et al. 1980). In contrast, the underthrust wedge may record a clockwise PTt path, depending on the final isostatic response to the deformation (curves 1 & 2 in Fig. 7.2), that would be dampened by a high degree of delamination.

Model 3 — Magma intrusion accompanying extension to produce one or more core complexes (Fig. 7.3). The extension in this model is envisaged to have been like that documented in the Basin and Range in western USA (Wernicke et al. 1988). In this model the metamorphic discordance may be explained by movement on a shallowly dipping extension zone (Wernicke & Axen 1981, compare with Lister et al. 1986). Thus, the boundary between the layered units is again tectonic rather than stratigraphic.

This model does not readily explain the compression suggested by the F_{b2-3} folding. In this model the two layered units could be similar in age and the intrusive rocks might be younger than both and associated with later crustal-scale extension. The bulk sense of shear would be expected to be the opposite to that of model 1.

Another problem with this model is that shear zones between the Lander Rock beds and the migmatitic unit are presently either sub-vertical or dip steeply towards the migmatitic unit, thereby implying either high-angle reverse faulting or strike-slip faulting, rather than the sub-horizontal decollement development predicted by a core complex model. Although such features might be explained by a subsequent deformation that folded the core-complex, thereby steepening the early gently dipping detachment zone, it is hard to envisage which of the documented deformations this could be as it should also affect the Lander Rock beds. Yet another related problem is the lack of a strong extensional lineation in the shear zones. Thus, this model is not supported by the field evidence.

Model 4 — The metamorphic "hot spot" model (Fig. 7.4). The metamorphism may be induced by a magmatic hot spot or some other similar mechanism. In this model the migmatitic gneisses are the stratigraphic equivalent of the Lander Rock beds. This model is supported by field evidence such as the metamorphic grade increasing across faults towards migmatites, lithological similarities, and parallelism of structural trends in both units.

The intrusion of hot granitic and/or mafic magma might have been the source of the heat that produced local metamorphism to granulite facies and at the same time weakened the rocks so that they were more readily deformed than nearby Lander Rock beds (Fig. 7.4), which are undergoing concurrent lower grade metamorphism under near hydrostatic conditions.

A potential problem with this scenario is that contacts between migmatite and low-grade Lander Rock beds can be interpreted as stratigraphic. For example, in places the migmatitic unit includes rock types such as hornblende-rich, banded calc-silicate rocks, quartzofeldspathic gneiss, and mafic granulite, the protoliths of which are not present in nearby Lander Rock beds. Some of these apparent lithological differences can be readily explained. For example, mafic granulite may represent gabbroic intrusions emplaced during migmatisation, or, as they form small pod-like bodies and lack a strong foliation, they may be post-deformational (ie. post - D_{b3}). Some calc-silicate rocks are present in lower grade Lander Rock beds, for example as pods forming mullions in F_{1a} folds southwest VAUGHAN. The felsic gneiss might represent felsic metavolcanics: they could, equally well, represent high-grade equivalents of pelitic units in the Lander Rock beds, as appears to be the case at the southern end of the Reynolds Range to the east of the Sheet area (e.g. between Aileron and Sandy Creek, Stewart et al. 1980, see also Dirks & Wilson 1990, Hand et al. 1992).

In Model 4 the migmatisation and the accompanying D_b deformational sequence would be predicted to be part of the same progressive event as the D_a sequence of deformations seen in the Lander Rock beds. Both the migmatitic gneisses and Lander Rock beds could be either similar in age to or much older than the granite and gabbro intrusions. The lack of D_a relict foliations in the migmatitic gneisses could be explained if the migmatisations and the accompanying D_b sequence of deformation were sufficiently intense that they obliterated an earlier D_a sequence of folding.

Collins & Vernon (1991) have proposed a similar model to explain low-P, high-T metamorphism, an anticlockwise P-T-t path, and peak metamorphism before or during the earliest compressional deformation in the Anmatjira Range to the east of sheet area. Their model involves repeated intrusion of large volumes of hot granite: the granite making up as much as 50 % the crust. In an earlier analysis of overprinting relationships by the same authors (Collins et al. 1991), a deformation equivalent to D_a (their F_{1a} - F_{1b}) pre-dates deformation equivalent to D_b (their F_{2c}) and D_c (their F_{2b}) (see Table 5). Collins & Vernon (1991) suggest that the thermal peak was reached during or before the beginning of deformation because thermal softening, caused by granite intrusion, allowed ductile deformation to take place. Meissner et al. (1987) suggest, on the basis of general geophysical evidence, that the heat transferred into the mid-crust by the emplacement of large volumes of granite might have been generated by a rising plume that was confined to the mantle.

On the other hand, a hot spot of sufficient size to produce migmatite might develop over a single intrusion if there were large-scale advection of hot fluid, as proposed by Chamberlain & Rumble (1988) to explain regional "hot spots" measuring 100 km^2 within a regionally extensive sillimanite zone in New Hampshire, USA. On the basis of an ^{18}O depletion halo and radiometric dating, they conclude that the hot spots resulted from hot metamorphic fluids flowing through a narrow zone of high fracture permeability. Such a model might also explain the migmatitic gneiss in the Mount Doreen area.

Blake (1991b) and Blake and Hoatson (1993) have suggested a variation of this hot magma model to explain the formation of migmatite in the Tickalara Metamorphics in the east Kimberley region of Western Australia, attributing these migmatites to contact metamorphism associated with post-tectonic penecontemporaneous granite and gabbro intrusion. They suggested that the already emplaced but still very hot, granites may have been superheated by the gabbro intrusions.

A similar origin may apply to other high-grade bodies forming a discontinuous belt along strike to the west. Alternatively, they may represent high-grade metamorphism produced in a subsequent younger event, during the *Hardy tectonic phase*. In YUENDUMU, rocks originally containing cordierite and garnet, that resemble hornfels and show little deformation, form a body located at 'Leopard Rock', 5 km south of Wolfram Hill. In northeast DOREEN, west of Yaloogarrie Creek, a strongly banded quartz-rich gneiss, showing limited migmatisation, has a thin marginal segment of migmatised, multiply folded, sillimanite biotite gneiss alongside it and also lies immediately along strike from a markedly xenolithic granite (e.g. Meercantie phase of the Carrington Granitic Suite south of Wolfram Hill). The highly migmatised marginal segment has mobilisate localised in shears which are axial-planar to upright, tight kink-like folds with rounded hinge regions. The folds are like F_{b3} folds recognised in YUENDUMU. These migmatites pass abruptly into typical low-grade Lander Rock beds. Both these two situations would be consistent with the migmatitic units being associated with granite intrusion as in Model 4. Model 4 is favoured by the regional metamorphic pattern. A shift in the centre of metamorphism and deformation in the Lander Rock beds from east to west is suggested by the concentration of F_{a2} folds in the west of the region (Fig. 3). The migmatite gneiss unit may represent a further shift in a continuing progressive, but contracting metamorphism.

In this scenario, the D_b sequence of deformations would post-date the D_a sequence of deformations, except for $D_{b5'}$ which may correlate with D_c*, D_{c1} and D_{a3}. However, $D_{b5'}$ is accompanied by incipient migmatisation not seen to accompany D_{b3} or D_{c1}, although $D_{b5'}$ may well be associated with the high-grade foliation of the *Hardy tectonic event*, D_c* This latter proposition is favoured because the spotted rock at 'Leopard Rock' is amazingly similar to rocks at Mount Stafford metamorphosed during the Mount Stafford Event (Table 5), and associated with the Mount Stafford Granite which has a preferred age of 1820 Ma (Collins & Shaw 1995).

A particular problem raised by this model, as applied to the older migmatites surrounding the 1880 Ma Ngadarunga Granite, is the implication that the Lander Rock beds are older than 1880 Ma: a result that conflicts with the commonly held correlation between the Lander Rock beds and the Warramunga Formation (Group) (Blake et al. 1987, Stewart et al. 1984, Black 1984), the preferred age of which is ~1860 -1870 Ma (Donnellan et al. 1995, Compston 1995).

None of these models is entirely satisfactory. More data is needed to provide some control on the PTt histories during the deformations and to confirm that both the migmatitic gneisses surrounding Ngadarunga Granite and the Lander Rock beds in the Mount Doreen-Yuendumu region are older than 1880 Ma.

The (garnet)-cordierite Ngadarunga Granite near Yuendumu, dated at 1880 Ma, is undeformed and contains xenoliths of deformed migmatite so it post-dates D_b and, thus, is unlikely to be the heat source for the migmatisation of the gneisses. Perhaps mafic magma, poorly represented in outcrop as mafic granulite, was the heat source.

In summary, the favoured explanation of the evidence is Model 4 - that the high-grade gneisses and migmatites are high-grade equivalents of the Lander Rock beds, deformed and metamorphosed (during D_b) as a progressive development of the regional deformation and low-grade metamorphism of the Lander Rock beds ($D_{a1, 2, 3}$).

The heat source for these migmatitic gneisses as well as the possibly younger series of pods of migmatitic gneiss to the west (e.g., Leopard Rock) remains a problem. Some form of magmatic underplating is implied.

However, the unconformity hypothesis, Model 1, as applied to the migmatitic gneiss surrounding the Ngadarunga Granite cannot be entirely discounted on the available evidence and has the added advantage that it preserves the preferred correlation of the Lander Rock beds with the Warramunga Group (see below and Stewart et al. 1984). A key fact in this connection is that, because the 1880 Ma granite is undeformed, it, and, hence, the migmatitic gneiss surrounding it may be older than the *Wolfram folding phase* in the Lander Rock beds as this appears to be a regiònal event affecting the whole region.

TECTONIC EVENTS IN THE ARUNTA BLOCK

Yuendumu Tectonic Event (1880 Ma)

In brief, the Yuendumu Tectonic Event is the earliest recognised in the Arunta Block, affecting the turbiditic Lander Rock beds. It involved several phases of deformation. It is defined as that event which (i) reached its climax with the high-grade metamorphism and migmatisation accompanied by complex folding referred to as the *migmatitic phase of the Yuendumu Orogeny*, and (ii) was intruded at about 1880 Ma by the undeformed, post-tectonic Ngadarunga Granite.

The event may also include the *Wolfram phase of folding* represented by the earliest two phases, D_{a1} and D_{a2}, of folding in the Lander Rock beds, neither of which are evident in the overlying Reynolds Range Group (see Tables 1, 2, 5, 6). In the first phase, D_{a1}, tight to isoclinal folds formed with a slaty cleavage as the axial planar structure. In the second phase, D_{a2}, a crenulation-like cleavage formed the axial planar structure to slightly more open folds. The event is somewhat complex as the high-grade deformation sequence $D_{b1\text{-}4}$ developed in migmatitic gneiss may represent the final stages of the same event.

Events affecting the Lander Rock beds are somewhat complex. The third phase of folding in the Lander Rock beds, D_{a3}, is even less clearly part of the Yuendumu Orogeny. In fact, the third phase of folding in the Lander Rock beds, D_{a3}, is probably not part of the Yuendumu Orogeny. It lies parallel to and may correlate with the first phase of tight, east-west folding, D_{c1} in the Reynolds Range Group. Relationships between D_{a3} and D_{c1} cleavages are well illustrated 9 km east of southeast of Mount Hardy where a strong penetrative crenulation cleavage S_{b3} in the Lander Rock beds to the north parallels an exceptionally strong slaty cleavage D_{c1} that is axial-planar to a tight east - west syncline in quartzite of the Reynolds Range Group to the south.

Present indications are that the deformation grouping $D_{b1\text{-}4}$, established in the migmatitic gneiss units northeast of Yuendumu, may have closely follow the deformation grouping $D_{a2\text{-}3}$ evident in the Lander Rock beds. Results of the recent dating program by NTGS (Young et al. 1995) suggests that the tectonism incorporating both these deformation groupings ($D_{a2\text{-}3}$, $D_{b1\text{-}4}$,) peaked shortly after the intrusion, at about 1880 Ma, of the garnet-cordierite granite exposed northeast of Yuendumu (Young et al. 1995). However, as the granite contains xenoliths of migmatite, its age only provides a possible minimum age for the two folding generations of the *Wolfram tectonic phase*.

Cordierite granulite and migmatite are assigned to map-units Plrc and Plm of the Lander Rock beds, around the syntectonic, cordierite and garnet-bearing Ngadarunga Granite near Yuendumu and in isolated outcrops elsewhere. Sillimanite is present in the highest-grade gneisses. The cordierite-bearing rocks, which in places preserve bedding and other sedimentary structures and so appears to be only weakly deformed, correspond to magnetic highs in a broad belt of high-grade metamorphic rocks traversing MOUNT DOREEN from east to west, north of the Ngalia Basin, and could represent localised metamorphic 'hot spots' related to either the *Hardy tectonic phase* or the earlier *migmatitic phase of the Yuendumu Orogeny*.

The unconformity between the Lander Rock beds and the Reynolds Range Group in the north is considered to represents the period from the end of the Yuendumu Tectonic Event to the deposition of the Mount Thomas Quartzite. During this period, as a result of uplift and erosion, a thickness of several kilometres appears to have been removed, resulting in greenschist to amphibolite-facies rocks being exposed at the time of Reynolds Range Group sedimentation.

In the Reynolds Range Region to the east of the Mount Doreen Sheet area, views concerning the importance of the unconformity between the Lander Rock beds and the Reynolds Range Group have varied widely (Stewart et al. 1984, Clarke et al. 1990, Collins et al. 1991). Dirks & Wilson (1990) considered that the unconformity died out southwards along the Reynolds Range, implying a minor stratigraphic break that did not separate two periods of major folding. However, Hand et al. (1992) have adopted the view that two major metamorphic and deformational episodes were separated by a period of basin development.

Structure relationships between D_{a1} and D_{c1-2}, that are evident in the Wabudali Range region in VAUGHAN and summarised in Fig. 8, point to D_{b1} pre-dating deposition of the Reynolds Range Group. On balance, it seems likely that a large time-gap separates D_{a1-2} from D_{c1-3} (see Tables 5 and 6). If this is correct, the tectonic event represented by D_{a1-2}, and probably also D_{b1-2}, might correlate with early phases of the Barramundi Orogeny recognised in northern and northwestern Australia to range from 1890 Ma to 1850 Ma (Table 6). Furthermore, the (garnet)-cordierite granite that intrudes high-grade gneiss 20 km west of Yuendumu is dated at 1880 ± 5 Ma (Young et al. 1995), implying an early Barramundi-like age for this particular pocket of high-grade metamorphism. Thus, the Yuendumu Event may fit into one of the stages of a 1850-1890 Ma Barramundi orogenic period.

So, the age of the Yuendumu Event is constrained by the undeformed 1880 Ma Ngadarunga Granite, which contains xenoliths of migmatitic country rocks. However, the widely, but sparsely, distributed cordierite gneisses within the Lander Rock beds in the north of the study area crop out in the same belt as, and may correlate with, similar cordierite gneisses of the Mount Stafford beds, dated at 1820 Ma (Collins & Williams 1995, Collins & Shaw 1995), in the Napperby sheet area to the east.

Our understanding of what constitutes the Barramundi Orogeny is also undergoing a reassessment. The Barramundi Orogeny was originally defined conceptually by Etheridge et al. (1987) as a tectonic sequence involving the termination of basin development, major folding, and metamorphism and syntectonic magmatism. As defined, this orogeny appears to have affected most of northern and northwestern Australia (Table 6). Etheridge et al. (1987) estimated that the orogeny spanned from 1870 to 1850 Ma, based on the geochronology reported in Wyborn & Page (1983) and Page (1985).

More recent geochronological data suggests that the Barramundi Orogeny is in fact an orogenic period that may have started as early as 1890 Ma and may vary somewhat in timing between one province and another. For example in the Mount Isa region, the metamorphism accompanying the Barramundi Orogeny has been dated at about 1890 ± 8 Ma (Wyborn et al. 1988), whereas in the Pine Creek Inlier the orogeny occurred between the folded Gerowie Tuff, dated at about 1885 Ma, and the younger and less well constrained age of volcanoclastics at the base of the El Sherana Group (Table 6, Coronation Sandstone - Page & Williams 1988). In the East Kimberley region the age of the Barramundi Orogeny is not well constrained (see Table 6), but probably developed rapidly and reached a peak before post-orogenic volcanism (Whitewater

Volcanics) dated at 1850 ± 5 Ma (Page & Hancock 1988). In the Tennant Creek Inlier, Blake et al. (1987) place the main folding of the Warramunga Group in the Barramundi Orogeny (see Table 6). Compston (1995) places this folding at about 1850 Ma, preceding erosion and subsequent deposition of felsic volcanics of the Flynn Group (including the Bernborough Volcanics at 1845 Ma), and post-dating emplacement of the ~ 1830-1840 Ma Tennant Creek Granite.

Until the extent of the tectonism that appears to have peaked within the northern Arunta Inlier at 1880 Ma is clarified and the age span of the 'Barramundi Orogeny' is better constrained, the term Yuendumu Event is preferred to the broader, conceptually based term 'Barramundi Orogeny'. Present indications from ongoing research are that the age span of the 'Barramundi Orogeny' may vary significantly from region to region.

Carrington granitic magmatism (~ 1780 Ma)

Granites of the Carrington Granitic Suite are foliated and in several places are spatially associated with migmatitic rocks, indicating probable emplacement under upper amphibolite-facies conditions, like the Napperby Gneiss in NAPPERBY to the east. Both the Carrington granites and Napperby Gneiss are dated at about 1780 Ma, corresponding to the start of the Strangways Orogeny (Collins & Williams 1995, Black & Shaw 1992, Collins & Shaw 1995). The suite includes the Yulyupunyu Granitic Gneiss which shows migmatitised shear zones indicating that regional deformation and metamorphism occurred at high metamorphic grade, and probably closely followed magma crystallisation.

The Yulyupunyu Granite shows marked similarity to and is correlated with the 1780 Ma Napperby Granite in the Reynolds Range, now grouped as part of the Weldon Event in the Strangways Orogeny, a major deformation in the Central Tectonic Province of the Arunta Block (Collins & Shaw 1995).

The orogeny produced major deformation, granulite metamorphism and magmatism and was concentrated in the central province. Its age is constrained to lie between 1780 to 1760 Ma (Collins & Shaw 1995, Black & Shaw 1992). Thus, the Carrington magmatism appears to correlates in time with the early stages of the Strangways Orogeny, recognised in the Arunta Block to the east and southeast. The volcanics of the Nicker beds dated at about 1770 Ma, may represent a high-level expression of the same event.

Hardy tectonic phase

This phase produced a strong north-to northeast-trending mica (biotite and muscovite) foliation, indicative of lower amphibolite-facies conditions, in granites of the Carrington Granite Suite southeast of Mount Hardy, so is probably younger than 1780 Ma. The foliation overprints the migmatitic foliation of the Yuendumu tectonic event and is truncated by a Wabudali high-strain zone at the western end of the Treachery schist zone. deformations labelled Db_5, and Dc* probably from part of the same event.

Andrew Young bimodal magmatism (~ 1635 Ma)

An igneous complex, composed mainly of gabbro and tonalite and lying south of the Ngalia Basin, has been dated at 1635 Ma (Young et al. 1995). What is surprising about the complex is that it is undeformed. This means that it escaped the Hardy and Wabudali tectonic phases. The style of magmatism implies an intracratonic tectonic setting, perhaps like that of the much younger 1200 Ma Mordor Igneous Complex in the southern Arunta Province (see Langworthy & Black 1978). Thus by 1635 Ma the central Arunta Province was substantially cratonised.

Wabudali tectonic phase

This phase is characterised by high-strain zones, boat-shaped synclines preserving rocks of the Reynolds Range Group, and formation and extensive boudinage of quartz veins in the northern part of the Mount Doreen Sheet area. In most places, the deformation fabric suggests a north-south flattening strain with minimal shearing. The Wabudali phase is exemplified by a high-strain zone affecting the Reynolds Range Group and adjacent Lander Rock beds along the south side of the Wabudali Range. Similar high-strain zones assigned to this tectonic phase, the Coxes and Treachery schist zones, trend east-west across the northern part of the Sheet area, where they caused lower amphibolite and greenschist facies metamorphic retrogression. The phase overprints folding of the Yuendumu Event and cuts the foliation of the Hardy phase. The Wabudali tectonic phase refers to those D_{c1-3} structures that post-date deposition of the Reynolds Range Group, but pre-date intrusion of the unfoliated, megacrystic feldspar granites. During the Wabudali tectonic phase, the Reynolds Range Group was folded into major synclines, as seen in the Wabudali Range and near Bundarunganu Hill, as well as farther to the west. These synclines form tight boat-like isoclinal synclines that may represent the footwall keels within north-directed zones of reverse faulting.

The dominant structures in the adjacent underlying Lander Rock beds are markedly discordant to these synclines, but are not folded by the synclines. In fact, the synclines themselves appear to be localised along high-strain zones, indicating that their origin is related to the development of these high-strain zones. For example, south of the Wabudali Range major F_{a1} folds in the Lander Rock beds (e.g., S91, S92; Table 3) plunge very steeply to the west, whereas the plunge of the nearby major syncline folding the Reynolds Range Group is sub-horizontal (Fig. 8, diagrammatic view of relationships).

A minor complication is that the D_{b3} deformation in the Lander Rock beds may be equivalent to the first deformation (designated D_{c1}) affecting the Reynolds Range Group. D_{a3} is expressed locally as a strong, penetrative crenulation-like cleavage, which typically trends east - west. Pencil slates outlining L_{a3} have formed over large regions at the intersection of S_{a2} and S_{a3}. Pencil slates are particularly well developed 7 km southeast of Gintys Bore, where kink folds have axes parallel to L_{a3}.

The deformation affecting the Patmungala beds is also probably a variation of the *Wabudali tectonic phase*, as is the narrower zone of deformation affecting the Nicker beds. In this region, which lies south of the Wearer Fault, deformation is more widespread and has a character suggestive of thin-skinned style of tectonics associated with a fold and thrust belt.

The Wabudali tectonic phase may represent transpressional tectonism. This is suggested by the upright faulting, the anastomosing nature of the high-strain zones, and the apparent minor displacements involved. For example, in many cases there is little change in metamorphic grade across the Wabudali high-strain zones.

The Wabudali tectonism is younger than 1772 Ma, the age of the youngest dated unit affected, the Nicker beds. It is also older than the 1567 Ma Yarunganyi Granite of the Southwark Granitic Suite. Like the Hardy tectonic phase, it may correlate with part of the Strangways Orogeny, which lasted from about 1780 to 1730 Ma (e.g. Black & Shaw 1992, Collins & Shaw 1995). Alternatively, it may correlate with the 1600 Ma Chewings Orogeny recognised documented in the southern part of the Arunta Block (e.g. Collins & Shaw 1995), as pegmatite emplacement and hydrothermal fluxing in shear zones of this age have been documented in the Anmatjira Range region in the Napperby Sheet area. However, this correlation is not supported by the undeformed nature of the Andrew Young Igneous Complex, dated at 1635 Ma, south of the Ngalia Basin. Even so, because of the similar style of deformation, a correlation with the Chewings Orogeny is favoured.

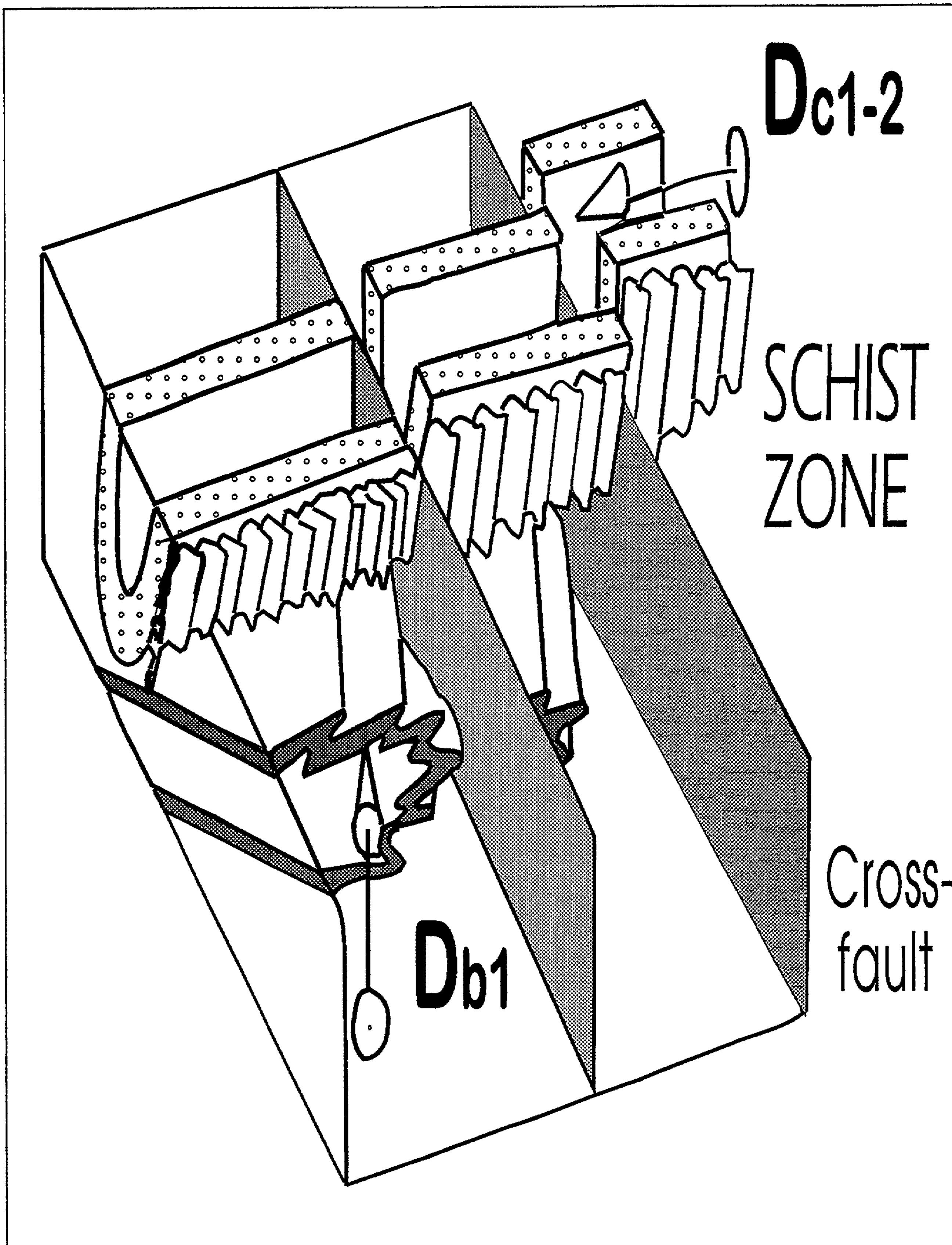

Figure 8. The relationship between Lander Rock beds folds and those in the Reynolds Range Group

A post-tectonic suite of highly fractionated, granites containing tabular-feldspar, phenocrysts was emplaced at upper crustal levels after the Wabudali tectonic phase, mainly north of the Ngalia Basin. These granites, which make up the Southwark Granitic Suite, form large discordant batholiths and for the most part, lack any tectonic foliation. However, they are cut by major quartz-filled faults. The Yarunganyi Granite, which characterises this suite, has been dated at about 1567 Ma. If the Wabudali phase immediately preceded this granite suite, then it may form part of the same tectonic cycle. However, there are reasons for thinking the Southwark magmatism is significantly younger than the Wabudali tectonism. For example, the shape of the Southwark granites is markedly discordant to Wabudali structural trends and their limited contact metamorphism overprints fabrics of the Wabudali schist zones.

Southwark granitic magmatism (around 1570 Ma)

A post-tectonic suite of highly fractionated, megacrystic-feldspar granites was emplaced at upper crustal levels after the Wabudali tectonic phase, mainly north of the Ngalia Basin. These granites, which make up the Southwark Granitic Suite, form large highly discordant batholiths. For the most part, they lack any tectonic foliation, but they are cut by major quartz-filled faults. The Yarunganyi Granite, which belongs to the suite, is dated at 1567 Ma. These granites record a major thermal event in the lower crust.

Uplift and erosion (1570-830 Ma)

Uplift and erosion recorded by the unconformity at base of the Ngalia Basin succession resulted in the exposure of granites of the Southwark Granitic Suite and older rocks by about 800 Ma. The exhumation may have been initiated during the *Anmatjira Uplift* at 1400-1500 Ma, like the early uplift along the Redbank Thrust Zone that separates the Central and Southern Provinces of the Arunta Block southeast of the Mount Doreen Sheet area (Shaw & Black 1991). This tectonism was first recognised as the *Anmatjira Event* in the Napperby Sheet area (Black et al. 1983).

The *Jubilee deformation*, labelled D_{dx}, is a field term for the deformation that produced the fine-grained biotite foliation that cuts the tabular-feldspar granites Yaloogarrie Granite (pgy) east of the Jubilee Silver King prospect. Its age is unknown. As some of these granites may be correlatives of 1775-1780 Ma post-tectonic granites of the *Weldon Event* in the Reynolds Range, deformation D_{dx} is probably younger than this event. However, the tabular-feldspar granites are currently grouped with the Southwark Granitic Suite, that includes the ~ 1570 Ma Yarunganyi Granite (see Tables 1a, 1b). So, the *Jubilee deformation* could be younger than the c. 1570 Ma, the age of the Yarunganyi Granite. If this is so, it might correlate with the 1400 - 1500 Ma *Anmatjira Event* (Redbank uplift) described from the boundary between the central and southern Arunta provinces (Shaw et al. 1992a, Collins & Shaw 1995). Yet another possibility, which cannot be excluded, that mylonitic foliations of this style could have formed during the early stages of the Alice-Springs Orogeny. As the fine-biotite foliation in the Yaloogarrie Granite does not appear to continue eastwards into the 1570 Ma Yarunganyi Granite, the preferred timing for the *Jubilee deformation* is shortly before 1570 Ma, in which case it may represent an expression of the *Wabulali tectonic phase*, like the folding in the Patmungala and Nicker beds.

NEOPROTEROZOIC - PALAEOZOIC DEFORMATIONS

Initiation of the Ngalia Basin (~830 Ma)

The subsidence that initiated the Ngalia Basin has been variously placed between 1200 and 830 Ma (see Wells & Moss 1983, Cooper et al. 1971). The basin was part of a much large depositional area that included the Amadeus and Georgina basins, and the Vaughan Springs Quartzite at the base of the Ngalia Basin succession is correlated with the Heavitree Quartzite of the Amadeus Basin. The Heavitree Quartzite overlies dolerite dykes dated at 1080 Ma (Nd-Sm age by Zhao & McCulloch 1993). If the development of these basins is linked to the development of the Adelaide 'Geosyncline', the subsidence in both basins may have commenced at about 830 Ma or slightly earlier (Fanning et al. 1986, Preiss 1987).

Episodic events affecting the Ngalia Basin (830 to 400 Ma)

Ten tectonic movements are known to have affected the Ngalia Basin, based on periods of uplift and erosion that resulted in major loss of section and are recorded as unconformities (Wells & Moss 1983). The tectonic and regional significance of many of these unconformities is discussed in Shaw et al. (1991b).

1. The last major uplift to affect the basement Arunta Block before the initiation of subsidence in the linked Amadeus-Ngalia basin system was possibly the Teapot Tectonothermal Event at about 1100-1200 Ma (Black & Shaw 1992). However, it is unlikely that this tectonism affected the Ngalia Basin region.

2. The *Vaughan Springs Movement* followed deposition of the Vaughan Springs Quartzite. The ensuing erosion of these features stripped much of the Vaughan Springs Quartzite from the region. Wells & Moss (1983) considered that it may have been extensional and resulted in the formation of several small horst and graben-like structures northeast of Newhaven. Deckleman & Davidson (1993) regarded these Newhaven structures as Neoproterozoic (Petermann Ranges Orogeny, see below

3. Minor differential uplift accompanied erosion of parts of the Neoproterozoic glacial succession. Wells and Moss (1983) applied the local named *Rinkabeena Movement* to the movement. However, recently acquired seismic data suggests some structures formed within the basin at this time (Deckleman & Davidson 1993). The style and timing of these structures suggest that they correlate with the *Petermann Ranges Orogeny* in the Amadeus Basin (see below).

4. An unnamed movement is postulated to explain the unconformity within the Yuendumu Sandstone. The Yuendumu Sandstone is itself a somewhat immature arkosic sandstone, suggesting some emergence in the source region. This emergence and the internal erosion at the unconformity suggest mild and continuing tectonism that may also correlate with the *Petermann Ranges Orogeny* that affected the southern Amadeus Basin (see below).

5. A very minor event was proposed by Wells and Moss (1983) to explain removal of part of the Yuendumu Sandstone from central part of the basin. They named it the *Yuendumu Movement*, but this name is not retained.

6. The *Bloodwood Movement* involved displacement along the Treuer thrust fault and caused uplift and local removal of a large part of the Cambrian succession. The movement roughly corresponds to the time of the Delamerian Orogeny in the Adelaide Geosyncline and Spielers Event recognised at the northern margin of the Canning Basin (Shaw et al. 1992c).

7. The *Djagamara Movement* resulted in uplift, folding, and erosion, particularly of the Ordovician succession and mostly concentrated in the west of the basin. It may correlate with the Rodingan Movement in the Amadeus Basin.

8. The *Kerridy Movement* produced major uplift along the northern margin of the basin. It is regarded as a precursor to the Mount Eclipse Movement.

9. The *Mount Eclipse Movement* produced most of the major structures in the basin. These are described at some length in Wells & Moss (1983).

Petermann Ranges Orogeny (530-550 Ma)

Minor tectonism in the Ngalia Basin at the end of the Proterozoic produced broad, open folding and minor faulting evident in seismic sections (Davidson 1993, Deckleman & Davidson 1993). This tectonism, which can be correlated with the Petermann Ranges Orogeny in the Amadeus Basin, is represented in surface exposures by a slight angular unconformity at the base of the Yuendumu Sandstone and by a slight unconformity within this unit. No structural features are readily linked to other breaks in the stratigraphic succession in the Ngalia Basin.

Particular structural features that may date from this orogeny include (1) the complex horst-like features in the central south of the basin, which may have been generated by dextral shear during this orogeny and later reactivated during the Alice Springs Orogeny; (2) a flower-structure, involving basement and Vaughan Springs Quartzite, outlined by seismic data at the Newhaven gas prospect; and (3) doming of the Vaughan Springs Quartzite and the Rinkabeena Shale at the West Treuer gas prospect, located 30 km southwest of Davis No. 1 petroleum well.

The Yuendumu Sandstone is itself a somewhat immature arkosic sandstone, suggesting some emergence in the source region. Such emergence would be consistent with the finding of an unconformity within the unit (see above).

The best evidence for the timing of the Petermann Ranges Orogeny comes from as far away as the Musgrave Block, where Marboko et al. (1992) deduce an age of about 530-550 Ma, based on ^{40}Ar - ^{39}Ar data.

Alice Springs Orogeny (300-400 Ma)

By far the most intense deformations in the region were the Kerridy Movement, most likely in the Late Devonian, and Mount Eclipse Movement in the Carboniferous. These latter two movements are regarded as part of the Alice Springs Orogeny. This intracratonic orogeny was responsible for major thrusting and other faulting throughout central Australia (e.g. Teyssier 1985, Shaw 1991, Shaw et al. 1991a, 1991b, 1992).

Kerridy Movement (~350-400 Ma)
(including syn-depositional tectonism)

Record of deposition and exhumation

This movement, which involved faulting, folding and erosion, resulted in the removal of much of the pre-Late Devonian Ngalia Basin succession, especially in the south and east of the Basin. The movement is recorded stratigraphically by the unconformity at the base of the Mount Eclipse Sandstone. Earlier exhumation, but possibly part of the same event, is apparent from the immature, feldspathic clastics that make up the Kerridy Sandstone. The movement may be correlated with Pertnjara Movement in Amadeus Basin (Shaw 1992a, Deckleman & Davidson 1993).

The age of the *Kerridy Movement* is poorly constrained. There is no direct evidence for the age of the preceding Kerridy Sandstone. However, an upper limit on the movement is provided by an Early Carboniferous (Tournaisian) palynoflora in the overlying Mount Eclipse Sandstone (E.M. Truswell, AGSO, pers. comm. 1993).

The *Kerridy Movement* may correlate with either one of several movements representing major pulses of the Alice Springs Orogeny recognised in the Amadeus Basin: namely the Pertnjara Movement (Wells & Moss 1983), the Henbury Movement, and/or the Brewer Movement (see Jones 1991). The exhumation history of Arunta basement between the Ngalia and Amadeus Basins, deduced from ^{40}Ar-^{39}Ar data, supports this broad correlation (Shaw et al. 1992a), and suggests an age of c. 350-370 Ma for uplift of the region bordering the Ngalia Basin.

On the other hand, deposition of the Kerridy Sandstone itself might partly correspond to the time-gap represented by the unconformity at the base of the Pertnjara Group. High contents of both K-feldspar (up to 20%) and detrital white mica in the sandstone, together with its dominantly fluviatile facies, suggest tectonic emergence of Arunta basement to the north during its deposition. In these respects, the Kerridy Sandstone is like neither the Mereenie Sandstone nor the Carmichael Sandstone: units previously suggested as plausible correlatives (Wells & Moss 1983, Shaw et al. 1992a). Rather, facies features in the Kerridy Sandstone more closely resemble those of the Pertnjara Group. Just as the unconformity at the base of the Kerridy Sandstone heralds a period of tectonism, so the unconformity at the base of the Pertnjara Group signals the start of the Alice Springs Orogeny (Forman 1966, Shaw et al. 1991b, Shaw et al. 1992a). On the other hand, the Pertnjara Movement, represented by the unconformity at the base of the Pertnjara Group in the Amadeus Basin, may correspond in time to the periods of non-deposition at the base of the Kerridy Sandstone, as well as of the period of deposition of the sandstone itself. In this case, the Kerridy Movement *sensu stricto*, defined as represented by the unconformity at the top of the Kerridy Sandstone, may correlate with either the Henbury Movement or the Brewer Movement, and be as young as Late Devonian (ie. Frasnian-Famennian; compare with Shaw et al. 1992a). A Late Devonian age for the Kerridy Sandstone and the following period of non-deposition is consistent with the interpretation of $^{40}Ar/^{39}Ar$ data that implies uplift and erosion in the region bordering the Ngalia Basin at c. 350-370 Ma (Shaw et al. 1992a; samples Ar1, 2).

Wells & Moss (1983) showed that the White Point Fault (Fig. 4), which follows the high-angle boundary between the Kerridy Sandstone and the Djagamara Formation, is overlapped unconformably by the Mount Eclipse Sandstone and is mainly the result of the *Kerridy Movement*. It appears to be a high-angle reverse fault. Nearby sub-parallel shears within the Kerridy Sandstone terminate upwards at the same unconformity. Numerous minor folds generated along detachment zones within the Kerridy Sandstone may date from either the Kerridy Movement or the Mount Eclipse Movement.

Weaner fault zone (Fig. 4) may also date from the Kerridy Movement, but appears to have reactivated Wabudali aged structures. It and linked faults to the east separate a region of generally high-grade metamorphic rocks to the north from granites of the Southwark Granitic Suite and low-grade Patmungala and Nicker beds to the south.

Quartz Veining and Brecciation

Complex linear zones of multiple quartz veins cut both the Arunta Block and northern parts of the Ngalia Basin. These veins commonly fill fault zones at contacts between the Lander Rock beds and granite. They also occur within several units including granite, the Lander Rock beds and the Patmungala beds (Fig. 6c, site is 3 km east-southeast of Djagamara Peak), as well as Late Proterozoic sedimentary rocks. They have also developed in a few places along the faulted contact between overturned beds of the Carboniferous Mount Eclipse Sandstone and upthrust Proterozoic rocks such as Vaughan Springs Quartzite and granite. These fault zones generally strike parallel to the northern margin of the Ngalia Basin, so that northeasterly trends dominate in the west, easterly trends in the central part, and east-southeast in the east of the Sheet area (Fig. 4). Veins within the zones are generally either sub-vertical or dip 50-60° north. However, some veins swing from north-dipping to south-dipping over short distances (ie. 100 to 200 m).

These zones are made up typically of a core region of multiple quartz veins commonly bordered by wider zones of silicification, recrystallisation and local brecciation. Some thick veins (0.5-m wide) consist of white non-foliated quartz, whereas some thinner veins are commonly filled with quartz fibres. An example of such vein complexes, in this case cutting the Patmungala beds, is illustrated in Fig. 6c. In other places, vuggy, open spaces and honeycomb-like structures are common. A few unusual quartz veins, cutting granite near the Walbiri prospect camp, occupy dyke-like zones that appear to also contain sedimentary infill.

Many of these complex zones of quartz veining probably result from the passage of hydrothermal solutions along fractures that opened and reopened several times. Because of the large volumes of silica deposited, it is presumed that enormous volumes of fluid flowed through the fractures (compare with Etheridge et al. 1984). The transport of such large volumes of fluid by advection would be feasible if the thermally driven fluid circulation was lateral and along strike rather than vertical. In such a scenario, fluid volumes would be enhanced if much of the fluid were derived from an overlying sedimentary succession such as the Ngalia Basin.

Some of the complex fault-filled zones of quartz veins are tens of kilometres long (Fig. 4). As they are extensional or transtensional features at least locally, they are probably not, in general, related to the compressional faulting and shearing that accompanied the formation of the greenschist mylonite zones in the Arunta Block. However, minor progressive development of quartz veins took place during compressional shearing under low-grade metamorphic conditions in the Arunta basement during the Alice Springs Orogeny (see section on the Doreen deformation, D_{ex}). Similar shearing and vein formation developed locally in the Ngalia Basin on more than one occasion. Examples include the White Point Fault, which was active during the Kennedy Movement, and along parts of the Yuendumu Thrust east of the Walbiri Ranges, during the Alice Springs Orogeny.

Timing of activity on quartz-filled faults

An extensive transtensional fault system, involving reactivation of the Wabudali high-strain zones and multiple injection of siliceous hydrothermal fluids, may have active during this movement in the Arunta Block to the north of the Ngalia Basin. Prominent quartz-filled faults, identical to those in the Sheet area are widely distributed in the Northern Province of the Arunta Block, where they cut the earliest Cambrian Central Mount Stuart beds in southeastern Mount Peak Sheet area and are overlapped by the Late Palaeozoic Lake Surprise Sandstone in the Lander River Sheet area (Stewart 1982). To a lesser extent quartz-filled faults formed in the Ngalia Basin itself. Some quartz veins cut the Vaughan Springs Quartzite (e.g. near Warbiri), and also the Mount Doreen Formation north of Narburula Hills and the Kerridy Sandstone along the White Point Fault, but are rare in the Mount Eclipse Sandstone, suggesting that the main period of quartz was during the Kerridy, rather than the Mount Eclipse Movement. This conclusion is strengthened by the locally quartz-filled White Point Fault (south of Yuendumu) that is well constrained in age. This fault, which places the Djagamara Formation over the Kerridy Sandstone, was active during the Kerridy Movement (Wells & Moss 1983) as the fault is unconformably overlapped by the Mount Eclipse Sandstone. However, the strata-parallel style of the faulting is more consistent with thrust faulting than with strike-slip or high-angle reverse faulting.

Fault movement and related fluid transport continued until the final phase of the Alice Springs Orogeny (Mount Eclipse Movement) in the Carboniferous as the Yuendumu Thrust shows of injection by siliceous hydrothermal fluids.

Near the Warlbiri Prospect Camp (abandoned), differences in the Palaeozoic stratigraphic succession north and south of the quartz-filled east-west fault zone imply that some faulting of similar style occurred during the Late Proterozoic in the Ngalia Basin. As the veining is much more abundant in the Arunta basement than in the Ngalia cover, it has been suggested that some of the faulting that produced abundant quartz veining is probably earlier than the onset of sedimentation in the Ngalia Basin in the Neoproterozoic. Quartz-filled faults cutting the southern part of the Yarunganyi Granite are much thicker and more continuous than those cutting units of the Ngalia Basin. If they pre-date basin formation, they may have formed during or following regional exhumation at the time of the Anmatjira uplift (Tables 4 & 5, Shaw & Black 1991).

A major period of faulting and possibly concurrent hydrothermal quartz veining may also have accompanied the onset of subsidence in the Ngalia Basin. This scenario is suggested by a basal conglomerate, resembling a talus deposit, that adjoins the major quartz-filled, east-west fault zone marking the limit of the Vaughan

Springs Quartzite at the northern edge of the Warlbiri Prospect Escarpment. The conglomerate contains sub-rounded to sub-angular boulders, cobbles, and pebbles of basement quartzite in an abundant green clay-rich feldspathic matrix itself formed from locally decomposed granite, a minor proportion of these clasts show brecciation and quartz veining. The conglomerate may represent a distal talus or piedmont deposit. These relationships imply fault scarp development alongside an active fault during basin initiation.

Faults in the Arunta Block south of the Ngalia Basin are largely inferred from the aeromagnetic data (Figs 3 & 4). Two recrystallised, locally haematite-bearing, quartz veins (mapped as quartzite on the first edition map) represent the surface expression of the Gurner Fault and an eastern splay. The Gurner Fault is part of a south-southeast-trending fault zone more than 100 km long interpreted from the regional magnetic data. The linear trace of the Gurner Fault suggests that it is a strike-slip fault displacing an earlier sub-parallel fault that affects the Vaughan Springs Quartzite, hence is probably a Palaeozoic structure.

In summary, the thick zones of quartz complex veining appear to have had a long and complex history, pre-dating and coeval with Mount Doreen deformation, D_e. Present indications are that the majority of the veins formed during the Kerridy Movement.

Mount Eclipse Movement ***(~300-350 Ma)***

(including syn-depositional tectonism)

Basement Deformation

The *Doreen deformation*, D_{ex}, is defined as that causing the late-stage mylonitic shear zones that cut the big-feldspar Yarunganyi Granite, dated at 1570 Ma. Similar zones also cut the tabular feldspar granites, such as the Wakurpa Granite (*Pgsw*) at Rock Hill north of Yuendumu. These zones are very narrow — commonly being less than 100-200 m across — show S-C fabrics at their margins, contain retrograde greenschist assemblages such as chlorite-sericite-oligoclase-quartz±epidote, and display marked grainsize reduction (ie. some < 0.02 mm). As such these mylonites are very similar to the Type 2 mylonites, described by Shaw and Black (1991) from the Redbank Trust Zone, for which a 350-400 Ma age of mylonitisation is indicated. Thus, the Deformation D_{dx} mylonitic shear zones are likely to have formed during the Alice Springs Orogeny in the Late Devonian to Carboniferous.

A program of K-Ar, ^{40}Ar-^{39}Ar and/or Rb-Sr dating of these foliations is recommended to clarify the age of these late-stage mylonitic foliations (for details on the methods see Shaw et al. 1992a, c; Shaw & Black 1991).

Deformation of the Basin

The deformation of the Mount Eclipse Sandstone is the result of this movement (Wells & Moss, 1983). It occurred no earlier than Early Carboniferous (Visean ~ 330 Ma): the age of the youngest fossils recorded in the Mount Eclipse Sandstone (see data in Li et al. 1989). The peak of the Alice Springs Orogeny in the Amadeus Basin, established by several geochronological studies, was at around 300-320 Ma (e.g., Mortimer et al. 1987, Dunlap et al. 1991, Shaw et al. 1992). A similar age is likely for the peak of the Mount Eclipse Movement. Like the Kerridy Sandstone, the coarse molasse-like Mount Eclipse Sandstone was probably deposited during the early stages of thrusting.

Activity on the Yuendumu and Waite Creek thrusts (Figs 3 & 4) at this time led to major overthrusting of the Arunta basement southwards over the Ngalia Basin (e.g. Stewart 1982) and to associated folding of the adjacent Ngalia succession. The Mount Eclipse Sandstone is overturned in several partly fault-bounded segments at or near the northern margin of the Ngalia Basin. For example, at the Bigrlyi Prospect Camp and in the upper reaches of Twelve Mile Creek, overturned beds and numerous faults are evident that lie sub-parallel to bedding. Similarly, the Yuendumu Thrust steepens eastwards, and north of the Walbiri Ranges places basement over sedimentary cover (Fig. 3). The Vaughan Springs Syncline in VAUGHAN was formed during this movement.

Numerous small folds in the Kerridy Sandstone south of Yuendumu township may be related to one or more detachment zones at shallow depth, possibly a shale unit within the Kerridy Sandstone. These folds may date from either the *Kerridy Movement* or the later *Mount Eclipse Movement.* Similarly, packages of small folds account for stratigraphic repetition of the Treuer Member, at or near the base of the Vaughan Springs Quartzite in the Treuer Range at the northwest margin of the Ngalia Basin. The limited strike-length of these fold packages and their apparent confinement to this part of the basin margin suggest control by intraformational detachment zones and/or by structures of limited extent along the basement-cover contact. Small intraformational folds and numerous slickensides attest to the importance of the orthogonal nature of shortening. Nowhere along the northern margin of the basin was any evidence found for an early stage of strike-slip faulting. As with those present within the Kerridy Sandstone, it is not clear whether these small folds belong to the *Kerridy Movement* or the *Mount Eclipse Movement.*

The Yuendumu and Waite Creek thrusts (Fig. 4) are thought to form part of a large thrust complex which corresponds to a major geophysical boundary, evident in the gravity and aeromagnetic data, that may have been initiated during the earlier Wabudali tectonic event. This boundary could account for some of the differences in the tectonic history and geophysical character between the Arunta Block north of the Ngalia Basin and that to the south.

Basin Structure

(derived from seismic data)

Seismic surveys have revealed major thrust faults at the northern and northeastern margin of the basin (Wells et al. 1972). The results confirm that the basin is asymmetrically with the greatest depth of section preserved near the northern margin. From the southern margin the sediments dip gently northwards at attitudes of 5-10°. Some tight anticlines in the central part of the basin (Fig. 4) may be related to low-angle thrusts originating from a detachment zone in the lower part of the sedimentary succession (Moss & Jones 1974, p.150).

The seismic expression of the Waite Creek Fault is shown in Figures 9a and 9b for traverses J and K located in Fig. 10. (compare with Fig. 4, see Moss & Jones 1974, plate 43 and Wells & Moss 1983). The presence of discontinuous reflections separating a basement region of poor reflection from the sedimentary pile with strong reflections indicates a large-scale overthrust fault (Traverse J, Fig. 9a, see Moss & Jones, 1974). The thrust fault is confirmed by a similar seismic event on a cross traverse (Traverse K in Fig. 9b). The fault has an estimated dip of about 20° - 25°, a vertical displacement of about 5 km and a horizontal displacement of about 11.5 km. Reflection, shown in Figure 9, is identified as the Vaughan Spring Quartzite, which lies at a depth of about 4500 - 5200 m (1.75 s at shot point 3800, ~ 2.0 s at shot point 3776; Moss & Jones, 1974). Mount Doreen Formation is identified at about 2100 m (0.82 s at Shot Point 3800). A high-angle reverse fault, with a throw of 1200 m or more, is also identified in the seismic data in the western part of the Yuendumu Thrust (Traverse A; Moss & Jones, 1974). This fault is estimated to have a northerly dip of about 40° from the seismic section, but surface dips indicate a dip of about 80° along strike to the northeast (see Figs 3 & 4).

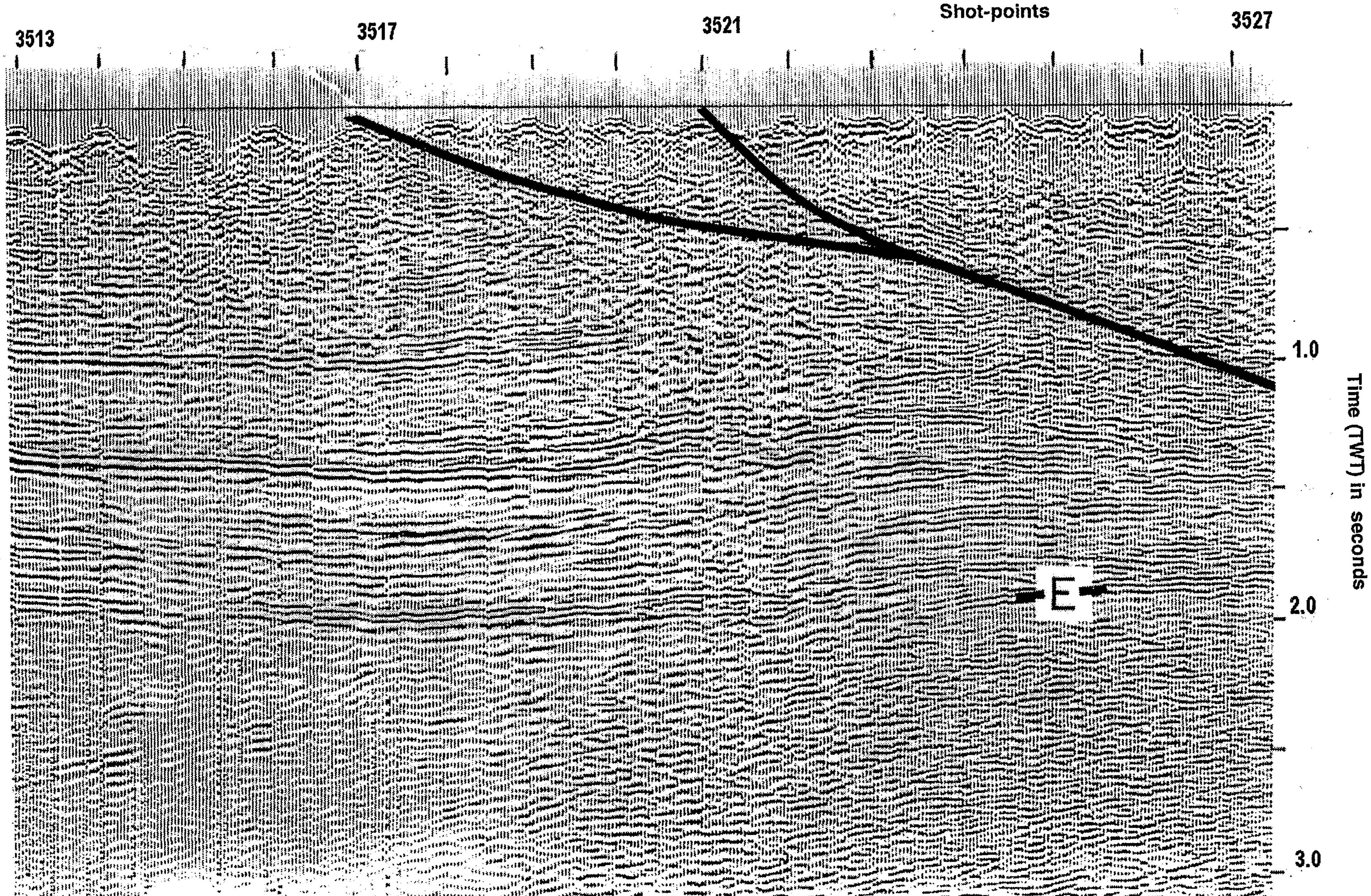

Figure 9a. Seismic sections across the Waite Creek Thrust. Traverse J
[view is from the northeast, located in Figure 10, after Moss & Jones 1974].

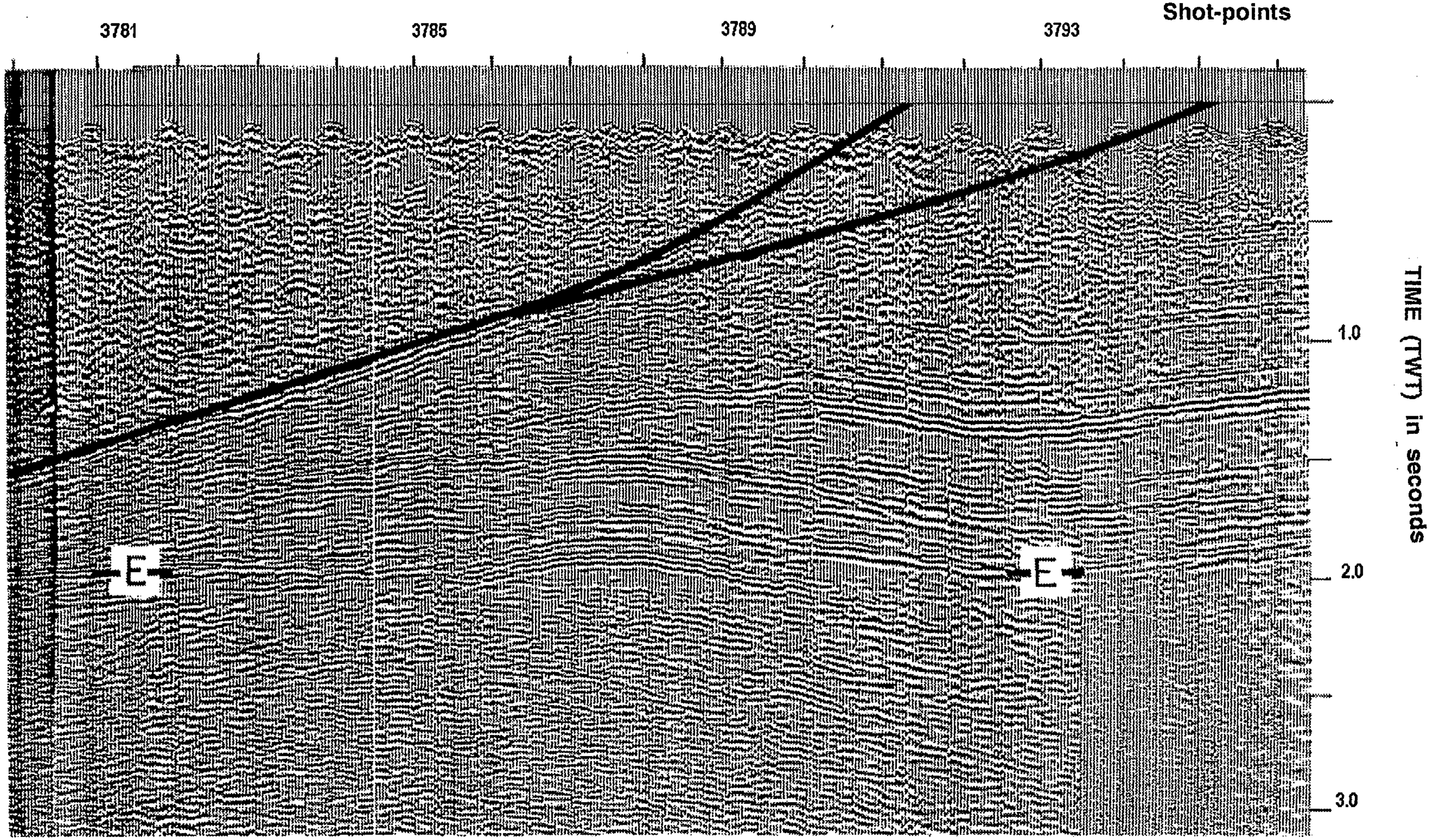

Figure 9b. Seismic sections across the Waite Creek Thrust. Traverse K [view is from the southwest]

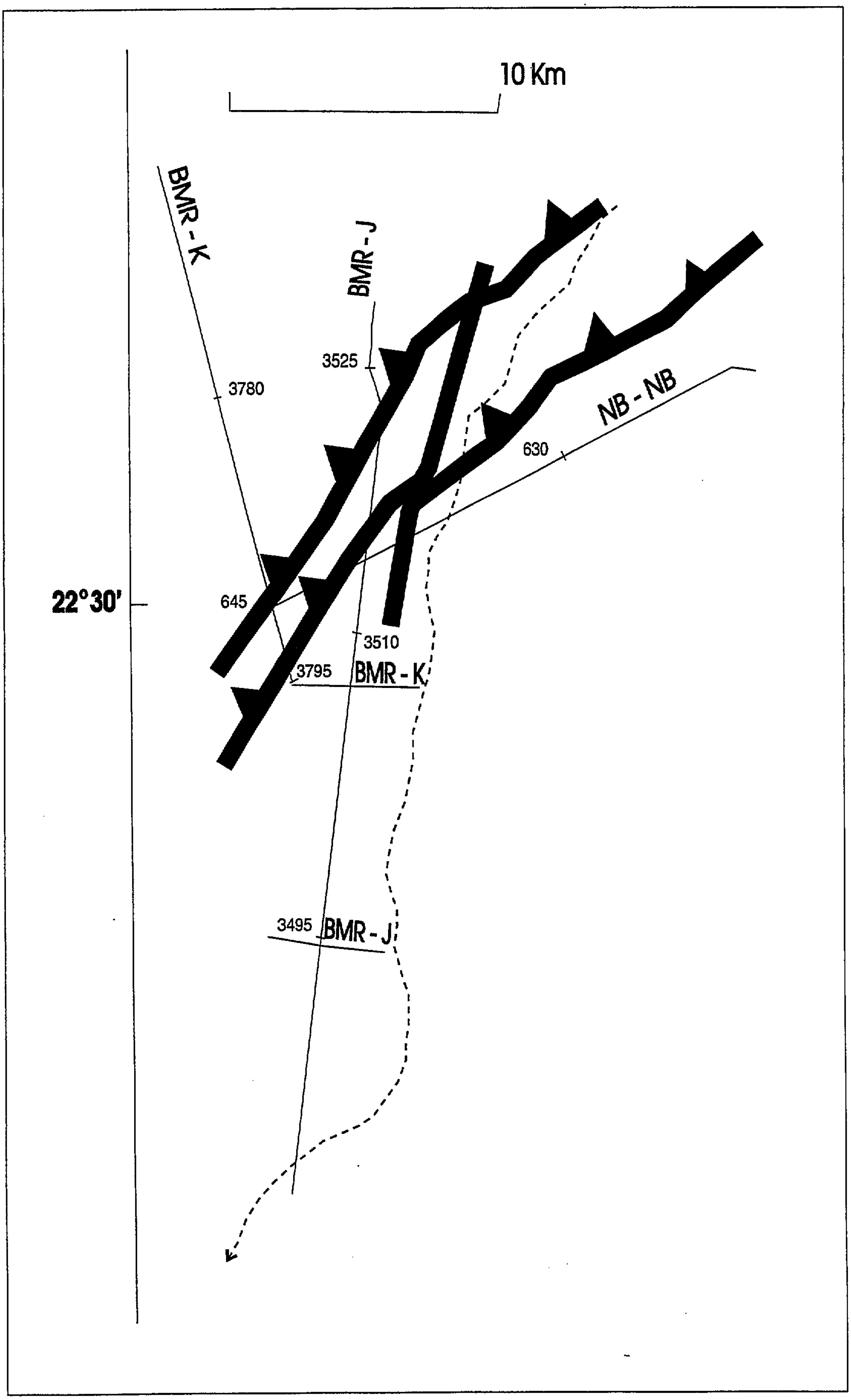

Figure 10. Location of seismic traverses (Figure 9a, b)

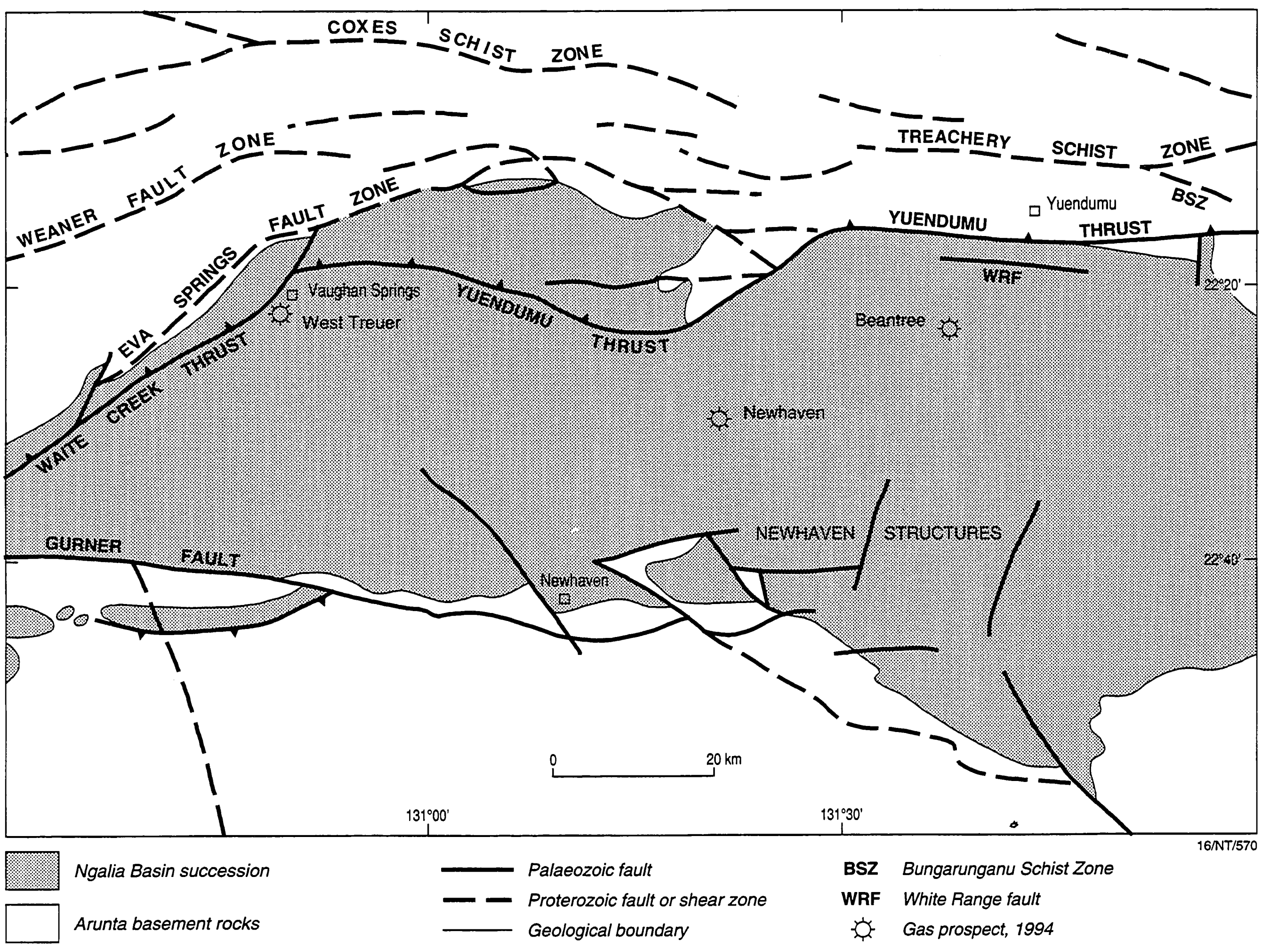

Figure 11. Palaeozoic faults, and Proterozoic faults and shears, Mount Doreen Sheet area

Tectonic Models

(for Palaeozoic Tectonism)

Outcrop patterns and interpretation of seismic data suggest that the *Mount Eclipse Movement* resulted from a series of disconnected, high-angle reverse faults involving basement (e.g., many of the Palaeozoic faults that are shown in Fig. 11). This structural style is well illustrated by the Yuendumu Thrust, which displaces Arunta basement at the southern end of the Walbiri escarpment at the Walbiri Prospect and has overturned the Mount Eclipse Sandstone on its downthrow-side east of the Escarpment. Variation in stratigraphic thicknesses of the Vaughan Springs Quartzite near the Walbiri Escarpment (Wells & Moss 1983, plate 2) suggest minor fault movement and tilting during or prior to Vaughan Springs Quartzite sedimentation such that the hanging-wall region remained a depositional high. However, during deposition of the Vaughan Springs Quartzite, the active reverse fault may have been the Walbiri Fault (basement fault south of the Wanapi Anticline) as the Vaughan Springs Quartzite was either never deposited or has since been removed from the nearby Djagamara Peak region to the north.

A thickening of the Ordovician Djagamara Formation in the Djagamara Peak region may be the consequence of syn-depositional sagging, possibly on the footwall side of a zone of reverse faulting north of the presently preserved margin of the basin. The east-striking Treuer fault zone at the northwest margin of the Ngalia Basin (Wells & Moss 1983) does not appear to have become active until much later, during the Mount Eclipse Movement in the Carboniferous. The Yuendumu and Waite Creek thrusts, the Treuer Fault Zone, and probably also the Weaner and Eva Spring fault zones were all active during the Alice Springs Orogeny (Wells & Moss 1983). All these thrusts displace the basement, and point to a 'thick-skinned' tectonic style. Evidence for displacements in excess of up to 10 km on these faults comes from seismic data (Wells & Moss 1983).

All these stratigraphic features can be explained by high-angle reverse faulting during deposition of the Ngalia Basin succession. The homoclinal upturn, leading to local overturning of the succession at the northern margin of the Basin, can also be explained by high-angle reverse faulting forming part of an imbricate-fan complex during the Mount Eclipse Movement. A similar upturn occurs at the northern margin of the Amadeus Basin (Shaw et al. 1991a). Since the Mount Eclipse Sandstone is involved, the upturning in the Ngalia Basin belongs to the *Mount Eclipse Movement*.

A pattern of closely spaced high-angle faults has been established by exploration drilling in the southeast of the Ngalia Basin (Saucier, pers. comm. p. 114 in Lambeck et al. 1988). This finding, together with the stratigraphic cut-offs and homocline development described above are consistent with the view that thick-skinned tectonics was widespread during the Alice Springs Orogeny in central Australia (Shaw et al. 1991a, compare with Teyssier 1985).

However, it should be emphasised that thin-skinned tectonic style is also an integral part of the regional deformation in central Australia (see Shaw et al. 1992b for discussion). In the Ngalia Basin, a minor amount of thin-skinned detachment may have taken place, possibly related to salt in the succession (presence suggested by efflorescence on siltstone exposures), in the Treuer Member of the Vaughan Springs Quartzite, near the base of the Ngalia Basin succession. Moss & Jones 1974) interpreted low-angle thrusts originating from a detachment zone near the base of the sedimentary succession from limited seismic evidence.

Thrusts of 'thin-skinned' style are also evident from seismic data within the basin. An example is a south-directed thrust that ramps from a decollement in the Treuer Member to surface on the southern limb of the Beantree Anticline (Deckleman & Davidson 1993, see Fig. 4). A similar thrust has been interpreted by the same authors within the Newhaven gas prospect. Folds with wavelengths of about 3 km on the northern margin of the basin may also be related to decollements within the Treuer Member. These include the Davis and Walbri Anticlines in the northwest and the Wanapi, Kerridi and Beantree Anticlines in the northeast (Fig. 4).

Tertiary Rejuvenation

From the end of the Alice Springs Orogeny to the Tertiary, the Mount Doreen region has been essentially stable part of the Australian craton. Rejuvenation in the Tertiary appears to have been localised along pre-existing faults and has produced much of the relief expressed in the present landscape. Senior et al. (1994, 1995) discuss Tertiary tectonism in their analysis of the Tertiary stratigraphy in the region to the east.

DISCUSSION OF ONGOING MAGNETIC INTERPRETATION

A major geophysical boundary, more evident in the magnetic data than the gravity data, separates the Arunta basement north of the Ngalia Basin from that underlying and south of the basin. This boundary roughly corresponds to a fault complex that includes the Yuendumu and Waite Creek Thrusts, as well as the Wearner Fault.

Intense magnetic anomalies in the Arunta Block south of the Ngalia Basin, where bedrock is largely concealed by surficial sediments, may be correlated in part with mafic to felsic granulites of the Narweitooma Metamorphic Complex exposed in the Hermannsburg Sheet area to the southeast (Warren & Shaw 1995). However, the Andrew Young Igneous Complex accounts for one of the most intense magnetic anomalies here, and some of the smaller intense anomalies correspond to outcropping tonalite, such as that at Oodnappinna waterhole, assigned to the Carrington Granitic Suite. Schists of low metamorphic grade, exposed south of the Siddley and Stuart Bluff ranges, and cordierite garnet gneiss, exposed west of Newhaven homestead, lie in a belt of low magnetic intensity (not highlighted in Figure 3).

Faults in the Arunta Block south of the Ngalia Basin are largely inferred from the aeromagnetic data (Figs 3 and 11). Two recrystallised, locally haematite-bearing, quartz veins (mapped as quartzite on the first edition map) represent the surface expression of the Gurner Fault and an eastern splay. The Gurner Fault is part of a south-southeast-trending fault zone more than 100 km long interpreted from the regional magnetic data. The linear trace of the Gurner Fault suggests that it is a strike-slip fault displacing an earlier sub-parallel fault that affects the Vaughan Springs Quartzite, hence it is probably a Palaeozoic structure. A major fault zone cutting the inferred granulite unit is indicated by a series of discontinuities in the magnetic data. The fault zone trends west of northwest and has en-echelon elements suggesting a component of transcurrent movement. It continues into the Mount Liebig Sheet area to the south and the Lake MacKay Sheet area to the west. As such, it represents one of the longest fault systems in the Arunta Block.

An outstanding problem for the basement geology to the south of the Ngalia Basin is the source of the marked magnetic anomalies there. In this region a thin unit of non-magnetic quartzose schist appears to overlie a magnetic unit inferred to be made up of felsic and mafic granulite (Fig. 3; compare with Table 6), as these rock types dominate the central province of the Arunta Block elsewhere (Stewart et al. 1984) and have a well documented strong magnetic response (Mutton & Shaw 1979, Mutton et al. 1983). For example, the Narweitooma Metamorphic Complex, exposed in the central province in the northern part of the Hermannsburg Sheet area, has a very similar magnetic response (Warren & Shaw 1995). A few small exposures of gneiss have been identified in GURNER during the current survey. Although the southern granulite unit is very poorly exposed, its aeromagnetic signature indicates that it dips shallowly northwards underneath the Ngalia Basin. Within the Hermannsburg Sheet area, these granulites (Table 6) had reached peak PT conditions of 8 ± 1 Kbars and 700-800°C and were folded and intruded by granite at about 1750-1760 Ma (Black & Shaw 1992). The age of their protoliths is unknown. The Andrew-Young magmatic complex in the southern part of the Napperby Sheet area includes strongly magnetic components and is expected to account for a minor part of these regionally extensive magnetic anomalies. The quartzose schist unit exposed south of Mount Stanley (or Kattku, Fig. 2, east of Waite Creek Settlement or Nyirrpi) in the southwest of the Mount Doreen Sheet area appears, from the magnetic data, to overlie the largely inferred magnetic granulite and gneiss unit. Although it might represent distal turbiditic equivalents of the Reynolds Range Group, as suggested by Stewart et al. (1984), it lithologically more closely resembles the Lander

Rock beds. If the Lander Rock beds did overlie the Narweitooma Metamorphic Complex and are themselves older than the 1880 Ma Ngadarunga Granite, then the magnetic interpretation implies that the Narweitooma Metamorphic Complex, or a component of this metamorphic complex, may represent one of the oldest elements in the Arunta Block (compare with prediction in Shaw et al. 1984, Fig. 32h).

Interpretation of magnetic and spectrometric data is continuing at the Northern Territory Geological Survey.

CONCLUSIONS

Arunta Block Tectonism

Correlations of deformational events in the Mount Doreen Sheet area with those recognised elsewhere in the Arunta Block and with events in the surrounding tectonic provinces are summarised in Tables 5 and 6. These correlations are the subject of continuing debate.

A early phase of tight to isoclinal folds, with axial plane, slaty cleavage is assigned to *the Wolfram tectonic phase* of the *Yuendumu Tectonic Event*. It may result from an episode of thrusting and crustal shortening — formed during one or more events. A series of migmatitic gneiss bodies can be traced discontinuously westwards from the northeast of the Mount Doreen Sheet area and may represent either basement or higher-grade and higher strain equivalents of the Lander Rock beds.

The *migmatitic phase of the Yuendumu Event*, represented by deformation sequence D_{b1-4}, in the migmatitic gneiss may have closely followed the *Wolfram tectonic phase* (folding D_{a1-2}) in the Lander Rock beds, and be part of the same progressive deformation. Isotopic dating (Young et al. 1995) suggests that this progressive deformation peaked shortly before intrusion of the (garnet)-cordierite granite at about 1880 Ma. This intrusion represents the *Ngadarunga magmatic phase*. The term *Yuendumu Event* is applied to migmatisations and deformations (D_{b1-4}) preceding granite intrusion and possibly extends to deformations D_{a1-2}. As such, it may correlate with the earliest stages of the broadly defined 1850-1890 Ma *Barramundi Orogeny* (Table 6).

Although there appears to be a general continuum from low to high-grade metamorphism within the Lander Rocks beds, abrupt changes in metamorphism commonly take place at faults, and it cannot be shown conclusively that all rocks assigned to the Lander Rock beds have been through the same tectonic events: some rocks may be either older or younger, by an orogenic event, than others. Assemblages in the pelitic rocks progress from muscovite-chlorite, through biotite-muscovite-andalusite and cordierite-andalusite-potassium feldspar-biotite, to sillimanite-cordierite-garnet-biotite.

The period 1930 to 1770 Ma saw the widespread development of intracratonic basins in rift settings, probably in several phases (compare with Table 6). The basalts in the Pine Hill Formation of the Reynolds Range Group [recorded in the Wabudali Range by Blake (1993)] records the first of these rift-related phases. Felsic volcanism in the 1800 Ma Patmungala beds and the 1770 Ma Nicker beds record additional phases.

The *Hardy tectonic phase* that produced a mica foliation in the ~ 1780 Ma Carrington Granitic Suite could correlate with the early stages of the 1780-1760 Ma *Strangways Orogeny* recognised in the Central Tectonic Province of the Arunta Block to the south (Shaw et al. 1984, Collins & Shaw 1995). The newly acquired date of 1779 ± 6 Ma for the Carrington Granitic Suite (Young et al. 1995) is consistent with this interpretation. However, the schistose fabrics that cut the dated granite formed under low amphibolite facies conditions and is cut by high-strain zones similar to those that cut the Reynolds Range Group. Thus, the

Hardy tectonic phase may be a precursory to the *Wabudali tectonic phase*, both events occurring at a similar grade of metamorphism.

The tight, boat-like isoclinal synclines outlined by the Reynolds Range Group are considered to belong to the subsequent *Wabudali tectonic phase*. They are accompanied by a strong cleavage of similar style to the late schistose fabrics developed in the Carrington Granitic Suite outcropping near Carrington Bore. The formation of the strong foliation and the synclines predates the older tabular feldspar granites such as the tabular-feldspar Wabudali Granite and the big-feldspar Yarunganyi Granite. The overturned southern limbs of these synclines may represent the footwall keels to north-directed zones of reverse faulting. A high-strain zone of the *Wabudali tectonic phase* cuts a micaceous foliation of the *Hardy tectonic phase* near Mount Hardy. High-strain zones (D_c), which show evidence of outlasting the D_{c1-3} folding phases, characterised this event. A minimum age for D_c high-strain zones of the *Wabudali tectonic phase*, as well as the *Jubilee deformation* cutting some post-tectonic granites, is set by the 1567 ± 6 Ma age for the voluminous big-feldspar Yarunganyi Granite (Young et al. 1995a). The lithologically similar, but less megacrystic, tabular - feldspar Southwark Granite may well have been intruded at about the same time.

Although the tabular-feldspar Wabudali Granite may also be of a similar age to the 1570 Ma Yarunganyi Granite, it could be equivalent to the megacrystic granites typical of the *Strangways Orogeny*, such as the 1780 Ma Napperby Granite (Collins & Williams 1995, compare with Collins & Shaw 1995). In this alternative scenario, the high-strain D_{c1-2} zones could correlate with the *Weldon Event* recognised in the Anmatjira-Reynolds Range, based on a similarity in style between the corresponding structural elements in the two regions (Collins & Shaw 1995, see also Tables 4, 5, 6). For example, folding during the *Wabudali tectonic phase* (D_c) is similar in style and orientation to the upright FII_2 folds in the Reynolds Range (Dirks & Wilson 1990) and the F_{2d} folds of the Anmatjira Range (Table 5; Collins et al. 1991). The *Hardy tectonic phase* could be an early manifestation of the same tectonism. The *Weldon Event* is correlated, in turn, with what was previously known as the Strangways Event in the Central Province of the Arunta Block (Table 6) and both events are now grouped in the *Strangways Orogeny* (Collins and Shaw 1993).

A more likely contender for correlation with deformation the *Wabudali tectonic phase* (D_c) is the thrusting and high-strain accompanying the *Chewings Orogeny* in the southern province of the Arunta Block (Warren & Shaw 1995). However, there is little direct evidence that the *Chewing Orogeny* affected the northern province of the Arunta Block, apart from pegmatite dykes in the Anmatjira-Reynolds range region (Collins et al. 1993) and localised new growth of zircon in granite (Collins & Williams 1995).

Granite of the Andrew Young Hills (norite - tonalite) igneous complex was emplaced earlier, at 1635 ± 9 Ma (Young et al. 1995) within what appears to be a separate tectonic element to the south of the Ngalia Basin.

The weak and diffuse foliation, outlined by fine-grained biotite assigned to *Jubilee deformation*, D_d, cuts the tabular feldspar granites, but in its reference area does not continue into the adjacent Yarunganyi Granite. So, it is probably younger than the 1780 Ma Carrington Granite suite and is most likely older than the ~1570 Ma Yarunganyi Granite.

The main period of exhumation and erosion that followed emplacement of the Southwark Granitic Suite could correlate with the *Anmatjira Uplift*, a period of major faulting at 1400 - 1500 Ma recognised elsewhere in the Arunta Block. Some of the quartz-filled faults in the basement north of the basin could have formed during this period. At 1400 - 1500 Ma thrusting occurred across the Redbank Thrust Zone separating the Central and Southern Provinces of the Arunta Block (Shaw et al. 1992a, Collins & Shaw 1995). Faulting of this age is also recognised in the Anmatjira Range in the Napperby Sheet area (Black et al. 1983). Locally developed foliations of similar style to foliations of the *Jubilee deformation* that cut the tabular-feldspar and coarsely porphyritic granites could also belong to the *Anmatjira Uplift*.

Ngalia Basin Tectonism

Ten tectonic episodes affected the Neoproterozoic to Palaeozoic Ngalia Basin along with the surrounding region, including the Georgina and Amadeus Basins. Except for the main event that invented the basin, the only tectonism to produce structures in the basin was minor broad open folding and some faulting that is correlated with the Petermann Ranges Orogeny in the Amadeus Basin.

The main structures evident in the basin were produced in two or more episodes during the Late Devonian to mid-Carboniferous Alice Springs Orogeny (Fig. 11). The proposition that mild basement uplift heralded the *Kerridy Movement* is consistent with the somewhat immature composition of the Kerridy Sandstone. This movement apparently involved reverse faulting, tilting, mild folding, followed by erosion — for the most part concentrated at the northern basin margin. The quartz-filled faulting, which are widespread in the basement, may belong to this movement. In this case, the pattern of faulting suggest transpressional tectonism. The magnitude and extent of the movement suggests this movement correlates with one of the Late Devonian phases of the *Alice Springs Orogeny* in the Amadeus Basin, possibly the Pertnjara Movement. The main phase of thrusting and thrust-related folding that inverted the basin was during the *Mount Eclipse Movement* of the *Alice Springs Orogeny*, which peaked in the Late Carboniferous.

For the most part, Palaeozoic tectonism in and around the Ngalia Basin is characterised by both widely spaced, low-angle thrust faults and high-angle reverse faults. Most of these faults cut basement and are not obviously linked by flat detachment zones. These features are consistent with the view that thick-skinned tectonics dominated. However, detachment zones are recognised in seismic section (Deckelman & Davidson 1993). Also a minor amount of slip on minor sub-horizontal decollements, representing thin-skinned detachment, is recognised near the base of the succession, possibly localised by suspected salt in the Treuer Member of the Vaughan Springs Quartzite.

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Table 1a. Deformation groupings: Da, Db, Dc, Dd, De

Composite scheme for labelling deformational groupings according to the stratigraphic unit and/or granite suite affected.

Deformation Grouping	Deformational Features	Stratigraphic Unit Affected	Deformation in Granite	Granite Suite Affected	Granite Relations
D_e	Narrow greenschist shears		D_{ex}		
				Coarsely porphyritic granite[1], and some tabular - feldspar granites[2]	Intrude Reynolds Ra. Gp, only deformed by D_{ex} shears
		Quiescent Tectonism			
D_d	Weak & diffusive, but pervasive fine biotite foliation		D_{dx}		
				Tabular-feldspar granites[2]	Intrude Reynolds Ra. Gp, deformed by D_{dx} diffuse foliation/ weakly metamorphosed

Deformation Grouping	Deformational Features	Stratigraphic Unit Affected	Deformation in Granite	Granite Suite Affected	Granite Relations
			Quiescent Tectonism		
D_c	Wide, co-axial, high strain zones	Reynolds Range Group	D_{cx}		
				Xenolithic and gneissic granites[3]	Intrude Lander Rock beds, granites post-tectonic with no regional foliation, cut by D_c high strain zones in places, some associated with migmatite units
			Unconformity		
D_b	Pervasive high- grade foliation or granoblastic fabric	Migmatitic units (arguably part of Lander Rk beds)			
			D_{bx}	Granular garnet-cordierite granite[4]	Intrudes migmatitic units
D_a	Regional slaty cleavage	Lander Rock beds (non-migmatitic)			

TABLE 1a (Continued) TECTONIC GROUPING OF GRANITES

1 Coarsely porphyritic granite, minor fine-grained granite; mainly from Southwark Granite Suite, *pgs* (e.g. 1567 ± 6 Ma Yarunganyi Granite, – previously 'Mt Doreen Granite', Southwark Granite on VAUGHAN and some tabular feldspar granites (e.g. undivided *pgs* from Moyles Bore area, Wabudali Granite).

2 Tabular-feldspar granites, some muscovite- and biotite-bearing granites, Post - D_c, Pre - D_d (e.g., Yalgoogarie Granite, pgs rapakivi granite, Wakurpa Granite', Ethel Creek Granite).

3 Xenolithic and gneissic granites, Pre - D_c (e.g. ~ 1780 Ma Carrington Granitic Suite, including Burger Creek Granite phase; Yulyupunyu Granitic Gneiss, Meercantie phase of *pgs* (above), Yumurrpa Granophyre, *pgm*, on MOUNT THEO).

4 Unfoliated, ?recrystallised granite, late D_b, post-tectonic (e.g., ~ 1880 Ma Ngadarunga Granite).

TABLE 1b MAPPED GRANITE ASSOCIATIONS

Southwark Granitic Suite *pgs* (~1570 Ma) VAUGHAN, DOREEN (including Burger Creek and Moyles Bore phases)

Ethel Creek Granite *pgse* Ethel Creek, VAUGHAN

Yarunganyi granite *pgsy* Mount Doreen, DOREEN

Wakurpa Granite pgsw Rock Hill, YUENDUMU

Other tabular-feldspar granites

Wabudali Granite *pgw* Wabudali Range, VAUGHAN

Yaloogarrie Granite *pgy* Silver King region, DOREEN

Carrington Granite Suite *pgc* (~1780 Ma) Carrington Bore region including Meercantie Creek phase, DOREEN; SE Mount Hardy, YUENDUMU

Yulyupunyu Granitic Gneiss *pgl* ?Related to Napperby Gneiss, NE YUENDUMU

Other gneissic granites

Yumurrpa Granophyre *pgm* Wabudali Range, MOUNT THEO

Nagadarunga Granite *pgn* (~1880 Ma) Yuendumu, NW YUENDUMU

Table 2. Summary of the structural elements that compose the five deformational groupings D_a, D_b, D_c, D_d, D_e (see Table 1).

Grouping	Phase of Folding	Foliation	Folding	Faulting	Comment
D_e		Asymmetric, mylonitic, phyllonitic, local extension shear	Intrafolial, affects quartz veins	NW-SE steeply N-dipping shears	Shear zones, top-to - S movement, crystallisation of fine biotite and/or chlorite and white mica
D_d		Penetrative, weak, steep fine biotite foliation, locally anastomosing			
D_{c3}	F_{c3}	Rare, steep foliation	N-S & NE-SW, Mesoscopic kinks, regional warping, conjugate crenulations	Some parallel to axial plane of kinks	
D_{c2}	F_{c2}	Local crenulation cleavage	Upright, tight micro folds, coaxial with Fa_1 in Wabudali Range		Deformed early andalusite, biotite growth in crenulated regions
D_{c*}, D_{cx}		Two-mica	Variable foliation trends.	Not recognised	Cut by D_{c1}, in 1780 Ma granite

Table 2. (Continued)

Grouping	Phase of Folding	Foliation	Folding	Faulting	Comment
D_{c1}	F_{c1}	High strain foln. in zones along overturned S limb of synclines, fabric generally symmetrical, rare S-C	E-W tight, upright, gentle plunges	S limb of faulted syncline SE Mt. Hardy	Oriented andalusite porphyroblasts
$D_{b5'}$	$F_{b5'}$	Pervasive, micaceous schistosity	ENE open, upright		Retrograde metamorphism, mid-amphibolite facies conditions
D_{b4}	F_{b4}		Local kink folds		Post peak prograde conditions
D_{b3}	F_{b3}	Mobilisate along axial planar fractures	Mesoscopic, shallowly plunging, open, upright crenulation-like folds, some kink folds		Peak prograde granulite facies conditions
D_{b2}	F_{b2}	Weak to absent, axial planar, metamorphic differentiation locally	Mesoscopic, intrafolial, reclined, tight, locally polyclinal	Microshearing	Prograde metamorphism

Table 2. (Continued)

Grouping	Phase of Folding	Foliation	Folding	Faulting	Comment
D_{b1}	F_{b1}	Transposed, migmatitic layering			Pervasive, high-strain fabric
D_{a3}	F_{ba}	Patchy, sub-vertical crenulation cleavage	E-W kinks up to 0.5 km across	S limb of syncline faulted SE of Mt. Hardy	Oriented andalusite porphyroblasts
D_{a2}	F_{a2}	Penetrative, sub-vertical crenulation cleavage	NE-SW to N-S, tight, upright isoclines and kink-like folds		Dominant in C & E
D_{a1}	F_{a1}	Penetrative, axial-planar sub-vertical slaty cleavage	E-W in W, N to NW in C & E, tight, upright isoclinal, steep plunges		Dominant in W, Early and late andalusite porphyroblasts formed

Table 3. Early (F_{1a}) folds in Lander Rock beds

Location	Lat. (S)	Long. (E)	Trace of axial plane	Plunge	Comment
South of Wabudali Range (S91, S92†)	22° 00.81'	130° 43.70'	75N105 75N105	75 to 100 57 to 50	Cleavage strongly refracted by bedding
South of Ethel Creek,30 km WSW of Vaughan Springs (S73A, S77)	22° 18.77'	130° 34.33'	77S97 trend 110° 85S75 63S107 82S86	62 to 200 65 to 260	Localised, tight associated with qtz veining
3.5 km SSE Ginty's Bore (S19, S20, Y202)	22° 4.80'	131°3 0.05'	trend 315°	65 to 16° 40° to 05°	
2 km SW Wolfram Hill (S15, S11)	22° 4.3.72'	131° 18.52'	trend 340°	65 to 355	
ENE Silver Jubilee Mine (S190)	22° 6.21'	131° 18.22'	trend NW	Steep to N	

† S92 is the geological site equivalent of the AGSO registered number 91114092, Y202 is an NTGS number equivalent to 99112202

Table 4. Outline of tectonic history for the Mount Doreen region

Orogeny Event (Based on correlations)	Movement, Tectonic phase	Age (Ma) (inferred)	Characteristic(s)	Reference Feature (locality)	Deformation Element, Hiatus	Key References
ALICE SPRINGS OROGENY	Mount Eclipse Movement (Doreen deformation)	300-350	Thrusts	Yuendumu & Waite Creek Thrusts (seismic sections J & K)	D_{ex}	Wells & Moss (1983), Shaw et al (1992a)
as above	Kerridy Movement	350-400	Quartz-filled faults	White Point Fault (White Point)		Wells & Moss (1983), Shaw et al. (1992a)
PETERMANN RANGES OROGENY	Rinkabeena Movement	530-550	Dextral shear	Faulting, Newhaven gas prospect (seismic sections)	Unconformity at base Yuendumu Sandstone	Deckleman & Davidson (1993); age from Maboko et al. (1992)
Uplift Anmatjira Uplift ~1450 Ma	Exhumation, (?Jubilee deformation)	> 1000-800 Greatest at ?1400-1500	Main exhumation biotite foliation, pegmatites	Foliation in Yalgoogarrie Granite (E of Jubilee Silver King)		This report, Shaw & Black (1991)
	Southwark magmatism	1570	Tabular-feldspar granites	Yarunganyi Granite (at Mount Doreen)		Young et al. (1995), Blake (1993)

Orogeny Event Correlation(s)	Movement, Tectonic phase	Age (Ma) (inferred)	Characteristic(s)	Reference Feature (locality)	Deformation Element, Hiatus	Key References
CHEWINGS OROGENY ~1600 Ma	Wabudali phase (? Jubilee deformation.)	<1780, >1570	Linear high-strain zones	Wabudali & Coxes Schist zones (S of Wabudali Range)	Dc1-3 ?Ddx,	Young et al. (1995), Warren & Shaw (1994)
as above	Hardy phase	<1780, >1570	Mica foliation of variable trend	Foliated Carrington Granite Suite (SE Mount Hardy)	Dc*	Young et al. (1995), this report
STRANGWAYS OROGENY (early)	Carrington magmatism	~1780	Granodiorite-tonalite, gneissic, migmatitic, xenolithic	Carrington Granitic Suite (SE Mt Hardy)	?Dbx	Young et al. (1995), Blake (1993)
YUENDUMU TECTONIC EVENT [Barramundi Orogeny]	Migmatitic phase	1880	Migmatitic	Migmatites surrounding Ngadarunga Granite (NW Yuendumu)	Db1-4, Dbx	Young et al. (1995), this report
as above	Wolfram phase	≥1880	Regional slaty cleavage	(Wolfram Hill)	Da1-2	Young et al. (1995), this report

Table 5. Correlation of tectonic events in basement

(with those in the Mt Stafford, Anmatjira Range and Reynolds Range regions of the Napperby 1:250 000 Sheet area).

AGE *Ma* approx.	MOUNT DOREEN REGION	MOUNT STAFFORD REGION	MOUNT WELDON REGION (incl. Reynolds Range)	REYNOLDS RANGE REGION	REGIONAL EVENTS - *Northern Arunta Province*
References:	This Report	Clarke et al. (1990); Collins et al. (1991)	Clarke et al. (1990); Collins et al. (1991)	Dirks & Wilson (1990)	Collins & Shaw (1995)
300-400	Doreen deformation D_{e}. D_{ex}			Steep DIII shears, MIII Minor folds	*Alice Springs Orogeny*
? ≤1400-1500	Regional exhunation		Shearing [Anmatjira Event of Shaw et al. (1994)]		Anmatjira Uplift
±1570	Southwark magmatism tabular-feldspar granite				
? 1600	Jubilee deformation D_d [§] D_{dx}				
?1600	Wabudali tectonic phase, high-strain zones	Pegmatite emplacement hydrothermal fluxing Upright, SE-trending F_4 folds	Kyanite-bearing pegmatite at ~1600 Ma[#]		? Chewings Orogeny
?1660	Dc1-3 boat-like folding				[? Chewings Orogeny this report]
≥1600 ?1650	Hardy tectonic phase? Migmatised shears in Gneissic Granite		Remelting of Napperby Gneiss ?1650 Ma	Rehydration (kyanite stage at 1660 Ma)[¥] DII_4 regional NW & WNW shears,	Argilke Event[1] (Southern Arunta Province)
? 1730 Ma			Rapid decompression F_3 folds with recumbent foliation	DII_3 FII_3 late upright folds and local conjugates	

Table 5 (continued)

AGE Ma	MOUNT DOREEN REGION	MOUNT STAFFORD REGION	MOUNT WELDON REGION	REYNOLDS RANGE REGION	REGIONAL EVENTS
?1740 or younger	[Hardy tectonic phase of Young et al. (1995)]		Waning D_2, M_2; equivalent to D_3, M_3 inferrred to occur at ~ 1730 Ma by Clarke & Powell , 1991) Open to tight folds F_{2d} of Collins et al. (1991)	Dominated by NW-trending tight, upright FII_2 folds; strong, slaty axial planar cleavage $D1I_{1-2}$, MII peaked during DII_2	***?Late Weldon Event,*** *part of Strangways Orogeny*
?1740-1770	[as above] ?Db5'		Peak D_2, M_2 Shears folded by $F_{2c:}F_{2b}$ SW-directed folds, W-SW directed shearing (M_2 peak)		***Weldon Event,*** *part of Strangways Orogeny*
1770	Deposition of Nicker beds				
1780	Carrington magmatism		Pre- & syn- tectonic granitioids 1775-1780 Ma† F_{2a} folds rare	Intrusion of granites (e.g. Napperby Gneiss at ~1780 Ma†)	***Early Weldon Event,*** *part of Strangways Orogeny*
1880	Deposition of Patmungala beds				
~1820-1800	Deposition of Reynolds Ra. Gp		Deposition of Reynolds Ra. Gp	Deposition of Reynolds Ra. Gp	

Table 5 (continued)

AGE Ma	MOUNT DOREEN REGION	MOUNT STAFFORD REGION	MOUNT WELDON REGION	REYNOLDS RANGE REGION	*REGIONAL EVENTS -*
≥1820	? Metamorphism to produce some cordierite gneisses	Widespread F_{1c} open to isoclinal, upright folds in low grade rocks; post-thermal peak	D_1, HTLP M_1 ς F_{1c} W-verging, recumbent fold F_{1b} NE-verging upright to reclined folds	DI, HTLP MI (NW end Range nr Mt Stafford), N - trending, upright, chevron folds; with slaty cleavage	*Mount Stafford Event*
		D1, M1; Intrusion of megacrystic Mt Stafford and Anmatjira granites ³ 1820 Ma† $F_{1a\text{-}1b}$ metre-scale, reclined to recumbent folds in highest grade zones			*as above*
≥?1880	Intrusion of Ngadurunga Granite at c. 1880 Ma*, Db folding & migmatisation, Wolfram tectonic phase $Da_{1\text{-}2}$ slaty cleavage				*Yuendumu Event*
?>1880			Deposition of Lander Rk bds		

Table 5 (continued)

Notes: [f] An age of 1760 Ma is implied for this event by Collins et al. (1991), and Collins & Vernon (1991) whereas Clarke et al. (1990, fig. 8) suggest that the Reynolds Range Group post-dates a 1770 Ma granitoid basement, and place the subsequent granulite metamorphism at c. 1730 Ma.

[§] D_d may correlate with the 1400-1500 Ma Anmatjira Event of Shaw et al. (1984) and Shaw & Black (1991)

[*] Ages from Young et al., 1995b

[†] Ages of Collins in Collins & Shaw (1995)

[¥] Dirks & Hand (1991)

[¢] Correlates with Hatches Creek Group (Blake & Page, 1988; Dirks, 1990)

[#] Collins & S.E. Shaw, unpublished data in Collins & Shaw (1995)

[ς] Vernon et al. (1990)

[1] Warren and Shaw. (1995)

Table 6. Stratigraphic correlation chart for the Proterozoic of the Arunta Block and nearby regions.

AGE Ma	THE GRANITES-TANAMI REGION	ARUNTA BLOCK (Mt Doreen Napperby & Hermannsburg regions)	TENNANT CK INLIER Davenport Province	TENNANT CK INLIER Tennant Ck Province	McARTHUR BASIN/ PINE CREEK INLIER	EAST KIMBERLEY	MOUNT ISA INLIER
1500		Anmatjira Uplift Phase (1400-1500 Ma)					
1530	BIRRINDUDU GROUP				Nathan Group	?Mount Parker Sandstone ?Bungle Bungle Dolomite	Upper 'McNambra Group'
1570		Southwark granites 1570 Ma*					Isan Orogeny D2 ~1532 Ma
1600		Warbudali tectonic phase, ?Chewings Orogeny 1600 Ma			Hiatus		Isan Orogeny D1 ~?1600-1620 Ma*
1650		Andrew Young Magmatism 1635 Ma*			McArthur Group, Tufts: 1640 Ma*		Mount Isa Group (cover sequence 3)
1710		Argilke Tectonic Event 1660-1680 Ma	Granite Intrusion	Granite Intrusion (poss. Warrego Granite)			Granite Intrusion; e.g., Sybella Batholith 1655-1660 Ma

AGE Ma	THE GRANITES-TANAMI REGION	ARUNTA BLOCK (Mt Doreen Napperby & Hermannsburg regions)	TENNANT CK INLIER Davenport Province	TENNANT CK INLIER Tennant Ck Province	McARTHUR BASIN/ PINE CREEK INLIER	EAST KIMBERLEY	MOUNT ISA INLIER
1750	Granite 1720 Ma		Hanlan Subgroup	Tomkinson Creek Subgroup	Tawallah Group top is 1710 Ma		Mount Albert Group (cover sequence 2-sag)
1760	Granites	Peak of Strangways Orogeny 1750-1760					
1770		Tuffs in Nicker beds 1770 Ma	Wauchope Subgroup				Haslingden Group (cover sequence 2-rift)
1790	The Granites Granite 1790 Ma	Carrington granites 1780*	as above			Taylors Lookout Granite (in south 1788)	as above
1810	Nanny Goat Creek beds 1800 Ma	Tuffs in Patmungala beds 1800 Ma* Reynolds Range Group (mega-assemblages)	Wauchope Subgroup	Timing of gold mineralisation †		Hart Dolerite 1800 Ma	
			Ooradidgee Subgroup (tuffs)				
1820	Winnecke Granophyre	Harverson & Mount Stafford granites 1820 Ma				Granites 1820 Ma	

Table 6. (Continued)

AGE Ma	THE GRANITES-TANAMI REGION	ARUNTA BLOCK (Mt Doreen Napperby & Hermannsburg regions)	TENNANT CK INLIER Davenport Province	TENNANT CK INLIER Tennant Ck Province	McARTHUR BASIN/ PINE CREEK INLIER	EAST KIMBERLEY	MOUNT ISA INLIER
1845	Mount Winnecke Formation			Flynn Group 1830-1845 Ma (include. Bernborough Formation)	Edith River Group 1830 Ma	Kimberley Group. Valentine Siltstone ~1835 Ma; Koongie Park sequence 1840-45 Ma	
1850		Stafford Tectonic Event ~1820-1850 Ma	Hill of Leeders Granite ~1850 Ma	Cabbage Gum and Tennant Creek granites 1850 Ma*		Orogeny in Kimberley Regions 'Bow' granites 1850-1865 Ma* Metamorphism 1850 Ma; McIntosh Gabbro Woodword Dolerite	
				Warramunga Formation ~1860 Ma*	Scrutton Volcs 1850 Ma* El Sherana Group	Olypio Formation 1855-1870 Ma	Kalkadoon Batholith 1860 Ma, Leichardt Volcanics 1865 Ma
		Yuendumu Tectonic Event: Ngadarunga Granite 1880 Ma, migmatitic phase			Barrimundi Orogeny 1870 Ma		Barrimundi Orogeny 1870-1900 Ma

Table 6. (Continued)

AGE Ma	THE GRANITES-TANAMI REGION	ARUNTA BLOCK (Mt Doreen Napperby & Hermannsburg regions)	TENNANT CK INLIER Davenport Province	TENNANT CK INLIER Tennant Ck Province	McARTHUR BASIN/ PINE CREEK INLIER	EAST KIMBERLEY	MOUNT ISA INLIER
≥1880	Tanami Complex	Lander Rock beds (mega-assemblage 2) >1880 Ma Narweitooma Metamorphic Complex a (mega-assemblage 1) »1750 Ma <2100 Ma			Bradshaw Complex 1870 Ma*, South Alligator Group ~1885 Ma	Biscay Formation, Saunders Creek Formation Ding Dong Downs Volcanics 1900 Ma	Yaringa Metamorphics, Murphy Metamorphics

Table 6. (Continued)

<u>Geochronological References: General: Blake et al. 1987; age listed are approximate.</u>

The Granites-Tanami: - Page et al. (1976); Blake et al. (1979, 1987).

Arunta Block:- Black et al. (1983); Black & Shaw (1992); Collins et al. (1989); Clarke et al. (1990); ages marked * are from Young et al. (1995b); Collins & Shaw (1995).

Tennant Ck Inlier: Black (1984); Blake et al. (1979, 1987); Blake & Page (1988), ages marked * are in Compston (1995); those marked † are Rb-Sr ages of Black (1977).

Pine Creek Inlier McArthur Basin:- Needham et al. (1988); cf. Page & Williams (1988) who place El Sherana Gp at ~ 1890 Ma ages marked * are from Page & Sweet (1993).

East Kimberley - Barramundi Orogeny: Hancock & Rutland, 1984; Page & Hancock (1988), Page (1988), Page & Williams (1988), Page in Blake (1991b) suggests orogeny younger than trachytic volcanics at ~ 1870 Ma ages marked in Page & Sun (1994).

Mount Isa Inlier - Wyborn et al. (1988); Blake & Page (1988); Black & Stewart (1992); ages marked * are from Connors & Page (1995).

<u>Notes</u>: based on the following correlations and relationships:

1. Mega-assemblage 3 with Hatches Creek Group (Stewart et al .1984).

2. Hatches Creek Group with Supple Downs Sandstone, Pargee Sandstone and Mount Winnecke Formation (Page et al. 1976; Blake et al. 1979, 1987).

3. The Hatches Creek Group unconformably overlies the main part of the Warramunga Group (Blake et al. 1987).

4. Mega-assemblage 2 with Warramunga Group (Stewart et al.1984).

5. Assemblage 1 represents the Narweitooma Metamorphic Complex (Warren & Shaw 1995).