COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

BULLETIN 100

GEOLOGY OF THE AMADEUS BASIN, CENTRAL AUSTRALIA

BY

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FRONTISPIECE

Satellite photograph of part of the northern margin of the Amadeus Basin showing steeply dipping Proterozoic and Palaeozoic formations in the MacDonnell Ranges (trending east-west from top centre to bottom). The Gosses Bluff astrobleme is the isolated circular feature in the Missionary Plain near the bottom of the photograph, with the Krichauff and Gardiner Ranges to the right (cut by the Finke River). The Waterhouse Range Anticline is the canoe-shaped range cut by the Hugh River in the upper right. The area to the left (north) of the MacDonnell Ranges consists mainly of Precambrian Arunta Complex with the Burt Plain on the extreme left. The Ormiston Nappe Complex lies slightly below the centre of the photograph to the north (left) of the MacDonnell Ranges. The width of the photograph is about 100 miles. (By courtesy of the National Aeronautics and Space Administration, U.S.A.).

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SUMMARY

The Amadeus Basin is a 500-mile-long intracratonic depression, with an area of about 60,000 square miles, which lies across the Northern Territory south of latitude 23°30′S and extends into Western Australia. It contains Proterozoic, Ordovician, possibly Silurian, and Devono-Carboniferous and minor Permian and Tertiary freshwater deposits. About 30,000 feet of sedimentary rocks are preserved.

The older Precambrian basement comprises the Arunta Complex along the northern margin of the basin, the Musgrave-Mann complex and Olia Gneiss in the south, and other unnamed Precambrian rocks. The Arunta Complex of igneous and metamorphic rocks was deformed during the Arunta Orogeny before deposition of the sedimentary rocks of the Amadeus Basin. In the southwest, thick sequences of younger Precambrian basement sediments and volcanic rocks lie between the older Precambrian rocks and the oldest sediments in the basin.

The first sediments deposited in the basin were about 2000 feet of sand (Heavitree and Dean Quartzites) laid down on a stable epicontinental shelf. After mild epeirogenic movement, evaporites were laid down in a shallow and restricted sea, and were succeeded by penesaline sediments, and finally by marine stromatolitic carbonate rocks and shale. The sediments of this evaporite cycle have a maximum thickness of 3000 feet, and have been named the Bitter Springs Formation and equivalent Pinyinna Beds. The only known volcanics interbedded with the sediments occur in the northeast in the upper part of the Bitter Springs Formation, and some poorly exposed mafic rocks in the southwest.

The tectonic events which followed represent the first phase in the development of an intracratonic depression roughly parallel to the present trend of the basin. There were two important periods of diastrophism during this tectonic phase, each recorded by unconformities in the Proterozoic sediments. The first, the Areyonga Movement, occurred after the deposition of the Bitter Springs Formation, and the second, the Souths Range Movement, after the deposition of the overlying Proterozoic rocks. Areas to the south were uplifted during each movement and became the main provenance of the Proterozoic sediments which poured into the subsiding area to the north, in which about 15,000 feet of clastic sediments accumulated. The depression was separated from a northern shelf area by an east-west linear zone, or hinge-line, along which the rate of subsidence changed. A thick sequence of Proterozoic sediments along the zone and to the south was uplifted and subsequently eroded in the late Proterozoic or early Cambrian Petermann Ranges Orogeny. The average thickness of the equivalent sediments on the shelf is about 3000 feet.

Two periods of Proterozoic glaciation are recognized. The older and more widespread resulted in deposition of the glacial sediments of the Areyonga Formation on the shelf area. The equivalent Inindia Beds of the depression in the south contain thin tillitic beds near the top, and correlation of these beds with the glacial deposits in the Areyonga Formation suggests that after the Areyonga Movement Proterozoic sedimentation probably began in the depression.

The younger glacial period was restricted to the northeastern part of the shelf, and during the deposition of the Pertatataka Formation a thickened lobe of sediments, partly glacial in origin, formed. The equivalent Winnall Beds of the depression have no identifiable tillitic beds.

The Petermann Ranges Orogeny uplifted and overfolded a large area in the southwest in the late Proterozoic or early Cambrian. The Pinyinna Beds and Dean Quartzite were complexly infolded with the basement in the Petermann Ranges Nappe, but the younger Proterozoic sediments slid northwards over the incompetent beds in the Bitter Springs Formation and were tightly folded along the margin of the nappe. The intensity of folding decreased to the north and its effect was almost negligible north of the Proterozoic hinge-line. The main effects of the Petermann Ranges Orogeny appear to be localized along the original axis of maximum sedimentation in the depression.

Isostatic uplift followed the Petermann Ranges Orogeny in the southwestern margin of the basin and provided the source of the Cambrian sediments. Thick conglomerate and arkose (Mount Currie Conglomerate and arkose at Ayers Rock) were deposited in the southwest, adjacent to the uplifted area. Farther north, deltaic sands (Cleland Sandstone) were deposited; to the northeast, the sands interfinger with sand, shale, and some marine sediments. The predominantly clastic sediments are thinner in a north-south zone near the centre of the basin, which was probably being uplifted during the sedimentation. To the east, about 7000 feet of predominantly carbonate rocks and lutites were deposited in the northeastern part of the basin. The Arumbera Sandstone, the basal formation of the Pertaoorrta Group in the northeast, was succeeded by evaporite deposits (Chandler Limestone) which were followed by penesaline and marine stromatolitic carbonate rocks (Giles Creek Dolomite and Shannon Formation). The Arumbera Sandstone and the youngest unit of the Pertaoorrta Group (Goyder Formation) show only minor facies changes across the central zone.

The sandstone, shale, and minor carbonate rocks of the Cambro-Ordovician Larapinta Group were deposited conformably on the Pertaoorrta Group in the north and disconformably in the south, during several marine regressions and transgressions in a widespread epeiric sea. Sedimentation was initially restricted to the northern half of the basin, but the Ordovician sea gradually spread to the south and the younger formations transgressed over the Pertaoorrta Group, and in the south and west they rest unconformably on Proterozoic rocks. During the Ordovician, the Amadeus Basin probably accounted for only a small area of the shallow epeiric sea, and the epicontinental deposits of this period extended well north of the present margin of the basin. The maximum thickness of the Larapinta Group on the northern margin of the basin is about 8000 feet. Larapinta Group sedimentation was brought to a close by the deposition of a regressive body of deltaic or estuarine sand which may represent the last marine deposits in the Amadeus Basin.

During the ensuing epeirogenic movement (Rodingan Movement), which probably started in the Silurian, the Amadeus Basin was subjected to broad vertical movements; in the northeast 5000 to 10,000 feet of sediments were eroded and the area was reduced to a peneplain. The resulting large deserts around and probably within the Siluro-Devonian basin provided the sediments of the Mereenie Sandstone, whose origin is partly shallow marine and partly fluviatile and aeolian: the shallow seas transgressed from the west. The Mereenie Sandstone is probably mostly Devonian. As a result of the constantly moving strandline there was probably no distinct form to the Amadeus Basin.

The first of several diastrophic events, the Pertnjara Movement, occurred in the late Devonian. The events resulted in successive uplifts of a large block of Precambrian rocks and the overlying Proterozoic and Palaeozoic sediments on the northern margin of the basin.

The uplifted rocks were deeply eroded, and a thick wedge of molasse, the Pertnjara Group, was deposited on the southern flanks of the mountain chains. The lacustrine siltstone at the base of the group followed conformably on the Mereenie Sandstone, and after further uplift of the provenance area coarser sediments were deposited. Along the northern margin of the basin younger formations of the Pertnjara Group successively overlap older formations; the youngest formation, the Brewer Conglomerate, overlies rocks as old as Proterozoic. The Pertnjara Group has a maximum thickness of about 12,000 feet, on the northern margin of the basin.

The molasse deposits of the Pertnjara Group become thinner and finer in grain to the south. In the southeast, the Finke Group was deposited penecontemporaneously in a basin which was probably separated from the Amadeus Basin by a peninsula.

Most of the folding took place during the Alice Springs Orogeny; but crestal thinning of the Palaeozoic sediments over anticlines shows that several of the structures were being formed during Lower Palaeozoic sedimentation; in places the folds were subsequently obscured by the Pertnjara Group. Some of the structures are the result of the formation of diapirs in the Bitter Springs Formation, and others may be caused by thrusting or a combination of thrusting and diapirism. Some were probably initiated during the Petermann Ranges Orogeny, others during the diastrophic movements in the Devonian and Carboniferous.

During the Alice Springs Orogeny the Heavitree Quartzite and Bitter Springs Formation in the north were infolded and overthrust with the crystalline basement to form structures such as the Blatherskite Nappe and the Arltunga and Ormiston Nappe Complexes.

Décollement surfaces in the Bitter Springs Formation and Cambrian sediments in the northeast, with a thrust plane connecting the upper and lower surfaces, facilitated the complex folding; the overlying sediments were strongly and isoclinally folded, but in places they yielded by thrusting. Another interpretation of the structure in the northeast suggests that the large blocks of sediments uplifted over the Arltunga Nappe Complex were possibly moved to the south by gravity sliding on the two décollement surfaces. In this way large complex thrust nappes were formed and most of the sediments are preserved in allochthonous blocks.

The Amadeus Basin was stabilized after the deposition of the Pertnjara Group and the deformation associated with the Alice Springs Orogeny. During the ensuing long period of erosion the weathered detritus was transported outside the basin and incorporated in the fluvioglacial and paludal Permian Buck and Crown Point Formations, and in the deltaic Jurassic(?) sands and the shallow-marine Cretaceous deposits in the Simpson and Gibson Deserts.

Middle Tertiary fluvial and lacustrine sediments were deposited in ancestral river valleys both before and after lateritization. The pre-silcrete sediments are Eocene to Miocene and the post-silcrete sediments are Miocene or younger. The Tertiary deposits indicate a wetter climate; tilting and minor faulting are associated with minor crustal movements.

The deposits in the Tertiary valleys were eroded, and the valleys were breached by headwater erosion by streams which were initiated by crustal downwarping in the Lake Eyre Basin. During an arid phase which followed the system of internal drainage was initiated and sand dunes formed. Resumption of drainage incision suggests an amelioration of the climate with the development of alluvial fans and flood-plains.

The two most important occurrences of hydrocarbons in the basin are wet gas accumulations in the Mereenie and Palm Valley Anticlines; in both production comes chiefly from the upper part of the Cambro-Ordovician Pacoota Sandstone. Small amounts of oil have been obtained from the Mereenie Anticline, but the permeability in the reservoir rocks is insufficient to give significant oil production. The Ordovician and Cambrian sediments offer the best prospects for petroleum accumulation, and the Missionary Syncline, in the northern part of the basin, is probably the most prospective area. Several large structures with closure in Ordovician and Cambrian rocks, have been mapped under the Devono-Carboniferous cover rocks. One of the main problems is to outline areas where there is permeability in the Ordovician reservoir sands. The transition zone where sandstone siltstone and carbonate rocks interfinger in the Pertaoorrta Group is probably worth further investigation. Reservoir rocks may be developed in the central northerly trending zone, where there was probably structural growth during deposition and which roughly corresponds to the transition zone in the Cambrian sediments. The existence of a submarine ridge during sedimentation suggests an area of reworked clean sands suitable for hydrocarbon traps.

Groundwater is important to the pastoral industry. Aquifers which usually yield large supplies of good-quality water are available in the Quaternary and Tertiary deposits, the Crown Point Formation, the De Souza Sandstone, parts of the Finke Group, the Mereenie Sandstone, and the Pacoota Sandstone and Goyder Formation.

Of a wide variety of metallic and non-metallic minerals recorded, only materials used in the building industry and semi-precious mineral and rock samples have any value at present.

INTRODUCTION

The area mapped lies in the southern part of the Northern Territory and in Western Australia between latitudes 23°S. and 26°S. and longitudes 127°30′E. and 136°30′E. (Pls 45, 46). It is 575 miles long and 205 miles wide and occupies 118,000 square miles. Sedimentary rocks of the Amadeus Basin crop out over an area of about 60,000 square miles; the remainder of the area is underlain by basement rocks or sedimentary rocks of the Great Artesian Basin in the southeast and of the Canning Basin in the west.

The mapping of the Amadeus Basin by the Bureau of Mineral Resources was completed in 1964. The basin was mapped in stages: Joklik and others in 1949-51; Prichard, Quinlan, and others in 1956; Wells, Forman, Ranford, and others in 1960-64. The results of these surveys have been published by Joklik (1955), Prichard & Quinlan (1962), Wells et al. (1964, 1965, 1966, 1967), Ranford et al. (1966), Forman (1966c), and Forman et al. (1967). This Bulletin is a summary and synthesis of the entire survey. Figure 1 shows the areas covered by the various publications; previous investigations have been described in detail in them, and only an outline of earlier work in the region is given here.

Figure 2 shows the main access routes and the location of cattle stations and tourist resorts, most of which are served by aerodromes.

Climate (Fig. 3)

Rainfall in central Australia is inadequate for the regular production of crops and the region is therefore classed as arid. The diurnal and seasonal variations in temperature are large, and the median annual rainfall ranges from 5 to 10 inches (Australian Water Resources Council, 1963). This is considerably less than the potential free-water evaporation of 94 to 104 inches (Slatyer, 1962).

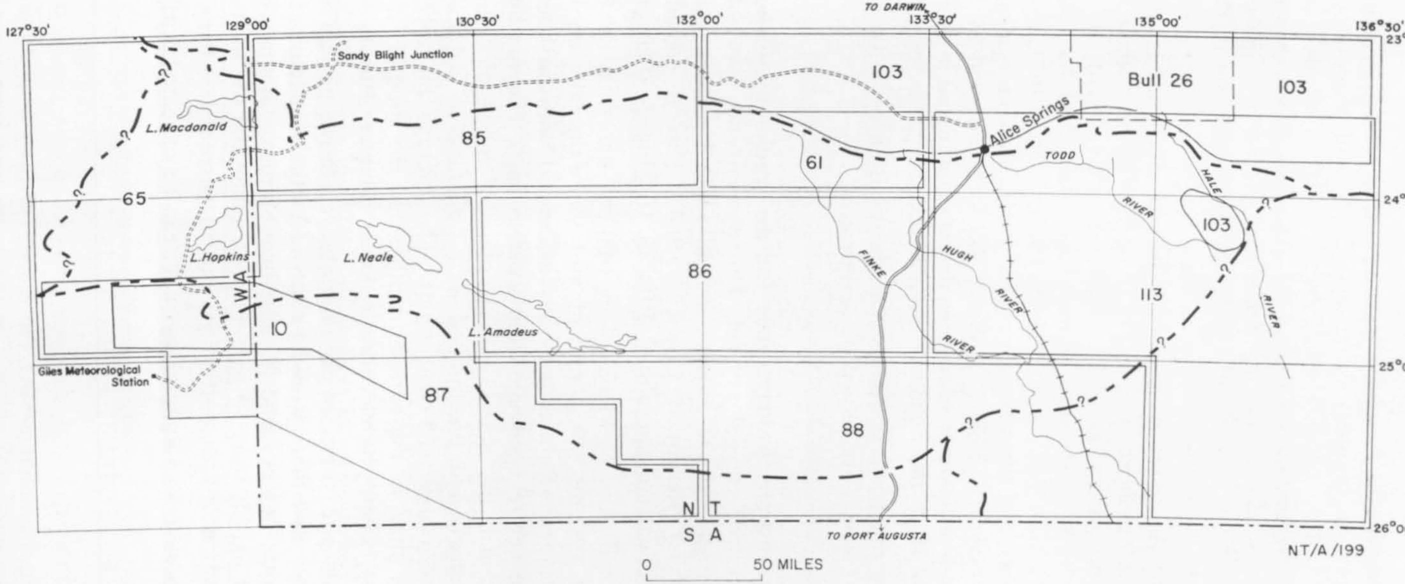
The Commonwealth Bureau of Meteorology (unpubl. data) has established that high-pressure weather systems are dominant and that rain falls on less than 8 percent of days in the year. Rain is generally associated with an intense trough, between high-pressure centres, moving from west to east. The northwesterly air flow preceding the trough introduces a deep mass of moist air into the area; the moisture is condensed and precipitated if a simultaneous depression to the northwest or southeast causes sufficient uplift. The average monthly rainfall is greater in the summer than in the winter months, and the monthly averages are lowest in the southeast, where the elevation is lower (Slatyer, 1962).

Not all falls of rain are sufficient to promote vegetative growth or produce runoff. Slatyer estimates that there would be 0.6 of 'initially effective' falls of rain per annum at Charlotte Waters and 2 at Alice Springs. Quinlan & Woolley (1967) have estimated that there is 50 percent probability that the interval between flows of the Todd River is less than 40 days, and 91 percent less than a year.

Droughts, or long periods of rainfall deficiency, can be expected fairly regularly. Foley (1957), using records of rainfall since 1880, has designated periods of drought and assessed the severity of each.

Early Exploration

In 1860 the area now known as the Northern Territory was administered by New South Wales. Attempts at settlement in the north had been unsuccessful and



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Reports — 88

Fig. 1. Areas covered by BMR Reports and Bulletins.

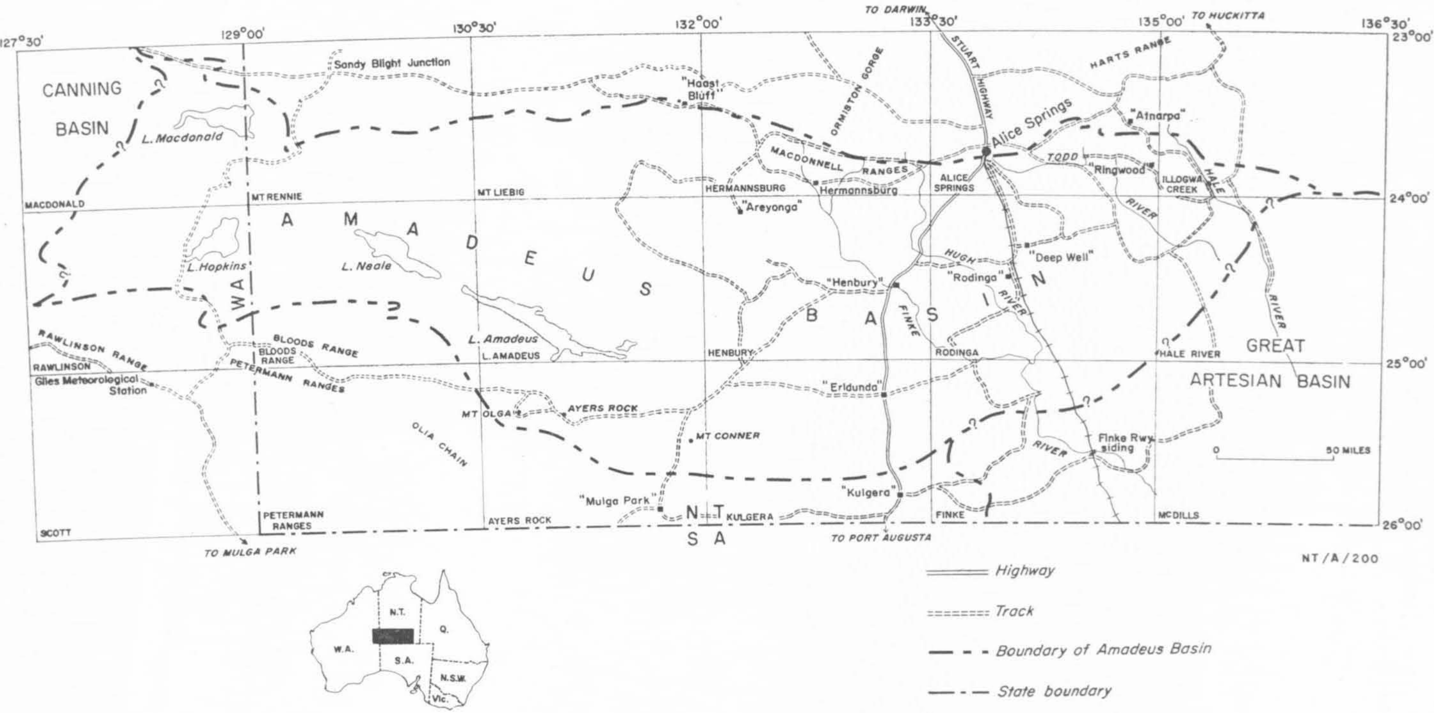


Fig. 2. Main access routes.

the southern part of the Territory was unknown. Stuart (1865) was the first explorer to cross Australia from south to north and the first white man to enter the Amadeus Basin. In 1860, he travelled north from Chambers Creek, near Port Augusta in South Australia, to the Finke River, which he followed to the Hugh

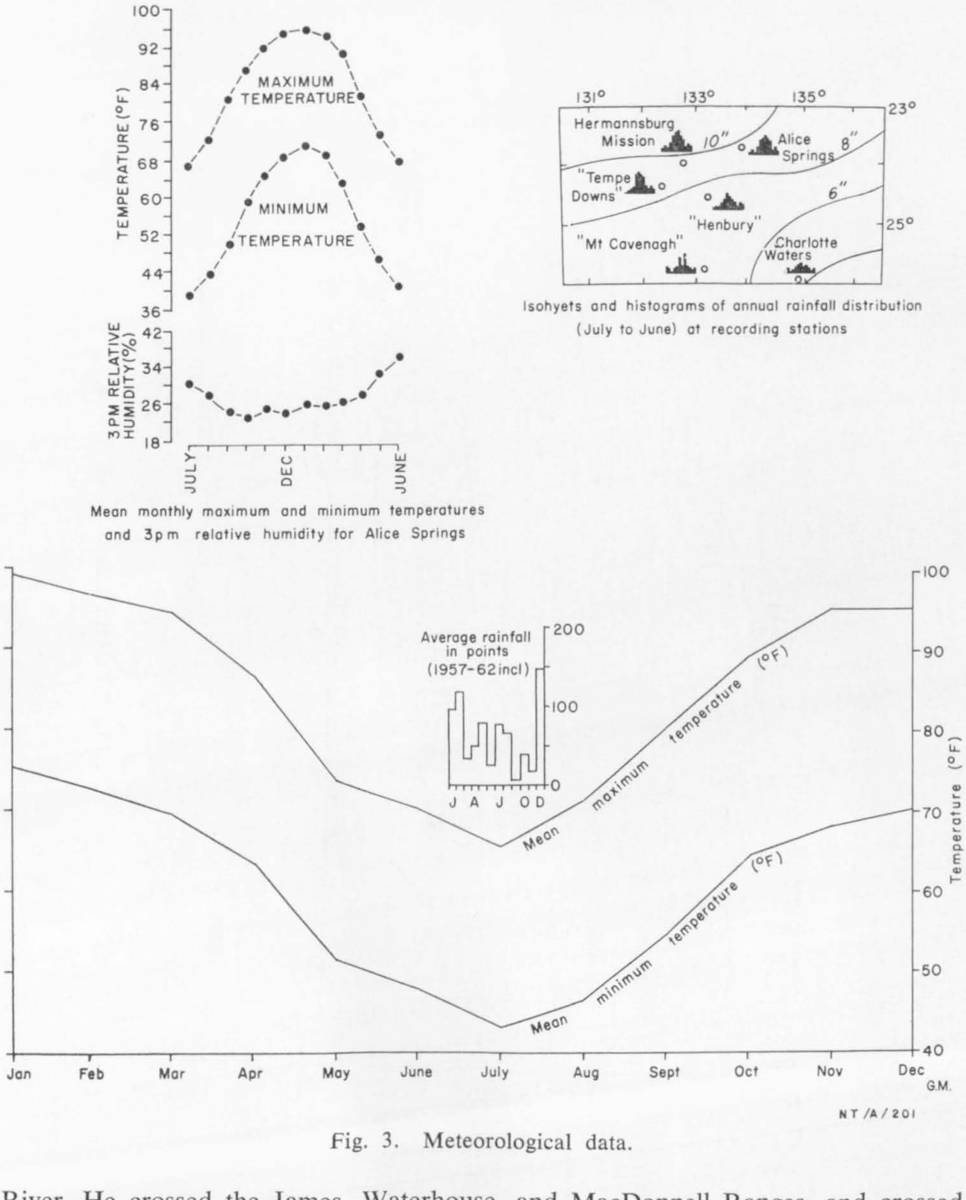


Fig. 3. Meteorological data.

River. He crossed the James, Waterhouse, and MacDonnell Ranges, and crossed the Chewings Range at Stuart Pass and then proceeded north to Attack Creek near Tennant Creek. He returned by the same route. On his second attempt in 1861 he followed the same route and penetrated as far north as Newcastle Waters, but was again forced to return. He left Adelaide on his third attempt in October

1861 and reached the Indian Ocean at Van Diemen Gulf in July 1862. On his return to Adelaide the South Australian Government applied for annexation of the Northern Territory, and the request was granted in July 1863.

In 1872 the overland telegraph line from Adelaide to Darwin was completed, and the earliest pastoral leases, 'Undoolya' and 'Owen Springs', were granted in the same year. In 1872-74 Giles (1889) explored the country west of the telegraph line. In 1872 he travelled from Chambers Pillar up the Finke River and then south of the MacDonnell Ranges to Gosses Bluff and west-northwest to the Ehrenberg Range. From here he travelled south to Lake Amadeus and then returned to Chambers Pillar. In 1873 he started from Ross Waterhole on the Alberga River and travelled west, near the present South Australian border, to the Musgrave, Mann, and Tomkinson Ranges and farther west into Western Australia. On the return trip he explored the Rawlinson Range, Schwerin Mural Crescent, Petermann Ranges, and Mount Olga. In 1873 Gosse (1874) left from the telegraph line at latitude 22°28'S. and travelled west-northwest and then southwest to Mount Liebig. From there he went south to the eastern arm of Lake Amadeus and to Ayers Rock, which he named. He continued to near the Warburton Ranges in Western Australia, and returned via the Mann and Musgrave Ranges and the Alberga River.

In 1876, Giles (1889) started from Perth and travelled via Geraldton and the Ashburton Range to the Rawlinson and Petermann Ranges and then south-eastwards to the telegraph line.

Tate (1880) studied specimens of rocks, minerals, and fossils from central Australia, including large plates of mica from the MacDonnell Ranges.

The first geologist to visit the Amadeus Basin was Chewings: in 1886 he investigated the source of the Finke River, and he revisited the area on several occasions between 1891 and 1935 (Chewings, 1886, 1891, 1894, 1914, 1928, 1931, 1935).

Gold was discovered at Paddys Hole near Arltunga in 1887 and mica-bearing pegmatites were being worked in the Harts Range area in November 1888. Garnets from the Maude and Florence Creeks and the Hale River were mistakenly identified as rubies (see Rennie, 1889).

East (1889) made geological observations along the telegraph line and between Alice Springs and the Harts Range. He drew the first section across the northern margin of the Amadeus Basin and recognized, but did not name, the Arunta Complex, Heavitree Quartzite, and Bitter Springs Formation. Brown (1889) visited the gold diggings near Paddys Hole Creek and south of the Hale River. When he revisited the area he recognized that sedimentary rocks, which he tentatively called Cambrian, rested unconformably on the metamorphic and plutonic rocks (Brown, 1890).

In 1889, Tietkins (1891) led an expedition to the west of Bond Springs Station to explore the country near the northern margin of the Amadeus Basin. He traversed Lake Macdonald in Western Australia and then travelled southeast to Bloods Range and back to the telegraph line via Mount Olga and Mount Conner.

Fossils were first found in the Amadeus Basin by Brown and Thornton in September 1890, probably near Tempe Downs (Brown, 1897; Etheridge, 1892b). Etheridge reported on additional fossils in 1893.

In 1892 the Horn Expedition (Tate & Watt, 1896, 1897; Winnecke, 1897) started from the Charlotte Waters Telegraph Station and studied the geology along the Finke River in the Finke, Rodinga, and Henbury Sheet areas. They collected many fossils from the Larapinta Group (Tate, 1896); Tate also reported on the glacial sediments at Yellow Cliff (Tate, 1897).

In 1897 Carnegie (1898) explored parts of the Macdonald, Mount Rennie, and Rawlinson Sheet areas on a journey from Halls Creek to Coolgardie. He passed to the east of Lake Macdonald and west of the Rawlinson Ranges. Brown investigated progress on the Arltunga Goldfield and the Harts Range mica-field (Brown, 1897). In 1897 gold was discovered and worked in the Heavitree Quartzite at White Range; and in 1902, gold was discovered in the Heavitree Quartzite south of Winnecke Depot (Brown, 1902, 1903).

In 1901, two South Australian Government prospecting expeditions investigated the Musgrave, Mann, and Rawlinson Ranges (Wells, 1904); another expedition in 1903 investigated the Musgrave, Mann, and Tomkinson Ranges (Wells & George, 1904). In 1902, Maurice (Murray, 1904) crossed the area from south to north near the Western Australian border. Basedow (1905) led a prospecting and geological expedition to the southwest in 1903; he reported on the Musgrave Ranges, Mount Olga, Mount Conner, and Ayers Rock.

Brown (1905) investigated the boundary of the Great Artesian Basin near Goyder Creek and the Finke River. In 1905 and 1906, George (George & Murray, 1907) led a government prospecting expedition into the southwestern corner of the Northern Territory and then via Deering Creek to Alice Springs.

In January 1911, control of the Northern Territory was formally transferred to the Commonwealth Government.

Summary of Later Geological Investigations

Since 1911 the Amadeus Basin has been the subject of numerous investigations most of which have dealt with various aspects of local geology, mineral deposits, water supply and geophysical surveys, by government and company geologists and geophysicists.

In this period the earliest comprehensive geological studies were made by Mawson & Madigan (1930), Chewings (1928, 1931, 1935) and Madigan (1932a, b, 1933, 1938, 1944). They carried out several investigations chiefly in the MacDonnell Ranges and named many of the formations. Many of their unnamed stratigraphic divisions were formalized during later mapping and their formal names were retained with some amendments to conform with current stratigraphic nomenclature.

Apart from the recent geological and geophysical investigations by the Bureau of Mineral Resources the Amadeus Basin has been discussed in a number of published and unpublished company reports. Frome Broken Hill Co. Pty Ltd made several regional geological investigations to assess the petroleum potential of the basin and were followed by Magellan Petroleum Corporation who continued with geological investigation and comprehensive geophysical surveys. The eastern part of the area covered by the Simpson Desert has been investigated by several geophysical surveys chiefly by Geosurveys of Australia. Many of these company reports are referred to specifically in later parts of this Bulletin.

Acknowledgments

The authors wish to thank Magellan Petroleum Australia Ltd, Exoil N.L. and their associated companies for permission to reproduce the graphic logs and other unpublished information from confidential well completion reports. The authors also wish to record their appreciation of the stimulating discussions and the continuous interchange of information with Dr D. A. McNaughton and geologists of Magellan Petroleum Corporation, the BMR staff of the Resident Geologist's Office, Alice Springs, and with all members of the BMR field parties. The residents of the Northern Territory deserve special thanks for their hospitality and assistance during the field work.

The section on structure in this Bulletin written by D. J. Forman is based on a Ph.D. thesis presented at Harvard University during the tenure of an Australian Public Service Board Scholarship. Professor M. P. Billings gave assistance and encouragement throughout the writing of the thesis. Professors M. P. Billings, J. Haller, R. Siever, and J. B. Thompson Jr, all made constructive criticisms of the text and Professor Robinson of the University of Massachusetts suggested drawing the structural relief diagram (Pl. 44).

PRECAMBRIAN BASEMENT

The Amadeus Basin succession includes Proterozoic, Cambrian, Ordovician, Silurian(?), Devonian, and Carboniferous(?) sedimentary rocks resting on Precambrian basement. It is overlain by superficial Permian, Mesozoic, Tertiary, and Quaternary rocks. The stratigraphy is summarized in Figure 4, and localities of reference and type sections of formations are shown in Figure 5.

All rocks older than the Proterozoic Heavitree and Dean Quartzites are called basement rocks.

The older basement rocks (Pl. 1, figs 1, 2) consist largely of moderately to highly metamorphosed gneiss, schist, quartzite, amphibolite, marble, and granite. Isotopic age estimates suggest that some granite north of the Amadeus Basin may be between 1800 and 1400 m.y. old (Hurley et al., 1961; Wilson et al., 1960), while granite south of the Amadeus Basin is about 1100 m.y. (Arriens & Lambert, 1969) and 1200 m.y. old (P. J. Leggo, pers. comm.). These granites are probably younger than the metamorphic rocks.

In places the older basement rocks are overlain unconformably by sequences of volcanic and sedimentary rocks, most of which are intruded by granite but are comparatively little metamorphosed. These are the younger Precambrian basement rocks. Their distribution is shown in Plates 45 and 46.

Older Precambrian Basement Rocks

The older basement rocks are called the Arunta Complex (Mawson & Madigan, 1930) north of the Amadeus Basin and the Musgrave-Mann complex (Sprigg et al., 1958) or Olia Gneiss (Forman, 1966a) to the south of the basin. The basement complexes are highly metamorphosed and intruded by granite, and by pegmatitic, felsic, and mafic dykes.

Joklik (1955) made a detailed lithological and stratigraphical study of the *Arunta Complex* in the Harts Range (Pl. 1, fig. 1) near the northeastern margin of the basin. He divided the gneiss into a number of distinct lithological units, all of which he considered to be of sedimentary origin. Some of them have been modified by deep-seated igneous activity, and were intruded by felsic and mafic igneous rocks that are metamorphosed to varying degrees. He also recognized a

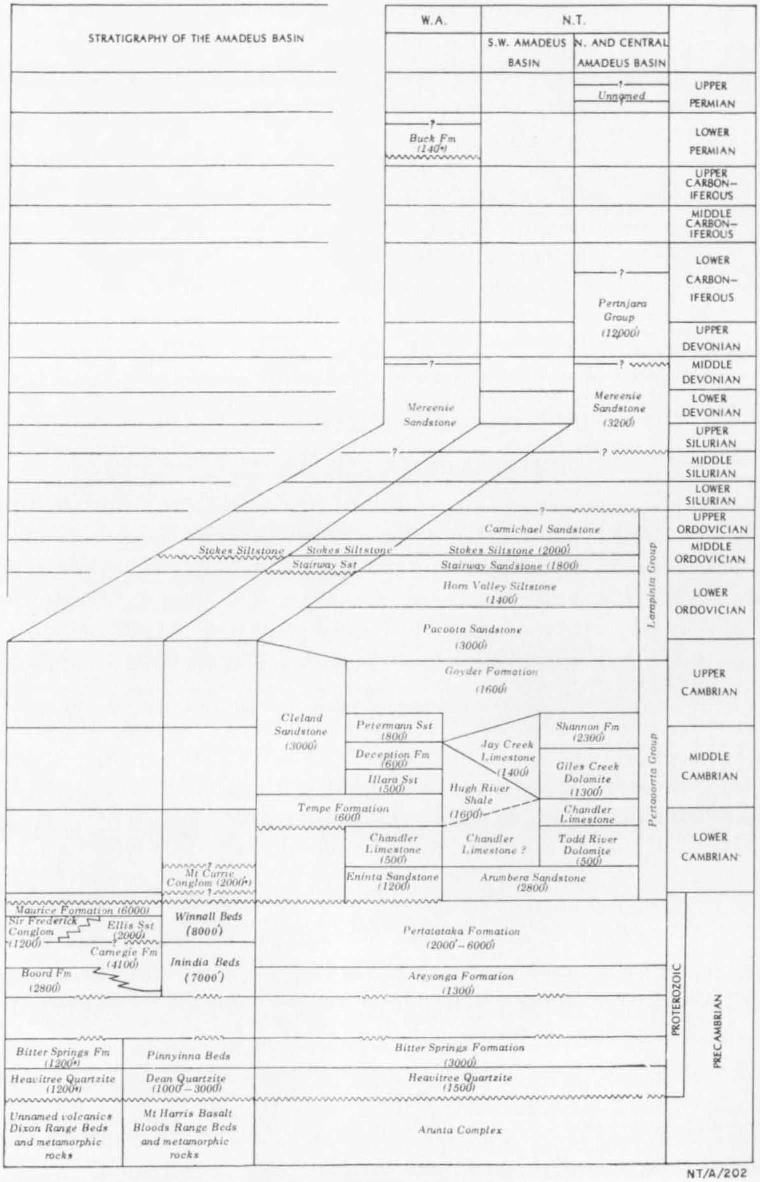
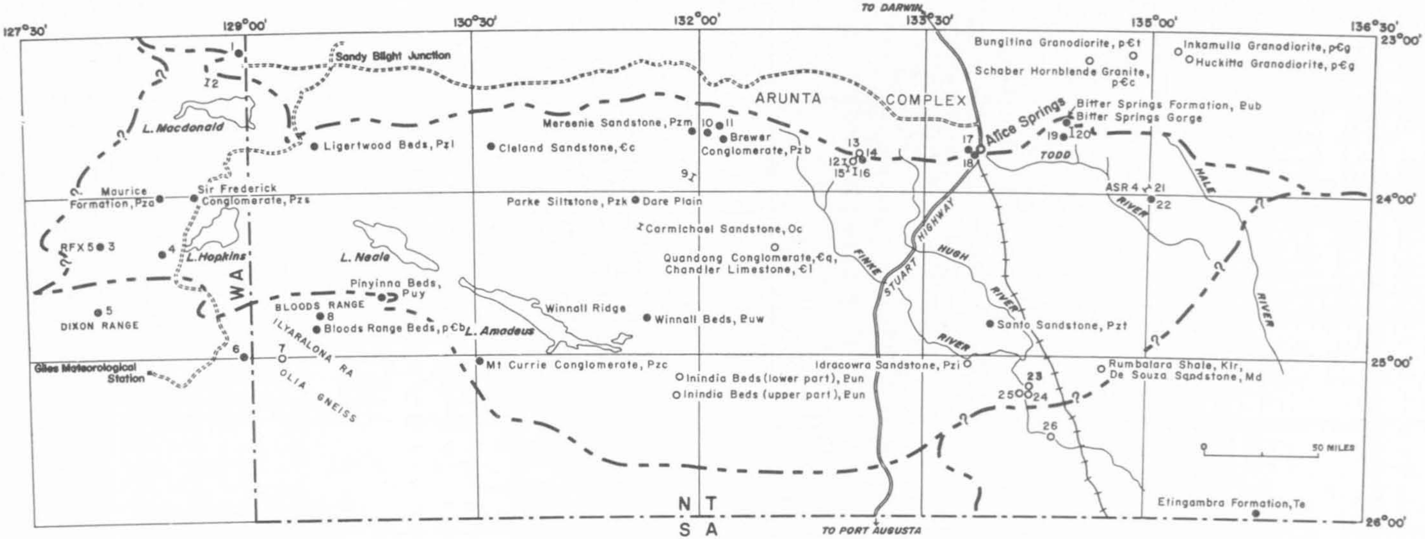


Fig. 4. Stratigraphy of the Amadeus Basin.

gigantic lens of metamorphic rock of doleritic composition. No other geological maps of the Arunta Complex show separate lithological units, partly because of outcrop limitations and partly because most of these surveys were directed towards the search for oil.



⊢ *Type section* • *Type area or locality* ⚬ *Reference section* o *Reference area* ASW1 *Section reference number*

1 Buck Formation, Pb
2 Boord Formation, Euo, MFX1
3 Carnegie Formation, Euc
4 Ellis Sandstone, Pze
5 Dixon Range Beds, p€d
6 Dean Quartzite, Eud
7 Pottoyu Granite Complex, p€o
8 Mt Harris Basalt, p€h
9 Petermann Sandstone, €e; Deception Formation, €d; Illara Sandstone, €i; Tempe Formation, €t; Eninta Sandstone, €n
10 Hermannsburg Sandstone, Pzr
11 Stokes Siltstone, Ot
12 Arumbera Sandstone, €a; Pertatataka Formation, Eup
13 Bitter Springs Formation, Eub
14 Loves Creek Member, Eue
15 Hugh River Shale, €h; Jay Creek Limestone, €j; Goyder Formation, €g
16 Areyonga Formation, Eua; Pacoota Sandstone, €-Op; Horn Valley Siltstone, Oh; Stairway Sandstone, Os
17 Gillen Member, Eug, of the Bitter Springs Formation
18 Heavitree Quartzite, Euh
19 N'Dahla Member, On
20 Cyclops Member, Euy; Julie Member, Euj } ASR5; Todd River Dolomite, €r; Giles Creek Dolomite, €k; Shannon Formation, €s } ASW1
21 Ringwood Member, Eur; Limbla Member, Eum; Olympic Member, Euf
22 Waldo Pedlar Member, Eul
23 Horseshoe Bend Shale, Pzh
24 Langra Formation, Pzn
25 Polly Conglomerate, Pzo
26 Crown Point Formation, Pc

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Fig. 5. Reference areas, type sections, and type areas.

The lithology of the *Musgrave-Mann complex* has been reviewed by Sprigg et al. (1958). The stratigraphic succession has not been deduced, but they consider that it could be determined. In their view much of the Musgrave-Mann complex is granitized metasediment. The rocks include: highly feldspathized and granitic quartzite; granitic gneiss of pelitic origin; actinolitic and highly epidotic gneiss; and garnet gneiss (in places with cordierite and spinel). Many gneisses are of the charnockite and hypersthene diorite type, but are said to preserve remnants of sedimentary structures. The gneisses are associated with large-scale intrusions of granite, charnockite, and pegmatite.

Arriens & Lambert (1969) report Rb/Sr isotope studies of granite and gneiss from the Musgrave Ranges of South Australia. Ten gneisses of granulite facies gave an isochron of 1380 $\pm$ 120 m.y. with an initial Sr^{87}/Sr^{86} ratio of 0.7072 $\pm$ 0.0025. The Ernabella Granite gave an age of 1120 $\pm$ 100 m.y. with an initial Sr^{87}/Sr^{86} ratio of 0.710 $\pm$ .001. Other gneiss from the Musgrave Ranges gave a possible isochron of 1655 $\pm$ 110 m.y. with an initial Sr^{87}/Sr^{86} ratio of 0.708 $\pm$ .001. Arriens & Lambert feel sufficient data are available from their analyses to document the granulite-facies metamorphism between 1300 and 1400 m.y. as an important tectonic event.

The *Olia Gneiss* is the name given to the basement gneiss in the southwestern part of the Northern Territory. It is lower in metamorphic grade (amphibolite facies) than the granulites of the Musgrave-Mann complex. The boundary between the two is probably a major thrust (the Woodroffe Thrust) first recognized by the South Australian Mines Department.

The Olia Gneiss contains quartzo-feldspathic layers and micaceous layers; it is either fine to medium-grained or coarsely porphyroblastic. It is intruded by coarse porphyritic granite, by a granite containing large ovoid phenocrysts of microcline, by even-grained granite, and by quartz-feldspar porphyry. Total rock ages by the Rb/Sr method on samples of granite give an age of about 1200 m.y. (P. J. Leggo, pers. comm.). The Olia Gneiss and the granite and mafic dykes that intrude it are overlain unconformably by the Dean Quartzite of Proterozoic age.

According to Sprigg et al. (1958), the latest phase of igneous intrusion south of the Amadeus Basin was the injection of doleritic dykes into a complex fracture pattern. Mafic rock intrudes the Musgrave-Mann complex above the Woodroffe Thrust near the South Australian border. The dykes are criss-crossed by pseudotachylitic veinlets and therefore are older than the Woodroffe Thrust.

Younger Precambrian Basement Rocks

The distinction between older and younger Precambrian basement rocks is not intended to be a time subdivision: it recognizes a metamorphic disconformity between two groups of basement rocks. In the absence of fossils, isotopic age determinations will be required to make correlations.

The distribution of the younger basement rocks is shown on Plate 45.

Sediments and Volcanic Rocks in the Northwestern Margin of the Basin

Basalt flows lie unconformably beneath the Heavitree Quartzite near the Western Australian border (pCl of Pl. 45). The base of the basalts is not exposed, but they probably rest nonconformably on gneissic granite (Wells et al., 1965).

Farther north and west (pCs on Pl. 45) and extending into Western Australia, there is an unnamed sequence of low-grade metasedimentary rocks (originally siltstone and sandy siltstone) associated with porphyritic dacite and rhyolite, porphyritic microgranite and microgranodiorite, quartz diorite, albitized dolerite, pyroxenite, and granite (Wells et al., 1964). The relations and thickness of these rocks are unknown; they are overlain unconformably by the Heavitree Quartzite.

The *Mount Harris Basalt* (Forman, 1966c) overlies basement gneiss and granite, probably unconformably, and is overlain, possibly conformably, by the Bloods Range Beds. In the type area near Mount Harris (Pl. 45) the formation contains quartzite, amygdaloidal epidotized basalt, breccia, and perhaps tuff, intruded by granite. The formation is overlain unconformably by the Dean Quartzite.

The nature of the contact between quartzite at the base of the Mount Harris Basalt and granite has been questioned. Forman (1966a) concluded that the rapakivi-like granite was most probably emplaced after the basalt was poured out, though he earlier considered (1963, unpubl.) that the quartzite rested nonconformably on the granite. Horwitz & Daniels (1967) re-examined the contact in the Kathleen Range area and decided that the Mount Harris Basalt rests unconformably on a basement of rapakivi-like granite, but that the relationship is locally obscured by a younger granite that contains large phenocrysts of feldspar. This explanation is acceptable.

The thick sequence of altered mafic and felsic volcanic rocks, interbedded quartzite and schist, in the Kathleen Range area (Pl. 45) is tentatively correlated with the Mount Harris Basalt.

Bloods Range Beds

The Bloods Range Beds (Forman, 1966c) are a sequence of slightly metamorphosed clastic sediments and predominantly felsic volcanics that overlie the Mount Harris Basalt and are overlain unconformably by the Dean Quartzite. The base of the Bloods Range Beds near the type area (south of Bloods Range, Pl. 45) may be unconformable on the Mount Harris Basalt. The Bloods Range Beds have been tentatively identified in other localities on the southwestern margin of the basin, and near the Kathleen Range in Western Australia they appear conformable on the Mount Harris Basalt. They are correlated with the Dixon Range Beds.

Dixon Range Beds

The Dixon Range Beds (Wells et al., 1964) are a sequence of unmetamorphosed but highly folded (Pl. 2, fig. 1) sandstone, siltstone, shale, arkose, and pebble conglomerate that crops out in the Dixon Range in Western Australia (Pl. 45). The sequence is over 6700 feet thick, and appears to be conformable beneath the Dean Quartzite, although the contact is not exposed.

PROTEROZOIC

Nomenclature

The nomenclature of the Precambrian rocks of Australia is under review. In this Bulletin the term Proterozoic is used for rocks between the fossiliferous Cambrian sediments and the unconformity at the base of the Dean and Heavitree Quartzites. The general terms Proterozoic and Precambrian are used because the precise age of the rocks is unknown.

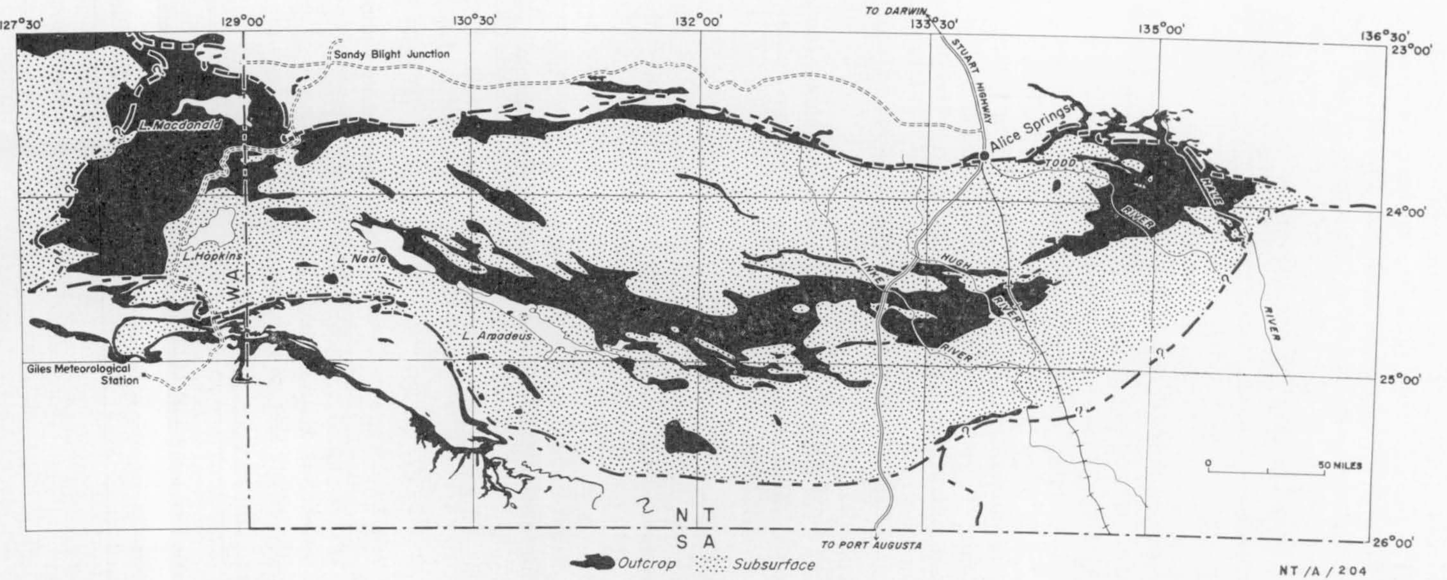

Fig. 6. Distribution of Proterozoic rocks.

The provisional isotopic ages of a few samples of the sedimentary rocks suggest that the Pertatataka and Areyonga Formations, and possibly the Bitter Springs Formation, are Adelaidean (below the base of the Cambrian and no more than about 1400 m.y. old). The age of the older rocks is uncertain.

Distribution and Thickness

Proterozoic sedimentary rocks crop out, or underlie thin superficial deposits, over about one-quarter of the Amadeus Basin (Fig. 6). They crop out extensively at the eastern and western ends of narrow strips along the northern and south-western margins, and in a wide belt in the centre. A large area of Proterozoic sediments is probably concealed by superficial Cainozoic deposits in the south. In the central zone incomplete sections of Proterozoic sediments are exposed in the cores of some of the eroded anticlines in the Palaeozoic rocks.

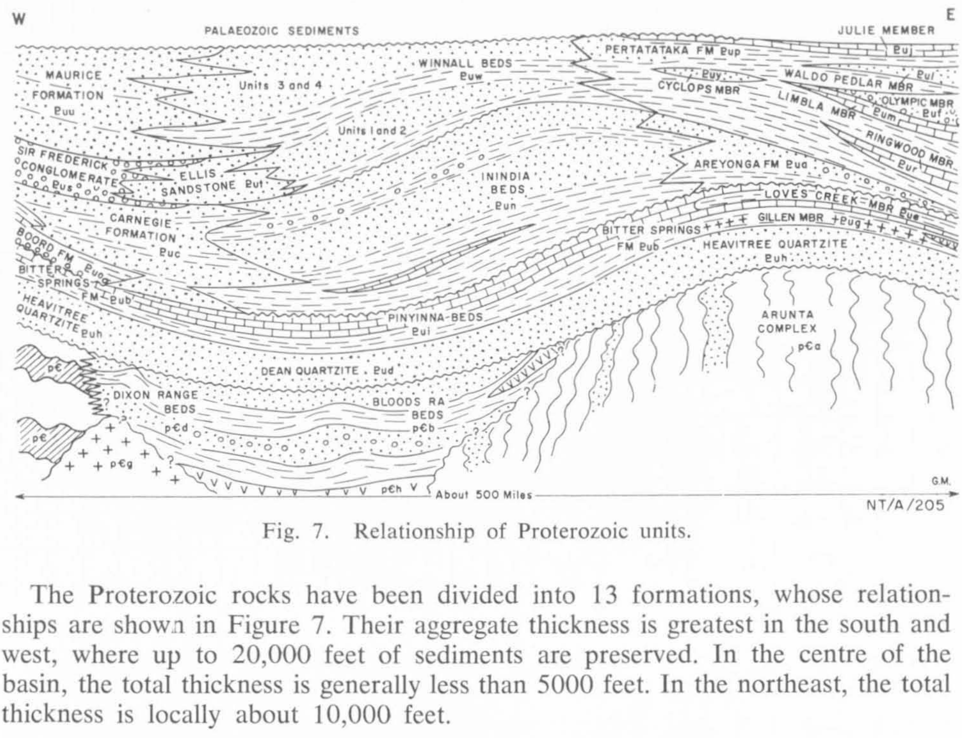

Fig. 7. Relationship of Proterozoic units.

The Proterozoic rocks have been divided into 13 formations, whose relationships are shown in Figure 7. Their aggregate thickness is greatest in the south and west, where up to 20,000 feet of sediments are preserved. In the centre of the basin, the total thickness is generally less than 5000 feet. In the northeast, the total thickness is locally about 10,000 feet.

THE PROTEROZOIC SEQUENCES

Heavitree Quartzite and Dean Quartzite

The Heavitree Quartzite was named and defined by Joklik (1955); Heavitree Gap, south of Alice Springs, is inferred as the type locality. The formation forms ridges and escarpments (Pl. 2, fig. 2) along the northern margin of the basin from the Hale River in the east to the Dovers Hills in Western Australia, a distance of about 470 miles. The correlative of the Heavitree Quartzite, the Dean Quartzite (Wells et al., 1964; Forman, 1966c), is known only in the southwest; it forms ridges and escarpments extending 250 miles from Mulga Park homestead

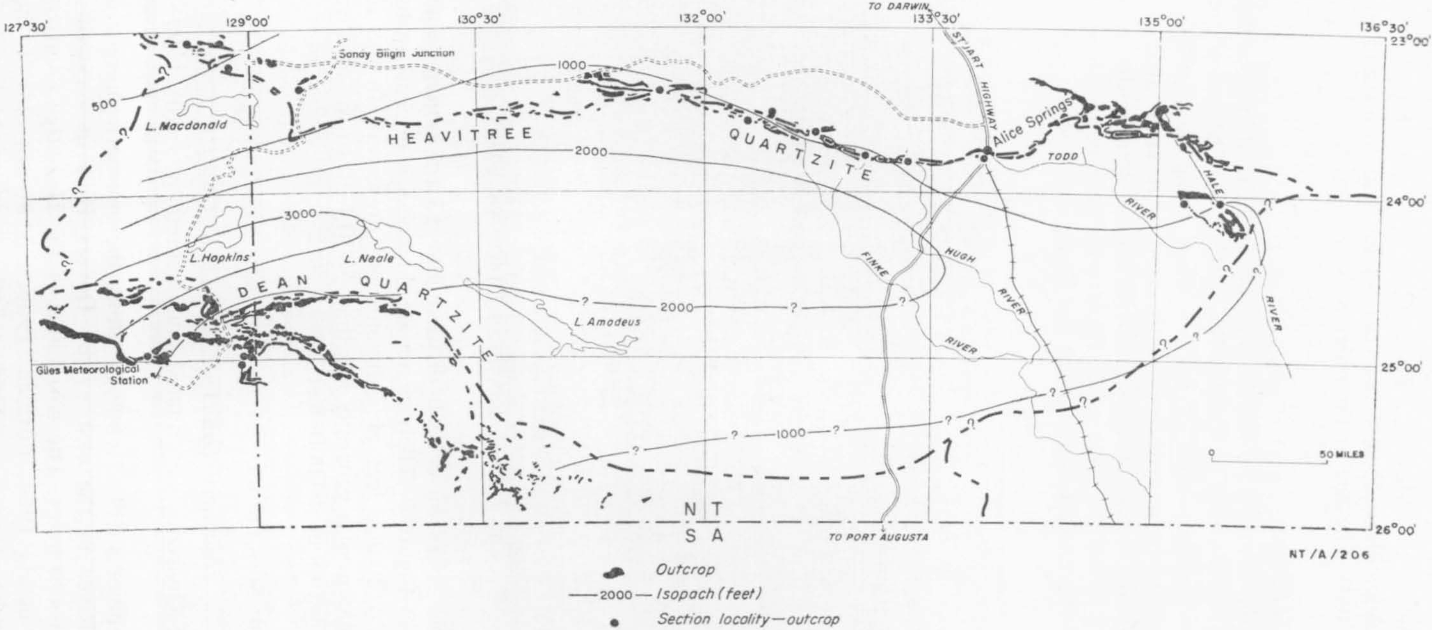

Fig. 8. Outcrops and thickness of Heavitree Quartzite and Dean Quartzite.

to the western end of the Rawlinson Range. The correlation is based on stratigraphic position and lithological similarity. The distribution of outcrops and thickness of both formations are shown in Figure 8.

The *Heavitree Quartzite* unconformably overlies the Arunta Complex (Pl. 3, figs 1, 2) and other Precambrian rocks. In the Kintore Range, in the west, it unconformably overlies slightly metamorphosed amygdaloidal and vesicular porphyritic basalt. The Heavitree Quartzite is overlain conformably throughout the basin by the Bitter Springs Formation.

The formation consists predominantly of white slabby silicified quartz sandstone, with minor conglomeratic sandstone, siltstone, and conglomerate, all of which weather pink and grey. The quartzite ridges have been strongly silicified by surface weathering, and silica has probably been concentrated at the surface and leached from deeper levels. The silicified rock grades down into a moderately friable sandstone, but the formation in depth is not everywhere friable and porous. The quartz sandstone is an orthoquartzite with a high maturity index. The quartz grains are moderately well rounded; they average about 1 mm across but the size distribution is commonly bimodal. The grains commonly show undulose extinction. The matrix is siliceous and and contains a little muscovite, sericite, and iron oxide. Part of the sandstone is ripple-marked and cross-bedded, with sun cracks and synaeresis cracks. Possible invertebrate tracks have been noted at Blanche Tower, at Temple Bar Gap, and near Bitter Springs. In the Dovers Hills the sandstone is commonly foetid when struck with a hammer. In many places, notably at Mount Rennie, it contains moulds of pyrite crystals up to half an inch across.

The basal part of the formation consists of conglomerate, arkose, greywacke, and siltstone in variable proportions, depending in part on the composition and topography of the underlying basement. A little siltstone is interbedded with the sandstone, but thicker sequences are found in places at different levels. A siltstone is well exposed at the base of the formation in Heavitree Gap just south of Alice Springs; it is 30 feet thick and overlies weathered gneiss of the Arunta Complex. In the Amunurunga and Belt Ranges and to the south at Blanche Tower and Mount Crawford, the contact with the Arunta Complex is well exposed; where the Heavitree Quartzite overlies pinnacles of the Arunta Complex a local conglomerate is present, but 100 to 120 feet of siltstone is present in the eroded valleys.

Prichard & Quinlan (1962) have described three members in the Heavitree Quartzite at Ellery Creek:

(3) 500 feet. *Quartz greywacke,* medium-grained, silicified to quartzite; and pale yellow-brown argillaceous *quartz siltstone* up to 100 feet thick.

(2) 200 feet. *Siltstone,* with 40 percent medium to coarse quartz grains.

(1) 700 feet. *Quartz sandstone,* medium to coarse, cemented to quartzite.

Condon (*in* Prichard & Quinlan, 1962) considers that the middle siltstone member is equivalent to the basal siltstone at Heavitree Gap.

Metamorphism of the Heavitree Quartzite has taken place where it is deeply infolded with the crystalline rocks of the Arunta Complex in nappe complexes along the MacDonnell Ranges (Forman et al., 1967). In places it may be brecciated, and deeper in the structures it develops schistosity, foliation and lineation, and may be partly recrystallized to sericitic quartzite, schistose quartzite and sericite - quartz schist. Stretched pebbles are common in some of the conglomeratic quartzite and in places are necked or even ruptured (Forman, 1969, unpubl.). Most of the original sedimentary structures, such as cross-bedding, have been obliterated. Where the Heavitree Quartzite is infolded with the Arunta Complex, the quartzite appears to be conformable with the schists on the overturned limb. These schists, however, were formed by retrograde metamorphism of the Arunta Complex rocks, and the schistosity was developed parallel to the bedding in the Heavitree Quartzite during the infolding.

Some of the quartzite near Ormiston Gorge which was mapped as Heavitree Quartzite by Prichard & Quinlan (1962) was generally referred to as the Chewings Range quartzite; most of it has since been shown to be older than the Heavitree Quartzite. Forman et al., (1967) have suggested that the quartzite is part of the Arunta Complex or may be intermediate in age between the Arunta Complex and Heavitree Quartzite. Most of the White Range Quartzite of Joklik (1955) is Heavitree Quartzite but a small part of it belongs to the Arunta Complex (Forman, pers. comm.).

The *Dean Quartzite* (Wells et al., 1964; Forman, 1966c) forms many prominent ranges, hills, and escarpments on the southwestern margin of the basin. It consists of a thick sequence of fine to coarse quartzite, conglomeratic quartzite, and conglomerate. It unconformably overlies the Olia Gneiss, Mount Harris Basalt, and Pottoyu Granite Complex, and is conformably overlain by the Pinyinna Beds. In the west, the Dean Quartzite apparently rests conformably or disconformably on the Dixon Range and Bloods Range Beds, although the contact is poorly exposed; farther east the contact with the older rocks is unconformable (Forman, pers. comm.). In the east, the surface of the unconformity is uneven and is overlain locally by beds of conglomerate and conglomeratic quartzite. Where the quartzite overlies the Mount Harris Basalt the basal beds contain small subangular fragments of amygdaloidal basalt and vein quartz.

In the Petermann Ranges and Olia Chain, and in the southern half of the Ayers Rock Sheet area, the Dean Quartzite was metamorphosed during the Petermann Ranges Orogeny. The formation has been metamorphosed to fine and medium-grained quartzite, sericitic quartzite, and sericite-quartz schist, where it has been deeply infolded with crystalline basement rocks in the Petermann Ranges Nappe (Forman, 1966c). Schistosity and lineation are common in the infolded and metamorphosed quartzite. The formation was subjected to metamorphism up to the lower amphibolite facies during the orogeny and pyrophyllite, kyanite, and staurolite can be found in the rocks with the assemblage depending on the grade of metamorphism (R. N. England, pers. comm.). A detailed report on the metamorphism of this unit and associated features is being prepared by D. J. Forman.

The Heavitree and Dean Quartzites are commonly doubled up in isoclinal folds in the nappe complexes and the thickness has been measured at only a few localities (Fig. 8). The isopachs suggest that the formations were deposited in a shallow downwarp trending parallel to the present trend of the Amadeus Basin, but there are no outcrops in the centre of the basin to support this conclusion. The thickest measured sections occur in the Rawlinson Range/Dean Range area; 3900 feet was measured in the Robert Range.

The widespread distribution of the Dean and Heavitree Quartzites suggests deposition in a shallow-marine epicontinental sea under relatively stable conditions. The coarse-grained lower part of the formation suggests a littoral environment, in contrast to the overlying beds, which may have accumulated in a neritic zone.

Bitter Springs Formation and Pinyinna Beds

The thick sequence of calcareous and arenaceous rocks conformably overlying the Heavitree Quartzite was named the Bitter Springs Limestone by Joklik (1955). The name was revised to Bitter Springs Formation by Wells et al. (1967). At the type locality, at Bitter Springs east of Alice Springs, the formation is complexly folded, and Wells et al. have selected a reference section at Ellery Creek. In the northeast, Wells et al. have subdivided the formation into the Gillen and Loves Creek Members.

The formation is best exposed on the northern margin and in the northeast. The distribution and thickness are shown in Figure 9.

The formation consists of interbedded crystalline dolomitic limestone, dolomite, and limestone, dololutite, dolarenite, calcarenite, shale, siltstone, gypsiferous siltstone, and sandstone. In places the carbonate rocks are hematitic or micaceous, sandy or pelletic; they range from cryptocrystalline to microcrystalline, and in places contain banded laminae of pre-diagenetic chert. Except in the north and northeast, outcrops consist mainly of crystalline dolomite. The calcareous rocks are commonly silicified, and laminae, lenses, and beds of chert and silicified dolomite and limestone are common. Oolites are common in the dolarenite and calcarenite, and the oolitic texture is well preserved where the rock has been replaced by chert. Large masses of sheared and brecciated gypsum crop out intermittently in a zone 50 miles long trending southeast from Johnstone Hill. Gypsum is also associated with the Bitter Springs Formation on the southern side of the Gardiner Fault on the north side of the Gardiner Range, and in the Ringwood Dome, about 65 miles east of Alice Springs. The gypsum is sheared and laminated and contains fragments of dolomite breccia; it is generally overlain by isoclinally folded and brecciated dolomite and limestone. Some of the gypsum is probably associated with diapiric intrusions. Salt and gypsum were intersected in the Bitter Springs Formation in the Ooraminna No. 1, Mount Charlotte No. 1, and Erldunda No. 1 wells. A thin band of dark purple-brown silicified sandstone, with pseudomorphs after halite, occurs at the top of the formation in the westernmost exposure in the Erldunda Range; salt casts are common in the mottled green and red-brown siltstone of the Gillen Member in the northeast.

Lenses of sandstone are present near the top of the Bitter Springs Formation (probably Loves Creek Member) in the Parana Hill Anticline. The sandstone is white or pale brown, well sorted, medium-grained, and friable, and has very little interstitial material. In the measured section in the Parana Hill Anticline the sandstone is 56 feet thick and its base is 200 feet below the exposed top of the formation. Thick beds of sandstone are present in the Gillen Member in the northeast, but sandstone outcrops are rare outside this area, especially in the Loves Creek Member.

Between the Belt Range and the Amunurunga Range the Heavitree Quartzite is overlain conformably by more than 300 feet of laminated micaceous siltstone and minor white medium-grained kaolinitic sandstone. The siltstone is overlain by fine and medium-grained laminated crystalline dolomite.

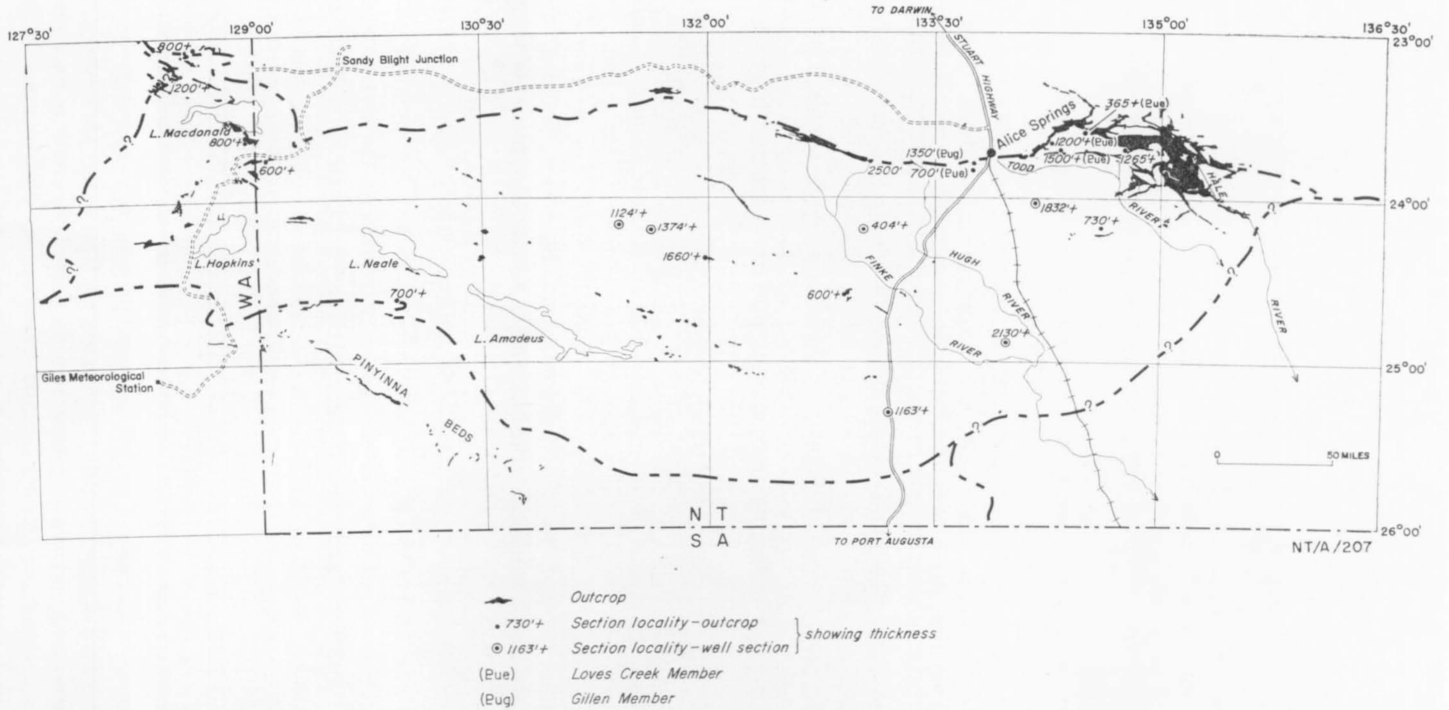

Fig. 9. Outcrops and thickness of Bitter Springs Formation and Pinyinna Beds.

The only complete measured section, at Ellery Creek (Prichard & Quinlan, 1962), is 2500 feet thick. A graphic log is figured in Wells et al. (1967).

At Ellery Creek, the formation consists mainly of dark grey well bedded laminated dolomite and cherty limestone; 100 feet of poorly exposed dark grey siltstone occurs at the base. The interval from 1270 to 1890 feet above the base consists of dull red argillaceous non-dolomitic limestone which contains no stromatolites. Colonial algae are found in a darker dolomitic limestone in the upper part, and algal biostromes (Pl. 4, fig. 1) and *Collenia* bioherms are common near the middle. In the northeast, the red argillaceous limestone and stromatolitic carbonate rocks form part of the Loves Creek Member.

The bedded carbonaceous cherts in the Ross River area contain a varied assemblage of exceptionally well preserved spheroidal and filamentous plant microfossils, which were first reported by Barghoorn & Schopf (1965) and later described by Schopf (1968). 'The organisms, three dimensionally preserved in a matrix of primary chalcedonic chert, comprise algal biocoenoses which grew in the form of laminar sheets or mats in the apparently marine environment of the Amadeus Basin, and they evidently contributed to the formation of widespread algal stromatolites'.

At Ellery Creek there is an unusual occurrence of brecciated carbonate rocks (Pl. 4, fig. 2) in the Bitter Springs Formation. Thin beds of alternating black limestone and grey dolomite can be traced laterally into the brecciated zones, where the beds of limestone have been disrupted into irregular pods and stringers set in a groundmass of dolomite. This change may have taken place during an early stage of diagenesis when the layers were only semiconsolidated.

In many exposures, the Bitter Springs Formation has been steeply overturned, and the beds are commonly intensely folded, brecciated, and faulted. These incompetent beds formed a décollement surface which has played an important role in the complex folding and thrusting of the overlying sediments.

In the west, the formation is overlain conformably by the Carnegie Formation or disconformably by the Boord Formation. In the north, it is overlain disconformably or unconformably by the Areyonga Formation, and by the Pertatataka Formation. In the south, it is disconformably or unconformably overlain by the Inindia Beds, and in places unconformably by the Stairway Sandstone, Pertaoorrta Group, Langra Formation, and Winnall Beds. In the central part of the basin, the base of the formation is not exposed and the upper contacts are rarely exposed. In some of the breached anticlines it is disconformably overlain by the Areyonga Formation or unconformably by the Tempe Formation of the Pertaoorrta Group.

Forman et al. (1967) have described the metamorphism of the Bitter Springs Formation. In the Arltunga and Ormiston Nappe Complexes the sediments have been converted into phyllite, slate and schist; other effects include brecciation, crushing, and the development of fracture cleavage near the nappe complexes. Samples from Ooraminna No. 1 show diagenetic changes such as recrystallization, dolomitization, silicification, and development of anhydrite in patches and fractures (Schmerber, 1966a, unpubl.).

A Rb/Sr determination on a single specimen of shale from Mount Charlotte No. 1 indicates an apparent maximum age of 1170 m.y. (V. M. Bofinger, pers. comm.).

The subdivision of the Bitter Springs Formation into the Gillen and Loves Creek Members (Wells et al., 1967) is based partly on the detailed work of Banks (1964, unpubl.), principally in the northeast.

The type section of the *Gillen Member* is south of Mount Gillen, west of Alice Springs. In some areas, particularly east of the Ross River, the member is overlain unconformably by the Areyonga Formation. The member consists mainly of dolomite with subordinate sandstone, siltstone, and shale. Most of the dolomite occurs in the middle and upper parts; it is dark grey, bluish grey, or grey-brown, fine-grained, laminated, closely jointed and fractured, and weathers grey-green. Veins of quartz, calcite, and earthy magnesite occur in places. Schmerber (1966a, unpubl.) and Schmerber & Ozimic (1966, unpubl.) consider that the dolomite in the Gillen Member is primary because of its relationship with the sulphate, silica, and halite deposits. Siltstone occurs mostly near the base; it ranges from white or green to red or brown, is slightly micaceous and laminated to thin-bedded, and contains interbeds of green micaceous shale. A little friable kaolinitic sandstone is also found near the base. The prominent 200-foot bed of sandstone and granule conglomerate near Limbla homestead contains halite pseudomorphs in places. Halite pseudomorphs are also common in the siltstone, and large 'hopper'*-shaped forms up to 3 inches across were noted. Brecciated and plastically deformed gypsum and anhydrite are present in the Ringwood Dome (Fig. 64). Most of the gypsum in the Amadeus Basin is associated with the Bitter Springs Formation, and the halite encountered in well sections was probably derived from the Gillen Member.

The *Loves Creek Member* rests conformably on the Gillen Member and is overlain disconformably or unconformably by the Areyonga Formation; 18 miles southwest of Alice Springs it is overlain disconformably by the Pertatataka Formation. Ellery Creek is the type locality, but the reference section (Wells et al., 1967) has been compiled from several localities. The member consists mainly of siltstone with interbeds of chert, dolomite, and rare limestone. The siltstone is red-brown, poorly bedded, and commonly calcareous; it is characterized by the presence of white bleached spots. Hematite concretions and chert are common. The dolomite is laminated and fine-grained, and contains interbeds of edgewise conglomerate and chert. Rare thin beds of limestone, commonly containing algae, are interbedded with the red siltstone. The limestone is dark grey or white and cavernous, and contains elongated nodules of chert. The dolomite is grey-brown and fine-grained, and contains abundant *Collenia*-like algae.

Most of the Bitter Springs Formation cropping out in the central and western parts of the basin probably belongs to the Loves Creek Member because the dolomite is usually rich in stromatolites and commonly contains interbeds of red-brown spotted siltstone.

Fine-grained oligoclase-albite spilites are present below, interbedded with, or above the Loves Creek Member. They only crop out east of Alice Springs and were intersected in the Ooraminna No. 1 well. The volcanics are generally deeply weathered, and are interbedded with and overlain by ferruginous and cherty fine-grained sediments, up to 5 feet thick.

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* Read, 1960, p. 216 (Rutley's Elements of Mineralogy).

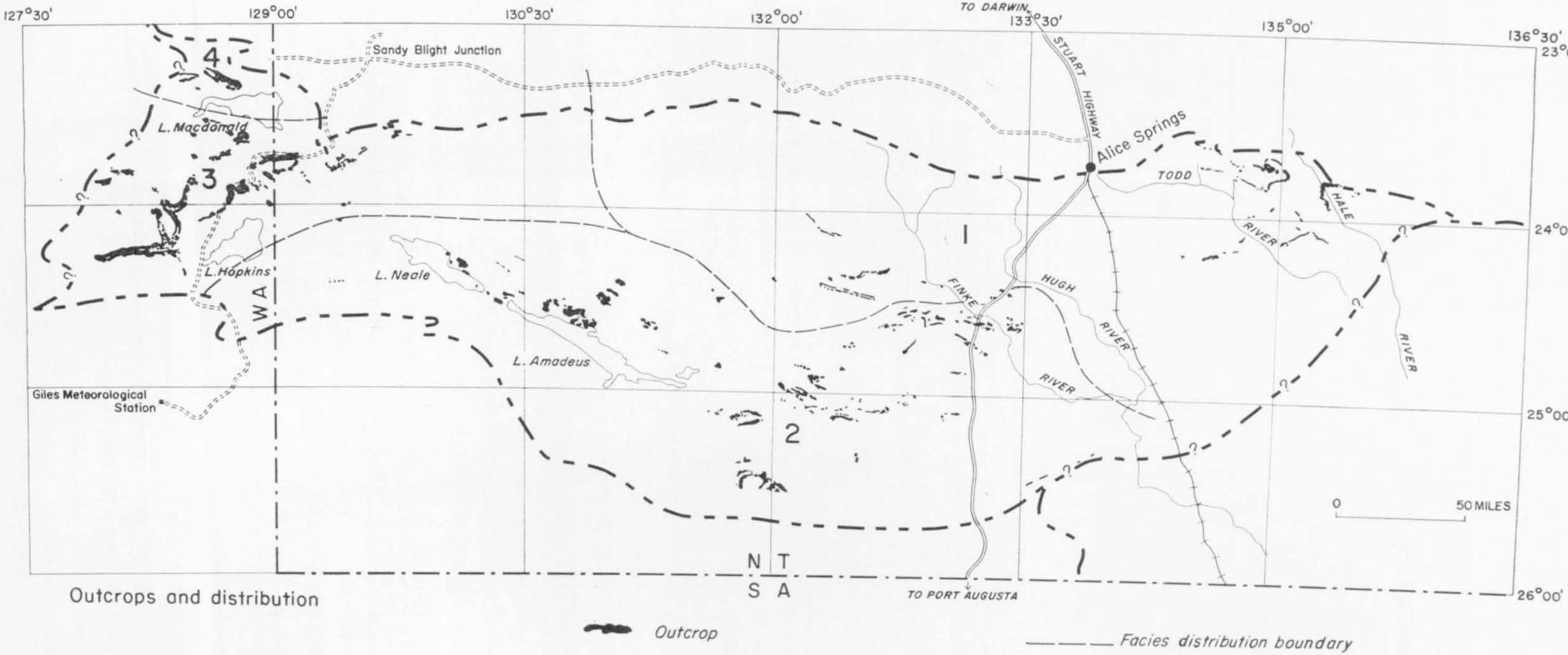
The sequence of dolomite, limestone, and siltstone which conformably overlies the Dean Quartzite in the southwest is defined as the *Pinyinna Beds* (Forman, 1966c). The limestone contains a few poorly preserved stromatolites. The beds are the infolded and metamorphosed part of the Bitter Springs Formation within or adjoining the Petermann Ranges Nappe. They are unconformably overlain by the Mount Currie Conglomerate. In the type section, a basal siltstone up to 700 feet thick overlies the Dean Quartzite, and is overlain by fine and medium-grained laminated dolomite, stromatolitic dolomite, and fine-grained limestone. The siltstone is more widely distributed than the carbonate rocks in the cores of many of the isoclinal and recumbent folds.

The Pinyinna Beds, which are commonly brecciated, contorted, and silicified, were metamorphosed during the Petermann Ranges Orogeny in the late Precambrian or early Cambrian. In the Petermann Ranges Nappe they are commonly sheared and recrystallized to medium-grained lineated schist, slate, micaceous slate, phyllite and in some places to quartz-sericite schist (Forman, 1966c). Chlorite and talc were produced by the metamorphism of the Pinyinna Beds and quartz-biotite-actinolite-epidote in the mafic rocks within the Pinyinna Beds. The carbonate rocks in the Beds have been altered to quartz-talc-dolomite schist, calcite schist, dolomite schist and quartz-chlorite-sericite-carbonate schist, and the interbedded siltstone to quartz-sericite schist (Forman, 1968, unpubl.).

Palaeogeography and Geological History

The Heavitree Quartzite, Dean Quartzite, Bitter Springs Formation, and Pinyinna Beds form a continuous sheet in the Amadeus Basin and were deposited over large areas beyond its present margin, some probably as far west as the Gibson Desert and as far north as the Ngalia Basin (Wells et al., 1968, unpubl.), but there are no indications that they were deposited in the Georgina Basin to the northeast.

The Precambrian basement was uplifted and eroded before the deposition of the basal beds of the Proterozoic succession. The Heavitree Quartzite and Bitter Springs Formation and their equivalents were deposited in a relatively stable shallow-marine environment. The Heavitree Quartzite was deposited as a blanket sand on the irregular basement floor of a shallow sea. As sedimentation proceeded parts of the sea became partly or totally landlocked, and in the barred basins and lagoons so formed, lutites and carbonate rocks, interspersed with evaporites, were laid down. The evaporites accumulated in local barred basins during the early stage of deposition of the Bitter Springs Formation. The line of gypsum occurrences southeast of Johnstone Hill may represent one or more interconnected basins of restricted circulation, although it can also be explained as a structural feature. The Bitter Springs Formation is characterized by a marked cyclical repetition of beds which represent stages in the restriction of a seaway and in the concentration of soluble salts. The presence of glauconite, phosphate, pyrite, and bituminous matter indicates shallow anaerobic conditions, ranging from a saline environment in a silled basin to a marine environment. The beds of shale and siltstone and numerous fine streaks of sandstone represent periods when detrital material was introduced. Halite and rhythmic interbeds of anhydritic dolomite and anhydrite were deposited in an initial highly saline sea; the saline deposits were followed by penesaline deposits of fine laminated dolomite and anhydrite, and finally by marine algal dolomite and fine detrital material.



Outcrops and distribution

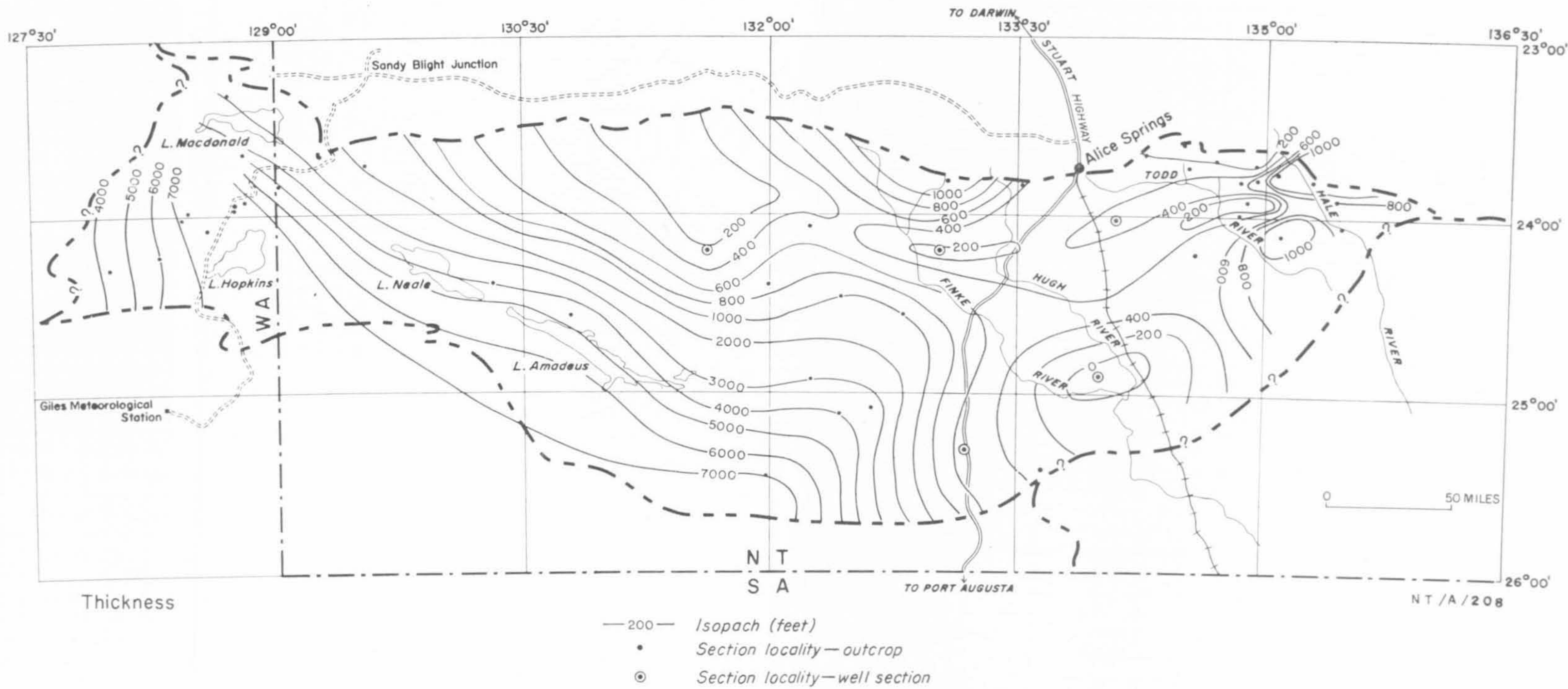


Fig. 10. Outcrops, distribution, and thickness of (1) Areyonga Formation (sandstone-conglomerate-carbonate facies), (2) Inindia Beds (sandstone-shale-chert facies), (3) Carnegie Formation (sandstone facies), and (4) Boord Formation (shale-carbonate-conglomerate facies).

Areyonga Formation, Inindia Beds, and Carnegie Formation and Boord Formation

The Areyonga Formation, Inindia Beds, and the Carnegie and Boord Formations have a similar stratigraphical position and environment of deposition, and were probably for the most part contemporaneous. Their distribution, lithology, and thickness are shown in Figure 10.

The sequence of siltstone and quartz greywacke at Ellery Creek which disconformably overlies the Bitter Springs Formation and is conformably overlain by the Pertatataka Formation was named the *Areyonga Formation* by Prichard & Quinlan (1962). In the central part of the basin the formation is overlain unconformably by the Pertaoorrta Group.

The Areyonga Formation crops out only in the centre and northeast and along the northern margin. It extends from the Parana Hill Anticline in the west to the Hale River in the east, a distance of 225 miles, and southwards to near the Chandler Range, about 70 miles southwest of Alice Springs. It has also been intersected in the East Johnny Creek No. 1 well, in which it lies unconformably below the Pertaoorrta Group.

The formation consists of boulder clay, pebble, cobble, and boulder conglomerate, arkose, poorly sorted siltstone, lithic or feldspathic sandstone, and dolomite. The dolomite commonly contains abundant chert, and the sandstone is cross-bedded in places. The sediments are immature. The boulders in the conglomerate range up to about 6 feet across. Arkose is prominent at the base of the formation in the northeast, and in places a thin bed of phosphate rock (Pl. 5, fig. 1) occurs at the contact with the underlying Bitter Springs Formation.

The lithology varies considerably, and the formation is characterized by the lenticular nature of the beds. The thickest section is probably north of Limbla homestead, where 1900 feet was estimated. In the central part of the basin the increase in thickness towards the south (500 feet at Areyonga and 1000 feet at Tempe Downs) is accompanied by an increase in the proportion of sandstone. In this area, a sequence of siltstone with chert interbeds is commonly exposed towards the base.

At Ellery Creek, the formation consists of two members (Prichard & Quinlan, 1962). The lower member is 750 feet thick and consists of interbedded tillitic siltstone, pebble conglomerate, and quartz greywacke. The erratics include many rock types and are mostly rounded; many are faceted and striated. In the Hermannsburg Sheet area, the lower member crops out between 8 Mile Gap and a point 9 miles east of the Finke River, and near Areyonga. The upper member, which consists of 550 feet of current-bedded quartz greywacke, is much more widespread; it crops out between Jay Creek and a point 1 mile west of the Finke River, and at Areyonga. Both members probably extend beyond the area mentioned, but have not been recognized because of the paucity of outcrops.

The fossils include algal stromatolites in the dolomite, pipe rock in a sandstone near Areyonga Native Settlement, and a possible fossil in a sandstone west of Alice Springs (figured by Wells et al., 1967).

Prichard & Quinlan (1962) consider that the whole of the Areyonga Formation in the Hermannsburg area is the product of a marine glacial environment. In other areas, however, there is evidence of several different conditions of sedimentation. In the Ooraminna No. 1 well (Schmerber, 1966a, unpubl.), for example, the lower arenaceous and calcareous sediments probably accumulated in a paralic environment with intercalations of marine oolitic dolomite. The pyritic siltstone with organic matter in the middle part of the well section indicates euxinic conditions, and the carbonate rocks in the upper part are shallow marine. The presence of phosphate in the formation in the northeast suggests a marine environment.

The *Inindia Beds* (Ranford et al., 1966) crop out in the south. They comprise a very varied sequence which disconformably or unconformably overlies the Bitter Springs Formation and is unconformably overlain by the Winnall Beds, Pertaoorrta Group, Larapinta Group (principally the Stairway Sandstone), and Finke Group. In the west, outcrops doubtfully referred to the Inindia Beds are unconformably overlain by the Mount Currie Conglomerate.

The Inindia Beds crop out between the Souths Range in the west and the Black Hill Range in the east, a distance of 290 miles. The original reference areas listed in Ranford et al. (1966) are amended here: the northern slopes of Mount Conner are nominated as the reference area for the upper part of the formation and the area 12 miles northeast of Curtin Springs homestead for the lower part.

The Inindia Beds include at least eight intervals of sandstone, most of which are less than 100 feet thick. Siltstone is also common. In the central-southern part of the basin a 7000-foot sequence has been described by Wells et al. (1966). A tillitic siltstone has been recorded in several localities: the erratics include quartzite, black oolitic chert, jasper, siltstone, banded chert, silicified dolomite, and rare fragments of igneous rocks. Beds of stromatolitic dolomite, up to 50 feet thick, crop out in the west.

Most of the formation is probably marine, but towards the end of this period of deposition, glacial conditions prevailed, and the overlying thickly cross-bedded coarse arenites may be terrestrial deposits. Halite pseudomorphs have been reported in the siltstone near Dead Bullock Dam north of the Seymour Range and thin interbeds of sandstone with scattered grains of glauconite occur a few miles northwest of Palmer Valley homestead, but these occurrences appear to be exceptional. Chert is abundant near the base of the Inindia Beds; it is commonly oolitic and was probably formed by replacement of oolitic carbonate rocks. The sandstone in the Erldunda No. 1 well (Schmerber, 1966d, unpubl.) contains rare glauconite, phosphate pellets, tourmaline, and zircon, and the calcareous shale contains abundant organic(?) material. These sediments are considered by Schmerber to be marine shelf deposits. Sandstone is predominant in the well section, but contains a few interbeds of dark siltstone and thin-bedded dolomite.

The *Boord Formation* disconformably overlies the Bitter Springs Formation in the west. It was named and defined by Wells et al. (1964); the type section is at Boord Ridges. The formation is probably conformably overlain by the Ellis Sandstone and interfingers with the Carnegie Formation. The greatest thickness measured is about 2800 feet.

The base of the formation is marked by a persistent zone of mounds of debris composed of angular fragments of chert, ferruginous material, and limestone, weathered out of a basal breccia derived from the underlying Bitter Springs Formation. The breccia is overlain by pebbly sandstone and calcareous sandstone, followed by about 250 feet of tillitic pebble and boulder conglomerate. The conglomerate contains fragments of algal limestone, sandy limestone, dolomite, fine conglomerate, chert, quartz sandstone, quartzite, jasper, vein quartz, schist, and quartz-feldspar porphyry, up to 8 feet across, set in a matrix of sandstone. Many of the phenoclasts are faceted and a few are striated.

The upper half of the formation consists of stromatolitic calcilutite and calcarenite which are partly oolitic. The calcareous rocks are interbedded with siltstone and shale, which probably predominate.

The basal boulder beds have many of the characteristics of glacial* sediments, and the overlying siltstone and stromatolitic carbonate rocks were deposited in a shallow-marine environment. Most of the coarse detritus derived from the south was deposited nearer the source to form the Carnegie Formation, and only the fine detritus reached the northern area, where the Boord Formation was deposited. The glacial boulder beds in the west appear to have been restricted to the northern edge of the basin, and were probably deposited in a shallow sea on a stable foreland.

The *Carnegie Formation* disconformably overlies the Bitter Springs Formation and is conformably overlain by the Ellis Sandstone and Sir Frederick Conglomerate. It was named by Wells et al. (1964). South of Ligertwood Cliffs, the Carnegie Formation underlies the Cleland Sandstone, but no contacts were seen. The formation is found only in the west — the most easterly outcrops are about 6 miles southwest of Mount Rennie. In the Mount Rennie Sheet area the formation contains beds of conglomerate with phenoclasts of dolomite probably derived from the Bitter Springs Formation.

The Carnegie Formation consists of sandstone, quartz sandstone, siltstone, and minor shale. It interfingers with the Boord Formation and has a maximum measured thickness of over 4000 feet. Clay pellets, ripple marks, and cross-bedding are common throughout the section. The arenites contain up to 20 percent of fragments of quartzite, chert, and fine sericitic quartzite. In places, the sediment has a calcareous cement and, rarely, contains up to 50 percent granular calcite. The current-bedding indicates movement from the west or southwest. The formation was probably deposited in a deltaic or paralic environment in a rapidly subsiding part of the basin where abundant detritus was available from the south.

Correlation and Age

The Boord and Carnegie Formations are correlated with the Areyonga Formation and Inindia Beds (Fig. 7). The presence of what appear to be glacially derived rudites at the base of the Boord Formation and in the upper part of the Inindia Beds, and the abundant evidence of glaciation in the Areyonga Formation, support the correlation. The upper part of the Boord Formation may be equivalent to part of the Pertatataka Formation, and the overlying Ellis Sandstone may be

* The general term glacial beds, sediments, and deposits etc. is used to denote rocks with a particular texture and fabric and implies a particular type of environment. They contain phenoclasts of a variety of rock types, which vary in size and show evidence of glacial abrasion, set in a matrix of poorly sorted silt and clay with variable proportions of angular quartz sand, and many other minerals. The deposits are generally unstratified. The proportion of matrix is generally greater than the phenoclasts.

Many of these sediments were probably deposited in the fringing meltwater environment of a glacier and the term periglacial could be used for the areas, conditions, processes, and deposits. As the depositional environment of most of these is not known with any certainty the general term is preferred.

equivalent to part of the Winnall Beds, a sandy facies of the Pertatataka Formation. It is possible, therefore, that the Winnall Beds may be equivalent to part of the Carnegie Formation, but the first interpretation is preferred (see also p. 40).

Palaeogeography and History of Deposition

The greatest thickness of the Inindia Beds and Carnegie Formation is preserved in a depression in the southwest and south. The area of maximum sedimentation is separated from the northern shelf area (where the Areyonga Formation is of comparatively small thickness) by an east-west eroded linear zone near the centre of the basin, where the sediments are thin or absent. The east-west zone was probably the hinge-line along the northern edge of the subsiding depression.

The Areyonga Formation was deposited on a shelf in a predominantly paralic environment. The rapid changes in lithology suggest periods of highly oxygenated shallow water alternating with periods of more stagnant water. Periodic influxes of glacial sediment may have lifted the surface of deposition above sea level. The changes in environment and the irregular topography of the depositional surface account for the remarkable variations in thickness and the abrupt changes in lithology. The boulders in the Areyonga Formation show that the Heavitree Quartzite, Bitter Springs Formation, and Arunta Complex were exposed in the glaciated land masses to the north.

In the west, glaciation ceased after the deposition of a thin basal part of the Boord Formation, and deposition continued in a shallow sea on a stable foreland.

The influence of the glacial period on the type of sediments deposited is more pronounced in the shelf area, and the sediments in the depression show only minor evidence of glaciation. The clastic red-beds of the Carnegie Formation are laterally equivalent to the Boord Formation, but there is no evidence that the glacial environment extended into areas where the Carnegie Formation was deposited.

The Inindia Beds are a thick pile of sediments deposited in the subsiding depression. They include a thin boulder clay horizon below the topmost sandstone. If there was only one glacial episode throughout the basin during the deposition of the Areyonga Formation and Inindia Beds, then sedimentation after the Bitter Springs Formation was probably initiated in the subsiding depression. The oolitic and fragmental texture of many of the beds of chert in the basal part of the Inindia Beds suggests that they were probably deposited as oolitic and fragmental limestones in shallow agitated water, and were subsequently silicified.

The red colour of some of the silt and clay in the lower part of the Inindia Beds was probably produced by the alteration in situ of iron-bearing detrital grains in the intertidal and subtidal parts of a desert basin in a similar fashion to that proposed by Walker (1967). They were probably deposited in sluggish streams, or in lakes on broad alluvial plains, or transported by streams and deposited in a marine delta. The thick sequences of sandstone in the upper part of the Inindia Beds, possibly indicate renewed uplift of the provenance area, an increase in the rate of sedimentation, and rapid filling of the subsiding depression with coarse detritus. The youngest arenites in the Inindia Beds may be continental. In the southeast, the thickness and lithology of the sandstone suggests deposition on a marine shelf (Schmerber, 1966d, unpubl.).

In the west, the subsiding depression was possibly closer to the source, where a thick wedge of sandstone (Carnegie Formation) was deposited. Its uniformity suggests that sedimentation kept pace with subsidence. Diastrophism occurred after the deposition of the Inindia Beds, and in a few places most of the sequence was eroded away before the Winnall Beds were deposited.

The central east-west eroded zone (Figs 11, 12), which separates the sediments on the shelf from those in the depression, represents a hinge-line along which the rate of subsidence changed (see p. 43). The Proterozoic sediments along the zone and to the south were folded during the Petermann Ranges orogeny and a large thickness subsequently eroded. Structural growth possibly continued in some areas during Palaeozoic sedimentation. The arching of the sediments along this zone was probably accentuated by décollement folding, accompanied by the movement of salt from the Bitter Springs Formation into the cores of the anticlines. The hinge-line possibly extends into the northwestern part of the basin, but there are very few outcrops of equivalent Proterozoic sediments to define its position.

The reduced thickness of the Areyonga Formation in the hinge area may have been due to the existence of a ridge during deposition, structural growth during sedimentation, erosion of part of the formation, or complete removal from the crests of anticlines after folding. The rapid variations in thickness of the formation beyond the areas which were strongly affected by the Petermann Ranges Orogeny suggest the presence of a high ridge along the hinge-line; an angular unconformity, whose surface is somewhat irregular, can be seen in places at the base of the Areyonga Formation. The isopachs on the Areyonga Formation (Fig. 10) show that the zone in which the formation is thin or absent trends into the northeastern part of the basin, where the effect of the Petermann Ranges Orogeny was more subdued. Hence erosion of the formation from high areas produced by the orogeny may be only part of the reason for the presence of a zone of thin sediments. The possibility of structural growth during sedimentation along the hinge-line cannot be proved because of the unconformity at the top of the formation, and there is little likelihood of tracing marker beds within the formation.

Pertatataka Formation, Winnall Beds,
Ellis Sandstone, Sir Frederick Conglomerate, and Maurice Formation

The Pertatataka Formation, Winnall Beds, Ellis Sandstone, Sir Frederick Conglomerate, and Maurice Formation are for the most part laterally equivalent. The distribution of outcrops, isopachs, and facies distribution are shown in Figure 11.

The *Pertatataka Formation* (Prichard & Quinlan, 1962) lies conformably on the Areyonga Formation, and is apparently conformable under the Arumbera Sandstone: at Ellery Creek the presence of thin beds with pellets of green siltstone in the base of the Arumbera Sandstone suggests that the upper contact is disconformable. South of the MacDonnell Ranges there is an unconformity between the Pertatataka Formation and the Arumbera Sandstone, Eninta Sandstone, and the Chandler Limestone. In the northeast, the Pertatataka Formation locally overlies the Bitter Springs Formation, and in places it is possibly overlain unconformably by the Pertnjara Group.

In the northeast between Jay Creek Native Settlement and Ringwood homestead, two members of the Pertatataka Formation, the Julie and Cyclops Members, have been distinguished by Wells et al. (1967). South and southeast of Ringwood homestead, as far as the Rodinga Range, five members have been defined and mapped. From top to bottom they are the Julie, Waldo Pedlar, Olympic, Limbla, and Ringwood Members. In the Ooraminna Anticline and Phillipson Pound only the Julie Member is exposed.

The members have not been distinguished over most of the basin, although the Julie Member, which comprises mainly carbonate rocks, is undoubtedly present in many of the outcrops.

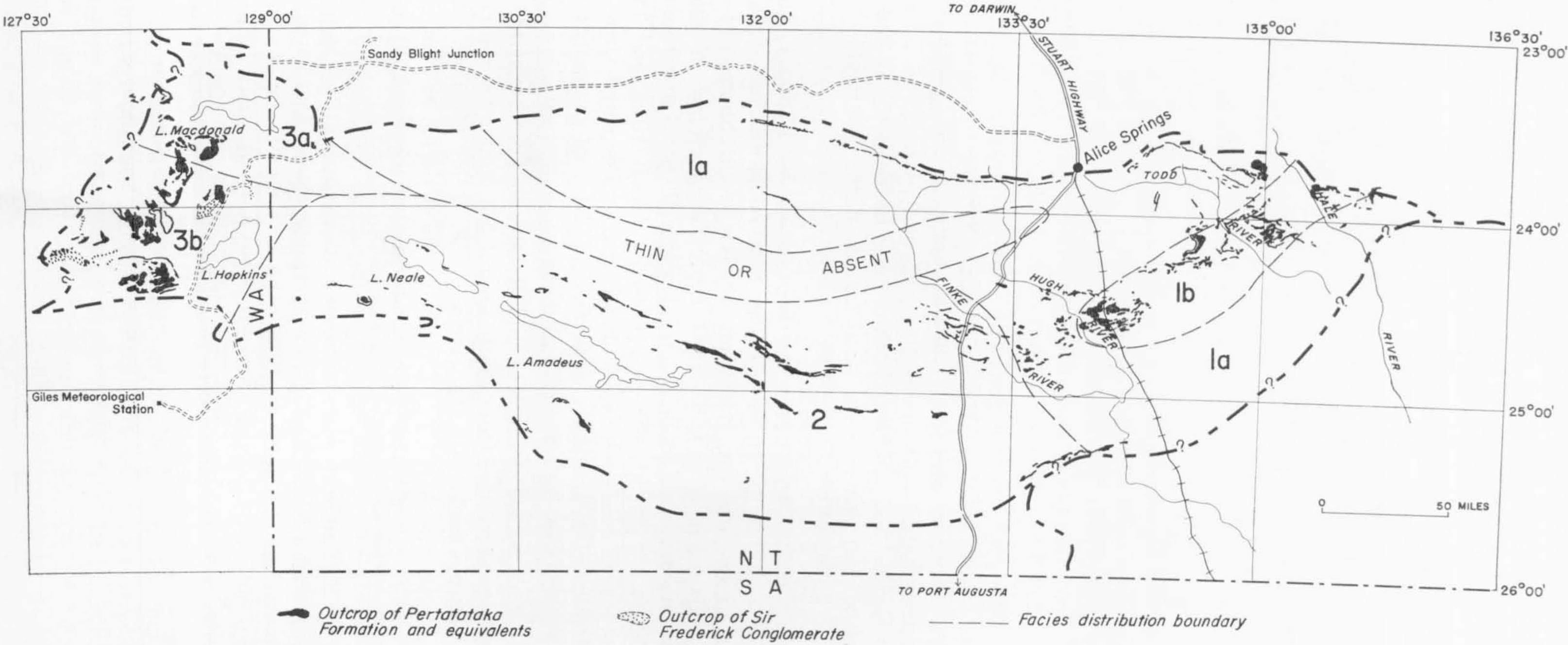
The type section of the Pertatataka Formation is in an area where the members have not been differentiated. The main outcrops, where the formation has not been subdivided, are described first, and the minor area of outcrops in the northeast, where several members have been defined, are described separately.

Siltstone is predominant but it is generally poorly exposed in the floor of wide alluviated valleys. In the Gardiner Range, lobate rill marks occur in the siltstone near the top of the sequence, and some beds are slumped. The sandstone overlying the siltstone is fine-grained, well sorted, chloritic, and pyritic, and contains some muscovite, green biotite, and apatite. The limestone near the top of the formation is commonly oolitic and stromatolitic, and much of the interbedded sandstone at Ellery Creek is glauconitic.

In the type section at Ellery Creek the Pertatataka Formation is about 2200 feet thick. To the west, the thickness increases to about 4500 feet at Stokes Pass; to the east it is fairly uniform, but south of Ringwood homestead it rapidly increases to a maximum of about 7000 feet. The increase in thickness is accompanied by an influx of coarser detrital material, pelletal carbonate rocks, and boulder beds with glacial affinities. Between Haast Bluff and the Idirriki Range the formation is coarser in grain and consists of isolated strike ridges of fine thin-bedded micaceous sandstone separated by beds of laminated micaceous siltstone.

Between Jay Creek Native Settlement and Ringwood homestead the Julie and Cyclops Members are separated from the base and top of the formation and from each other by varying thicknesses of siltstone. The *Julie Member* consists predominantly of carbonate rock (Pl. 6, fig. 1) with sandstone lenses, and the *Cyclops Member* consists of fine laminated flaggy sandstone and rhythmically thin-bedded sandstone.

Schmerber (1966a, unpubl.) and Schmerber & Ozimic (1966, unpubl.) have described the Pertatataka Formation in the Ooraminna No. 1 and Mount Charlotte No. 1 wells. Grey-green and rare red-brown finely laminated shale and siltstone predominate. The sediments contain from 20 to 80 percent quartz, muscovite and rare green biotite, and are cemented by chlorite, illite(?), limonite, hematite, pyrite, and organic(?) matter; minute dolomite crystals occur throughout. Sandstone occurs in fine laminae composed of fine angular well sorted grains of quartz, some potash feldspar, rare albite, fragments of igneous rocks and sericitized rocks, and rare muscovite. Authigenic glauconite is associated in part with phosphatic grains and opaque minerals; a little tourmaline, zircon, and apatite are present. The cement consists of chlorite, kaolinite, sericite, intergranular quartz, and rare



Outcrops and distribution

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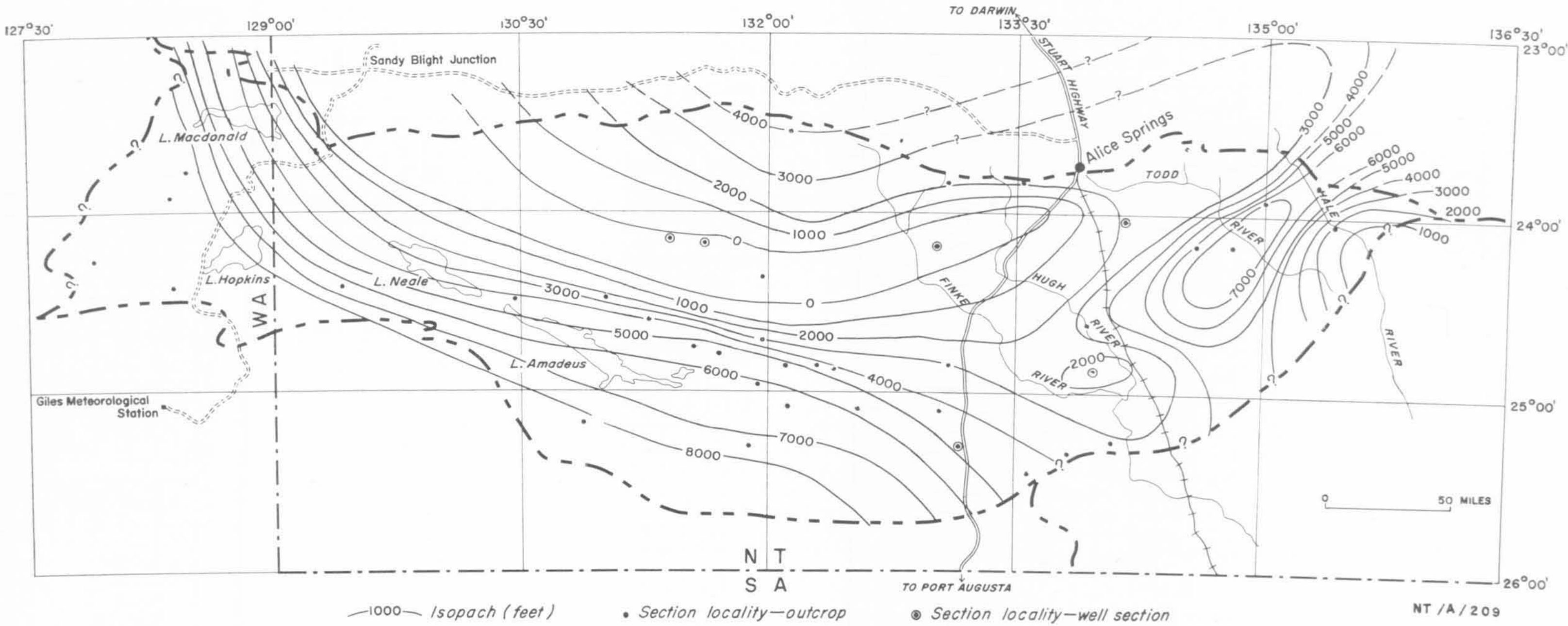

Thickness

Fig. 11. Outcrops, distribution and thickness of (1) Pertatataka Formation (1a, siltstone-shale facies; 1b, sandstone-conglomerate-limestone facies), (2) Winnall Beds (sandstone-shale facies), (3) Maurice Formation/Sir Frederick Conglomerate/Ellis Sandstone (3a, finer-grained, better sorted sandstone-conglomerate facies; 3b, coarser-grained, poorly sorted sandstone-conglomerate facies).

dolomite. The presence of glauconite and phosphate in the sandstone suggests a neritic environment on a stable shelf. The thick shale and siltstone probably accumulated in a reducing environment under quiet conditions and possibly in slightly deeper water. Age determinations by the Rb/Sr method were made on two samples of the Pertatataka Formation from well cores. The sample from Ooraminna No. 1 gave an age of 760 m.y. and the sample from Mount Charlotte No. 1 gave an age of 822 m.y. (V. M. Bofinger, pers. comm.).

The Julie Member was penetrated in Ooraminna No. 1 (Schmerber, 1966a, unpubl.), but not in Mount Charlotte No. 1. The lower beds are poorly sorted sandstone and the upper are dolomitized limestone. The upper part of the sandstone is similar to the overlying Arumbera Sandstone; it is ferruginous and contains abundant biotite and altered chlorite. The cement consists of hematite, silica, and euhedral dolomite. Dark green chloritic siltstone, cryptocrystalline limestone, and dolomitized sandy limestone occur as interbeds. The lower part of the sandstone contains quartz (30-70%), microcline, and muscovite set in a matrix of cryptocrystalline calcite and microcrystalline dolomite. The upper beds consist of recrystallized microcrystalline dolomitized limestone with thin oolitic bands, abundant rounded to angular grains of quartz (0.1-2 mm), orthoclase, microcline, lithic fragments, muscovite, and altered biotite. A little pyrite, rounded tourmaline, and hematite are present.

The Julie Member has been mapped as far west as Jay Creek Settlement and southwards into the Rodinga Sheet area. It has been recognized but not mapped in the eastern MacDonnell Ranges and in the Gardiner Range. Along the northern part of the Gardiner Range the siltstone is poorly exposed. Two separate ridges are present: the upper consists predominantly of carbonate rock which is identified as the Julie Member; the lower consists of laminated silicified platy sandstone which is tentatively identified as the Cyclops Member.

The thick sequence of the Pertatataka Formation in the northeast, south and southeast of Ringwood homestead, has been divided into five members by Wells et al. (1967).

The Julie Member persists into the region of maximum thickness of the formation with little lithological change (Fig. 7), but the Cyclops Member has not been recognized south of Ringwood homestead. It is not known therefore whether deposition of the Pertatataka Formation began in the northeast before the sequence farther west was laid down, or whether sedimentation was approximately synchronous throughout the basin. The members of the Pertatataka Formation in the northeast are (from top to bottom) as follows:

The *Julie Member* (1800 ft) forms ridges consisting of dark grey oolitic dolomite and limestone containing poorly preserved stromatolites. Thick lenses of sandstone are present, usually towards the base (Pl. 6, fig. 2), and there are a few interbeds of siltstone.

The *Waldo Pedlar Member* (200± ft) crops out in rounded low hills of silicified sandstone. The sandstone is thin-bedded, fine-grained, flaggy, and dark green-grey, and contains ripple and current flow markings.

The *Olympic Member* (630 ft) comprises lenticular beds of sandstone, siltstone, conglomerate, shale, boulder clay, and dolomite. The topographic expression is variable. The sandstone is commonly marked by weathered-out clay pellets (Pl. 7, fig. 1). The thin beds of pink and grey dolomite at the top of the member are fine-grained and laminated, and contain manganese stains and pseudomorphs after pyrite. The conglomerate and boulder clay contain phenoclasts of dolomite, sandstone, quartz, and a variety of igneous and metamorphic rocks. Many of the clasts are striated and soled, and the matrix ranges from poorly sorted siltstone to edgewise conglomerate composed of thin plates of dolomite (Pl. 7, fig. 2), and coarse angular granules of milky quartz.

The *Limbla Member* (470 ft) is probably disconformable under the Olympic Member, in which fragments of it occur. The upper part consists of cross-laminated and convolute laminated fine-grained sandstone (Pl. 8, fig. 1) and the lower part is sandy calcarenite and minor siltstone, slumped sandstone, and intraformational conglomerate.

The *Ringwood Member* (540 ft) is characterized by cherty algal dolomite (Pl. 8, fig. 2) overlain by cross-laminated fragmental dolomite, limestone, and calcarenite (Pl. 5, fig. 2). A little interbedded siltstone occurs, particularly near the base.

The members are separated from each other and from the overlying and underlying formations by siltstone, with the exception of the Olympic and Limbla Members, which are probably separated by a disconformity. Even where all six members are present in the Pertatataka Formation siltstone is predominant (see Fig. 7). The presence of tillitic beds in the Olympic Member indicates a second period of Proterozoic glaciation; the beds extend southwestwards from near Ringwood homestead to the Mount Burrell area.

The *Winnall Beds* of Ranford et al. (1966) lie unconformably between the Inindia Beds and Pertaoorrta Group in the southern part of the basin. In places, they may rest directly on the Bitter Springs Formation. In the west, they are unconformably overlain by the Mount Currie Conglomerate or the Cleland Sandstone; farther east, by the Stairway Sandstone and Carmichael Sandstone of the Larapinta Group; and on the southeastern margin, by the Polly Conglomerate and Langra Formation of the Finke Group. The maximum exposed thickness is about 7000 feet. The Winnall Beds can be subdivided into four units — a basal siltstone, followed by sandstone, siltstone, and sandstone. The resistant sandstone beds form many of the prominent topographic features in the southern part of the basin — Souths Range, Longs Range, Mount Unapproachable, Mount Cowle, Winnall Ridge, Mount Conner, Kernot Range, Liddle Hills, Basedow Range, Erldunda Range, Mount Kingston, and the Black Hill Range.

The sandstone units, particularly the lower one, show a variety of ripple marks, cross-bedding, slumping, convolute laminations, mud cracks, current-lineation, groove casts, synaeresis cracks, and mud-pellet markings. The sands were probably deposited close to, and in places even across, strandlines. The 'sand sticks', 30 miles southwest of Reedy Rockhole, are comparable with *Syringomorpha* Nathorst.

The four units in the Liddle Hills area are, from top to bottom:

Unit 4 (600 ft): Sandstone, dark brown, poorly sorted, medium-bedded, moderately well exposed, silicified in places and friable in others. Contains weathered-out clay pellets, chert fragments in places, small cross-beds, ripples, and slumps.

Unit 3 (1100 ft): *Siltstone* and *silty sandstone,* poorly exposed, variegated, and thin-bedded.

Unit 2 (1800 ft): *Sandstone,* massive cross-bedded, fine-grained, silicified below; and *sandstone* above, thin to medium-bedded, coarse-grained, silicified, with interbeds of *conglomerate* containing chert fragments. 15-20 feet of basal conglomerate is present at Mount Conner. The resistant sandstone forms prominent ranges.

Unit 1 (500 ft): *Siltstone,* thin-bedded, dark; some fine-grained slightly calcareous *silty sandstone.*

Unit 2 is the most common in outcrop. In places, the lower siltstone unit is absent and unit 2 rests unconformably on the Inindia Beds. In the Henbury Sheet area unit 4 is the more consistent of the sandstone units and crops out over a wide area. The distribution of this sandstone and its proximity to outcrops of the Inindia Beds suggest that the unit 2 sandstone may only have been deposited to the south of this area.

The same four lithological units have been recognized in the Erldunda No. 1 well (Schmerber, 1967, unpubl.).

In the southeast, at the Souths Range, the basal pebble conglomerate beds at the unconformity with the Inindia Beds are well exposed. The pebbles consist of chert, feldspathic sandstone, coarse quartz sandstone, and silicified siltstone, set in a sandstone matrix. The conglomerate is overlain by a cross-laminated sandstone with cross-bedding sets up to 10 feet thick.

The beds in the Black Hill Range and at Mount Kingston have been mapped as Winnall Beds, although there is considerable variation in lithology along the strike: sandstone predominates in the west and siltstone in the east. The siltstone contains glauconite, and shows lobate rill marks, flow casts, and silt and clay pellets, and is similar in lithology to the Pertatataka Formation.

Deposition of the Winnall Beds began with siltstone laid down in slightly stagnant water with nearby peneplaned landmasses. The abrupt change to the overlying conglomerate suggests tectonic uplift of the southern source area and the erosion of the Bitter Springs Formation as well as metamorphic and igneous rocks.

The presence of glauconite and phosphate in the siltstone and sandstone (Schmerber, 1967, unpubl.) suggests that conditions approached those of a stable shelf, but the environment generally was shallow marine in a subsiding depression. The detrital content is mainly submature to mature reworked material.

Wells et al. (1964) introduced the name *Ellis Sandstone* for the sequence of kaolinitic sandstone and pebbly sandstone with subordinate calcareous sandstone and siltstone in the western part of the basin. The Ellis Sandstone overlies the Carnegie or Boord Formations, interfingers with the Sir Frederick Conglomerate, and is conformably overlain by the Maurice Formation. The contact between the Ellis Sandstone and Boord Formation is not exposed, but in most places they appear to be conformable. The greatest measured thickness is about 2000 feet. Outcrops are confined to the area between the Rawlinson Range and Lake Macdonald.

The formation consists mainly of cross-bedded kaolinitic quartz sandstone, containing up to 15 percent of metaquartzite and chert grains. The cross-beds indicate transport from the west and southwest. Current lineation, ripple marks, current crescents, slump structures, scour-and-fill structures, and laminae with heavy

Plate 1, fig. 1. Looking south towards the older Precambrian Arunta Complex in the Harts Range.

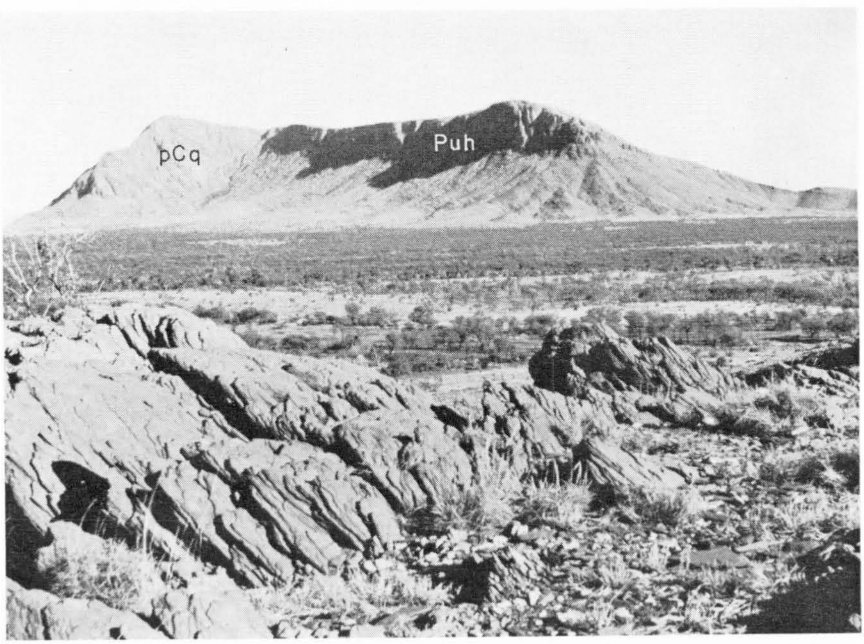

Plate 1, fig. 2. Arunta Complex metamorphics in the foreground (near Blanche Tower) and older Precambrian quartzite (pCq) overlain by Heavitree Quartzite (Puh) in the background (near Mount Palmer).

Plate 2, fig. 1. Dixon Range Beds in the Dixon Range, Western Australia. The Carnegie and Robert Ranges on the horizon consist of Dean Quartzite.

Plate 2, fig. 2. Flaggy Heavitree Quartzite, eastern scarp of Mount Leisler, in the Kintore Range.

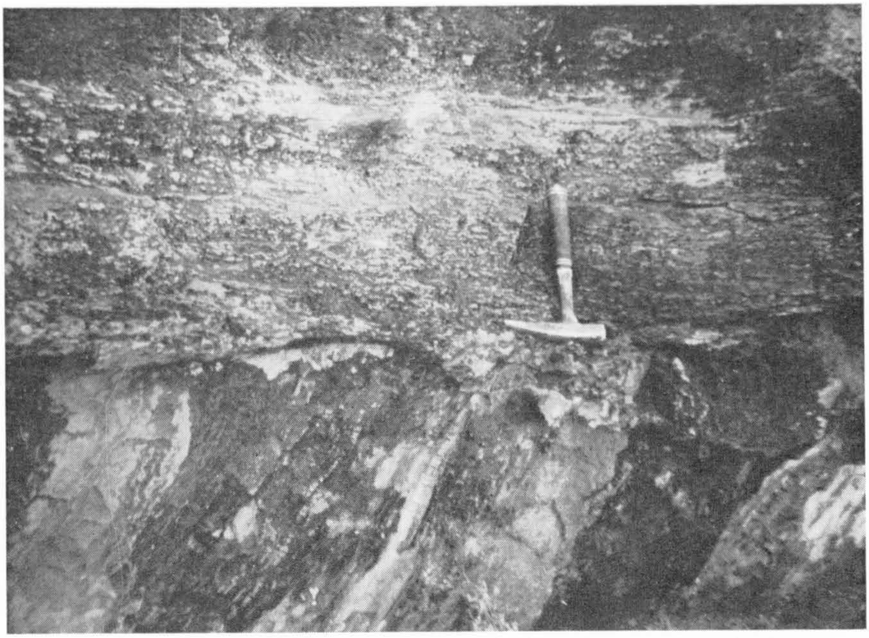

Plate 3, fig. 1. Unconformity between the Heavitree Quartzite and quartzite of the Arunta Complex (below hammer), 40 miles northeast of Alice Springs.

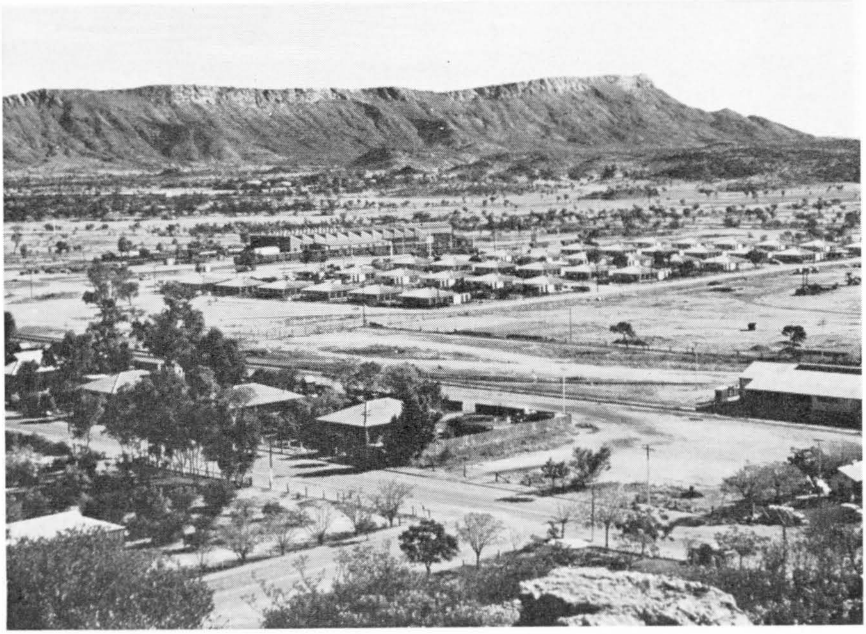

Plate 3, fig. 2. Heavitree Quartzite resting unconformably on the Arunta Complex at Mount Gillen, near Alice Springs (in foreground). The contact is just below the cliffs at the top of the scarp.

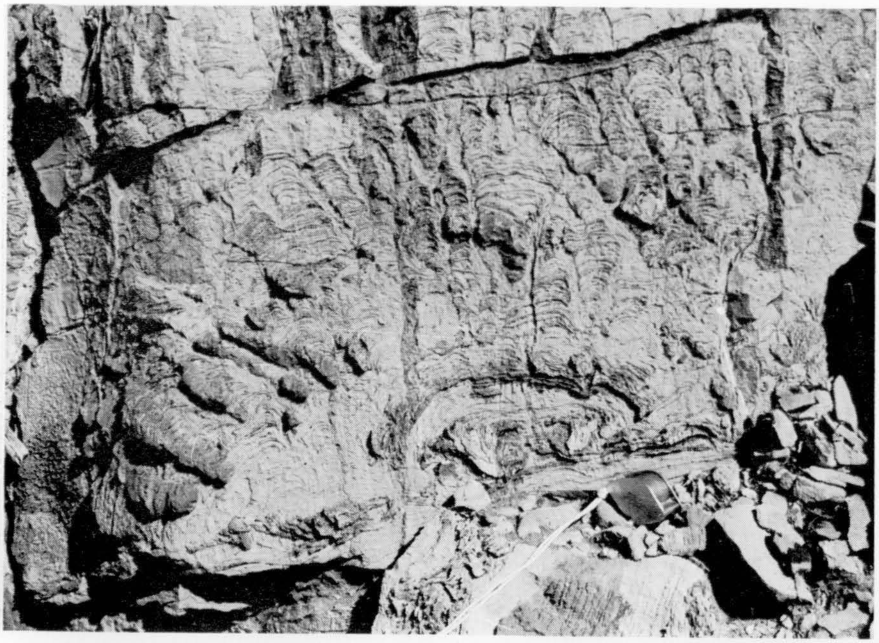

Plate 4, fig. 1. Stromatolite colony in the Bitter Springs Formation at Katapata Gap in the Gardiner Range.

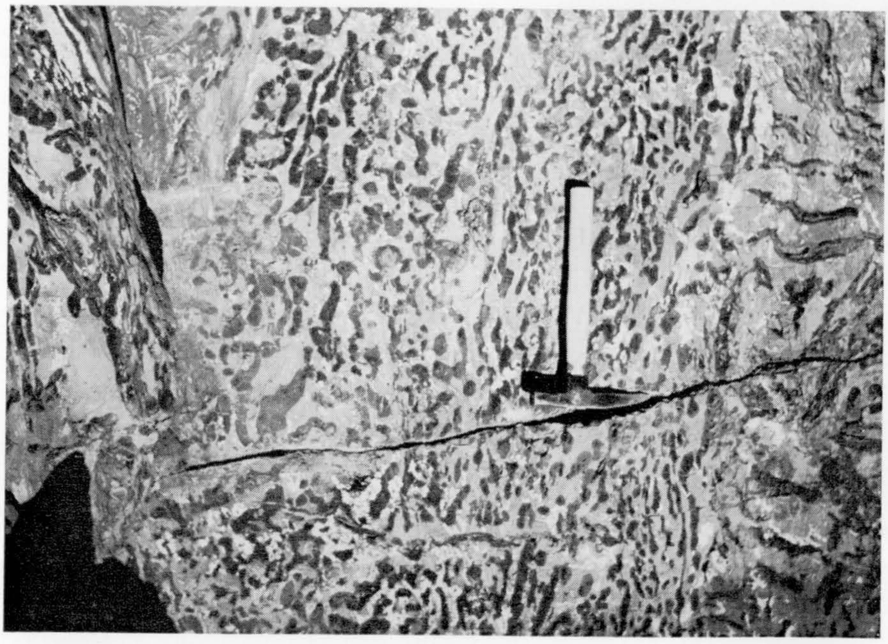

Plate 4, fig. 2. Irregular fragments of black limestone set in a matrix of grey dolomite, Bitter Springs Formation at Ellery Creek in the MacDonnell Ranges.

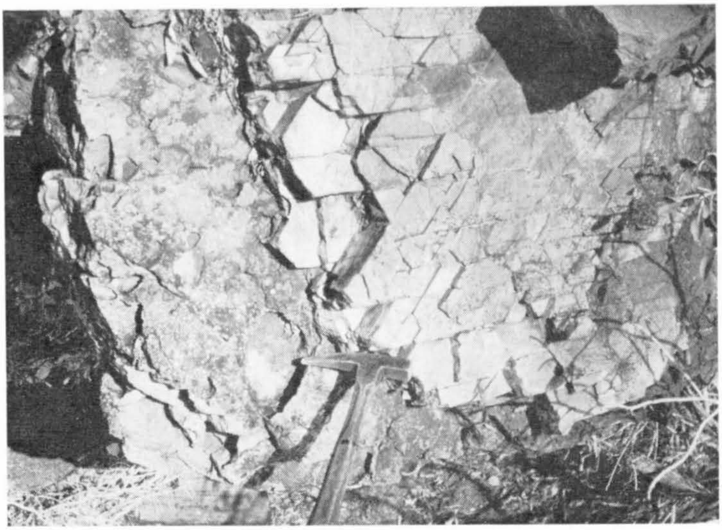

Plate 5, fig. 1. Polygonal joints in thin bed of phosphate at the base of the Areyonga Formation, 2 miles north of Pulya-Pulya Dam, 68 miles east of Alice Springs.

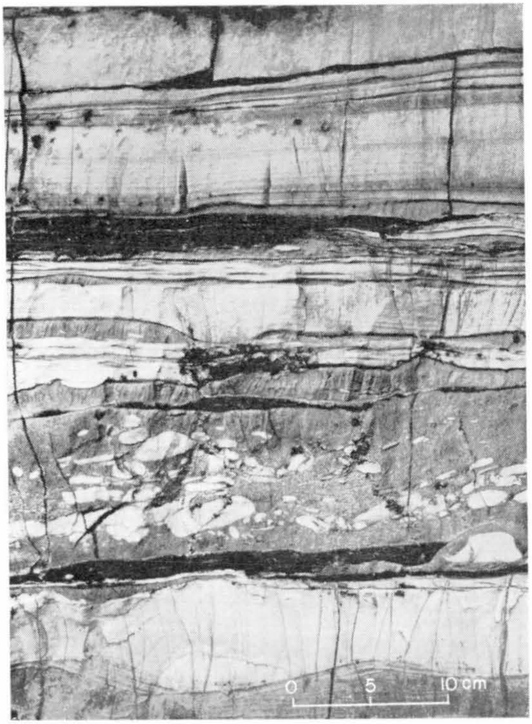

Plate 5, fig. 2. Pelletal and cross-laminated carbonate rocks of the Ringwood Member, Illogwa Creek Sheet area, 4 miles north of Limbla homestead.

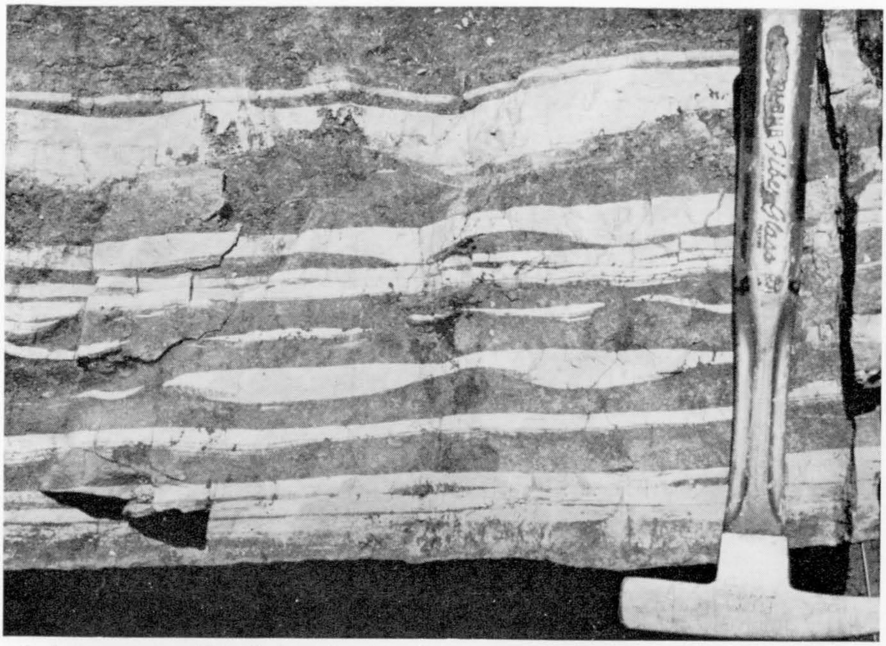

Plate 6, fig. 1. Lensoid beds in dolomite of the Julie Member, 4 miles southeast of Boxhole Bore, 54 miles east of Alice Springs.

Plate 6, fig. 2. Julie Member, eastern end of the Fergusson Syncline, 56 miles east of Alice Springs. The upper massive oolitic dolomite forms a scarp above the vertically jointed sandstone (centre) and dark thin-bedded limestone and shale (lower slope).

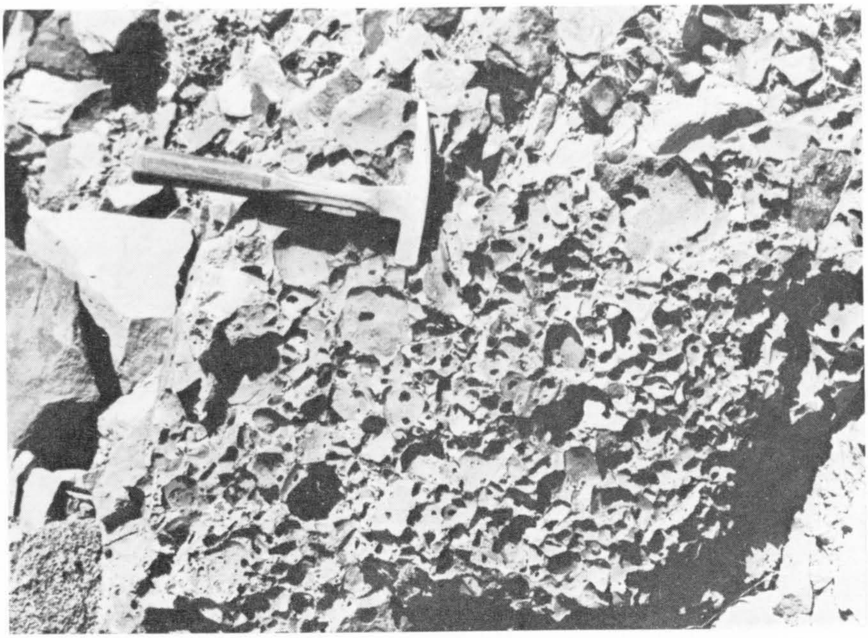

Plate 7, fig. 1. Cavities formed by weathering out of clay pellets in the sandstone of the Olympic Member, about 1 mile southeast of Olympic Bore, Alice Springs Sheet area.

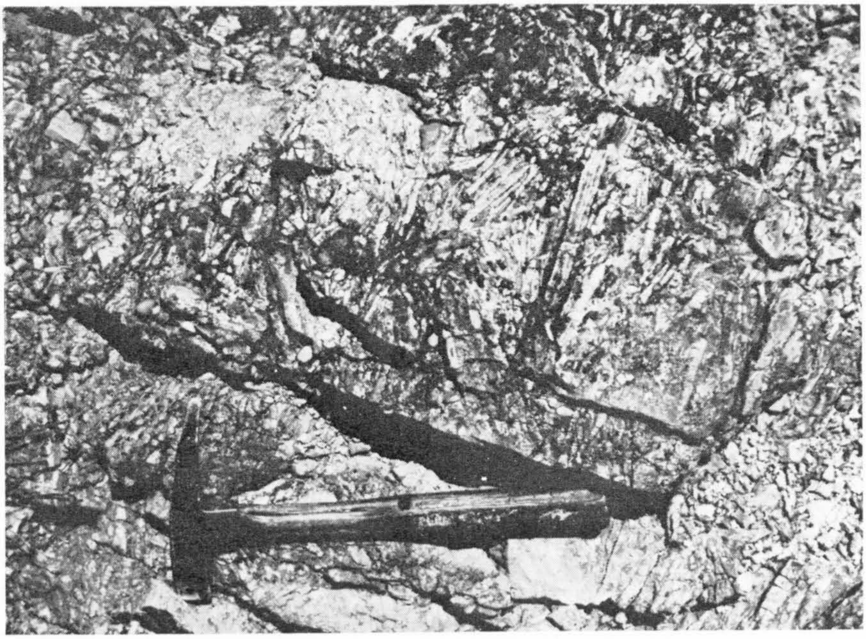

Plate 7, fig. 2. Edgewise conglomerate composed of plates of dolomite set in a matrix of coarse sand, Olympic Member, about 1 mile southeast of Olympic Bore.

Plate 8, fig. 1. Convolute lamination in sandstone of the upper part of the Limbla Member, eastern end of the Olympic Syncline, 83 miles east-southeast of Alice Springs.

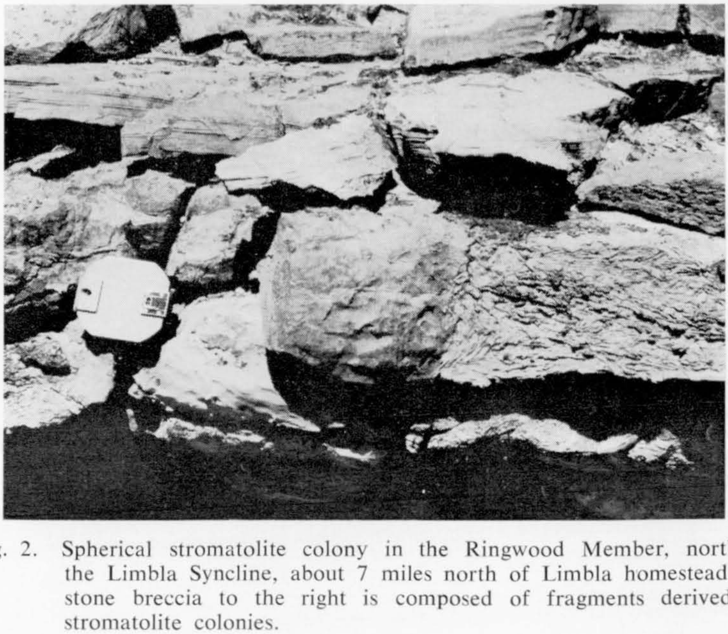

Plate 8, fig. 2. Spherical stromatolite colony in the Ringwood Member, north flank of the Limbla Syncline, about 7 miles north of Limbla homestead. The limestone breccia to the right is composed of fragments derived from the stromatolite colonies.

minerals are common. Interbeds of calcareous sandstone and micaceous siltstone are rare. Scattered pebbles are common in the southernmost outcrops. North of the Sir Frederick Range and at the western end of a large range north of the Carnegie Range, the pebbly sandstone grades into the Sir Frederick Conglomerate.

The *Sir Frederick Conglomerate* (Wells et al., 1964) is a sequence of pebble, cobble, and boulder conglomerate, with a kaolinitic sandstone matrix and thin interbeds and lenses of sandstone and pebbly sandstone, which is conformably overlain by the Maurice Formation; it lenses laterally into the Ellis Sandstone and possibly unconformably overlies the Carnegie Formation.

Outcrops are confined to the area between the Rawlinson Range and Lake Macdonald. The combined thickness of the Ellis Sandstone and Sir Frederick Conglomerate at the northern end of the Sir Frederick Range is about 7000 feet.

The boulders in the conglomerate, which range up to 3 feet 6 inches in diameter, include silicified sandstone and metaquartzite with subordinate vein quartz and quartz-mica schist. The coarsest conglomerate is exposed in the Gillespie Hills. All the rock types found as phenoclasts in the Sir Frederick Conglomerate are present in the Proterozoic and Precambrian metamorphic rocks to the south, but most of them were probably derived from the Dean Quartzite.

The *Maurice Formation* conformably overlies the Ellis Sandstone and Sir Frederick Conglomerate (Wells et al., 1964). The top is eroded and unconformably overlain by the Buck Formation or other Permian sediments. The formation is estimated to be at least 6000 feet thick in the Maurice Hills. The beds grade from predominantly even-grained quartz sandstone and siltstone in the north to predominantly cross-bedded quartz greywacke with minor greywacke and micaceous siltstone in the south. The basal beds in the north consist of medium to thin-bedded cross-bedded finely micaceous sandstone with clay pellets. The ridges in the middle of the formation at the Maurice Hills consist of quartz sandstone with interbedded micaceous siltstone. The sandstone is thick-bedded, cross-bedded, and ripple-marked, and contains interbeds rich in clay pellets and laminae rich in heavy minerals. The youngest beds comprise fine micaceous sandstone and interbeds of chocolate siltstone and minor shale. Clay pellets are common in the sandstone. Most of the upper part of the formation is poorly exposed and probably consists mainly of friable calcareous sandstone.

In the south, the sediments are much coarser and are poorly sorted. They consist of cross-bedded, poorly bedded, and poorly sorted quartz greywacke and interbedded chocolate-brown laminated micaceous siltstone. Some heavy mineral concentrations and pebbles occur in the quartz greywacke. The cross-beds indicate movement from the southeast and south. The quartz greywacke contains 20 percent of fragments of subangular quartz, quartz-sericite schist, quartzite, chert, and rare large flakes of mica, set in a matrix of fine sericite, limonite, and kaolin. Some specimens contain up to 20 percent of tabular cleaved plates of kaolinite.

The lithology of the Ellis Sandstone and Maurice Formation suggests derivation from the south and southeast; the coarser sediments were deposited comparatively rapidly in nearshore areas to the south, and the better sorted sandstone was deposited farther north.

Correlation of the Proterozoic Sequences in the Western and Southern Parts of the Basin

The relationship of the Proterozoic units in the Amadeus Basin is shown diagrammatically in Figure 7.

The basal part of the sequence in the MacDonnell Ranges comprises the Heavitree Quartzite and Bitter Springs Formation; the same sequence continues with little lithological change into the western part of the basin. The metamorphosed equivalents of the Heavitree Quartzite and Bitter Springs Formation in the Rawlinson and Petermann Ranges in the southwest are the Dean Quartzite and Pinyinna Beds. In the west, the Bitter Springs Formation is disconformably overlain by the Boord Formation, which contains basal boulder beds of probable glacial origin. The Boord Formation and the equivalent Carnegie Formation are correlated with the Inindia Beds and Areyonga Formation. They occur in similar stratigraphic positions, and glacial beds are present in all except the Carnegie Formation.

The Ellis Sandstone, Sir Frederick Conglomerate, and Maurice Formation, which rest conformably on sediments equated with the Areyonga Formation, can be correlated with the Winnall Beds. Folding and considerable erosion of the Proterozoic rocks preceded the deposition of the Cambrian and Ordovician sediments in the west and south. The Proterozoic rocks were eroded to different stratigraphic levels, and are generally overlain unconformably by the Larapinta Group or Pertaoorrta Group, or both. Between the Sir Frederick Range and the Maurice Hills flat-lying Ordovician rocks occur close to strongly folded outcrops of the Bitter Springs and Carnegie Formations and other Proterozoic formations. The Ellis Sandstone, Sir Frederick Conglomerate, and Maurice Formation are essentially conformable with each other and with the underlying formation, and have a similar style of folding to the Winnall Beds. These relationships suggest that they were all folded at the same time during the Petermann Ranges Orogeny. If they were equivalent to the Cambrian Cleland Sandstone or to the late Proterozoic or early Cambrian Mount Currie Conglomerate, there would probably be an angular unconformity at the base of the sequence, and the folding would not be so intense.

Comparison of the lithology, topographic expression, photo-pattern, and style of folding indicates a fairly close correlation between the Ellis Sandstone, Sir Frederick Conglomerate, and Maurice Formation and the Winnall Beds. The Ellis Sandstone can be correlated with the unit 2 sandstone of the Winnall Beds, and the Maurice Formation with the unit 4 sandstone. The formations in the west are generally coarser and less well sorted, and the siltstone occurs as thin interbeds rather than as distinct units as in the Winnall Beds. The difference in lithology suggests that the equivalents of the Winnall Beds in the west were deposited under high-energy conditions adjacent to source areas where ridges of both the Dean Quartzite and older Precambrian rocks were exposed. In this environment arenites predominated, and most of the lutite fraction was probably washed basinwards and incorporated in the Pertatataka Formation and Winnall Beds. The occurrence of slumped cross-laminated beds and intraformational contortions indicates that subaqueous sliding was common.

The evidence suggests that the sequence in the west between the Carnegie Formation and the Ordovician rocks is equivalent to the whole of the Winnall Beds in the south.

Palaeogeography and History of Deposition

The Pertatataka Formation, Winnall Beds, Ellis Sandstone, Sir Frederick Conglomerate, and Maurice Formation were deposited in an essentially uninterrupted period of sedimentation. The distribution, thickness, and facies distribution of the formations are shown in Figure 11.

Sedimentation took place in a southern subsiding depression and on a northern shelf, separated by an east-west eroded linear zone near the centre of the basin which was probably a hinge-line (see p. 43). The thickest deposits (Winnall Beds and equivalent Ellis Sandstone, Maurice Formation, and Sir Frederick Conglomerate) were laid down in the depression and the thinner deposits (Pertatataka Formation) on the shelf. A subsidiary basin was developed in the northeast, in which a comparatively large thickness of sediments (Pertatataka Formation) accumulated. The sub-basin includes the only known occurrence of the younger of the two Proterozoic glacial deposits in the Amadeus Basin.

The presence in the south of a comparatively thick arenaceous facies (Winnall Beds) which grades northwards into thin lutites and carbonate rocks (Pertatataka Formation) suggests that the bulk of the sediments were derived from the south.

In the west, the distribution and variations in lithology of the Ellis Sandstone, Sir Frederick Conglomerate, and Maurice Formation also suggest provenance areas to the south and southwest. The predominance of rounded quartzite boulders in the Sir Frederick Conglomerate and the complex interfingering of the conglomerate with the Ellis Sandstone suggest deposition close to the provenance area, in alternating continental and transitional environments. The conglomerates were probably mainly fluvial and the interfingering sand mainly littoral. The Sir Frederick Conglomerate can be correlated with the lower sandstone unit in the Winnall Beds, and a thin conglomerate commonly occurs at the base of this sandstone.

In the succeeding Maurice Formation, the passage of poorly sorted coarse-grained sediments in the south into more mature sediments in the north also indicates a southerly provenance. The formation was probably deposited in alternating fluvial and shallow-marine environments.

On the northern shelf, the Pertatataka Formation was deposited in a predominantly reducing environment under quiet conditions and only fine detritus accumulated. Towards the end of deposition of the Pertatataka Formation, when the shelf was practically filled by sediment and the supply of terrigenous sediments was reduced, limestone deposition predominated in the shallow seas. The provenance area was probably a low-lying landmass to the north, and very little detritus was derived from it probably because it had been peneplaned during the preceding Areyonga glacial phase.

Along the hinge-line separating the southern depression from the northern shelf the Pertatataka Formation is absent or very thin. Erosion in this zone and to the south followed the folding of the sediments during the Petermann Ranges Orogeny. The Pertatataka Formation was completely removed from anticlinal culminations, and in places the underlying Areyonga Formation was removed and the Bitter Springs Formation exposed and eroded before the deposition of the Pertaoorrta Group.

The varied lithology of the Pertatataka Formation in the northeastern sub-basin indicates a different environment of deposition from that prevailing elsewhere on the northern shelf. Evidence of a glacial environment is found only in the sub-basin where the deposition of siltstone was interrupted by prolonged intervals of deposition of coarser detrital material, including boulder beds and boulder clays. The cross-laminated and slumped fine sandstone of the interbeds and underlying member may have been deposited in fluvioglacial meltwater; the sedimentary structures are similar to the point bar deposits in modern rivers (Davies, 1966). In periods of quiescence, when there was less detritus, oolitic and fragmental sandy shelf carbonate rocks were deposited. The boulders in the conglomerates in the Pertatataka Formation were derived from older members of the same formation, and from the Bitter Springs Formation, Heavitree Quartzite, and igneous and metamorphic rocks (Arunta Complex) exposed to the northeast, where they were vigorously eroded by glaciers. The presence of arkose and fresh feldspar indicates the proximity of crystalline source rocks. Clasts derived from the underlying Limbla Member and edgewise dolomite breccia indicate penecontemporaneous erosion of the Pertatataka Formation.

Evolution of the Proterozoic Basin

The Proterozoic sediments deposited after the Bitter Springs Formation fall into two broad groups — the Areyonga Formation and its equivalents (Boord Formation, Carnegie Formation, and Inindia Beds), and the younger Pertatataka Formation and its equivalents (Winnall Beds, Ellis Sandstone, Sir Frederick Conglomerate, and Maurice Formation).

The distribution and thickness of the two groups are broadly comparable, and the similarity in lithology and facies distribution (Figs 10, 11) indicates that the same general environmental conditions prevailed during the deposition of both.

The first stage in the Proterozoic cycle of sedimentation began with the deposition of a shallow marine blanket sand (Heavitree Quartzite) on a stable continental platform. This was followed conformably by the Bitter Springs Formation, which consists of basal saline deposits overlain by penesaline and marine sediments. The presence of thick evaporites at or near the base of the formation marks the development of an intracratonic basin with limited access to the open sea. The youngest sediments of the formation were laid down in a shallow sea. The boundaries of the intracratonic basin are unknown.

Major tectonic events, which followed the deposition of the Bitter Springs Formation, resulted in a radical change in the palaeogeography and was the initial stage in the development of the Amadeus Basin. This tectonism resulted in the second stage of the Proterozoic cycle of sedimentation; it was responsible for the development of the southern mobile belt, including the southern borderland or geanticlinal welt, a subsiding southern depression, and a northern shelf and stable foreland area. This period of crustal instability resulted in the uplift of the southern Proterozoic and Precambrian basement provenance area followed by the complementary downwarping of the depression to the north.

Two important periods of diastrophism are recorded by unconformities in the Proterozoic rocks. The first is the unconformity between the Bitter Springs and Areyonga Formations in the northeast, and elsewhere by the probable disconformity between the Bitter Springs Formation and one of the correlatives of the Areyonga Formation. This event is called the Areyonga Movement (see p. 129). The second period of diastrophism produced the angular unconformity between the Winnall Beds and Inindia Beds in the southern part of the basin, and has been named the Souths Range Movement (see p. 129).

In the south, the areas uplifted as a result of the Areyonga Movement provided a source for sediment, and the Souths Range Movement provided a southerly source for the Sir Frederick Conglomerate, Ellis Sandstone, Maurice Formation, and Winnall Beds.

The thickness of both groups in the southern depression and the facies distribution suggest that the sediments were derived from uplifted areas to the south of the present margin of the basin. Predominantly coarse-grained sediments accumulated in a subsiding depression north of the provenance area, and it is postulated that an east-west hinge-line† developed between the depression and the stable shelf* to the north on which finer-grained sediments were deposited. Correlation of the glacial beds suggest that a considerable thickness of sediment accumulated in the depression before sedimentation started on the shelf. The thickest sediments of both groups were deposited in the depression, and they wedge out considerably onto the shelf area.

The east-west linear zone where the formations are thin or absent roughly outlines the hinge-line along the northern edge of the depression; the sediments along the hinge-line and to the south were folded during the Petermann Ranges Orogeny and a large part of the sequence was subsequently removed by erosion. These basin elements are shown in Figure 12.

The Proterozoic period of sedimentation was terminated by mountain building and recumbent folding during the Petermann Ranges Orogeny; the effects were mainly localized near the axial zone of the southern depression and the maximum amount of folding and faulting occurred here.

The variations in lithology in the two groups and the changes in facies across the basin are similar. Thus the transition of the relatively thin siltstone-shale facies (Pertatataka Formation) in the north to the sandstone-shale facies of the Winnall Beds in the south corresponds to a similar change from the siltstone-sandstone-conglomerate facies (Areyonga Formation) to the sandstone-shale facies in the south (Inindia Beds).

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† The term hinge-line is used in the sense given by Krumbein & Sloss (1963, p. 553) 'During the activity of an interior basin or of the cratonic border of a marginal basin, these subsiding elements are separated from adjoining neutral or positive elements by a linear zone along which the amount of subsidence changes at a high rate—the hinge-line. Where a hinge-line has remained fixed for a significant amount of time, the isopach map of the sediments formed will illustrate this change; structural cross sections will show a point of inflection, and facies patterns will commonly show an abrupt change at the hinge-line'.

* The term shelf is used here to indicate a part of the craton which has displayed no marked tectonism during the Proterozoic period of deposition. The shelf area subsided slowly and received comparatively thin deposits of mostly fine detritus, whereas the thickness of the equivalent beds preserved in the depression to the south indicates subsidence at a much greater rate.

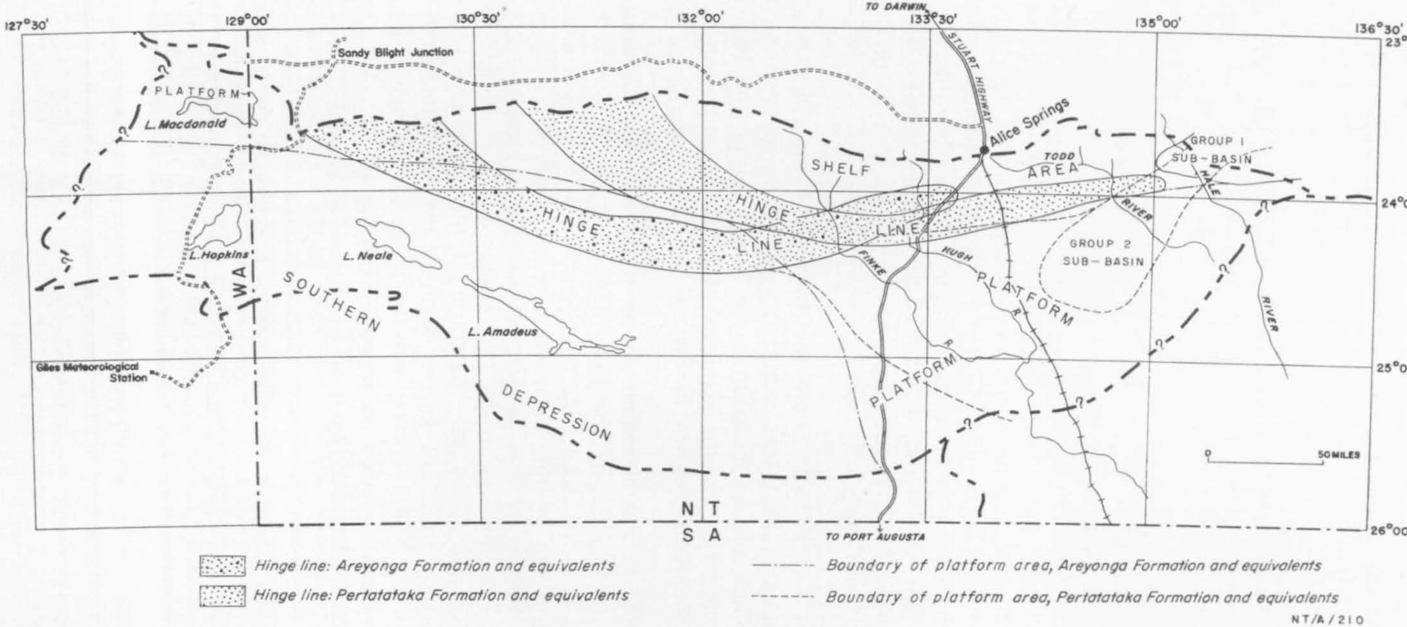


Fig. 12. Proterozoic basin elements.

The sediments on shelf areas along the cratonic border include marine stromatolitic fragmental limestone and green and black glauconitic shale. The limestone of the shelf deposits commonly contains spherical quartz grains; gradation from quartz sandstone to carbonate deposits is common (Krumbein & Sloss, 1963). These features are typical of the Julie Member of the Pertatataka Formation. Glauconite is common in the siltstone of the Pertatataka Formation, a feature which is commonly found in stable shelf areas.

In the west coarser red-beds and sands of the Carnegie Formation grade northwards into siltstone and carbonate rock of the Boord Formation. Similarly, in the later group, the coarse conglomerate of the Sir Frederick Conglomerate and the coarser poorly sorted sediments of the Maurice Formation predominate in the south, while the finer-grained Ellis Sandstone and the more mature sediments of the Maurice Formation are found mainly in the north.

The hinge-line probably changed its position slightly during deposition of the two groups (Fig. 12), but the basin elements are poorly defined in the northwest because of poor outcrop and platform areas with very thin sediments may be present. In the southeast, platform areas covered with thin sediments are common to both groups, and the thickened lobes of the sediments in each group reflect major developments of glacial sediments in the northeastern sub-basins.

The sequences in both groups show the influence of glacial environments, but to different degrees. The earlier period of Proterozoic glaciation was widespread; it has only a slight influence on the type of sediments in the southern depression, but most of the shelf sediments contain glacial detritus in places and are predominantly glacial in origin. The later period of glaciation was restricted to the northeast sub-basin, and produced a different lithological association from that found in the earlier period.

Tentative Correlations with Proterozoic Sequences in other Parts of Australia

The Proterozoic succession in the Amadeus Basin can be tentatively correlated with sequences in the Kimberley area and with the Adelaide Geosyncline and Georgina Basin by correlation of the glacial beds, stromatolitic algae, and stratigraphic sequences, and by comparison of the isotopic data. The glacial beds probably offer the best means of correlation at present.

The older Proterozoic glacial sediments in the Areyonga Formation and its equivalents can be correlated with the Fargoo Tillite and Moonlight Valley Tillite in the East Kimberley region (Dow & Gemuts, 1969), with the Yudnamutana Subgroup (Coats, 1964) in the Adelaide Geosyncline, and with the Field River Beds in the Georgina Basin (Smith, in press). The Olympic Member of the Pertatataka Formation, which contains the younger glacial beds, can be correlated with the Egan Glacials of the East Kimberley region (Dow & Gemuts, 1969), with the Elatina Formation and Nuccalena Formation (Marinoan) in the central Flinders Ranges (Coats, 1964; Dalgarno & Johnson, 1964), and with the Mount Cornish Formation in the Georgina Basin (Smith, in press).

LATE PROTEROZOIC TO EARLY CAMBRIAN

Mount Currie Conglomerate and the Arkose at Ayers Rock

Forman (1966c) defined the Mount Currie Conglomerate and described the arkose from Ayers Rock. He suggested that both units could have been deposited at the same time and that they were wedge-like bodies of non-marine sediments deposited in front of the mountain chain formed by folding and thrusting during the Petermann Ranges Orogeny. The distribution of outcrops and probable sub-surface extent of the units are shown in Figure 13.

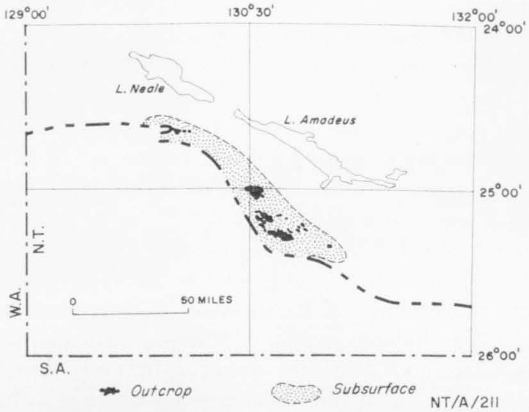


Fig. 13. Distribution of Mount Currie Conglomerate and the arkose at Ayers Rock.

The *Mount Currie Conglomerate* rests unconformably on Proterozoic sediments near Mount Currie (type area) in the northwestern corner of the Ayers Rock Sheet area. The contact is best exposed in the Pinyinna Range about 50 miles northwest of the type area. The formation crops out between the Pinyinna Range in the Bloods Range Sheet area and Mount Olga (Pl. 9) in the Ayers Rock Sheet area. Forman (1966c) estimates that the exposed thickness at Mount Olga is 2000 feet, and tentatively suggests that the maximum thickness may be as much as 20,000 feet.

Forman noted that the phenoclasts near the base of the formation are mainly of sandstone; in the middle part they are fine-grained felsic and mafic rocks, and towards the top of the formation they are mostly granite and gneiss. The inselbergs at Mount Currie and Mount Olga consist of the middle and upper parts of the formation, which are more resistant to erosion.

The basal unit is composed mainly of phenoclasts of orthoquartzite, up to 2 feet in diameter, set in a sandy matrix. The phenoclasts were probably derived from the Dean Quartzite and Winnall Beds. The middle part of the unit is well exposed at Mount Currie; it is a conglomerate with phenoclasts of brown feldspar porphyry, greenish grey basalt, green epidotized amygdaloidal basalt, grey quartz sandstone, and rare vein quartz. The boulders are well rounded and ellipsoidal, and range up to about 14 inches in length. The matrix of the conglomerate contains the metamorphic assemblage quartz-albite-epidote-actinolite-chlorite (Forman, pers. comm.). At Mount Olga, which is considered to be higher in the section, the conglomerate contains phenoclasts of granite, gneiss, and fine-grained acid and basic igneous rocks, set in an epidote-rich matrix. W. Oldershaw (pers. comm.) has described a specimen of the Mount Currie Conglomerate from Mount Olga: 'the phenoclasts are set in a granular matrix of angular fragments, 0.2-2 mm across, of quartz-albite intergrowths, devitrified glass, fresh microcline, orthoclase perthite, plagioclase, quartz, and augite. The interstices are filled with fine-grained epidote'. He notes that the epidote cement may have been formed by regional metamorphism which only affected the fine-grained cement of the rock, or that it may be of hydrothermal or volcanic origin; the feldspars show very little alteration.

The Mount Currie Conglomerate overlies the Pinyinna Beds with a visible unconformity at Pinyinna Range; it is assumed to rest unconformably on the Winnall Beds in the Ayers Rock Sheet area because of the presence of phenoclasts apparently derived from the Winnall Beds and because of the discordance in strike. Since deposition, the Mount Currie Conglomerate has been folded and deeply eroded. Forman (1966c) has suggested that it may be correlated with the thin conglomerate at the base of the Cleland Sandstone; but this formation is now considered to be younger.

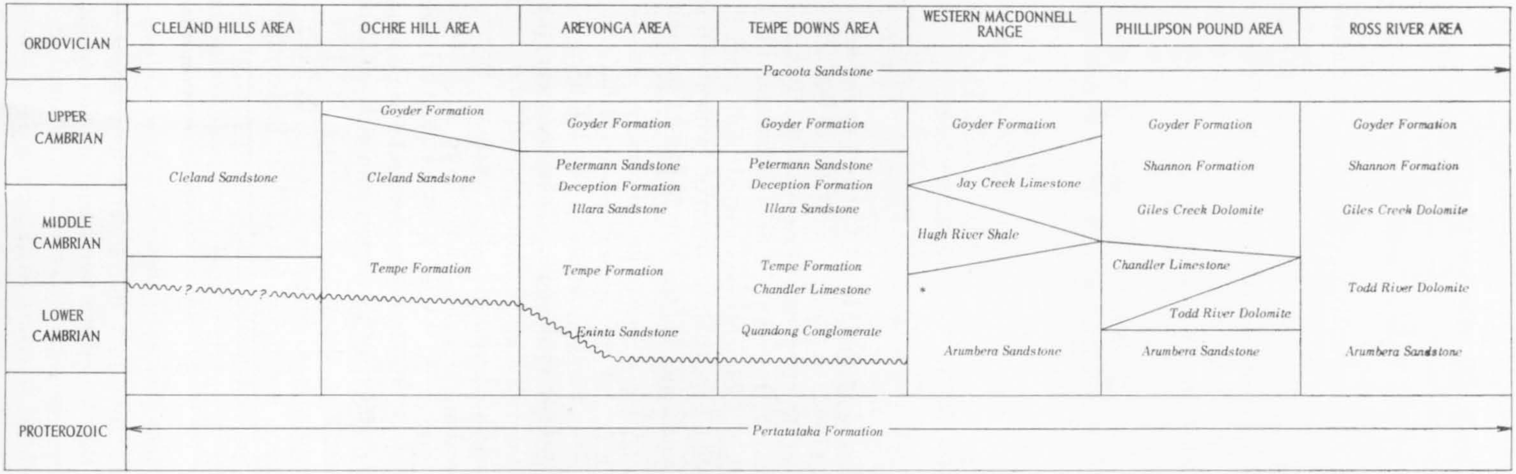
The *arkose at Ayers Rock* (Pl. 10, fig. 1) ranges from pale to dark grey, or pink-grey to green-grey; it is coarse-grained with some medium-grained laminae. The arkose is cross-laminated and contains fragments of feldspar up to 1 inch long; it is poorly sorted, the grains are subangular, and it contains scattered clay pellets. Forman (1966c) estimates that about 8000 feet of arkose is exposed at Ayers Rock, and that the total thickness may be over 20,000 feet. The contacts between the arkose and older or younger formations are not exposed.

Correlation and Age

No fossils have been found in the Mount Currie Conglomerate or in the arkose at Ayers Rock. Quinlan (1962) tentatively correlated the arkose at Ayers Rock and the boulder conglomerate at Mount Olga with the Pertnjara Group because of the similarity in lithology. Forman (1966c) considers the conglomerate and arkose to be molasse-type sediments associated with the Petermann Ranges Orogeny, and has suggested a possible correlation with the thin conglomerate at the base of the Cleland Sandstone. He tentatively placed the unit in the Cambrian.

The Mount Currie Conglomerate rests unconformably on the Winnall Beds of Proterozoic age, and both it and the arkose appear to have been largely derived from Precambrian igneous rocks exposed along the southern margin of the basin. The flat-lying or gently folded Ordovician sediments near the southern margin of the basin rest unconformably on metamorphosed and intensely folded Precambrian rocks (Forman, 1966c), and thus the Petermann Ranges Orogeny and the associated molasse-type sediments could range from Precambrian to Ordovician. However, in the central part of the basin, Ranford et al. (1966) have established a major hiatus between lower Middle Cambrian and Proterozoic sediments, which is thought to represent the effects of the Petermann Ranges Orogeny. If this is so, the orogeny can be limited to the period between the Proterozoic and lower Middle Cambrian. It is difficult to imagine a major tectonic event, such as the Petermann Ranges Orogeny, not being reflected in the conformable sequence of sediments which were deposited in the northeastern part of the basin during the late Proterozoic or early Cambrian, and any major movements would have interrupted the carbonate-shale deposition which started in the Lower Cambrian and continued without major change until the Upper Cambrian.

It seems probable therefore that the Petermann Ranges Orogeny correlates with the appearance of the Arumbera Sandstone in the northeastern part of the basin in the late Proterozoic or early Lower Cambrian, and that the Mount Currie Conglomerate and the arkose at Ayers Rock accumulated during this period.



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* Chandler Limestone is considered to be present although it has not been mapped in the western MacDonnell Ranges.

Fig. 14. Formations of Pertaoorrta Group.

Plate 9. Gently dipping beds of Mount Currie Conglomerate at Mount Olga. Ayers Rock in the background. (By courtesy of Australian News and Information Bureau).

Plate 10, fig. 1. Near-vertical beds of arkose at Ayers Rock. (By courtesy of Australian News and Information Bureau).

Plate 10, fig. 2. Beds and lenses of pebble and cobble conglomerate in the Pertaoorrta Group, about 5 miles northeast of Angas Downs homestead.

Plate 11, fig. 1. Westerly view across the Parana Hill Anticline showing ridges of the Bitter Springs Formation (Pub) in the eroded core unconformably overlain by the Pertaoorrta Group (Cp).

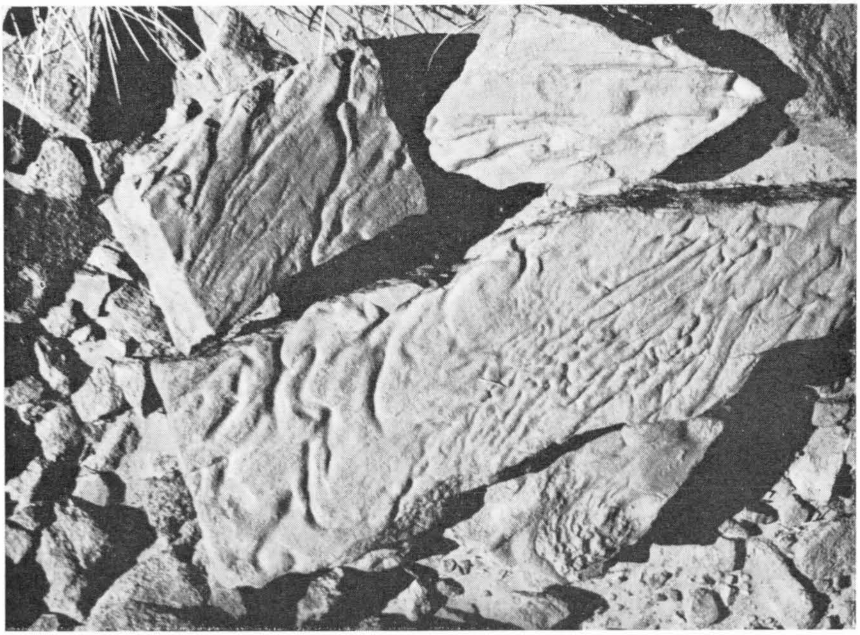


Plate 11, fig. 2. Flute casts in the Cleland Sandstone, about 22 miles south of Johnstone Hill in the Mount Rennie Sheet area.

Plate 12, fig. 1. Shannon Formation, southern flank of the Ross River Syncline. The formation is composed of interbedded siltstone, dolomite, and limestone.

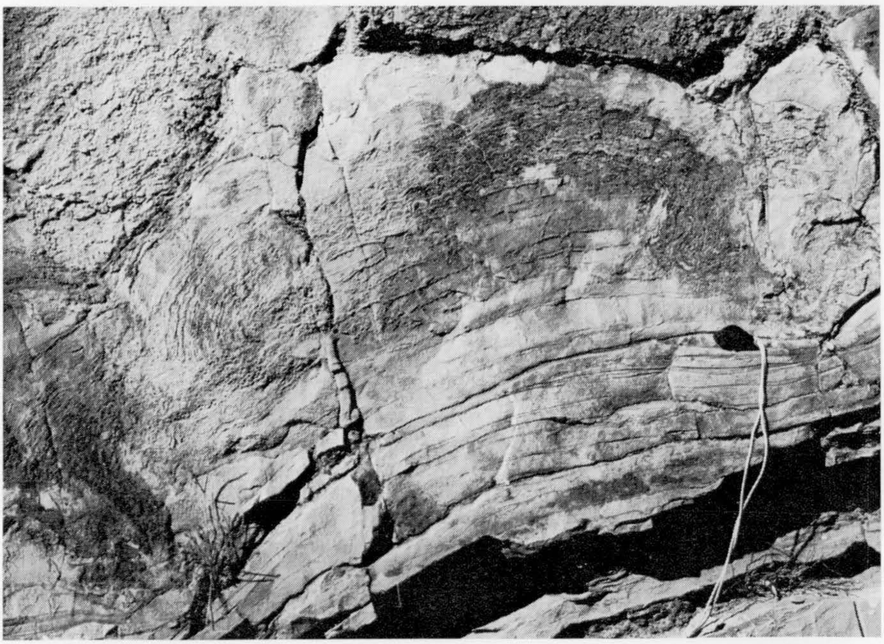


Plate 12, fig. 2. Stromatolite colony in the Shannon Formation, southern flank of the Fergusson Syncline, about 1½ miles north of Shannon Bore.

CAMBRIAN

Pertaoorrta Group

The name Pataoorrta Series of Mawson & Madigan (1930) was amended to Pertaoorrta Series by Madigan (1932a). Prichard & Quinlan (1962) defined the Pertaoorrta Group in the Hermannsburg Sheet area. Wells et al. (1965) redefined the interval and named it the Pertaoorrta Formation. It was again raised to group status by Ranford et al. (1966); the latter also defined two new formations in it, and Wells et al. (1967) and Ranford (1969) have since defined others. Figure 14 shows the formations of the Pertaoorrta Group at seven localities which have been selected to include all the defined formations and indicate the changes which take place across the basin from west to east. The relationships between the formations are shown diagrammatically in Figure 15.

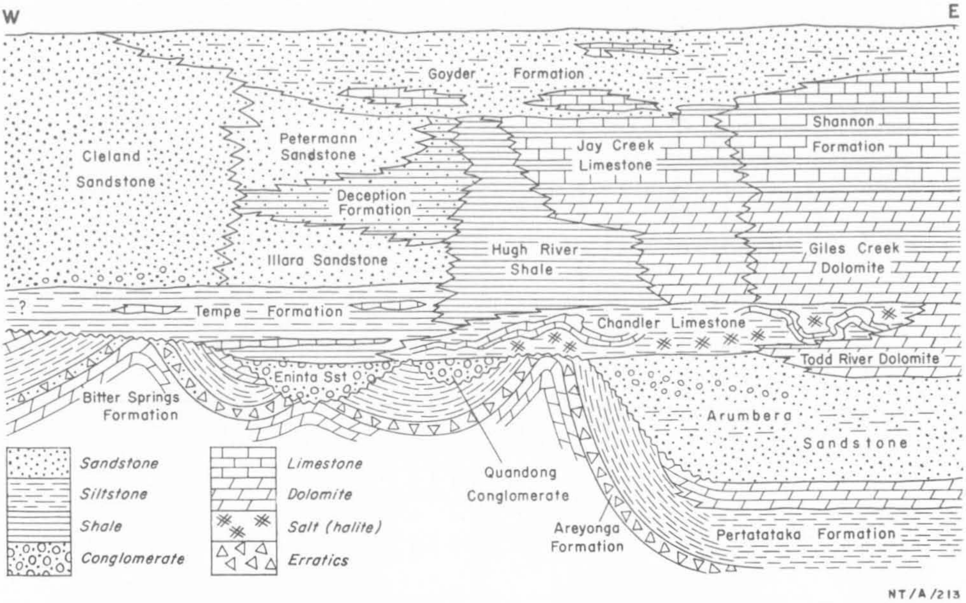


Fig. 15. Relationship of rock units in Pertaoorrta Group.

The Pertaoorrta Group (Pl. 10, fig. 2) comprises a wide variety of rocks, and ranges in age from lowermost Cambrian (or possibly late Proterozoic) to middle Upper Cambrian. The distribution and isopachs of the group are shown in Figure 16. The isopachs indicate two main centres of sedimentation. The occurrence of the thickest sequence near the present northern margin is a characteristic feature of the pre-Permian Palaeozoic sediments in the basin.

Maps showing clastic ratios and the proportion of sand, siltstone and sand, shale, and carbonate rock are given in Figure 17. The maps are based on information from about 25 surface sections and data from the Alice No. 1 and Mount Charlotte No. 1 wells. The surface information was compiled from sections published by the Bureau of Mineral Resources and from the field notes of Bureau geologists.

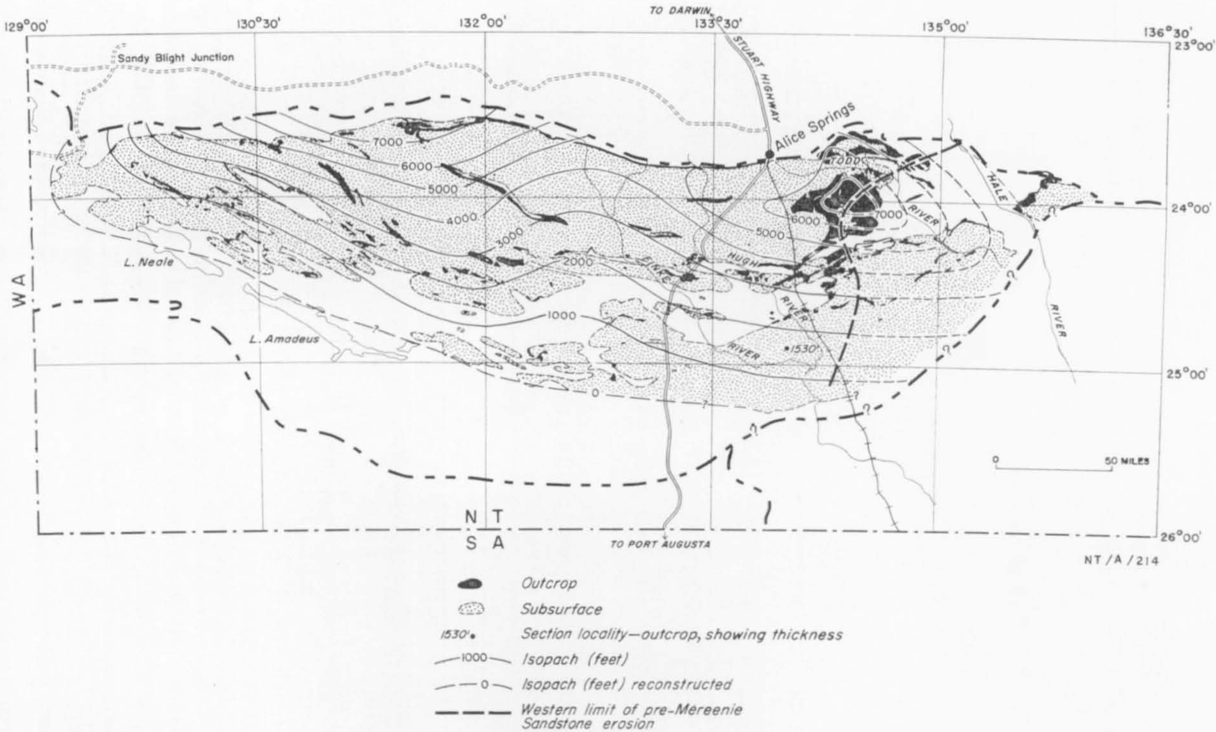


Fig. 16. Distribution and thickness of Pertaoorrta Group.

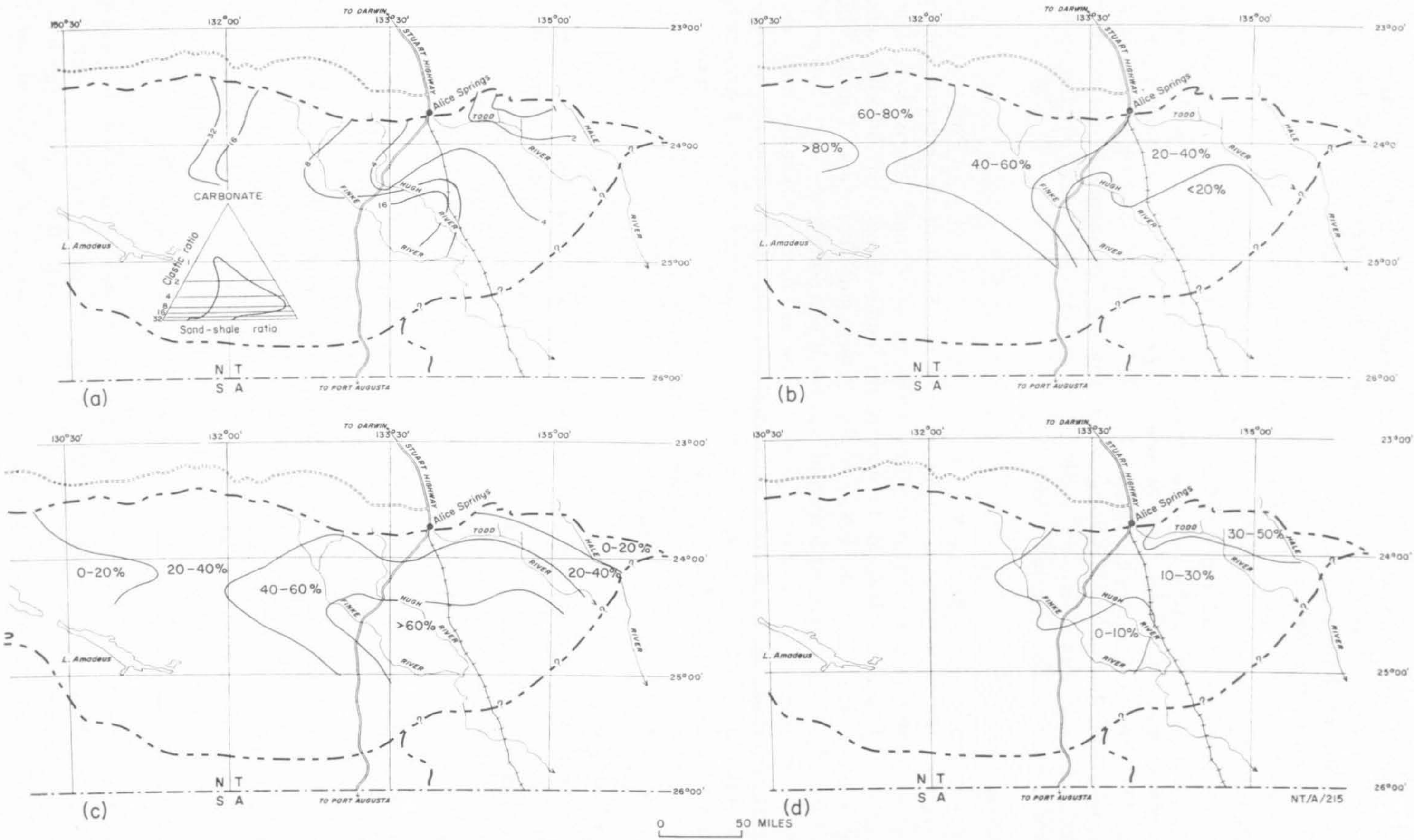


Fig. 17. Maps showing (a) clastic ratios; and percentages of (b) sand, (c) siltstone-shale, and (d) carbonate rock in Pertaoorrta Group.

The clastic ratio map shows the predominance of carbonate rocks and evaporites in the northeast. The maps showing the proportions of the main types of sediments have the same pattern as the clastic ratio map; they show that coarse clastics predominate in the west and finer clastics (siltstone and shale) in the southeast. Figure 18 shows the distribution of the formations of the Pertaoorrta Group, with isopachs where sufficient data are available.

The relationships of all the formations of the Pertaoorrta Group are shown in Figure 15 and will not be discussed under the descriptions of each formation except where they have special significance or cannot be shown adequately on the figure. The Eninta Sandstone, Tempe Formation, Illara Sandstone, Deception Formation, and Petermann Sandstone were originally distinguished as members of the Pertaoorrta Formation by Wells et al. (1965), and raised to the status of formations by Ranford et al. (1966).

Quandong Conglomerate

The Quandong Conglomerate was defined by Ranford et al. (1966). It is a conglomerate and conglomeratic sandstone, and crops out in the Henbury Sheet area as a prominent strike ridge 6 miles northeast of Tempe Downs homestead (type area) and as a low ridge in the core of the James Ranges 'B' Anticline, and in the small eroded anticline between the Petermann Creek and Parana Hill Anticlines. The Quandong Conglomerate is a basal conglomerate which changes in thickness and lithology over short distances. The estimated maximum thickness, northeast of Tempe Downs homestead, is 500 feet. The distribution of the formation is unknown, but it is considered to be equivalent to the Eninta and Arumbera Sandstones, whose distribution is shown in Figure 18a. It is not fossiliferous, but as it lies conformably beneath the lower Middle Cambrian Tempe Formation, it is considered to be Lower Cambrian in age.

Eninta Sandstone

The Eninta Sandstone consists of sandstone with minor siltstone and conglomerate and is exposed only in the Gardiner Range, where it forms a prominent dark red-brown strike ridge. Its full extent is not known, but it is considered to be equivalent to the Arumbera Sandstone and Quandong Conglomerate (see Fig. 18a). The Eninta Sandstone has a maximum measured thickness of 1200 feet, in the Gardiner Range. No fossils have been found in it, but its stratigraphic position indicates that it is probably Lower Cambrian.

Chandler Limestone

The Chandler Limestone was defined by Ranford et al. (1966). The outcrops consist of limestone, dolomite, and interlaminated chert; evaporites and shale may be present subsurface. The formation is exposed in low ridges and hills; the outcrops are generally discontinuous, and the sediments are usually strongly contorted and, in places, brecciated. The Chandler Limestone is widespread in the central and eastern parts of the basin (Fig. 18c), and the evaporites encountered in the Alice No. 1 and Mount Charlotte No. 1 wells probably also belong to it.

The Chandler Limestone is strongly folded at the surface and is poorly exposed; the thickness is uncertain, but probably ranges from 10 to 460 feet in outcrop (Ranford et al., 1966; Wells et al., 1967). The limestone in the basal part of the Tempe Formation in the Gardiner Range could be considered a tongue of the Chandler Limestone which overlies the Eninta Sandstone. In parts of the Ooraminna Anticline and Phillipson Pound, the Chandler Limestone lies between the fossiliferous Lower Cambrian Todd River Dolomite and the lower Middle Cambrian Giles Creek Dolomite. No fossils have been found in the Chandler Limestone, but it is tentatively regarded as Lower Cambrian.

Tempe Formation

The Tempe Formation comprises siltstone, dolomite, and glauconitic sandstone. It crops out in the Gardiner Range, Walker Creek, Petermann Creek, and Parana Hill Anticlines, and in a small unnamed anticline 12 miles south of Reedy Rockhole in the Lake Amadeus Sheet area. It has not been recognized east of longitude 132°30′E. or south of latitude 24°30′S. The probable area of deposition is shown in Figure 18d.

Contacts with the Proterozoic rocks occur in the western culmination of the Petermann Creek Anticline and in the Parana Hill Anticline, where the Tempe Formation rests unconformably on the Bitter Springs and Areyonga Formations. The brachiopods, trilobites, hyolithids, and gastropods in the upper part of the formation are considered to be lower Middle Cambrian (Joyce G. Tomlinson, pers. comm.). The Tempe Formation contains the oldest Palaeozoic fossils found in the western half of the Amadeus Basin and represents the first marine transgression in this area since the Proterozoic.

Illara Sandstone

The Illara Sandstone is restricted to the Gardiner Range, Walker Creek, Petermann Creek, and Parana Hill Anticlines, where it forms prominent strike ridges. The area of deposition of the Illara Sandstone and the overlying Deception Formation and Petermann Sandstone is shown in Figure 18b. The maximum measured thickness is about 650 feet in the Gardiner Range. Wells et al. (1965) have suggested that the Illara Sandstone is equivalent to part of the Arumbera Sandstone (p. 20) or to part of the Hugh River Shale (p. 22); the latter is now preferred because of the stratigraphic position of the Chandler Limestone at the base of the Tempe Formation and above the Arumbera Sandstone. No fossils have been found in the Illara Sandstone, but it is considered to be of Middle Cambrian age because of its stratigraphic position.

Deception Formation

The Deception Formation crops out in the Gardiner Range, Walker Creek, Petermann Creek, and Parana Hill Anticlines. The formation consists mainly of red siltstone and shale and is easily eroded. It is usually concealed beneath alluvium in strike valleys, but in places the more resistant beds form low strike ridges. The area of deposition is shown in Figure 18e. The Deception Formation has a maximum thickness of about 600 feet in the Gardiner Range. No fossils have been found in it, but its stratigraphic position indicates a Middle Cambrian age.

Petermann Sandstone

The Petermann Sandstone consists of sandstone with minor siltstone and sandy limestone and forms a prominent red-brown strike ridge in the Gardiner Range, Walker Creek, Petermann Creek, and Parana Hill Anticlines (Pl. 11, fig. 1). It is

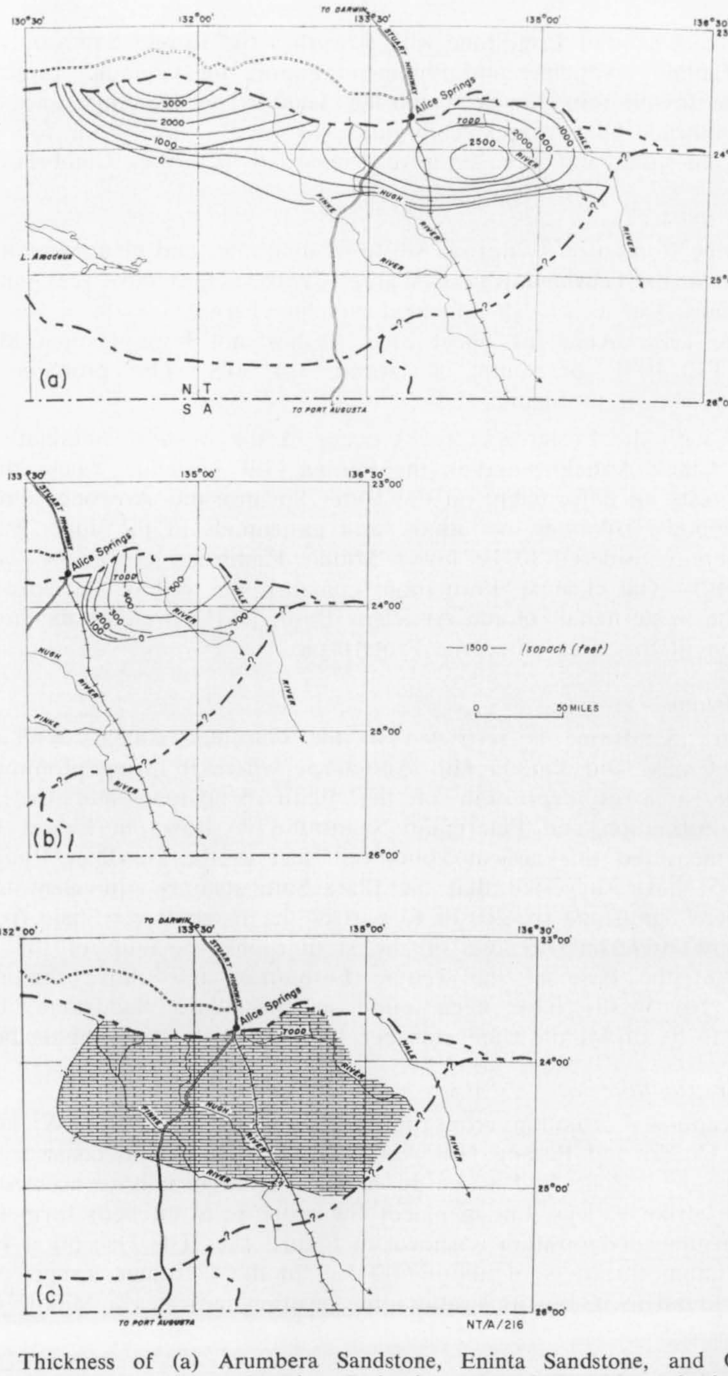


Fig. 18. Thickness of (a) Arumbera Sandstone, Eninta Sandstone, and Quandong Conglomerate, (b) Todd River Dolomite; area of deposition of (c) Chandler Limestone, (d) Hugh River Shale and Tempe Formation; thickness and area of deposition of (e) Cleland Sandstone, Petermann Sandstone, Deception Formation, Illara Sandstone, Jay Creek Limestone, Shannon Formation, and Giles Creek Dolomite; and thickness of (f) Goyder Formation.

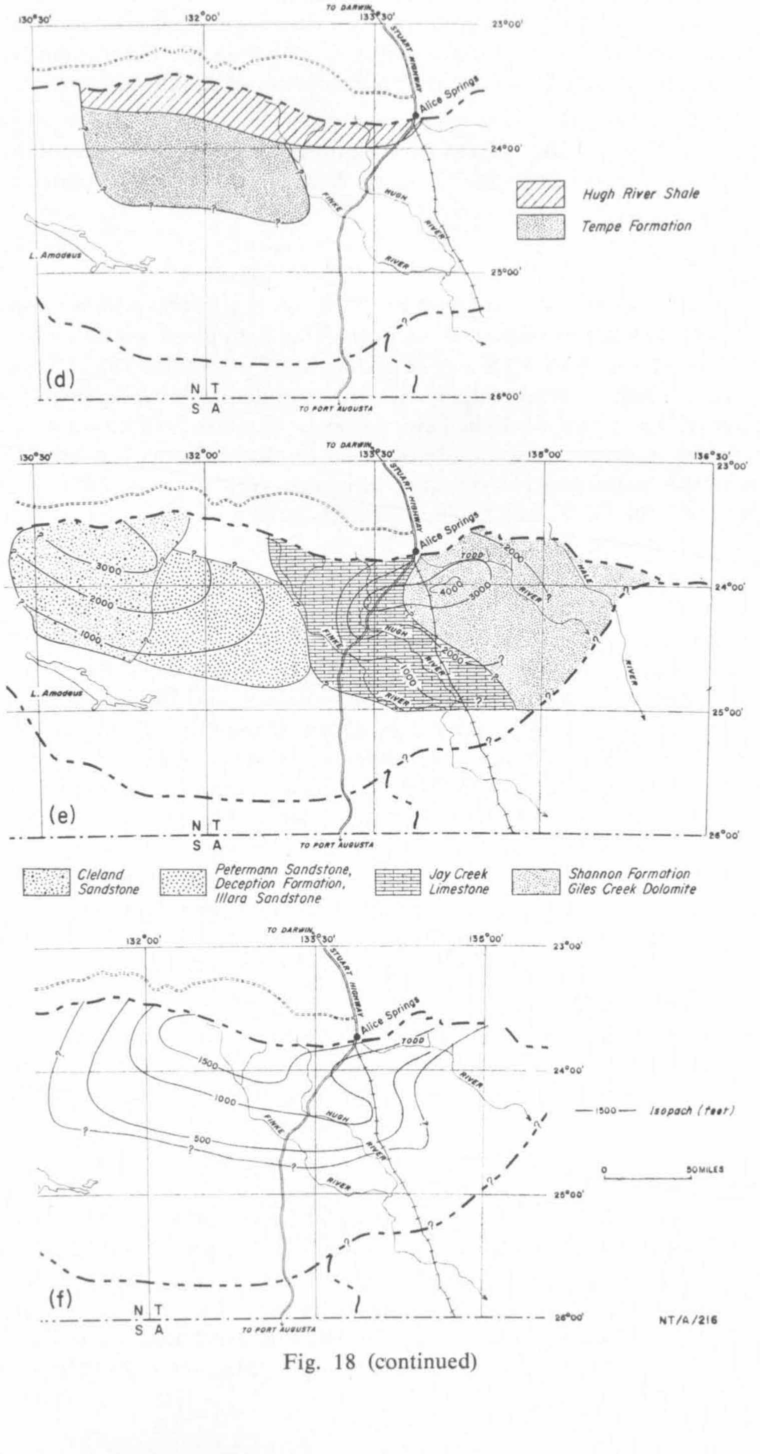


Fig. 18 (continued)

not exposed east of Areyonga Native Settlement. In Figure 18e, the distributions of the Petermann Sandstone, Deception Formation, and Illara Sandstone are combined to show the area of deposition, but this is an approximation as the two older units extend farther east (and possibly south) than the Petermann Sandstone. The Petermann Sandstone has a maximum thickness of about 640 feet.

The only fossil recorded is a gastropod from the south of Areyonga Native Settlement, which is possibly of Upper Cambrian age (Joyce G. Tomlinson, pers. comm.). The formation is considered to be late Middle to early Upper Cambrian in age.

Cleland Sandstone

The Cleland Sandstone was defined by Wells et al. (1965) and was included in the Pertaoorrta Group by Ranford (1969). The formation comprises sandstone and pebbly sandstone, with a variety of sedimentary structures (Pl. 11, fig. 2), and crops out as prominent strike ridges and low rounded hills. It is restricted to the western part of the basin and thickens towards the northern margin (Fig. 18e). The sequence is uniform; in some areas it can be divided into two units according to the air-photo patterns. The greatest thickness recorded is 3490 feet in the hills to the north of Glen Edith. The Cleland Sandstone is conformably overlain by the Pacoota Sandstone west of the Idirriki Range.

Todd River Dolomite

The Todd River Dolomite was defined by Wells et al. (1967); it crops out in low scarps, rounded hills, or discontinuous ridges in the Ross River, Fergusson, and Gaylad Synclines, and in the Ooraminna Anticline and Phillipson Pound in the northeast. The most easterly exposure is about 4 miles southeast of the Aralka Bore in the Hale River Sheet area, and the most westerly is the Ooraminna Anticline. The area of deposition and thickness is shown in Figure 18b. The greatest thickness recorded is 510 feet at Ross River Gorge. The contact between the Todd River Dolomite and the overlying units is conformable or disconformable (Wells et al. 1967). Parts of the Hugh River Shale and Chandler Limestone have been considered as possible time-rock equivalents (Wells et al., 1967), and field evidence suggests interfingering of the Todd River Dolomite and Arumbera Sandstone as shown in Figure 15.

Joyce G. Tomlinson (pers. comm.) has subdivided the Todd River Dolomite into an older part containing archaeocyathans and the brachiopod *Micromitra etheridgei* (Tate) and a younger part containing archaeocyathans, brachiopods, hyolithids, and trilobite fragments. Both faunas are considered to be Lower Cambrian.

Giles Creek Dolomite

The Giles Creek Dolomite was defined by Wells et al. (1967). The formation consists of dolomite with interbeds of limestone, siltstone, and shale. It crops out as sharp strike ridges in the northeast, as far west as the railway and as far south as latitude 24°30′S. The easternmost exposure (Fig. 18e) is 15 miles east-southeast of No. 6 Phillipson Bore in the Hale River Sheet area. The thickest measured section, on the northern flank of the Ooraminna Anticline, is about 1320 feet thick.

The fossils from the Giles Creek Dolomite (Joyce G. Tomlinson, pers. comm.) are hyolithids (including *Biconulites),* brachiopods, gastropods, and trilobites, which indicate an early Middle Cambrian age. *Girvanella* is also present.

Shannon Formation

The Shannon Formation was defined by Wells et al. (1967). The formation comprises siltstone, limestone, and dolomite; it crops out in the northeast as a series of strike ridges and valleys (Pl. 12, fig. 1). Stromatolite colonies are common (Pl. 12, fig. 2). The area of deposition is shown in Figure 18e. The thickest measured section, on the northern flank of the Ooraminna Anticline, is 2340 feet.

Near the northern margin of the basin, the Shannon Formation is conformably overlain by the Goyder Formation, but in the northeast it is overlain by the Pacoota Sandstone, Stairway Sandstone, Mereenie Sandstone, and Pertnjara Group. The Shannon Formation may also interfinger with the Goyder Formation in the northeast, and it is possible that the relationship between the two is similar to that between the Cleland Sandstone and Goyder Formation on the western side of the basin (Fig. 15). If this is so, the Pacoota Sandstone and the Shannon Formation may be conformable. However, the Stairway Sandstone rests disconformably, and the Mereenie Sandstone and Pertnjara Group rest disconformably or possibly unconformably on the Shannon Formation. The Shannon Formation overlies the Giles Creek Dolomite throughout the northeast.

The fossils from the Shannon Formation 'are of early Upper Cambrian age (late Mindyallan; zone of *Glyptagnostus stolidotus*) and are indistinguishable from those of the overlying (carbonate part) of the Goyder Formation. Fossils of the same age have been found in the upper part of the Jay Creek Limestone in the western MacDonnell Ranges and in the Waterhouse Range (Joyce G. Tomlinson, pers. comm.).

Arumbera Sandstone

The Arumbera Sandstone was originally defined as the Arumbera Greywacke by Prichard & Quinlan (1962). It was redefined as a member of the Pertaoorrta Formation by Wells et al. (1965) and as the Arumbera Sandstone by Wells et al. (1967).

The formation consists of red-brown and white sandstone, with minor siltstone, shale, conglomerate, and dolomite. Load casts in the sandstone are shown in Plate 13, figure 1. The formation is typically ferruginous and feldspathic, and forms prominent red-brown strike ridges along the northern margin of the basin (Pl. 13, fig. 2). The formation is considered to be equivalent to the Eninta Sandstone and Quandong Conglomerate. The combined area of deposition and thickness of all these units are shown in Figure 18a.

The beds are about 4000 feet thick near the western end of the MacDonnell Ranges, and about 2700 feet in the Phillipson Pound area. Impressions in sandstone beds in the basal part of the Arumbera Sandstone about 4 miles east of Deep Well homestead have been assigned to the Proterozoic *Rangea arborea* by Glaessner (*in* Taylor, 1959b, unpubl.), but the arthropod tracks and *Scolithus* higher in the sequence in the eastern MacDonnell and Fergusson Ranges (Pl. 14, fig. 1) and in Phillipson Pound are considered to be of Cambrian age (Joyce G. Tomlinson, pers. comm.).

Hugh River Shale

The Hugh River Shale was defined by Prichard & Quinlan (1962). It was redefined as a member of the Pertaoorrta Formation by Wells et al. (1965) and reinstated as a formation by Ranford et al. (1966).

The formation consists of shale and siltstone with minor thin carbonate and sandstone beds. The beds are easily eroded and poorly exposed. The area of deposition is shown in Figure 18d.

The Hugh River Shale has an established maximum thickness of 1600 feet. According to Prichard & Quinlan (1962) and Wells et al. (1967) the Hugh River Shale lies conformably between the Arumbera Sandstone below and the Jay Creek Limestone above. However, Cook (pers. comm.), has recognized the Chandler Limestone in the Ellery Creek area of the western MacDonnell Ranges in the basal part of the Hugh River Shale as shown in Figures 14, 15, and 18. The Hugh River Shale is considered to be equivalent to several formations of the Pertaoorrta Group (except for the Goyder Formation and the Arumbera Sandstone and its equivalents). No fossils have been found in the Hugh River Shale; it is considered to be Lower Cambrian to lower Middle Cambrian because of its stratigraphic position.

Jay Creek Limestone

The Jay Creek Limestone was defined by Prichard & Quinlan (1962). It consists of algal and oolitic limestone and dolomite, siltstone, and shale with a few thin interbeds of calcareous sandstone. The unit crops out in low rises with ridges of more resistant carbonate beds. The area of deposition is shown in Figure 18e. According to Joyce G. Tomlinson (pers. comm.) the fossils from the Jay Creek Limestone range from Middle Cambrian near the base to lower Upper Cambrian (Mindyallan) at the top.

Goyder Formation

The Goyder Formation was defined by Prichard & Quinlan (1962). It was redefined as a member of the Pertaoorrta Formation by Wells et al. (1965) and reinstated as a formation by Ranford et al. (1966).

The formation consists of sandstone, siltstone, dolomite, and limestone. Bedding planes commonly show halite pseudomorphs (Pl. 14, fig. 2). It is generally poorly exposed in a dissected pediment below the Pacoota Sandstone. The distribution and thickness of the Goyder Formation are shown in Figure 18f.

Prichard & Quinlan (1962) measured a thickness of about 1800 feet near Stokes Pass in the western MacDonnell Ranges.

The Goyder Formation conformably underlies the Pacoota Sandstone and conformably overlies several formations of the Pertaoorrta Group.

According to Joyce G. Tomlinson (pers. comm.) the algal stromatolites, trilobites, gastropods, and hyolithids in the Goyder Formation are early Upper Cambrian (Mindyallan) in the lower carbonate beds, and middle Upper Cambrian (late Franconian) in the upper arenitic beds.

Palaeogeography and Geological History

The Amadeus Basin is the preserved remnant of an intracratonic basin which was filled by sediments ranging from Proterozoic to Upper Palaeozoic in age. The outline of the basin in Lower Palaeozoic times was controlled by the Petermann Ranges Orogeny, centred near the southwestern margin of the basin, in which the Proterozoic sediments were folded in the western part of the basin, and seas generally regressed. Coarse continental post-orogenic sediments (Mount Currie Conglomerate and the arkose at Ayers Rock) were laid down in a depression formed in front of the newly developed mountain ranges (Fig. 13); the depression was probably separated by a ridge from the main basin to the north, where transitional deltaic sediments (Arumbera Sandstone) were deposited without a major break on the Proterozoic marine sediments (Pertatataka Formation). The general shape of the basin during the early Lower Cambrian is indicated by the distribution of the Arumbera Sandstone and its lateral equivalents (Eninta Sandstone and Quandong Conglomerate), and the zero isopach on Figure 18a approximately marks the margin of the basin. The truncation of the isopachs on the northern margin of the basin is almost certainly due to uplift and erosion after the Alice Springs Orogeny in Upper Devonian or Carboniferous times. Similarly, the close spacing of the isopachs to the southeast of Alice Springs can be explained by crustal shortening due to folding and thrust faulting during the Alice Springs Orogeny. The two sub-basins, indicated by the isopachs, may have been of fundamental importance throughout the Palaeozoic history of the basin. Even in early Lower Cambrian time there is evidence of a stronger marine influence in the Arumbera Sandstone in the eastern sub-basin and the connexion to the sea was almost certainly to the east.

Sediments were laid down in a long shallow basin, elongated east-west, of the shelf or embayment type; the basin was open to the sea on the east and received detritus mainly from the west and south. This pattern of sedimentation continued without major change throughout the Cambrian. The clastic ratio map of the Pertaoorrta Group (Fig. 17a) indicates clearly the predominance of clastic sediments in the west, and the approximate northerly trend of the changes in facies. The facies maps, showing the distribution of sand, siltstone and shale, and carbonate rocks (Figs 17b, c, d), display the same general trend as the clastic ratio map, and emphasize the relationship between the facies and the sub-basins. Broadly speaking, the western sub-basin was a centre of coarse clastic sedimentation and the eastern sub-basin one of carbonate sedimentation. The facies distribution is clearly related to a westerly provence and the meagre data available on the current-bedding in the Cambrian sandstone suggest a predominance of currents from the west.

During the Lower Cambrian the influx of coarse detrital material into the eastern sub-basin almost ceased, and carbonate and shale deposition predominated until the Upper Cambrian. The Lower Cambrian Todd River Dolomite is rich in glauconite, and contains archaeocyathans and phosphatic brachiopods. On the northwestern margin of the basin a large area of the Pertaoorrta Group was uplifted during the Alice Springs Orogeny and subsequently eroded, so that only the truncated edges of the formation are exposed. This explains the thick development of the group along the northern margin of the present basin (Fig. 16). Fossils of Lower Cambrian age have not been found in the western half of the basin, and it is uncertain whether clastic sedimentation continued in the west during the period of deposition of the Todd River Dolomite in the east. The probable extent of the Lower Cambrian seas is shown in Öpik (1957).

The Lower Cambrian marine sediments in the east and the continental or transitional sediments in the central part of the basin were followed by unfossiliferous evaporitic sediments (Chandler Limestone) in the Lower Cambrian or early Middle Cambrian. The most likely distribution of the Chandler Limestone is shown in Figure 18c.

The lower Middle Cambrian was a time of transgression in the Amadeus Basin and elsewhere in Australia, and the first fossiliferous marine sediments (Tempe Formation) were deposited in the western sub-basin during this period. However, the lithology of the sediments in the eastern sub-basin (Giles Creek Dolomite and Jay Creek Limestone) is quite different from that of the Tempe Formation in the west. After the widespread transgression in the lower Middle Cambrian, a mixture of continental and transitional red-beds was deposited in the west, but shallow-marine conditions prevailed in the east. The pattern of sedimentation during this period is clearly shown in Figure 18e.

In the Upper Cambrian there was a change in the pattern of distribution of the detrital material: the coarse clastics gradually migrated to the east, and correspondingly the marine environment migrated to the west. The Upper Cambrian Goyder Formation is a mixture of marine sandstone, shale, and limestone and represents the most widespread marine transgression since the lower Middle Cambrian. The formation interfingers with a continental and transitional red-bed sequence (Cleland Sandstone) in the west, and with a marine carbonate and shale facies (Shannon Formation) in the east.

In summary, the Pertaoorrta Group was deposited as a result of isostatic uplift following the Petermann Ranges Orogeny in late Proterozoic or early Lower Cambrian time, in an intracratonic basin of the embayment type; the direction of transport and the palaeoslope were probably parallel to the axis of the basin. The sediments were deposited during two broad cycles of regression and transgression, and range from predominantly continental or transitional deltaic sandstone in the west to marine carbonate rock and shale in the east.

CAMBRO-ORDOVICIAN

Larapinta Group

The name Larapintine Series was first used by Tate (1896) in the report on the Horn Expedition of 1892. Madigan (1932a) used the same name and placed his No. 4 Quartzite (Pacoota Sandstone) at the base of the series. Chewings (1935) subsequently revised the name to Larapinta Series, and Prichard & Quinlan (1962) renamed it the Larapinta Group. They formally defined the constituent formations, but two of the names (Horn Valley Siltstone and Stairway Sandstone) were amended by Wells et al. (1965).

Because of its economic potential for oil, gas, and phosphate, the Larapinta Group has been investigated in more detail than the other sediments in the Amadeus Basin. Haites (1963; 1963, unpubl.) studied the relationship of the various formations; Cook (1963, 1966a, unpubl.), Barrie (1964, unpubl.), and Pritchard & Cook (1965) have discussed the Stairway Sandstone, and Williams et al. (1965) the Pacoota Sandstone in some detail. The group has been discussed in various reports on the regional geology by the Bureau of Mineral Resources, Frome Broken Hill Pty Ltd, and Magellan Petroleum Australia Ltd.

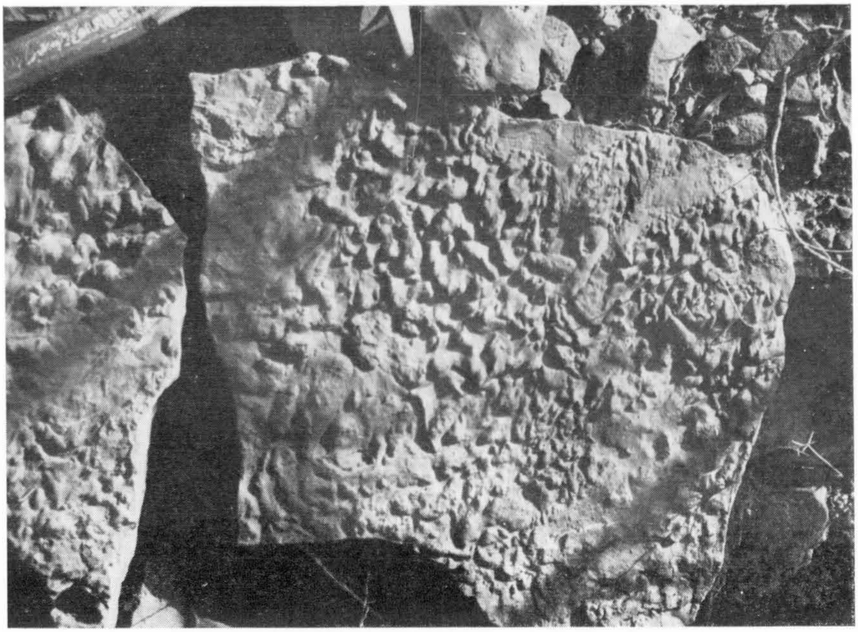


Plate 13, fig. 1. Load casts in the upper part of the Arumbera Sandstone, near Allua Well, 54 miles east of Alice Springs.

Plate 13, fig. 2. Upper beds of the Arumbera Sandstone on the southern flank of the Ross River Syncline, about 2 miles northwest of Shannon Bore.

Plate 14, fig. 1. Invertebrate tracks in the middle part of the Arumbera Sandstone, near Allua Well, 54 miles east of Alice Springs.

Plate 14, fig. 2. Pseudomorphs after halite in the Goyder Formation near the contact with the Petermann Sandstone, about 1 mile north of Mount Levi in the western part of the Petermann Creek Anticline.

Plate 15, fig. 1. Western nose of the Walker Creek Anticline, near Boomerang Valley. The Larapinta Group (C-Ol) in the core of the anticline is surrounded by prominent ridges of steeply dipping Mereenie Sandstone (Pzm). The Parke Siltstone underlies the wide alluvium-covered valley in the foreground.

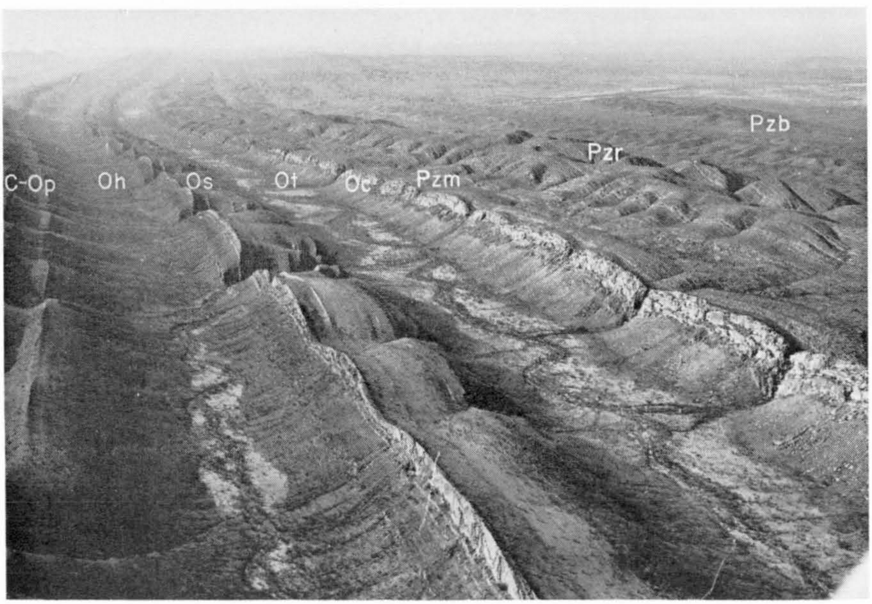


Plate 15, fig. 2. Western MacDonnell Ranges looking east towards the Finke Gorge. The formations from left to right are — the Pacoota Sandstone (C-Op), Horn Valley Siltstone (Oh), Stairway Sandstone (Os), Stokes Siltstone (Ot), Carmichael Sandstone (Oc), Mereenie Sandstone (Pzm), Hermannsburg Sandstone (Pzr), and Brewer Conglomerate (Pzb).

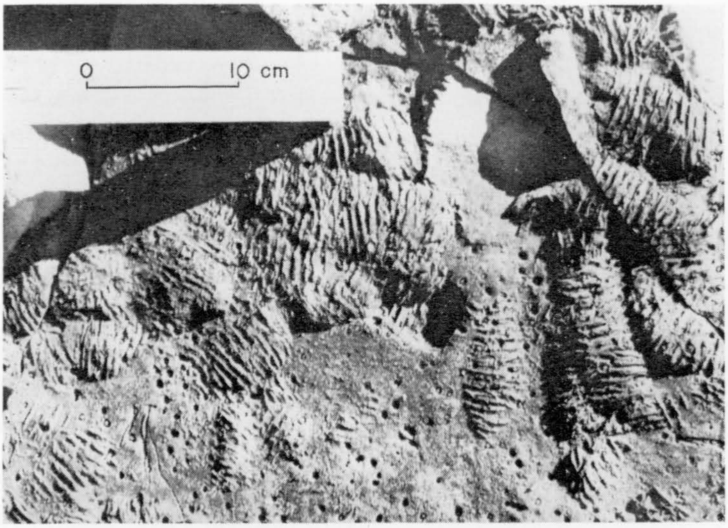


Plate 16, fig. 1. *Cruziana* on a bedding plane in the Pacoota Sandstone at Ellery Creek, in the MacDonnell Ranges. Transverse sections through *Scolithus* are also visible. (By courtesy of K. A. W. Crook).

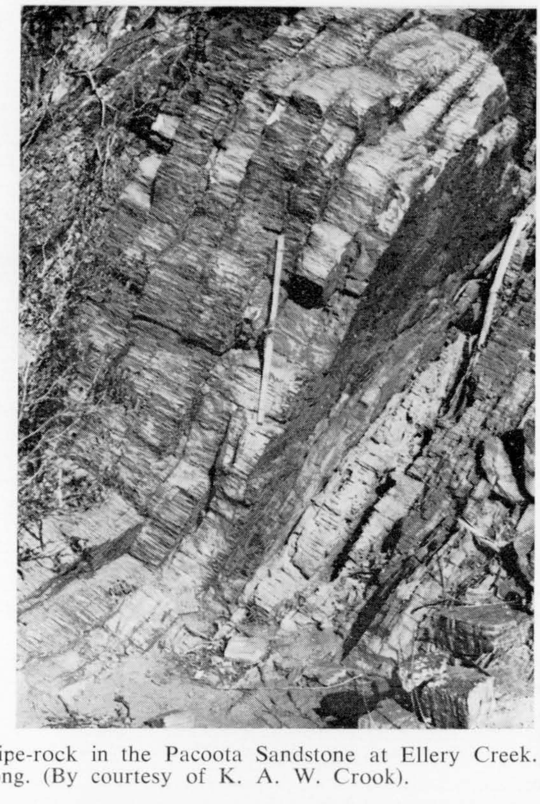


Plate 16, fig. 2. Pipe-rock in the Pacoota Sandstone at Ellery Creek. The scale is 2 feet long. (By courtesy of K. A. W. Crook).

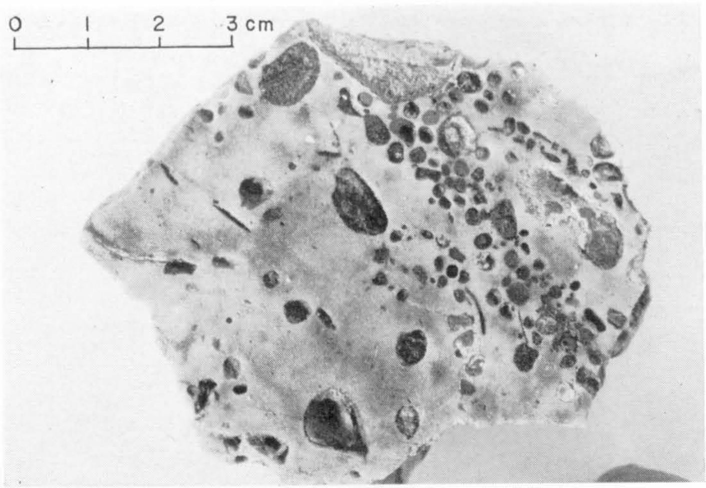


Plate 17, fig. 1. Sandstone containing vugs filled with limonite, Pacoota Sandstone, south of the George Gill Range.

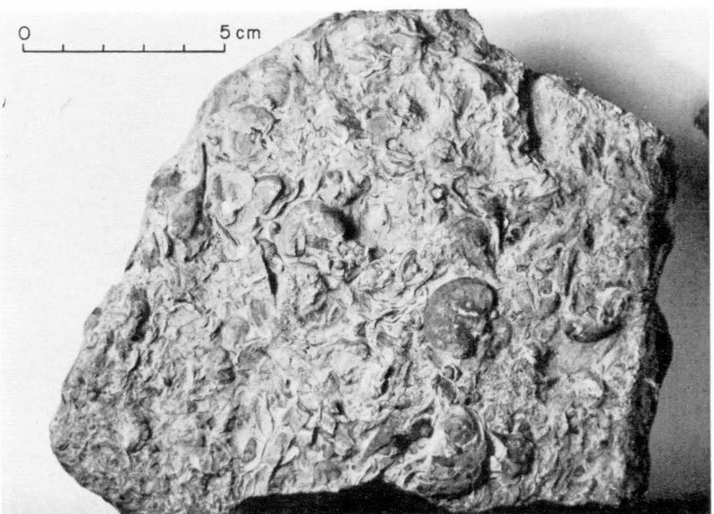


Plate 17, fig. 2. Richly fossiliferous limestone of the Horn Valley Siltstone. The fossils include *Carolinites* and asaphid trilobites.

Plate 18, fig. 1. Invertebrate tracks in the Stairway Sandstone, Basedow Range, about 16 miles west-northwest of Mount Ebenezer homestead.

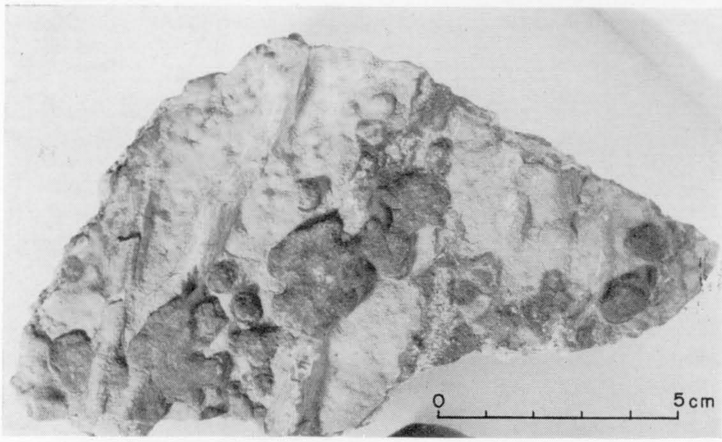


Plate 18, fig. 2. Manganese nodules on the unconformity surface between the Stairway Sandstone and Pertaoorrta Group in the Mount Sunday Range.

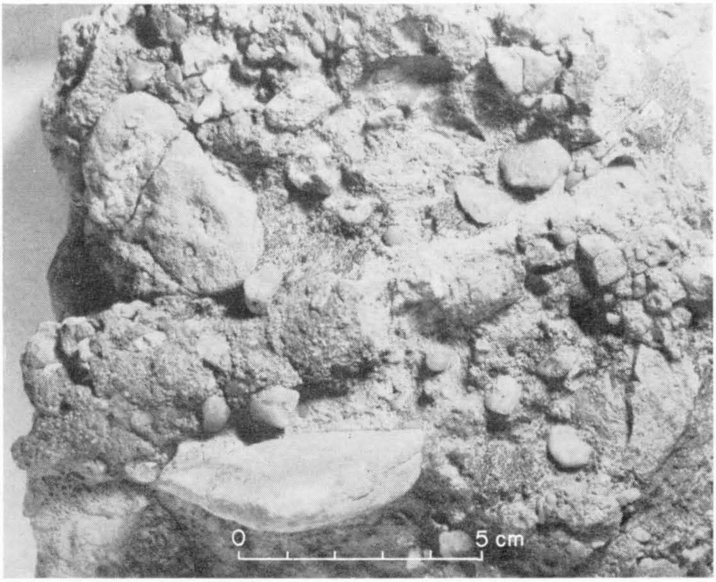


Plate 19, fig. 1. Phosphatic nodules in the basal conglomerate of the Stairway Sandstone in the Mount Sunday Range.

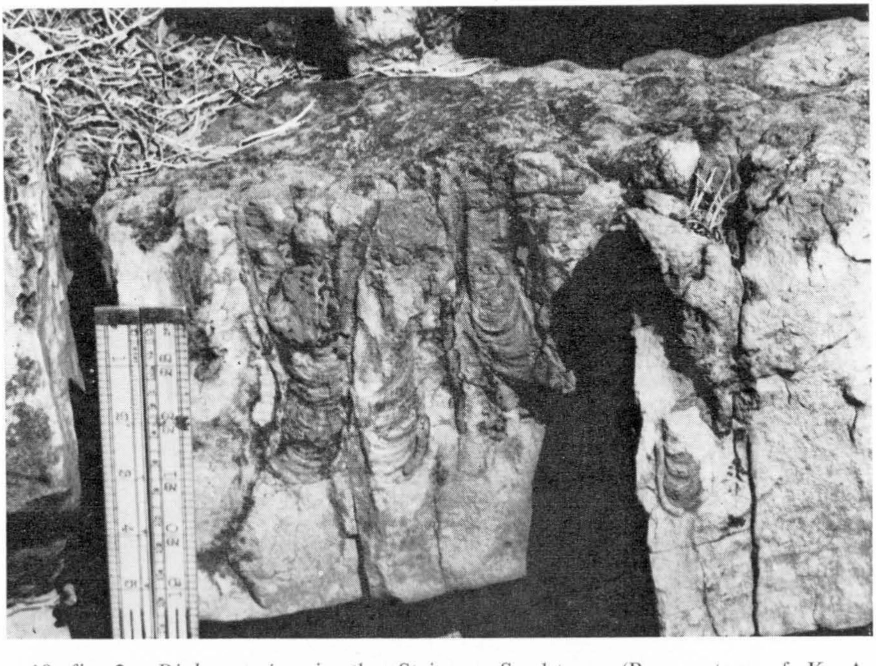


Plate 19, fig. 2. *Diplocraterion* in the Stairway Sandstone. (By courtesy of K. A. W. Crook).

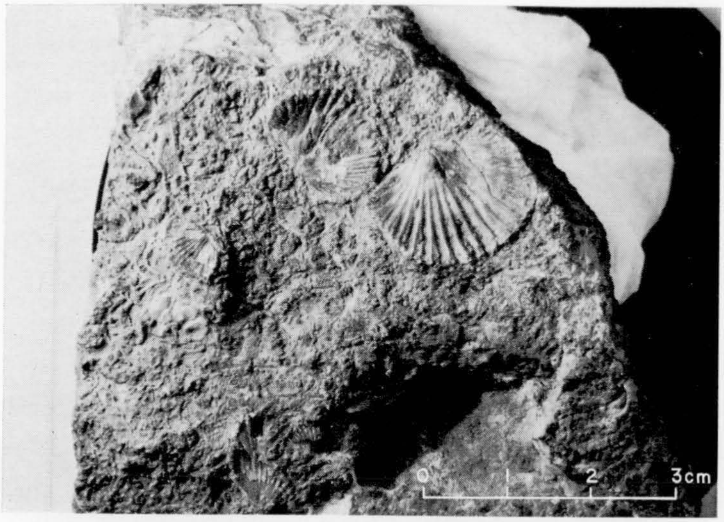


Plate 20, fig. 1. *Orthis leviensis* in limestone of the Stokes Siltstone.

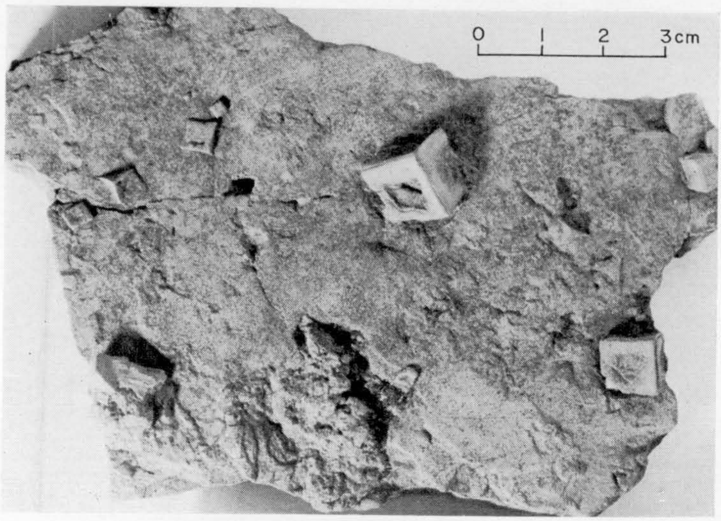


Plate 20, fig. 2. Pseudomorphs after halite in the Stokes Siltstone.

When Prichard & Quinlan (1962) defined the Larapinta Group, they included a silty red-brown sandstone (now known as the Carmichael Sandstone) at the top of the Stokes Formation. Later, Wells et al. (1964, 1965) and Ranford et al. (1966) mapped the same sandstone, in areas where it is well developed, as the lower part of the Mereenie Sandstone. Their upper part of the Mereenie Sandstone corresponded to the original Mereenie Sandstone as defined by Prichard & Quinlan (1962). This misunderstanding was only discovered during the compilation of this Bulletin, and to avoid confusion two separate formations, the Stokes Siltstone and the Carmichael Sandstone, have been defined.

The Larapinta Group is therefore redefined to include five formations, which in ascending order are: Pacoota Sandstone, Horn Valley Siltstone, Stairway Sandstone, Stokes Siltstone, and Carmichael Sandstone. The group, which ranges in age from Upper Cambrian to Upper Ordovician, conformably overlies the Pertaoorrta Group in places. Elsewhere it unconformably overlies Pertaoorrta Group and Proterozoic sediments. It is unconformably overlain by the Mereenie Sandstone in the east but in the west the contact is apparently conformable.

The Larapinta Group is sporadically distributed throughout much of the Amadeus Basin, and is particularly well developed in the northern half, where all five formations are present (Pl. 15, figs 1, 2). In the south, the Pacoota Sandstone, Horn Valley Siltstone, and lower part of the Stairway Sandstone are absent; the limits of deposition of the formations are shown in Figure 19. The geology of the surface on which the group was deposited is shown in Figure 20. The Larapinta Group was generally deposited conformably or disconformably on the Pertaoorrta Group, but on the southern and western margins of the basin, the upper formations were deposited unconformably on the Proterozoic rocks. The Larapinta Group has a maximum thickness of 7700 feet, at the eastern end of the Idirriki Range (Fig. 19). In the south, the total thickness is about 1000 feet, and towards the western margin of the basin it is only a few hundred feet thick.

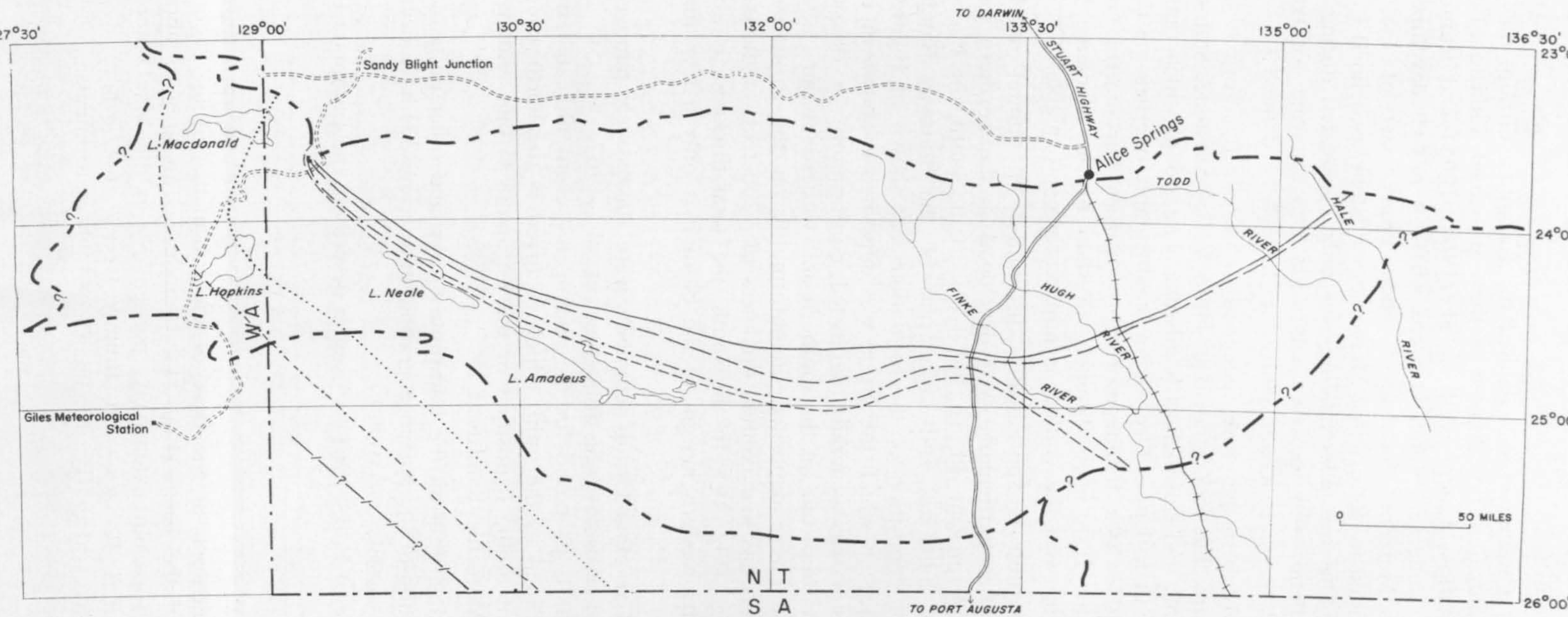
To the east the Larapinta Group sediments were successively removed by pre-Mereenie Sandstone erosion (see Johnstone et al., 1967, fig. 5). The name Rodingan Movement is proposed for the epeirogenic event indicated by this unconformity. It is defined as the uplift which occurred in the northeastern part of the basin subsequent to the deposition of the Larapinta Group and prior to the deposition of the Mereenie Sandstone.

The palaeontological data on the Larapinta Group and other parts of Australia used in the compilation of the palaeogeographic maps (Fig. 33) have been supplied by Joyce G. Tomlinson (pers. comm.).

The nomenclature of Folk (1961) is used in describing the Larapinta Group and Mereenie Sandstone.

Pacoota Sandstone

The Pacoota Sandstone at the base of the Larapinta Group occurs only in the northern half of the basin (Fig. 21). It underlies an area of about 10,000 square miles and crops out extensively, particularly in the MacDonnell Ranges, Idirriki Range, James Ranges, and Johnny Creek area, where it commonly forms prominent strike ridges (Pl. 15, fig. 2) or high escarpments.



(a)

Pacoota Sandstone
Horn Valley Siltstone
Stairway Sandstone (lower part)
Stairway Sandstone (middle part)
Stairway Sandstone (upper part)
Stokes Siltstone
Carmichael Sandstone

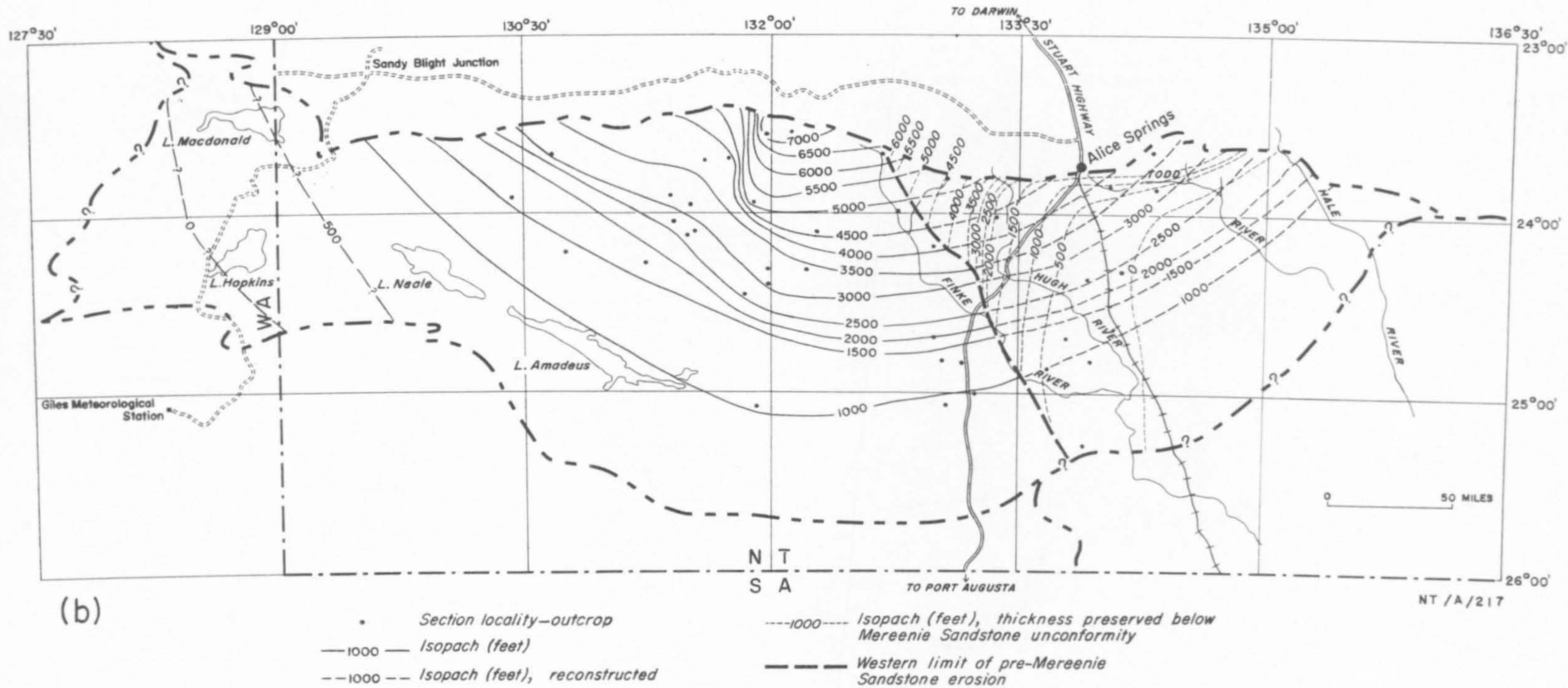


Fig. 19. (a) Southern limit and (b) thickness of Larapinta Group.

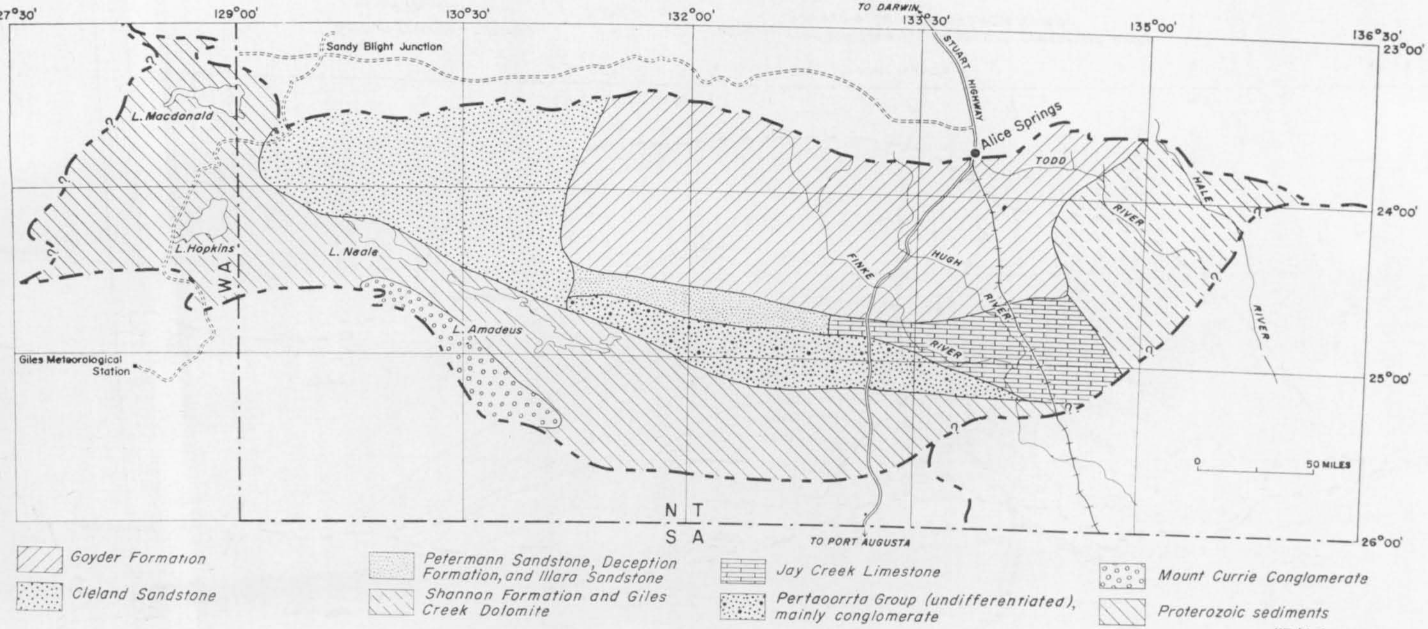


Fig. 20. Pre-Larapinta Group surface.

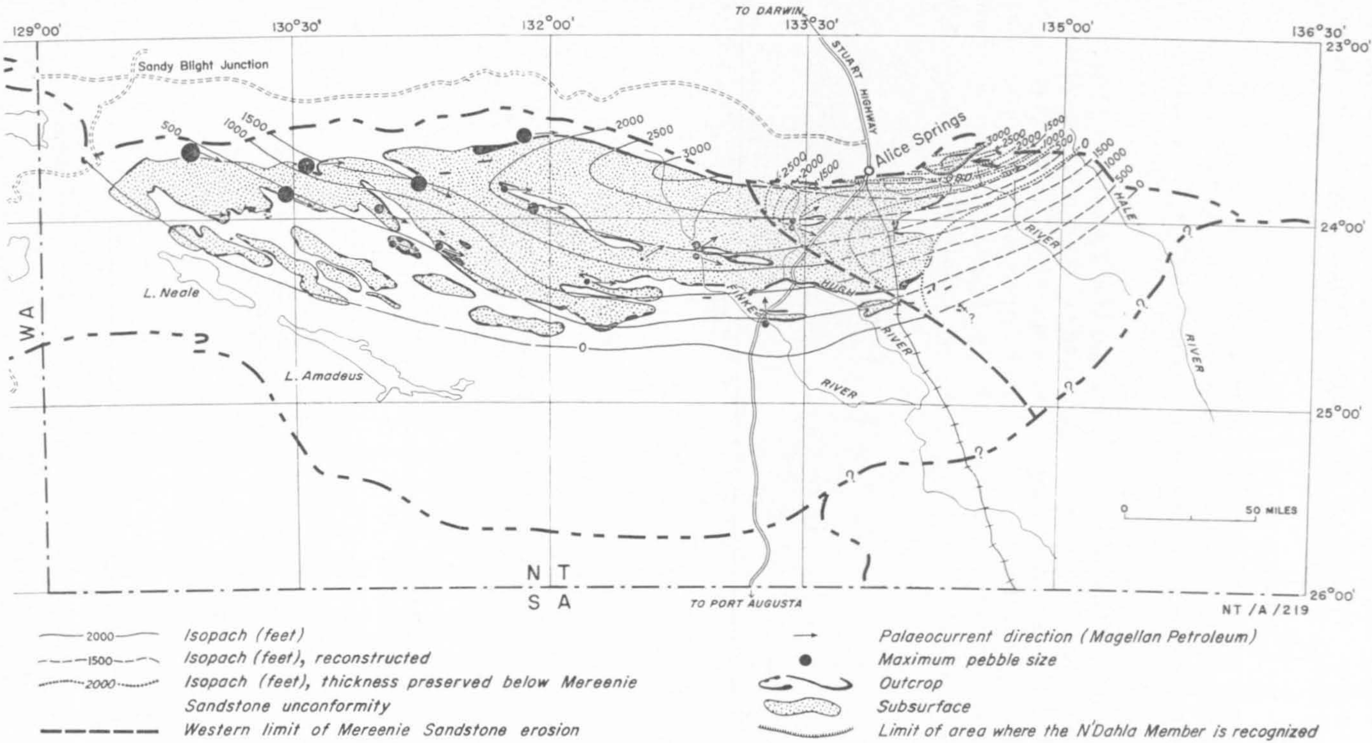


Fig. 21. Distribution and thickness of Pacoota Sandstone.

The Pacoota Sandstone generally overlies the Goyder Formation with a gradational contact, but to the west it rests conformably or disconformably on the Cleland Sandstone. It is generally overlain conformably by the Horn Valley Siltstone, but in the northeast corner of the basin is unconformably overlain by the Mereenie Sandstone.

The maximum preserved thickness is about 3000 feet, in the Finke Gorge area of the western MacDonnell Ranges, but it is estimated to have been about 4000 feet thick in the northeast corner of the basin before the post-Rodingan erosion (Fig. 21).

The Pacoota Sandstone ranges from the late Upper Cambrian (Trempealeauan) to Lower Ordovician (Arenigian) in age (Joyce G. Tomlinson, pers. comm.). Most of the sandstone is apparently barren, but some bands, particularly in the Ross River area, are rich in trilobites, brachiopods, pelecypods, gastropods, ribeirioids, nautiloids, and numerous trace fossils (Pl. 16, fig. 1). The vertical worm tube, *Scolithus,* forms pipe-rock, which is a common feature of the Pacoota Sandstone (Pl. 16, fig. 2).

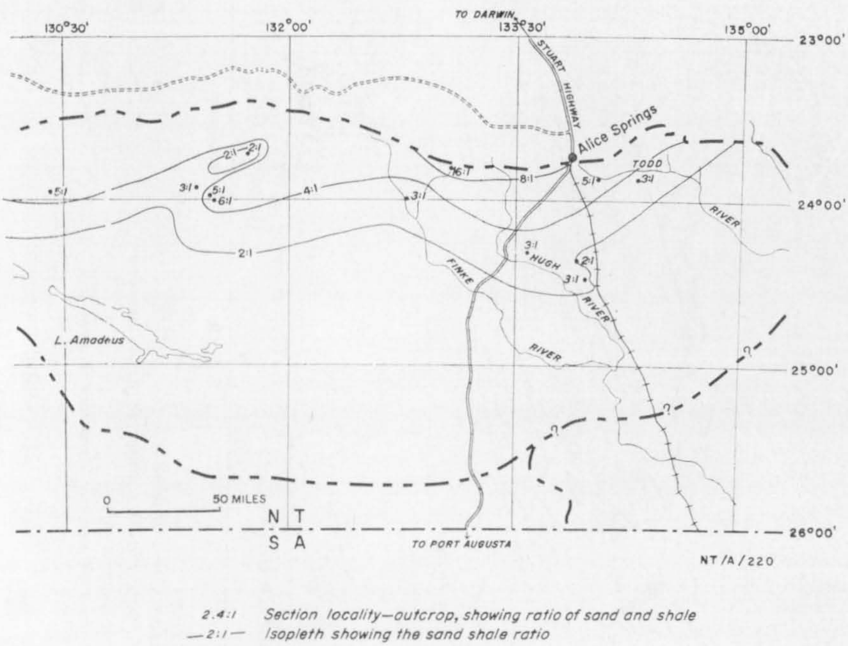


Fig. 22. Sand-shale ratio in Pacoota Sandstone.

Miss Tomlinson has distinguished eight faunal assemblages from which three time units can be recognized. These time units are informally designated Pacoota I, Pacoota II, and Pacoota III, and correspond respectively to uppermost Cambrian (Trempealeauan), Tremadocian, and Arenigian. Only one member, the N'Dahla Member, has been distinguished in the Pacoota Sandstone. It is 50 feet thick, and crops out on the northern flank of the Ross River Syncline, in the northeast. It has a Pacoota II fauna.

Lithology. The Pacoota Sandstone consists predominantly of quartzose sandstone with thin interbeds of siltstone which become thicker towards the top. The ratio of sand to shale decreases to the south (see Fig. 22).

The sandstone is fine to coarse-grained and in places very coarse-grained. Pebbly sandstone, with pebbles up to 4 inches in diameter, is also fairly common. The size of the pebbles increases to the west (Fig. 21); they are generally composed of vein quartz or silicified sandstone. Both the pebbles and the sand grains are well rounded and moderately well sorted. The sandstone is commonly friable in outcrop; it is generally grey, white, or brown, thinly to thickly bedded, ripple-marked, and cross-bedded. The cross-beds indicate palaeocurrents from the west or northwest (Fig. 21). Mud-pellet marking and fossil tracks and trails, particularly *Scolithus* and *Cruziana,* are also common. The sandstone is generally well exposed and forms prominent scarps or strike ridges. In places, it contains abundant glauconite. In the Gardiner and Idirriki Ranges there is a particularly prominent glauconite band, about 20 feet thick, in the upper part of the formation, which persists over hundreds of square miles. The glauconite forms up to 50 percent of the rock and may be granular or intergranular.

The sandstone is commonly ferruginized, and in places in the western half of the basin there is a thin pisolitic ironstone at the base of the unit. South of the George Gill Range in the central part of the basin, near the top of the Pacoota Sandstone, a sandstone about 4 feet thick contains abundant ferruginous vugs, which commonly weather out to give the rock a characteristic honeycomb appearance (Pl. 17, fig. 1).

The interbedded siltstone and claystone are variegated white, grey, brown, and red. They are thin-bedded, micaceous, and possibly kaolinitic in places, and invariably poorly exposed. The contacts between the lutites and arenites are commonly gradational. Thin bands of phosphorite, with nodules up to 3 inches in diameter, occur but are not common. Rare beds of limestone are present near the base in the Ross River Gorge area. The limestone is ferruginized and glauconitic, and has a maximum thickness of 10 feet.

The N'Dahla Member has a distinctive appearance. It comprises dark red-brown and purple-brown medium to coarse-grained poorly sorted sandstone, clayey sandstone, and pebbly sandstone. Some of the sandstone is glauconitic. There are a few conglomeratic beds, with poorly rounded pebbles and cobbles of siltstone and limestone set in a coarse matrix of glauconitic sandstone. Some thin bands of limestone are also present.

Petrography. Quartzose sandstone is predominant in the Pacoota Sandstone. Most of it is well sorted and well rounded. The modal grainsize ranges from very fine to coarse sand. Most of the arenite may be classified as supermature orthoquartzite with 30 to 60 percent non-undulating quartz, 30 to 60 percent undulatory quartz, and 10 to 30 percent composite quartz. Chert grains are rare. In a few specimens, grains of metaquartzite or feldspar are common and the rock grades into subgreywacke or subarkose. A little tourmaline and zircon are present. The cement is commonly siliceous, with well developed quartz overgrowths; less commonly it is clayey, calcareous, glauconitic, or phosphatic. The diagenetic silica has considerably reduced the porosity and permeability of the rocks. The clays are predominantly kaolinitic and illitic, with minor chlorite and montmorillonite.

The N'Dahla Member contains up to 10 percent reworked sand grains and up to 20 percent metaquartzite grains. Some of the metaquartzite grains are better rounded than the non-undulatory quartz, which suggests that they are multi-cycle grains.

Environment of Deposition. The fauna, the abundant cross-beds and ripple marks, and the presence of glauconite indicate that the Pacoota Sandstone is a shallow-marine deposit. Williams et al. (1965) have suggested that the presence of inter-granular sulphates and carbonates indicates relatively high salinity and restricted circulation, but they were more probably introduced during diagenesis. The abundance of cross-beds and the coarse grainsize suggest vigorous conditions. The presence of glauconite and phosphorites and the rich faunal development suggest periods of slow deposition.

Middlemiss (1962) suggests that the straightness of burrows indicates rapid deposition, the burrowing organism being one able to keep pace with the rapid sedimentation by 'straight chewing'. Application of this criterion to the Pacoota Sandstone, in which *Scolithus* is common, suggests that sedimentation was rapid at first but somewhat slower in the upper part of the section, where *Scolithus* is less common. Arenites may have acquired their supermaturity during the period of slow sedimentation.

The Pacoota Sandstone is a thick and extensive body of orthoquarzite which could have originated in a number of ways, such as coalescing of longshore bars during repeated minor transgressions and regressions, or by subaqueous reworking of a desert area. Williams et al. (1965) suggest that some of the quartz grains show aeolian frosting, but it is more likely that the frosted grains were formed by chemical weathering and diagenesis. An extensive body of coarse sand can also form by impact of high-energy waves on a shelf; this results in winnowing out of the finer grains and the formation of an elongate body of coarse sand, which may ultimately cover a large area in response to repeated transgressions and regressions.

Horn Valley Siltstone

The distribution of the Horn Valley Siltstone (Fig. 23) is similar to that of the Pacoota Sandstone. The formation underlies a considerable area, but it rarely crops out in the deep alluvium-covered strike valleys. The best exposures are in the western MacDonnell Ranges, the Ochre Hill area, Mount Olifent, and on the flanks of some of the anticlines west of Tempe Downs homestead.

The Horn Valley Siltstone rests conformably on the Pacoota Sandstone, except in a small area in the south (e.g. in the Seymour Range area), where it rests disconformably on the Goyder Formation or Jay Creek Limestone. It is generally conformably overlain by the Stairway Sandstone, except to the east, where it is unconformably overlain by the Mereenie Sandstone. The maximum thickness is 1500 feet, in the western MacDonnell Ranges (see Fig. 23), but this includes about 600 feet of siltstone and shale of doubtful affinities, and the true maximum thickness may be only about 800 feet.

The Horn Valley Siltstone contains a rich and extremely well preserved fauna of trilobites, brachiopods, pelecypods, nautiloids, ostracods, conodonts, graptolites, and gastropods (Pl. 17, fig. 2) of Lower Ordovician (Arenigian) age (Joyce G. Tomlinson, pers. comm.).

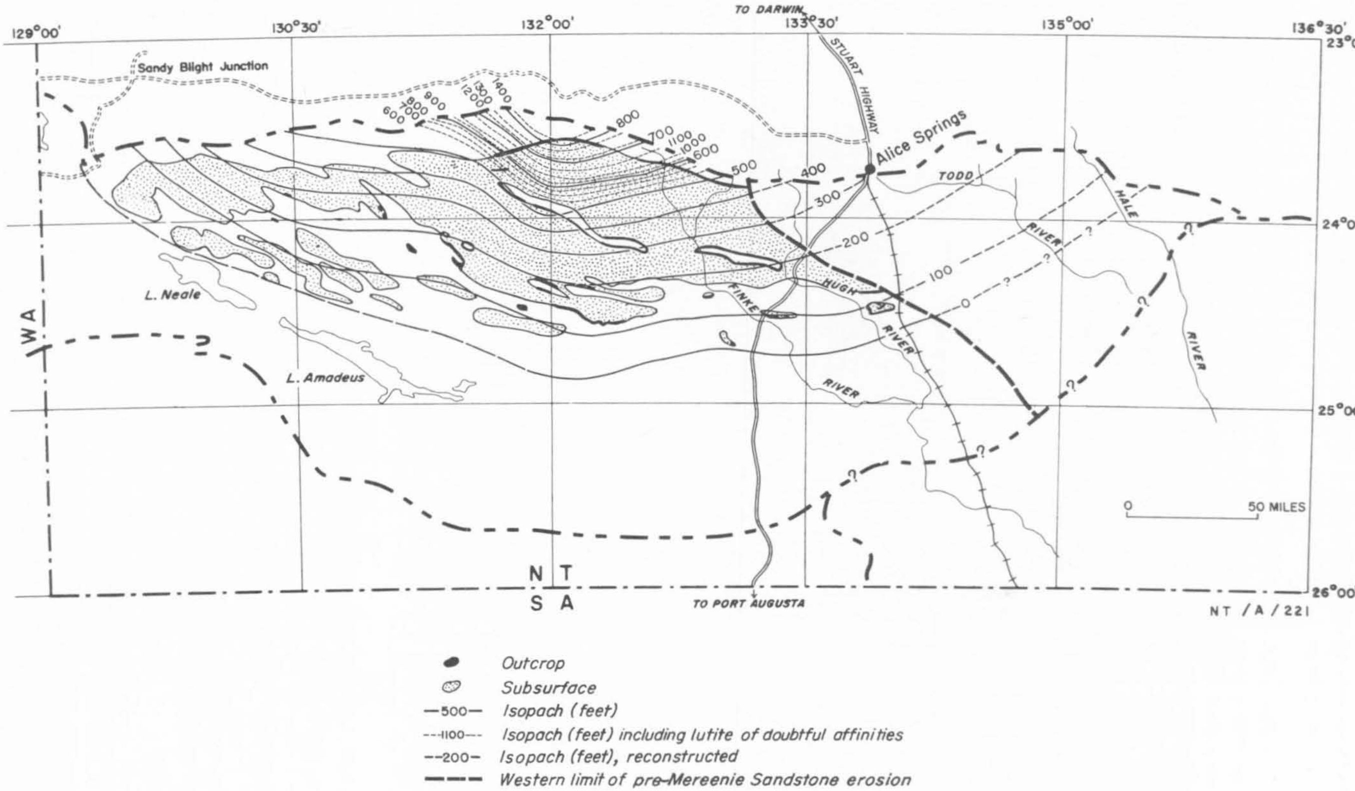


Fig. 23. Distribution and thickness of Horn Valley Siltstone.

Lithology. The Horn Valley Siltstone contains siltstone, calcareous siltstone, claystone, limestone, and minor sandstone and sandy siltstone. The ratio of non-calcareous to calcareous sediments (Fig. 24) ranges from 2:1 to over 32:1, with the highest proportion of calcareous sediments in the south and west.

The siltstone and claystone are predominantly grey-green and pale brown in outcrop, but black subsurface. They are laminate to thinly bedded, calcareous in part, soft and readily weathered, pyritic, and possibly gypsiferous (the selenite which forms a superficial deposit in places over the Horn Valley Siltstone may have been derived from the alteration of pyrite).

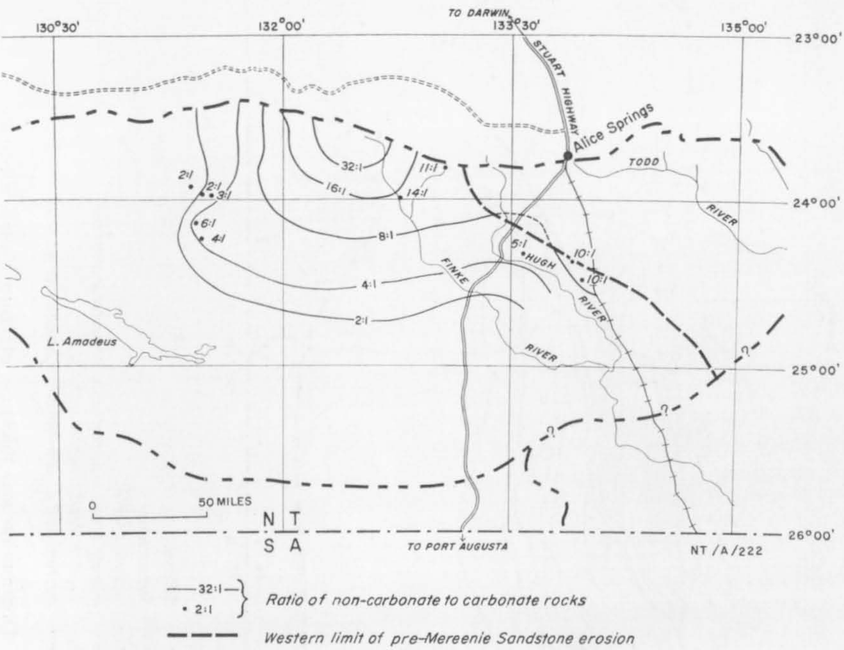


Fig. 24. Ratio of non-carbonate to carbonate rocks in Horn Valley Siltstone.

The limestone is yellow-brown, grey-brown, or dark grey in outcrop, but is commonly light grey subsurface; it is thin-bedded, brittle, moderately resistant to weathering, rarely sandy, and largely composed of fossil fragments. The limestone is recrystallized and veined by calcite in places.

The subordinate sandstone is brown or grey-brown, thin-bedded, silty, friable, and easily weathered. Glauconite is rarely present in the sandstone and limestone. A few bands of pelletal phosphorite, similar to those in the Stairway Sandstone, are present towards the top of the formation. A distinctive band of oolitic ironstone is also present near the top of the formation, and although it is generally only a few inches thick, it extends over thousands of square miles. The ooliths are limonitic in outcrop, but pyritic when fresh.

Petrography. The limestones are composed largely of fossil fragments, with a sparry calcite cement; they may be classified as biosparites or biosparrudites.

The quartz in the sandy limestone, sandy siltstone, and sandstone, is mainly non-undulatory with minor undulatory and rare composite grains. The sand-size grains are moderately well to well sorted and poorly rounded. Granular or intergranular glauconite occurs only rarely, and in some cases it replaces calcite. Pyrite ooliths are occasionally present. The claystone is composed mainly of illite and kaolinite with minor chlorite.

Environment of Deposition. The Horn Valley Siltstone is marine. The abundance of graptolites suggests that the upper waters were well aerated and able to support a prolific fauna; the lack of infauna and the extremely good preservation of the numerous fossils suggest euxinic conditions on the sea bottom. The presence of pyrite also suggests strongly reducing bottom conditions, as do the foetid smell, the black colour, and the abundance of organic carbon.

Most of the formation was probably laid down in tranquil water, either fairly deep water below wave base or in enclosed basins or lagoons with restricted circulation. However, biosparites are considered by Folk (1961) to indicate fairly strong winnowing action during or immediately after deposition of calcareous sediments. The lithofacies map (Fig. 24) shows that the proportion of calcareous sediments increases towards the margin of the basin, where waves and winnowing are most likely to have been active. The anaerobic conditions probably resulted from stagnation in deep bottom waters below wave base.

Stairway Sandstone

The Stairway Sandstone is one of the most widespread units of the Larapinta Group. It is estimated to underlie an area of at least 20,000 square miles, although its actual outcrop area is only about 600 square miles (Fig. 25).

In the northern half of the basin, the formation rests conformably on the Horn Valley Siltstone, but to the south it rests disconformably on the Pertaoorrta Group and unconformably on Proterozoic sediments. Farther south and west (e.g. in the Petermann Range area), the formation rests unconformably on igneous and metamorphic rocks. The Stairway Sandstone is generally conformably overlain by the Stokes Siltstone, but in the east it is overlain unconformably by the Mereenie Sandstone.

Thickness ranges from 1840 feet in the Idirriki Range to about 100 feet on the southern margin of the basin (Fig. 25).

The Stairway Sandstone is estimated to range from Upper Llanvirnian to Llandeilian (Joyce G. Tomlinson, pers. comm.). The rich fauna includes trilobites, brachiopods, pelecypods, gastropods, nautiloids, sponge spicules, numerous trace fossils, and microfossils.

Lithology. The Stairway Sandstone has an arenite/lutite ratio ranging from about 1:1 to 4:1 with the highest proportion of lutite in the middle of the basin (Fig. 26). The lithofacies map shows the present distribution; the distribution in the original basin is unknown. Cook (1966a, unpubl.) has divided the Stairway Sandstone into lower, middle, and upper units on the basis of the lithology. The boundary between the middle and upper units corresponds approximately to the early Larapintan/late Larapintan time boundary (Joyce G. Tomlinson, pers. comm.). All three units are present in the northern half of the basin, but in the south only the uppermost unit is present (see Fig. 27).

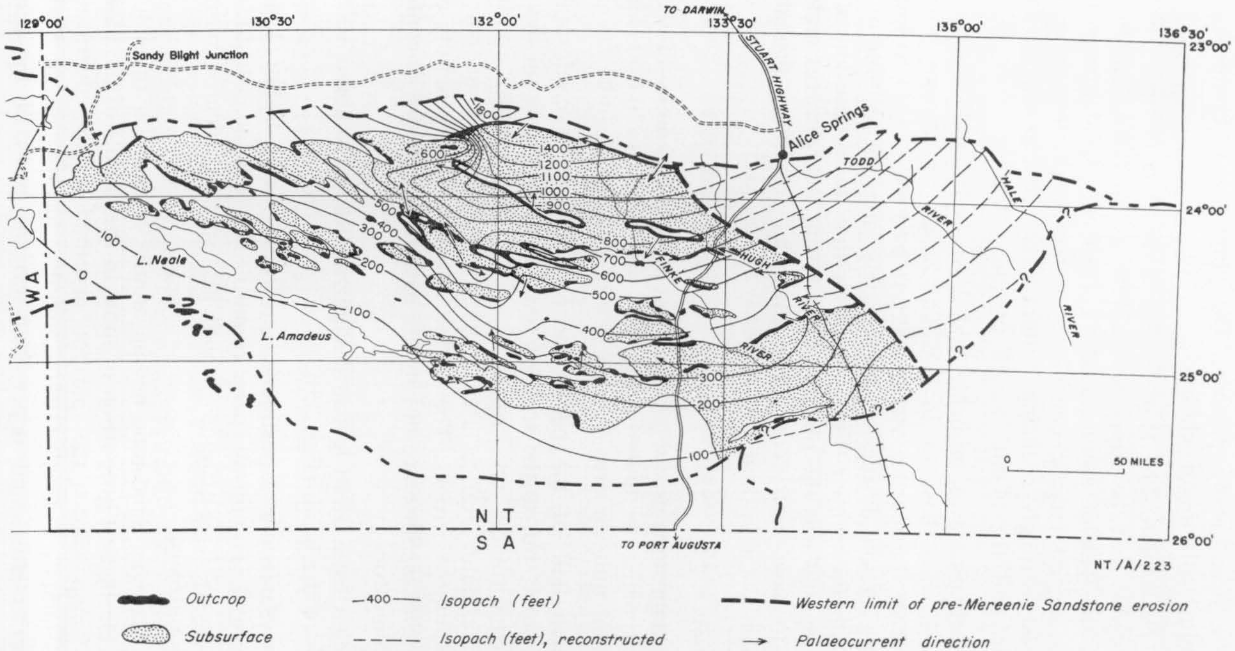
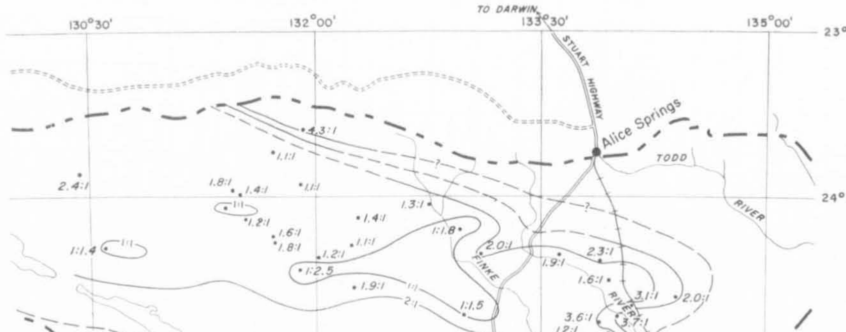


Fig. 25. Distribution and thickness of Stairway Sandstone.

The lower unit of the Stairway Sandstone shows little lateral variation in lithology or thickness; its maximum thickness is 200 feet on the northern margin of the basin (Fig. 28). It is a white or grey fine to very coarse-grained sandstone,



• 2.4:1 Section locality—outcrop, showing ratio of sand to shale
—2:1— Isopleth showing the sand shale ratio

Fig. 26. Ratio of arenite to lutite in Stairway Sandstone.

with well rounded and well sorted quartz grains. It is pebbly in places, and one pebble band, about 1 foot thick, forms a useful marker over an area of at least 10,000 square miles in the Rodinga, Henbury, and Lake Amadeus Sheet areas. The sandstone is thinly to massively bedded, ripple-marked, and cross-bedded; bedding-plane markings, tracks and trails (Pl. 18, fig. 1), and pipe-rock—which in places is difficult to distinguish from some of the pipe-rock in the Pacoota Sandstone—are common. In places, the sandstone near the base of the unit contains up to 20 percent of ooliths, which are pyritic subsurface but limonitic in outcrop. The lower unit of the Stairway Sandstone is a typical blanket sand.

The lithology of the middle unit is more varied, and its maximum thickness is about 700 feet near the northern margin of the basin (Fig. 28). It contains siltstone, mudstone, and claystone, which are black subsurface but grey or green in outcrop. The lutites are commonly sandy, micaceous, laminate, easily weathered and poorly exposed. Grey or white fine-grained thin-bedded sandstone and grey, brown, or black pelletal and nodular phosphorites are interbedded with the lutites. The middle unit shows a marked lateral variation, and the lutite-arenite-phosphorite sequence passes into a lutite-carbonate sequence to the southeast (Seymour Range area). The carbonate rocks in the southeast include thin-bedded dark grey limestone and dolomite which contain a distinctive fauna of small pyritized gastropods. Farther east, the middle unit is composed mainly of red lutites and arenites. Phosphorites occur in both the carbonate and red-bed facies, but are rare. There is a striking similarity between the phosphatic shale/carbonate/red-bed facies variation in the middle unit of the Stairway Sandstone (Cook, 1967) and the facies distribution shown by Sheldon (1964) in the Phosphoria Formation of western Wyoming.

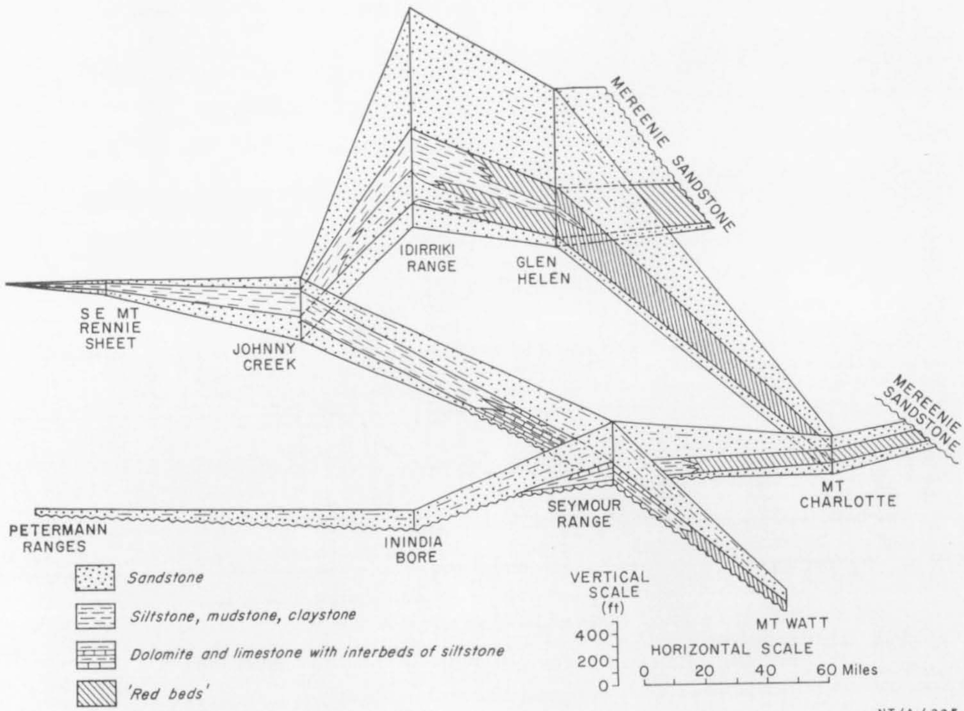


Fig. 27. Facies variations in Stairway Sandstone.

The thickness of the upper unit ranges from less than 100 feet in the south to 1000 feet in the north (Fig. 28). It is predominantly an arenite sequence and its lithology is similar to the lower unit, but there are some interbeds of lutite and thin bands of phosphorite. Nodules of phosphorite and manganese occur in the basal conglomerate in the Mount Sunday Range (Pl. 18, fig. 2; Pl. 19, fig. 1). The arenites consist predominantly of white or grey fine-grained silicified sandstone; they are cross-bedded, and commonly contain abundant trace fossils such as *Diplocraterion* and *Cruziana* (Pl. 19, fig. 2).

Petrography. There are four main rock types in the Stairway Sandstone—arenites, lutites, carbonates, and phosphorites.

The majority of the arenites can be classified as supermature orthoquartzites which contain over 95 percent quartz grains. The quartz is generally non-undulatory, with only a small proportion of undulose quartz and an even smaller number of composite grains. The cement is siliceous, less commonly calcareous, phosphatic, or glauconitic. The orthoquartzites in the lower unit are generally coarse-grained, and the grains well rounded and sorted. Bimodality is fairly common, and the two modes are each well sorted. The orthoquartzite in the upper

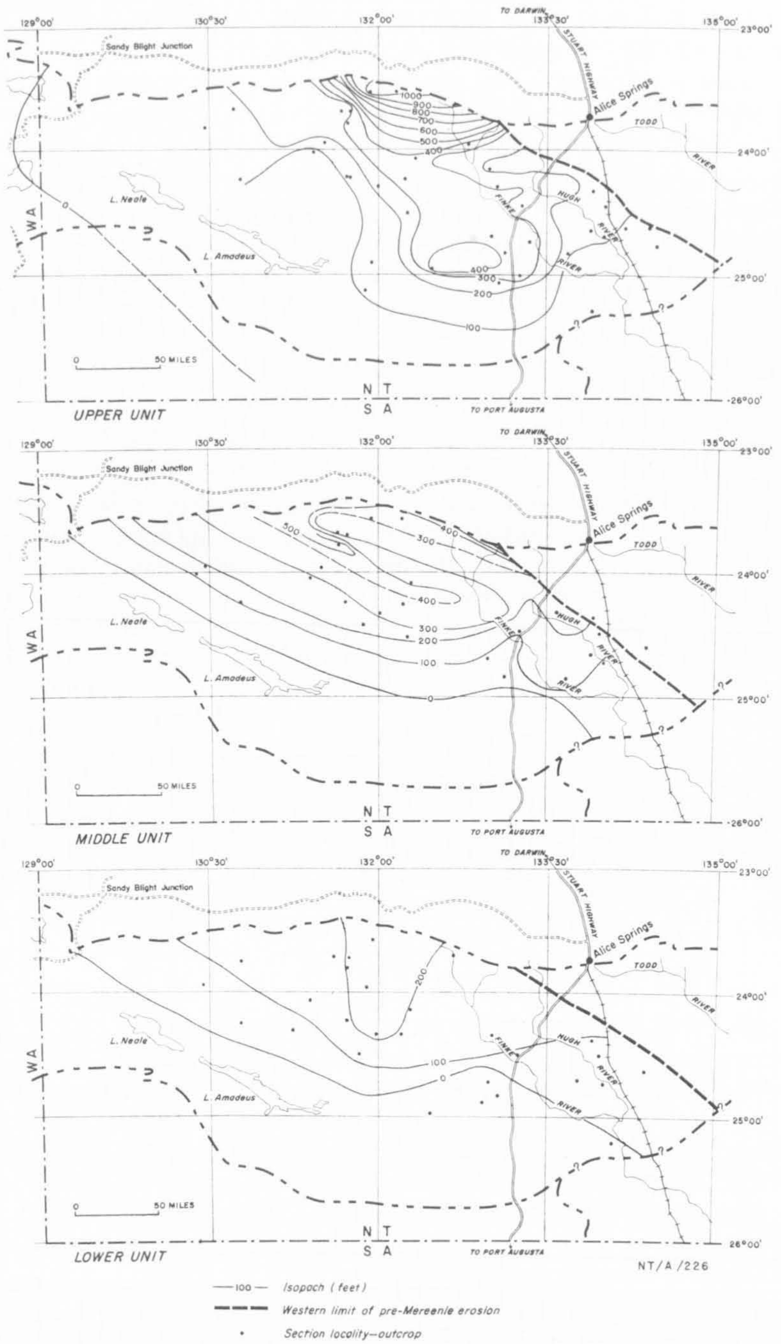


Fig. 28. Thickness of lower, middle, and upper units of Stairway Sandstone.

unit is of fine sand size; some of the sands are subangular and moderately well sorted. The proportion of grains of chert and feldspar is low, but is higher in the upper than in the lower unit. The arenites of the middle unit are mainly very fine-grained submature to immature orthoquartzites. The heavy minerals constitute a typical supermature tourmaline-zircon (both well rounded) assemblage. A few of the Stairway Sandstone arenites fall into the subarkose group, containing 5 to 25 percent of feldspar, mainly microcline.

The lutites include both siltstone and claystone. The mineralogical composition of the siltstone is similar to that of the quartz arenites, except that it contains more feldspar. The grains are much less well rounded and less well sorted. The mudstone and claystones are rarely sandy or silty, rarely pyritic, and very rarely calcitic, dolomitic, or sideritic. The clay minerals are predominantly illitic, with minor kaolinite and chlorite.

The limestone and dolomite contain appreciable amounts of terrigenous quartz in places. The limestones are mainly micrites and biomicrites, and the dolomites are generally aphanocrystalline to coarsely crystalline. In places, the dolomite crystals have well developed rhombic form, and have replaced calcite.

Cook (1966a, unpubl.) has described 10 distinctive types of phosphorite. The most common forms are pellets showing no internal structure or sandy pellets containing up to 60 percent detrital quartz grains. Other modes of occurrence include pellets with concentric banding; composite pellets composed of smaller pellets; structured pellets with an irregular (commonly convoluted) internal form; and encasing pellets which form a thin skin around detrital grains (generally quartz). Phosphate also occurs as a cement, as phosphatized fossils, and as secondary minerals.

Environment of Deposition. The coarseness of the sand grains in the lower unit of the Stairway Sandstone and the high degree of rounding and sorting suggest that the orthoquartzite was deposited in a vigorous environment, or, less probably, that the rate of sedimentation was so slow that the efficiency of the rounding and sorting mechanism matched the rate of deposition. The bimodality suggests that sediments from different environments were mixed. The orthoquartzite of the upper unit was probably deposited in much the same environment as the lower unit, except that it was much less vigorous. A barrier island or a beach are environments which would produce this type of sandstone, and the body of blanket sand was formed by the coalescing of elongated bodies of sand.

The presence of phosphorites and the abundance of chewing by infauna (suggested by Middlemiss, 1962, as an indication of the rate of deposition) suggest that the middle unit was probably laid down very slowly. The presence of pyrite, organic matter, and phosphorites suggests that the pH ranged from 7.0 to 7.8 (Krumbein & Garrells, 1952), and the Eh from -0.2 to -0.4, that is, strongly reducing, but possibly becoming more oxidizing to the southeast. These conditions are consistent with a poorly aerated lagoonal environment.

Detailed studies of the Stairway Sandstone, using the graphic log method of Bouma (1962), suggest either a lagoon-barrier island environment of the Laguna Madre type (Rusnak, 1960), or an intertidal-flat environment of the Wash type (Evans, 1965). Both these environments today are restricted in areal distribution, whereas the original area of deposition of the Stairway Sandstone was probably

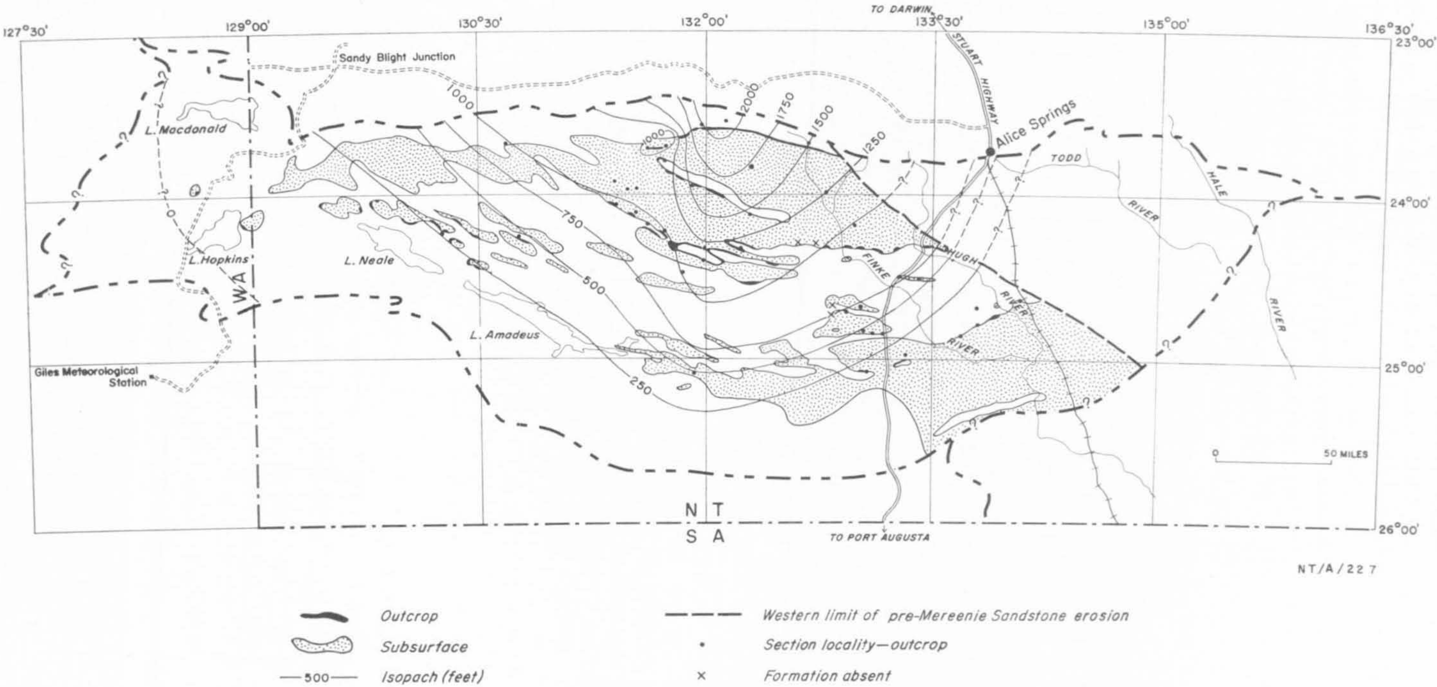


Fig. 29. Distribution and thickness of Stokes Siltstone.

at least 40,000 square miles. Irwin (1965) and Shaw (1964) have suggested a model for epeiric sea sedimentation with a wide low-energy open-sea environment, a narrow high-energy environment where the open-sea waves impinge on the epeiric sea floor (which may have been the depositional environment of the lower and upper units of the Stairway Sandstone) and a wide landward zone of low energy, where there are few currents or large waves with a reducing environment (the probable depositional environment of the middle unit of the Stairway Sandstone).

Stokes Siltstone (renamed and redefined)

The name Stokes Siltstone is given to the sequence of grey and green siltstone and claystone with minor thin-bedded limestone and a few sandstone interbeds which lies conformably between the Stairway Sandstone below and the Carmichael Sandstone above. The base of the Stokes Siltstone has been selected at the top of the last major sandstone in the Stairway Sandstone. The top is taken at the base of the first prominent sandstone of the Carmichael Sandstone. The type section, where the formation is about 2000 feet thick, is at Stokes Pass.

The Stokes Siltstone underlies a considerable portion of the Amadeus Basin (Fig. 29) and is one of the most extensive formations of the Larapinta Group. It is rarely exposed, and generally forms wide alluvium-covered valleys. The only areas where it is well exposed are in the western MacDonnell Ranges, at the extreme western end of the Johnny Creek Anticline, and on the flanks of the anticlines west of Tempe Downs homestead.

The Stokes Siltstone overlies the Stairway Sandstone with a conformable and gradational contact, except on the extreme western margin of the basin, where it unconformably overlies the Bitter Springs Formation and other Proterozoic units. In the west, it is overlain by the Carmichael Sandstone; the contact is both conformable and gradational. To the east, it is unconformably overlain by the Mereenie Sandstone. The formation is thickest—about 2000 feet—at Stokes Pass, but is less than 200 feet thick on the southern margin of the basin (Fig. 29).

Fossils are fairly common, particularly in the limestone, but most of them are fragmentary. They include brachiopods, trilobites, gastropods, pelecypods, echinoderms, nautiloids, conodonts, and some trace fossils. The most characteristic fossil is the brachiopod *Orthis leviensis* (Pl. 20, fig. 1). The fossils are of Upper Ordovician (Caradocian) age (Joyce G. Tomlinson, pers. comm.).

Lithology. The Stokes Siltstone is composed mainly of siltstone and claystone, with minor limestone and sandstone.

The lutites are generally green, grey-green, or pale brown in outcrop. In places they are micaceous, sandy, or calcareous; they are generally laminate or thin-bedded, and easily weathered. One notable feature of the lutites of the Stokes Siltstone is the abundance of pseudomorphs after halite (see Pl. 20, fig. 2).

The limestones which are most common in the lower half of the formation, are pink, grey, or grey-green, thin-bedded, moderately resistant to weathering, and generally composed of a large number of fossil fragments; the limestones can probably be classed as coquinites. The ratio of non-calcareous to calcareous sediments ranges from 4:1 to 64:1, with the highest proportion of limestone toward the margin of the area of deposition (Fig. 30).

Plate 21, fig. 1. View looking southeast over the George Gill Range. The lower slopes of the scarp consist of Carmichael Sandstone, and the upper part of the scarp and the plateau beyond are composed of Mereenie Sandstone. Kings Canyon is visible in the middle of the photograph.

Plate 21, fig. 2. Well developed cross-bedding in the Mereenie Sandstone at Mount Winter in the Cleland Hills.

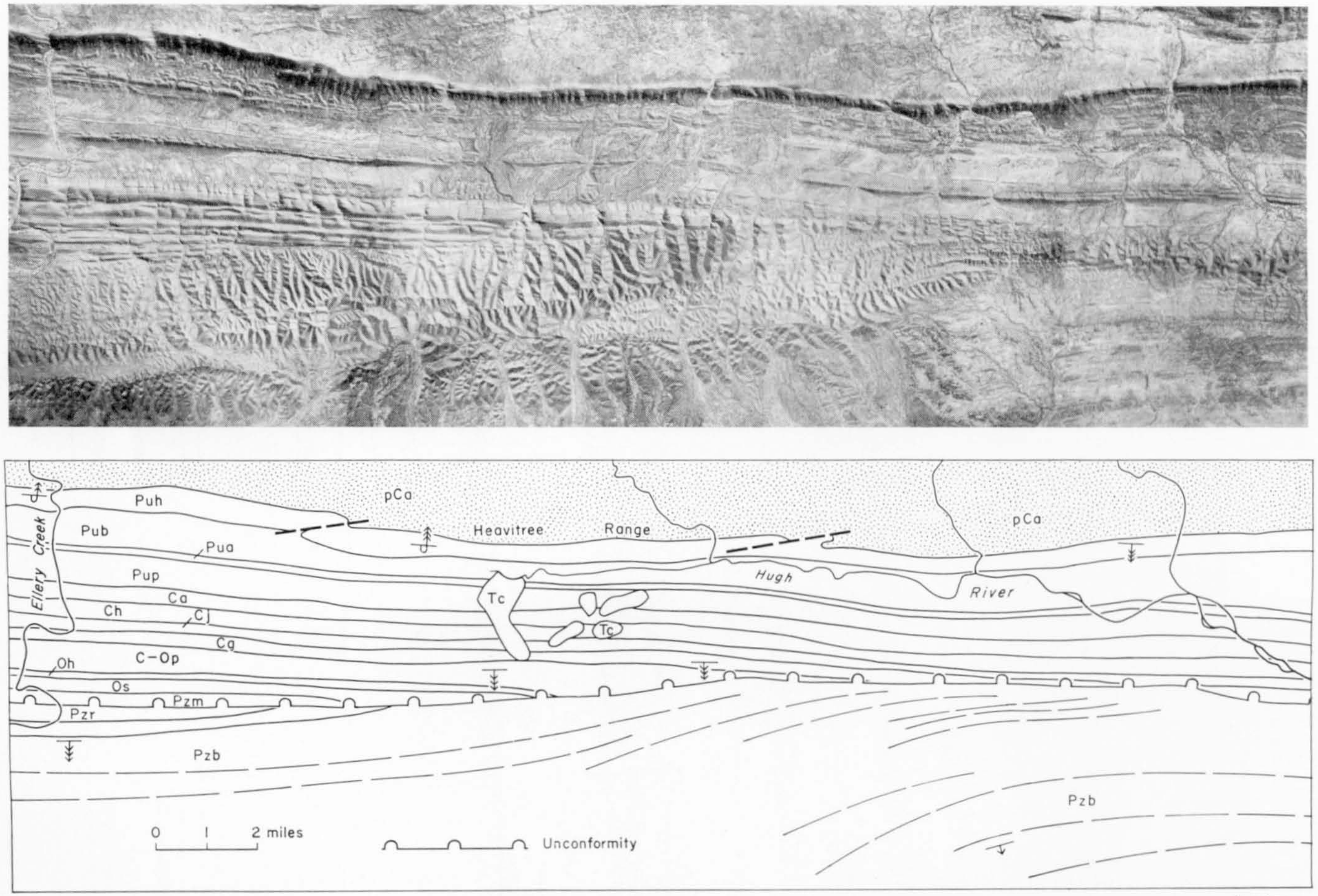


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Plate 22. Unconformity at the base of the Pertnjara Group between Ellery Creek and the Hugh River in the MacDonnell Ranges. Arunta Complex (pCa), Heavitree Quartzite (Puh), Bitter Springs Formation (Pub), Areyonga Formation (Pua), Pertatataka Formation (Pup), Arumbera Sandstone (Ca), Hugh River Shale (Ch), Jay Creek Limestone (Cj), Goyder Formation (Cg), Pacoota Sandstone (Co-Op), Horn Valley Siltstone (Oh), Stairway Sandstone (Os), Mereenie Sandstone (Pzm), Hermannsburg Sandstone (Pzr), Brewer Conglomerate (Pzb), Tertiary conglomerate (Tc).

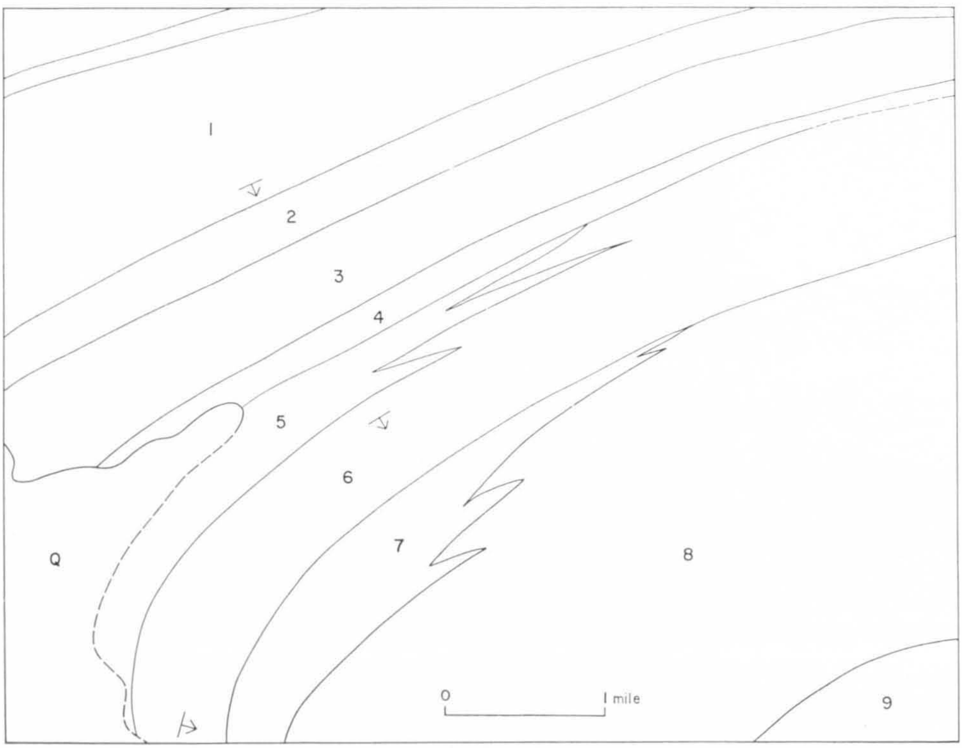

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Plate 23. The Pertnjara Group at the western end of the MacDonnell Ranges. Mereenie Sandstone (1), Parke Siltstone (2, 3, 4; Sandstone of 3 is probably equivalent to the fish-bearing sandstone at the Mereenie Anticline), Hermannsburg Sandstone (5, 6, 7), and Brewer Conglomerate (8, 9).

Plate 24, fig. 1. Prominent hills of steeply dipping sandstone in the basal part of the Pertnjara Group on the northwest rim of Gosses Bluff.

Plate 24, fig. 2. Basal conglomeratic beds of the Hermannsburg Sandstone near the contact with the Mereenie Sandstone at Ellery Creek in the MacDonnell Ranges.

Sandstone generally occurs in the upper half of the formation close to the contact with the Carmichael Sandstone. It is brown, grey-brown, or grey, fine-grained, silty, commonly calcareous, thin-bedded, and poorly exposed.

Petrography. The commonest type of limestone is a biomicrite or a biomicrudite, in which the fossil fragments are embedded in a microcrystalline calcite cement. In places, the cement is sparry, or patches of sparry calcite occur within a predominantly microcrystalline calcite cement, possibly owing to disturbance of the matrix by boring organisms. Some of the limestones are composed mainly of fossils belonging to one phylum: for example, echinoid biomicrites are common.

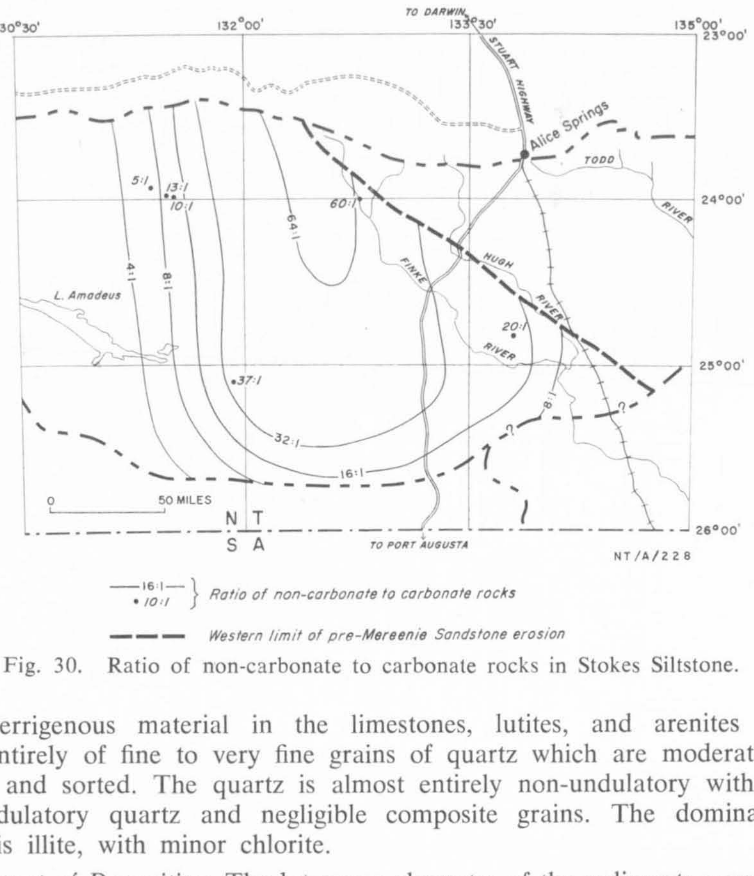


Fig. 30. Ratio of non-carbonate to carbonate rocks in Stokes Siltstone.

The terrigenous material in the limestones, lutites, and arenites consists almost entirely of fine to very fine grains of quartz which are moderately well rounded and sorted. The quartz is almost entirely non-undulatory with only a little undulatory quartz and negligible composite grains. The dominant clay mineral is illite, with minor chlorite.

Environment of Deposition. The lutaceous character of the sediments suggests that conditions of deposition were generally tranquil. The abundance of illite is not environmentally significant (Weaver, 1958).

The pseudomorphs after halite suggest abnormally high salinities, possibly resulting from restriction of circulation by a topographic barrier, followed by evaporation. There is, however, no evidence of a topographic barrier in the Amadeus Basin during Stokes Siltstone time, and it is unlikely that a lagoon with an areal extent of 60,000 square miles existed. It is possible that the high salinity resulted from the restriction of circulation in an epeiric sea (Shaw, 1964), and that ocean currents and tides were unable to enter the sea because it was too broad and shallow. Owing to their higher density, the more saline waters sank to form supersaline bottom waters in which large halite crystals were formed at the sediment-water interface or just below.

Carmichael Sandstone (new name)

The name Carmichael Sandstone is given to the sequence of brown and red-brown cross-bedded sandstone, and silty sandstone with interbeds of red-brown siltstone and claystone, which conformably overlies the Stokes Siltstone and is unconformably overlain by the Mereenie Sandstone. The bottom of the Carmichael Sandstone is at the base of the first major sandstone; the top is at the change from poorly sorted silty sandstone and siltstone to the clean well sorted sandstone of the Mereenie Sandstone. The type section, where the formation is about 300 feet thick, is 1 mile south of Langs Well on the north side of the George Gill Range (Wells et al., 1963, sect. L.A.C. 1). The name is derived from Carmichael Crag, a prominent feature at the western end of the George Gill Range, about 8 miles west of the type section. The lower slopes of Carmichael Crag are composed of Carmichael Sandstone.

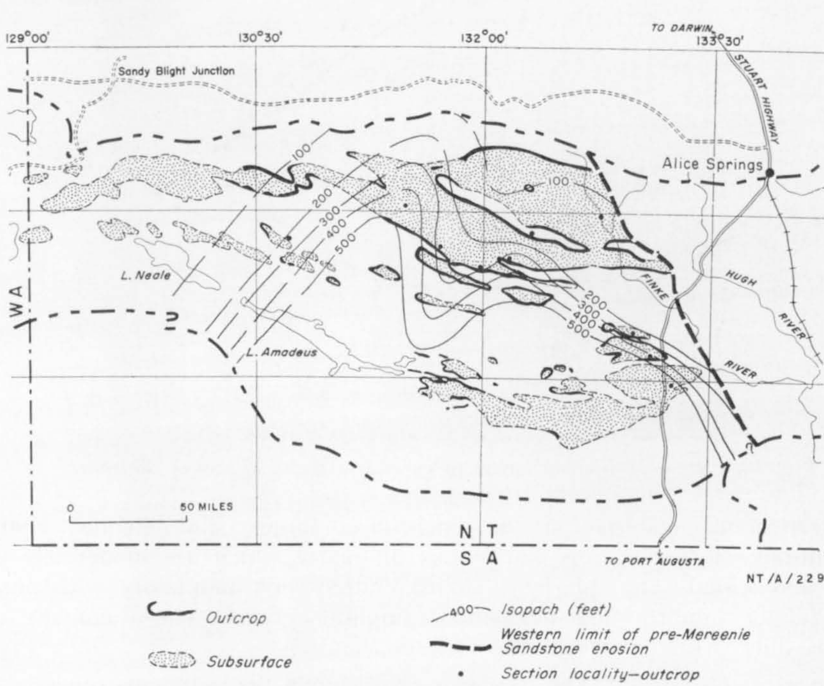


Fig. 31. Distribution and thickness of Carmichael Sandstone.

The Carmichael Sandstone crops out sporadically over a large area (Fig. 31). The western limits are uncertain, but it is thought to have an extent similar to that of the Stokes Siltstone. To the south, it may be the most extensive unit of the Larapinta Group (see Fig. 19). To the east, the formation was removed by the erosion that followed the Rodingan Movement.

The Carmichael Sandstone is generally poorly exposed. It commonly underlies the steep scree-covered slopes below the Mereenie Sandstone scarp and is only exposed in the creek beds cutting through the scree. The isopach map is based on incomplete data, but Figure 31 suggests that the formation thickens to the south, the thickness ranging from less than 100 feet in the western MacDonnell Ranges to about 500 feet near the southern margin of the basin. The increase in thickness to the south is contrary to the general pattern of the Larapinta Group and may be due either to original deposition or to post-Rodingan erosion. The fact that the Carmichael Sandstone becomes coarser and more pebbly to the south suggests that the original thickness may have increased to the south.

Fossils are rare, but *Cruziana* and other trace fossils suggest that the formation is Ordovician (late Caradocian or Ashgillian).

Lithology. The Carmichael Sandstone is composed mainly of red-brown, yellow, purple-brown, and pale brown sandstone and silty sandstone. The sediments are moderately to poorly sorted and rounded, and become more poorly sorted and pebbly in the south. The sandstone is thinly to thickly bedded, cross-bedded, and ripple-marked in places. Mud cracks and halite pseudomorphs occur in the silty sandstone and siltstone.

Interbeds of siltstone and claystone are common throughout the formation; they are red-brown or green in outcrop, micaceous in part, thinly bedded or laminate, and poorly exposed.

Petrography. The arenites are generally immature or submature orthoquartzites ranging from very fine to medium-grained. Non-undulatory quartz predominates over undulatory quartz, and only a few grains of composite quartz, metaquartzite, and chert are present. Feldspar rarely forms more than 2 to 3 percent of the rock. Iron-rich cement is common, and kaolinitic(?) cement is fairly common. In the siltstone and claystone kaolinite is predominant.

Environment of Deposition. The presence of *Cruziana* suggests a shallow marine environment—probably very shallow, according to the abundance of ripple marks and cross-beds; and the presence of the halite pseudomorphs probably indicates high salinity. Some of the arenites are immature, and the environment was not vigorous enough for the sorting and rounding of the sediments to keep pace with the rate of deposition in a low-energy estuary or delta.

The Carmichael Sandstone shows both shallow-marine and continental characteristics, and the most likely environment of deposition is an estuary or delta with periods of high salinity. This is supported by the thickening of the formation toward the source area.

Geological History

Palaeoclimate. The abundance of supermature orthoquartzites and the almost complete absence of feldspar in the arenites of the Larapinta Group suggest either severe tropical weathering or a predominantly sedimentary source area. The palaeolatitude data of Irving (1964) suggest that during the Ordovician, the Amadeus Basin may have been approximately at latitude 15°N., and that there was a drift to the north during Larapinta Group time. The climate may have become more arid: the type of clay in the Larapinta Group supports this; kaolinite, which is commonest in the lower half of the group, is abundant in the soils of humid areas (Jackson, 1959). Phosphorites are also commonly found in the present-day trade-wind belt, in places where the climate is generally arid. The presence of pseudomorphs after halite also indicates a fairly arid climate

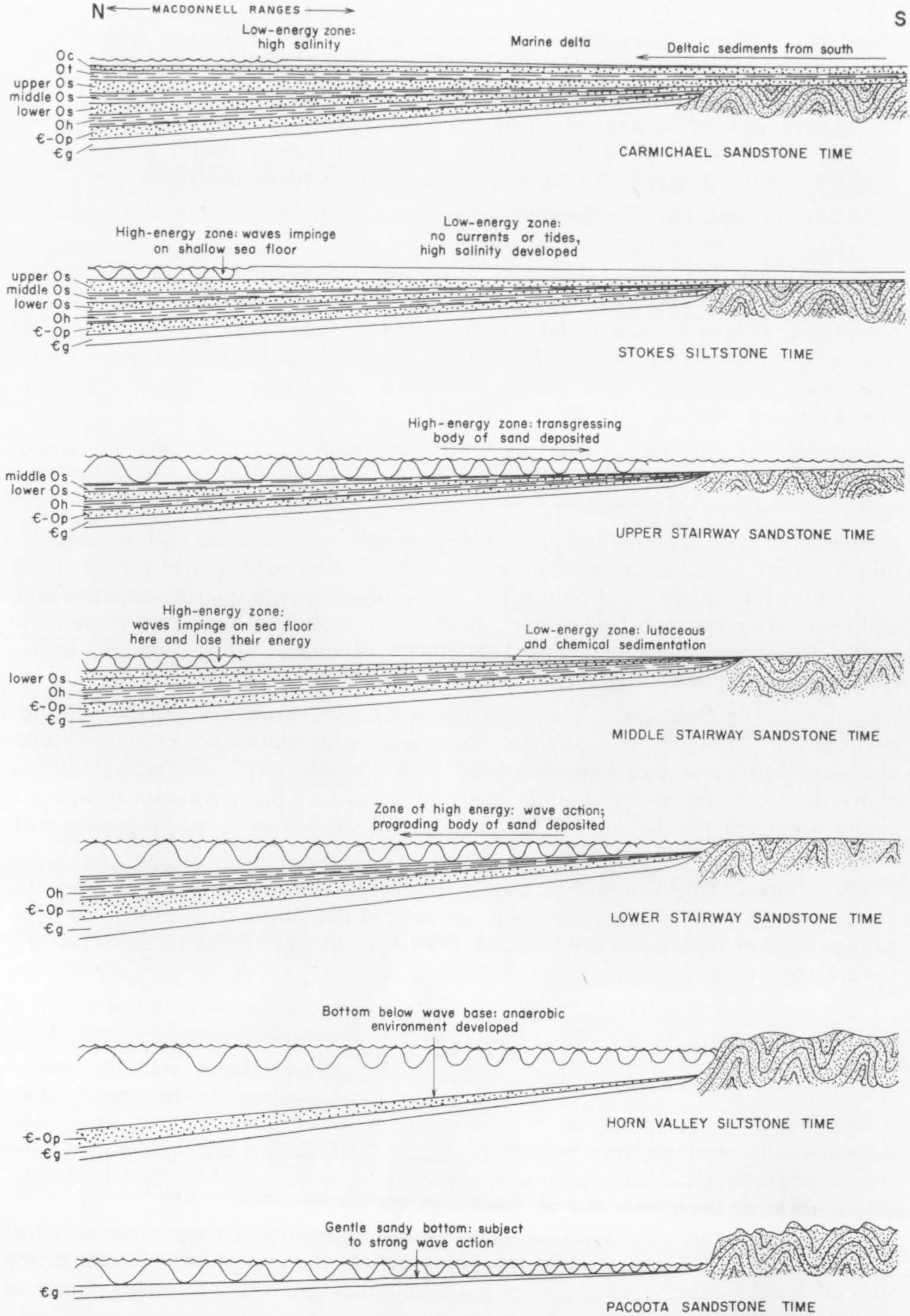


Fig. 32. Cross-sections showing history of sedimentation of Larapinta Group.

during Stokes Siltstone and Carmichael Sandstone times. Therefore, Larapinta Group sedimentation may have started in a humid tropical climate, but in the course of time the climate became drier, and was finally semi-arid or arid.

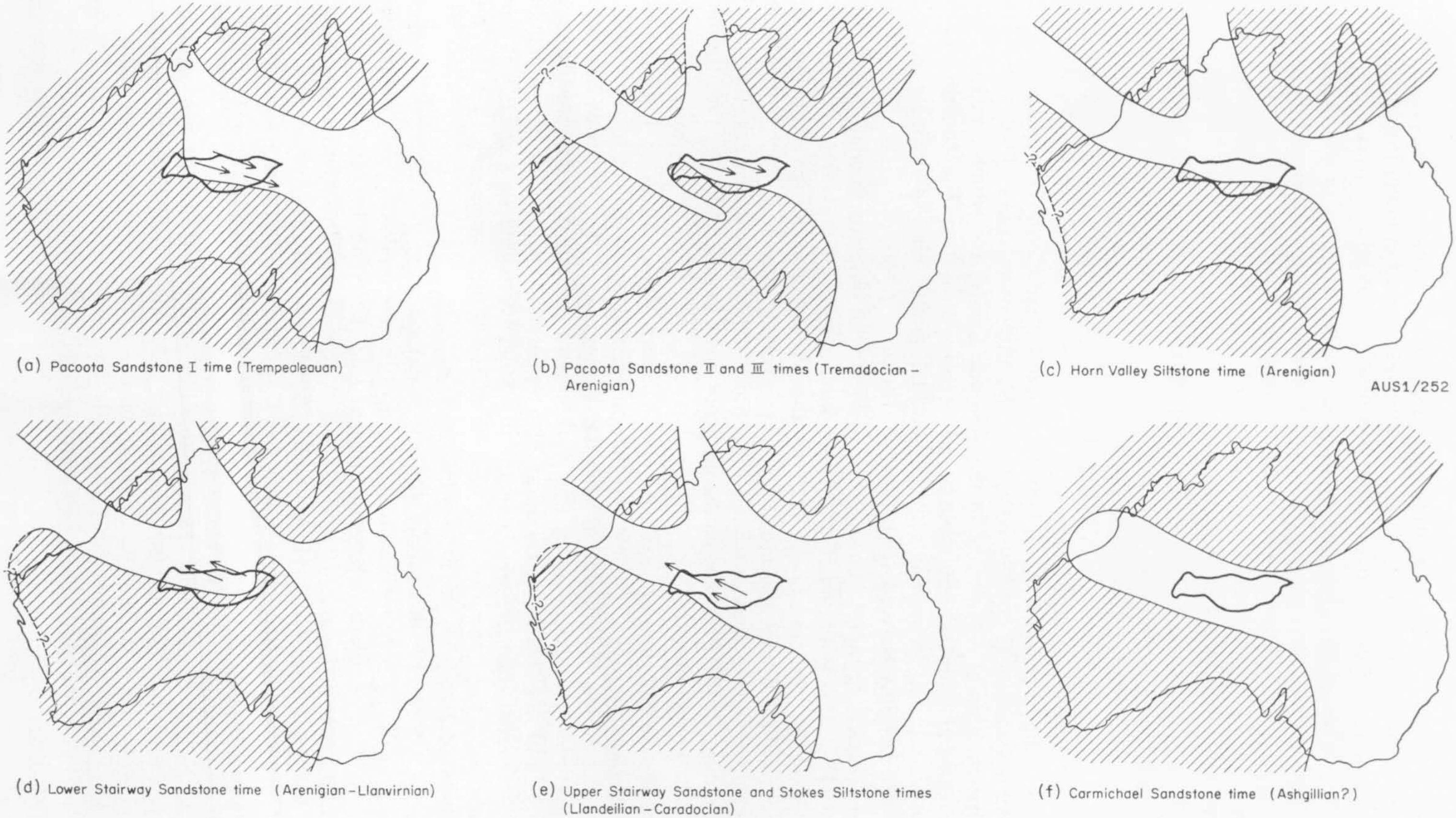
Provenance. The well rounded but poorly sorted sand grains in the arenites, and the presence of reworked sand grains (with abraded overgrowths) and chert grains, indicate that the provenance was in part sedimentary. In particular, the N'Dahla Member of the Pacoota Sandstone and the upper part of the Stairway Sandstone show evidence of reworking of sedimentary rocks.

Blatt (1963, 1964) and Blatt & Christie (1963) have shown that the abundance of non-undulatory quartz in arenites is an indication of a predominantly sedimentary provenance. In Pacoota Sandstone time the provenance area was probably composed mainly of sedimentary rocks and subordinate igneous rocks. In upper Stairway Sandstone, Stokes Siltstone, and Carmichael Sandstone times, there was a high proportion of non-undulatory quartz, which suggests that the source area was almost entirely composed of sedimentary rocks. This is supported by the heavy mineral assemblage in the Stairway Sandstone, which consists mainly of well rounded grains of tourmaline and zircon with only a few euhedral grains. The rounded grains represent recycled detrital grains; the subordinate euhedral grains were possibly derived from plutonic rocks.

Palaeogeography. Larapinta Group time opened with currents flowing mainly from the west (Fig. 21). Williams et al. (1965) have suggested that there is divergence around some of the anticlines, such as the Waterhouse Range Anticline; they therefore concluded that the anticlines were growing and that they formed topographic ridges during Pacoota Sandstone time. The marked decrease in the size of the pebbles in the Pacoota Sandstone from west to east indicates that the main source area lay to the west.

No palaeocurrent data are available for the Horn Valley Siltstone, but it appears that there was a major change in the palaeogeography between the close of Pacoota Sandstone sedimentation and the beginning of the Stairway Sandstone. During Stairway Sandstone time, the predominant current direction was from the southeast, and the facies distribution also suggests a southeasterly provenance. No palaeocurrent data are available for the Stokes Siltstone or Carmichael Sandstone, although the latter becomes coarser to the south, suggesting that the main source area probably lay to the south.

Little is known of the topography of the land area on the margin of the basin, but at the opening of Larapinta Group time the land was probably considerably elevated, particularly where the Proterozoic sediments cropped out (see Fig. 20). Comparison of Figures 19 and 20 shows how closely the southern boundaries of the Pacoota Sandstone, Horn Valley Siltstone, and the lower and middle parts of the Stairway Sandstone follow the Cambrian/Proterozoic palaeogeological boundary, probably because the Proterozoic sediments were above sea level throughout much of the Lower Palaeozoic. The development of the Mount Charlotte Embayment (Cook, 1966a, unpubl.) probably followed the erosion of the Jay Creek Limestone, for the Mount Charlotte Embayment corresponds closely with the area of pre-Larapinta Group outcrop of the Jay Creek Limestone as shown in Figure 20. By the opening of upper Stairway Sandstone time the hinterland had been peneplaned and there was little or no relief (see Fig 32).



(a) Pacoota Sandstone I time (Trempealeauan)

(b) Pacoota Sandstone II and III times (Tremadocian – Arenigian)

(c) Horn Valley Siltstone time (Arenigian)

(d) Lower Stairway Sandstone time (Arenigian – Llanvirnian)

(e) Upper Stairway Sandstone and Stokes Siltstone times (Llandeilian – Caradocian)

(f) Carmichael Sandstone time (Ashgillian?)

Fig. 33. Palaeographic maps from Pacoota Sandstone time to Carmichael Sandstone time.

The probable form of the Amadeus Basin throughout Larapinta Group time is shown in Figure 33. The basin appears to have been a small, probably marginal portion of a much larger depositional basin. During the late Cambrian (Pacoota I time), the Amadeus Basin was part of a broad shallow embayment which opened to the east (Fig. 33a). In the Tremadocian and early Arenigian (Pacoota II and III times) the embayment expanded mainly to the west (Fig. 33b). By Horn Valley Siltstone time (Arenigian) strong connexions had been established to the west, probably with a deep trough connecting the Amadeus and Fitzroy Basins (Fig. 33c). Well developed connexions still existed with the open sea to the east. In lower Stairway Sandstone time (Arenigian-Llanvirnian), a minor embayment was formed in the southeast by the erosion of Pertaoorrta Group carbonate rocks, and the connexions to the east became slightly restricted by the development of a small peninsula (Fig. 33d). This peninsula continued to develop until it formed a major feature by middle Stairway Sandstone time and severely restricted any link with the open sea to the east. The main link with the open sea now lay to the west. At the opening of upper Stairway Sandstone time (Llandeilian) there was a major expansion of the Ordovician sea. The sea transgressed over the peneplaned hinterland and broad open connexions were once more established with the open sea, both to the east and west (Fig. 33e).

The trangression of the Ordovician sea continued into Stokes Siltstone time (Caradocian), so that the Amadeus Basin lay well within the broad shallow embayment, with the nearest margin some distance to the south. The palaeogeography during the deposition of the Carmichael Sandstone is uncertain, because of the lack of diagnostic fossils and because a considerable area of the Carmichael Sandstone was removed in the east during the post-Rodingan erosion. The Carmichael Sandstone may be the time equivalent of the Tandalgoo Red-beds and Carribuddy Formation in the Sahara No. 1 well in Western Australia: if so, after the Stokes Siltstone was deposited the connexion to the open sea lay to the east and the connexion to the west was again closed (Fig. 33f).

In the Amadeus Basin area the Carmichael Sandstone seas were probably initially as extensive as those of Stokes Siltstone time, although in the west and possibly in the north some regression occurred. By the close of Carmichael Sandstone time the seas may have regressed considerably in many areas.

Depositional History (see Fig. 32). With the close of Pertaoorrta Group sedimentation no major change took place in the limits of deposition, but there was a major change in the type of deposition. Thick orthoquartzites were deposited in place of carbonate rocks.

The Pacoota Sandstone sediments were probably deposited in a broad shallow sea with submarine sand flats and some low longshore bars and possibly submarine dunes. All the sands were situated above wave base, and by reworking, a continuous sand body was gradually built up.

This pattern of sedimentation was brought to a close by a relative rise in sea level so that the bottom of the sea was now below wave base. Anaerobic conditions developed in the deep bottom waters, and the main sediments deposited were the black carbonaceous lutites of the Horn Valley Siltstone.

Predominantly sandy sediments were again deposited during lower Stairway Sandstone time. The change was associated with a regression and shallowing of the sea so that the bottom of the sea was above wave base and subject to considerable agitation. There may have also been a corresponding increase in the supply of sand-sized detritus. As the sea shallowed throughout lower Stairway Sandstone time a high-energy zone gradually migrated across a broad shallow shelf to produce a regressive body of sand.

By middle Stairway time, the low-energy zone of a shallow epeiric sea covered the area (see Shaw, 1964; Irwin, 1965). This zone was situated shoreward of the point where the waves first impinge on the shelf. All the energy of the waves was lost in the zone of impingement, and the shoreward part of the epeiric sea was not subjected to strong current or tidal action. In the low-energy middle Stairway epeiric sea the sediments deposited were predominantly lutaceous and chemical (phosphorites and carbonates).

At the opening of upper Stairway Sandstone time, sea level again rose, and the sea transgressed over the peneplaned hinterland to the south. This transgression continued into Stokes Siltstone time, particularly on the western margin of the basin. As a result of the transgression and the resultant deepening of the sea, a large transgressive body of sand was deposited over the area as the high-energy zone migrated forward. There may also have been an accompanying increase in the supply of detrital sand.

By Stokes Siltstone time, the sea was very broad and shallow. Shaw (1964) has shown that such a sea is tideless and without currents, so no new sea water flows in, and salinity rises by evaporation and ultimately halite and other evaporites are precipitated. The sea was shallow at the close of Stokes Siltstone time, when the deltaic or estuarine body of sand started to spread across the area. It is not known whether this regressive body of sand brought marine sedimentation to a close in the Amadeus Basin or whether there was a further transgression, as a considerable thickness of sediments was probably removed by erosion after the Rodingan (Silurian?) Movement. It is suspected that the Rodingan Movement brought Larapinta Group sedimentation to a close, or that the movement started a short time after sedimentation ceased.

SILURO(?)-DEVONIAN

Mereenie Sandstone

The name Mereenie Bluff Formation was first used by Chewings (1894) for the sandstone of the George Gill Range (Pl. 21, fig. 1) and other areas. Madigan (1932a) introduced the term Mareenie Sandstone, and Prichard & Quinlan (1962) amended the spelling to Mereenie Sandstone.

The Mereenie Sandstone crops out sporadically throughout much of the basin; the outcrops have a total area of about 1000 square miles, but it underlies an area of about 10,000 square miles.

In the western half of the basin, the Mereenie Sandstone apparently rests conformably on the Carmichael Sandstone, but in the east it is regionally unconformable with the Larapinta and Pertaoorrta Groups. In the extreme west it may rest unconformably on Proterozoic sediments, but the contacts are not exposed. It is overlain by the Pertnjara Group.

The Mereenie Sandstone has a maximum preserved thickness of about 3000 feet in the Gardiner Range (Fig. 34). Erosion in the northeast may have stripped off a considerable thickness of Mereenie Sandstone before the Hermannsburg

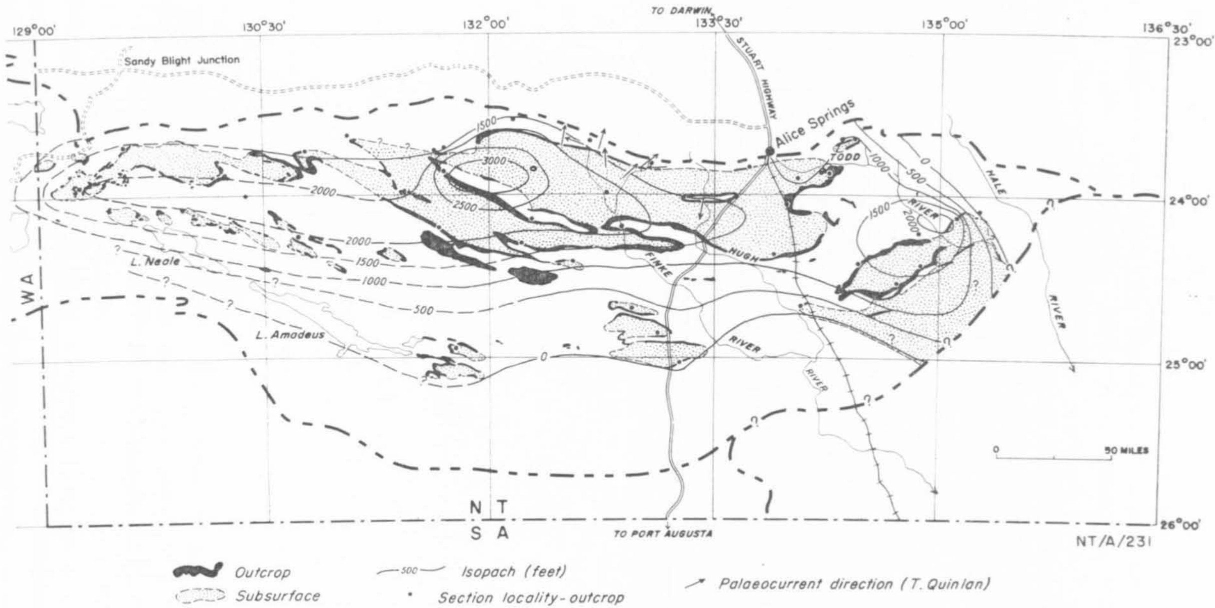


Fig. 34. Distribution and thickness of Mereenie Sandstone.

Sandstone was laid down; the greatest thickness may perhaps have been originally deposited in the Steele Gap area, where about 2000 feet is still preserved. The formation thins considerably to the south (Fig. 34), and the southern limit of sedimentation was about latitude 25°10′S.

The only fossils in the Mereenie Sandstone are vertical or near-vertical *Scolithus*-like pipes in places, and a few trace fossils, none of which are diagnostic. The writer also found several fragments of arthrodiran armour of Devonian age (Tomlinson, 1968) at Gosses Bluff. Their stratigraphic position was uncertain, but it was suspected to be from the Pertnjara Group. Milton (1967, unpubl.) subsequently reported that the fish fragments were actually from just below the pipe-rock horizon in the Mereenie Sandstone. Thus, the Mereenie Sandstone is at least in part Devonian. Devonian *Bothriolepis* and spores occur in the overlying Parke Siltstone.

Lithology. The Mereenie Sandstone consists of white or pale brown fine-grained sandstone, which weathers dark brown in places. It is thinly to thickly bedded and strongly cross-bedded (Pl. 21, fig. 2). Occasional cross-laminae are slumped and a few mud cracks are found, and in the Tempe Downs area Ranford et al. (1966) have recorded a sand pipe which is probably a sand volcano. Cross-bedding is a conspicuous feature; the cross-bed sets are up to 10 feet thick and single beds may be traced for 100 feet or more. In a few places in the northeast, there is a thin basal conglomerate and a few thin conglomeratic lenses.

Petrography. The arenites of the Mereenie Sandstone are generally fine-grained mature or supermature orthoquartzites. They are well rounded and well sorted.

The orthoquartzite contains about 40 to 50 percent non-undulatory quartz, and 40 to 50 percent undulatory quartz, and 5 to 20 percent composite quartz grains. Rarely, 1 to 2 percent chert, and 1 to 2 percent metaquartzite, and up to 1 percent feldspar (mainly microcline) are present. The only heavy minerals observed were well rounded grains of tourmaline and zircon.

Lutites are uncommon in the Mereenie Sandstone; the commonest clay mineral is kaolinite.

Environment of Deposition. The presence of indeterminate trace fossils and vertical worm tubes suggests that part of the Mereenie Sandstone was probably laid down in a shallow sea. In other respects the formation is similar to the 'desert sandstone' such as the Coconino Sandstone in the western United States. The prevalence of massive cross-bedding and the frosting and pitting of the grains suggest aeolian deposition, although it is difficult to explain how a predominantly aeolian sandstone can attain a thickness of 3000 feet. Abundant aeolian sand was perhaps blown into the lakes and seas. The depositional environment was evidently complex, and probably included aeolian, deltaic, lacustrine, and shallow marine environments.

Provenance. The presence of detrital grains with reworked overgrowths indicates that the provenance was at least partly sedimentary. Some of the arenites are well rounded, but poorly sorted, which also suggests reworking of a sedimentary source area. Blatt (1963, 1964) and Blatt & Christie (1963) have shown that a high percentage of non-undulatory quartz is indicative of reworking of sedimentary rocks. It appears, therefore, that the provenance was predominantly sedimentary; the chert grains may indicate a minor limestone or dolomite provenance, but most of the source area probably consisted of sandstone. In a few areas (e.g. towards the western margin of the basin), the presence of a relatively high proportion of metaquartzite grains suggests that metamorphic rocks were exposed in the provenance area for a short time.

Palaeoclimate. There is abundant evidence of aeolian activity, and a desert climate probably prevailed throughout most of Mereenie Sandstone time. The palaeolatitude data of Irving (1964) suggest that the Amadeus Basin in Mereenie Sandstone time was situated at about latitude 20° S, which corresponds with the present trade-wind belt.

Palaeogeography. The lack of time control in the Mereenie Sandstone makes palaeogeographic reconstruction conjectural. Lithologically and probably chronologically, it is equivalent to the lower part of the Dulcie Sandstone in the Georgina Basin (Joyce G. Tomlinson, pers. comm.).

In early Mereenie Sandstone time, there was probably a major ridge in the northeastern part of the basin, which extended far beyond its present limits. The ridge was formed as a result of the Rodingan Movement (Silurian?), which initially may have caused the separation of the Georgina and Amadeus Basins. Pebbles and cobbles also become considerably more common in the Mereenie Sandstone to the east, which suggests that the main source area lay to the east. Initially, the source area consisted of Cambro-Ordovician sediments of the Amadeus Basin (see Fig. 35). As the Mereenie Sandstone (and its equivalents) may be partly continental, an area of land may have constituted a 'connexion' rather than a barrier. It is suggested that the connexion between the open sea and the Amadeus Basin lay to the west. As Mereenie Sandstone sedimentation proceeded, the sea transgressed to the east until the Georgina and Amadeus Basin were linked.

Geological History

Some time after the close of Carmichael Sandstone time, an uplift or upwarping, occurred in the Amadeus Basin. The name Rodingan Movement is proposed for this Silurian(?) epeirogeny. It was followed by erosion which may have continued for some considerable time, perhaps for much of the Silurian and possibly even into the Lower Devonian. The age of the pegmatites from the Harts Range determined by J. T. Wilson (Walpole & Smith, 1961) suggests that movement probably started about 420 m.y. (Lower Silurian), but as 5000 to 10,000 feet of sediments were eroded in the northeast before the Mereenie Sandstone was deposited, there was probably a major time break between the epeirogenic movement in the Silurian and the onset of Mereenie Sandstone sedimentation. The lack of massive conglomerate, such as the type found in the Pertnjara Group, suggests that there was no violent movement. The area was probably finally reduced to a peneplain. As a result, large continental desert areas were established around, and probably within, the Siluro-Devonian basin. It was from these desert areas that the Mereenie Sandstone sediments were derived by both fluviatile and aeolian action; they were deposited in part in a shallow sea which may have been gradually transgressing across the area from the west.

Throughout deposition the form of the Amadeus Basin was ill defined, and the constantly moving strandline and shallow-marine environments graded into and interfingered with lacustrine and aeolian environments. This pattern of sedimentation was brought to a close with the onset of Pertnjara Group sedi-

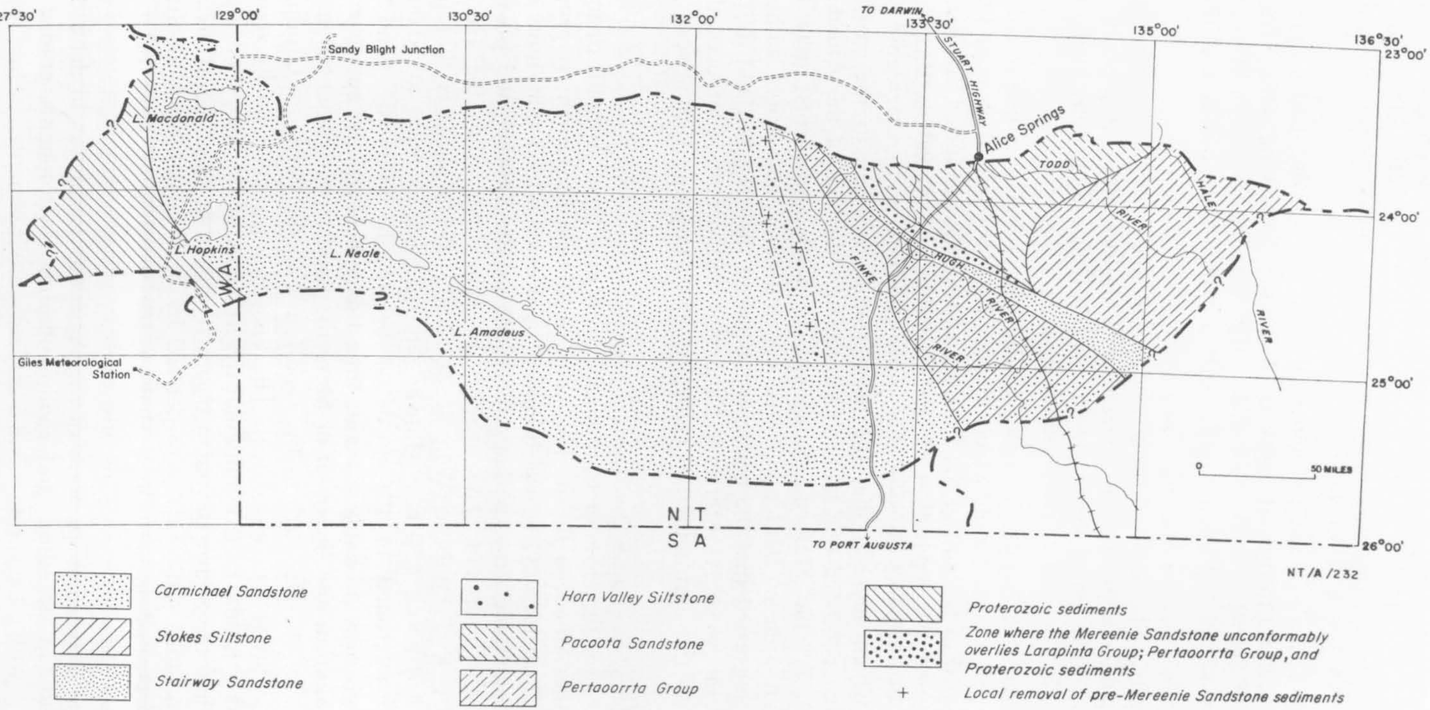


Fig. 35. Pre-Mereenie Sandstone surface.

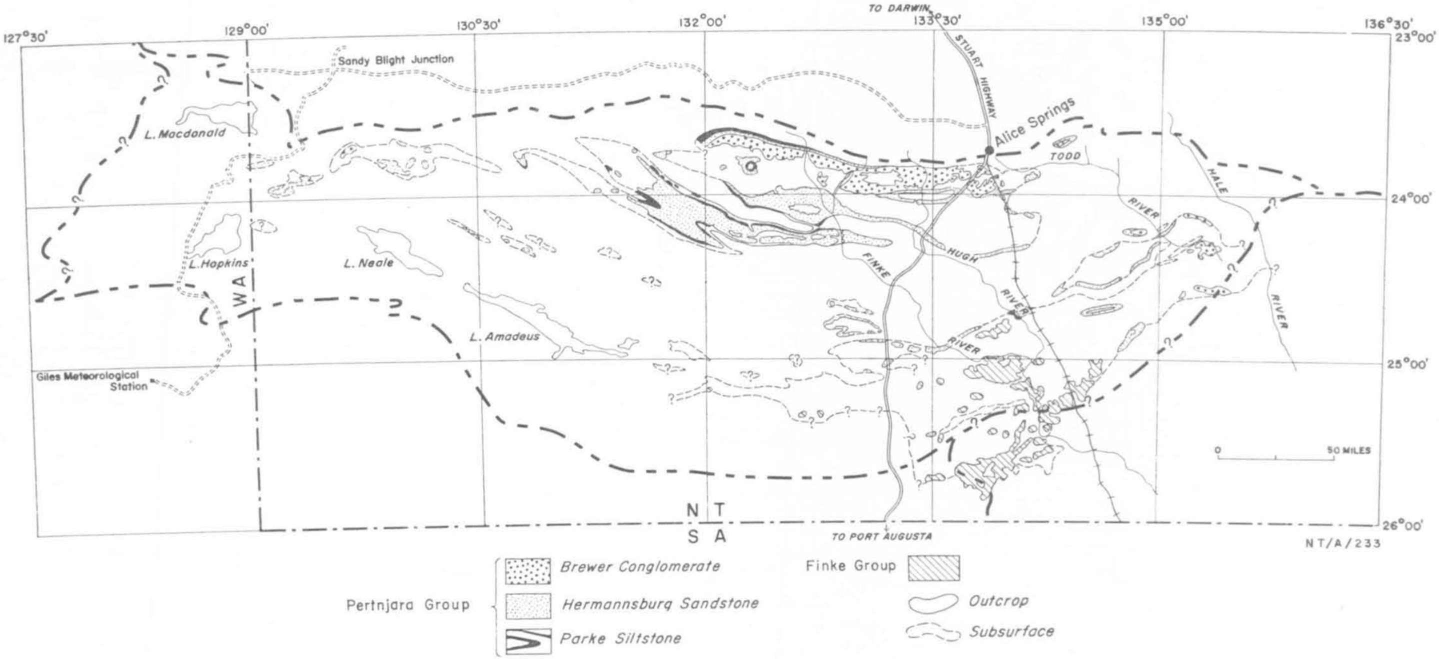
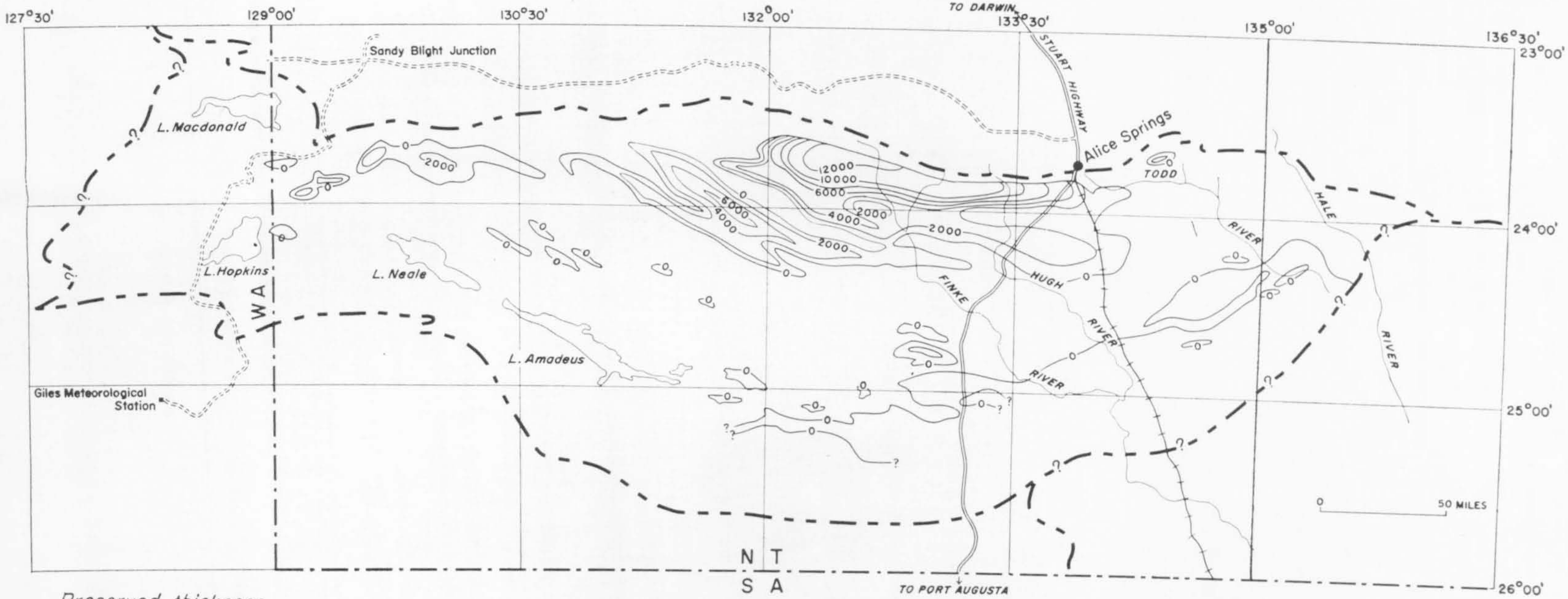


Fig. 36. Distribution of Pertnjara and Finke Groups.



Preserved thickness

——12000—— *Isopach (feet)*

Plate 25, fig. 1. Brewer Conglomerate on the southern flank of the western MacDonnell Ranges.

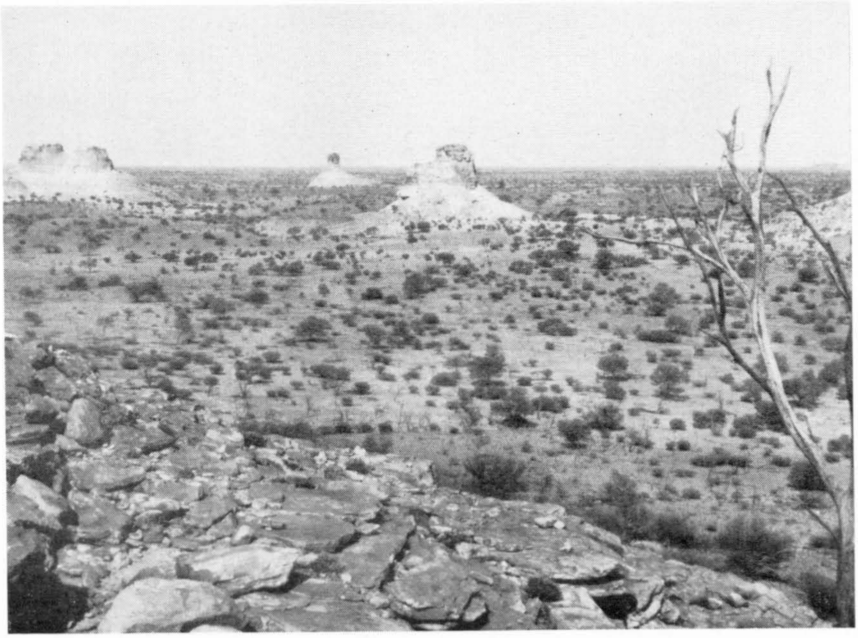


Plate 25, fig. 2. Buttes of Santo Sandstone near Chambers Pillar, south of the Charlotte Range.

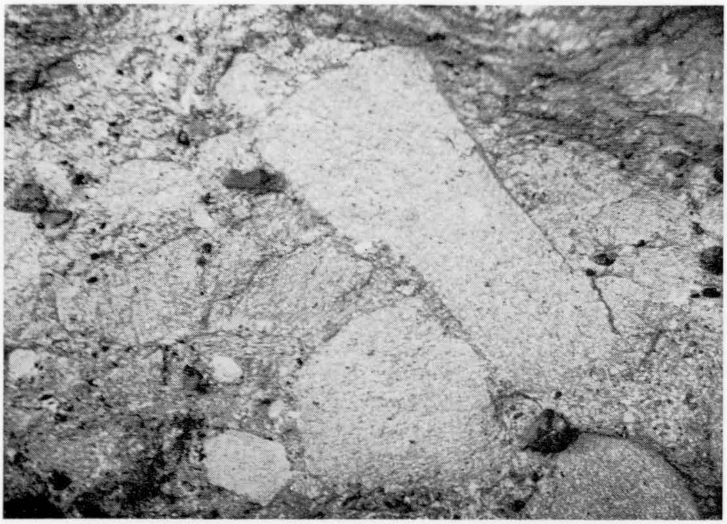


Plate 26, fig. 1. Conglomerate at the base of the Buck Formation, Buck Hills, Western Australia. The phenoclasts consist of quartz-feldspar porphyry up to about 1 foot long.

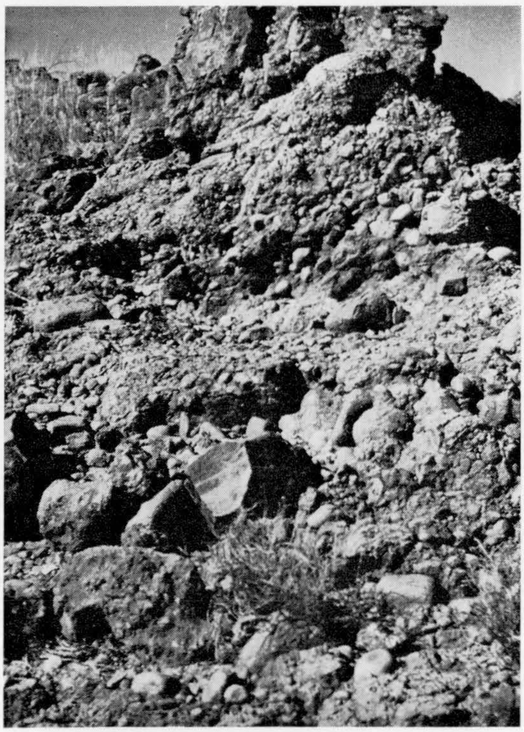


Plate 26, fig. 2. Boulder beds of the Buck Formation, north of Lake Macdonald, Western Australia.

Plate 27, fig. 1. Flame structure in the Buck Formation, Dovers Hills. Macdonald Sheet area, Western Australia.

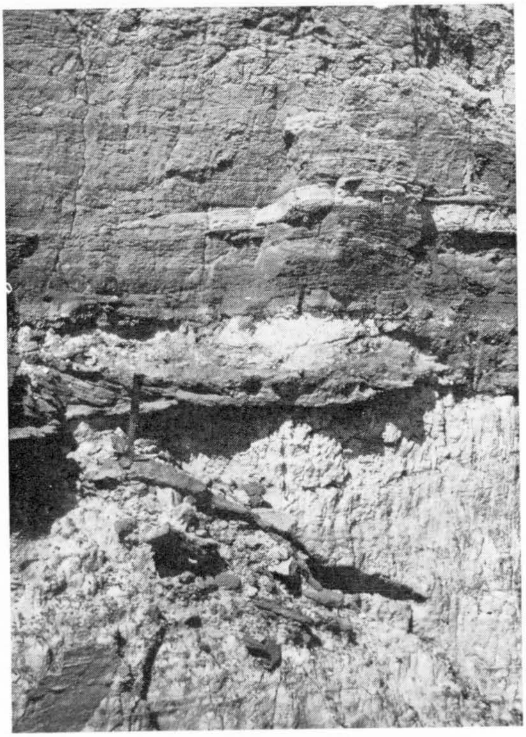


Plate 27, fig. 2. Crown Point Formation resting unconformably on the Langra Formation, near Rumbalara siding, about 6 miles west of Mount Rumbalara.

Plate 28, fig. 1. Reference locality of the Crown Point Formation at Crown Point in the Finke River, about 13 miles northwest of Finke township.

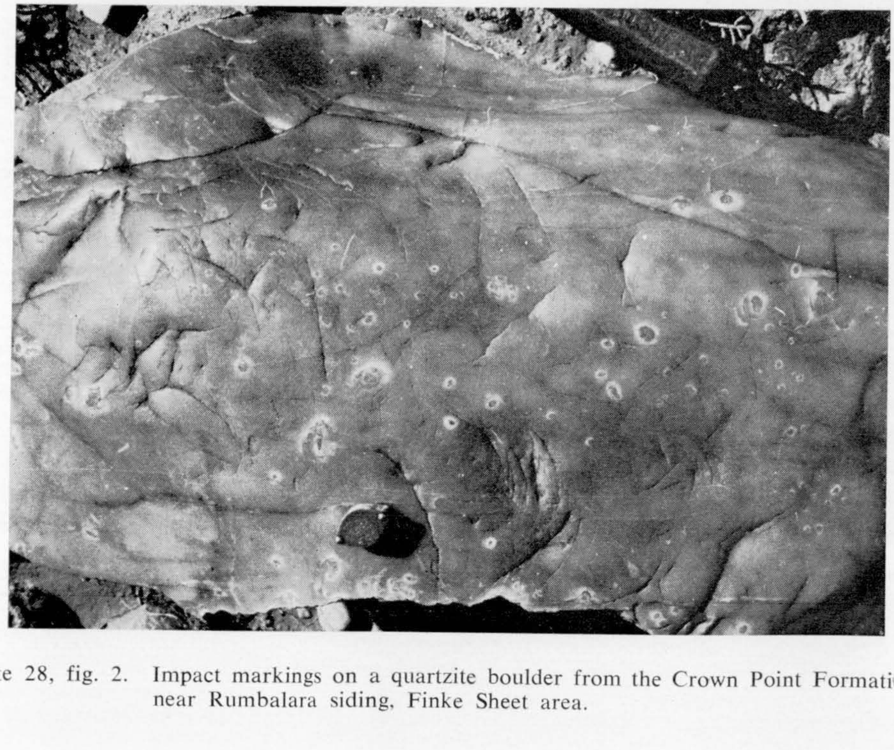


Plate 28, fig. 2. Impact markings on a quartzite boulder from the Crown Point Formation, near Rumbalara siding, Finke Sheet area.

Plate 29, fig. 1. Large slumps in sandstone of the Crown Point Formation, near Mount Humphries, Finke Sheet area.

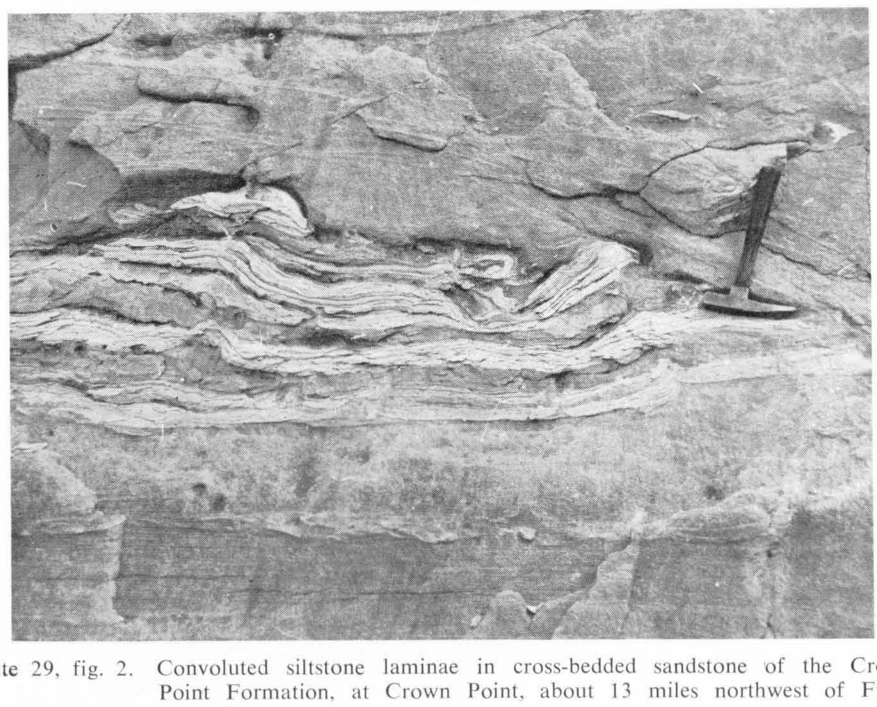


Plate 29, fig. 2. Convoluted siltstone laminae in cross-bedded sandstone of the Crown Point Formation, at Crown Point, about 13 miles northwest of Finke township.

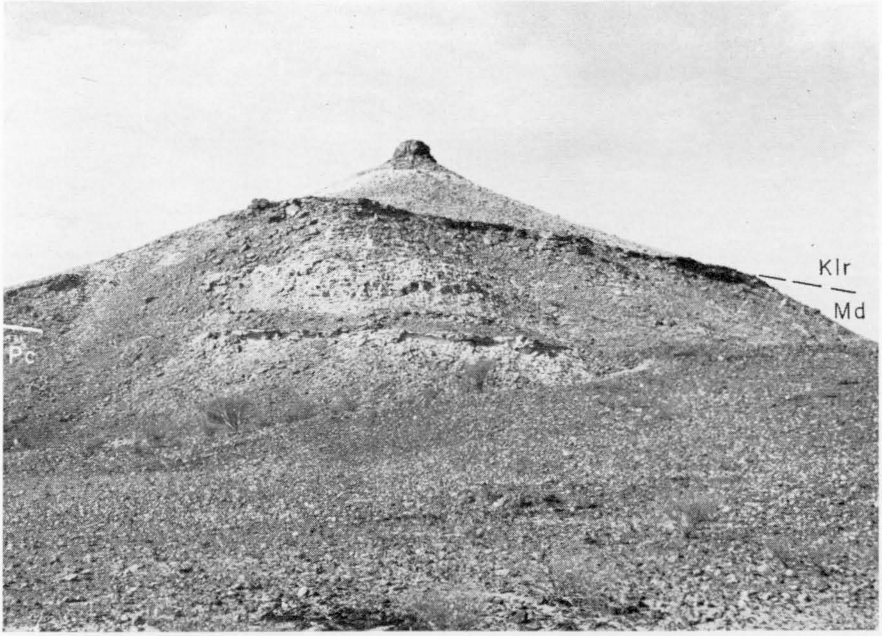


Plate 30, fig. 1. Crown Point Formation (Pc), De Souza Sandstone (Md), and Rumbalara Shale (Klr) at Colsons Pinnacle, Finke Sheet area. The prominent benches are ferruginized beds at the top and base of the De Souza Sandstone.

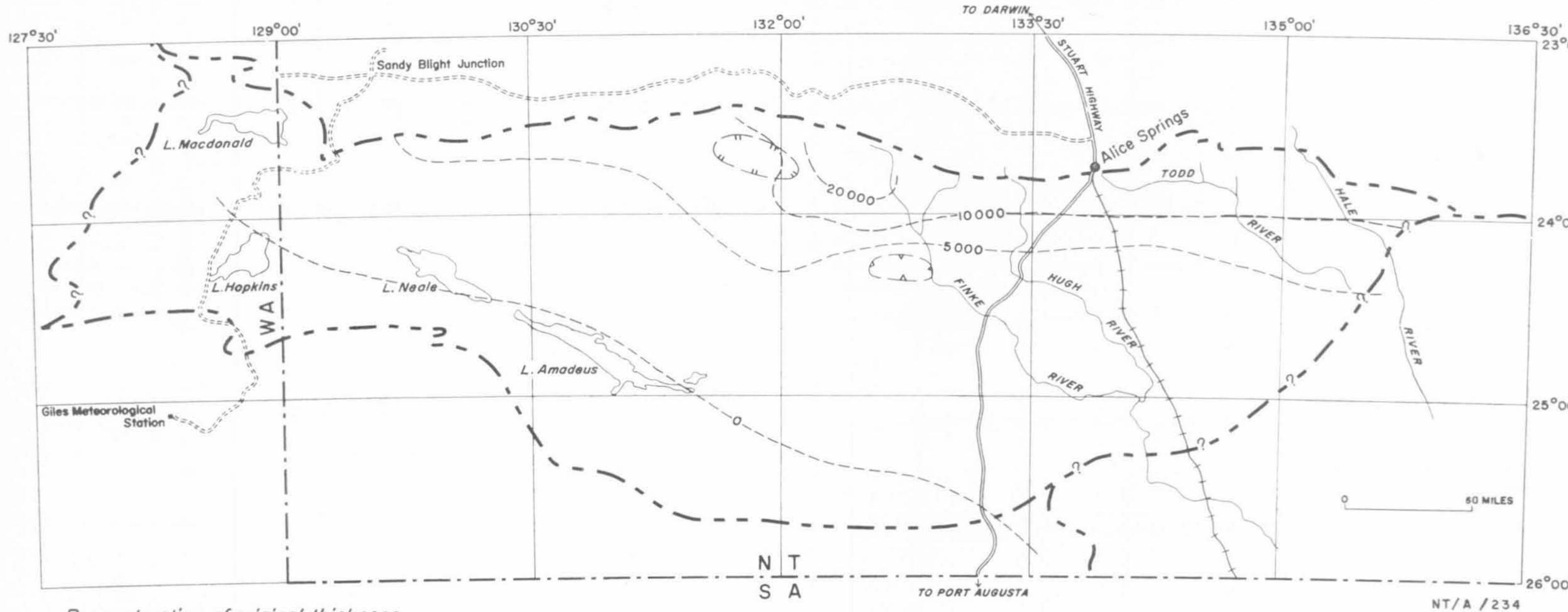
Plate 30, fig. 2. Rumbalara Shale (light-coloured) overlying the De Souza Sandstone (dark-coloured beds) at Mount Rumbalara, Finke Sheet area.

Plate 31, fig. 1. Mesa of Tertiary sediments overlying the Parke Siltstone in the Mereenie Anticline.

Plate 31, fig. 2. Dune field 10 miles west-northwest of Finke township. Finke River and De Souza Sandstone in the background.

Plate 32, fig. 1. 'Ribbon' dune on ferricrete platform 25 miles east of Finke township, on the western edge of the Simpson Desert.

Plate 32, fig. 2. Longitudinal dune in the Simpson Desert showing active sand along the crest.



Reconstruction of original thickness

— — 5000 — — *Isopach (feet), reconstructed*

Area of thinning over Carmichael Structure

Area of thinning over Illamurta Structure

Fig. 37. Thickness of Pertnjara Group.

mentation, and perhaps by the violent orogenic movement reflected in an age of 367 ± 10 m.y. obtained on Irindina Gneiss of the Arunta Complex from the Harts Range area (Hurley et al., 1961).

DEVONO-CARBONIFEROUS(?)

The Pertnjara Group is a sequence of continental siltstone, sandstone, and conglomerate with a maximum thickness of about 12,000 feet; they are the youngest Palaeozoic sediments in the Amadeus Basin. Upper Devonian fossils have been found near the base and the uppermost beds may be Carboniferous. The group is thickest on the southern flank of the MacDonnell Ranges; it thins rapidly to the south and intertongues with the Finke Group in the southeast. The Finke Group is about 1500 feet thick in outcrop, and is probably also Devonian to Carboniferous in age. The distribution of the Pertnjara and Finke Groups is shown in Figure 36. The preserved thickness of the Pertnjara Group and a diagrammatic reconstruction of its depositional thickness are given in Figure 37.

Pertnjara Group

Prichard & Quinlan (1962) defined the Pertnjara Formation as a sequence of sandstone, quartz greywacke, and conglomerate that overlies the Mereenie Sandstone with a regional unconformity in the type area on the southern flanks of the western MacDonnell Ranges (Pl. 22). It has since been shown that there is a thick wedge of basal siltstone in the central part of the basin. In previous reports, the siltstone, sandstone, and conglomerate were mapped as informal units, but because of their wide extent and continuity they are here defined as separate formations—the Parke Siltstone at the base, followed apparently conformably by the Hermannsburg Sandstone, and the Brewer Conglomerate at the top (Pl. 23). The distribution of the formations is shown in Figure 36. Of the three, the Hermannsburg Sandstone is the most widespread; the underlying Park Siltstone is confined to a central belt trending south of the western MacDonnell Ranges, and outcrops of the Brewer Conglomerate are confined to the southern flank of the MacDonnell Ranges and in isolated erosional remnants in the northeast and northwest.

The surface on which the group was deposited consisted largely of Mereenie Sandstone, but in places, mainly in the northeast and southeast, the Pertnjara Group overlapped the Mereenie Sandstone to rest on the Larapinta Group and older formations. In the north the Parke Siltstone generally follows apparently conformably on the Mereenie Sandstone, whereas the Hermannsburg Sandstone is partly unconformable on the Mereenie Sandstone, and the Brewer Conglomerate transgresses the Hermannsburg Sandstone and unconformably overlies rocks as old as Proterozoic. The distribution of the formations in the north shows that the shoreline of the depositional basin moved eastwards from near Ellery Creek at least as far as the Hale River. This concept is illustrated in Figure 38.

The maximum thickness of the Pertnjara Group on the southern flank of the western MacDonnell Ranges is estimated to be about 12,000 feet, but about 22,000 feet was measured by Prichard & Quinlan (1962) between Ellery Creek in the MacDonnell Ranges and the axis of the Missionary Syncline in the south. This large apparent thickness can be partly accounted for by foresetting, which is particularly evident in the upper conglomerate.

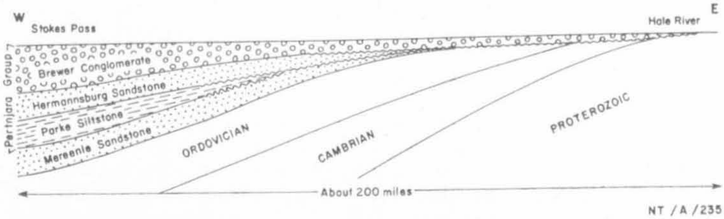


Fig. 38. Relationship of Pertnjara Group to older rocks.

A summary of the succession in the western MacDonnell Ranges, south of Ellery Creek based mainly on the description by Prichard & Quinlan (1962), is given in Table 1.

TABLE 1. PERTNJARA GROUP, WESTERN MACDONNELL RANGES

Thickness (ft)	
Top Several thousand feet	*Conglomerate*, pebbles, cobbles, and boulders in sandy matrix, in part calcareous. Fragments of Pertaoorrta Group in base, Proterozoic towards top, and mostly Arunta at top. Interbeds of calcareous greywacke in upper part. *Greywacke*, friable, massive, calcareous, scattered pebbles and pebble bands, grades into coarse conglomerate along strike. *Conglomerate*, with derived pebbles from base to top in reverse of normal stratigraphic order as in lower conglomerate unit.
1000	*Quartz greywacke*, interbedded pebble conglomerate in upper part.
250	*Conglomerate*, cobbles and boulders from Larapinta Group.
1000	*Quartz sandstone*, fine to medium-grained, feldspathic, scattered pebbles and pebble lenses, grading into sandstone-pebble conglomerate (derived from Mereenie Sandstone).

The basal 1000 feet, which consists predominantly of sandstone, is included in the Hermannsburg Sandstone and the overlying thick sequence of conglomerate is the Brewer Conglomerate. The basal Parke Siltstone is not present in this section.

The distribution and composition of the sediments indicate four major phases of deposition, each associated with successive uplifts of the source areas. In the initial phase, when the Parke Siltstone was laid down, the source areas were relatively low, but as the diastrophic periods gradually increased in intensity they were uplifted, so that the basal siltstone was succeeded by sandstone and then by conglomerate. The composition of the phenoclasts in the youngest formation of the Pertnjara Group indicates two major periods of uplift. The distribution and thickness of the main rock types indicate a provenance mainly to the north of the present outcrops.

Parke Siltstone (new name)

The Parke Siltstone is the basal formation of the Pertnjara Group; in the type area it consists of siltstone with minor sandstone interbeds. The formation is named from Parke Creek, the headwaters of which drain Dare Plain in the northeastern part of the Lake Amadeus Sheet area. The Parke Siltstone underlies Dare Plain, and the type area is on the southwestern flank of the Mereenie Anticline.

The formation crops out mainly in the western MacDonnell Ranges (Pl. 23), and in the large ranges to the south in the central part of the basin. In the north, the formation does not crop out east of the Finke River, but has been tentatively identified in water bores in the Brewer Plain. Outcrops extend as far west as the Cleland Hills, and as far south as the Charlotte Range. The sandstone of the underlying and overlying formations form prominent escarpments, but the Parke Siltstone weathers recessively.

The Parke Siltstone was deposited apparently conformably on the Mereenie Sandstone and is generally overlain apparently conformably by the Hermannsburg Sandstone. It is locally overlain by remnants of Tertiary sediments. The distribution and thickness of the formation adjacent to the MacDonnell Ranges were probably modified by local erosion before the Hermannsburg Sandstone was laid down. Consequently the Parke Siltstone wedges out to the east of Finke Gorge, and between the gorge and Stokes Pass the upper contact is probably

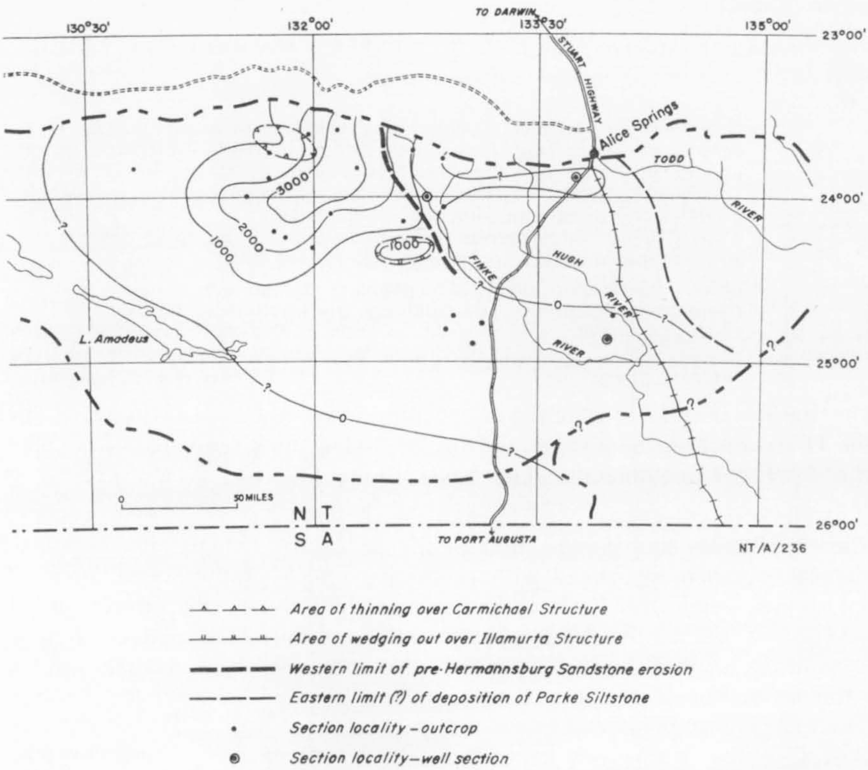


Fig. 39. Thickness of Parke Siltstone.

unconformable. The unconformity is also apparent to the south between the Gardiner Range and the eastern part of the James Range, where the Hermannsburg Sandstone overlaps the Parke Siltstone and gradually transgresses over the Mereenie Sandstone. In the water bores west of the transgressive boundary, there is a gradational contact between the Parke Siltstone and Hermannsburg Sandstone.

In the south the regional geology indicates that the Parke Siltstone is probably locally unconformable on the younger formations of the Larapinta Group, although the contacts are not exposed.

The thickness of the Parke Siltstone is shown in Figure 39. The thickest deposits occur in the area between the Mereenie Anticline, Gosses Bluff, and Stokes Pass. At Stokes Pass the formation attains a maximum thickness of about 3000 feet. The sequences penetrated in water bores indicate that there is a smaller basin of preservation, south of Alice Springs, which was probably connected to the larger basin. The thickness of the formation here is about 600 feet. The formation is absent over the Illamurta Structure (Cook, 1966b, unpubl.) and is considerably thinner on the Carmichael Structure (cross-section C-G, Pl. 45). Both structures were probably 'growing' during sedimentation.

On Dare Plain, the top few feet of a thick bed of sandstone 300 feet above the base of the formation contain fragments of the dermal armour of the antiarchan placoderm *Bothriolepis* (Tomlinson, 1968). Spores have been recorded by Hodgson (1968) from a water bore at about the same horizon. The fossils from Dare Plain are Upper Devonian, and probably no older than late Frasnian.

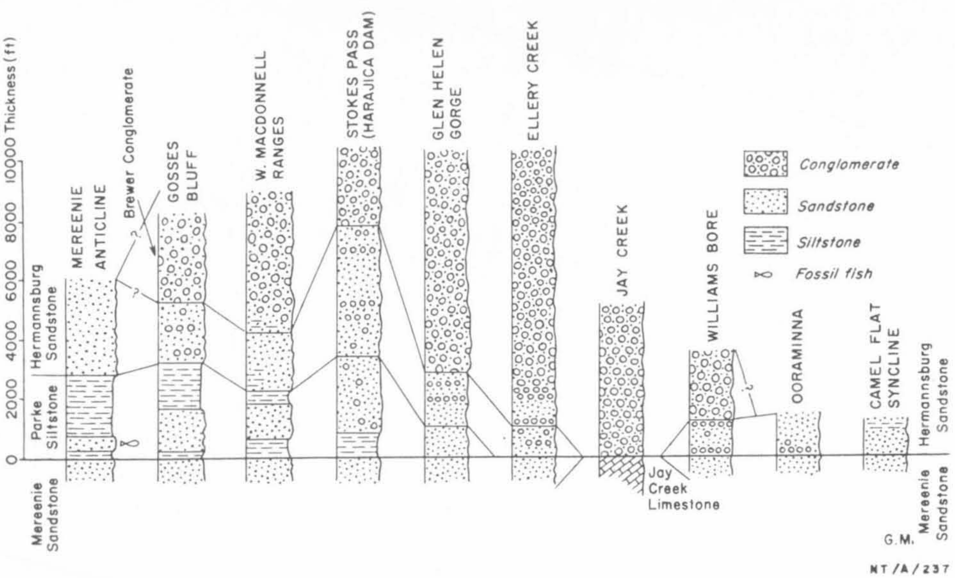


Fig. 40. Sections of Pertnjara Group from Mereenie Anticline to Camel Flat Syncline.

The Parke Siltstone is poorly exposed. In the type area, the siltstone ranges from chocolate-brown to yellow-brown, purple, brown, green, grey, and orange-brown, but the weathered rock is typically white. Much of the siltstone is micaceous and calcareous, and laminated to massive. Some beds are sandy, and in places a few thin beds of limestone are present. Pseudomorphs after halite were noted in some of the siltstones. The poorly sorted fossiliferous silty sandstone, 300 feet thick, near the base of the formation at Dare Plain, increases in thickness towards the north and northeast as shown in Figure 40; at the western end of the MacDonnell Ranges (Pl. 23) and at Gosses Bluff (Fig. 40; Pl. 24, fig. 1) it constitutes about half the total thickness of the formation. At Stokes Pass, the upper siltstone unit is absent, and conglomeratic sandstone predominates. At Glen Helen, only about 1000 feet of sandstone remains, and at Ellery Creek the Hermannsburg Sandstone rests unconformably on the Mereenie Sandstone.

In the central part of the basin the prominent sandstone member is missing, and the formation consists primarily of red-brown and purple-brown micaceous laminated to thin-bedded siltstone, with minor interbeds of calcareous siltstone, grey limestone, and silty sandstone. In the southwest, the Parke Siltstone is only about 200 feet thick and consists of green and red laminated micaceous siltstone and shale with pseudomorphs after halite.

The lithology, distribution, and fossil content of the Parke Siltstone indicate a lacustrine environment of deposition. The salt casts suggest playa lake deposits, which probably accumulated in a shallow desert basin with periodic influxes of sediment and seasonal evaporation. The fine grain of the sediments suggests that they were derived by desert weathering of relatively low source areas.

The increased thickness of the sandstone unit and the increase in grainsize to the north and east indicate major source areas in these directions. A large part of the Mereenie Sandstone was probably exposed and eroded in the eastern half of the basin during the deposition of the Parke Siltstone. The presence of muscovite and biotite suggests that metamorphic and igneous rocks were exposed in the provenance areas.

Hermannsburg Sandstone (new name)

The Hermannsburg Sandstone is a sequence of red-brown sandstone and minor conglomerate and conglomeratic sandstone; in the type area near Stokes Pass on the southern flank of the western MacDonnell Ranges, the formation lies between the Parke Siltstone below and the Brewer Conglomerate above (Pl. 23). It is widely distributed and is invariably well exposed (Pl. 23); the most continuous outcrops occur in the central and northern areas. Discontinuous outcrops occur as far south as the Charlotte Range, westwards to near the Western Australian border, and eastwards to the eastern end of the Rodinga Ranges. The formation is named after Mount Hermannsburg in the Krichauff Ranges about 4 miles southwest of Hermannsburg Mission.

In the west, the contact with the Parke Siltstone is apparently conformable, but to the east there is a regional unconformity and the Hermannsburg Sandstone overlaps the Parke Siltstone and transgresses the Mereenie Sandstone. The contact with the overlying Brewer Conglomerate is apparently conformable in the west, but east of the Finke Gorge the contact is unconformable.

The Hermannsburg Sandstone forms the present erosion surface over a large part of the area. It is locally overlain by isolated outcrops of Tertiary sediments, and in the east passes beneath the sediments of the Great Artesian Basin. In the east, it is probably unconformably overlain by the Permian Crown Point Formation, but the contact is obscured by sand.

The preserved thickness of the formation and a reconstruction of the original thickness are shown in Figure 41. It was thickest adjacent to the MacDonnell Ranges, and the greatest measured thickness is about 4500 feet, south of Stokes Pass. In the central part of the basin, the thickness preserved in the synclinal areas is probably less than 3000 feet. The formation thins rapidly east of the type area, and is absent along most of the northern margin of the basin east of a point about 2 miles east of Ellery Creek. It thins locally over the Carmichael Structure, and may have been eroded here before the Brewer Conglomerate was deposited. South and west of the area of thickest sedimentation, the formation thins gradually and eventually wedges out. To the southeast, it intertongues with the Finke Group.

The Hermannsburg Sandstone is a red-brown and grey-brown kaolinitic and silty sandstone. It is medium to thick-bedded and cross-bedded.

In places, it contains a few thin interbeds of siltstone, and is conglomeratic in part, particularly in the basal beds along the northern edge of the basin (Pl. 24, fig. 2). The only fossils found are poorly preserved plant fragments. Leslie (1960, unpubl.) has reported a plant fossil (aff. *Sigillaria*) about 1500 feet above the base of the formation in the Tempe Downs area, which is considered to be possibly Carboniferous in age (Taylor, 1959b, unpubl.). The sandstone is regarded as Upper Devonian or Devonian-Carboniferous.

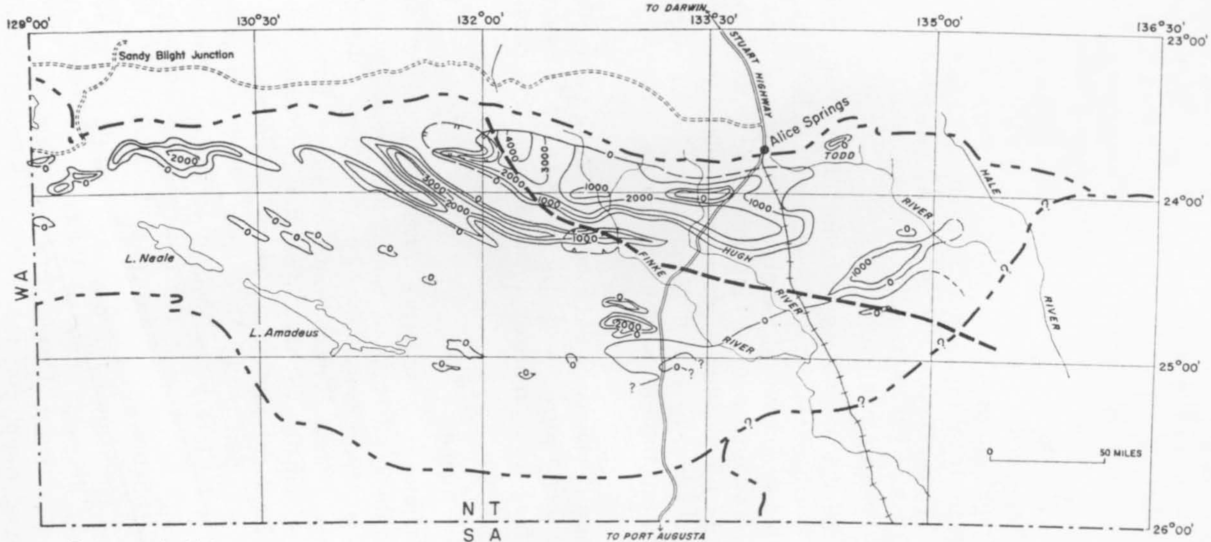
The distribution and red colour and the presence of plant fragments indicate that the Hermannsburg Sandstone is mainly continental. The thickest deposits were laid down close to the mountains on the northern margin of the basin, where sediment poured out to form large alluvial fans; elsewhere most of the formation was probably deposited on broad alluvial plains. The presence of glauconite in the sediments of the Erldunda No. 1 well (Schmerber, 1966d, unpubl.), which are correlated with the Hermannsburg Sandstone, suggests a marine environment in the south.

The coarse grainsize and thickness of the sandstone along the northern margin of the basin suggest a northerly provenance. The clasts in the basal conglomeratic beds were probably derived from uplifted blocks of older Palaeozoic and Precambrian rocks to the north.

Brewer Conglomerate (new name)

The Brewer Conglomerate is a sequence of pebble, cobble, and boulder conglomerate and subordinate interbedded sandstone and conglomeratic sandstone overlying the Hermannsburg Sandstone. The type area is on the southern flank of the western MacDonnell Ranges south of Stokes Pass (Pl. 23). The formation is exposed principally in the Missionary Syncline south of the MacDonnell Ranges. Isolated remnants crop out in the core of the Ross River Syncline, in the northwestern part of the Hale River Sheet area; about 10 miles southeast of the Ligertwood Cliffs in the Mount Rennie Sheet area; and near Larrier Bore in the Rodinga Sheet area. The outcrops are generally covered by mounds of phenoclasts weathered out of the conglomerate (Pl. 25, fig. 1).

The contact with the Hermannsburg Sandstone is poorly exposed but is apparently conformable in the west. East of Ellery Creek, along the northern margin of the basin, the Brewer Conglomerate overlaps the Hermannsburg Sandstone and rests unconformably on the Mereenie Sandstone and Palaeozoic sediments as old as the Cambrian Jay Creek Limestone. In the Hale River area to the east, the formation rests unconformably on the Pertaoorrta Group and probably on the Pertatataka Formation. In the eastern half of the basin, it is clear that the Hermannsburg Sandstone was deeply eroded before the Brewer Con-



Preserved thickness

— 1000 — Isopach (feet)

Area of thinning and erosion over Carmichael Structure

Area of thinning over Illamurta Structure

Southern limit (?) of pre-Brewer Conglomerate erosion

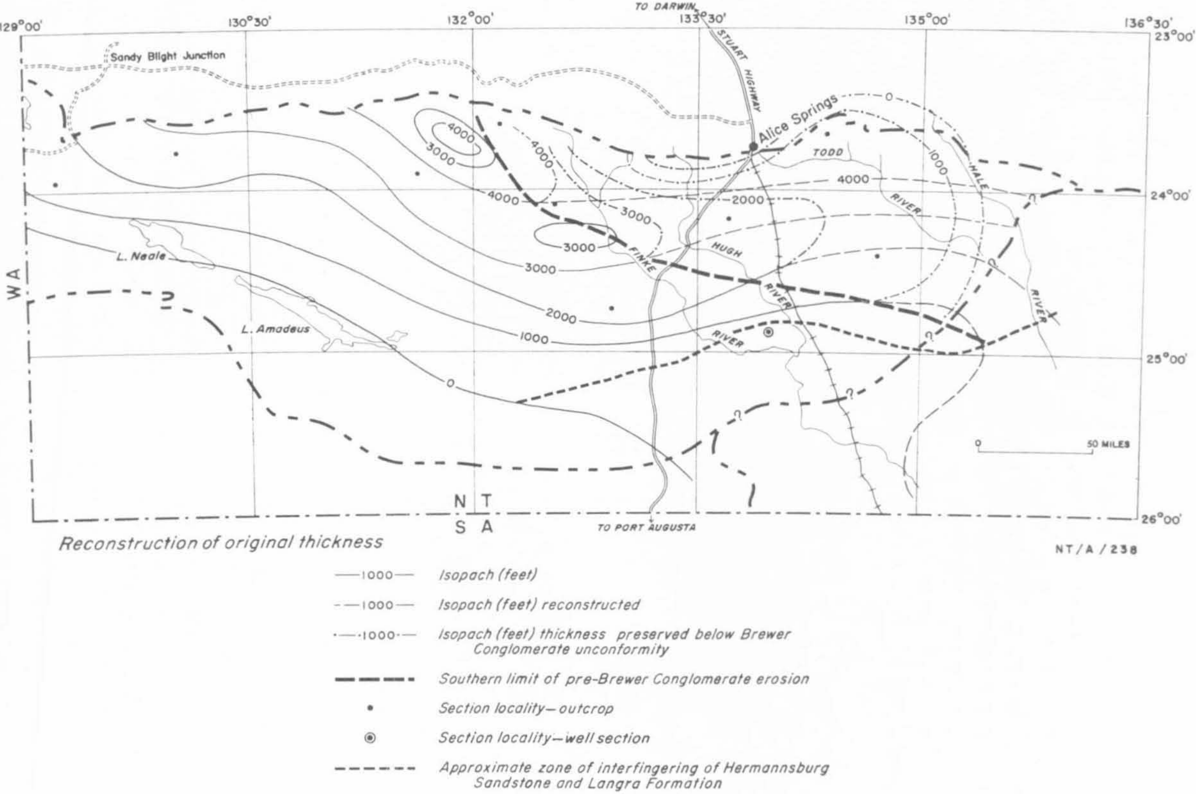


Fig. 41. Thickness of Hermannsburg Sandstone and Langra Formation.

glomerate was laid down. The top of the conglomerate is generally an erosion surface, but it is locally overlain by remnants of Tertiary lacustrine deposits. On the eastern edge of the basin, the formation appears to continue beneath the sediments of the Great Artesian Basin, and it may be unconformably overlain by the Permian Crown Point Formation.

The thickness is difficult to estimate because the outcrops are generally covered by gravel and because most of the dips were probably measured on cross-beds. The formation is about 4000 feet thick under Brewer Plain (Wells et al., 1967), and the maximum thickness on the northern flank of the Missionary Syncline is probably less than 10,000 feet. Seismic surveys by Magellan Petroleum Corporation (Krieg & Campbell, 1965, unpubl.) suggest that the Pertnjara Group is about 10,000 feet thick on the axis of the Missionary Syncline, and that the maximum thickness of the Brewer Conglomerate in this area is probably about 8000 feet. The thickness of the formation and a reconstruction of the original thickness are shown in Figure 42.

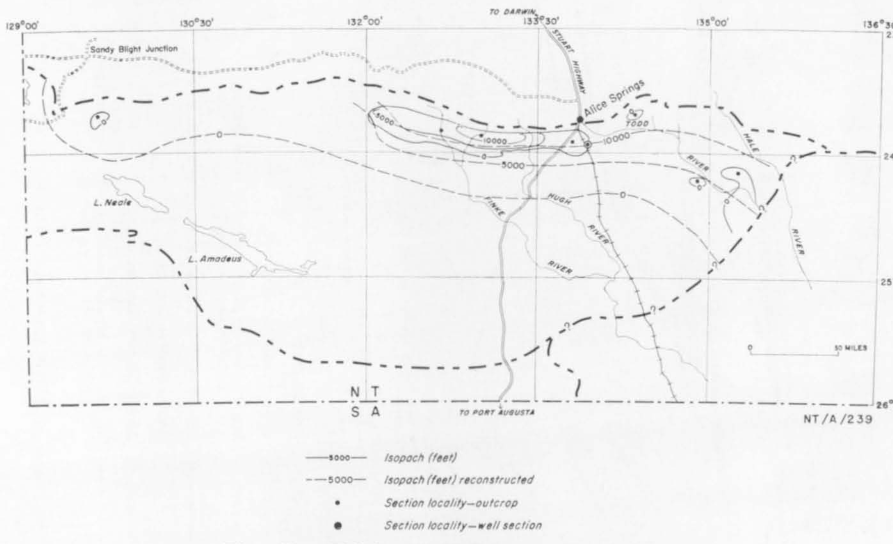


Fig. 42. Thickness of Brewer Conglomerate.

No fossils have been found in the Brewer Conglomerate, except in the phenoclasts. It may be Carboniferous.

The Brewer Conglomerate consists of polymictic pebble, boulder, and cobble conglomerate, and contains phenoclasts of most of the older formations, including the Arunta Complex. The matrix, where preserved, is generally calcareous sandstone. The conglomerate contains some thick lenses of pebbly sandstone, and on the southern side of the Missionary Plain it grades into a pebbly and cobbly calcareous sandstone.

The Brewer Conglomerate is a synorogenic piedmont deposit. The sediments probably accumulated in coalescing alluvial fans on the southern flank of high mountain ranges along the northern margin of the basin. It was probably associated with a diastrophic episode which was responsible for the contemporaneous uplift of the mountains and subsidence of the basin to the south. The deposits are poorly sorted and became finer in grain to the south. The freshness of the phenoclasts, including the unweathered feldspars in the igneous rocks, suggests an arid environment. Bedding is poorly developed. The degree of rounding of the fragments in places suggests reworking in a fluvial environment, and their variety indicates rapid and deep erosion of the source area.

Finke Group

The term 'Finke River Sandstone or series' of Chewings (1914) was used for the sediments exposed between Horseshoe Bend homestead and Finke (Wells et al., 1966). The name Finke Group refers to the sediments which lie unconformably below the Permian Crown Point Formation and Mesozoic sediments and unconformably above Precambrian rocks in the Finke Sheet area. The group consists of four conformable formations—the Polly Conglomerate at the base, followed by the Langra Formation, Horseshoe Bend Shale, and Idracowra Sandstone. South of the Charlotte Range, the Santo Sandstone rests conformably on the Horseshoe Bend Shale; it is probably laterally equivalent to the Idracowra Sandstone farther south, but it has not been formally included in the Finke Group.

The Finke Group crops out only in the southeast, on the western edge of the Great Artesian Basin (Fig. 36). The sediments are generally flat-lying and occur in mesas, buttes, and poorly exposed mounds, usually with a thick capping of duricrust. Most of the outcrops are covered by windblown sand. The Finke Group underlies large areas of Permian and Mesozoic rocks in the Hale River and McDills Sheet areas. In Mount Charlotte No. 1 well the Finke Group overlies the Stairway Sandstone, and in McDills No. 1 it lies between the Mereenie Sandstone below and Permian sediments above. The Finke Group overlapped the southern boundary of the Larapinta Group and, in part, the Mereenie Sandstone. The surface on which it was deposited included large areas of Precambrian igneous and metamorphic rocks and Proterozoic sediments.

The Finke Group is about 1500 feet thick in outcrop. It is about 3000 feet thick in the McDills No. 1 well, and an incomplete section of 1150 feet is present in Mount Charlotte No. 1. The Finke Group is equivalent to at least a large part of the Pertnjara Group and is probably mostly Devonian in age.

Polly Conglomerate

The Polly Conglomerate (Wells et al., 1966) crops out near the Black Hill Range, where it rests unconformably on the Winnall Beds, and in the Umbeara homestead area where it rests unconformably on the crystalline basement. In Mount Charlotte No. 1 well the equivalent beds below the Langra Formation consist of red shale about 150 feet thick which rests on the Stairway Sandstone. In McDills No. 1 the interval correlated with the Polly Conglomerate is 1290 feet thick (5800-7090 ft). The thickness in the Black Hill Range is about 200 feet, and about 80 feet was measured at Horseshoe Bend homestead on the Finke River. The formation is a polymictic conglomerate with pebbles, cobbles, and boulders of granite, and metamorphic and sedimentary rocks. Near Umbeara homestead, where it overlies granitic rocks, the phenoclasts consist mainly of granite and vein quartz; near the Black Hill Range there is a high proportion of angular fragments of siltstone and sandstone derived from the underlying Winnall Beds. Near this ridge of Proterozoic rocks the phenoclasts range up to 8 inches across and consist of pink granite, porphyritic rocks, pegmatite, sandstone and siltstone from the Winnall Beds, some quartz, and a few boulders of pink dolomite which were probably derived from the Bitter Springs Formation. In McDills No. 1 the Polly Conglomerate contains pebbles, up to 3 inches across, of quartzite, chert, granite, marble, and shale set in a matrix of fine to coarse sandstone. Some interbeds of fine to medium-grained sandstone and shale are present. The lithology and distribution of the Polly Conglomerate indicate that the beds are fluvial, and that they were formed as a result of vigorous erosion of uplifted areas of Precambrian crystalline and sedimentary rocks.

Langra Formation

The Langra Formation rests conformably on the Polly Conglomerate. It contains beds of conglomerate, but consists predominantly of sandstone. Three units have been distinguished by Wells et al. (1966) at Horseshoe Bend.

Top 50 ft: *Sandstone,* white fine-grained

50 ft: *Siltstone,* red-brown, micaceous

400 ft: *Sandstone,* yellow, white, poorly sorted, cross-bedded, with interbedded *conglomerate* and red *siltstone.*

The phenoclasts in the conglomerate in the basal unit comprise granite, banded chert, porphyry, metamorphic rocks, and large fragments of Stairway Sandstone. The Langra Formation crops out more extensively than the other formations of the Finke Group: the upper sandstone unit is the most common in outcrop. The formation is about 1730 feet thick in McDills No. 1 and 530 feet thick in Mount Charlotte No. 1. The three units found in outcrop can be distinguished in Mount Charlotte No. 1—the upper sandstone is 110 feet thick, the middle siltstone 130 feet, and the lower sandstone 290 feet. No conglomeratic units are present. In McDills No. 1 the formation consists of sandstone with interbeds of grey to green shale. The sandstone is fine to coarse-grained, cross-bedded, and porous; the upper part is calcareous and the lower part conglomeratic. Some of the sandstone is pyritic.

The Langra Formation crops out only in the Finke Sheet area, but probably extends subsurface westwards into the Kulgera Sheet area and northwards into the Hale River and Rodinga Sheet areas.

The sediments contain slumps and cut-and-fill structures, and the finer-grained sediments show penecontemporaneous brecciation. The lithology and sedimentary structures indicate rapid erosion of the source areas and rapid deposition in a predominantly fluvial environment.

Horseshoe Bend Shale

The Horseshoe Bend Shale is a sequence of red-brown and green shale and siltstone resting conformably on the Langra Formation (Wells et al., 1966).

It is overlain disconformably by the Idracowra Sandstone, apparently conformably by the Santo Sandstone, and unconformably by the Crown Point Formation and De Souza Sandstone. It is widely distributed in the central part of the Kulgera and Finke Sheet areas. Biotite is abundant in the shale; gypsum, pseudomorphs after halite, ripple marks, and mud cracks are also present. It is about 300 feet thick at Horseshoe Bend, 280 feet in McDills No. 1 well, and 460 feet in Mount Charlotte No. 1. In McDills No. 1, it is in part interbedded with fine calcareous sandstone.

The finer grainsize of the sediments suggests less rapid erosion of the source areas, and the sediments were probably deposited in a fluviatile or estuarine environment. The abundance of biotite and muscovite indicates that the source areas were probably mainly Precambrian crystalline rocks.

Idracowra Sandstone

The Idracowra Sandstone (Wells et al., 1966) is found only between Horseshoe Bend homestead on the Finke River and Idracowra homestead. It rests disconformably on the Horseshoe Bend Shale; the top is an erosion surface, and is generally capped by silcrete. The formation consists of medium to fine-grained kaolinitic quartz sandstone; the sandstone is thin-bedded or massive, and contains some clay pellets and rare pebbles of quartz and quartzite. It is generally well sorted, but some interbeds of poorly sorted yellow sandstone are present in places. The Idracowra Sandstone is seldom more than 200 feet thick in outcrop. The beds are probably mainly fluvial.

Santo Sandstone

The Santo Sandstone (Wells et al., 1967) is a white cross-bedded and pebbly sandstone which rests unconformably on the Horseshoe Bend Shale. The formation is found only between the Mount Charlotte Range and Idracowra homestead, where it crops out as flat-lying beds in isolated buttes and mesas (Pl. 25, fig. 2); the top is eroded. The sequence consists of white poorly sorted sandstone with subordinate silty kaolinitic sandstone and conglomeratic sandstone. The conglomeratic sandstone contains pebbles and cobbles of vein quartz, metamorphic quartzite, chert, and silicified sandstone up to 6 inches across. Most of the pebbles and cobbles are well rounded, but the quartz in the matrix is generally poorly rounded. The sandstone is generally friable, thin to thick-bedded, and cross-bedded; concentrations of heavy mineral are present in places. The silt is intergranular or forms large lenses and pellets.

The Santo Sandstone is laterally equivalent to the Idracowra Sandstone.

Correlation and Age

Evidence of the interfingering of the Pertnjara and Finke Groups has been deduced mainly from outcrops south and west of the Charlotte Range and by correlation of the Pertnjara Group with the sequence in Mount Charlotte No. 1 well (Fig. 43). On the southern side of the Charlotte Range, the Stairway Sandstone is overlain by the basal red-brown siltstone of the Pertnjara Group, which is probably continuous with the red-brown siltstone above the Stairway Sandstone in Mount Charlotte No. 1. Hence the sandstone cropping out in the Pertnjara Group is probably continuous with the basal sandstone unit of the Langra Formation in the well section. The upper sandstone unit of the Langra Formation is not exposed south of the Charlotte Range, but is probably contiguous with the upper part of the sandstone sequence exposed at Mount Duff south of the Finke River, and with the upper white sandstone of the Hermannsburg Sandstone in the Camel Flat Syncline, and at Deep Well homestead and Mount Ooraminna, and perhaps with the white sandstone beneath the Brewer Conglomerate southeast of Williams Bore.

On the northern flank of the Camel Flat Syncline, the upper white sandstone in the Hermannsburg Sandstone is separated from the lower red-brown sandstone by a thin red-brown siltstone, probably continuous with the middle red siltstone unit of the Langra Formation.

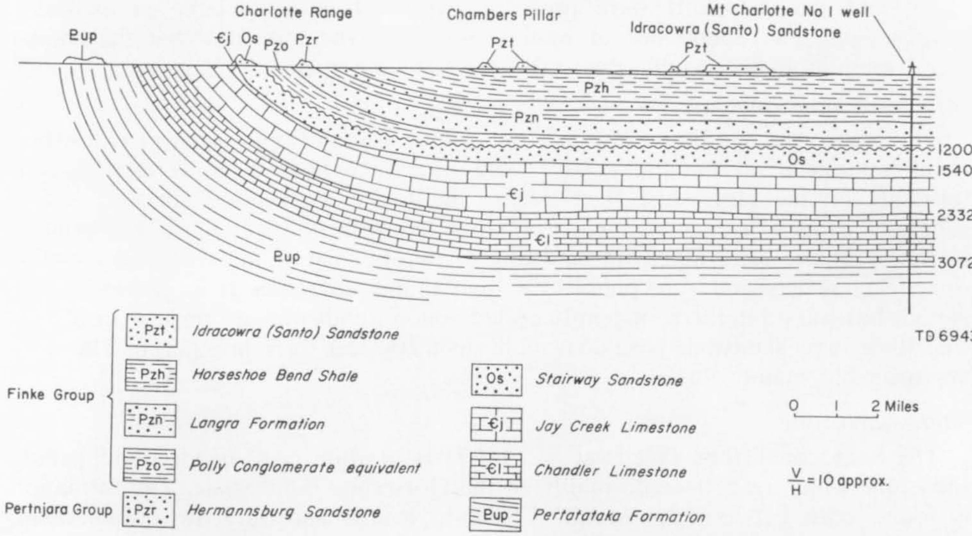


Fig. 43. Correlation of outcrops in Charlotte Range with section in Mount Charlotte No. 1 well.

The field relationships indicate that the Finke and Pertnjara Groups interfinger in the area between the Charlotte Range and the Finke River (Fig. 44), and that the Horseshoe Bend Shale and Idracowra (Santo) Sandstone were probably deposited at the same time as the Brewer Conglomerate.

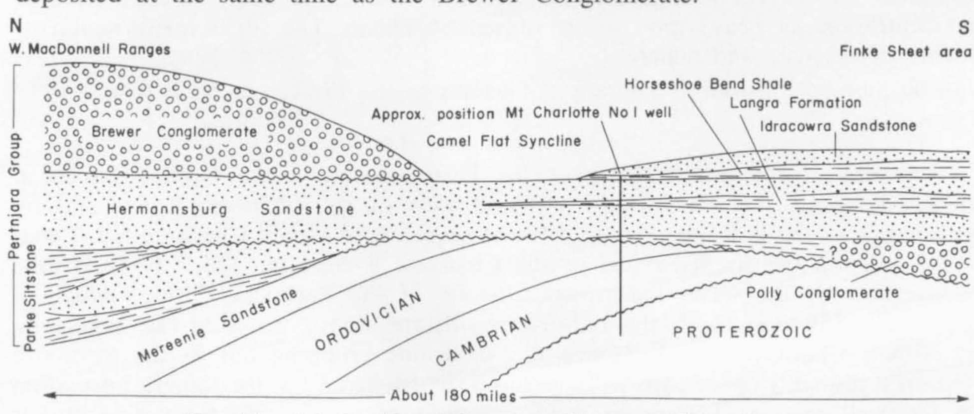


Fig. 44. Relationship of Pertnjara Group to Finke Group.

The fossil fish plates and spores in the basal part of the Parke Siltstone are of Upper Devonian age. The upper part of the group has not been dated accurately, and it is possible that it ranges up into the Carboniferous. In the western and eastern parts of the basin, folded Pertnjara Group sediments crop out close to outcrops of unfolded sediments which are believed to be Permian.

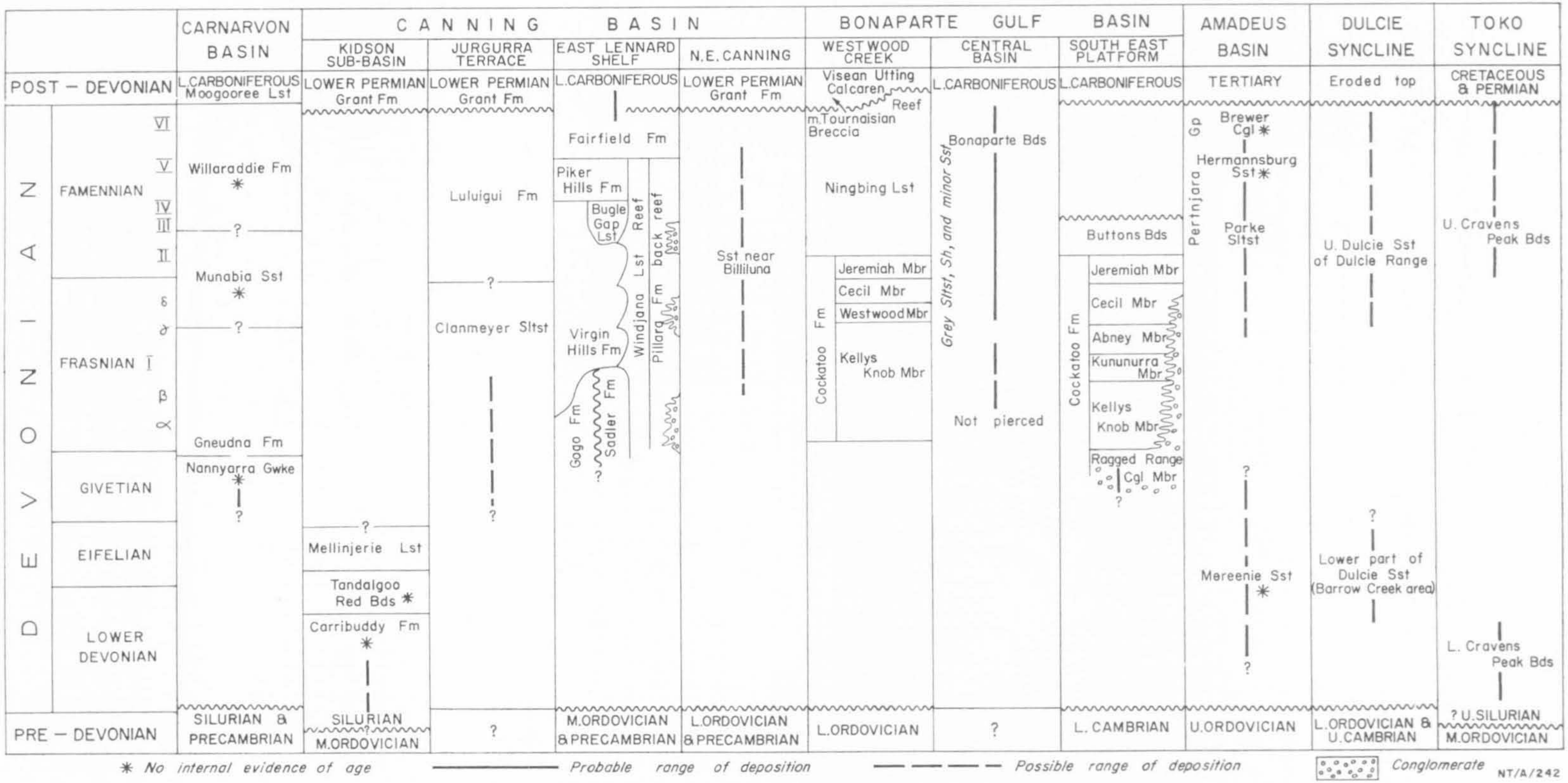


Fig. 45. Correlation of Devonian rocks in central Australia and Western Australia. (After Johnstone et al., 1967).

Indirect evidence of the age of the group is provided by the isotopic ages obtained on the Arunta Complex from the Harts Range area. The age of 367 m.y. (Hurley et al., 1961) may correspond to the age of the Alice Springs Orogeny which folded the Pertnjara Group.

Devonian fish are known from three distinct faunas in Australia (Tomlinson, 1968). In Western Australia, the fauna is marine and early Frasnian, in western New South Wales it is non-marine and Famennian. The western New South Wales fauna may also be present in the Toko and Toomba Ranges in the Northern Territory.

The fossils in the Parke Siltstone are comparable with the faunas found in the Dulcie Sandstone and Cravens Peak Beds in the southern part of the Georgina Basin, and in southeastern Australia. In the Ngalia Basin, 7000 feet of sandstone and minor conglomerate containing Carboniferous plants rest unconformably on Lower Palaeozoic rocks. They are probably synorogenic continental deposits and resemble the Pertnjara Group. Farther north, isolated outcrops of similar sandstone occur in the Wiso Basin. The correlation of the Devonian rocks in central and Western Australia is shown in Figure 45.

Geological History

During several periods of diastrophism in the late Devonian and possibly in the Carboniferous a large block of Precambrian basement and the superincumbent sediments was uplifted. The Palaeozoic and Precambrian rocks of the uplift were deeply eroded, and a thick wedge of molasse was deposited on the southern flank of the mountains to form the Pertnjara Group.

The first period of diastrophism, called the Pertnjara Movement (see p. 133), is recorded at the base of the Pertnjara Group. It caused the unconformity between the Mereenie Sandstone and Pertnjara Group in the central-northern and northeastern part of the basin, and initiated the deposition of the Parke Siltstone. Other unnamed crustal movements in the north and northwest preceded and in places accompanied deposition of the other units of the group.

The Pertnjara Group was folded either late in the Devonian or in the Carboniferous during the Alice Springs Orogeny.

The thickest and coarsest sediments accumulated close to the source area, and the youngest formation (Brewer Conglomerate) is confined to a relatively narrow strip on the southern flank of the MacDonnell Ranges. The presence of two cycles of phenoclasts, arranged in reverse stratigraphic order, suggests successive major uplifts during sedimentation. The underlying Parke Siltstone and Hermannsburg Sandstone are more widespread, but they thin considerably to the southeast, where the finer-grained and better sorted sediments were deposited.

The bulk of the sediments of the Pertnjara Group were confined to the northern part of the basin by a ridge which was probably the surface manifestation of a basement swell trending northeast along the southeastern margin of the basin; the Pertnjara Group was deposited in the north, the Finke Group to the south and they interfingered across the ridge. The history of the Pertnjara and Finke Groups is illustrated by the diagrammatic cross-section in Figure 46. The early fine-grained sediments of the Pertnjara Group were probably laid down in large interconnected lakes. The great thickness of siltstone with subordinate sandstone interbeds indicates

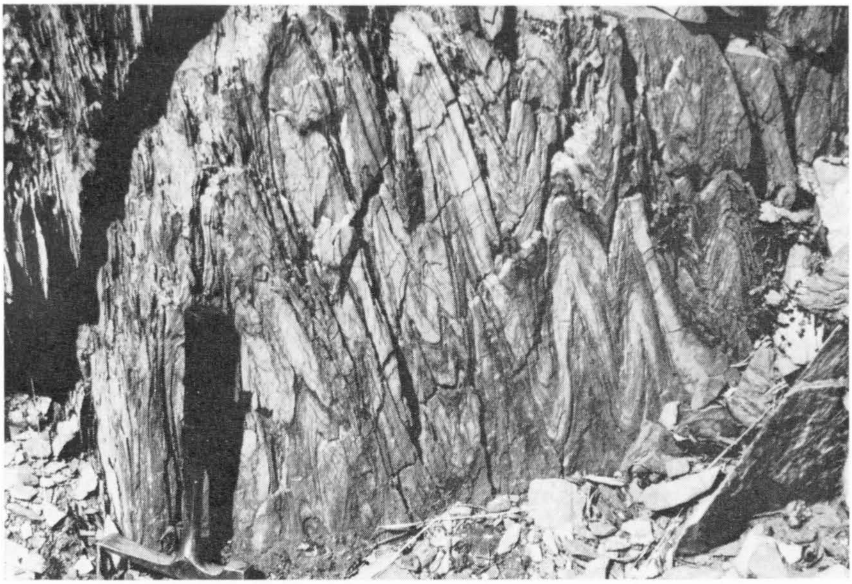


Plate 33, fig. 1. Isoclinally folded quartzite in the older Precambrian basement 60 miles west of Alice Springs. The axes of the folds trend northerly.

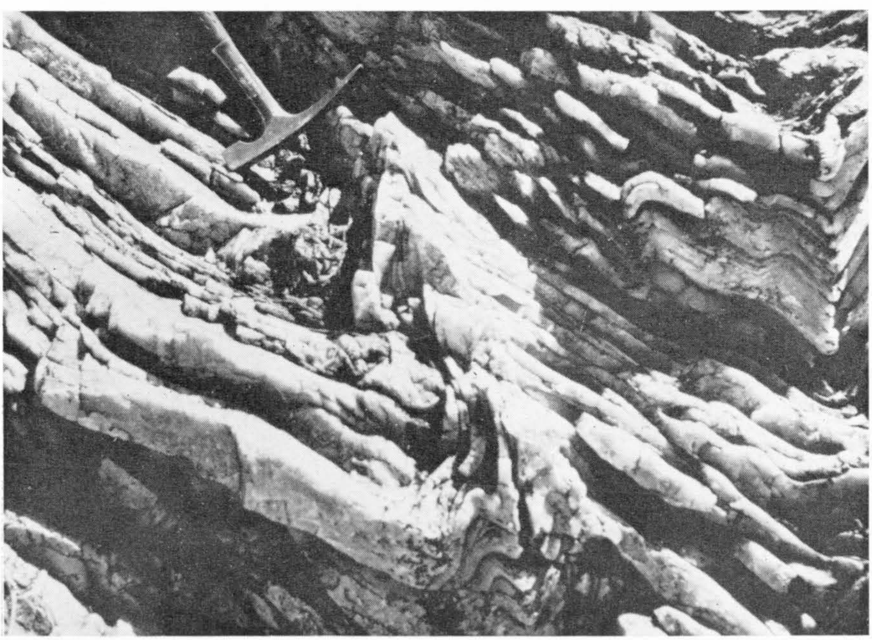


Plate 33, fig. 2. Chevron folds, with steeply dipping east-west axial planes, in quartzite of the older Precambrian basement.

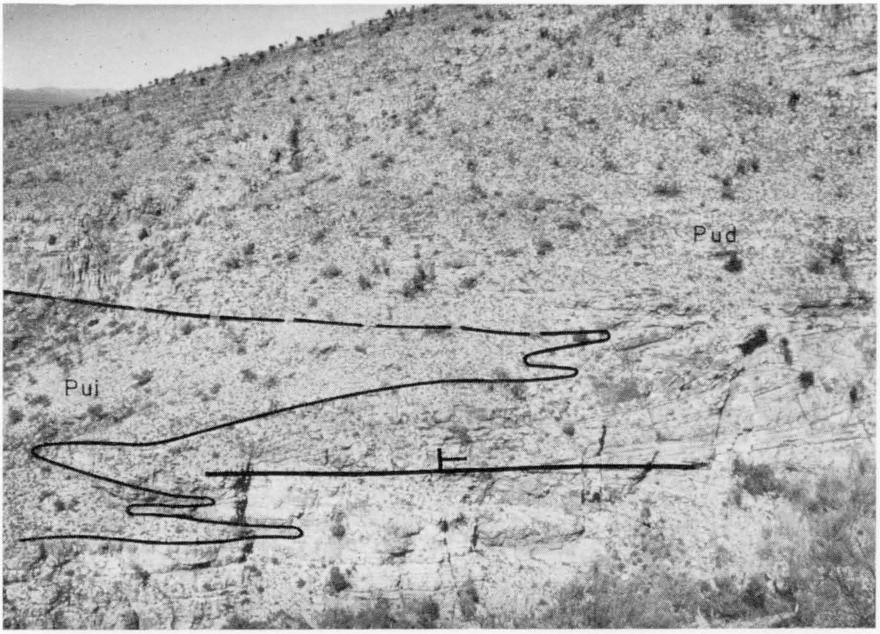


Plate 34, fig. 1. Recumbent folding in the Dean Quartzite at Foster Cliff in the Olia Chain. The fold axes trend southerly.

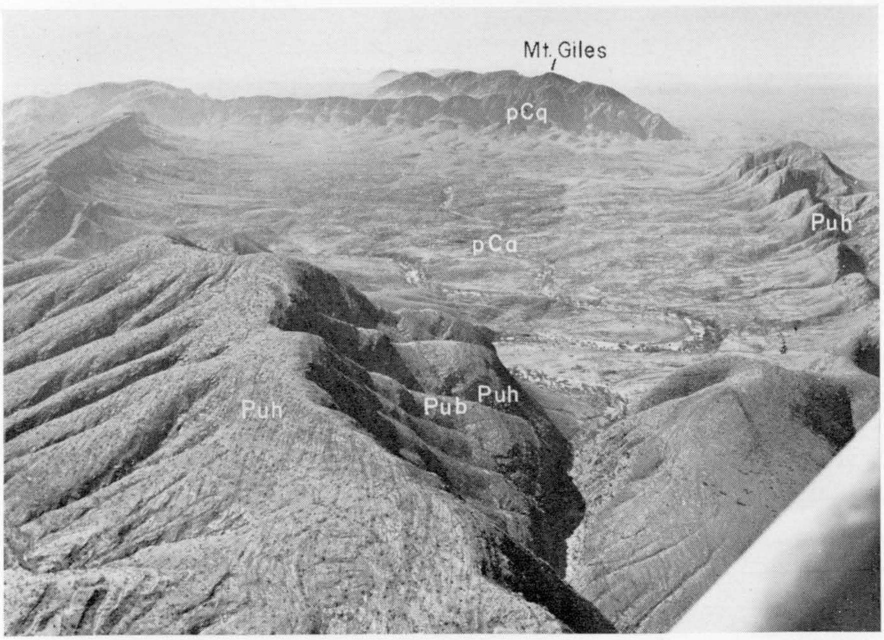


Plate 34, fig. 2. The Ormiston Nappe Complex, showing prominent ridges of Heavitree Quartzite (Puh) and Precambrian quartzite (pCq), and low-lying areas underlain by the Arunta Complex (pCa).

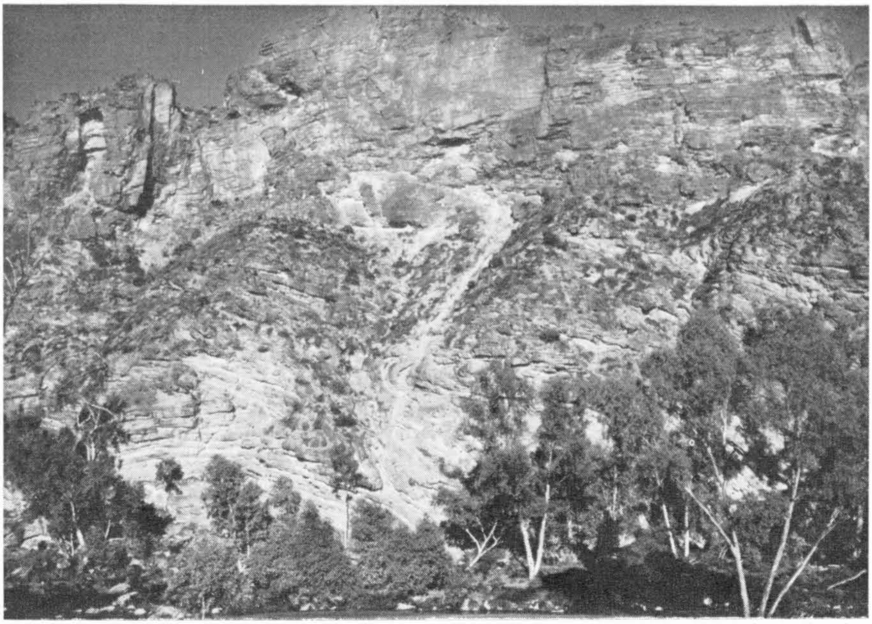


Plate 35, fig. 1. Bitter Springs Formation with recumbent folds overlain by allocthonous Heavitree Quartzite in the base of the Ruby Gap Nappe, near Ruby Gap, 72 miles east-northeast of Alice Springs.

Plate 35, fig. 2. Autochthon and base of Ruby Gap Nappe, near Ruby Gap, 73 miles east-northeast of Alice Springs. The autochthonous Heavitree Quartzite (in foreground) dips beneath the Bitter Springs Formation (in middle distance). The distant scarp consists of allochthonous Heavitree Quartzite resting on the Bitter Springs Formation.

Plate 36, fig. 1. Cross-bedding in overturned allochthonous Heavitree Quartzite in the frontal part of the White Range Nappe, near the Ross River Tourist Chalet, 41 miles east-northeast of Alice Springs.

Plate 36, fig. 2. Mass of sheared and brecciated gypsum in the Johnstone Hill Diapir. The gypsum has a weathered earthy crust and contains a rafted mass of dark dolomite from the Bitter Springs Formation.

stable conditions of deposition in shallow water; the bulk of the coarser material was deposited closer to the source in the north. Salt casts in the siltstone show that the water was brackish and subject to periodic evaporation. In the east, the provenance of the Parke Siltstone included large areas of Mereenie Sandstone, which was partly or wholly removed by erosion before the Hermannsburg Sandstone was deposited.

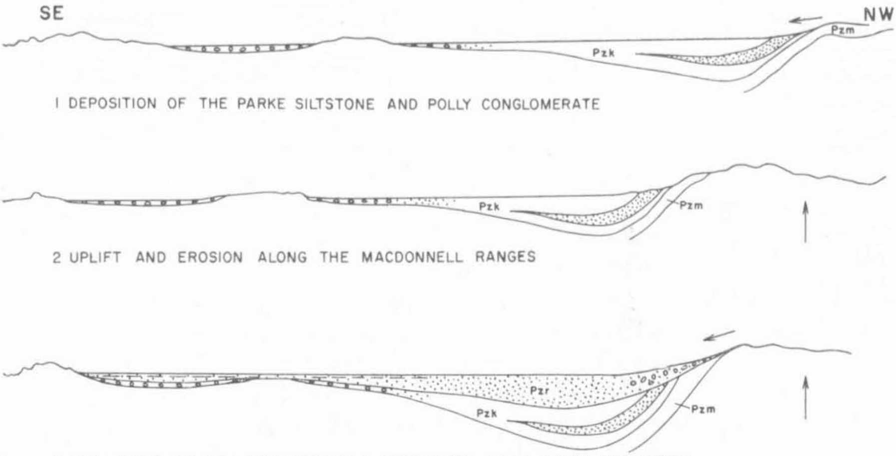


Fig. 46. Cross-sections showing history of sedimentation in Pertnjara Group and Finke Group times.

The sandstone and subordinate conglomerate of the Hermannsburg Sandstone were deposited mainly by rivers, with the coarser material accumulating in alluvial fans next to the uplifted source area. A thinner sequence of better sorted and finer-grained sediments was deposited on a wide platform in the southeast. At this stage, the Mereenie Sandstone had probably been removed from a large part of the source area, and much of the detritus was derived from Palaeozoic and Precambrian rocks. The Parke Siltstone was partly removed close to the gradually rising source area, and in the eastern half of the basin the Hermannsburg Sandstone overlapped onto the Mereenie Sandstone. The main paroxysm of several diastrophic movements that occurred during the deposition of the Pertnjara Group caused the major uplift and vigorous erosion of the Precambrian and Palaeozoic rocks of the provenance area and resulted in the deposition of the Brewer Conglomerate. The Hermannsburg Sandstone was eroded next to the mountain front, and was overlapped by the Brewer Conglomerate resting on the upturned Palaeozoic and Precambrian beds exposed in the eroded mountain cores. Farther south in the subsiding basin, fine-grained pebbly sediments were apparently deposited conformably on the Hermannsburg Sandstone.

The coarse material in the Brewer Conglomerate was probably deposited in piedmonts, which were reworked and redistributed by large rivers. The conglomerate grades into finer conglomerate and conglomeratic sandstone to the south, but is not preserved south of Missionary Plain. The fine-grained constituents were probably carried considerably farther southeast.

The Finke Group was formed by the intermingling of fine-grained sediments from the northern edge of the basin with coarser sediments from the Precambrian igneous and metamorphic rocks in the south. The presence of coarse conglomeratic sediments in the Finke Group as far east as McDills No. 1 well in the Simpson Desert suggests considerable uplift of the provenance area.

During the deposition of the Parke Siltstone in the north, a freshwater conglomerate (Polly Conglomerate) filled the hollows in the slowly sinking basement swell and marginal basement outcrops in the south. The conglomerate is a local piedmont deposit. The basement swell became ineffective as a barrier, and the finer equivalents of the Hermannsburg Sandstone overlapped it and interfingered with the Langra Formation to the southeast. The finer-grained equivalents of the Brewer Conglomerate were probably also transported into this area and contributed to the formation of the Horseshoe Bend Shale and Idracowra Sandstone. The Idracowra (Santo) Sandstone, the youngest formation of the Finke Group, is not known south of latitude 25°15′S., and was probably confined to the area north of the Black Hill Range, which was uplifted, probably during the later stages of sedimentation.

The Finke Group was probably mainly deposited in piedmonts and alluvial flood-plains. The coarse basal conglomerates were probably formed as piedmonts close to outcrops of Precambrian rocks, and the subsurface data suggest that they grade northwards into red fluviatile siltstone. Coarser sediments apparently persisted much farther southeast, where they have been identified in McDills No. 1 well. The finer-grained sediments of the Finke Group may have been deposited by sluggish streams or in temporary lakes on broad alluvial plains. The mud cracks and halite pseudomorphs in the siltstone can be accounted for by periodic evaporation, and the preservation of the red colour indicates an oxidizing environment. The red-beds were probably formed in situ by alteration of iron-bearing detrital grains after deposition of the sediments in desert basins, in a similar way to that proposed by Walker (1967). Palaeomagnetic studies by Irving (1964) show that, during the Devonian, Australia was equatorial, which confirms the hot dry climate suggested by some of the depositional features of the Finke Group.

The large-scale heterogeneity of the Langra Formation, the cut-and-fill structures, brecciation of the finer beds, and irregular textural variations are consistent with the type of structures commonly found in alluvial flood-plain deposits.

Ligertwood Beds

The Ligertwood Beds were named by Wells et al. (1965). In the type area at Ligertwood Cliffs they consist of two disconformable units: a lower unit over 40 feet thick of interbedded sandstone, calcareous sandstone, and calcareous pebble and cobble conglomerate. The conglomerate is tightly packed with angular to subangular fragments of chert and dolomite derived from the Bitter Springs Formation. The upper unit consists of over 30 feet of silicified sandstone, conglomeratic sandstone, and pebble conglomerate. The conglomerate contains pebbles of siltstone, silicified sandstone, chert, and fine and medium-grained sandstone. Farther west in the Mu Hills the upper unit is a pebble, cobble and boulder conglomerate and the phenoclasts were derived mostly from the Sir Frederick Conglomerate.

Bedding is mostly horizontal though locally dips exceed 10°. The total thickness of the beds probably ranges up to several hundred feet.

In the Mount Rennie Sheet area the lower unit was eroded and cut by steep-sided channels before the upper unit was deposited. In outcrops farther west there is probably also a disconformity separating the two but it is not as obvious. In the type area the top of the sequence is eroded and the base is concealed. North of the Ligertwood Cliffs, the lower unit is absent, and the upper unit rests unconformably on the Carnegie Formation. Farther west in the Macdonald Sheet area, the lower unit overlies the Bitter Springs Formation with an angular unconformity.

The distribution of the Ligertwood Beds follows major faults. The main period of folding has affected the Pertnjara Group in the region and because the Ligertwood Beds are essentially flat-lying they are considered to be younger, probably Upper Palaeozoic.

PERMIAN

*Crown Point Formation, Buck Formation, and Unnamed Permian Rocks**

Permian sediments crop out at the eastern and western extremities of the Amadeus Basin. In the west they were named the Buck Formation by Wells et al. (1964), and the reference area is in the Buck Hills in the Macdonald Sheet area. Many of the Permian sediments in the west are poorly exposed and have not been subdivided into formations.

Scattered remnants, probably of the Buck Formation, extend as far east as Worman Rocks in the Mount Rennie Sheet area (Wells et al., 1965). The Buck Formation is about 150 feet thick and consists of poorly sorted coarse sandstone, conglomerate with a tillitic texture, and siltstone (Pl. 26, figs 1, 2). The erratics include granite, schist, vein quartz, acid porphyry, and black and white banded chert; many of them are striated and faceted. Many of the erratics have deformed the underlying sediments, and beds of coarse sandstone have deformed the underlying incompetent siltstones (Pl. 27, fig. 1). The formation unconformably overlaps the folded Proterozoic sediments and Precambrian basement; the unconformity has considerable relief. At one locality in the Dovers Hills, there is possibly a glacial pavement where the Buck Formation rests on the Heavitree Quartzite. The faint striae on the pavement trend north-south. The Buck Formation includes terrestrial and fluvioglacial sediments (Wells et al., 1964); the top has been eroded or is obscured by Quaternary sand.

*These units are shown as 'Permian' (P) on the maps (Pls 45, 46).

The Permian sediments extend into the Canning Basin to the northwest and into the Officer Basin to the southwest. The nearest fossiliferous beds are recorded in a BMR seismic shot hole, 28 miles west of Mount Everard in the Gibson Desert (Wells, 1963, unpubl.). The core was found to contain Lower Permian spores and pollen grains equivalent to the *Nuskoisporites* assemblage defined by Balme (1964) (P. R. Evans, pers. comm.). To the north, Permian fossiliferous sediments are found in the northeastern part of the Canning Basin (Casey & Wells, 1964); they extend as far south as the Waterlander Breakaway. Lower Permian spores were found in the Point Moody No. 1 well in the Stansmore Range (Evans, *in* Aust. Aquitaine, 1966, unpubl.). The Buck Formation is similar in lithology to the Paterson Formation and Braeside Tillite (Traves et al., 1956), the Grant Formation (Guppy et al., 1958), and the Crown Point Formation (Wells et al., 1966).

In the southeast, the *Crown Point Formation* unconformably overlies the Finke Group (Pl. 27, fig. 2), and is unconformably overlain and overlapped by the Mesozoic De Souza Sandstone. Information from water bores north of Kulgera suggests that the formation may be unconformably overlain by the Cretaceous Rumbalara Shale. The Crown Point Formation is mainly Permian in age, but an Upper Carboniferous spore assemblage has been reported from the lower part of the formation in the McDills No. 1 well (Evans *in* Amerada, 1965, unpubl.).

The Crown Point Formation consists of siltstone, sandstone, tillite, and conglomerate. The reference locality is Crown Point in the Finke Sheet area (Pl. 28, fig. 1). Many outcrops are covered by mounds of rounded boulders, and some of the phenoclasts of quartzite and quartz are up to 5 feet across. Smaller fragments of granite and schist occur in the residual gravels. Many of the quartzite boulders show impact markings (Pl. 28, fig. 2) and a few of the smaller fragments are striated. Large slump structures (Pl. 29, fig. 1) and convolute laminations (Pl. 29, fig. 2) are common; the larger structures were probably formed in the unconsolidated sediment by ice wedging.

In outcrop, the Crown Point Formation is about 200 feet thick. In Malcolms Bore it may be up to 1200 feet thick (Rochow, 1965, unpubl.) and in McDills No. 2 it is about 1440 feet thick. In McDills No. 1 the sandstone is fine to medium-grained and locally coarse-grained, partly pyritic and conglomeratic, and calcareous towards the base; the upper part of the sequence, from 2330 to 2630 feet, contains thin lenses of lignite. Nodules of mudstone are present in the sandstone both in the well section and in outcrop. Grey shale and siltstone are interbedded with the sandstone throughout. The conglomeratic shale in the basal part of the formation contains phenoclasts of chert and metamorphic rocks.

Permian spores have been recovered from several water bores in the Finke Sheet area (Evans, 1964, unpubl.), from Malcolms Bore (Balme *in* Sprigg, 1963; Evans, 1964, unpubl.), and from the McDills No. 1 well (Evans *in* Amerada, 1965, unpubl.). The well preserved Lower Permian microfloras from the Finke Sheet area are of probable Sakmarian age (spore unit P1b), and Evans (1964, unpubl.) considers that they were deposited towards the end of the Upper Palaeozoic glacial phase. The samples from Malcolms Bore contain a microflora of Lower Permian age (spore unit P1c). Balme (pers. comm.) comments that the assemblage is similar to that in the upper part of the Grant Formation in the Canning Basin, and could be as old as late Sakmarian. Rochow (1965, unpubl.) reported that the fossiliferous samples in Malcolms Bore were in an interval overlying typical sediments of the Crown Point Formation. The Lower Permian spores in McDills No. 1 are older than the assemblage reported from Malcolms Bore, and some of the microfloras (from 2381 ft, spore unit P1b) are comparable with those previously described from shallow bores in the Crown Point Formation. Spores of unit P1a were recorded from 2908 to 3128 feet, and Upper Carboniferous spores (spore unit C1/2) were found in samples from 3687 feet, about 130 feet above what is interpreted as the base of the formation; so deposition of the Crown Point Formation in the McDills area began in the late Carboniferous. The basal sediments here consist of fine and coarse-grained calcareous sandstone; unlike the rest of the formation they are not conglomeratic and contain no pyrite, lignite, or mudstone nodules.

The Crown Point Formation is composed mainly of the erosion products formed during a period of continental glaciation. On the western edge of the Great Artesian Basin the coarsest deposits were laid down on the margins, and the estuarine or lagoonal deposits farther east—lignite is present in the upper part of the sequence in McDills No. 1. The piles of rounded boulders on the outcrops suggest that the original terrestrial deposits were reworked to form the fluvioglacial sediments around the paralic deposits. No marine fossils have been found in the Crown Point Formation.

Upper Permian spores were found in a water bore (F53/13-224)* on the western side of the Hermannsburg Sheet area. The bore passed through about 120 feet of sediments and bottomed in granite of the Arunta Complex. The sample (96-116 ft) consisted of unconsolidated sand with a brown-grey clay matrix. P. R. Evans (pers. comm.) has suggested that the microflora from this bore appears to indicate the existence of a small pocket of late Permian deposits on the Precambrian basement. No late Permian deposits have been previously recorded in the Northern Territory outside the Bonaparte Gulf Basin.

MESOZOIC

Mesozoic sediments are found only in the southeast on the western fringe of the Great Artesian Basin, whose sediments overlap the succession in the Amadeus Basin. Two formations have been mapped—the Jurassic(?) De Souza Sandstone and the Lower Cretaceous Rumbalara Shale.

The De Souza Sandstone (Sullivan & Öpik, 1951) is composed predominantly of friable white sandstone. It is medium to coarse-grained, steeply cross-bedded, micaceous, and commonly conglomeratic. The sandstone generally weathers reddish brown or dark brown, and the outcrops are covered by a crust rich in limonite. The contacts with underlying and overlying formations are usually defined by iron-rich beds (Pl. 30, fig. 1). Some of the phenoclasts of quartz and subordinate quartzite were derived from the Crown Point Formation and some from the Brewer Conglomerate. In places, the formation is rich in kaolin, and contains lenses and layers of siltstone and shale.

De Souza Sandstone

In the Finke Sheet area, the De Souza Sandstone rests unconformably on the Finke Group or Crown Point Formation, and is overlain by the Rumbalara Shale.

*The system used for numbering water bores is explained on p. 194.

In several places, the top of the De Souza Sandstone has been eroded, and cut-and-fill structures and angular discordances were observed at the contact with the Rumbalara Shale, but elsewhere the contact appears to be conformable.

In water bores, the thickness ranges from 50 to 300 feet, but the maximum thickness in outcrop is about 100 feet.

The De Souza Sandstone contains undiagnostic plant remains, and the provisional Jurassic age assigned to it is based on its similarity to the sediments between Permian glacigene deposits and Lower Cretaceous lutites at Mount Anna and Mount Dutton in the Peak and Denison Ranges, in South Australia (Wopfner & Heath, 1963; Wopfner, 1964; Heath, 1965). The sandstone at Mount Anna is overlain by bleached silty shale of presumed Cretaceous age and rests unconformably on Proterozoic rocks. The top few feet of sandstone are impregnated with limonite as in the De Souza Sandstone. The well preserved plant fossils in the sandstone have been dated as Upper Triassic to Lower Cretaceous. The Permian deposits in the Mount Dutton inlier are unconformably overlain by the Jurassic-Cretaceous Algebuckina Sandstone, and rest with angular unconformity on Proterozoic rocks. The similar geological settings in South Australia and the Amadeus Basin suggest that both the Permian and Mesozoic formations are probably equivalent.

The De Souza Sandstone may be present in the McDills No. 1 well. Amerada Petroleum Corporation (1965, unpubl.) consider that the 830 feet of clean quartz sandstone above the Crown Point Formation is equivalent to the De Souza Sandstone. It is fine to very coarse sandstone with clear quartz grains. The grains are subangular, and the beds are unconsolidated, porous, and pyritic towards the base. The overlying 80 feet of fine to very fine sandstone with a white clay matrix and interbeds of dark grey mudstone and siltstone is placed in a transition zone between the De Souza Sandstone and Rumbalara Shale. This zone has been mapped as part of the De Souza Sandstone outcrops in the Finke Sheet area. The geologists of the Resident Staff, Alice Springs, however, believe that the sequence assigned to the De Souza Sandstone in McDills No. 1 well is part of the Crown Point Formation.

The De Souza Sandstone is probably deltaic. The clean sands with abundant steep cross-beds and fragmentary plants indicate deposition by fast currents in wide deltas and possibly lagoons. Much of the sediment, particularly the conglomeratic fraction, was probably derived from the underlying Crown Point Formation, and possibly from the Pertnjara Group. There is no evidence of marine deposition.

Rumbalara Shale

The Rumbalara Shale (Sullivan & Öpik, 1951) rests unconformably and in some places possibly conformably on the De Souza Sandstone (Pl. 30, fig. 1). It is part of a Lower Cretaceous marine transgression that covered a large part of the Australian continent (Skwarko, 1966). The formation has been correlated with the Bejah Beds in Western Australia (Veevers & Wells, 1961) and the lower Wilgunyah Formation in the Great Artesian Basin, and has been dated by Öpik (*in* Sullivan & Öpik, 1951), Skwarko (1962, 1966), and Terpstra & Evans (1963) as Aptian.

The top of the Rumbalara Shale is generally an erosion surface (Pl. 30, fig. 2), but in places it is unconformably overlain by Tertiary sand and fine conglomerate of the Etingambra Formation. Evidence from water bores between Erldunda homestead and Kulgera suggests that the Rumbalara Shale rests unconformably on the Crown Point Formation or Finke Group.

Rochow (1963) estimates that the thickness of the Rumbalara Shale south of Charlotte Waters Bore is 900 feet, but it decreases gradually to the west towards the old Lower Cretaceous shoreline. At least 300 feet is present in Malcolms Bore, about 300 feet in Peebles Bore, 450 feet in Birthday Bore, and about 1300 feet in McDills No 1.

In outcrop, the Rumbalara Shale consists predominantly of soft white porcellanite, claystone, and siltstone, with interbeds of sandstone. Yellow ochre is common at the base of the formation, especially around the Rumbalara Ochre mine. The sediments are typically white, friable, and leached, but are commonly blue-grey below the weathering profile. Most of the exposures are covered by a thick capping of silcrete. The sediments are commonly opalized by white translucent chalcedony, and ferruginized by iron oxide. The lithology is remarkably persistent over large areas.

The sequence in McDills No. 1 well consists of dark grey mudstone interlaminated with darker grey siltstone. The beds are in places glauconitic, and contain limonite inclusions, scattered *Inoceramus* prisms, and interbeds of tan cryptocrystalline limestone in the lower part.

TERTIARY

Sediments of probable Tertiary age crop out at numerous localities in and around the Amadeus Basin. They are subhorizontal, and rest unconformably on the Precambrian, Palaeozoic, and Mesozoic rocks.

The sediments include piedmont gravels, fluviatile sandstone and conglomerate, lacustrine limestone, shale, and sandstone, and the associated silcrete ('grey billy'), ferricrete (laterite or ironstone gravel), and kunkar.

Three stratigraphic units, the Etingambra Formation (Wells et al., 1967), Arltunga Beds (Smith, 1964), and Waite Formation (Woodburne, 1967) have been defined in the Amadeus Basin and environs, and a number of informal units have been recognized on the basis of lithology, contained fossils, and age relative to the time of formation of the silcrete and ferricrete.

Pre-silcrete Sediments

Etingambra Formation

The Etingambra Formation (Wells et al., 1967) is up to 40 feet thick, and consists of sandstone, siltstone, and conglomerate. It is exposed above the Rumbalara Shale in mesas in the central-southern part of the Hale River Sheet area, and at scattered localities in the McDills Sheet area. The formation rests disconformably and unconformably on the Rumbalara Shale and is capped with about 5 feet of silcrete.

Unnamed Units

The unnamed sediments are subhorizontal, and comprise sandstone, claystone, siltstone, and conglomerate. They crop out in mesas capped with silcrete (Pl. 31, fig. 1), and also include some sequences known only in scattered water bores.

In the past, some of the sediments were mapped as Mesozoic(?) (Prichard & Quinlan, 1962; Quinlan, 1962; Wells et al., 1965; Ranford et al., 1966) on the basis of unpublished reports by Crespin (1948, 1949, 1950, 1951, all unpubl.). The specimens identified by Crespin have been lost, but Lloyd (1968), who has examined one of the samples from which Crespin described radiolaria, considers that the radiolaria-like objects are of inorganic origin and that there is no evidence for the Mesozoic age.

Evans (*in* Wells et al., 1967) has recently described a Tertiary microflora from a water bore in the Farm area south of Alice Springs, and Lloyd (1968) has suggested that the pre-silcrete Tertiary sediments may be Eocene to Miocene. Wells et al. (1967) correlate the fossiliferous subsurface sediments in the Alice Springs Farm area with unfossiliferous pre-silcrete sediments in the northeast.

The subhorizontal coarse-grained sandstone mapped by Forman (1966c) in the southwest and the older Tertiary sediments described by Forman et al. (1967) on the northeastern margin may also be equivalent to the pre-silcrete Tertiary sediments.

Ferricrete (laterite)

Laterite profiles with pisolitic ironstone are rarely developed on sediments in the Amadeus Basin, but they are present on the Arunta Complex in the northeast (Forman et al., 1967). Ferruginized sediments, however, have been recorded in the central (Ranford et al., 1966) and northeastern (Wells et al., 1967) parts of the basin.

Most of the ferruginization appears to have taken place before the deposition of the post-silcrete sediments, and Wells et al. (1967) have suggested that it may have been contemporaneous with the formation of the silcrete. However, a few small occurrences of ferruginized post-silcrete sediments have been recorded in the central and northeastern parts of the basin.

Silcrete ('billy')

In the eastern half of the basin, many mesas, composed of sediments ranging in age from Precambrian to Tertiary, are capped with silcrete. The silcrete is best developed on clastic formations with a high percentage of clay in the matrix. It generally forms subhorizontal or gently dipping sheets, but vertical dyke-like bodies of silcrete are present in places in the Pertnjara Group and Mereenie Sandstone (Wells et al., 1967).

The silcrete cappings were probably formed during a prolonged period of weathering in the Tertiary, and the dyke-like bodies by the precipitation of silica from solutions moving along joint planes.

Post-silcrete Sediments

The post-silcrete Tertiary sediments have been described by Madigan (1932a, b); Joklik (1955); Prichard & Quinlan (1962); Wells et al. (1965, 1966); Ranford et al. (1966); Forman (1966c); Lloyd (1968); and Woodburne (1967). The sediments have been subdivided, in most areas, into a conglomerate and a sequence of finer clastics with interbeds of limestone.

The conglomerate ranges from a lithified sediment with a sandy calcareous matrix to an unconsolidated deposit of angular to well rounded phenoclasts with very little matrix. Much of the conglomerate is locally derived and occurs as piedmont gravels adjacent to prominent ranges. Some is fluviatile in origin and is preserved in low rises along the margins of the rivers. In the central part of the basin, river conglomerates are found up to 50 feet above the surrounding plain (Ranford et al., 1966). The disposition of the conglomerates indicates that there has been very little change in the position of the major drainage channels in post-Tertiary time. Madigan (1932a) recorded abundant fossil wood in conglomerate in the Waterhouse Range and suggested that the sediments were Tertiary or Quaternary in age. Prichard & Quinlan (1962) consider that the sediments may be Tertiary, but Condon (footnote, *in* Prichard & Quinlan, 1962) considers them to be

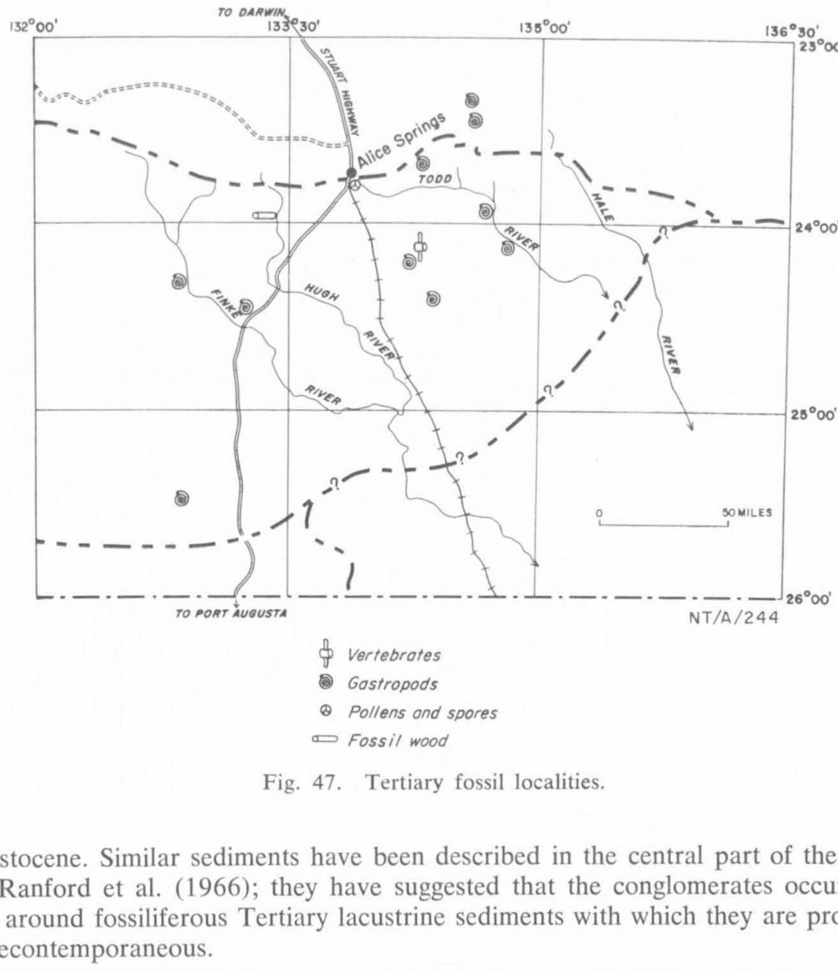


Fig. 47. Tertiary fossil localities.

Pleistocene. Similar sediments have been described in the central part of the basin by Ranford et al. (1966); they have suggested that the conglomerates occur as a rim around fossiliferous Tertiary lacustrine sediments with which they are probably penecontemporaneous.

The post-silcrete sediments consist of interbedded sandstone, siltstone, claystone, and limestone. They crop out in mesas which are generally capped by resistant chalcedonic limestone.

Arltunga Beds

Madigan (1932b) used the name Arltungan Beds for all Tertiary sediments east of Alice Springs; Smith (1964) revised the name to Arltunga Beds and extended it to include the Tertiary(?) sediments in the Huckitta Sheet area. Forman et al. (1967) and Lloyd (1968) consider that the name Arltunga Beds should not be used outside the type area near the Arltunga airstrip, because the Tertiary sediments were deposited in separate lakes. Lloyd (1968) has listed the known fossil localities (Fig. 47) and discussed their environmental significance and age. The fossils include kangaroos, crocodiles, turtles, birds, ostracods, pelecypods, gastropods, and oogonia of the alga *Chara*. The molluscs have been described by McMichael (1968).

The post-silcrete sediments are predominantly lacustrine and fluviatile, but some of the limestone may represent a type of caliche or kunkar. The sediments were probably deposited in a series of lakes which were distributed along the major rivers. Lloyd (1968) has suggested that the fossiliferous post-silcrete Tertiary sediments are Miocene and the unfossiliferous sediments Miocene or younger.

Waite Formation

Similar Middle Tertiary sediments at Alcoota, about 80 miles northeast of Alice Springs, have been named the Waite Formation by Woodburne (1967). The formation rests with angular unconformity on Precambrian basement and on the laterite profile developed on these rocks. The lower lacustrine siltstone and minor limestone contain gastropods and vertebrate remains, and are disconformably overlain by fluviatile sandstone and conglomerate. The fossil vertebrates are late Miocene or early Pliocene and the laterite here is considerably older. The chalcedonic limestone capping the sediments was probably formed by silicification of calcium carbonate deposited in the soil profile.

It is unlikely that the widespread deposits formed a lithogenetic unit, and they seem to occur as old fillings of present-day river valleys.

QUATERNARY

About three-quarters of the Amadeus Basin is covered by superficial Quaternary deposits. The principal deposits are wind-blown sand, alluvium in valleys, outwash plains, and alluvial fans, and evaporites in the large salt lakes. Perry et al. (1962) have described the land systems, geomorphology, geology, soils, and surface deposits in the Alice Springs area.

Quinlan (1962) has divided the Quaternary deposits into five categories which correspond approximately to those mapped in the Amadeus Basin:

1. *Terrace gravel* — formed during the Pleistocene period of erosion. The gravels cover bevelled surfaces of older rocks, and occur in strike valleys; the material has been derived from the valley walls.

2. *Evaporite and clay* — in basins of interval drainage. The salts have been concentrated by the evaporation of groundwater.

3. *Travertine, kunkar, calcrete, and alluvium* — around the edges of salt lakes. The travertine, kunkar, and calcrete have been formed by evaporation of groundwater. Travertine has also been precipitated from groundwater in alluvium and sand in low-lying areas.

4. *Aeolian sand* — ancient and active longitudinal dunes and redistributed sand. The sand is now generally fixed by vegetation. The greatest concentrations of dunes are in the Simpson and Gibson Deserts at the eastern and western ends of the basin.

5. *Recent sediments* — superficial soil, creek alluvium, and alluvial fans. The soils are strongly weathered and leached, and include red clayey sand and subordinate yellow earth. There are also extensive areas of shallow skeletal soils and some alluvial soils. Calcareous earths are associated with basic rocks or alluvium. Black soils are not common.

Sand dunes and sand plains are widespread. In the west, on the eastern fringe of the Gibson Desert, the trend of the dunes is east-west. Around the larger ranges, complex braided dunes are common, and the trend varies considerably because of the influence of the high strike ridges on the prevailing winds. Around Lake Amadeus and in the central part of the basin, dunes are less common and are comparatively poorly defined. They trend southwest.

In the east, in the Simpson Desert, well defined longitudinal dunes trending south-southeast are common. The eastern faces of the dunes are commonly steeper than the western slopes. The parallel red dunes average about 50 feet high; they are about 500 yards apart and are separated by flat sandy swales. Small areas of bare sand occur on the unstable crests. An area of unstable bare dunes occurs to the east of the Finke River about 10 miles west-northwest of Finke township. They have an irregular pattern, but crescent-shaped crests are common (Pl. 31, fig. 2). The sand has been derived from the underlying friable De Souza Sandstone and the wide flat bed of the Finke River. An unusual type of dune is found on the lateritized rock platforms about 25 miles east of Finke. The dunes are wide and composed of unstable sand; they have a braided pattern but are heaped into a well defined ribbon (Pl. 32, fig. 1). They are widely separated, and the intervening rock platforms are practically bare. Long, nearly symmetrical longitudinal dunes (Pl. 32, fig. 2) predominate in the Simpson Desert.

Evaporite deposits are found in most of the large salt lakes. They include Lakes Macdonald, Hopkins, Anec, Orantjugurr, Amadeus, and Neale, and a chain of salt pans trending eastwards from Lake Amadeus for about 140 miles. The evaporites consist mainly of halite, with some chlorides and sulphates of calcium and magnesium. The thin surface crust consists predominantly of halite, but the underlying layers are composed mainly of large crystals of gypsum and dark sand and silt saturated with brine.

The recent history of the area has been summarized by Perry et al. (1962). A deep weathering profile developed in the Tertiary, and was later dissected. The presence in the southeast of 300-foot mesas, capped by deep weathering products, indicates the degree of dissection initiated by crustal warping in the Lake Eyre Basin. To the west and northwest, the Tertiary plain was altered mainly at higher levels, accompanied by erosion and extensive deposition in the lowlands. The system of internal drainage, initiated at this stage, suggests an arid phase, characterized by the formation of dunes.

When the climate became wetter, incision of the drainage was resumed in places, and alluvial fans and flood-plains were formed. The Finke River is the only stream which has maintained its flow beyond the basin; all the other rivers die out within the basin.

STRUCTURE*

Introductory Review

The structural map at 1:1,000,000 scale (Pl. 41) and the cross-sections on the 1:500,000 geological maps (Pls 45, 46) show the major structural features to be explained.

Regional anticlinoria separate the Amadeus Basin from the Ngalia Basin, Georgina Basin, and Officer Basin. The Amadeus Basin is a downwarped area lying between the anticlinoria.

Nappe structures, involving both basement rocks and cover sedimentary rocks, occur on the southwestern, northern, and northeastern margins of the Amadeus Basin (Pl. 41). All the nappes front towards the basin. The largest, the Petermann Ranges Nappe on the southwest margin, extends at least 200 miles in an east-west direction and its middle limb is overturned and overthrust for 30 miles or more across the strike. In the north and northeast the nappes are smaller. Their middle limbs are overturned and overthrust for 8 to 15 miles across the strike, and in the Arltunga and Ormiston Nappe Complexes, two nappes are piled one on the other.

The sedimentary rocks in the Amadeus Basin are strongly folded; their deformation is of the Jura or Appalachian type. There are two major unconformities: a folded unconformity between late Proterozoic and Cambrian sedimentary rocks proves that there were at least two periods of folding, and another between the folded Devono-Carboniferous(?) sedimentary rocks and flat-lying Permian and Mesozoic sedimentary rocks suggests that the later folding was of Carboniferous(?) age.

The late Proterozoic folds in the south (Pl. 41) are poorly exposed and therefore their geometry and mutual relations over much of the area are unknown. Generally only close or tight canoe-shaped synclines with flat plunges are preserved. Steep dips and overturning occur in some areas. Many of the folds in Western Australia were formed in the late Proterozoic. Strike-slip faults occur in the sedimentary rocks of this area, but practically no faults have been mapped in the Northern Territory probably because of the poor outcrop. Forman (1966c) gave evidence to suggest that these folds formed over a décollement within the Bitter Springs Formation during northwards tectonic transport.

The Carboniferous(?) folds are well exposed in the north. There are numerous folds of great regularity and length (Pl. 41), several of which can be traced for 150 miles. The folding style ranges from gentle to closed; the folds may be symmetrical, asymmetrical, or overturned. The interlimb angle of the folds (Ramsay, 1967, p. 349) is usually more acute (Pl. 11, fig. 1; Pl. 15, fig. 1) than that of the synclinal troughs, which are typically box-shaped or gentle. The structure becomes more complex deeper in the anticlinal cores, where crumpling of strata, faulting, and thrusting are common. Many folds have a core of isoclinally folded Bitter Springs Formation, and a number have a core of highly sheared or brecciated gypsum (Pl. 36, fig. 2; Pl. 37, fig. 1) with large included blocks of carbonate rock. The gypsum mass commonly intrudes the deepest strata in the anticlinal core. At several localities gypsum also intrudes Palaeozoic strata (Pl. 41; Pl. 37, fig. 2).

*Some of the concepts expressed here were first developed in an unpublished Ph.D. thesis by D. J. F. (Forman, 1968a, unpubl.).

The Heavitree Quartzite is not exposed in the core of any of the anticlines, and it is clear that the folding of the sediments above the Bitter Springs Formation does not extend downwards to the Heavitree Quartzite or basement rocks. This conclusion is supported by the results of structural interpretation, seismic profiling (Froelich & Krieg, 1969), and aeromagnetic and gravity interpretation, which have largely confirmed the theory of décollement in the Bitter Springs Formation that was first proposed in 1962 (Wells et al., 1965).

There are two planes of décollement or detachment in the northeastern part of the basin, one in the Bitter Springs Formation and the other in the Chandler Limestone just above the Arumbera Sandstone. The sedimentary strata have been folded over both surfaces, and the thrust plane connecting the lower and upper décollements is itself folded and imbricated (Pl. 41; Figs 48, 49, 50). The folds over the lower décollement surface have a different amplitude (8000-10,000 ft) from those over the upper surface (2000-4000 ft). This is related to the depth of folding (Billings, 1954, p. 60).

The wavelength of the folds is variable. Adjacent to the northern (Frontispiece) and southern margins of the basin there are large broad synclines. The subsidiary folds in the synclines have a wavelength of about 12 miles. In the centre of the basin the wavelength ranges from 6 to 14 miles.

The position of the décollements within the Bitter Springs Formation and Chandler Limestone have not been mapped. It is assumed, however, that they follow the evaporite beds which are present in both formations. The décollement thrusts can only be recognized in regions where the Bitter Springs Formation or Chandler Limestone have been thrust over younger rocks. The thrusts pass upwards from the lower to the upper décollement, and may there be dissipated by folding and imbricate thrusting over the evaporite beds in the Chandler Limestone.

This type of structure is developed in the core of the Hi Jinx Anticline (Pl. 41; Fig. 51), which has developed independently of the basement cropping out nearby to the east. The sedimentary rocks within the anticline have been thrust from the north so that near the crest of the fold the Bitter Springs Formation lies above the Arumbera Sandstone. In the southern flank of the fold however, the succession has not been disturbed, but the Arumbera Sandstone has been 'boudinaged' (Wulff, 1960, unpubl.). The boudinaging of the Arumbera Sandstone suggests that the thrust continues in the Chandler Limestone above, and it can be also shown that a thrust (or décollement) must be present in the Bitter Springs Formation below because the Heavitree Quartzite has been stripped off the underlying Arunta Complex at two localities and doubled up farther along the strike (Fig. 51).

Thrusting of this type occurs at least at four other localities. Two of these are interpreted on Plate 41 as windows: one in the Mount Burrell Anticlinorium (Fig. 49), and the other farther northeast between Phillipson Pound and Camel Flat Syncline (Pl. 41; Fig. 48). The thrusts exposed in the Mount Burrell Anticlinorium are entirely within the Pertatataka Formation. The Bitter Springs Formation is thrust over the Arumbera Sandstone in the other window. The Bitter Springs Formation is also thrust over the Arumbera Sandstone between the Fergusson and Gaylad Synclines and latitude 24°S. The manner in which these thrusts are connected is not known, but one interpretation is given on Plate 41. All the interpretations suggest that the Bitter Springs Formation has been thrust from the north over a large area of the Arumbera Sandstone and that several thrusts are involved.

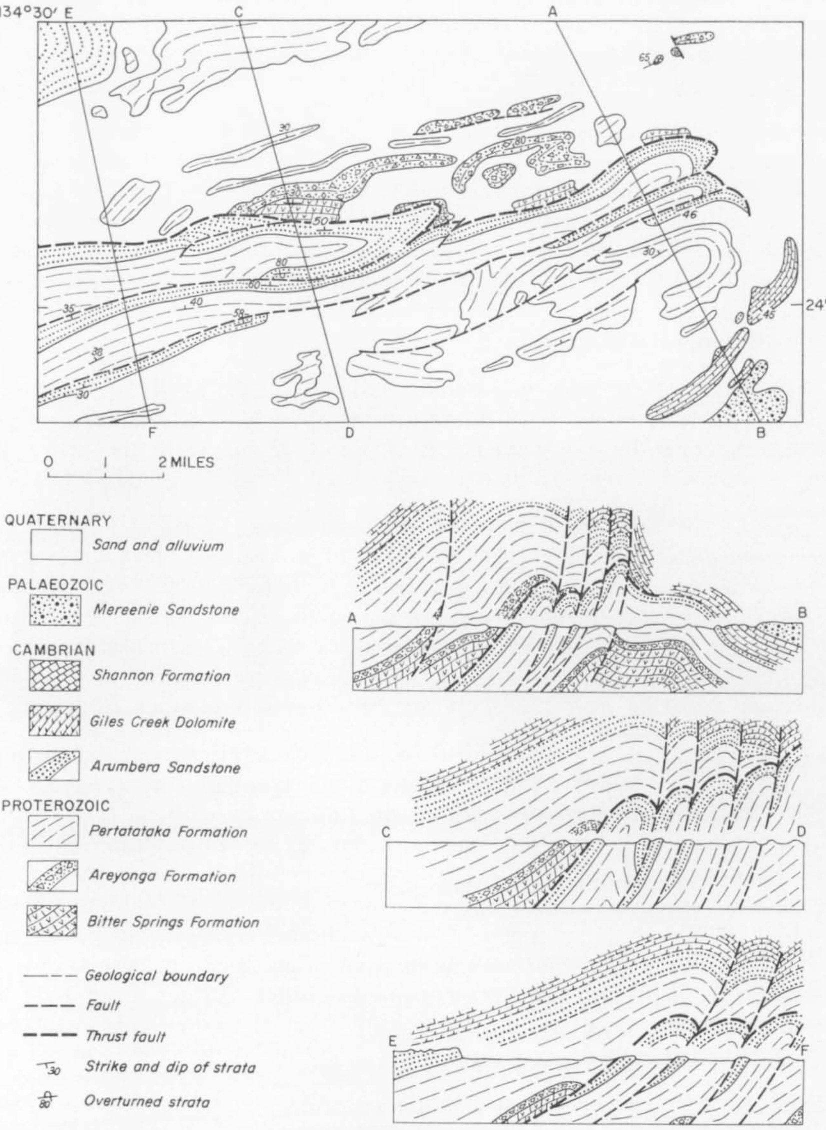


Fig. 48. Imbricate structure and folded thrust fault, 50 miles south-southeast of Alice Springs. (After Wells et al., 1967).

The fourth area lies on the northwest side of the Ross River Syncline (Pl. 41). Here the décollement in the Bitter Springs Formation passes up into the overlying strata to the top of the Arumbera Sandstone. The extent of the Arumbera Sandstone down dip below the thrust is unknown. The geometry of the thrusts can be interpreted in four ways. The first (Fig. 52a) is used to explain the structure at the northwestern side of the Ross River Syncline. The second (Fig. 52b) differs from the first only in scale, and is believed by the author to be typical of the structure developed in the northeastern Amadeus Basin. Thrusting upwards from

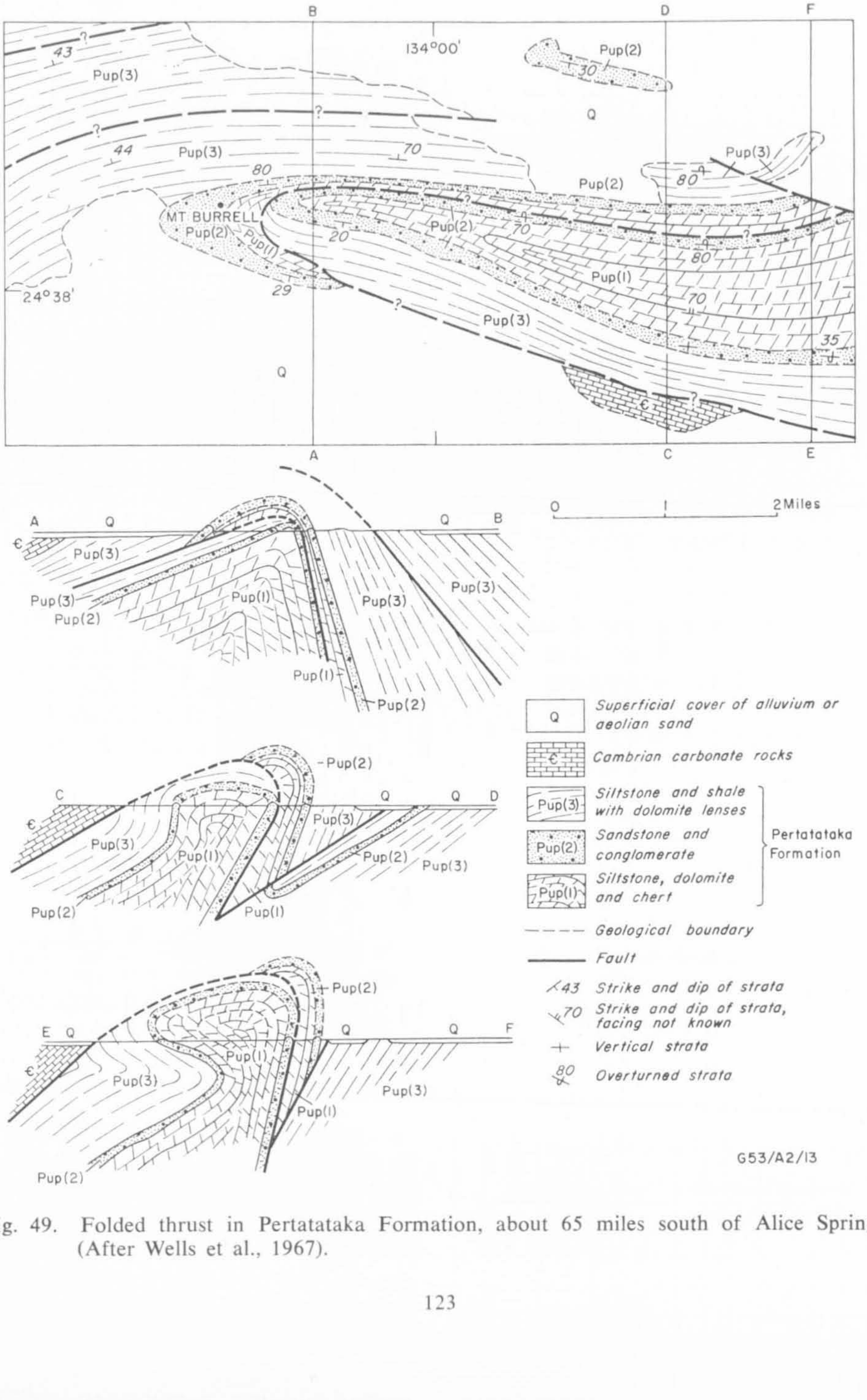


Fig. 49. Folded thrust in Pertatataka Formation, about 65 miles south of Alice Springs. (After Wells et al., 1967).

the décollement in the Bitter Springs Formation into the décollement in the Todd River Dolomite is visible at a number of localities, including the Hi Jinx Anticline and Todd River Anticline (Fig. 52c). Thrusting also occurs downwards from the upper to the lower décollement at a number of localities, possibly including Goyder Pass (Fig. 52b; Pl. 38, fig. 1).

The third interpretation of the thrust pattern in the northeast has been made by A. J. Stewart (pers. comm., see also pp. 151-3). This interpretation (Fig. 52c) differs from the preceding interpretation in one important aspect, namely that the thrust having passed from the lower to the upper décollement then continues onwards up to ground level. Distinct thrust nappe sheets may be formed by this method. I do not agree with this interpretation because it implies that the thrusts break through from the upper décollement to the top of the succession in the Hi Jinx and Todd River Anticlines, whereas Figures 51 and 53 show that the thrust does not pass up above the Todd River Dolomite in these structures.

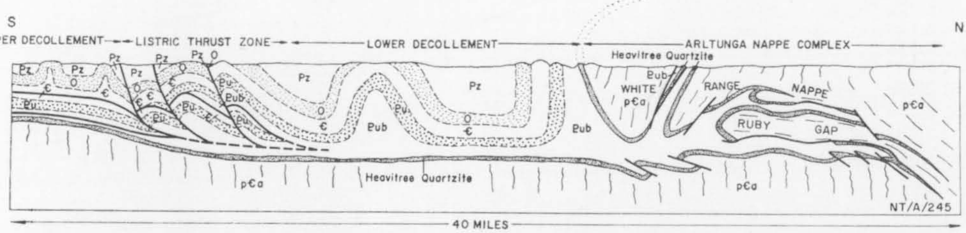


Fig. 50. Composite cross-section across northeastern part of Amadeus Basin.

The fourth type of thrust structure associated with décollement occurs in the cores of anticlines in the Gardiner Range, and possibly in the Illamurta Structure (Pl. 41; Fig. 52d). In these areas there appears to be little or no movement along the upper décollement surface perhaps because the Cambrian salt does not extend this far to the west. The thrusts dip to the south and are confined to the anticlinal cores, and die out laterally and vertically.

Faults occur within the anticlinoria of basement rocks, but the direction and sense of displacement is unknown. Where the faults cut the Proterozoic strata on the northeastern and northwestern margins of the basin displacements of several thousands of feet are suspected. Major thrusts occur north and south of the Amadeus Basin. Where thrusts in the basement rocks intersect the Proterozoic strata thrust nappes are formed which are dissipated in the incompetent Bitter Springs Formation.

Table 2 is based on the distribution and mutual relations of the folds, faults, unconformities, and patterns of sedimentation. It shows the times at which the area was deformed with reference to the standard time scale and to the stratigraphic succession in the Amadeus Basin.

The terms 'orogeny', 'event', 'movement', and 'tectonism' have been used in many senses, but the term orogeny is here applied only to those events that caused basement reactivation. Unconformity and facies changes in sedimentary basins result from orogeny, but are not used to prove it. The term movement is here

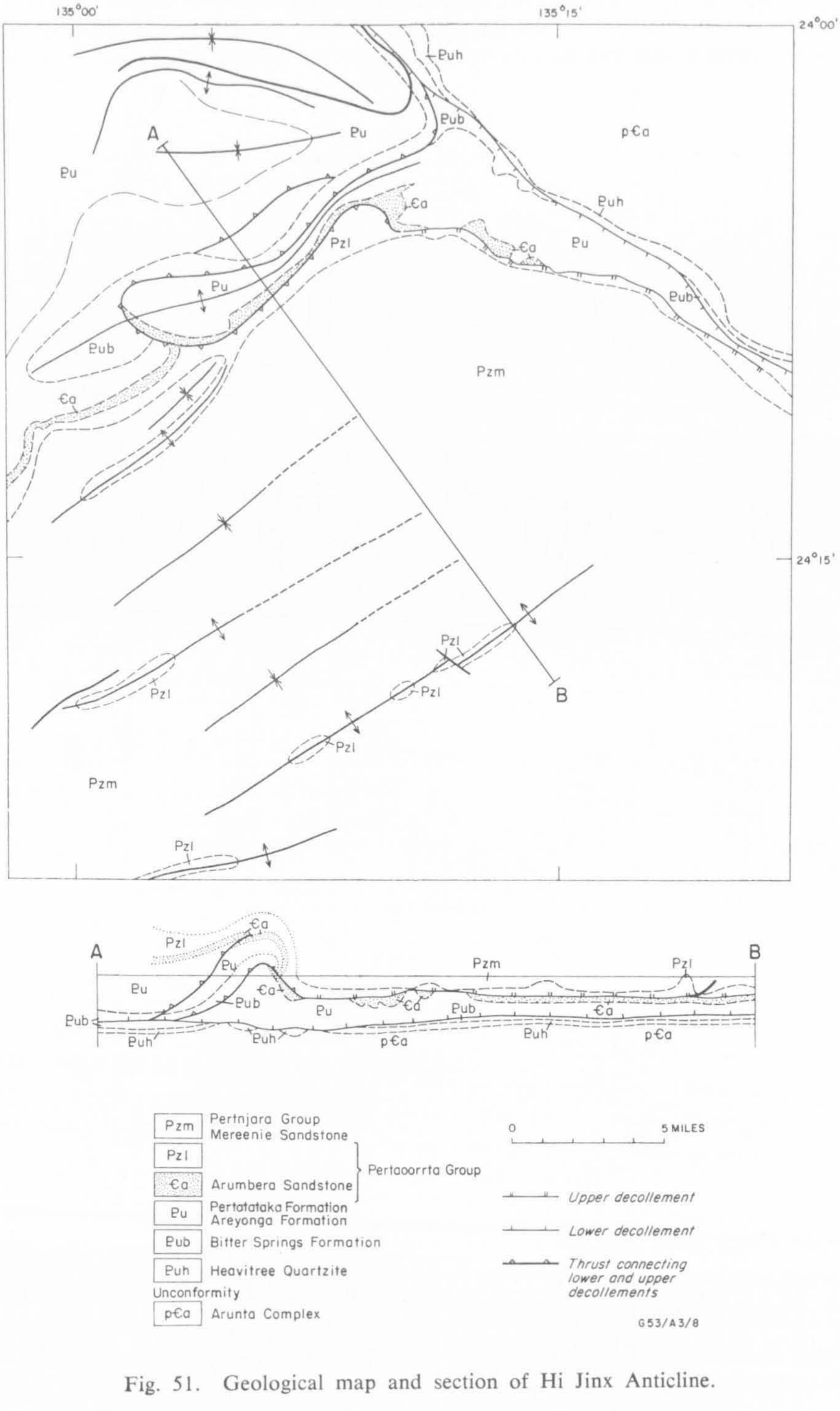


Fig. 51. Geological map and section of Hi Jinx Anticline.

used as a name for the events that resulted in disconformity or unconformity within the sedimentary succession, but for which basement reactivation cannot be proved. It seems certain that the basement was folded or faulted during the movements,

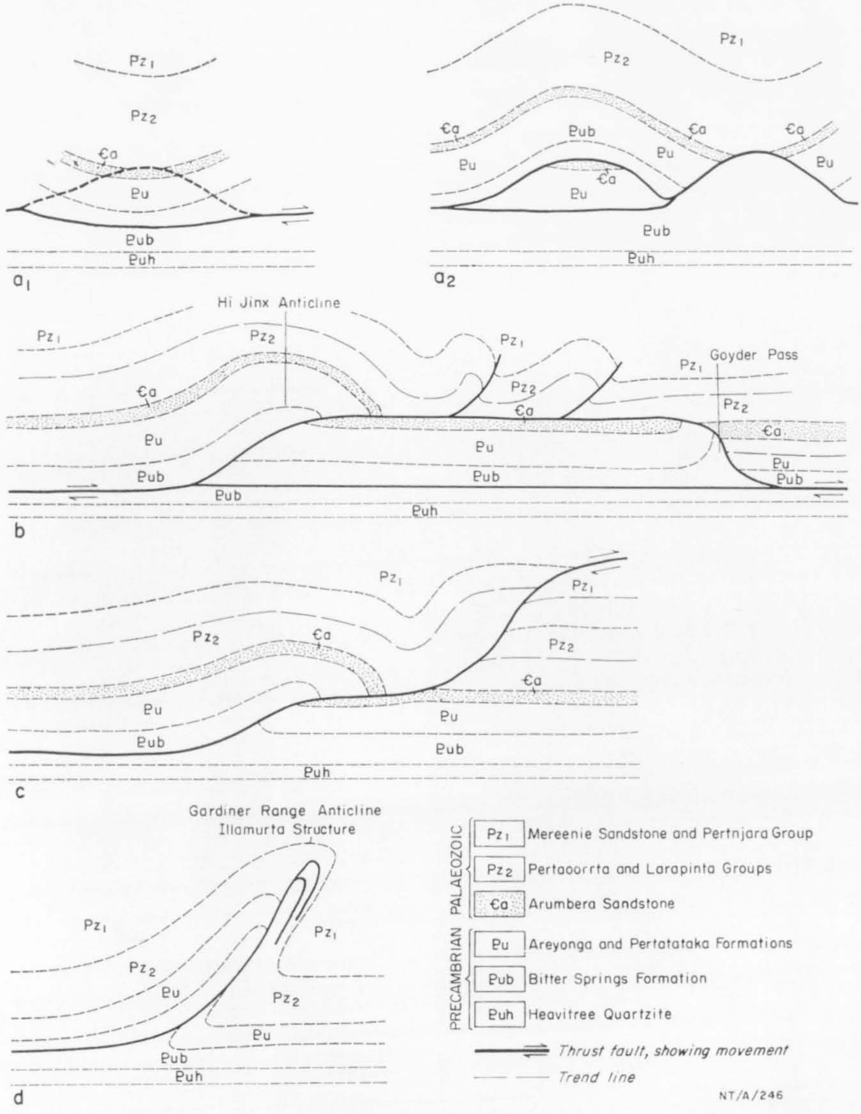


Fig. 52. Thrust fault interpretations.

but the intensity or nature of the diastrophism, cannot be judged. The terms deformation, tectonism, and event are used throughout the text to describe diastrophism of an unknown nature.

Some of the orogenies and movements of central Australia are correlated with diastrophism in the Tasman Geosyncline in eastern Australia (see pp. 141-2).

Record of Diastrophism Recorded by Unconformity in Precambrian Basement Rocks

A complex record of diastrophism is preserved in the basement rocks to the north and south of the Amadeus Basin. The two areas are discussed separately as the times of deformation in each area cannot be correlated.

Northern Margin

Arunta Orogeny

The Arunta Orogeny (Forman et al., 1967) was defined as the orogeny that folded and metamorphosed the Arunta Complex before the Heavitree Quartzite was deposited. It is redefined as the orogeny that folded and metamorphosed the

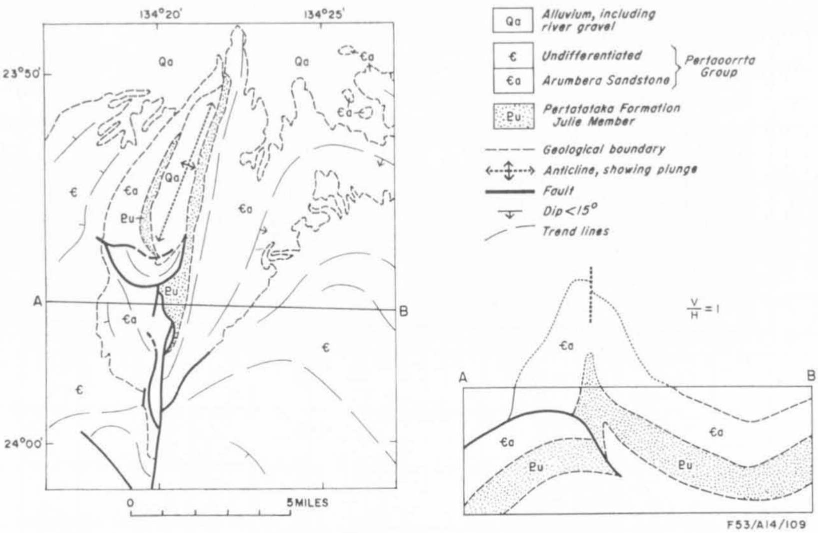


Fig. 53. Geological map and section of Todd River Anticline.

Arunta Complex before the Warramunga Group was deposited in the Georgina Basin region. During the orogeny the Arunta Complex was isoclinally folded about north-south axes (Pl. 33, fig. 1) and was tightly refolded about steeply dipping east-west axes (Pl. 33, fig. 2). Metamorphic minerals such as staurolite, kyanite, and sillimanite grew parallel to the axes of the north-south folds. This lineation was refolded, but not everywhere destroyed, by the development of the east-west folds. The map pattern resulting from this deformation in the Alice Springs Sheet area (see Fig. 54) is typical of Ramsay's 'type (2)' pattern (Ramsay, 1967, p. 525).

The age of the orogeny is unknown, but isotopic dates on granite in the margin of the Georgina Basin suggest it is older than 1800 m.y.

Unnamed Diastrophisms

The unconformities above and below the volcanics and little altered metasediments of the northwestern Amadeus Basin are evidence of at least two further periods of diastrophism. The low-grade metamorphism of these units and of mafic dykes within the Arunta Complex demonstrates that metamorphism accompanied at least one of these events.

Southern Margin

The oldest event that can be recognized is the unnamed orogenetic event that folded and metamorphosed the Musgrave-Mann complex and Olia Gneiss. The style and pattern of deformation are similar to that of the Arunta Orogeny, but it appears to be a younger event, about 1400 m.y. ago.

TABLE 2. SUMMARY OF DIASTROPHIC EVENTS PRODUCING UNCONFORMITY IN PRECAMBRIAN AND PALAEOZOIC ROCKS OF CENTRAL AUSTRALIA

TIME SCALE	ROCK UNIT (AMADEUS BASIN)	DIASTROPHIC EVENT	CRITERIA FOR RECOGNITION (INCLUDES UNCONFORMITY) BASEMENT REACTIVATION	REGIONAL METAMORPHISM	CHANGE OF LITHOLOGY
	Flat-lying Permian				
CARBONIFEROUS		Alice Springs Orogeny	Yes	Yes	
	Pertnjara Group				
DEVONIAN		Pertnjara Movement			Yes
SILURIAN	Mereenie Sandstone				
		Rodingan Movement			Yes
ORDOVICIAN	Larapinta Group				
CAMBRIAN	Pertaoorrta Group				
		Petermann Ranges Orogeny	Yes	Yes	Yes
PROTEROZOIC	Pertatataka Formation				
		Souths Range Movement			
	Areyonga Formation				
		Areyonga Movement			Yes
	Bitter Springs Formation				
	Heavitree Quartzite				
YOUNGER PRECAMBRIAN BASEMENT	Younger volcanics	Several unnamed diastrophisms	Folding, igneous intrusion, and metamorphism		
	Mixed volcanics				
	Hatches Creek Group				
	Warramunga Group				
		Arunta Orogeny	Yes	Yes	
OLDER PRECAMBRIAN BASEMENT	Arunta Complex				

NT/A/265

The Mount Harris Basalt in the west overlies the Olia Gneiss or granite unconformably (Horwitz & Daniels, 1967). The Bloods Range Beds were then laid down with possible unconformity on the Mount Harris Basalt, and were folded and eroded before the Proterozoic Dean Quartzite was deposited.

Record of Diastrophism Recorded by Unconformity in Late Precambrian to Carboniferous(?) Sedimentary Rocks

Diastrophism is recorded by unconformity in the Proterozoic to Carboniferous(?) sedimentary rocks of the Amadeus Basin. The diastrophisms are listed in Table 1 and classified according to the type of evidence used to recognize them.

Areyonga Movement

The Areyonga Movement is defined as the regional tectonic event that produced unconformity between the Areyonga Formation and Bitter Springs Formation in the northeast. The unconformity is not severe, as the Bitter Springs Formation was never completely eroded away. Throughout the remainder of the basin the Bitter Springs Formation is overlain with probable disconformity by the Areyonga Formation, or one of its correlatives. Erosion of the Bitter Springs Formation is proved by the presence of phenoclasts derived from the Bitter Springs Formation within the overlying clastic units. The Areyonga Movement uplifted areas in the south of the Amadeus Basin, and thus provided a source for sediment (Fig. 10). The diastrophism also uplifted areas north of the Amadeus Basin.

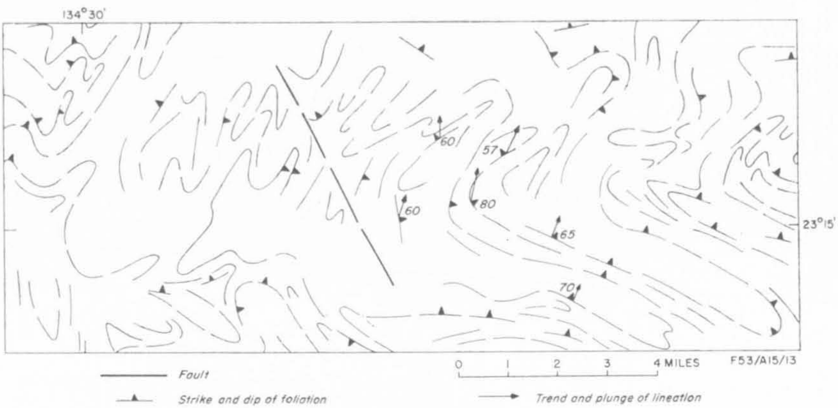


Fig. 54. Structural pattern of Arunta Complex, 60 miles east-northeast of Alice Springs.

Souths Range Movement

The name Souths Range Movement is suggested for the diastrophism that produced angular unconformity between the Winnall and Inindia Beds in the south. The movement provided a southerly source for the clastic sequence: Sir Frederick Conglomerate, Ellis Sandstone, Maurice Formation, and Winnall Beds (Fig. 11). The unconformity is clearly exposed at Souths Range in the Bloods Range Sheet area (Forman, 1966a). The diastrophism also resulted in uplift of source areas to the north of the Amadeus Basin (Fig. 11).

Petermann Ranges Orogeny

The term Petermann Ranges Orogeny was introduced by Forman (1966c) for the isoclinal and recumbent folding and metamorphism of the Mount Harris Basalt, Bloods Range Beds, Dean Quartzite, and Pinyinna Beds, and the tight folding of the Winnall and Inindia Beds. The Olia Gneiss and possibly the Musgrave-Mann complex were retrogressively metamorphosed during the orogeny.

The folding was most severe on the southwest margin of the basin (Fig. 55; Pl. 41), where at least one large-scale recumbent anticline and syncline developed in the rocks below the Bitter Springs Formation (= Pinyinna Beds, Forman, 1966c). The Dean Quartzite and Pinyinna Beds were metamorphosed within the nappe. Pyrophyllite (G. H. Berryman, pers. comm.), pyrophyllite-kyanite, kyanite, and

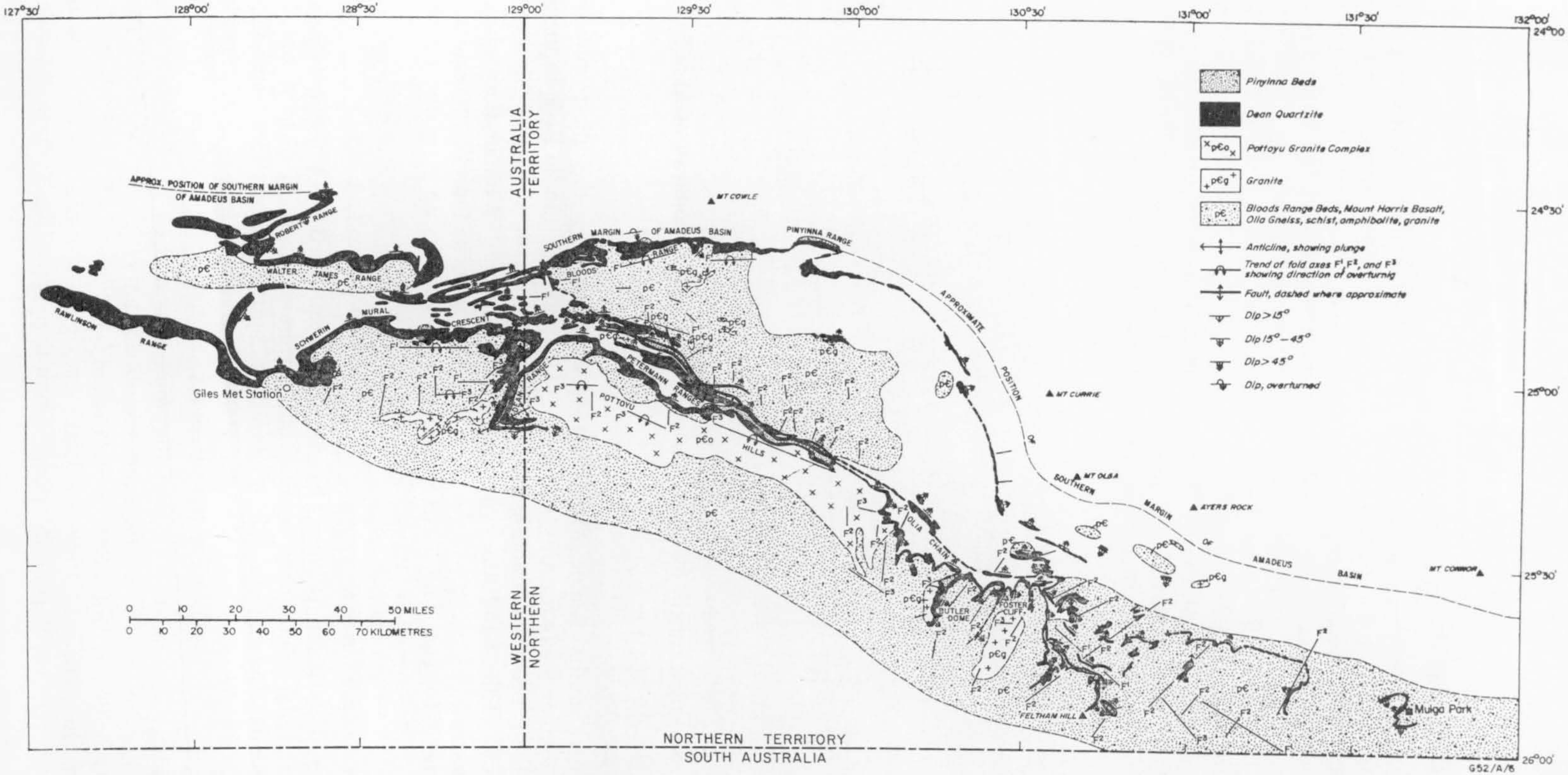


Fig. 55. Structural interpretation of southwest margin of Amadeus Basin. (After Forman, 1966a).

kyanite-staurolite have been identified in the Dean Quartzite in different areas, with the grade of metamorphism increasing from the front of the nappe towards the root zone. At the same time, the more competent Winnall Beds and Inindia Beds were detached from the underlying strata and slid northwards on a décollement surface in the Bitter Springs Formation. The folding is of the Jura type, and is believed to have occurred late in the Precambrian or early in the Cambrian (about 600 m.y. ago). The reality of the recumbent fold and the style of deformation within the recumbent fold area are discussed in Forman (1966c).

It is probable that a large basement thrust nappe, the Woodroffe Thrust first recognized by geologists of the South Australian Mines Department, developed at this time. Granulite facies Musgrave-Mann complex rocks are thrust over low to moderate-grade Olia Gneiss and probably the Dean Quartzite and Pinyinna Beds. These relationships are to be described further in another report.

At least three foldings affected the Dean Quartzite, Pinyinna Beds, and the underlying younger and older Precambrian basement rocks during the Petermann Ranges Orogeny. These are represented diagrammatically as F^1, F^2, and F^3 on Figures 55 and 56. The first(?) folding F^1 produced minor isoclinal and recumbent folds which are thought to be sympathetic to a major regional recumbent fold structure represented diagrammatically in Figure 55. The second(?) folding F^2 (Pl. 34, fig. 1) produced folds of the same style as F^1, but oriented generally at right angles to them, as shown in Figure 55. The shortening of the crust, indicated by the F^1 folds, was probably accompanied by movement of material at right angles to produce the F^2 folds. The schistosity which is parallel to the axial planes of these two sets of folds may be common to both. Lineations parallel the plunge of each set of fold axes. At many localities kyanite occurs parallel to the F^2 fold axes, and is refolded about the F^3 axes.

The last folding to affect the area is known as F^3 on Figures 55 and 56. The axial planes of the minor folds strike east-southeast, parallel to the trend of the ranges, and they generally dip south at a moderate to steep angle. The folds are closed or tight, and the northern limbs of anticlines are overturned. Many of the folds in the more schistose members are strain-slip folds. Axial-plane schistosity and lineation are developed within many of the folds.

An earlier interpretation that the Olia Gneiss was progressively metamorphosed and granite emplaced during the Petermann Ranges Orogeny (Forman, 1966c) has been disproved by detailed mapping which demonstrated that the Dean Quartzite overlies gneiss, granite, and mafic dykes unconformably. The gneiss was metamorphosed a second time during the Petermann Ranges Orogeny and metamorphic minerals including kyanite, viridine, garnet, and amphiboles developed.

The Petermann Ranges Orogeny may be dated by unconformity (Pl. 41) and change of type of sediment within the Amadeus Basin (Figs 13, 17). Thick conglomerate and arkose (the Mount Currie Conglomerate and the Ayers Rock arkose; Pl. 9; Pl. 10, fig. 1) occur on the southwestern margin of the basin. The age of these formations is unknown except that the conglomerate unconformably overlies Proterozoic sediments and contains phenoclasts of the Winnall Beds. Farther north a major unconformity (Pl. 41) is known between late Proterozoic sediments (the Winnall Beds) and a cross-bedded pebbly sandstone of Cambrian age (the Cleland Sandstone). The conglomerate in the Cleland Sandstone contains cobbles of metamorphosed Dean Quartzite.

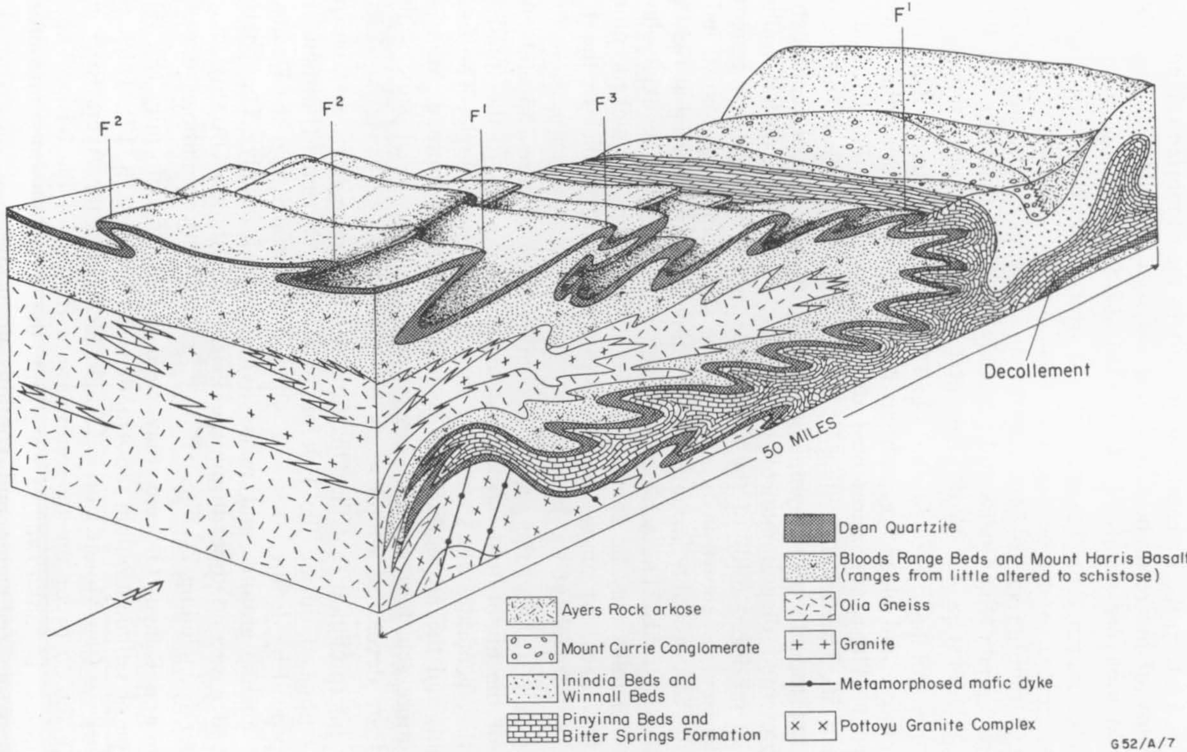


Fig. 56. Diagrammatic interpretation of structure in Petermann Ranges Nappe and south-western part of Amadeus Basin. (After Forman, 1966a). The upper limb of the anticline is eroded and the folds are shown there just for convenience.

The same unconformity (Pl. 11, fig. 1) is preserved beneath the Lower Cambrian Quandong Conglomerate, Eninta Sandstone, and Arumbera Sandstone (Pl. 41; Fig. 18). The red-beds represent the first influx of sediment that followed the orogeny and fix its age as very latest Precambrian. Biotite and microcline from the reactivated basement rocks in the southwest have been isotopically dated by the Rb/Sr method at about 600 m.y. (P. J. Leggo, pers. comm.).

The Petermann Ranges Nappe has not been traced along to the southeastern margin, but there is an unconformity farther north within the sediments of the Amadeus Basin and it is known that its intensity diminishes away from the margin. The Woodroffe Thrust may extend along the southeastern margin of the basin, thrusting Musgrave-Mann complex rocks over the sedimentary rocks in the Amadeus Basin (Pl. 41). The presence of Cambrian molasse adjacent to the southeastern margin (Fig. 17) suggests that strong diastrophism occurred there during the orogeny. The mafic dykes in the southeast are unmetamorphosed, so this area was not metamorphosed at the time of the Petermann Ranges Orogeny.

Palaeozoic Diastrophism

Rodingan Movement

The name Rodingan Movement (Table 1) is given by Cook (this Bulletin, p. 89) to the uplift that preceded deposition of the Mereenie Sandstone. The unconformity that indicates the movement is developed in the northern and northeastern parts of the basin. It is generally low angle and cuts down section to the northeast (Wells et al., 1967).

The uplift probably drove the sea from the whole area late in the Ordovician. Gentle folds developed in the northeast during the movement. The movement affected a large area but did not produce any immature types of sediment. Erosion of the Larapinta Group in the northeast was accompanied by continental sedimentation of the clean well sorted Mereenie Sandstone (Fig. 34). Subsequently the area within the basin, which had been folded and eroded, was covered by the Mereenie Sandstone.

Pertnjara Movement

The name Pertnjara Movement is used for the Middle to Upper Devonian event that produced unconformity between the Mereenie Sandstone and the Pertnjara Group in the central-northern and northeastern part of the basin. The movement does not appear to have affected the central to southwestern part of the basin, where the Parke Siltstone is apparently conformable on the Mereenie Sandstone. It is possible that the unconformity lies above the Parke Siltstone and not beneath it.

The sedimentary rocks in the north and northeast may have been gently folded or thrust during the Pertnjara Movement. This folding and subsequent erosion produced unconformity beneath the Pertnjara Group in parts of the Hermannsburg and Mount Liebig Sheet areas (Pl. 22). The regional unconformity in the northeast is most probably the result of widespread upwarping and erosion. The Pertnjara Movement initiated the deposition of the continental Parke Siltstone, and the deposition of the Hermannsburg Sandstone and Brewer Conglomerate was also preceded by crustal movements to the north and northeast. These movements of Upper Devonian or Carboniferous age are unnamed as their effects on the sedimentary rocks are not well known.

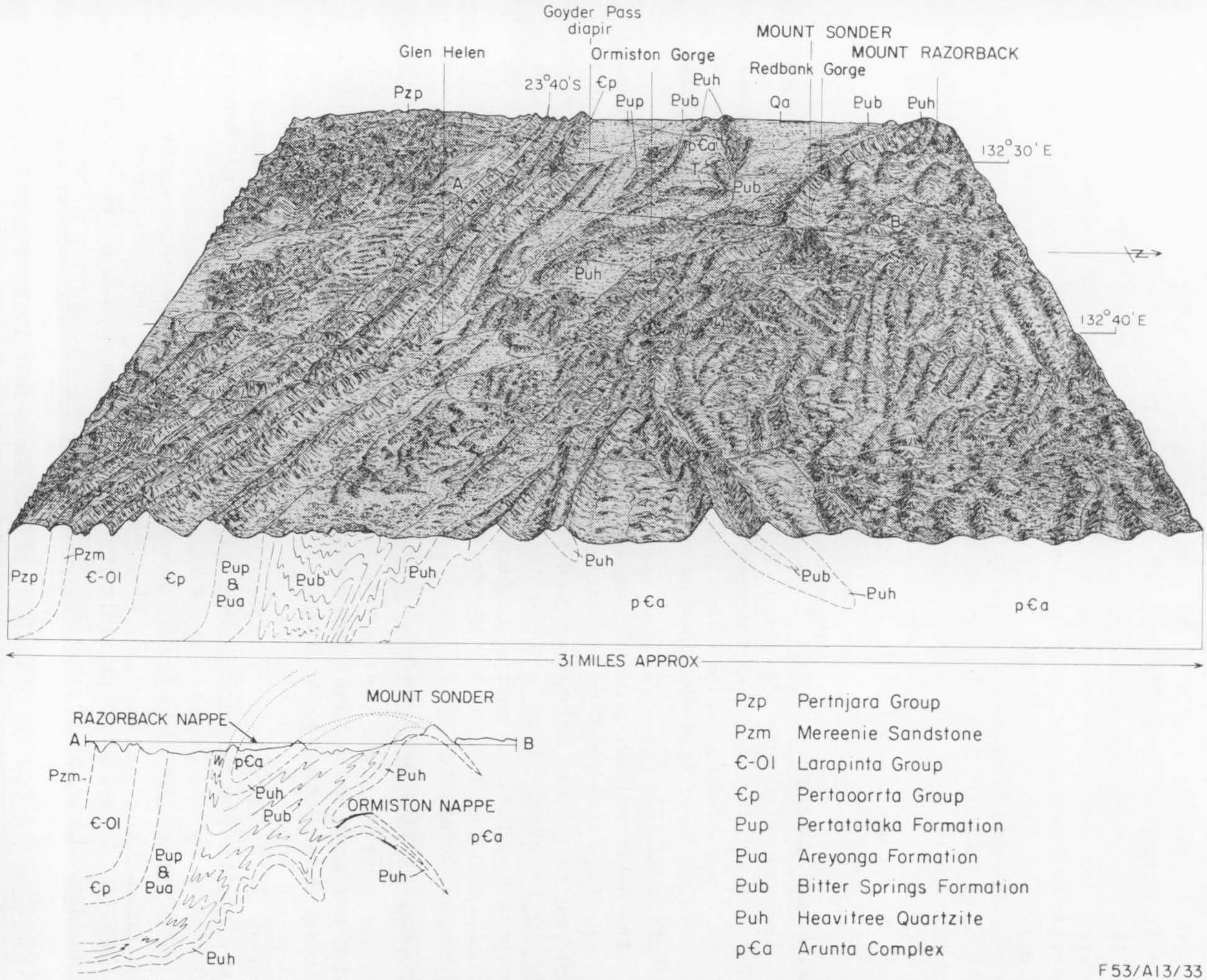


Fig. 57. Ormiston Nappe Complex on northern margin of Amadeus Basin. (After Forman & Milligan, 1967).

Alice Springs Orogeny

The name Alice Springs Orogeny (Forman, 1966c; Forman et al., 1967) was applied to the event that resulted in the deposition and subsequent deformation of the Pertnjara Group. It is redefined as the event during which the Pertnjara Group in the Amadeus Basin was folded, either late in the Devonian or in the Carboniferous.

The Ormiston (Pl. 34, fig. 2) and the Arltunga Nappe Complexes and the Blatherskite Nappe (Stewart, 1967) developed on the northern margin during the orogeny (Fig. 57; Pl. 44). At the same time, the sediments above the Bitter Springs Formation were detached from the nappes and moved southwards over a major plane of tectonic transport within the Bitter Springs Formation ('Pub' in Fig. 50). Another décollement surface or plane of detachment developed in the Cambrian sediments during this movement, and in places the sediments above the lower décollement surface were thrust higher up in the succession, and came to rest on the upper décollement surface (Fig. 50). The décollement was accompanied by tight isoclinal folding, mainly over the deeper décollement surface. The nappe complexes are described in Forman et al. (1967). The décollement, thrusting, and folding of the sediments of the Amadeus Basin are described in Wells et al. (1967).

In the nappe complexes the Heavitree Quartzite and Bitter Springs Formation are sandwiched within the Arunta Complex. The sandwiches mark the bottoms of the nappes. Within them the Heavitree Quartzite and Bitter Springs Formation are highly deformed (Pl. 35, fig. 1), and the Heavitree Quartzite at the base may be overlain by Bitter Springs Formtaion which is in turn overlain by Heavitree Quartzite (Pl. 35, fig. 2). The Arunta Complex above the sandwich is intensely mylonitized; the intensity of mylonitization diminishes according to the distance from the top of the sandwich. The reversal of stratigraphy in some of the sandwiches suggests overfolding, but in others the sandwich consists of Heavitree Quartzite overlain by Bitter Springs Formation, again followed by Heavitree Quartzite overlain by Bitter Springs Formation. These relationships suggest overthrusting.

The Arltunga Nappe Complex has been drawn as a structural relief diagram (Pl. 44) showing the surface of contact between the Arunta Complex and the Heavitree Quartzite or Bitter Springs Formation. The relative importance of overfolding or overthrusting in the complex is still uncertain, but a programme of more detailed mapping was begun in 1969. Preliminary results suggest the nappes at Ruby Gap and Trephina Gorge are the result of overthrusting from the north, while the White Range Nappe contains extensive overturned areas suggesting an origin by a combination of recumbent folding and thrusting. A report on these detailed investigations is in preparation.

Overturning can be proved in places along the front of the nappes where shearing has not destroyed cross-bedding (Pl. 36, fig. 1) or oscillation ripple marks. Deeper in the nappes shearing and recrystallization are generally so advanced that sedimentary structures have been destroyed. However, there are several localities where the highly stretched basal conglomerate has been recognized in an overturned position.

The Arunta Complex has been retrogressively metamorphosed to the upper greenschist facies in the Arltunga Nappe Complex. Granulite facies rocks in the Arunta Complex directly north of the complex (Pl. 41) were probably uplifted during nappe formation.

The most striking feature developed during the Alice Springs Orogeny is the structure of the northern margin of the basin. The margin is defined by the unconformity between the Heavitree Quartzite and the Arunta Complex. Along the margin, over 300 miles long, the unconformity drops as much as 30,000 feet towards the south within a few miles. The structure is largely a monocline, but near the centre of the northern margin and at its eastern end, the Arunta Complex and the Heavitree Quartzite have been deformed into the nappe complexes. The Bitter Springs Formation is preserved in the nappes, but the younger, more competent, units are not. These sedimentary rocks now lie in the Amadeus Basin to the south, where they are folded and thrust over the décollement surfaces.

The age of the folding is either Upper Devonian or Carboniferous(?) as the Pertnjara Group contains Upper Devonian fossils near its base. Isotopic mineral ages of 367 to 420 m.y. have been obtained from within the Arunta Complex.

Diastrophism Without Unconformity

Epeirogenies or broad vertical movements of the crust are recorded in the sedimentary succession by overlap, offlap, disconformity, and facies change. It is axiomatic that these occurred continuously over a long period of time. Local vertical movements could also take place continuously over a long period of time. They can produce local overlap, offlap, disconformity, and facies change, but in particular they result in local thickening or thinning of the sedimentary succession. Cook (1966b, unpubl.; pers. comm.) has demonstrated that the Larapinta Group thins in the vicinity of the Illamurta Structure (Pl. 41). The Pertaoorrta Group, Mereenie Sandstone, and Parke Siltstone also thin, or appear to thin, and the regional unconformities of the Rodingan Movement and Pertnjara Movement are stronger in this area.

McNaughton et al. (1968) recognized stratigraphic thickening of late Proterozoic and early Cambrian sedimentary rocks near Goyder Pass, and thinning of the Larapinta Group and Mereenie Sandstone on the crest of the Goyder Pass 'Diapir' (Pl. 38, fig. 1; Fig. 64). They also recognized a locally developed erosion surface within the Pertaoorrta Group.

Local thinning (stratigraphical or structural?) of at least some units occurs near the Deering Fault and within the Gardiner Range Anticline; Seymour Range; and possibly near the Johnstone Hills Diapir (Pl. 37, fig. 2; Fig. 64) and Waterhouse Range Anticline.

Some of the thinning described in the Mereenie Sandstone and Pertnjara Group may be a reflection of buried topography following the Rodingan and Pertnjara Movements. Local thinning of the Larapinta Group and Pertaoorrta Group is less likely to reflect buried topography following a movement or orogeny, and more likely to be the result of continuous local vertical movement.

The nature of any prolonged structural growth that might have occurred is still unproven. Cook (1966b, unpubl.) thought the structural growth occurred as a result of folding and thrusting of the basement and diapirism of the Bitter Springs

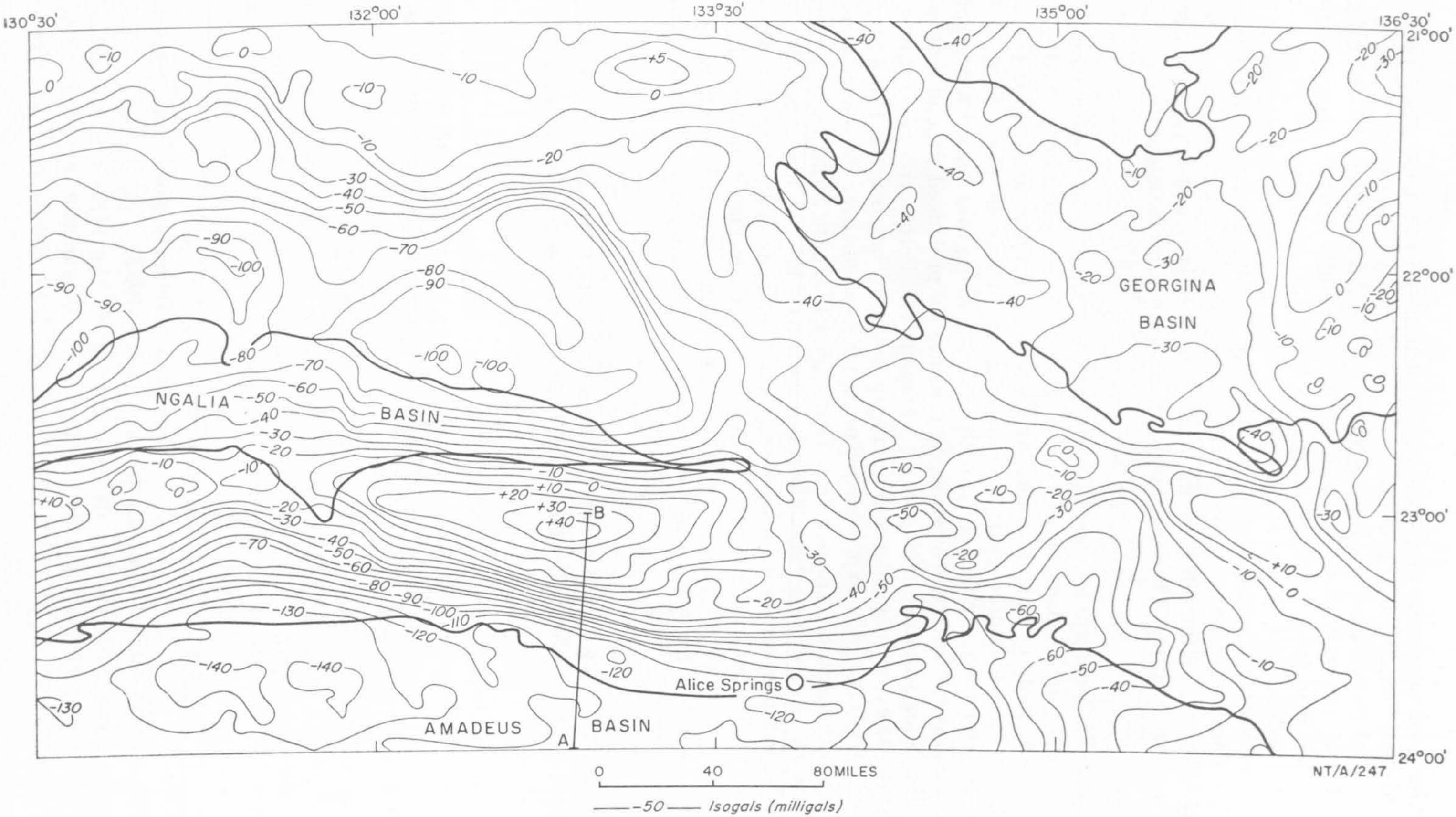


Fig. 58. Bouguer anomaly map. (From preliminary Bouguer anomaly maps prepared by the Geophysical Branch of the BMR).

Formation, and suggested that prolonged structural growth took place over an elongated zone trending north-northwest at a high angle to the trend of the folds produced later during the Alice Springs Orogeny. On the other hand, McNaughton et al. (1968) consider that the evidence for structural growth indicates that anticlines and diapirs in the northern part of the basin 'were initiated at an early stage in the sedimentary history of the basin and that they continued to grow as the result of salt flowage in response to sedimentary loading during late Proterozoic and early Palaeozoic sedimentation'. They believe that the structures so formed were accentuated and modified by the Rodingan, Pertnjara, and later movements, and by the Alice Springs Orogeny, but were not formed by these events.

Conclusions

Except where local stratigraphic thinning may be related to an obvious structural feature the case for local prolonged structural growth has not been proved. Even where local thinning of units is related to a structural feature, such as the Goyder Pass 'Diapir' or Illamurta Structure, thinning or thickening of units may be explained in other ways: either structurally, or by thinning over buried topography on an unconformity surface. The strongest evidence for prolonged structural growth during deposition is local thinning in the Larapinta and Pertaoorrta Groups, which were otherwise evenly deposited during a long period of broad vertical movement; this thinning is not easily explained by uneven deposition over an unconformity. In the best examples, the Goyder Pass 'Diapir' and Illamurta Structure, the trends of the structures are probably different from the trends of the anticlines and synclines developed discontinuously during the Rodingan and Pertnjara Movements, and Alice Springs Orogeny. Therefore I consider that if prolonged local structural growth occurred during deposition of the sedimentary rocks, the resultant structures were not the precursors of the structures developed during the movements and orogenies.

Relationship Between Surface Geological Structure and Subcrustal Structure—Rodingan Movement, Pertnjara Movement, and Alice Springs Orogeny

The surface structure revealed by geological mapping may be related to deformation of the crust and mantle as suggested by interpretation of the Bouguer anomaly map (Fig. 58). The relationship can be best demonstrated in the area between the Amadeus and Ngalia Basins.

Geophysical Evidence

Figure 58 and Plate 43 show a positive Bouguer anomaly parallel to, and north of, the Amadeus Basin. It is flanked to the north by a large negative Bouguer anomaly in the vicinity of the Ngalia Basin, and to the south by a large negative Bouguer anomaly in the Amadeus Basin. The Bouguer anomaly curve along A-B of Figure 58 is shown by the solid line at the top of Figure 59.

The hypotheses which have been advanced to explain regional linear gravity anomalies are summarized in Figure 60 (after Bean, 1953).

It can be shown that low-density sediments in the Amadeus Basin could not cause the Bouguer anomaly gradient to the north. If a density of 2.5 is chosen for the sediments of the Amadeus Basin, the resultant density contrast between basin sediments and upper crustal rock (density 2.7) should produce an anomaly difference of about 50 mgals over the northern margin of the basin (see calculated curve at top of Fig. 59), which is too small to explain the difference of 160 mgals observed between the anomalies to the north of the margin. It is clear that the 160-mgal difference in the anomalies cannot be explained by density contrast between the sediments in the basin and their basement rocks.

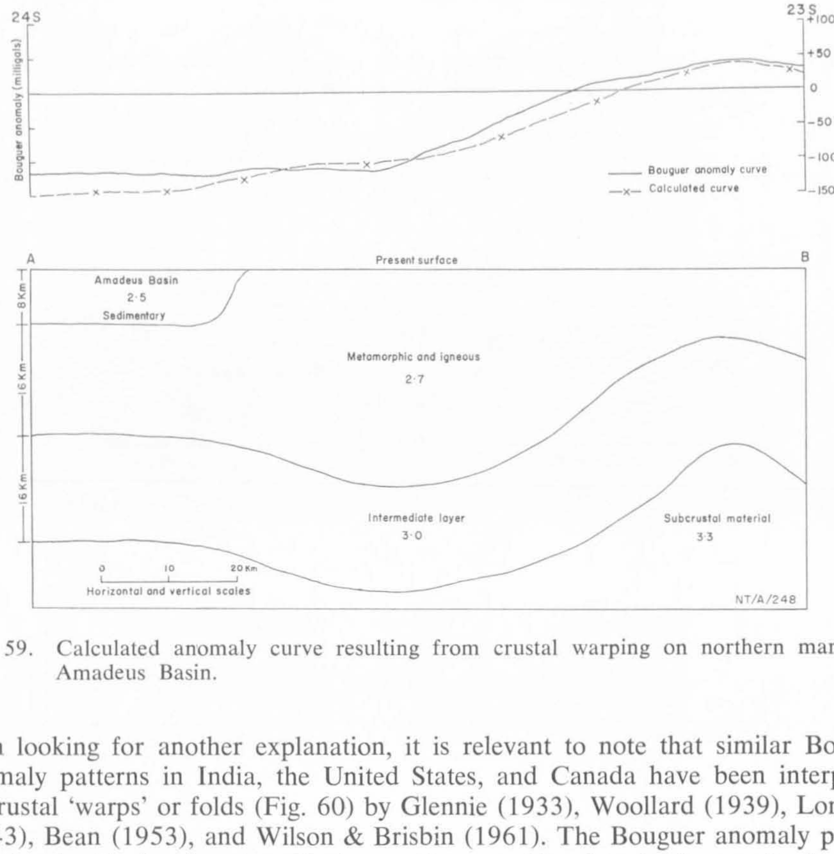


Fig. 59. Calculated anomaly curve resulting from crustal warping on northern margin of Amadeus Basin.

In looking for another explanation, it is relevant to note that similar Bouguer anomaly patterns in India, the United States, and Canada have been interpreted as crustal 'warps' or folds (Fig. 60) by Glennie (1933), Woollard (1939), Longwell (1943), Bean (1953), and Wilson & Brisbin (1961). The Bouguer anomaly pattern associated with the Amadeus Basin was first considered to be the result of crustal warping by Marshall & Narain (1954).

Figure 59 demonstrates the close fit between a calculated Bouguer anomaly curve assuming crustal folding (using a line integral method; Hubbert, 1948) and the actual Bouguer anomaly curve. A two-layer crustal model with the commonly accepted rock densities for these layers has been used. Of the many possible variations and combinations the section in the lower part of Figure 59 gives a calculated anomaly curve in fair agreement with the actual curve. This is therefore a logical explanation of the Bouguer anomaly profile shown in the upper part of Figure 59.

The distribution of granulite facies rocks in the Arunta Complex rocks along the northern margin (Pl. 41) suggests however that these lower crustal rocks may have been brought to the surface by major thrusts similar to the Woodroffe Thrust along the southern margin of the Amadeus Basin. This hypothesis will be further tested by field mapping in 1970 and deep seismic profiling of the crust and mantle in 1971.

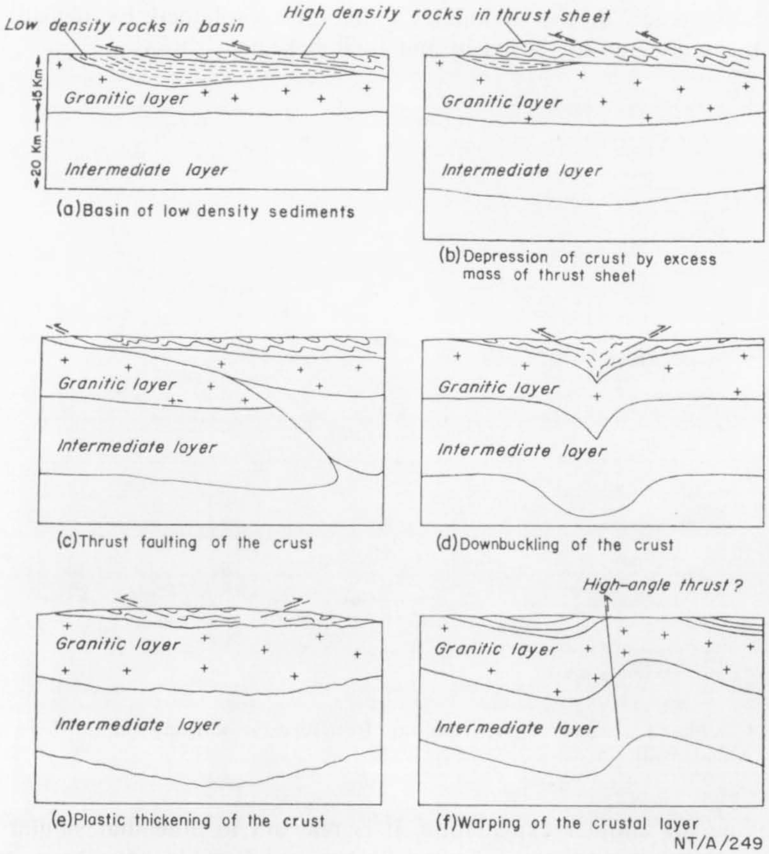


Fig. 60. Structural configuration of crust which would produce negative gravity anomaly strips. (After Bean, 1953).

Correlation of Surface Structure with the Suggested Crust-mantle Structure

It has been postulated that the Bouguer anomaly reflects folding or thrusting of the crust and mantle. The area north of the basin was uplifted, and the sediments in the basin were folded during the Rodingan Movement (late Ordovician/early Silurian), the Pertnjara Movement (early Upper Devonian), at several times during the Upper Devonian, and finally during the Alice Springs Orogeny in the Upper Devonian or Carboniferous. So far as it is known, the area has not been affected except by mild warping since. This suggests that the Bouguer anomaly is a fossil anomaly dating from the Devonian or Carboniferous.

If this is true then the lower crustal structure may be related to the surface structure in one of two ways: either the lower crustal structure was reflected at the surface by a nearly identical fold (Fig. 61a), which was then modified by gravity to the present geometry (Fig. 61a-d); or the lower crustal structure may be related to the surface structure if it passes upwards into a conjugate fold or thrust 'system' as in Figure 62.

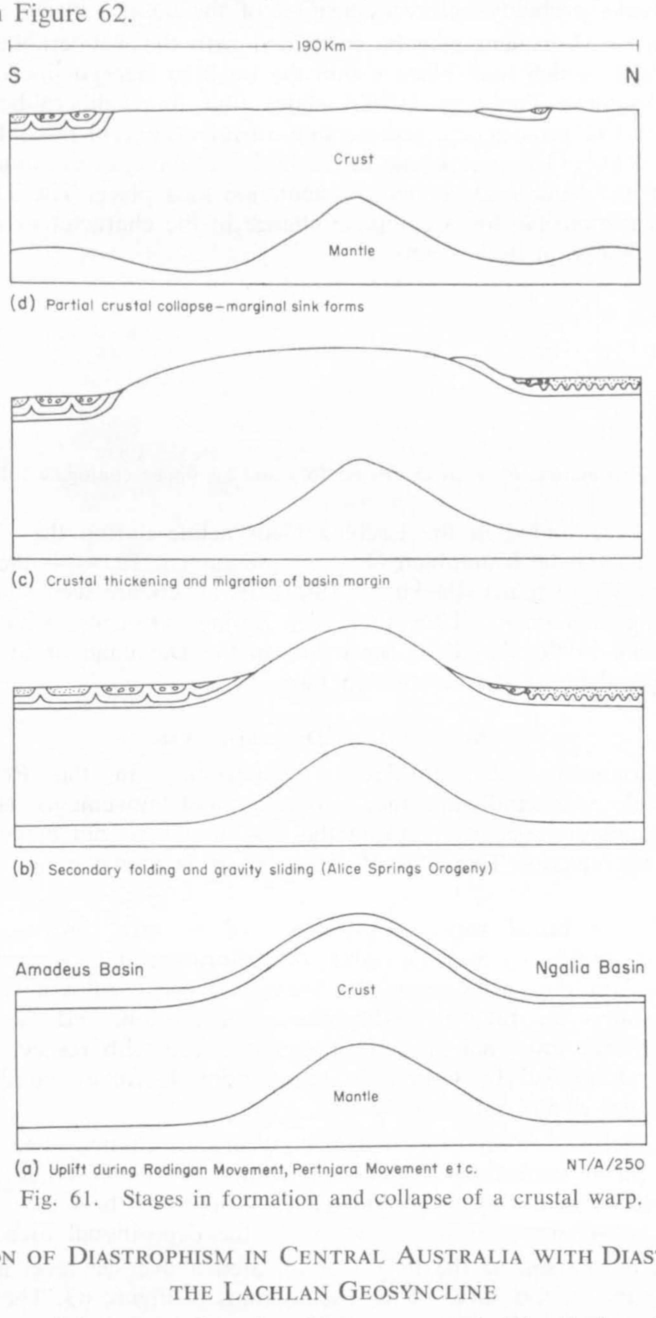


Fig. 61. Stages in formation and collapse of a crustal warp.

Correlation of Diastrophism in Central Australia with Diastrophism in the Lachlan Geosyncline

The Rodingan Movement, Pertnjara Movement, and Alice Springs Orogeny may be correlated with three diastrophic events in the Lachlan Geosyncline. The Rodingan Movement may be correlated with the Benambran Orogeny. The

Benambran Orogeny (David, 1950) is recognized in the Lachlan Geosyncline (Packham, 1960) of New South Wales and Victoria. The orogeny affected Upper Ordovician rocks probably before deposition of the basal Silurian sediments.

The Pertnjara Movement may be correlated with the Tabberabberan Orogeny (Andrews, 1938) which took place within the Lachlan Geosyncline of New South Wales and Victoria. Packham (1960) states that the Tabberabberan Orogeny marked the end of geosynclinal sedimentation over all except possibly the eastern edge of the Lachlan Geosyncline and the expulsion of the sea from much of the area where Lower and Middle Devonian sedimentation took place. The Tabberabberan Orogeny was responsible for a complete change in the character of sedimentation as well as a change in its location.

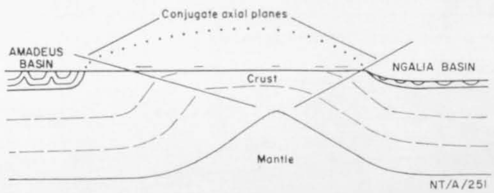


Fig. 62. Formation of a lower crustal fold and an upper conjugate fold system.

Sediments were folded in the Lachlan Geosyncline during the Carboniferous. This folding, called the Kanimblan Orogeny (Süssmilch, 1914), is the final folding in the Lachlan Geosyncline (Packham, 1960). Its effects are seen wherever Upper Devonian sediments occur. Thus the Alice Springs Orogeny, which folded the Pertnjara Group in the Amadeus Basin late in the Devonian or in the Carboniferous, is equivalent to the Kanimblan Orogeny.

Summary of Diastrophism

The diastrophism which produced unconformity in the Proterozoic or Palaeozoic rocks was subdivided into 'orogenies' and 'movements' (see Table 1). Basement reactivation occurred during the two orogenies, but cannot be proved for the four movements. This type of diastrophism is shown in the tectonograms of Figure 63.

Epeirogenies or broad vertical movements of the crust are recorded in the sedimentary succession by overlap, offlap, disconformity, and facies change. These are represented in the oscillograms of Figure 63. The oscillograms contain two curves: one shows the rates of sedimentation or erosion, and the other shows the position of the erosional or depositional interface with respect to sea level. They were first applied by Gurich in representing Devonian conditions in the central mountains of Poland (von Bubnoff, 1963).

The rate of erosion is controlled by tectonism and climate. The rate of sedimentation is partly dependent on the rate of erosion in the source area and the rate of subsidence in the depositional area. The depth of the sea is controlled by the rates of subsidence and sedimentation in the depositional area.

The depth of the sea or the height of an area above sea level is shown diagrammatically by the top curve of the oscillograms of Figure 63. These curves are drawn using von Bubnoff's (1963) method. The depth of the sea is estimated by the type of marine sedimentary rocks deposited—littoral, neritic, or bathyal. The height of an area above sea level can only be crudely estimated.

The rate of sedimentation, or erosion, is shown by the slope of the bottom curve in the oscillogram. The curve is obtained by plotting the cumulative thickness of the rocks deposited. Comparison of the upper and lower curves shows the history of broad vertical movements of the area. The disparity between the two curves shows whether subsidence was faster than sedimentation, or whether erosion or deposition was taking place.

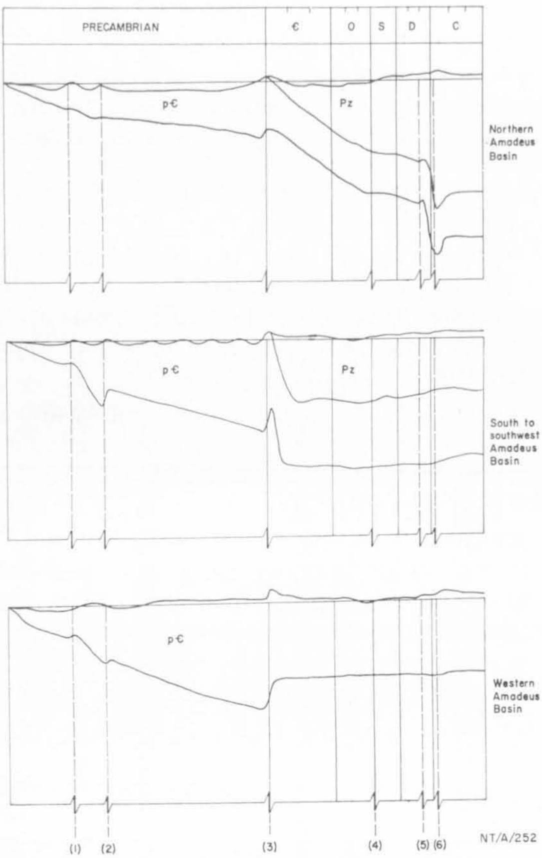


Fig. 63. Oscillograms and tectonograms for Proterozoic and Palaeozoic rocks in central Australia. (1, Areyonga Movement; 2, Souths Range Movement; 3, Petermann Ranges Orogeny; 4, Rodingan Movement; 5, Pertnjara Movement; 6, Alice Springs Orogeny).

Tectonograms beneath the oscillogram curves show the times at which the orogenies and movements occurred. The effects of these diastrophic disturbances are reflected in the oscillograms above.

Figure 63 summarizes the palaeotectonic history of the Amadeus Basin to the end of the Carboniferous. Sedimentation was almost continuous from Proterozoic to Palaeozoic in the north, but in the remainder of the basin, sedimentation was typically discontinuous.

The locus of thickest sedimentation shifted from the south in the Proterozoic to the north in the Palaeozoic. Two major cycles of sedimentation are evident in Figure 63. The older cycle began in the Proterozoic with mature orthoquartzite and carbonate rocks and finished with relatively immature fluviatile sandstone in the Cambrian. The second cycle commenced late in the Cambrian with mature marine sediment predominant, and ended in the Carboniferous(?) with immature continental sandstone. These cycles are related to the Petermann Ranges Orogeny and Alice Springs Orogeny. Smaller, local cycles are associated with the four movements that have been named.

The facies changes in the sedimentary succession are less distinct cycles related to broad vertical uplifts of the crust or distant orogenic events. These movements produced: (1) the initial Proterozoic transgression which crossed central Australia; (2) a major transgression during the latest Proterozoic; (3) a Lower to Middle Cambrian transgression; (4) a regression at the end of Middle Cambrian time that carried into the middle Upper Cambrian; (5) a late Upper Cambrian to Lower Ordovician marine transgression; (6) a possible early Middle Ordovician regression; (7) a transgression during the Middle Ordovician which may have continued into the Upper Ordovician; and (8) an Upper Ordovician regression. Epeirogenic uplift and downwarp probably occurred in the geanticlines and Amadeus Basin during the Silurian and Devonian.

The elongate downwarped area which crossed central Australia in the Proterozoic and the Palaeozoic was a continuation of the late Precambrian Adelaide Geosyncline and the Lower to Middle Palaeozoic Lachlan Geosyncline of New South Wales and Victoria.

The area has remained relatively stable since the Alice Springs Orogeny. Epeirogenic movements brought the area close to submergence in the Permian and Mesozoic, whereas its present general elevation ranges from less than 1000 to over 2000 feet above sea level.

Diastrophism of Extraterrestrial Origin

Gosses Bluff Astrobleme and the Henbury meteorite craters are of extraterrestrial origin.

Gosses Bluff Astrobleme

Gosses Bluff, 100 miles west of Alice Springs, is a circular range about 3 miles in diameter, in the centre of a disturbed zone about 12 miles in diameter. Early workers regarded Gosses Bluff as a diapiric structure with a core of salt (Prichard & Quinlan, 1962; McNaughton et al., 1968) or a core of igneous rock (Brunnschweiler, 1959). Crook & Cook (1966) regarded it as a cryptoexplosion structure; Cook taking the view that it was of cryptovolcanic origin and Crook that it was an astrobleme. Cook (1968) subsequently revised his opinion in support of the impact origin for the structure following further geological mapping and a drilling programme in 1966. Later geological work (Milton & Glikson, 1968, unpubl.) by Glikson (BMR) and Milton & Brett (USGS) supports the view that the disturbance in and around Gosses Bluff is an astrobleme.

Dietz (1967) regarded Gosses Bluff as an astrobleme and tentatively suggested that it originated by impact of a comet head with an effective diameter of 7000 feet. A considerable amount of gravity, seismic, radiometric, and magnetic work and drilling has also been carried out over the structure. The structure consists of steeply dipping and overturned plates of bedrock of Larapinta Group, Mereenie Sandstone, and Pertnjara Group bounded by fault zones and in many cases separated by crater breccia.

The most convincing evidence for the astrobleme origin advanced by the later workers has been: the discovery of shock-melted flow breccia, shock-induced lamellae in quartz, and shatter cones caused by shock fracturing (Crook & Cook, 1966), and the preferential orientation of the shatter cones (Dietz, 1967; Milton & Glikson, 1968, unpubl.).

Crook & Cook (1966) think the Gosses Bluff structure is probably of Mesozoic age.

Henbury Meteorite Craters

The Henbury meteorite craters lie 80 miles southwest of Alice Springs and 7 miles west-southwest of Henbury homestead. Many geologists have investigated the craters.

The following description is based on Cook (1968). Their existence has been known since at least 1922, though they were first described in detail by Alderman (1932). He mapped a total of 13 craters but later workers (Taylor & Kolbe, 1965) have suggested that the existence of crater 9 is doubtful. The area around the craters originally contained a considerable amount of meteoritic iron (octohedrite) (with individual fragments up to 170 lbs weight) and impact glass (fused country rock), but most of the material has now been removed. Rayner (1939) carried out a geophysical survey of the craters, but failed to find indications of a large body of iron in any.

The largest crater (No. 7), which is 600 feet in diameter and 40 to 50 feet deep, was mapped in some detail in 1963 by Milton & Michel (1965) and Milton (1968). They found that much of the crater rim is composed of overturned flaps of what were previously underlying sediments. Two of the craters (Nos 3 and 4) display rays and ray loops of ejecta similar in pattern to those around craters on the moon (Milton & Michel, 1965); this is the only terrestrial locality known to show such features. The age of the craters is uncertain; Alderman (1932) thinks that they are thousands of years old, but D. J. Milton (pers. comm.) has suggested that they may only be hundreds of years old.

Aeromagnetic and Radiometric Anomalies

The results of the aeromagnetic surveys conducted by Young & Shelley (1966, unpubl.), Geophysical Associates (1965, unpubl.) and Hartmann (1963, unpubl.) are shown in Plate 41. The survey by Young & Shelley covered most of the sedimentary basin; a radiometric survey was made concurrently. The following summary is based on their report.

The aeromagnetic surveys show that the deepest part of the basin lies along the northern border and that the maximum depth to magnetic basement is 38,000 feet below sea level in the area south of the western MacDonnell Ranges. The general shape of the basin, as interpreted from magnetic results, agrees with the gravity data, and many of the basement features correspond fairly closely.

The magnetic data show that the strong Bouguer anomaly gradients north and southwest of the basin are due to changes in the type of basement rocks. The trends of the magnetic anomalies are generally ill defined where the basement crops out.

The form of the basement in the Ooraminna and Gosses Bluff localities corresponds to the data obtained by seismic surveys. For comparison, the main results of the BMR seismic surveys (Turpie & Moss, 1963, unpubl.; Moss, 1964, 1966, both unpubl.) are as follows: the Palm Valley Anticline continues with depth and includes at least 18,000 feet of sediments. Three miles east of Hermannsburg Mission good reflections were obtained from depths in excess of 26,000 feet. Another survey indicates that the Missionary Plain syncline contains about 26,000 feet of sediment at the Gardiner Fault and about 33,000 feet of sediment 25 miles farther north. Gosses Bluff was shown to be essentially a structure in the sediments and not an expression of basement relief. The traverses from Deep Well siding across the Ooraminna Anticline show that the sediments attain a thickness of about 20,000 feet north and south of the fold axis, with about 16,000 feet over the crest.

The seismic survey in the Missionary Plain (Krieg & Campbell, 1965, unpubl.) shows that the maximum thickness of sediment above the Bitter Springs Formation northwest of Gosses Bluff is about 28,000 feet, so that the maximum depth to basement is about 31,000 feet below sea level. This depth and the form of the seismic contours agree well with the magnetic basement contours.

The depth to the top of the Bitter Springs Formation based on seismic structure contours decreases at a greater rate south of the Missionary Plain than the interpreted depths to magnetic basement. This may indicate a thickening of the Bitter Springs Formation across the axis of the Palm Valley Anticline.

In the southeast, the seismic traverses in the Kulgera Sheet area indicate a tectonically disturbed Proterozoic sequence with a maximum depth of 8000 feet to the deepest reflector near the top of the Bitter Springs Formation. The depth to magnetic basement is about 12,000 feet. The differences between the irregular surface of this lower seismic horizon and the simple form of the underlying magnetic basement suggest that salt from the Bitter Springs Formation may have formed diapiric structures on the south side of the reverse faults.

The interpretation of magnetic data shown in Plate 41 is quantitative in the sedimentary basin, but only qualitative where the basement crops out to the north and south. The probable error of the contours is about 10 percent. In the basement to the north and south, three zones of magnetic intensity have been defined (see Pl. 41).

In the north, the magnetic contours trend east-west, parallel to the surface geological trends. The east-west trend coincides roughly with the direction of the maximum gravity gradient to the north of the basin. The increase in magnetic disturbance north of this boundary is interpreted as evidence of an increase in the density of the basement rocks.

The Arltunga and Ormiston Nappe Complexes correspond with zones of low magnetic intensity, which suggests the presence of less dense acid rocks, and elsewhere similar anomalies correspond with large outcrops of granite. Intense magnetic disturbances are confined to the Alice Springs Sheet area, where mineralization is known in the basement rocks.

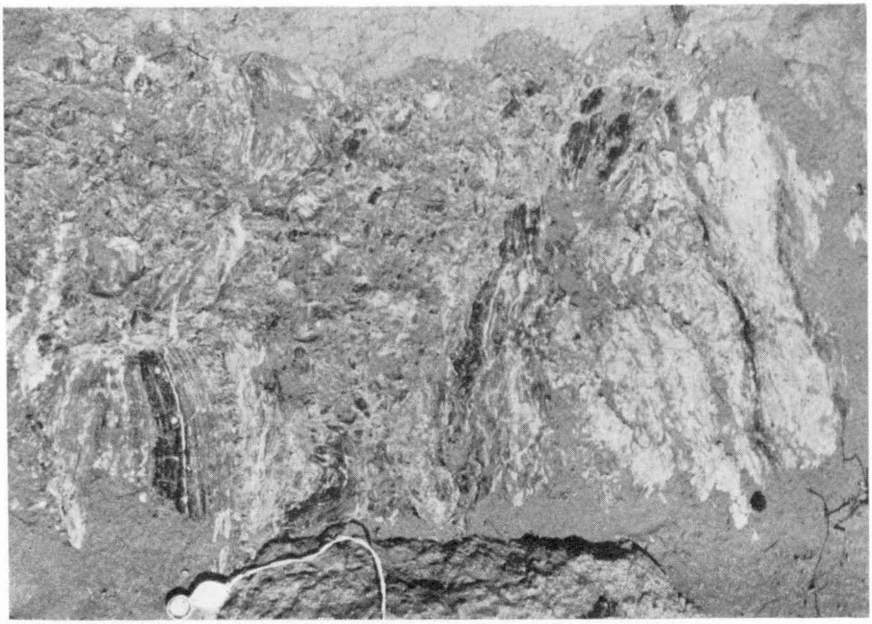


Plate 37, fig. 1. Banded and contorted gypsum of the Bitter Springs Formation in the core of an eroded anticline, southeastern part of the Mount Rennie Sheet area, about 35 miles south of the Ehrenberg Range.

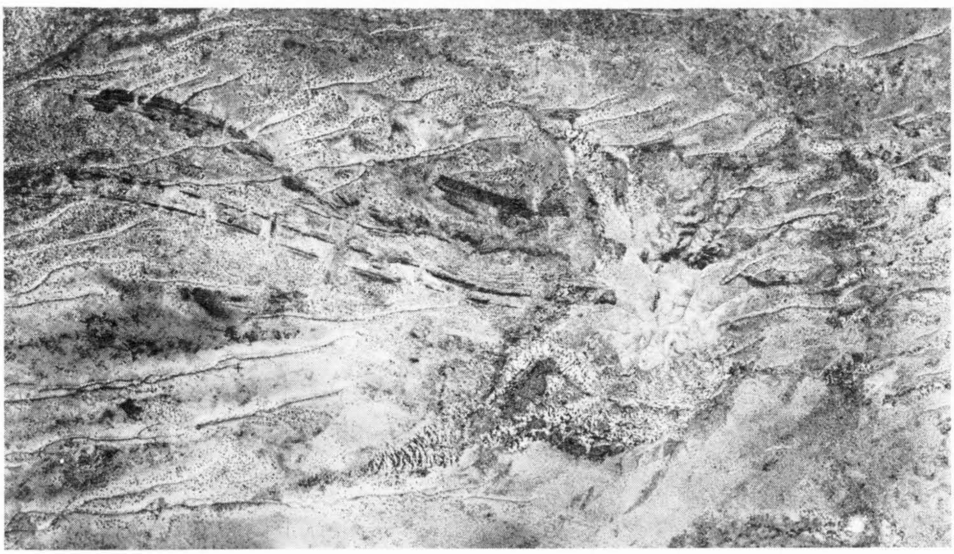


Plate 37, fig. 2. Johnstone Hill Diapir. The large mass of gypsum (light-toned rounded hills to the right of the centre of the photograph) intrudes the Palaeozoic and Proterozoic formations which crop out in strike ridges to the west and in the arcuate ridge to the south of the gypsum hills. The Bitter Springs Formation crops out at Johnstone Hill on the northern margin of the gypsum mass and as small patches within the gypsum.

Plate 38, fig. 1. Goyder Pass Diapir (from the west) in the western MacDonnell Ranges. The prominent ridge in the centre of the photograph is the Pacoota Sandstone.

Plate 38, fig. 2. Western nose of the Ooraminna Anticline with dark hills of the Arumbera Sandstone in the core.

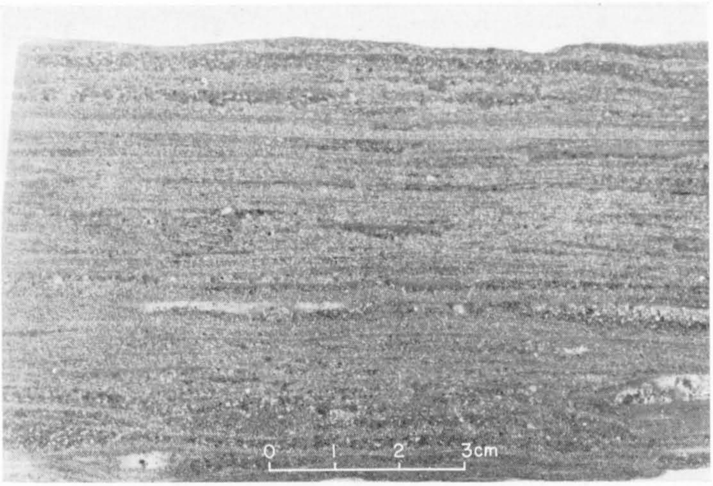


Plate 39, fig. 1. Banded phosphorite from the Areyonga Formation, about 8 miles north of Ringwood homestead, Alice Springs Sheet area. The rock is composed of thin bands of collophane and chert.

Plate 39, fig. 2. Pelletal phosphorite from the Stairway Sandstone. The rock is composed of dark phosphatic pellets set in a light-coloured sandy matrix.

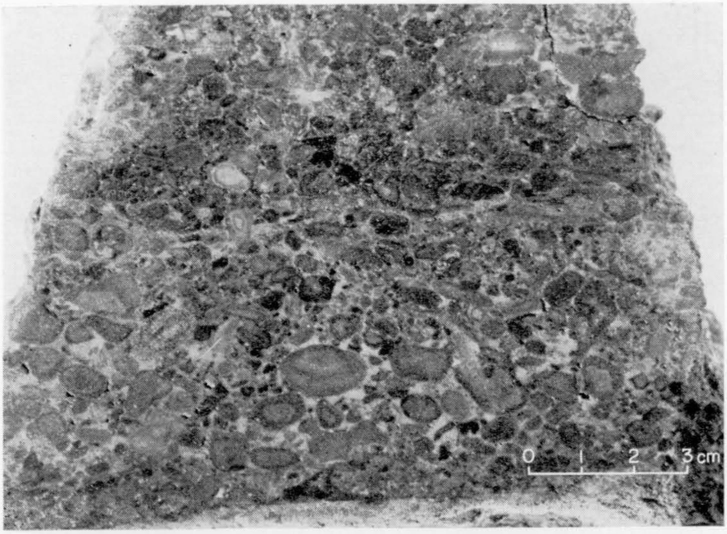


Plate 40, fig. 1. Pelletal phosphorite from the Stairway Sandstone. Some of the nodules have a concentric banded structure.

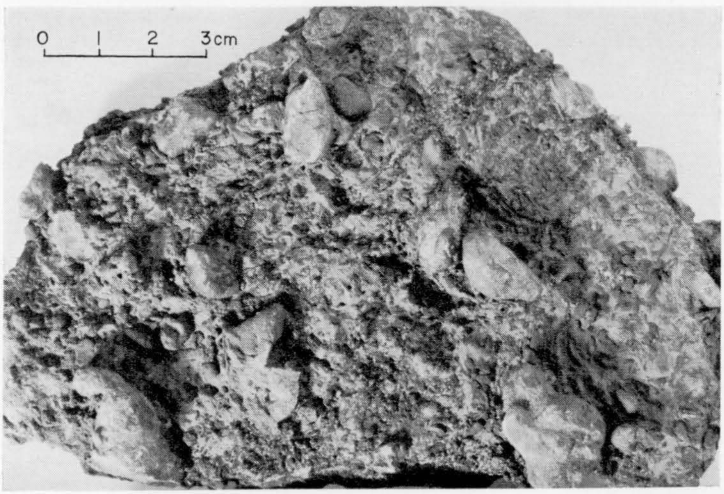


Plate 40, fig. 2. Phosphatic nodules from the Stairway Sandstone at Johnny Creek. The nodules have been partly weathered out of the limestone matrix.

The southern boundary of the basin is obscured by minor magnetic anomalies within the basin. The anomalies throughout the Ayers Rock Sheet area suggest the presence of near-surface dykes or volcanic rocks, but none are present in outcrop. The magnetic anomalies in the south, in the Petermann Ranges, Ayers Rock, and Kulgera Sheet areas, appear to have a north-south trend. The east-west trends in the Bloods Range Sheet area correspond to outcrops of the Mount Harris Basalt. In the basement outcrops the magnetic zones correlate with Bouguer anomalies.

The major basement susceptibility contrasts within the Amadeus Basin are oriented approximately north-south, in contrast to the trends in the exposed basement. They correspond with those indicated by the gravity anomalies and probably represent plutonic bodies in the Arunta Complex. The deepest part of the magnetic basement is collinear with the axis of thickest sedimentary sections as indicated by the gravity data.

The main features on the magnetic basement contour map (Pl. 41) are as follows:

L1. A basement depression with 29,000 feet of sediments; control is poor.

L2 & L3. The most prominent magnetic depressions along the axis of the deepest part of the basin, which coincide with regions of maximum thickness of sediments indicated by the Amadeus Gravity Depression. The greatest thicknesses of sediments are 35,000 feet at L2 and 37,000 at L3.

It is possible that the crystalline basement is shallower than the magnetic basement in the southeastern part of the Mount Rennie Sheet area, where 35,000 feet of sediment is indicated. The granite basement which crops out to the north shows little associated magnetic disturbance. Depth estimates at L3, south of the western MacDonnell Ranges, are in the range of 31,000 to 39,000 feet. The magnetic data do not reveal the minor basement uplift associated with Gosses Bluff as indicated by the seismic results (Moss, 1964, unpubl.).

L4. A maximum sedimentary thickness of 23,000 feet. The structure is confirmed by gravity and seismic data.

L5. Magnetic basement is 34,000 feet below sea level, but this is not supported by gravity data and is unreliable because of the few depth estimates.

L6. An extension of the depression L3; associated with a gravity low.

L7. Probably caused by a basement fault; a maximum of 23,000 feet of sediments.

L8. Corresponds to the western end of a gravity low; crystalline basement is within 10,000 feet of sea level.

L9. A basement low with relief of about 6000 feet superimposed on a northerly dipping basement surface. No corresponding features are indicated by the gravity data.

H1. An uplift in the magnetic basement surface with about 6000 feet of relief.

H2, H6, & H7. A major ridge in the magnetic basement. H7 has about 10,000 feet of relief; H6 is a small associated high; H2 separates the depressions at L2 and L3. The basement highs correlate well with gravity features. The lineaments produced by contours between L5 and L6, and H6 and H7, suggest major basement faulting.

H3. A west-trending ridge with 2000 feet of relief.

H4 & H5. Northeast-trending ridges with 4000 and 2000 feet of relief respectively.

H8. A minor east-west high with 2000 feet of relief.

H9. A prominent high in the magnetic basement with a relief of 6000 feet; there is little agreement with the gravity data.

H10. A high in the magnetic basement with 4000 feet of relief; good correlation with the Bouguer gravity contours.

H11. A magnetic basement feature with 2000 to 4000 feet of relief; it trends northwest and correlates with the eastern end of the Angas Downs Gravity Ridge; its continuation to the west corresponds approximately to the axis of this gravity feature. Hence the gravity ridge attributed to shallow Proterozoic rocks is probably also controlled by upwarping of the Precambrian basement.

H12. A minor basement feature which may be correlated with the extension of the Angas Downs Gravity Ridge.

G1. A discontinuity of the contours corresponding to a mapped fault. Estimated displacement is about 10,000 feet.

G2 & G3. The gradients show deepening basement to the north and west, and correlate with the gravity and seismic results.

G4. The gradient shows magnetic basement rising steeply to the southwest.

G5. A steep rise to the north in the magnetic gradient is probably due to upfaulting of the basement. Agrees with the gravity results.

G6. A Precambrian basement upwarp which probably delineates the south-eastern margin of the main area of thick sediments. No direct correlation with gravity data.

G7. The gradient is interpreted as evidence of a fault, and continues eastwards for a considerable distance.

A contour presentation of the radiometric data (Pl. 42) reveals a correlation between radiometric anomalies and outcrops of the Larapinta and Pertaoorrta Groups. Although no definite correlation has been established between gamma radiation and the phosphorites, a radiometric anomaly associated with the Johnny Creek Anticline suggests that it is one of the most promising areas for phosphate deposits.

In the west, the northern basement has a uniform radioactive mineral content, but the basement in the east is more radioactive. There is generally a correlation between high radioactivity and moderate to low magnetic disturbance. The abrupt change in magnetic basement coincident with a steep gravity gradient is also shown by the radiometric contours. The basement cropping out in the southwest shows two well defined belts of radiometric anomalies which correspond to zones of different magnetic susceptibility.

There are numerous anomalies over the sediments in the basin, particularly in the Lake Amadeus and Henbury Sheet areas, many of which are associated with outcrops of the Larapinta and Pertaoorrta Groups. Radiometric anomalies near the northern margin of the basin correspond with outcrops of the Brewer Conglomerate and are probably due to the high proportion of igneous rocks in the conglomerate.

Few samples of the phosphate-bearing Larapinta Group appear to be abnormally radioactive. The radioactivity of the shales in the Pertaoorrta Group, for example, appears to be greater when the gamma ray logs of both groups are compared on well logs. The anomaly associated with the Johnny Creek Anticline is the most significant, but the relationship between radioactivity and phosphate minerals is uncertain.

Summary

1. The agreement of the gravity and magnetic form of the basement suggests that in general the magnetic and crystalline basements are identical.

2. The absence of direct correlation between the individual magnetic anomalies and Bouguer anomalies supports this conclusion: the Bouguer anomalies are primarily dependent on the density contrast between the sediments and crystalline basement, whereas magnetic anomalies are produced by intrabasement susceptibility contrasts.

3. The magnetic trends in the basement beneath the basin differ from those in basement outcrops. The northerly trend beneath the basin may be due to susceptibility contrasts between crystalline rocks, and the more common easterly trend in outcrop may reflect tectonic activity associated with the development of the basin.

4. The rapid change in the depth to basement on the boundary of the basin masks the typical magnetic anomalies associated with the basement rocks.

5. The easterly magnetic trends in the southwest correlate with outcrops of the Mount Harris Basalt.

6. The presence of numerous magnetic anomalies in the southwest suggests the presence of volcanic rocks. Some of the anomalies are similar to those produced by dyke-like bodies.

7. The radiometric anomalies over the Pottoyu Hills indicate granitic rocks. The decrease in radioactivity and increase in magnetic disturbance over the basement rocks to the south, like the gravity data, suggest the presence of more basic rocks. Similar correlation between gravity, magnetic, and radiometric anomalies on the basement cropping out in the north suggests that the basement becomes more basic in composition to the north.

Décollement and Diapirism

Thick beds of evaporites are present in the Gillen Member of the Bitter Springs Formation and in the Lower Cambrian Chandler Limestone (Figs 70, 71). The distribution of gypsum and evaporites in both formations is shown on Figure 64. The Ooraminna No. 1 well, on the crest of the Ooraminna Anticline, penetrated over 130 feet of rock salt in the Bitter Springs Formation. About 150 feet of salt was also penetrated in the Bitter Springs Formation in both the Mount Charlotte No. 1 and Erldunda No. 1 wells, but the sections were incomplete. About 300 feet of Lower Cambrian salt was penetrated in Alice No. 1, about 650 feet in Mount Charlotte No. 1, and about 60 feet in Orange No. 1, all of which penetrated complete sequences of the Chandler Limestone. BMR No. 3 Alice Springs (Ringwood) (Fig. 67) penetrated about 850 feet of gypsum, anhydrite, siltstone, and dolomite (Stewart, 1969, unpubl.).

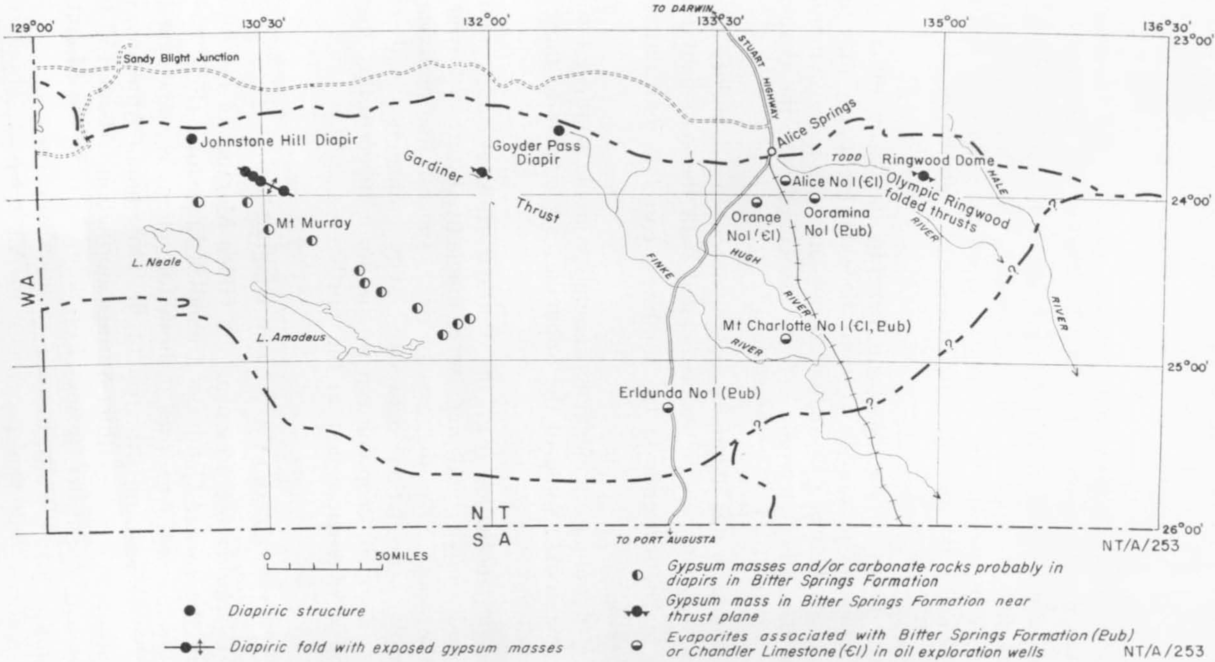


Fig. 64. Occurrences of gypsum, evaporites, and diapiric structures associated with Bitter Springs Formation and Chandler Limestone.

The known outcrops of gypsum (Pl. 36, fig. 2; Pl. 37, fig. 1) extend southeastwards from the Johnstone Hill Diapir (Pl. 37, fig. 2; Fig. 64) to a point about 12 miles north-northwest of Inindia Bore, a distance of 145 miles (Fig. 64). The occurrences in this zone are thought to be of diapiric origin, with the possible exception of the outcrops in the core of the eroded anticline south of the Cleland Hills. The movement of the salt in the Bitter Springs Formation was probably initiated during the Petermann Ranges Orogeny. Most of the gypsum outcrops occur in the northern part of a depression where the thickest sequence of Proterozoic sediments was deposited.

Outcrops of gypsum outside the central southeasterly zone occur on the northern flank of the Gardiner Range next to the Gardiner Fault, and in a dome, 7 miles southwest of Ringwood homestead, in the Olympic-Ringwood Thrust Zone (Wells et al., 1967; Fig. 64).

The gypsum southwest of Ringwood crops out in the well defined Ringwood Dome (Fig. 64) which is surrounded by upturned beds of the Bitter Springs Formation. The dome has a cap of brecciated as well as bedded dolomite which suggests that piercement may have taken place. A BMR stratigraphic bore on the Ringwood Dome (Stewart, 1969, unpubl.) penetrated about 850 feet of brecciated and tightly folded gypsum, anhydrite, dolomite, and dark grey siltstone. Small piercement structures, in which Bitter Springs Formation is intruded into younger formations involved in thrusts, have been described in the northeast (Wells et al., 1967). Large blocks of Palaeozoic and Proterozoic sediments were disrupted by differential stresses in the underlying mass of incompetent Bitter Springs Formation, and listric surfaces were produced where thrusts originating in the Bitter Springs Formation migrated up section and formed a higher thrust plane in the Chandler Limestone or near the base of the Cambrian Giles Creek Dolomite where evaporites provided a second lubricant layer. The sediments were tightly folded when they moved southwards over the two décollement surfaces. An alternative explanation of the structure in the northeast part of the Amadeus Basin (A. J. Stewart, pers. comm.) suggests that the thrusts broke to the surface and thrust nappes were formed when large blocks of sediment slid southwards over the two décollement surfaces (Figs 65, 66). The nappes as shown have a considerable lateral displacement and in places one thrust sheet is superimposed on top of another.

The Goyder Pass Diapir (McNaughton et al., 1968) (Pl. 38, fig. 1; Fig. 64) is probably a trap-door structure. In the east, a large block of sediments was disrupted by a fault along which the evaporites were intruded, but on the hinge in the west there was considerable bending but no disruption of the beds. The variation in thickness of the sediments, and the arching of the formations over the structure, show that gradual movement continued until the deposition of the lower part of the Pertnjara Group. The first movements were probably no younger than Cambrian. Beds of dolomite, which are apparently concordant with the overlying Areyonga and Pertatataka Formations, crop out in the core of the diapir and are probably part of the more competent Loves Creek Member of the Bitter Springs Formation. There are no outcrops in the zone where diapiric intrusion is postulated. The zone corresponds to the position where beds stratigraphically below outcrops of the Loves Creek Member would be expected, and evaporites and incompetent beds of the Gillen Member probably occur in depth.

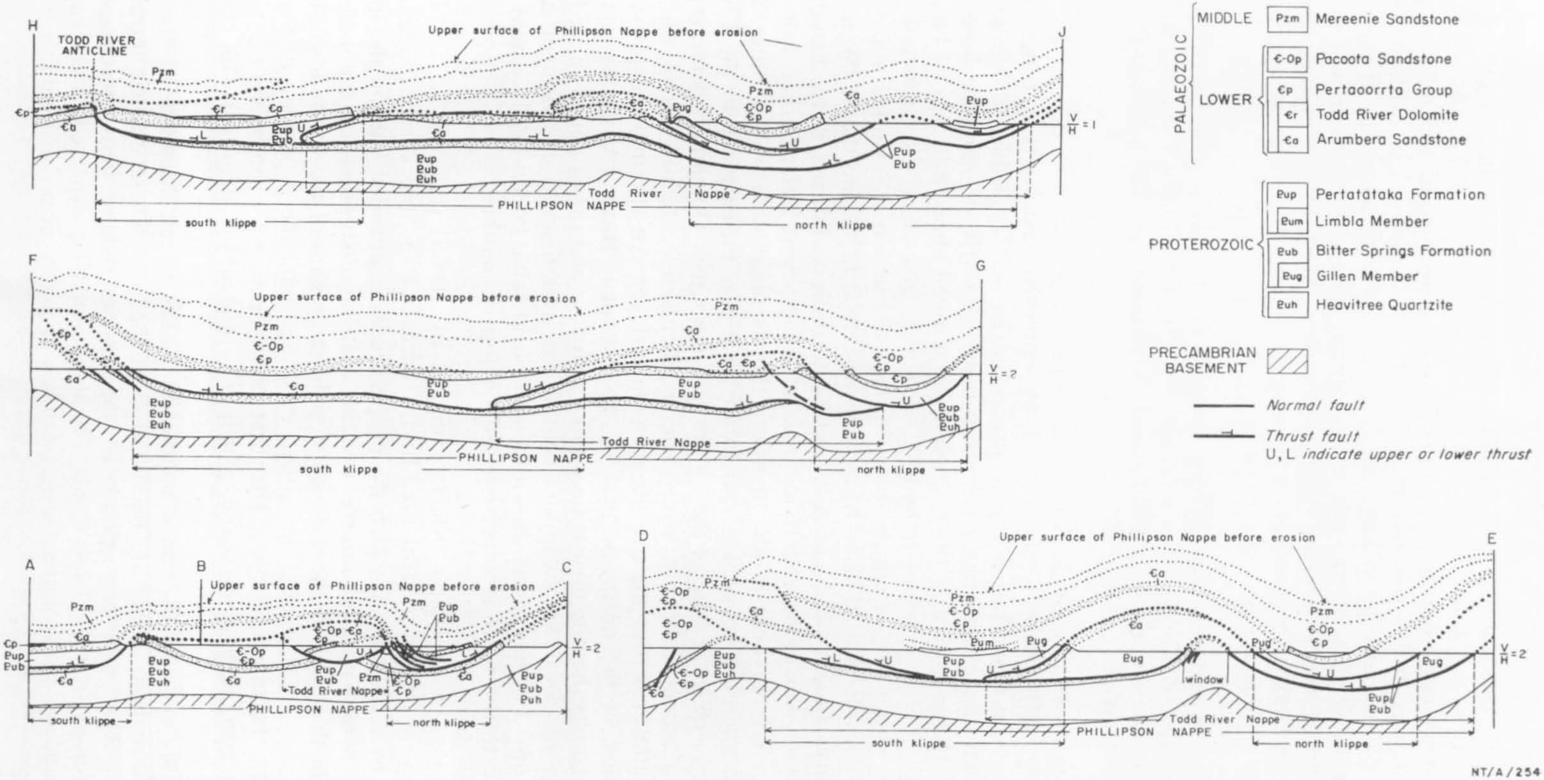


Fig. 65. Cross-sections of thrust nappes in northeastern part of Amadeus Basin.

Seismic surveys (Krieg & Campbell, 1965, unpubl.) suggest that the zone of disrupted sediments at Goyder Pass trends southwest towards the eastern end of the Carmichael Structure (cross-section C-G, Pl. 45). The anticline trends east-west, and the beds on the southern flank are steeply overturned. The thinning of the Pertnjara Group over the eastern end of the anticline suggests structural growth during sedimentation. The measured sections in the Ordovician sediments also show that there is considerable thinning over the Carmichael Structure.

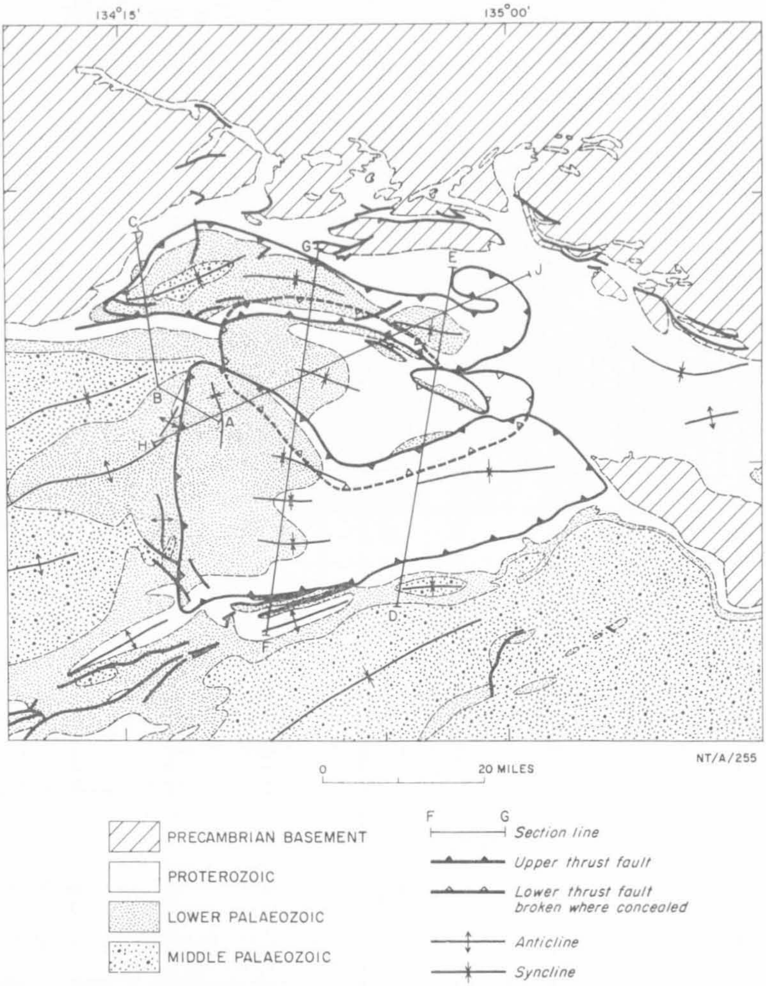


Fig. 66. Interpretation of thrust nappes in northeastern part of Amadeus Basin.

The Illamurta Structure (Cook, 1966b, unpubl.), in the central part of the basin, is a complex anticline with a core of Bitter Springs Formation, which grew during sedimentation. Aeromagnetic and gravity data suggest that the structure resulted from faulting in the Precambrian basement and diapirism of the Bitter Springs Formation. The Illamurta Structure, and three other similar structures, lie on a zone named the Goyder Structural Zone (Cook, pers. comm.) trending north-northwest across the basin. The Goyder Pass Diapir, Gardiner Range 'pinchout', and Seymour Range 'pinchout' all lie in this zone. Growth of structures in this zone probably influenced the distribution of sedimentary facies throughout the late Proterozoic and Palaeozoic. The zone marks the western limit of carbonate sedimentation in the Cambrian.

ECONOMIC GEOLOGY

PETROLEUM

About 30,000 feet of sediments are preserved in the northern part of the Amadeus Basin, where the most prospective beds are the conformable marine Cambrian and Ordovician sediments which form about 40 percent of the section. The rest of the sequence consists of about 20 percent Proterozoic rocks, and 40 percent continental Devono-Carboniferous sediments.

In the southwest the Cambrian Pertaoorrta Group sediments are arenaceous, but they pass through a transition zone of sand, silt, and minor carbonate rocks into a sequence of predominantly carbonate rocks in the northeast. The predominantly arenaceous and lutaceous Ordovician sediments were mostly deposited under shallow marine conditions during several transgressive and regressive phases.

During the Rodingan Movement, 5000 to 10,000 feet of Cambrian and Ordovician sediments were removed in the northeast before several thousand feet of continental sediments were laid down in the Upper Palaeozoic. Potential structural traps for hydrocarbons in the sediments were formed during the Alice Springs Orogeny. The crestal thinning of the Palaeozoic sediments over some structures suggests that they were being formed during the Lower Palaeozoic sedimentation.

The horizontal Permian glacial beds and Mesozoic deltaic and marine sediments in the Great Artesian Basin in the southeast, and the Permian glacial beds in the west are less prospective.

Source and Reservoir Rocks

The most promising source rocks are the marine Cambrian and Ordovician siltstones, shales, and carbonate rocks. In the Larapinta Group, the Horn Valley Siltstone was laid down in a euxinic environment which was favourable for the generation of hydrocarbons, but most of the Stokes Siltstone probably accumulated in a less favourable epeiric sea with restricted circulation and high salinity. The fauna in the Stokes Siltstone is restricted to minor limestone beds and shows evidence of considerable reworking, and the original organic content was probably considerably less than in the Horn Valley Siltstone.

The high organic content of the Pacoota and Stairway Sandstones indicates that they are probably potential source rocks as well as potential reservoirs. The Carmichael Sandstone, at the top of the Larapinta Group, possesses good reservoir rock properties.

Potential source rocks in the Pertaoorrta Group include the siltstone and carbonate rocks in the Jay Creek Limestone, Hugh River Shale, Shannon Formation, Giles Creek Dolomite, Todd River Dolomite, Chandler Limestone, and Tempe Formation. The Arumbera Sandstone is probably the best reservoir rock; other potential reservoirs are the Petermann, Illara, Eninta, and Cleland Sandstones.

The only Proterozoic formation with potential as a source rock is the Bitter Springs Formation. Lenses of clean sandstone with good reservoir properties are also present.

Potential cap rocks are widely distributed. They include the Parke, Stokes, and Horn Valley Siltstones, and siltstone in the middle unit of the Stairway Sandstone; lutites in the Jay Creek Limestone, Hugh River Shale, and Shannon and Deception Formations; and beds of salt and shale in the Chandler Limestone and Bitter Springs Formation.

The reservoir potential of sands in the Ordovician sequence has been confirmed by drilling, and both the Stairway Sandstone and Pacoota Sandstone have been proved to contain gas and oil (see p. 167).

Structural Traps

The structures in the potential source and reservoir beds were formed mainly during the Alice Springs Orogeny. In some cases, the structural relief on pre-existing anticlines was increased during this period of folding. Well defined,

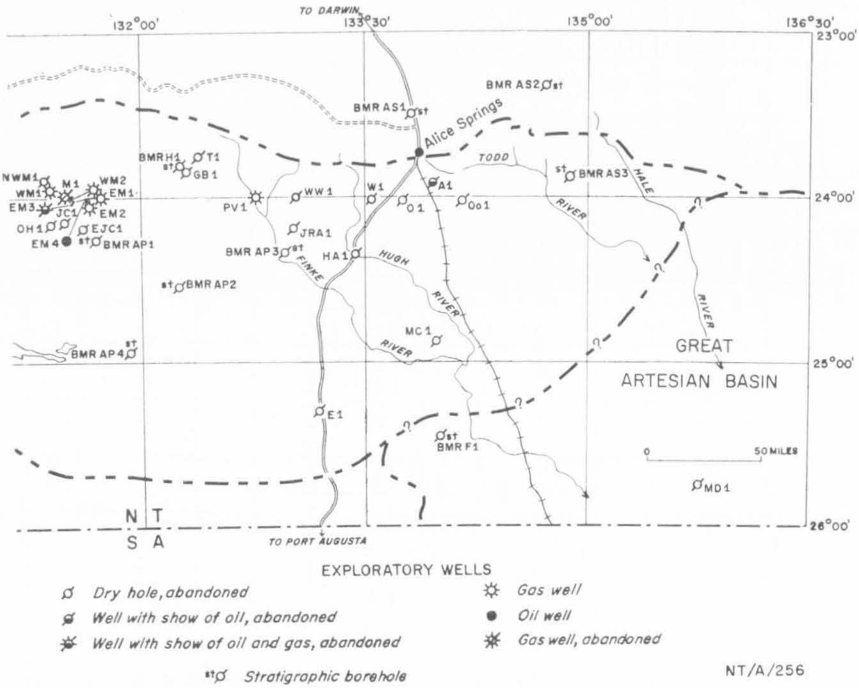


Fig. 67. Location of exploratory wells and stratigraphic boreholes. (Names of wells are given in Table 3).

practically symmetrical, doubly plunging canoe-shaped folds predominate; they generally have a northwesterly trend. Over most of the basin the folds were formed by slippage over décollement surfaces in the Bitter Springs Formation. The incompetent beds, including salt, flowed into the cores of many of the folds and the formation is now exposed in the breached axial zones of several of the anticlines; salt has been penetrated in several wells. In places, structural growth during sedimentation is indicated by crestal stratigraphic convergence and the presence of local unconformities. These structures can be explained by flowage of salt from the Bitter Springs Formation to form salt anticlines and diapiric structures, such as the Johnstone Hill and Goyder Pass Diapirs (Fig. 64) and the

Carmichael Structure. It is possible that supratenuous folds such as the Illamurta Structure (pp. 153-4), which were formed during deposition, provided potential traps for hydrocarbons prior to the Alice Springs Orogeny. Folding during the Alice Springs Orogeny greatly increased the structural relief on the anticlines and thereby created traps with greater closure. Many of the structures formed during or after deposition of the Lower Palaeozoic sediments have been obscured by the overlying Upper Palaeozoic continental deposits.

Structural traps may be present beneath or above thrust planes. The traps may be bounded on one side of the fault, or formed by folding after the thrust faulting.

Porosity and permeability may also be produced by fracturing of brittle reservoir rocks, and can occur in almost flat-lying uniform-textured sediments. Fracturing is present in the Ordovician sediments in the Palm Valley No. 1 well, and has probably played an important part in the production of hydrocarbons from the Horn Valley Siltstone.

Stratigraphic Traps

Potential stratigraphic traps include traps controlled by changes in facies and secondary cementation, and traps formed by the abutment of reservoir rocks against unconformities.

The lithofacies change in the Pertaoorrta Group (see p. 59) suggests that lenticular bodies of sand enclosed by shale may be present in the zone of interfingering. The ridge on which the Illamurta and other structures are situated probably influenced the separation of the arenaceous rocks in the west from the carbonate rocks in the east. As the structure was active during sedimentation, the sands may have been reworked and a trap formed by arching of the sand lenses over the structure.

In outcrop, the Arumbera Sandstone contains discrete lenses of white clean sandstone enclosed by siltstone and silty sand, and apparently possessing good reservoir properties. This lithological variation is more noticeable in the northeast, and is not known in areas of closed structures.

Algal bioherms occur in the Bitter Springs Formation and Pertaoorrta Group and coquinas in the Cambrian and Ordovician sediments, but their potential as reservoirs is uncertain. In the northeast, porous dolomites may have been developed during the dolomitization of the thick carbonate sequence of the Pertaoorrta Group.

Potential unconformity traps may be present at the base of the Cambrian in the central and southern parts of the basin, and at the base of the Mereenie Sandstone in the east. The Pertaoorrta Group transgresses the Pertatataka, Areyonga, and Bitter Springs Formations in the central folded belt, and the Mereenie Sandstone transgresses the Larapinta Group and unconformably overlies the Pertaoorrta Group in the east. A similar overstep is present at the base of the Pertnjara Group and the youngest formation rests in places on rocks as old as the Pertatataka Formation.

Reservoirs may be present in sands truncated by the unconformity, or buttress sands may be present where beds of sandstone intersect the underlying unconformity. Buttress sands of this type may have been developed at the unconformity

TABLE 3. SUMMARY OF OIL EXPLORATION WELLS DRILLED IN THE AMADEUS BASIN

Name	*Latitude, Longitude Sheet Area*	*Total Depth (ft)*	*Remarks*
Ooraminna No. 1	24°00′06″S 134°09′50″E Alice Springs	6097	Subsidized. Gas show in Areyonga Formation. Dry, abandoned
Alice No. 1	23°54′47″S 133°58′00″E Alice Springs	7518	Subsidized. Oil bleeding from core in Giles Creek Dolomite. Dry, capped as water well
Mereenie No. 1	23°59′08″S 131°30′10″E Mt Liebig	3983	Not subsidized. Open flow of 11 mmcfd gas from Pacoota Sandstone and Stairway Sandstone. Plugged and temporarily abandoned gas well
East Mereenie No. 1	24°00′31″S 131°33′51″E Lake Amadeus	4710	Not subsidized. Gas flow of 20 mmcfd. Completed as gas condensate well from Pacoota Sandstone
East Mereenie No. 2	24°02′47″S 131°38′50″E Lake Amadeus	5175	Not subsidized, but completion report released. Completed as gas condensate well. Gas flow of 4.5 mmcfd from Pacoota Sandstone
West Mereenie No. 1	23°56′57″S 131°24′44″E Mt Liebig	5504	Not subsidized. Completed as gas condensate well. Gas flow of 10.1 mmcfd from Pacoota Sandstone
West Mereenie No. 2	23°58′49″S 131°32′22″E Mt Liebig	4997	Not subsidized. Gas flow of 10.6 mmcfd. Completed as gas well in Pacoota Sandstone
East Mereenie No. 3	24°00′45″S 131°33′10″E Lake Amadeus	5215	Not subsidized. Abandoned
Mt Charlotte No. 1	24°53′41″S 133°59′11″E Rodinga	6943	Subsidized. Abandoned. Water well
Palm Valley No. 1	24°00′00″S 132°46′20″E Hermannsburg and Henbury	6658	Subsidized. Completed as gas well with 11.7 mmcfd from Horn Valley Siltstone, Pacoota Sandstone, and Stairway Sandstone
Johnny Creek No. 1	24°08′46″S 131°28′41″E Lake Amadeus	877	Not subsidized. Abandoned
East Johnny Creek No. 1	24°11′00″S 131°37′55″E Lake Amadeus	6344	Not subsidized. Dry, abandoned
Gosses Bluff No. 1	23°49′15″S 132°18′00″E Hermannsburg	4535	Subsidized. Dry, abandoned
James Range No. 1	24°10′42″S 133°00′40″E Henbury	3000	Not subsidized. Dry, abandoned
Highway Anticline No. 1	24°20′23″S 133°27′06″E Henbury	3770	Subsidized. Dry, abandoned
Erldunda No. 1	25°18′36″S 133°11′48″E Kulgera	5463	Subsidized. Dry, abandoned
Ochre Hill No. 1	24°07′58″S 131°23′49″E Lake Amadeus	3761	Not subsidized. Abandoned
McDills No. 1	25°43′50″S 135°47′25″E McDills	10,515	Subsidized. Dry, abandoned
Orange No. 1	24°02′34″S 133°46′32″E Rodinga	8886	Subsidized. Dry, abandoned
Waterhouse No. 1	24°01′00″S 133°32′00″E Rodinga	3081	Not subsidized. Dry, abandoned.

Footnote: The following wells have been completed since the compilation of this table: East Mereenie No. 4 (TD 8750), Northwest Mereenie No. 1 (TD 5000), Tyler No. 1 (TD 12,599), West Waterhouse No. 1 (TD 6528), Palm Valley No. 2 (TD 6559).

TABLE 4: FORMATION THICKNESSES IN OIL EXPLORATION WELLS

(Data from well completion reports unless otherwise stated; thickness in feet)

Datum (ft a.s.l.)	*Ooraminna No. 1* KB 1624	*Alice No. 1* KB 1753	*Mereenie No. 1* KB 2583	*East Mereenie No. 1* KB 2529
Quaternary				
Rumbalara Shale				
De Souza Sandstone				
Crown Point Formation				
Pertnjara Group				
Brewer Conglomerate		539 + (surf.- 550)		
Hermannsburg Sandstone		615 (550-1165)		
Parke Siltstone				
Finke Group				
Idracowra Sandstone				
Horseshoe Bend Shale				
Langra Formation				
Polly Conglomerate				
Mereenie Sandstone		950 (1165-2115)	1205 + (surf.-1216)	1193 + (surf.-1204)
Larapinta Group				
Carmichael Sandstone			315 (1216-1531)	296 (1204-1500)
Stokes Siltstone			1039 (1531-2570)	1016 (1500-2516)
Stairway Sandstone			830 (2570-3400)	812 (2516-3328)
Horn Valley Siltstone			230 (3400-3630)	222 (3328-3550)
Pacoota Sandstone		889 (2115-3004)	353 + (3630-3983)	1065 (3550-4615)
Pertaoorrta Group				
Goyder Formation		800 (3004-3804)		95 + (4615-4710)
Jay Creek Limestone				
Hugh River Shale				
Shannon Formation		1343 (3804-5147)		
Giles Creek Dolomite		1471 (5147-6618)		
Chandler Limestone		522 (6618-7140)		
Todd River Dolomite				
Petermann Sandstone				
Deception Formation				
Illara Sandstone				
Cleland Sandstone				
Tempe Formation				
Eninta Sandstone				
Arumbera Sandstone	1519 + (surf.-1530)	378 + (7140-7518)		

TABLE 4 (continued)

Datum (ft a.s.l.)	*Ooraminna No. 1* KB 1624	*Alice No. 1* KB 1753	*Mereenie No. 1* KB 2583	*East Mereenie No. 1* KB 2529
Pertatataka Formation	2200 (1530-3730)			
Julie Member	420 (1530-1950)			
Winnall Beds				
Inindia Beds				
Areyonga Formation	535 (3730-4265)			
Bitter Springs Formation	1832 (4265-6097)			
Loves Creek Member	1015 (4265-5280)			
Gillen Member	817 + (5280-6097)			
	TD 6097	TD 7518	TD 3983	TD 4710
	Modified from Schmerber (1966a, 1967, both unpubl.)	After Fehr (1966, unpubl.)		

Datum (ft a.s.l.)	*East Mereenie No. 2* KB 2357	*West Mereenie No. 1* KB 2482	*West Mereenie No. 2* KB 2535	*East Mereenie No. 3* KB 2532
Quaternary				
Rumbalara Shale				
De Souza Sandstone				
Crown Point Formation				
Pertnjara Group				
Brewer Conglomerate				
Hermannsburg Sandstone				
Parke Siltstone	583 + (surf.- 594)			347*+(surf.- 386)
Finke Group				
Idracowra Sandstone				
Horseshoe Bend Shale				
Langra Formation				
Polly Conglomerate				
Mereenie Sandstone	1274 (594-1868)	1081 + (surf.-1092)	1518 + (surf.-1532)	1770* (386-2352)
Larapinta Group				
Carmichael Sandstone	210 (1868-2078)	348 (1092-1440)	314 (1532-1846)	293* (2352-2677)
Stokes Siltstone	1028 (2078-3106)	1158 (1440-2598)	1060 (1846-2906)	1094* (2677-3834)
Stairway Sandstone	777 (3106-3883)	852 (2598-3450)	830 (2906-3736)	824* (3834-4668)
Horn Valley Siltstone	201 (3883-4084)	258 (3450-3708)	230 (3736-3966)	231* (4668-4902)
Pacoota Sandstone	1021 (4084-5105)	1095 (3708-4803)	1031 + (3966-4997)	309*+(4902-5215)

TABLE 4 (continued)

Datum (ft a.s.l.)	*East Mereenie No. 2* KB 2357	*West Mereenie No. 1* KB 2482	*West Mereenie No. 2* KB 2535	*East Mereenie No. 3* KB 2532
Pertaoorrta Group				
Goyder Formation	70 + (5105-5175)	701 + (4803-5504)		
Jay Creek Limestone				
Hugh River Shale				
Shannon Formation				
Giles Creek Dolomite				
Chandler Limestone				
Todd River Dolomite				
Petermann Sandstone				
Deception Formation				
Illara Sandstone				
Cleland Sandstone				
Tempe Formation				
Eninta Sandstone				
Arumbera Sandstone				
Pertatataka Formation				
Julie Member				
Winnall Beds				
Inindia Beds				
Areyonga Formation				
Bitter Springs Formation				
Loves Creek Member				
Gillen Member				
	TD 5175	TD 5504	TD 4997	TD 5215 * Thickness corrected for deviation and dip

Datum (ft a.s.l.)	*Mt Charlotte No. 1* KB 1260	*Palm Valley No. 1* RT 1921	*Waterhouse No. 1* —	*Johnny Creek No. 1* KB 2211
Quaternary	42 + (surf.-56) possibly includes some Idracowra Sandstone			
Rumbalara Shale				
De Souza Sandstone				
Crown Point Formation				

TABLE 4 (continued)

Datum (ft a.s.l.)	*Mt Charlotte No. 1* KB 1260	*Palm Valley No. 1* RT 1921	*Waterhouse No. 1* —	*Johnny Creek No. 1* KB 2211
Pertnjara Group				
Brewer Conglomerate				
Hermannsburg Sandstone		456 + (surf.- 470)		
Parke Siltstone		546 (470-1016)		
Finke Group				
Idracowra Sandstone				
Horseshoe Bend Shale	464 (56- 520)			
Langra Formation	500 (520-1020)			
Polly Conglomerate	180 (1020-1200) shale equivalent to Polly Conglomerate			
Mereenie Sandstone		1744 (1016-2760)		
Larapinta Group				
Carmichael Sandstone		448 (2760-3208)		
Stokes Siltstone		1112 (3208-4320)		
Stairway Sandstone	340 (1200-1540)	976 (4320-5296)		
Horn Valley Siltstone		338 (5296-5634)		
Pacoota Sandstone		1024 + (5634-6658)		539 + (surf.-550)
Pertaoorrta Group				
Goyder Formation				327 + (550- 877)
Jay Creek Limestone	792 (1540-2332)		2254 + (surf.-2254)	
Hugh River Shale				
Shannon Formation				
Giles Creek Dolomite				
Chandler Limestone	740 (2332-3072)			
Todd River Dolomite				
Petermann Sandstone				
Deception Formation				
Illara Sandstone				
Cleland Sandstone				
Tempe Formation				
Eninta Sandstone				
Arumbera Sandstone			827 + (2254-3081)	

TABLE 4 (continued)

Datum (ft a.s.l.)	*Mt Charlotte No. 1* KB 1260	*Palm Valley No. 1* RT 1921	*Waterhouse No. 1* —	*Johnny Creek No. 1* KB 2211
Pertatataka Formation	1598 (3072-4670)			
Julie Member				
Winnall Beds				
Inindia Beds				
Areyonga Formation				
Bitter Springs Formation	2130* (4670-6943)			
Loves Creek Member	430 (4670-5100)			
Gillen Member	1843 + (5100-6943)			
	TD 6943	TD 6658	TD 3081	TD 877
	After Schmerber & Ozimic (1966, unpubl.) * True thickness		After Schmerber (1966c, unpubl.)	

Datum (ft a.s.l.)	*East Johnny Creek No. 1* KB 2200	*Gosses Bluff No. 1* KB 2453	*James Range 'A' No. 1* KB 1600	*Highway Anticline No. 1* KB 1616
Quaternary				
Rumbalara Shale				
De Souza Sandstone				
Crown Point Formation				
Pertnjara Group				
Brewer Conglomerate				
Hermannsburg Sandstone				
Parke Siltstone				
Finke Group				
Idracowra Sandstone				
Horseshoe Bend Shale				
Langra Formation				
Polly Conglomerate				
Mereenie Sandstone				
Larapinta Group				
Carmichael Sandstone				
Stokes Siltstone		1032*+(surf.-1046)		
Stairway Sandstone	149 + (surf.-160)	3489*+(1046-4535)		
Horn Valley Siltstone	187 (160-347)			
Pacoota Sandstone	926 (347-1273)			

TABLE 4 (continued)

Datum (ft a.s.l.)	*East Johnny Creek No. 1* KB 2200	*Gosses Bluff No. 1* KB 2453	*James Range 'A' No. 1* KB 1600	*Highway Anticline No. 1* KB 1616
Pertaoorrta Group				
Goyder Formation	682 (1273-1955)			467*+(surf.-480)
Jay Creek Limestone				3290 ** (480-3770)
Hugh River Shale			2013 + (surf.-2026)	
Shannon Formation				
Giles Creek Dolomite				
Chandler Limestone				
Todd River Dolomite				
Petermann Sandstone	789 (1955-2744)			
Deception Formation	550 (2744-3294)			
Illara Sandstone	651 (3294-3945)			
Cleland Sandstone				
Tempe Formation	740 (3945-4685)			
Eninta Sandstone	69 (4685-4754)			
Arumbera Sandstone			400 (2026-2426)	
Pertatataka Formation Julie Member				
Winnall Beds				
Inindia Beds				
Areyonga Formation	216 (4754-4970)		170 (2426-2596)	
Bitter Springs Formation	1374 + (4970-6344)		404 + (2596-3000)	
Loves Creek Member Gillen Member	(Includes Loves Creek and Gillen Members?)		(Probably Loves Creek Member)	
	TD 6344	TD 4535 * Not true thickness due to steep dip	TD 3000	TD 3770 After Schmerber (1966b, unpubl.) * True thickness about 436 **True thickness about 2950

TABLE 4 (continued)

Datum (ft a.s.l.)	*Erldunda No. 1* KB 1343.5	*Ochre Hill No. 1* KB 2300	*McDills No. 1* KB 412	*Orange No. 1* KB 1938
Quaternary	126.5 (surf.-140)		85 (surf.-101)	
Rumbalara Shale			1335 + (101-1436)	
De Souza Sandstone			916 (1436-2352)	
Crown Point Formation			1438 (2352-3790)	
Pertnjara Group				
Brewer Conglomerate				
Hermannsburg Sandstone	760 (140-900)			927 + (surf.-940)
Parke Siltstone				
Finke Group				
Idracowra Sandstone				
Horseshoe Bend Shale			280 (3790-4070)	
Langra Formation			1730 (4070-5800)	
Polly Conglomerate			1290 (5800-7090)	
Mereenie Sandstone			1120 (7090-8210)	1120 (940-2060)
Larapinta Group				353 (2060-2413)
Carmichael Sandstone	340 (900-1240)			
Stokes Siltstone				
Stairway Sandstone			814 (8210-9024)	
Horn Valley Siltstone			(unnamed unit)	
Pacoota Sandstone				1467 (2413-3880)
Pertaoorrta Group				
Goyder Formation		414 + (surf.-428)		923 (3880-4803)
Jay Creek Limestone				851 (4803-5654)
Hugh River Shale				966 (5654-6620)
Shannon Formation				
Giles Creek Dolomite				842 (6620-7462)
Chandler Limestone				748 (7462-8210)
Todd River Dolomite			1491 + (9024-10,515)	84 (8210-8294)
Petermann Sandstone				
Deception Formation				
Illara Sandstone				
Cleland Sandstone		1762 (428-2190)		
Tempe Formation		447 (2190-2637)		
Eninta Sandstone				
Arumbera Sandstone				592 + (8294-8886)

TABLE 4 (continued)

Datum (ft a.s.l.)	*Erldunda No. 1* KB 1343.5	*Ochre Hill No. 1* KB 2300	*McDills No. 1* KB 412	*Orange No. 1* KB 1938
Pertatataka Formation				TD 8886
Julie Member				
Winnall Beds	2510 (1240-3750)			
Inindia Beds	550 (3750-4300)			
Areyonga Formation				
Bitter Springs Formation	1163 + (4300-5463)	1124 + (2637-3761)		
Loves Creek Member	450 (4300-4750)	(Probably Loves Creek		
Gillen Member	713 + (4750-5463)	Member)		
	TD 5463	TD 3761	TD 10,515	
	After Schmerber (1966d, unpubl.)		Modified from well completion report	

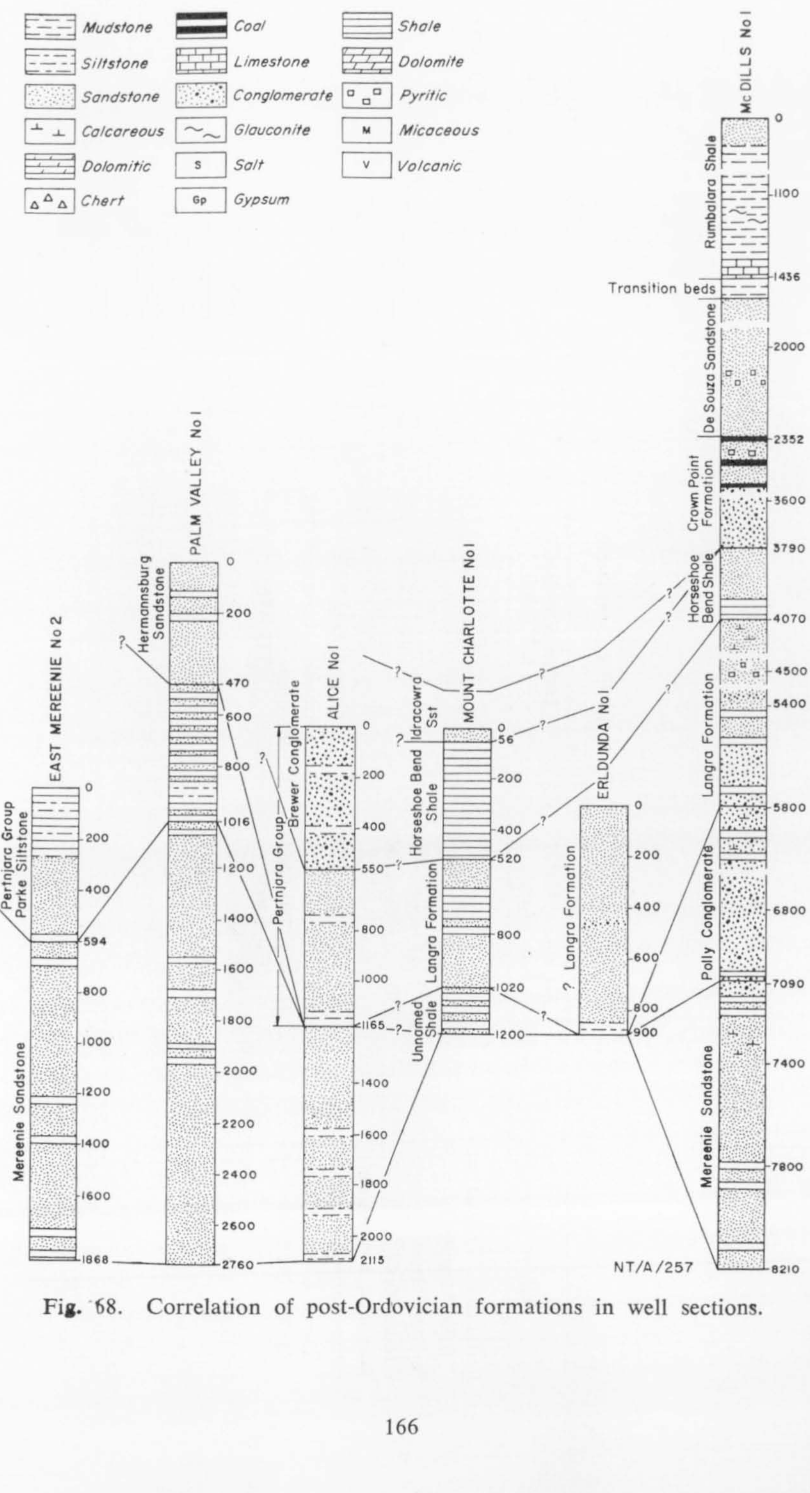


Fig. 68. Correlation of post-Ordovician formations in well sections.

at the base of the Pertaoorta Group in the central part of the basin. The Eninta Sandstone at the base of the Pertaoorrta Group is not exposed in the cores of the eroded anticlines, but may be present subsurface as pinchouts against the unconformity. In these examples the stratigraphic element forms the edge of permeability of the reservoir rock, and subsequent deformation completes the trap.

Several types of traps may be associated with the diapiric structures — the lifting of sediments against the dome, block faulting, overlapping of the reservoir formation during successive phases of movement of the evaporites, and accumulation of hydrocarbons under salt dome cap rocks. None of the salt diapirs occur in a suitable structural position in potential source and reservoir rocks.

Results of Drilling

By early 1970, twenty-four exploratory wells had been completed in the Amadeus Basin and one on the western fringe of the Great Artesian Basin; the results of twenty of these wells are summarized in Table 3 and formation thicknesses are given in Table 4. The location of the wells and stratigraphic bores is shown in Figure 67; the formations penetrated and the correlations between wells are shown in Figures 68, 69, 70, and 71.

The exploratory drilling resulted in the discovery of two gas fields on the Mereenie and Palm Valley Anticlines. Eight wells have been drilled on the Mereenie Anticline (Fig. 72) which is a major gas field, but only two wells have been drilled on the Palm Valley Anticline. In the remaining wells occurrences of hydrocarbons include a small gas show recorded in Proterozoic sediments in the Ooraminna Anticline, oil bleeding in an impermeable zone in Cambrian rocks in Alice No. 1, and oil saturated cores from the Stairway Sandstone in six intervals from about 652 to 675 feet in BMR AP No. 1 phosphate exploration corehole (Fig. 67). Other minor indications of petroleum include small amounts of residual hydrocarbons, gas shows, and fluorescence in Cambrian and Proterozoic rocks.

The producing formation in the Mereenie and Palm Valley Anticlines is the Pacoota Sandstone of the Larapinta Group. Smaller gas production is obtained from the Stairway Sandstone in the Mereenie and Palm Valley Anticlines, and from fractured siltstone in the Horn Valley Siltstone in the Palm Valley Anticline. The cap rocks in the wells are the fine lutites of the Stokes Siltstone, the siltstone of the middle unit of the Stairway Sandstone, and the Horn Valley Siltstone.

The Larapinta Group formations in these and other wells, the occurrences of oil and gas, and correlations between wells are shown in Figure 69.

An oil column was proved in the Pacoota Sandstone in a well on the flanks of the Mereenie Anticline, but there was insufficient permeability to give significant production.

The Mereenie wells produce condensate at the rate of about 10 barrels per million cubic feet of gas. The gross thickness of the gas column is about 1072 feet, and the oil column has a minimum thickness of 355 feet. The similarity of the levels of the gas/oil/water contacts in the wells drilled on the Mereenie field suggest continuity of reservoir beds. The main problem is the erratic porosity and permeability of the sediments.

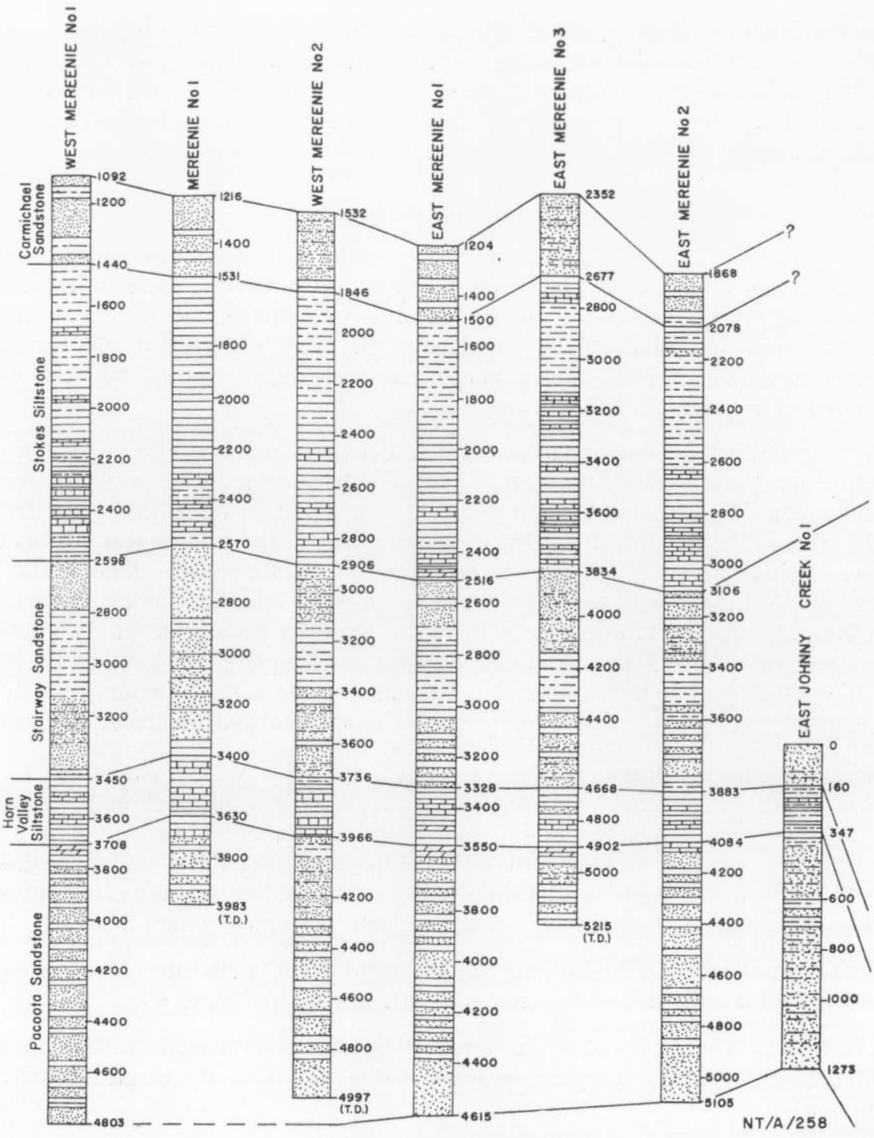


Fig. 69. Correlation of Cambro-Ordovician formations (Larapinta Group) in well sections.

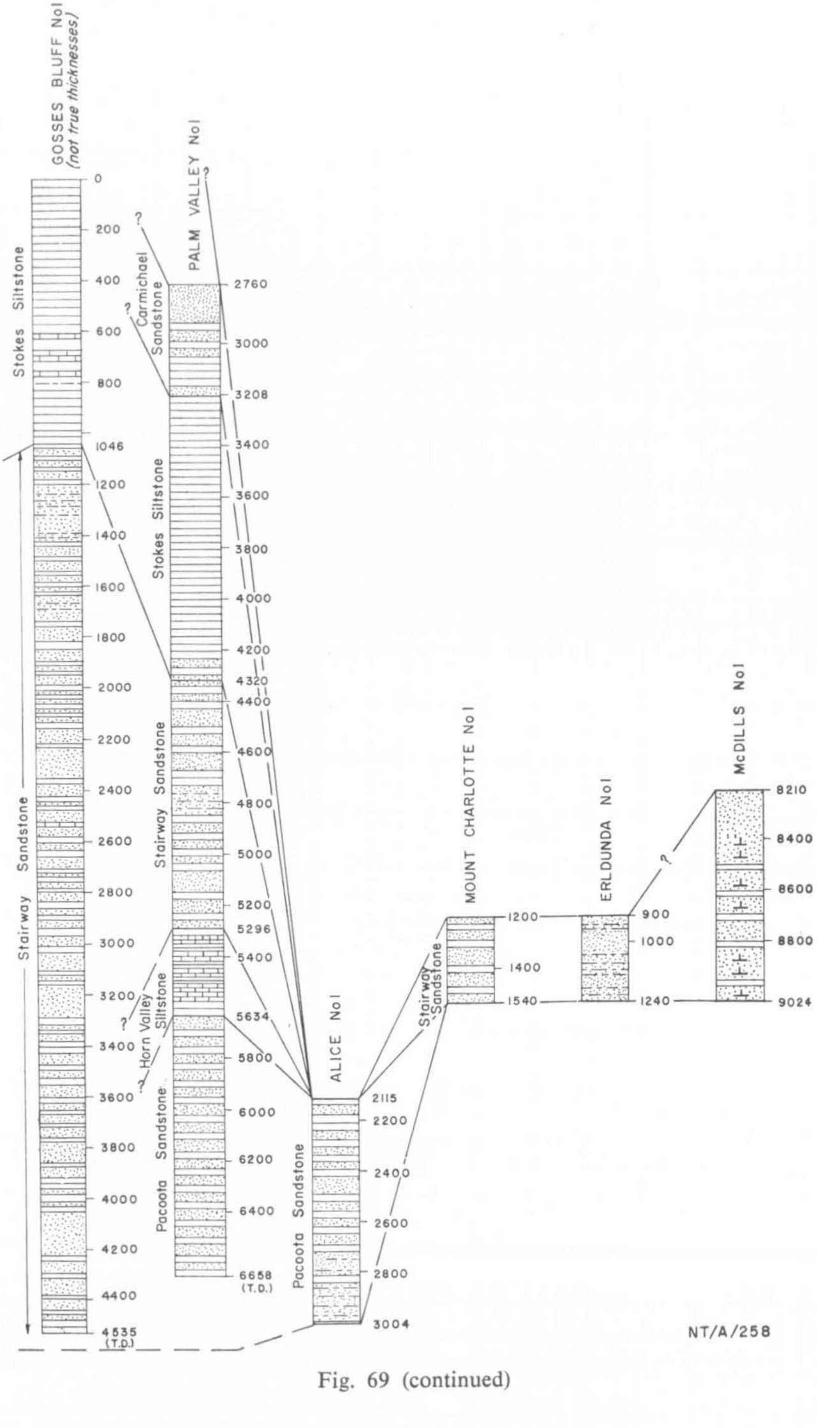


Fig. 69 (continued)

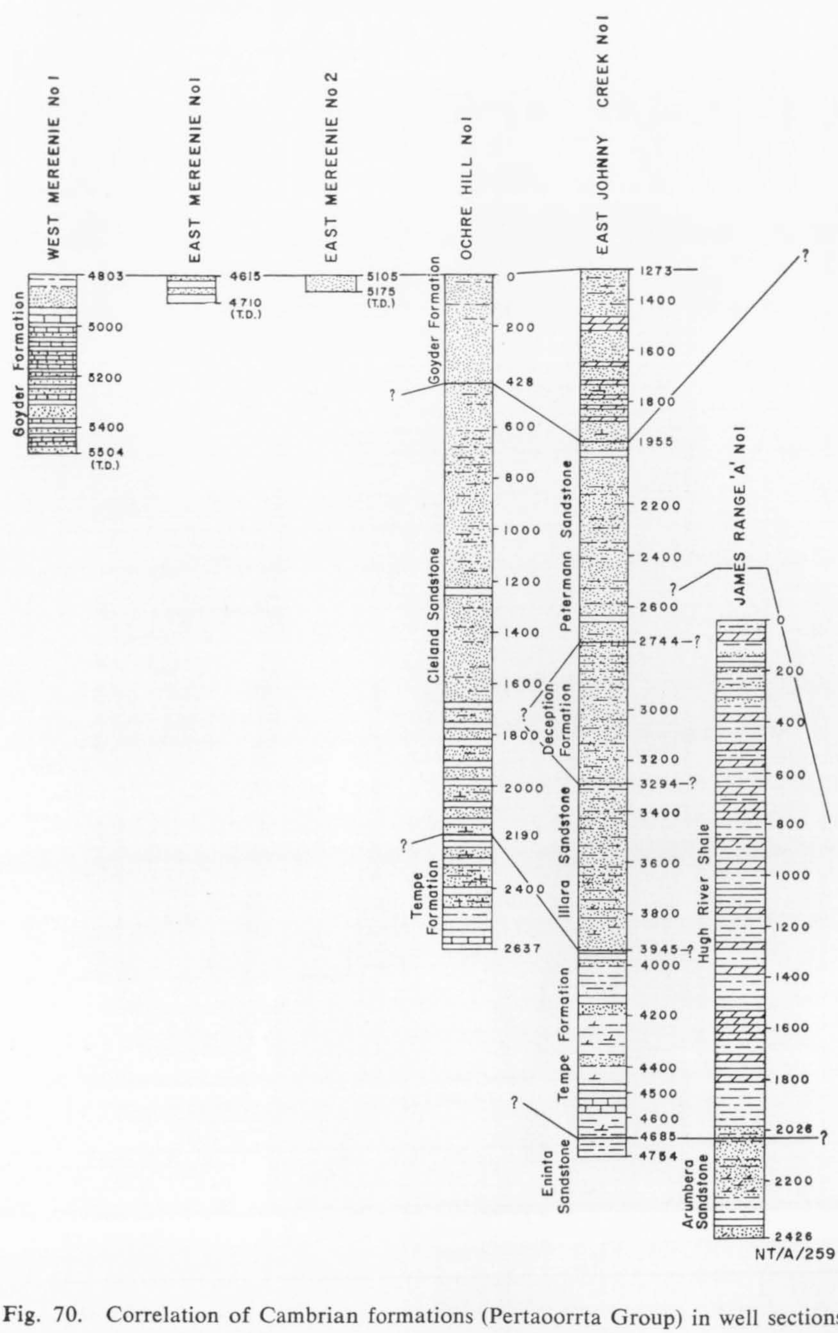


Fig. 70. Correlation of Cambrian formations (Pertaoorrta Group) in well sections.

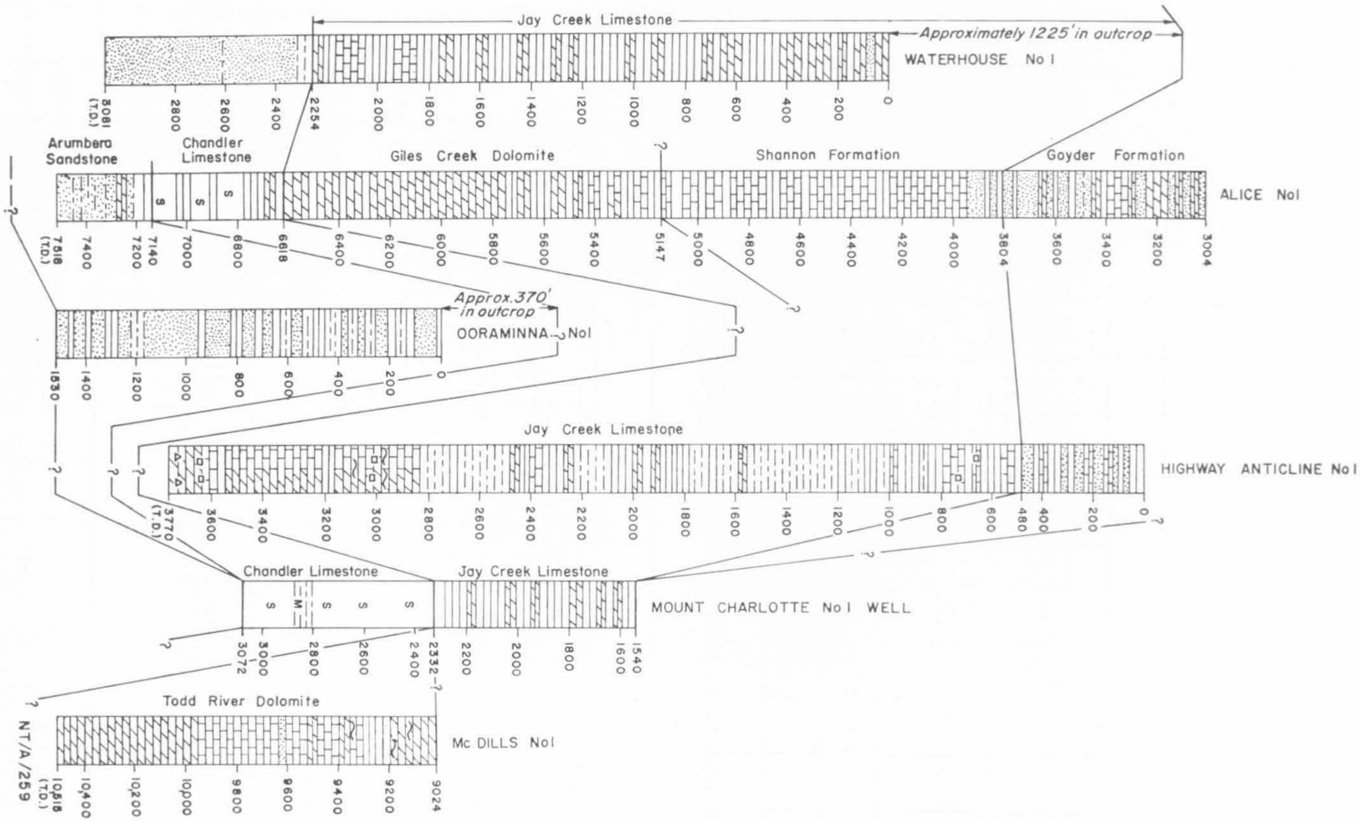


Fig. 70 (continued).

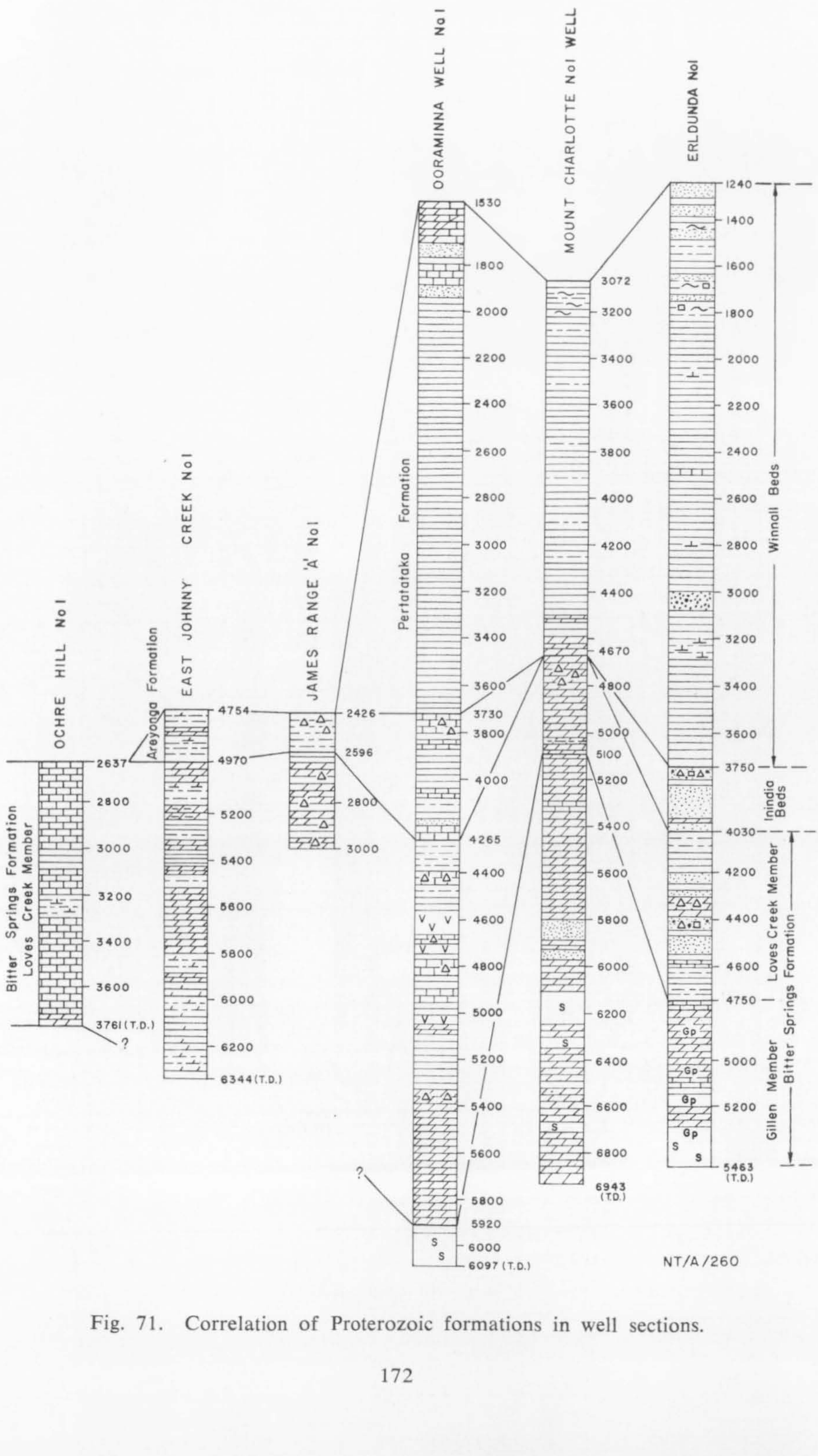


Fig. 71. Correlation of Proterozoic formations in well sections.

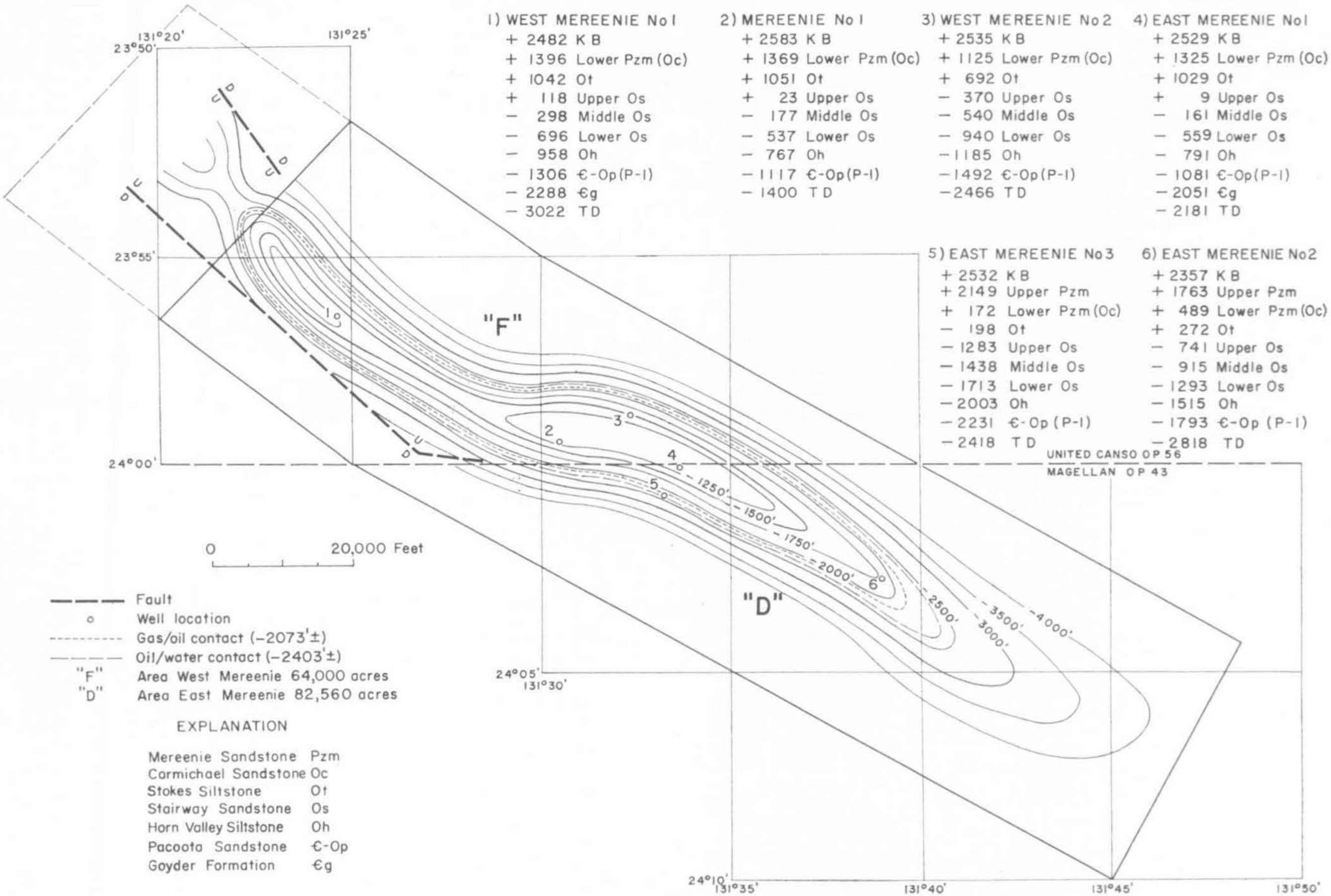


Fig. 72. Structure contour map of top of Pacoota Sandstone in the Mereenie Anticline. (After Krieg & Campbell, 1965, unpubl.).

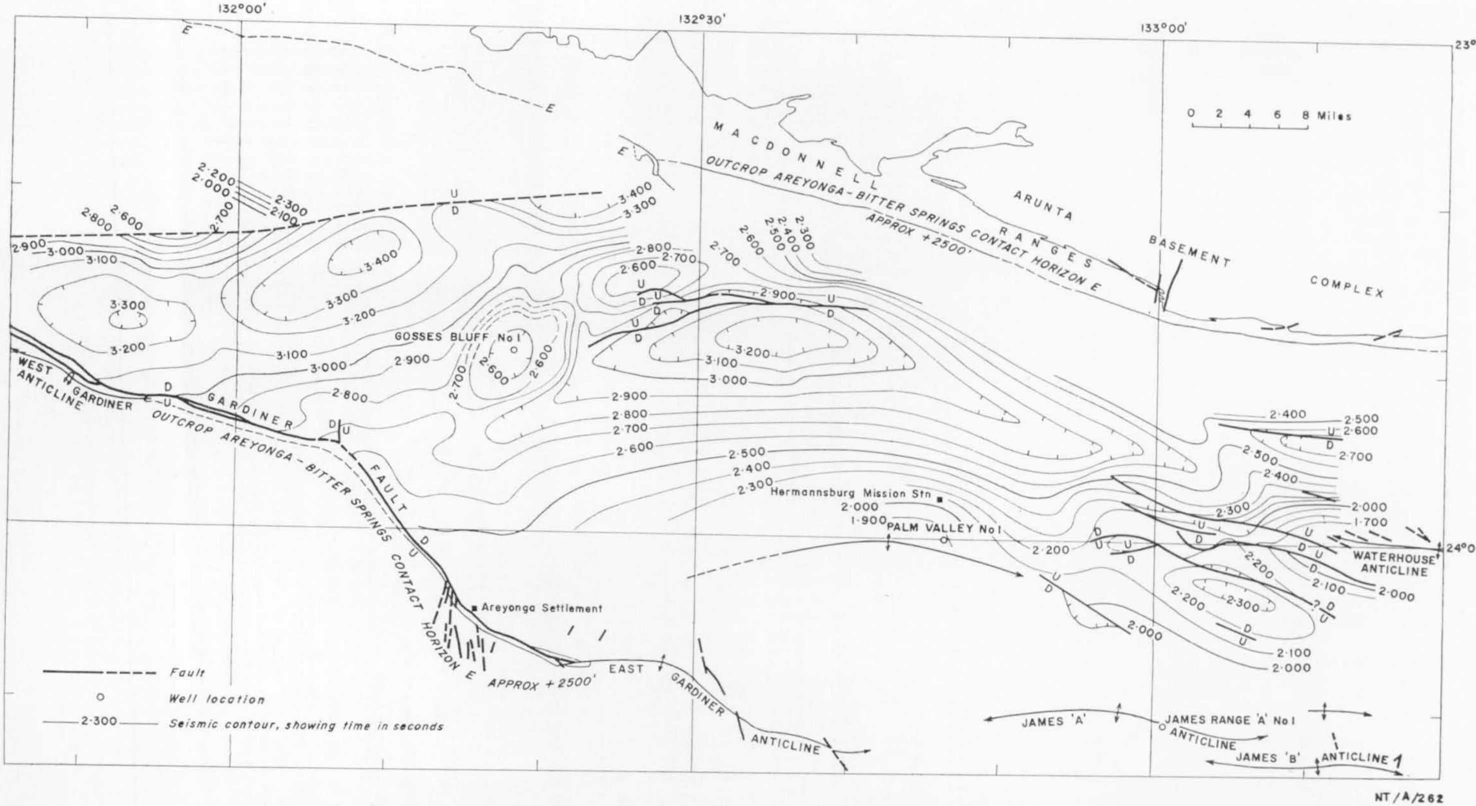


Fig. 73. Missionary Plain seismic survey showing contours on deep reflectors. (After Magellan Petroleum Corp.).

Northern Area

The northern area includes the deepest part of the Amadeus Basin, where the thickest Palaeozoic sediments are preserved. Several wells have been drilled and potential source rocks and reservoir sands have been encountered in the Larapinta Group. Details of the Ordovician rocks penetrated in the wells are shown on Figure 69.

The Mereenie and Palm Valley Anticlines are well defined at the surface. A seismic survey over the western end of the Mereenie Anticline (Patch, 1964, unpubl.) showed that a major reverse or thrust fault is indicated on the southern flank of the fold. A saddle occurs between the Mereenie and Glen Edith Anticlines, but neither the saddle nor the fault can be detected at the surface.

Several other anticlines outlined by seismic surveys are obscured by the thick continental deposits preserved in the Missionary and Brewer Plains (Fig. 73).

The Mereenie wells encountered flows of gas ranging from about 3 to 30 mmcfd* from the Pacoota Sandstone. Flows of up to 650,000 cfd occurred in the Stairway Sandstone and gas pressure was unusually high in the lower part of the formation. Much of the intergranular porosity in the Pacoota Sandstone has been destroyed by silicification. The silicification is probably related to local variations in groundwater flow, to fluctuations in the piezometric surface, and to depth of burial of the sediments. The extreme variation in permeability and porosity in the Pacoota Sandstone is probably caused by the rapid alternation of sandstone and shale.

The lower and upper parts of the Pacoota Sandstone, the Carmichael and Mereenie Sandstones, and lower part of the Stairway Sandstone in the Mereenie wells were permeable. The permeability in the upper Pacoota Sandstone appears to be the most persistent, but decreases with an increase in argillaceous or asphaltic content, or a decrease in grainsize. In East Mereenie No. 1, the porosity in the Pacoota Sandstone ranges up to 14 percent and the permeability ranges up to 814 millidarcys (horizontal) and 1350 millidarcys (vertical).

Fracturing plays an important part in determining permeability in the Stairway Sandstone. The zones of permeability in the formations appear to be continuous throughout the Mereenie wells, but low porosities and permeabilities prevail where the oil column was encountered. Cores of upper Pacoota Sandstone in the oil column from West Mereenie No. 2 have a maximum permeability of 11.3 millidarcys and maximum porosity of about 12 percent.

Gas occurs over an interval of about 1000 feet in Palm Valley No. 1, with production chiefly from the lower Stairway and upper Pacoota Sandstones. The Pacoota Sandstone, Horn Valley Siltstone, and lower part of the Stairway Sandstone show fracture porosity, and the sandstone in these formations shows some intergranular porosity. The upper part of the Pacoota Sandstone has 13 to 16 percent porosity, but permeability is less than 0.1 millidarcys.

The well drilled in the centre of Gosses Bluff encountered steeply dipping sediments of the Larapinta Group which were fractured and sheared almost from the surface to total depth (Fig. 69). A show of gas was recorded at 3076 to 3088 feet.

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* mmcfd = million cubic feet per day.

Alice No. 1 was drilled on a seismic anomaly north of the Ooraminna Anticline beneath the Brewer Plain. The anomaly was thought to be caused by reefing in Cambrian carbonate rocks, but no evidence was found in the well samples to prove this theory. There is no surface indication of structure, and the amount of closure (estimated at 140 feet by the seismic survey) is small. The anomaly may be due to a small salt pillow in the Cambrian sequence causing local flexuring of the sediments, although Fehr (1966, unpubl.) has suggested the possibility of algal reef development in the Shannon Formation. About 300 feet of salt was penetrated in the Chandler Limestone in the well. The Larapinta Group is partly truncated in this part of the basin, and only the Pacoota Sandstone was penetrated in the well (Fig. 69). An aggregate thickness of 1240 feet of porous and permeable sediments was encountered within the Mereenie Sandstone, Pacoota Sandstone, and Pertnjara Group (Fig. 68).

Maximum figures obtained for horizontal permeability and the corresponding values of porosity from selected cores are listed below:

Formation	*Horizontal Permeability (md)*	*Porosity (%)*
Hermannsburg Sandstone	515	23.7
Mereenie Sandstone	217	19.7
Pacoota Sandstone	53	31.5
Goyder Formation	0.1	10.1
Giles Creek Dolomite	0.1	8.7
Chandler Limestone	0.1	17.1
Arumbera Sandstone	0.1	2.3

The low permeabilities in the Cambrian sequence are due mainly to secondary anhydrite. Oil bled from an impermeable zone in the Giles Creek Dolomite, and a small amount of asphaltic oil was found in the Goyder Formation.

Central Folded Belt

The east-west line of wells in the centre of the basin, Ochre Hill No. 1, East Johnny Creek No. 1, James Range 'A' No. 1, Waterhouse No. 1, Highway Anticline No. 1, and Ooraminna No. 1, penetrated similar sequences. All the wells were sited at or near the crest of deeply breached anticlines which have good surface expression, and all terminated in the Bitter Springs Formation except Waterhouse No. 1 and Highway Anticline No. 1, which were in Cambrian rocks at total depth. Only residual hydrocarbons, fluorescence, and small shows of gas were encountered.

In the western part of the central folded belt, there is an angular unconformity at the base of the predominantly arenaceous Cambrian sequence, and over the crests of the anticlines the basal sand of the Pertaoorrta Group is missing and the Pertatataka Formation has been eroded away. Many of the anticlines are breached to Proterozoic rocks and the Bitter Springs Formation is exposed in the cores of the folds. The unconformity gradually disappears towards the east, and a complete sequence is present between the Proterozoic rocks and the predominantly calcareous rocks of the Pertaoorrta Group in the Ooraminna Anticline (Pl. 38, fig. 2). The 'bald-headed' type of structure showing the basal Cambrian unconformity in the west and the change in composition of the Pertaoorrta Group from west to east are due primarily to the effects of the Petermann Ranges Orogeny, which occurred after the deposition of the Pertatataka Formation and the equivalent Winnall Beds. The eroded anticlinal crests in the Proterozoic rocks were covered by early Middle Cambrian sediments of the Tempe Formation, and then by predominantly arenaceous rocks, whereas to the east predominantly calcareous rocks were deposited farther from the provenance area. It is uncertain whether the Lower Cambrian Eninta Sandstone at the base of the Pertaoorrta Group underlies the flanks of the anticlines in the central folded belt, but it does crop out in the Gardiner Range to the north, where it overlies the Pertatataka Formation with angular unconformity. In places, the equivalent(?) Quandong Conglomerate is thinly developed on the crests of the folds. The Eninta Sandstone could form a buttress sand reservoir at the unconformity surface.

The wells in the central folded belt were drilled to test the petroleum potential of the Cambrian and Proterozoic sequences. Most of the wells revealed residual hydrocarbons and some fluorescence in the Cambrian rocks and Bitter Springs Formation. The Cambrian formations penetrated, and their correlations, are shown in Figure 70, and the Proterozoic formations in Figure 71.

The Chandler Limestone, or its equivalent, invariably has signs of petroleum, and most of the outcrops include beds of black foetid bituminous limestone. Ooraminna No. 1 produced gas at the rate of about 12,000 cfd from pyritic dark grey shale and dolomitic limestone in the Areyonga Formation. Intergranular porosity is present in the Arumbera Sandstone and Goyder Formation. Some fracture porosity is present in the Cambrian and Proterozoic sequences and vuggy porosity was noted in the Cambrian carbonate rocks in Waterhouse No. 1; by contrast there was very little porosity in the Arumbera Sandstone.

The presence of water in the Petermann Sandstone, the upper part of the Deception Formation, and the Illara Sandstone indicate some permeability. The water is mostly fresh, which suggests that the reservoirs have been flushed out, whereas the upper part of the Tempe Formation is moderately porous and contains salt water. The Goyder Formation and upper part of the Cleland Sandstone in Ochre Hill No. 1 contain porous sands, and permeability is indicated by flows of fresh water. The sandstone in the Bitter Springs Formation in East Johnny Creek No. 1 showed intergranular porosity.

Southern Area

In the southern area, the few wells drilled have generally encountered unprospective sediments. Erldunda No. 1, for example, penetrated over 4000 feet of Proterozoic rocks in a total depth of 5463 feet (Fig. 71). Seismic surveys support the field evidence that 2000 to 3000 feet of Palaeozoic rocks rest unconformably on large thicknesses of Proterozoic sediments. The thin sequence of Palaeozoic rocks in the area are unlikely to contain potential source rocks because they are unfossiliferous, arenaceous, and partly continental. There are no cap rocks over most of the sequence.

The seismic surveys indicate several large structures with large closure in the Proterozoic formations, and diapiric folds with Bitter Springs evaporite in their axial zones are probably present. The ability of Proterozoic rocks, in particular the Bitter Springs Formation, to produce petroleum must be regarded with some reserve at present. Analyses of the hydrocarbons in the black shale from the Bitter Springs Formation in Mount Charlotte No. 1 indicates a source rock of moderate quality (McTaggart et al., 1965, unpubl.). The Proterozoic sequence above the Bitter Springs Formation in the south contains a few reservoir rocks, and the Cambrian Arumbera Sandstone, a potential reservoir rock for Proterozoic oil migration, was not deposited in the south.

Most of the Larapinta Group is missing in Mount Charlotte No. 1 (Fig. 69), but 1400 feet of Cambrian sediments were penetrated (Fig. 70). Seismic structure contours show that the apex of the structure in the Bitter Springs Formation does not coincide with that in the Cambrian sediments, and the well was sited midway between them. The outcrops near the well site are flat-lying sediments of the Finke Group. The only petroleum indications in the well were small shows of wet gas and fluorescence in black shale of the Bitter Springs Formation. The Cambrian sequence lacked porosity and gave no indication of hydrocarbons. There does not appear to be any likelihood of permeable Cambrian reservoir beds in this region. The southern marginal facies of the Cambrian is generally silty, and thin porous sands have only been noted in a few places.

Western Margin of Great Artesian Basin

McDills No. 1 (Fig. 68) and Hale No. 1* have been drilled to completion to test the sequence on the western fringe of the Great Artesian Basin. McDills No. 1 was drilled on a seismically defined asymmetrical anticline below flat-lying Mesozoic rocks. The only hydrocarbon indication in the well was a small gas show in the lower part of the Rumbalara Shale.

Porosity is present in the De Souza Sandstone (25-35%), the Crown Point Formation (15-25%), the Finke Group (20-25%), and the Mereenie Sandstone (10-15%), and these formations probably have good reservoir potential. The Mereenie Sandstone would be an excellent reservoir for petroleum generated in any thick sequence of Lower Palaeozoic marine sediments. The Todd River Dolomite penetrated in the bottom of the well is a possible source rock. However, as the top of the formation has been eroded and may have been left uncovered for a considerable length of time, any hydrocarbons may have escaped. There are only a few encouraging petroleum indications in similar Cambrian carbonate rocks tested in the Amadeus Basin.

McDills No. 1 penetrated only a thin sequence of possible Ordovician sandstone between the Todd River Dolomite and the Mereenie Sandstone: the age is based only on stratigraphic position and lithological similarity to Ordovician sediments in the Amadeus Basin. Thick sequences of Palaeozoic rocks may have been eroded from the crests of the anticlines in this area leaving thicker sediments preserved on the flanks of the folds; but it is more likely that a large part of the Palaeozoic sequence was stripped from most of the region. The effects of the Rodingan Movement and the subsequent period of erosion in the eastern part of the basin may have extended farther east, in which case not only would the Larapinta Group be removed, but a large part if not all of the Pertaoorrta Group may have been eroded in parts of the Simpson Desert.

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*Details of Hale No. 1 were received too late to be included in the text.

The isopach maps of the Palaeozoic sediments in the Amadeus Basin show that they thin out considerably towards the east, and all the Larapinta Group formations except the Stairway Sandstone pinch out in the southeast.

The Kulgera seismic survey (Milliken & Bowman, 1965, unpubl.) has shown that the southeast margin of the basin appears to be a major fault, which can be projected to the northeast through Mount Kingston and the Black Hill Range and has been outlined by the aeromagnetic survey. The northeasterly trend of outcrops of the Finke Group and Mesozoic sediments beyond Horseshoe Bend is probably a surface expression of the extension of the faulted basement high. South and east of this fault both gravity and aeromagnetic surveys show shallow basement. This is supported by the BMR refraction seismic survey at Lilla Creek and the BMR Finke No. 1 Bore (Fig. 67).

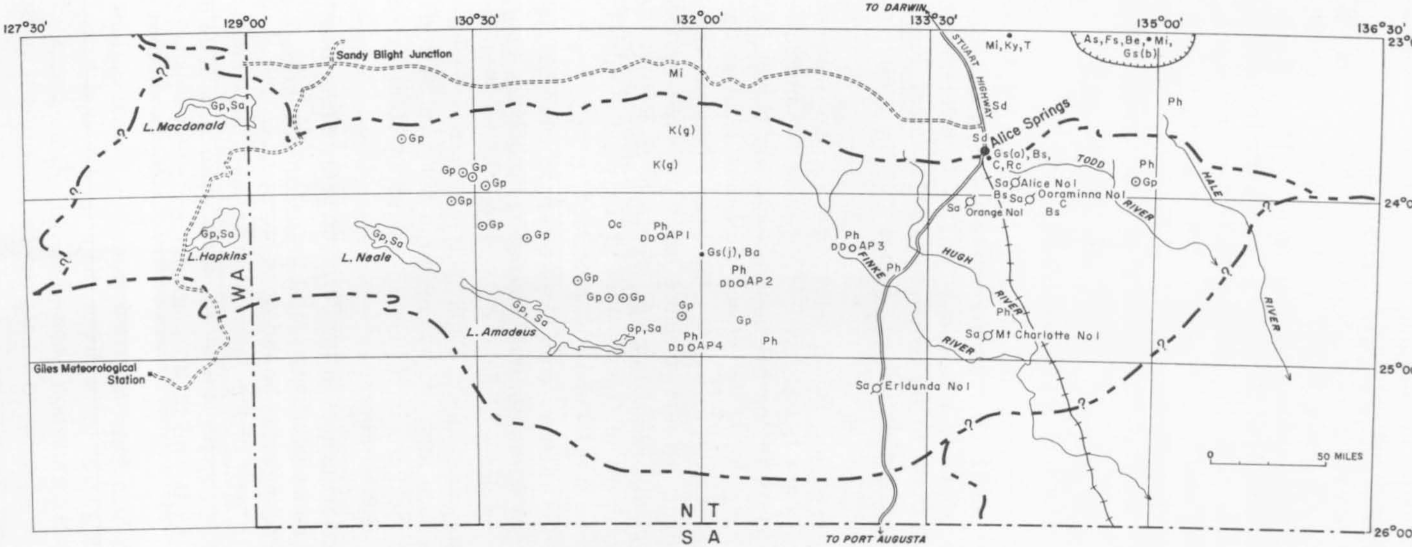
Summary and Conclusions

The main exploration programme in the Amadeus Basin is now focused on the northern area, where there has been intensive exploration by seismic methods. The surveys were designed primarily to locate structures beneath the continental sediments of the Pertnjara Group in the Brewer and Missionary Plains, and to outline any concealed structures in the area as far west as the central part of the Mount Rennie Sheet area.

The central-northern part of the basin, where a complete sequence of the Larapinta and Pertaoorrta Groups is preserved, is the most favourable for further exploration. The seismic surveys in the Missionary Plain, on behalf of Magellan Petroleum (N.T.) Pty Ltd, have shown that closed structures occur in the potential Ordovician and Cambrian reservoir rocks in some places beneath the Pertnjara Group. They are shown on the seismic structure maps prepared by Geophysical Associates (Krieg & Campbell, 1965, unpubl.; Froelich & Krieg, 1969). The Tyler Structure (Pl. 46), northeast of Gosses Bluff, is a typical closure in an area in which the full Larapinta Group sequence is preserved.

There are other prominent structures with closure beneath the Pertnjara Group near the western end of the Waterhouse and Ooraminna Anticlines. Orange No. 1 was recently drilled on a seismically defined dome beneath the Pertnjara Group between the Waterhouse and Ooraminna Anticlines, but it was found that part of the Larapinta Group has been removed by erosion in this area. A horizon about 4000 feet below the top of the Pertaoorrta Group has about 1000 feet of closure over an area of about 42 square miles.

One of the most important sequences in the Pertaoorrta Group is the area where the eastern carbonate-shale facies interfingers with the sandstone facies to the west. The transition occurs over an area bounded approximately by Parana Hill, Petermann Hills, the western part of the James Ranges, and the Gardiner Range. Important reservoir rocks may be present in the north-south zone trending across the basin on which the Illamurta and other structures are situated (see pp 153-4), and where it intersects the transition area. Any existing traps would be favourably situated for hydrocarbons which have migrated from the marine carbonate rocks of the Pertaoorrta Group. Some of the wells in the central folded belt penetrated sections of these rocks in the transition zone (Fig. 70). Only traces of residual hydrocarbons and gas have been found; many of the sandstones possess intergranular porosity, but contain fresh water.



As Asbestos
Ba Baryte
Be Beryl
Bs Building stone
C Coal
Fs Feldspar
Fl Fluorspar
Gs Gemstones
(b) Beryl
(o) Opal
(j) Jasper
Gp Gypsum
K(g) Potash (glauconite)
Ky Kyanite
Mi Mica
Oc Ochre
Ph Rock phosphate (only principal localities shown)
Rc Aggregate
Sa Halite
Sd Sand and gravel
T Talc

⊙ Diapiric structure
DDOAP1 Diamond drill hole (phosphate search)
ø Dry oil exploration well (abandoned)—salt in sequence
Approximate limit of Harts Range Mica Field

NOTE: Where non-metallic deposits involve the whole of a formation (e.g. dolomite in the Bitter Springs Formation) this is not shown. The distribution map for the relevant formation should be consulted in such cases

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Fig. 74. Occurrences of non-metallic minerals.

Further exploration along the Mereenie anticlinal trend is warranted to ascertain if reversals are present, and further wells are required at Palm Valley to delineate the gas field and ascertain if oil is present.

The remaining parts of the basin can be given lower priority. The large areas of outcropping Proterozoic rocks and their subsurface extensions are considered to be poor prospects. The sediments are practically unmetamorphosed, and contain some residual hydrocarbons and small amounts of gas, but it seems unlikely that they contain large quantities of hydrocarbons.

In the west, there is only a relatively thin marginal sequence of Ordovician rocks, and the Cambrian sequence is represented by deltaic sandstone, which can only be considered worthy of further prospecting if it can be demonstrated that petroleum has migrated into the sandstone facies of the Pertaoorrta Group in the central part of the basin. Most of the exposed anticlines are breached, and Proterozoic rocks are exposed in the eroded cores.

In the east, most of the Larapinta Group has generally been removed by erosion, and the Cambrian sediments are generally too deeply dissected to be prospective.

In the Simpson Desert, the Mesozoic, Permian, and Devono-Carboniferous sediments contain potential reservoirs. Possible source rocks include the Lower Cambrian carbonate sediments and the marine equivalents of the Permian sediments developed basinwards. Present indications suggest that most of the Palaeozoic source rocks have been removed by erosion, and much of the sequence as known in the Amadeus Basin was not deposited. The problem remains to discover areas of thick Palaeozoic source beds. A large part of the sequence consists of over 3000 feet of non-prospective deltaic, fluviatile, and transitional deposits of the Finke Group which would add considerably to the cost of drilling.

NON-METALLIC DEPOSITS

(Fig. 74; Table 5)

Few of the non-metallic mineral deposits in the Amadeus Basin are of economic importance.

The ochre deposits have been described by Sullivan & Öpik (1951), the mica in the Harts Range and Strangways Range areas by Joklik (1955), and the phosphate deposits by Barrie (1964, unpubl.) and Cook (1966a, unpubl.); McLeod (1966) has given a general account of the mineral resources of the Northern Territory.

Asbestos

Anthophyllite veins occur in serpentine in the Brett Creek area of the Harts Range. The asbestos is of poor quality and is unlikely to be of economic value.

Barite

Veins of barite, up to about 6 inches thick, occur in the Bitter Springs Formation in the core of the Parana Hill Anticline.

Beryl

Small quantities of beryl are found in association with potash feldspar in some of the mica-bearing pegmatites of the Harts Range.

TABLE 5. STRATIGRAPHIC DISTRIBUTION OF NON-METALLIC MINERALS

Geological formations (and their equivalents)						clays						gemstones										potash					
		asbestos	barite	beryl	building stone	brick	ceramic	coal	dolomite	feldspar	fluorspar	beryl	garnet	opal	jasper	gypsum	kyanite	limestone	mica	ochre	phosphate	carnallite, sylvite etc	glauconite	halite	sand and gravel	aggregate	talc
CAINOZOIC	QUATERNARY															X						?		O	O		
	TERTIARY					X	X	+						+				O									
MESOZOIC	Rumbalara Sh and De Sousa Sst					X	X													O							
DEVONO-CARBONIFEROUS(?)	Pertnjara Gp				O	X																					
SILURO(?)-DEVONIAN	Mereenie Sst																										
Larapinta Gp (CAMBRO-ORDOVICIAN)	Carmichael Sst																										
	Stokes Sltst					X															+						
	Stairway Sst					X															X		+				
	Horn Valley Sltst					X														+	+		+				
	Pacoota Sst				O																+		X				
Pertaoorrta Gp (CAMBRIAN)	Goyder Fm																			+							
	Jay Creek Lst				O				X									X									
	Hugh River Sh					X																					
	Tempe Fm																	X			+		+				
	Chandler Lst																	X				?		X			
	Arumbera Sst				O																		+				
PROTEROZOIC	Pertatataka Fm					X			X									X		+			+			X	
	Areyonga Fm														X						+						
	Bitter Springs Fm		+						X							X		X				?		X		X	
	Heavitree Qzt				O									+												O	
BASEMENT	Arunta Complex	+		+						X	+	X	X				+		O		+						+
	Musgrave—Mann Complex			?						X	?	?	?						?		?						?

? *Probably present, but not so far reported* + *Present in minor quantities* X *Present in moderate or large quantities (not necessarily commercial)* O *Large quantities (is being worked or has been worked commercially)*

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Building Stone

Sandstones from the Heavitree Quartzite, Arumbera Sandstone, Pacoota Sandstone, and Hermannsburg Sandstone of the Pertnjara Group have been used for building stone on cattle stations and in Alice Springs. The Jay Creek Limestone has been used for building at the Santa Teresa Mission.

Clay

Some of the Proterozoic and Palaeozoic lutites may be suitable for brick-making and the Tertiary clays for ceramics.

Coal

Thin beds of lignite occur in the Tertiary sediments of the Farm area south of Alice Springs. The deposits occur at a depth of 900 to 1000 feet, and have a high ash content. Similar occurrences have been reported near Yam Creek north of the Santa Teresa Mission, near the Palmer River, and at 16-mile Bore on Burt Plain. Coal may also be present in other Tertiary basins around the eastern MacDonnell Ranges (e.g. near Ambalindum homestead).

Dolomite

The Bitter Springs Formation, Pertatataka Formation, and Pertaoorrta Group contain large reserves of dolomite. Commercial exploitation seems unlikely because of the remoteness of the occurrences from potential markets.

Feldspar

Microcline is common in the thick pegmatites of the Arunta Complex in the Harts Range.

Fluorspar

Fluorspar has been reported in the eastern MacDonnell Ranges, but no details are available.

Gemstones

Beryl occurs in the eastern MacDonnell Ranges and in the pegmatites of the Harts Range, but gem-quality material is only found in small amounts. Almandite is common in the eastern MacDonnell Ranges (e.g. Lizzie Creek); some of the stones are of gem quality.

Rare occurrences of opal have been reported in the duricrust on the Heavitree Quartzite, and jasper is common in the Areyonga Formation and Inindia Beds.

Gypsum

Gypsum is common in the salt lakes (Lake Macdonald, Lake Amadeus, etc), and one attempt has been made to exploit the deposits in the Erldunda area for use in the local building industry. It is also common in the Bitter Springs Formation, and occurs in the cores of many of the diapiric structures in the Lake Amadeus and Mount Rennie Sheet areas.

Kyanite

Kyanite-biotite schist crops out in the Strangways Ranges northerly from Alice Springs and kyanite occurs in the Dean Quartzite. It is richest in local valley-fill deposits at the base of the quartzite in the Petermann Ranges. A review of the aluminium silicate minerals and their potential economic significance in central Australia is given in Kalix et al. (1970).

Limestone

Thick beds of limestone occur in the Bitter Springs Formation, Pertatataka Formation, and Pertaoorrta Group; Tertiary limestone and travertine are also common. Travertine has been used for the manufacture of lime in the Alice Springs area.

Mica

Mica has been mined mainly in the Harts Range Mica Field about 80 miles north-east of Alice Springs, but small quantities of phlogopite have been mined in the Strangways Range, about 35 miles north-northeast of Alice Springs.

The Harts Range Mica Field (Joklik, 1954) has been worked sporadically since about 1890, but all activity ceased in 1961. The total value of the mica produced is over $2,000,000. The mica is mainly good-quality muscovite; it occurs in pegmatites, in the Arunta Complex, which are widely distributed over an area of about 400 square miles.

Ochre

Ochreous bands occur in various formations. There is a minor ochre occurrence in the Goyder Formation at Ochre Hill, but good-quality ochre is found only in the Cretaceous sediments around Rumbalara.

The yellow ochre occurs in a horizontal bed 1 to 4 feet thick in several mesas east of Rumbalara siding. The ochre is of good quality, and contains up to 55 percent ferric oxide. Until 1951, when the mine was closed, the deposit supplied the bulk of Australia's needs; a total of 7900 tons, valued at about $60,000, was extracted. Artificial pigments are now widely used, and it is unlikely that the mine will reopen.

Phosphate

Pelletal phosphorites occur in the Areyonga Formation, Tempe Formation, Pacoota Sandstone, Horn Valley Siltstone, Stairway Sandstone, and Stokes Siltstone. Other formations, such as those in the Pertaoorrta Group, which in places contain the typical black shale-chert assemblage of Sheldon (1964), have not been thoroughly examined. Schmerber & Ozimic (1966, unpubl.) report phosphate intervals in the Bitter Springs and Pertatataka Formations. Apatite also occurs in the Arunta Complex.

Areyonga Formation. Thin phosphorites occur in the basal conglomerate of the Areyonga Formation, about 8 miles north of Ringwood homestead (Wells et al., 1967). The basal conglomerate, which overlies the Bitter Springs Formation, is about 4 feet thick and is composed of subangular pebbles, cobbles, and boulders with a poorly sorted quartz arenite matrix which is phosphatic in part. The lenticular phosphatic bands range from 3 inches to 1 foot thick, and from 5 to 10 feet long. The phosphatic mineral (cryptocrystalline apatite?) is grey or black and occurs as thin stringers (Pl. 39, fig. 1), commonly interbedded with thin laminae of chert. Samples of the conglomerate were found to contain 1 to 7 percent P_2O_5, and individual phosphorite bands contain up to 30 percent P_2O_5. The deposits are too small to warrant commercial exploitation.

Tempe Formation. Thin pelletal phosphorites occur in a few places in the Tempe Formation. They are associated with glauconitic sandy limestone which contains abundant echinoderm plates and phosphatic brachiopod shells. Some of the pellets appear to be fragments of phosphatic shells which have been rounded by current action, but most have a concentric structure around a nucleus of quartz or calcite.

The phosphatic bands are of low grade and of limited lateral extent and thickness; the formation has little economic potential, unless high P_2O_5 values are found in the associated black shale.

Pacoota Sandstone. The Pacoota Sandstone is generally poorly phosphatic; but rare phosphatic pellets are scattered throughout the orthoquartzite, and the rare pelletal and nodular bands contain up to 16 percent P_2O_5. The pellets and nodules contain abundant detrital quartz and are equivalent to the 'sandy pellets' in the Stairway Sandstone. These phosphorites are unlikely to be of economic importance.

Horn Valley Siltstone. The Horn Valley Siltstone is slightly phosphatic throughout, and probably averages about 1 percent P_2O_5. There are also a few pelletal phosphorite bands near the top of the formation. The pellets occur in limestone, sandstone, or siltstone. The maximum P_2O_5 content recorded in the Horn Valley Siltstone is 7 percent. The pelletal bands are generally only about 1 inch thick, but a phosphatic band about 12 inches thick occurs near the top of the formation in outcrops northwest of Monument Waterhole on the south flank of the James Ranges. There are no economic phosphorites in the Horn Valley Siltstone.

Stairway Sandstone. Phosphorites occur sporadically throughout the Stairway Sandstone, but are particularly common in the lutites in the middle of the formation. The phosphatic bands are generally pelletal or nodular in form, and range from less than 1 inch to 8 inches thick. They are poorly exposed, and their lateral extent is unknown. The nodules range up to 5 inches in diameter; they are grey, brown, white, or purple in outcrop, but invariably black subsurface. The pelletal bands contain up to 22 percent P_2O_5, and individual nodules up to 27 percent. The brown pellets, which are well rounded, subspherical, and sandy contain up to 12 percent P_2O_5.

Cook (1966a, unpubl.) has shown that there are ten distinctive modes of occurrence of the phosphatic mineral (generally cryptocrystalline apatite) which are characterized by their internal or external structure. Numerically, the two most important types are the 'structureless' pellets, which show no internal structure, and the 'sandy' pellets, which contain a high percentage of terrigenous quartz grains. Other pelletal types show 'concentric', 'irregular', 'composite', or 'encasing' internal forms. The phosphate may also form the cement in arenites, have a laminate habit, replace fossils, or occur as secondary phosphate minerals.

The phosphorites occur throughout the Stairway Sandstone, and about 200 individual phosphatic bands were identified in the AP1 corehole, but most of the bands are found in silty units or in thin sandy bands (Pl. 39, fig. 2; Pl. 40, fig. 1) within silty units, and rarely in limestone bands (Pl. 40, fig. 2).

There are very large reserves of phosphate in the Stairway Sandstone, but most of it is too low in grade to be workable. Economic concentrations might possibly be found in regions where there has been vigorous winnowing. In addition, in the Johnny Creek area some of the Quaternary gravels are composed almost entirely of phosphatic pellets and nodules derived from the underlying Stairway Sandstone.

Stokes Siltstone. Thin pelletal phosphorites, similar to those in the Stairway Sandstone, occur near the base of the Stokes Siltstone. The maximum P_2O_5

content recorded is 13.9 percent in a sample from the Johnny Creek area, but the Stokes Siltstone is unlikely to contain phosphorites of economic importance.

Origin of the Sedimentary Phosphorites. Most of the phosphorites are shallow marine shelf deposits. The ultimate source of the phosphate was probably cold upwelling oceanic currents which impinged upon the shelf (see Sheldon, 1964, for a discussion of this concept). A notable feature of the phosphate pellets in the Stairway Sandstone is the marked textural difference of detrital grains in the pellets compared with those of the surrounding matrix. Barrie (1964, unpubl.) and K. A. W. Crook (pers. comm.) have suggested that the textural difference is due to the pellets being allochthonous. Cook (1966a, unpubl.) has however shown that the pellets are 'lag deposits' concentrated by winnowing action. The skewness* values of the sediments associated with the phosphorites vary inversely as the P_2O_5 content; this relationship can be explained by the winnowing out of the fine material from the coarser residual quartz and phosphatic pellets and nodules.

The phosphorites of the Areyonga Formation are amongst the oldest sedimentary phosphorites known (the age of the overlying Pertatataka Formation is about 730 m.y.). They were formed on an unconformity surface. The association of phosphorites with a formation regarded as predominantly glacigene is unusual: the glaciomarine sediments on the Antarctic shelf are markedly deficient in phosphorus. This deposit has not been studied in detail and its origin is uncertain. It is likely that most of it formed as a residual deposit rather than as a primary precipitate. Such karst phosphorites are a fairly common feature of unconformity surfaces on the top of a limestone. They result from the weathering out of a slightly phosphatic limestone, and the fluorapatite, being considerably less soluble than calcite or dolomite, forms a residuum.

Arunta Complex. Bodies rich in magnetite and apatite occur at two localities in the Arunta Complex.

McCarthy (*in* Forman et al., 1967) has described a magnetite-apatite metaquartzite containing about 15 percent apatite, from the upper reaches of Illogwa Creek. The metaquartzite shows sedimentary banding and the body is probably a metamorphosed sedimentary phosphorite of Precambrian age. Owen (1944, unpubl.) has recorded small bodies rich in magnetite and apatite in the Alcoota Sheet area; he thought they were pegmatites in a metamorphosed limestone in the Arunta Complex, but the occurrences appear to be similar to those described by McCarthy. Up to 38.7 percent P_2O_5 has been recorded in samples from the Alcoota area, but the deposit is considered to be uneconomic by Owen. I. P. Youles & D. R. Woolley (pers. comm.) consider that recent geophysical work (Tipper, 1966, unpubl.) suggests that reserves may be the order of 100,000 tons of apatite per vertical foot.

Apatite, magnetite, and zircon occur in probable carbonatites in the Strangways Range about 60 miles north-northeast of Alice Springs (Crohn & Gellatley, 1968, unpubl.). The minerals occur in a group of crystalline calcitic and dolomitic carbonate rocks which are surrounded by schist, gneiss, and basic igneous rocks of the Precambrian Arunta Complex. The apatite occurs as massive aggregates, some of

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*Skewness is a measure of the degree of asymmetry of a sediment (Folk & Ward, 1957).

which are up to 2 feet in diameter, the magnetite occurs in crystals up to 3 inches across and the zircon crystals are up to 6 inches across. Trace elements in the samples are present in greater concentrations than those normally found in sedimentary carbonate rocks.

Potash

Carnallite and sylvite may be present in the evaporites in the Bitter Springs Formation and associated diapirs and salt anticlines, and in the Cambrian Chandler Limestone, although they have not been recorded in any of the analysed specimens of the bedded evaporites or of the salts in the Lake Amadeus salt lake system.

Glauconite occurs in the Pertatataka Formation, Tempe Formation, Arumbera Sandstone, Pacoota Sandstone, Horn Valley Siltstone, and Stairway Sandstone. A rich concentration occurs in the Pacoota Sandstone, in a 20-foot interval about 500 feet below the top of the formation in the Idirriki and Gardiner Ranges. In places, the glauconite forms up to 50 percent of the rock. The beds are gently dipping, and the reserves are probably large.

Youles (1966b, unpubl.) has reported the presence of potash in grey-green, red-brown, and brecciated siltstone of the Areyonga Formation from diamond drill cores at the Ringwood copper prospect about 20 miles southeast of Ringwood homestead. Several samples of grey-green siltstone above a depth of 256 feet in hole No. 1 were found to contain 5.3 to 6.0 percent K_2O. Below 256 feet, the K_2O values ranged from 3.6 to 3.8 percent.

Salt (halite)

Halite is found in the Bitter Springs Formation in the Ooraminna No. 1, Mount Charlotte No. 1, and Erldunda No. 1 wells, and in the Chandler Limestone in the Alice No. 1, Orange No. 1, and Mount Charlotte No. 1 wells, but is nowhere found in outcrop. Salt incrustations, generally in association with gypsum, cover the surfaces of Lakes Amadeus, Neale, Hopkins, and Macdonald. Salt has been extracted from the eastern end of Lake Amadeus for local use.

Sand, Gravel, and Aggregate

Sand and gravel for the building industry in Alice Springs is extracted from the bed of the Todd River just north of the township, and from Sixteen Mile Creek farther north. Reserves are large. Unlimited supplies of fine aeolian sand are available in many parts of the area.

Aggregate is obtained by crushing the Heavitree Quartzite near Alice Springs. Some of the massive limestone and dolomite in the Bitter Springs and Pertatataka Formations may also be suitable for aggregate.

Talc

Talc schist occurs in the Strangways Range, 40 miles north-northeast of Alice Springs, but the deposit is small and low grade. Disseminated talc occurs in the Pinyinna Beds at Chirnside Creek in the Petermann Ranges.

Metalliferous Deposits

Copper

Forman (1966c) and Wells et al. (1964) have reported occurrences of copper on the southwestern margin of the Amadeus Basin, but none of them is of economic importance.

On the northeastern margin, copper has been recorded in a number of localities, principally in the gold fields and in the northwesterly extension of the belt of gold mineralization (Forman et al., 1967). The copper occurs in stockworks of red copper oxide in quartz on the edges of intrusive quartz reefs, or as veins containing malachite, azurite, and atacamite. Chalcanthite has also been recorded. Arsenic is associated with the copper in the Excelsior mine, White Range. Copper shows also occur within a 5-mile radius east and north of Southern Cross Bore; 3 miles south-southwest and 7 miles south of Mount Riddock homestead; and 2 miles north of Ruby Gap.

A minor occurrence of copper, near Haast Bluff Native Settlement, is reported in Wells et al. (1965).

Copper has also been reported in the Pertaoorrta and Larapinta Groups (Ranford et al., 1966), and copper mineralization is known in four localities in the Henbury Sheet area (Ranford et al., 1966; Bell, 1953a, b, both unpubl.).

Malachite and cuprite occur in the Goyder Formation on the northern flank of the Waterhouse Range Anticline (Owen Springs prospect). Some nickel is also present. The copper appears to be stratigraphically controlled, and may be syngenetic: no veins or intrusives are known in the area. Five holes were drilled by the Titanium Alloy Manufacturing Company in 1954 to investigate the deposit, but the results were disappointing and the project was abandoned.

Copper minerals occur in a crush zone or fault breccia in the Eninta Sandstone about 10 miles east-southeast of the Areyonga Native Settlement (Namatjiras prospect). There is evidence of the presence of syngenetic copper in the Eninta Sandstone nearby, and the concentration in the fault breccia was probably derived from the sandstone. One mineralized specimen from the fault breccia was found to consist mainly of a fine-grained mixture of chalcocite and digenite, with subordinate chrysocolla, covellite, malachite, and azurite, and possibly some enargite and gold.

Pellets of malachite occur in micaceous sandstone of the Goyder Formation, near Alalgara Yard, about 22 miles northwest of Henbury homestead (Lalgra prospect).

Malachite has been reported in a band of ferruginous oolite grit, 5 to 10 feet thick, in the banks of the Finke River, about 42 miles north-northwest of Henbury homestead (Bell, 1953b, unpubl.). Unlike the other copper shows this occurrence is in the Larapinta Group.

Patchy copper mineralization occurs in the Pinnacles Bore area about 35 miles north-northeast of Alice Springs. Drill sites have been selected to test the deposits.

Native copper and chalcocite occur in the Arunta Complex near Tommys Gap near the front of the Arltunga Nappe Complex.

The copper mineralization in the basal part of the Areyonga Formation, about 2 miles south of the Phillipson No. 6 Bore, has been investigated by two drill holes (Youles, 1966b, unpubl.). The green and grey siltstone intervals in the formation contain chalcopyrite, and secondary copper minerals have been traced at the surface for 7 miles along strike. Spectrographic analyses show up to 2500 ppm of copper and up to 120 ppm cobalt in the mineralized intervals.

The mineralized zone in the Bitter Springs Formation at Undoolya Gap extends over about 2 feet, and values of 0.2 and 0.5 percent copper were recorded (Youles, 1966a, unpubl.). The sequence penetrated in the drill hole was part of the Gillen Member.

Lead, Zinc, Silver, and Bismuth

Secondary lead and copper minerals, galena, silver, and gold have been found in small quartz veins intruding the Mount Harris Basalt in the Bloods Range Sheet area (Forman, 1966a).

On the northeastern margin of the basin, small occurrences of lead, associated with silver, and in one case with bismuth, have been prospected at the Glankroil mine on the Winnecke Goldfield; at Kennys prospect, a few miles to the north; and at a locality about 1 mile west of Mount Gordon. Two samples from Kennys prospect (unpubl. AMDL Report AN339-63) assayed 30 and 14 oz of silver per long ton.

About 900 samples of exploratory well cuttings, at intervals of 10 feet, from the Ooraminna No. 1, Waterhouse No. 1, and Alice No. 1 wells have been analysed for base metals (Youles, 1966c, unpubl.). Spectropraphic analyses on the samples from Ooraminna No. 1 revealed consistent high lead and zinc values in the 450-foot shale section near the top of the Pertatataka Formation. Maximum values were: lead, 2000 ppm, and zinc, 800 ppm. The lead apparently occurs as oxide and the zinc as carbonate. In the samples from Waterhouse No. 1, sporadic high lead values occur near the base of the Jay Creek Limestone, but no high zinc values were recorded. In the Alice No. 1 cuttings the whole of the Goyder Formation was found to contain high values of lead (400-800 ppm) and zinc (up to 400 ppm).

Gossans

Ferruginous cappings are widespread on the Pinyinna Beds in the Petermann Ranges in the southwest. Four prospects were briefly inspected at Butler Dome, Stevensons Peak, Katamala Cone, and Chirnside Creek by the Bureau in 1966 (J. F. Ivanac, pers. comm.) and the following remarks are condensed from his unpublished report.

At Butler Dome three groups of steeply dipping manganiferous and siliceous gossans and collapse breccias extend over a strike length of about 7000 feet. Each group is about 1000 feet long, and occurs in highly folded and contorted carbonaceous and dolomitic rocks of the Pinyinna Beds. The main gossan is 45 feet wide, and stands out as a prominent blue-black outcrop. A shaft, about 40 feet deep, has been sunk in the footwall of the gossan to prospect quartz veins which cut it. The gossans contain boxworks and limonite derived from sulphides. The surrounding sediments are rich in muscovite, and contain substantial amounts of limonite and hematite. Several chip samples of the gossans were found to contain anomalous lead, zinc, and cobalt values. The results are tabulated in Table 6.

Three other localities showed minor gossanous material, but no upstanding jasper bodies similar to those at Butler Dome. There appears to be a change from carbonaceous to dolomitic facies westwards from Butler Dome.

The gossans in the region have been prospected by Planet Metals.

Trace element analysis on 20 samples from Butlers Dome, Chirnside Creek, and Stevensons Peak in the Petermann Ranges is tabulated in Table 6. Trace metals were extracted by digestion with hydrochloric/nitric acid and determined by atomic absorption spectrophotometry.

TABLE 6. TRACE ELEMENTS IN GOSSANS, PETERMANN RANGES

Locality and Sample No.	Cu (ppm)	Pb (ppm)	Zn (ppm)	Co (ppm)	Ni (ppm)	Cd (ppm)	Ag (ppm)
Butlers Dome							
G1A	66	60	50	37	46	<1	<2
G1B	70	60	170	240	86	2	3
G1C	15	20	17	9	12	<1	<2
G1D	<2	<10	1	<5	<5	<1	<2
G1E	175	20	79	25	49	<1	<2
G1F	51	25	180	140	52	<1	<2
G1G	120	15	640	980	120	4	6
G1H	32	20	500	170	125	2	<2
G1I	41	40	29	15	22	<1	<2
G1J	53	25	55	43	43	<1	<2
G1K	62	25	140	31	46	<1	<2
G1L	200	25	110	21	46	<1	<2
G1M	350	15	64	25	26	<1	<2
G1N	150	15	77	15	45	<1	<2
G1O	290	20	100	27	62	<1	<2
G1P	3	<10	2	<5	<5	<1	<2
G1Q	<2	<10	2	<5	<5	<1	<2
G1R	57	<10	33	10	18	<1	<2
Stevensons Peak							
G41	28	25	470	1300	100	7	2
Chirnside Creek							
G51	3	25	25	12	14	1	2

All digestions were analysed for Au by solvent extraction followed by atomic adsorption spectrophotometry. Au was not detected at a limit of 1 ppm for all samples.

Analysts: A. D. Haldane and J. R. Beevers, B.M.R.

Tin and Columbite

Small amounts of tin have been reported from two of the copper prospects in the Strangways Range, and a little columbite has been recorded in the pegmatites in the Harts and Strangways Ranges.

Radioactive Minerals

Small amounts of betafite, samarskite, and monazite have been recorded in the mica-bearing pegmatites in the Harts and Strangways Ranges. Walpole (1951, unpubl.) has reported on minor occurrences of radioactive minerals in the Mount Cavenagh area near Kulgera.

Gold

Deposits of gold were worked at Arltunga (near Mount Gordon), Winnecke, and White Range between 1897 and 1937. Attempts to discover new deposits have been discouraging.

Only a small amount of gold has been won from the Winnecke Goldfield and production figures are incomplete. Hossfeld (1940) states that the total recorded production was 933 oz of reef gold and 127 oz of alluvial gold up to the latter part of 1905. From 1933 to mid-1937 the recorded production of reef gold was 275 oz.

Iron

Ferruginous and manganiferous surface encrustations are found above the Goyder Formation, and up to 59 percent iron has been recorded in a selected sample from the south side of the Levi Range about 18 miles southwest of Tempe Downs homestead. Thin beds of pisolitic ironstone are present in the Horn Valley Siltstone on the western side of the Amadeus Basin. Near Running Water Yard, on the Finke River, flat-lying ferruginized sediments crop out over an area of about 20 square miles. A specimen of the ferruginized sediment was found to contain 43.5 percent iron and 10 percent silica. Small limonitic deposits on the Bitter Springs Formation have been reported in the northeast (Wells et al., 1967).

Nickel

Nickeliferous ochre occurs in the Claude Hills of South Australia. The nickeliferous ochres overlie the centre of an ultramafic intrusion bounded by norite and pyroxenite. The ochre is intimately associated with jasper and magnesite, and is underlain by serpentinite. Work has been carried out by the South Australian Mines Department to test possible extensions of this deposit into the Northern Territory (Miller & Rowan, 1968).

Of four boreholes drilled in the Northern Territory three found no ochre or evidence of ochre or deep chemical weathering. One hole encountered a low-grade siliceous ochre beneath 40 feet of Quaternary sediments. Average grade of the ochre profile was 0.51 percent nickel over a depth of 153 feet.

There are no other records of significant or anomalous nickel values along the margins of the Amadeus Basin, but there are large areas of metamorphosed mafic rocks in the Arunta Complex that warrant prospecting. Some, but by no means all of these are located on Plate 46. These rocks include the Riddock Amphibolite and bodies of norite in the Alice Springs and Illogwa Creek Sheet areas (Joklik, 1955) and large areas of norite metamorphosed to granulite facies in the Hermannsburg Sheet area (R. D. Shaw, pers. comm.) and Mount Liebig Sheet area near Mount Larrie. Ultramafic rocks occur in the Arunta Complex at localities given in Joklik (1955) and dunite occurs at the phlogopite mine 35 miles north-northeast of Alice Springs. Mafic and ultramafic(?) intrusive rock crop out in the Arunta Complex near the Georgina Range, and pyroxenite crops out in an area of low-grade metamorphic schist in the northwestern corner of the Mount Rennie Sheet.

Mafic dykes, including norite, intrude the Olia Gneiss and Pottoyu Granite Complex, south of the Petermann Ranges, and mafic and ultramafic dykes intrude the Musgrave-Mann complex in the Mann Ranges area.

HYDROLOGY

by

D. R. Woolley and T. Quinlan

Surface water and groundwater are used by the pastoral industry and by settlements in the area bounded by longitudes 131°00′E. and 136°00′E. and latitudes 23°00′S. and 26°00′S. Only meagre and largely qualitative basic data are available, and this severely limits attempts to assess the resources. Development to date has been undertaken with little knowledge of the resources available.

Previous Investigations

Ward (1926) compiled an inventory of water bores and wells in existence at the time of his visit to the Northern Territory. He described the occurrence of groundwater and drew attention to the potential of aquifers in the Great Artesian Basin. This inventory was expanded by the Chief Engineer of the United States Army Service of Supply (United States Army, 1942).

Aird (1953, unpubl.) reported to the Commonwealth Government on the 'suitability both in quantity and quality of the available waters for the production of fodder on pastoral holdings' in the Alice Springs and Barkly Tableland districts. He concluded that the significant aquifers occurred in the alluvium along the watercourses and in solution cavities in limestones. He recognized that aquifers are not available at all localities, because of the complex geological structure, and that careful siting of bores is often necessary. Acting on one of his recommendations, the Commonwealth Government established the Water Resources Branch of the Northern Territory Administration, to provide for the development and regulation of the use of water resources in the Northern Territory.

The earliest reports on the occurrence and hydrology of groundwater in the Alice Springs Town Basin and Inner Farm Basin (about 3 miles south of Alice Springs) are by Owen (1952, 1954, both unpubl.), who considered aspects of salinity, recharge, and groundwater movement. Jones (1957a, unpubl.) refined Owen's ideas and prepared a more accurate bedrock contour map with the aid of additional information. He was the first to consider the Inner Farm Basin.

The Bureau of Mineral Resources carried out resistivity and seismic surveys in the two basins in 1956 (Dyson & Wiebenga, 1957, unpubl.). The results of their surveys were used by the Department of Works in planning their drilling programme. Wilson (1958, unpubl.) reported the results of this investigation, and examined groundwater movement, salinity distribution, and groundwater storage. He also carried out pumping tests on some of the production wells, and measured some flows of the Todd River.

Jephcott (1959) studied the relationship between groundwater salinity and river flow in the Town Basin, and concluded that sodium and bicarbonate are the most sensitive indicators of recharge to the basin. Forbes (1962, unpubl.), discussed groundwater movement and salinity in both the Town and Inner Farm Basins, and estimated that 149 million gallons is the annual safe yield from the Town Basin. He also estimated the average annual yield of surface runoff at Heavitree Gap to be 3180 million gallons.

Quinlan & Woolley (1968) discussed the occurrence of groundwater in the two basins, using the results of drilling to 1964. They drew attention to the decline in the volume of groundwater in storage since 1953, and made a preliminary interpretation of the results of their pumping tests. They concluded that the safe yield of the Town Basin is dependent on the time interval between successive river flows.

Woolley (1966, unpubl.) discussed the occurrence and use of groundwater in the Emily and Brewer Plain area, south of Alice Springs township, including the Alice Springs Outer Farm area (about 5 miles south of Alice Springs).

The occurrence of groundwater in the Amadeus Basin has been discussed by Rade (1957), Jones & Quinlan (1962), and Quinlan (1961, unpubl.). Information on the types of aquifers and on the salinity of the water which they contain is shown on a map prepared by the Australian Water Resources Council (1965). Jones & Quinlan (1962) and Perry et al. (1963) drew attention to the potential value of groundwater for irrigation. Rochow (1965, unpubl.) described the occurrence of groundwater in the Finke Sheet area; and Woolley (1965, unpubl.) assessed the resources available to supply the township of Kulgera.

Legislation and Assistance

Since 1952, the staff of the Resident Geological Section in Alice Springs has selected bore sites for pastoralists. In the period 1952-61, bore sites were selected for pastoralists free of charge. The pastoralist controlled the drilling operations, but could refer to the Geological Section as drilling progressed.

During the latter part of this period a scheme of drought relief drilling was undertaken, administered by the Commonwealth Department of Works and the Lands Branch of the Northern Territory Administration. Once a pastoralist had convinced an inspector of the Lands Branch that his property was drought-stricken, the inspector decided if any area on the property, outside the range of the existing watering points, carried sufficient feed to warrant additional bores. If he nominated an area in which a bore would be useful, the Resident Geologist was asked to select a site. Drilling was carried out by contractors under the supervision of the Department of Works. Up to three attempts were allowed in any area, and the pastoralist was required to pay only for successful bores, for which financial assistance was also available.

Since 1961, assistance to pastoralists and agriculturists has been available under the Water Supplies Development Ordinance 1960-65, administered by the Water Resources Branch, and an increasing proportion of bores in the Northern Territory has been drilled under this Ordinance; at present they account for nearly 70 percent of the total number of private bores drilled.

Under the Ordinance, the Commonwealth Government bears the cost of unsuccessful drilling. The Commissioner for Water Development may give advice on the location and design of bores, earth tanks, pumping equipment, storage and distribution equipment, and the layout and preparation of land for irrigation. He may also provide financial assistance for any or all of these projects. For pastoral areas, up to three bores can be drilled unless the first or second attempts indicate that further drilling would be unsuccessful. The pastoralist pays only for bores considered successful by the Commissioner.

The greater flexibility in the selection of bore sites under the Ordinance and reduction of financial risk to the pastoralist have greatly assisted the Resident Geologist to establish usable watering points in many difficult areas. Most sites drilled in central Australia under the Ordinance have been selected by the Resident Geologists, who provide a written opinion on the prospects at each proposed site for the guidance of the Commissioner.

The Administrator in Council has the power to proclaim a Declared Area, that is, a Water Control District, in which he controls, among other things, the construction of water bores.

Availability of Data

The data used in this Bulletin are held by the Resident Geological Section, Water Resources Branch, and Animal Industry Branch of the Northern Territory Administration. Most of the information has been drawn from the records in the Resident Geological Section, which include some data supplied by the other two branches.

One set of Bore Data Files has been prepared for each 1:250,000 Sheet area, and individual bores are numbered according to the Sheet area: thus, the 173 bores in the Rodinga Sheet (G53/2) are numbered G53/2-1 to G53/2-173. The data recorded include: yields, quality of water, depth, standing water level, depth of aquifers, date drilled, name of driller, location and selection of site, and description of strata samples.

If the location of the bores is known accurately, they are plotted on a set of transparent maps, generally at the 4-mile scale, based on the photomosaics; the surface drainage has also been plotted (Kingdom et al., 1967, unpubl.).

The Bore Data Files are supplemented by a set of edge punch cards, which can be used as a rapid means of extracting information from the files.

Samples of cuttings from many of the bores are available for inspection in the Resident Geological Section.

History of Development

Information on early bores and wells is scarce, and it is only since about 1950 that the records are nearly complete. Ward (1926) noted 19 existing wells and bores, mainly along the north-south stock route, and selected 6 sites, which apparently were all subsequently drilled. These, and a few others, constitute the 31 bores and wells known to have been drilled before 1930. This figure is the basis for the graph (Fig. 75) of the progressive total of bores and wells drilled in the area. Practically no detailed information about dates of drilling is available for the years 1930 to 1940, but 102 bores appear to have been drilled in this period. Slightly more detail is available for the 1940-50 period and the graph shows progressive totals at 1945 and 1950 (each plot on the graph is for January of the particular year). From 1950 onwards, it has been possible to obtain an approximate yearly figure for the number drilled. About 200 bores are known for which the date of drilling could not be determined, and these have been omitted from the graph.

The most notable features of the graph are the increased rate of drilling from 1945 onwards and the decline in the number of bores drilled in 1951, 1959, and 1965. The first decrease was at the beginning of the drought in 1951-54 (Foley, 1957) and the second was early in the present drought.

In both these periods the fall-off in the drilling could have been due to the poor season, but in both cases also the rate of drilling increased again, while the drought progressed, as pastoralists endeavoured to provide watering points for remaining areas of feed. The decrease in drilling in the period 1956-66 was apparently due to the generally depressed state of the pastoral industry as a result of the drought which had been continuous since 1958. Many holdings are approaching the stage where they have all the stock watering points required.

The 1227 bores and wells represented in Figure 75 include both successful and unsuccessful bores.

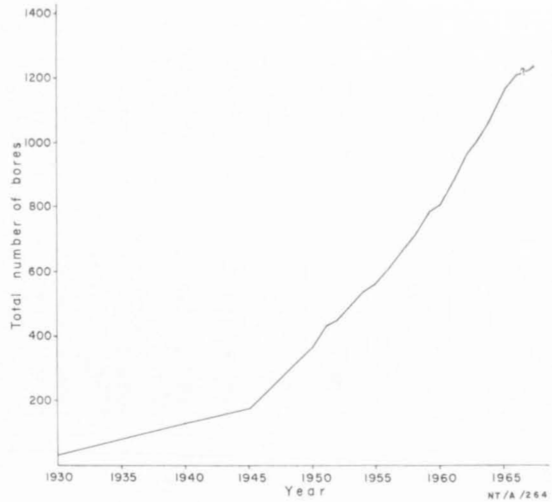

Fig. 75. Progressive total number of bores drilled for pastoral industry.

Of the 1427 bores recorded by April 1966, about 800 have been adjudged successful. Where information is available, the bores are regarded as successful if the yields are over 450 gph and the salinity is less than 7000 ppm. In many cases, however, no information is available except that the bore (or well) has been used, in which case the bores are deemed to have been successful if they have been equipped. The total of 800 includes many old wells and some bores in which the supply was probably less than 450 gph. It also includes a small number of bores with water containing total dissolved solids of over 7000 ppm, and in a few cases it includes duplicate or replacement bores.

Under the terms of the Water Supplies Development Ordinance, a successful bore is generally regarded as one with a supply of 500 gph or more, and a salinity of less than about 7000 ppm (depending on individual ionic concentrations in marginal cases). The lower limit of 450 gph has been used here in order to include a few marginal cases with supplies of 450 to 500 gph.

Availability of Groundwater

The availability of groundwater in the Amadeus Basin is discussed qualitatively in relation to the rock units that are known to contain aquifers. Table 7 summarizes the results of drilling to provide water for the pastoral industry in the area.

Arunta Complex. The igneous and metamorphic rocks of the Arunta Complex are not inherently porous. Aquifers occur in zones of fracturing and jointing, formed

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TABLE 7. SUMMARY OF THE RESULTS OF WATER BORES DRILLED FOR THE PASTORAL INDUSTRY

Formation	*No. of Bores*	*Depth*		*No. of Bores with Yields of*			*Maximum Tested Yield* (gph)	*No. of Bores with Salinity*		*Salinity Range* (ppm)	*Availability of Groundwater*
		Range (ft)	*Average* (ft)	0	<450	>450		<7000 ppm	>7000 ppm		
Quaternary	85	12- 310	75	0	19	66	3000	75	10	170- 29,000	Excellent
Tertiary	76	16- 675	190	12	24	40	6000	47	17	400- 10,261	Good
Rumbalara Shale	12	50- 420	180	0	9	3	1000	2	10	3000- 29,000	Very Poor
De Souza Sandstone	33	75-1474	500	0	0	33	29,000	33	0	417- 6213	Excellent
Ligertwood Beds	0										
Buck Formation	0										
Crown Point Formation	22	100- 687	445	3	7	12	1200	19	0	397- 3854	Excellent
Finke Group (undiff.)	4	90- 350	190	1	2	1	900	2	1	3086- 7000+	Poor to moderate
Santo Sandstone	5	70- 570	210	0	3	2	5000	5	0	201- 550	Good
Horseshoe Bend Shale	13	40- 700	340	0	11	2	700	9	4	2945- 8200	Poor
Langra Formation	13	60- 600	300	0	7	6	1200	0	13	8000-130,000	Very Poor
Polly Conglomerate	0										
Brewer Conglomerate }											
Hermannsburg Sandstone }	60	82-1040	340	13	23	24	2500	35	25	464- 10,000	Poor to moderate
Parke Siltstone }											
Mereenie Sandstone	17	7- 900	280	1	2	14	1460+	16	0	85- 7000	Excellent
Carmichael Sandstone	0										
Stokes Siltstone	3	272- 770	570	1		?	460	0	2	7650- 14,000	Very Poor
Stairway Sandstone	18	130- 771	280	0	3	15	2000	12	6	1156- 20,000	Moderate
Horn Valley Siltstone	0										
Pacoota Sandstone	4	203- 550	310	0	1	3	8000	4	0	764- 1914	Good
Goyder Formation	3	250- 448	330	0	1	2	1500	3	0	567- 1184	Good
Hugh River Shale	0										
Jay Creek Limestone	6	134- 426	240	0	1	5	1800	5	1	642- 10,000	Moderate
Shannon Formation	6	100- 165	150	0	2	4	1200	6	0	388- 2700	Poor
Giles Creek Dolomite	3	183- 250	210	1	1	1	1000	0	2	8700- 15,000	Poor
Chandler Limestone	2	75- 150	110	0	0	2	—	0	2	8600- 23,000	Poor
Todd River Dolomite	1	200	—	1	0	0	—	—	—	—	Poor
Arumbera Sandstone	13	116- 450	200	0	0	13	1500	11	2	824- 9300	Moderate to good
Petermann Sandstone	0										
Deception Formation	0										
Tempe Formation	1	160	160	0	0	1	2000	1	0	2000	Poor
Eninta Sandstone	0										
Quandong Conglomerate	0										

TABLE 7 (continued)

Formation	*No. of Bores*	*Depth*		*No. of Bores with Yields of*			*Maximum Tested Yield* (gph)	*No. of Bores with Salinity*		*Range Salinity* (ppm)	*Availability of Groundwater*
		Range (ft)	*Average* (ft)	0	<450	>450		<7000 ppm	>7000 ppm		
Cleland Sandstone	4	25- 100	70	4	0	0	—	—	—	—	Very Poor
Mt Currie Conglomerate	0										
Ayers Rock arkose	0										
Maurice Formation	0										
Sir Frederick Conglomerate	0										
Ellis Sandstone	0										
Carnegie Formation	0										
Inindia Beds	4	215- 345	275	0	4	0	350	3	1	850- 9062	Poor
Boord Formation	0										
Pinyinna Beds	0										
Dean Quartzite	0										
Winnall Beds	5	140- 412	300	0	2	3	1000	4	1	1440- 8000+	Poor to moderate
Pertatataka Formation											
Limbla Member	6	10- 300	140	2	0	4	2400	4	0	816- 5400	Moderate
Undifferentiated	19	84- 388	160	1	6	12	2800	17	1	718- 13,000	Moderate
Areyonga Formation	5	102- 300	240	1	1	3	1200	4	0	277- 2400	Moderate to good
Bitter Springs Formation	18	61- 315	200	4	7	7	1200	12	2	809- 8350	Poor to good
Heavitree Quartzite	3	20- 146	80	2	0	1	700	1	0	2400	Poor
Arunta Complex	183	20- 485	135	43	97	43	4000	91	49	505- 41,000	Poor

during periods of structural deformation, and in zones of weathering, in which intergranular porosity has been developed as a result of the chemical reconstitution of the rock minerals. Both types of aquifers are narrow.

The fractured and jointed zones are of variable length, and are usually porous to depths of less than 200 feet from the surface. It is difficult to select sites for bores to intersect prospective aquifers below the piezometric surface, because they are usually steeply dipping, and small variations in dip may result in a dry hole. Moreover, the hardness of the rock may prevent drilling at an economic rate except with expensive special equipment.

Recharge is derived from alluvial beds in watercourses where the streams cross the aquifers, and occurs only for short periods following runoff. The narrowness of the fractured zones limits the quantity of water entering as recharge, and thus limits the safe yield of the system. Large fluctuations in the piezometric surface can be expected under natural conditions. The available drawdown in the bores in the Arunta Complex of the MacDonnell Ranges which failed during the recent drought was probably less than the fluctuations of the piezometric surface. The rate of the withdrawal of groundwater by the pastoral industry is modest, less than 1000 gph from bores pumping an average of less than 12 hours per day, and their failure is not considered to be an indication of regional depletion.

The zones of weathering are horizontal tabular bodies in which the parent rocks have been reconstituted. The depth of weathering is variable, and depends on the susceptibility of the parent rock to alteration and to solution by percolating groundwater. The maximum depth intersected in water bores in central Australia is less than 250 feet. The weathered zones lie beneath plains which are pediments to the MacDonnell Ranges. It is difficult to predict the position of aquifers, and the convenience of the pastoralist is often a major factor in the selection of a bore site.

Recharge probably occurs by direct infiltration from the surface; this is an inefficient mechanism, and limits the quantity of recharge water entering the aquifers. This, together with their low permeability, adversely affects the quality of the groundwater.

Only 43 of the 183 recorded bores drilled in the igneous and metamorphic rocks (Table 7) obtained adequate supplies (over 450 gph) of groundwater, and in 6 of them the water was too saline for stock. About half of the 183 bores intersected aquifers which contained salt water. Individual aquifers of the jointed and weathered types lack interconnexion; this prevents the regional movement of groundwater, reduces the efficiency of the processes of recharge, and increases the proportion of dissolved salts.

Of the 43 bores which produced 450 gph or more, 17 were less than 100 feet deep, 21 were 100 to 200 feet deep, and 5 were 200 to 300 feet deep. None was deeper than 300 feet. This is in agreement with the conclusions of Davis & Turk (1964), who consider that the optimum depth for wells in crystalline rocks is less than 150 to 250 feet. They also concluded, from their study of 2336 bores in granite and schist in eastern USA, that in unweathered rock from 5 to 15 percent are failures (less than 60 gph), median yields are less than 480 gph, and 10 percent will have yields of 3000 gph or more. Results in this type of rock in the Amadeus Basin area are even poorer, as indicated in Table 7.

Heavitree Quartzite. The Heavitree Quartzite consists mainly of silicified kaolinitic quartz sandstone. The siliceous cement reduces the permeability considerably.

Three bores have been drilled in the formation: two were abandoned because of hard drilling before intersecting an aquifer and the third obtained a supply of stock-quality water from joints. The formation crops out in areas of pronounced relief where there is little demand for the development of groundwater.

Bitter Springs Formation. The Bitter Springs Formation yields variable quantities of groundwater. The total dissolved solids range from 1000 to 323,000 ppm, depending on the geological environment of individual aquifers.

Most of the limestones and dolomites are massive and without porosity. Vugs are present in some of the cores and cuttings from water bores and from wells drilled by petroleum exploration companies, but it cannot be demonstrated that they provide permeability; nor can it be demonstrated that there is a stratigraphic control for their development. The lining of drusy calcite and dolomite may indicate that the rocks were once permeable, even if they are not so now.

In many localities the carbonate rocks and siltstone are jointed. The jointed rocks form good aquifers if the joint systems are open below the piezometric surface, but they are unpredictable. Anhydrite and gypsum fill the fractures and joints in the cores from the Ooraminna No. 1 and Mount Charlotte No. 1 wells (Planalp & Pemberton, 1963, unpubl.; McTaggart, Pemberton, & Planalp, 1965, unpubl.). The anhydrite and gypsum were probably deposited from groundwater and were probably derived from interbedded evaporites.

Beds of black pyritic siltstone are aquifers. The pyrite occurs as fine crystals and as large porous aggregates of very fine euhedral crystals. The porosity of the aquifer may be intergranular and associated with zones of mineralization, or fracture porosity. The groundwater in aquifers of this type is generally saline, with more than 2500 ppm total dissolved solids, but it may be of better quality where there is an opportunity for recharge. In either case it contains appreciable quantities of the sulphate radical.

Subaerial weathering can result in an increase in the porosity and permeability of some of the rocks in the vicinity of an unconformity, particularly strongly deformed and contorted dolomitic limestone, siltstone, and intraformational breccia. Many of the dolomitic limestones are cherty and contain ankerite. Vugs lined with drusy calcite are common in the intraformational breccias. The breccia and fractures provide the porosity, and if they are interconnected the permeability of this type of aquifer is very high. Large quantities of groundwater with a salinity less than 2000 ppm are stored in these aquifers, and much of the water contains less than 1000 ppm.

Areyonga Formation. Lenses of sandstone in the upper portion of the formation are porous, but their permeability is low because of the presence of a kaolinitic matrix and calcareous cement. The smallness of the lenses and low permeability may adversely affect the quality and the quantity of the water which can be extracted.

Pertatataka Formation. Aquifers in the Pertatataka Formation are small. Bore sites have to be carefully selected to ensure that porous zones are intersected below the piezometric surface, and to reduce the amount of hard drilling to a minimum. Twenty-five bores have been drilled to provide water for stock (Table 7), of which 16 were successful.

The siltstone and shale generally have low porosity and permeability, and bores drilled in these rocks will produce less than 100 gph of saline water. Weathering has increased the porosity and permeability of beds of steeply dipping pyritic siltstone. In areas of good local recharge, and where the base of the weathered zone is below the piezometric surface, these rocks will yield limited quantities of water containing appreciable quantities of sulphate which is suitable only for use by stock.

The sandstone is mainly hard, very fine to fine-grained, calcareous and silicified, and without interstitial porosity. Zones of jointing in the laminated, thinly bedded sandstone in the vicinity of faults, and on the crests of tight folds, are aquifers. Bores which intersect them may yield up to 3000 gph of water containing between 1000 and 9000 ppm total dissolved solids. Permeable beds of sandstone in the Julie Member, and rare interbeds of sandstone, between 1 and 5 feet thick, in sequences of siltstone and impermeable sandstone in the remainder of the formation have been used as aquifers. They will produce up to 1000 gph of water containing between 1000 and 5000 ppm total dissolved solids. The aquifers in the Julie Member are not always accessible, as the sites at which they could be developed are in hilly country of little pastoral value.

Winnall Beds. Some of the sandstone with intergranular porosity in the Winnall Beds has been used as aquifers for pastoral bores. Not all of the sandstone is permeable, and bore sites should be selected to intersect specific beds. The groundwater is usually only suitable for use by stock; yields are adequate for watering stock.

Aquifers in the Mount Kingston/Black Hill Range in the Finke Sheet area contain water with 13,000 ppm total dissolved solids, which is thought to have migrated from the Langra Formation.

Arumbera Sandstone. Some beds of sandstone in the Arumbera Sandstone are aquifers. The porosity and permeability of cores from the Ooraminna No. 1 well (Planalp & Pemberton, 1963, unpubl.) indicate that the permeable sandstone has a porosity of over 20 percent. The aquifers may be thin beds of quartz sandstone in a sequence of silty quartz sandstone, or large lenses of quartz sandstone in units 2 and 4 of Wells et al. (1967). The groundwater usually contains between 1000 and 8000 ppm total dissolved solids, and appreciable quantities of the sulphate radical. The water is generally suitable for pastoral use.

The Arumbera Sandstone generally crops out in areas of strong to moderate relief which are of little pastoral value. Aquifers have been exploited in areas where the dip of the formation is less than 45°, and where it is possible to select sites to intersect specific beds of sandstone which appear to be permeable on the surface.

Cleland Sandstone. In the Mount Liebig Sheet area four attempts have been made to drill holes in the Cleland Sandstone, but all were abandoned before an aquifer was intersected, because of hard drilling. In outcrop, the sandstone appears to be impermeable because of the amount of matrix between the sand grains. Some permeable beds may be present, but the prospects are poor.

Pertaoorrta Group. The six formations of the Pertaoorrta Group in the northeast have been established on the basis of lithology and the relative proportions of interbedded limestone, dolomite, shale, siltstone, and sandstone. Two types of permeability may be recognized. The first is related to the original texture of the rock and the diagenetic processes which have been operative. Some of the carbonate rocks are vuggy, and if the pores are interconnected the rocks are permeable. Thin beds of permeable sandstone and sugary dolomite have been intersected in some water bores and petroleum exploration wells. The occurrence and distribution of this type of permeability in these rocks cannot be predicted.

The second type of permeability is considered to result from the processes of deformation and weathering. Groundwater for the pastoral industry and for domestic consumption is usually taken from aquifers which are less than 250 feet from the surface. In central Australia, the aquifers are generally within zones of weathering, as they have been exposed to more than one period of subaerial weathering since Palaeozoic time. Weathering and structural deformation have in some cases been responsible for the development of permeability in the carbonate rocks. Interbedded limestone, siltstone, and shale act as a sequence of competent and incompetent beds during folding. In structurally favourable locations, joint systems developed in the competent beds provide channels for the entry of water from the surface into the carbonate rocks.

These concepts are not supported by an analysis of the results of drilling in the six formations (Table 7), from which the Shannon Formation and Jay Creek Limestone seem to be the only important aquifers. Such an analysis is not statistically sound, and is not supported by information available on the permeability in the petroleum exploration wells.

Hugh River Shale. Aquifers have been intersected in the James Range 'A' No. 1 and Highway Anticline No. 1 wells (McTaggart & Pemberton, 1965a, b, both unpubl.). In both cases the porosity is mainly due to fracturing and jointing on the crests of anticlines. The yield and quality of the groundwater obtained are suitable for stock. The logs of the holes show that the formation contains appreciably more limestone and dolomite than in the type section at Ellery Creek.

No water bores have yet been drilled in the formation.

Todd River Dolomite. The Todd River Dolomite is crystalline and very poorly or thickly bedded; it has little or no porosity. In the McDills No. 1 (Amerada, 1965, unpubl.) and Alice No. 1 wells (Pemberton et al., 1963, unpubl.) the fractures are filled with anhydrite and calcite. The beds of sandstone at the base of the formation may be permeable.

Chandler Limestone. The folding and contortion of the beds of limestone and dolomite have been accompanied by recrystallization, which has largely destroyed any original porosity. The presence of beds of salt in the section has an adverse effect on the quality of the groundwater.

Giles Creek Dolomite. The Giles Creek Dolomite does not contain aquifers which could be exploited by the pastoral industry (Table 7). The drill stem test of the cavernous interval from 6375 to 6382 feet in Alice No. 1 indicated that it was permeable and contained water with 23,000 ppm total dissolved solids. Two other intervals, at 6520 and 6600 feet, appear to be permeable on the microlaterolog.

Shannon Formation and Jay Creek Limestone. Beds of sandstone and of fractured limestone and dolomite are aquifers, which will yield adequate quantities of groundwater. The water from bores drilled to date is generally suitable for stock, and some is suitable for domestic consumption.

Goyder Formation. The sandstone beds in the Goyder Formation are aquifers, which yield 1500 gph or more of water containing less than 1200 ppm total dissolved solids (Table 7). The logs of the Alice No. 1 and East Johnny Creek No. 1 wells indicate that below 900 feet from surface, the permeable beds of sandstone are 1 to 2 feet thick. They occur sporadically in a sequence of interbedded calcareous sandstone, limestone, dolomite, siltstone, and shale.

In outcrop, much of the sandstone is a fine to medium-grained porous quartz sandstone with an open texture; small amounts of siliceous cement occur at the point-to-point contacts of the grains. The calcareous cement was probably leached from the sandstone during three periods of weathering since pre-Permian time, and the siliceous cement was introduced to the upper part of the weathered zone during the same periods. The base of the weathered zone on the crest of the Johnny Creek Anticline is below 600 feet (Benbow & Planalp, 1965, unpubl.).

Where the base of the weathered zone is below the piezometric surface, the sandstone is a very permeable aquifer. In other areas, groundwater can only be obtained from thin lenses of porous sandstone, and from joints if they are present. The permeability of such an aquifer may be low, and only bores which intersect more than one will be capable of producing an adequate supply of groundwater. The dip of the formation must be low if more than one permeable bed is to be intersected within an economic depth.

Pacoota Sandstone. Aquifers in the Pacoota Sandstone are generally beds of medium-grained quartz sandstone, from 5 to 10 feet thick, in a sequence of interbedded silty quartz sandstone, siltstone, and shale. The variable proportion of silica and carbonate cement in the quartz sandstone may adversely affect the permeability. In the Palm Valley No. 1 and East Mereenie No. 1 wells the formation is fractured (Magellan, 1965, unpubl.; Benbow et al., 1964, unpubl.) and the permeability due to fracturing is much greater than the intergranular permeability of the sandstone. Fractures and joints are probably only developed in structurally favourable locations.

Supplies of groundwater ranging from 200 to 800 gph have been obtained from bores less than 550 feet deep. All the water is suitable for stock and some for domestic consumption. Only 4 holes have been drilled in the Pacoota Sandstone, because it occurs mostly in hilly areas unsuitable for pastoral use.

Stairway Sandstone. Eighteen bores have been drilled for water in the Stairway Sandstone, of which 12 produce sufficient water suitable for stock (Table 7).

In the syncline south of the Mount Burrell Anticlinorium, the water contains 13,650 ppm total dissolved solids. The salinity is derived from beds of salt in the Chandler Limestone, which unconformably underlies the Stairway Sandstone. The contamination would presumably be greater if impermeable sediments of the Finke Group did not transgress the Stairway Sandstone on the southern limb of the syncline and prevent the movement of groundwater through the formation. On the northern flank of the syncline, the water contains only about 8000 ppm total dissolved solids, because of the effects of local recharge through the outcrop.

The available core analyses and the logs of the petroleum exploration wells indicate that significant intergranular porosity and permeability is restricted to the basal member of the formation. In the northwest, this type of porosity has been destroyed by secondary enlargement of quartz grains, but may be replaced by fracture porosity in structurally favourable situations.

Stokes Formation. The limited information available indicates that groundwater prospects are poor due to low permeability. Of the 3 bores drilled, 1 was dry, 1 yielded 400 gph with 7650 ppm total dissolved solids, and 1 yielded 150 gph with 14,000 ppm total dissolved solids.

Carmichael Sandstone. No water bores have been drilled in the Carmichael Sandstone. The formation is permeable and has yielded 1000 gph of good-quality water in petroleum exploration wells on the Mereenie Anticline.

Mereenie Sandstone. The Mereenie Sandstone consists of fine to medium-grained quartz sandstone and some thin interbeds of siltstone. The sandstone has an intergranular porosity of 18 to 25 percent, and a permeability between 80 and 1500 millidarcys (BMR, unpubl. data). The lithology does not change significantly and the whole of the formation can be considered an aquifer with variable permeability. Adequate supplies of water for all purposes can be obtained from suitably constructed bores. Those currently used for the Alice Springs Town Supply have specific capacities between 500 and 1400 gph per foot of drawdown.

The content of total dissolved salts in the groundwater is generally less than 1000 ppm, and it may be less than 500. It rises to 7000 ppm in the Gardiner Range, where saline water moves into the Mereenie Sandstone from the Bitter Springs Formation across a faulted contact. The regional significance of this contamination cannot be assessed.

Parke Siltstone. The distribution of the Parke Siltstone is not well known. Outcrop is restricted to the area southwest of Alice Springs, but production bore P6 of Alice Springs intersected about 500 feet (true thickness); this is the maximum known thickness. There is no intergranular permeability in the siltstone, but in the western part of the Amadeus Basin there is locally some joint permeability. Some sandy beds near the base of the siltstone are also aquifers in the Mereenie Anticline, but the extent of the beds is unknown.

Hermannsburg Sandstone. Two or three thin porous sandstones near the base of the Hermannsburg Sandstone are aquifers; they yield from 1000 to 3000 gph and the total dissolved solids range from 750 to 3000 ppm. The aquifers occur as large lenses in beds of siltstone and impermeable sandstone, and may not be present in all areas.

Close to the top of the formation there is commonly a zone of jointing, which is an aquifer. On the northern margin of the Krichauff Ranges the bores which intersect this aquifer will yield water under small artesian pressure.

The yield of successful bores ranges from 1000 to 3000 gph of water containing 750 to 3000 ppm total dissolved solids. They are useful aquifers for the pastoral industry and for small settlements. The Areyonga Native Settlement and the Hermannsburg Mission rely on these aquifers for domestic supplies.

Apart from these aquifers, significant permeability of any type is absent, and many successful holes have been drilled at sites selected at random by water diviners and others.

Most of the bores shown in Table 7 as being in the Pertnjara Group have been drilled in this formation.

Brewer Conglomerate. The porosity and permeability of the Brewer Conglomerate have been largely destroyed by the introduction of calcareous cement into the sandstone and conglomerate. Most bores in the formation were abandoned as dry holes, or because they produced inadequate supplies of water. The water was saline or of good quality. Some holes were abandoned because of difficult drilling conditions.

Horseshoe Bend Shale. Interstitial permeability in the Horseshoe Bend Shale is negligible, but bedding plane joints create some permeability. Supplies are all small, the highest being 700 gph (Table 7); the quality of the water is moderate to poor. The formation is not an important source of groundwater.

Langra Formation. Permeability in the Langra Formation is generally good, and supplies over 1000 gph are normal, but the salinity is always high. In the upper sandstone unit, above the shale near the top of the formation, the water generally contains 8000 to 9000 ppm total dissolved solids, which is barely suitable for stock. In the lower sandstone unit the water contains over 10,000 ppm total dissolved solids, and the highest salinity recorded is 130,000 ppm in Clough Bore (G53/6-79). This bore is unusual in being artesian; the piezometric surface is 3 to 4 feet above natural surface.

Santo Sandstone. The Santo Sandstone is the only formation in the Finke Group which contains good-quality water (Table 7). The other formations may yield waters suitable for stock, but only in exceptional cases where local recharge dilutes the main body of saline water.

Very few bores have been drilled in the Santo Sandstone, and it is not an important aquifer, because it only occurs below the piezometric surface in a few small areas, most of which are situated a short distance south of Maryvale homestead. Of the bores in the Santo Sandstone, those with small supplies have almost certainly been stopped before reaching the base of the sandstone, and hence may produce adequate supplies. It is a most useful aquifer in the area between Maryvale homestead and the confluence of the Finke and Hugh Rivers, although its distribution is difficult to predict because of the cover of Quaternary sand. Usable water is stored in the Santo Sandstone in small synclines, where pockets of good water occur in a generally saline area.

There is no information on long-term yields, but bore G53/2-126, a few miles south of Maryvale homestead, has been used for about 12 months for irrigation. It has been tested at 5000 gph. Recharge to the formation is dependent on flows in the Finke and Hugh Rivers and Alice Creek.

Crown Point Formation. The Crown Point Formation is a particularly valuable and reliable aquifer over a large area in the southeastern part of central Australia. The most saline water known contains less than 4000 ppm total dissolved salts (Table 7) and supplies are adequate for domestic or stock purposes, except where the base of the formation lies above or only slightly below the piezometric surface. With a few exceptions, the aquifer is a medium to coarse-grained sandstone; it is commonly pyritic, and in places pebbly to conglomeratic.

Availability of water depends largely on the pre-Permian topography, as for instance in the area around the northwestern margin of the Great Artesian Basin. Relief on this surface is marked, and successful bores occur where there is sufficient depth below the piezometric surface. Farther southeast, in the deeper parts of the Great Artesian Basin, little information is available in the Northern Territory. Where the overlying De Souza Sandstone is present, water bores are not drilled as deep as the Crown Point Formation. At McDills No. 1, a major artesian flow was encountered at 2375 feet from a pyritic grey sandstone immediately above the top band of Permian coal. This aquifer is thought to be within the Crown Point Formation, or at least to be of Permian age, and may be extensive beneath the Jurassic aquifers in the Great Artesian Basin.

Little is known about recharge to the Crown Point Formation, but some recharge is certainly taking place along the belt of outcrop extending east-northeast from Rumbalara siding. Maximum yields and the effects of long-term pumping are unknown.

Rumbalara Shale. Two types of porosity are found in the Rumbalara Shale. Firstly, there is commonly a weathered zone below the superficial sediments, which generally yields about 100 gph of highly saline water from small perched bodies of groundwater. Secondly, thin sandstones are present, apparently mainly near the base, which produce up to at least 1000 gph of highly saline water. It is only in Lucky Bore, east of Erldunda homestead, that the salinity is low enough for the water to be used by stock. The records indicate a salinity of 3000 ppm, but the identification of Rumbalara Shale in the driller's log is suspect and the aquifer may be in one of the small Tertiary basins known to occur in the area. Except for Lucky Bore, the salinity ranges from 9000 to 30,000 ppm, and the water from the Rumbalara Shale is of no use for stock, irrigation, or domestic purposes. The source of the salts, mainly sodium chloride, is unknown, but it is probably connate or the result of stagnant conditions.

Except around Erldunda Station, the Rumbalara Shale is usually underlain by the De Souza Sandstone, which is a reliable aquifer. Lack of good-quality water in the Rumbalara Shale is not a serious problem, except in a restricted area.

De Souza Sandstone. The De Souza Sandstone is one of the main aquifers of the Great Artesian Basin within the Northern Territory. Only the Anacoora and Dakota Bores are artesian, as most bores have been drilled on the northwestern margin where the piezometric surface is below ground surface. Groundwater enters along the outcrop and subcrop of the formation between Rumbalara siding and Finke.

The total dissolved solids range from about 600 to 3500 ppm, except to the west of Kulgera, where water with over 6000 ppm is present in aquifers tentatively assigned to the De Souza Sandstone. Tested supplies range up to 3000 gph from pumped holes, and the flow at Anacoora Bore was initially about 30,000 gph. The head at Anacoora Bore was 48 feet in 1900 and at present is estimated at less than 5 feet. The only other data on water level changes are from Charlotte Waters Bore, where there was no decline in the period 1900 to 1938. The present water level is not known.

Results of drilling in the De Souza Sandstone are summarized in Table 7.

Tertiary Pre-Silcrete Sediments. The older or pre-silcrete Tertiary sediments are of lacustrine origin (I. R. Pontifex, pers. comm.; Woolley, 1966, unpubl.); they consist predominantly of white and grey clay and sandy clay with no effective permeability. The aquifers are sand, with a few possible exceptions (e.g. the laterite aquifer in Alice Springs Farm area). The sands are oligomict quartz sand; the sand is fine to very coarse, and commonly angular. The quartz is generally clear to translucent. There is a varying amount of white kaolinitic matrix, but size sorting is generally good. The sands are generally less than 10 feet thick, and rarely as much as 20 feet. Tested supplies up to 3000 gph have been obtained, and except in a few cases this is also the maximum yield. The quality of the water is generally good to moderate for stock purposes, and is commonly suitable for domestic use. Woolley (1966, unpubl.) concluded that the water in the Alice Springs Farm area is suitable only for watering stock, and for limited domestic use.

Tertiary Post-Silcrete Sediments. The post-silcrete conglomerate (Tc) is impermeable. It is not known to occur below the piezometric surface, and is of no importance as an aquifer.

The sequence of limestone, sandstone, siltstone, and claystone, capped with chalcedony (Tl of Wells et al., 1967) probably contains permeable zones, but they are unlikely to be extensive below the piezometric surface.

Post-silcrete fluvial unconsolidated sediments are known in some areas, mostly outside the Amadeus Basin. The best known occurrences are at Willowra (Morton, 1964, unpubl.), Utopia (Woolley, 1965, unpubl.), and Alcoota (Woodburne, 1967). At Utopia and Willowra, supplies of up to 10,000 gph are used for irrigated agriculture. Similar deposits probably occur in the Alice Springs Outer Farm area, but are difficult to distinguish from the overlying Quaternary deposits.

Table 7 summarizes results of drilling in Tertiary sediments, but does not distinguish between the pre-silcrete and post-silcrete deposits.

Quaternary Deposits. Quaternary clastic deposits are widespread in the Amadeus Basin, but they extend below the piezometric surface in only relatively small areas, mainly in long narrow zones along the major rivers. There are also extensive piedmont deposits north of the MacDonnell Ranges, which include both clastic and non-clastic aquifers.

Quinlan & Woolley (1968) have described the alluvial deposits in the Alice Springs Town Basin. The deposits are representative of most of the Quaternary alluvial deposits, and consist predominantly of grey and brown silt and clay, with varying amounts of sand. Thin lenses of sand, generally less than 10 feet thick, form a minor proportion by volume, but are the only aquifers. The sands are angular, polymict, fine to coarse-grained, and in places gravelly; they represent buried river bed deposits. The sandy silt and clay represent bank and flood-plain deposits. Along some of the major rivers, particularly the Finke, the individual beds of sand range up to 50 feet thick.

The extensive piedmont deposits along the northern flank of the MacDonnell Ranges contain up to 300 feet of Quaternary deposits; over a large part of this area they overlie a considerable thickness of Tertiary and Permian lacustrine and fluvial deposits. Because of the presence of better aquifers in the older deposits, only a few of the bores in this region obtain water from Quaternary aquifers. The most important area is around Haast Bluff Settlement, where about 6 bores produce good supplies of good-quality water from Quaternary sand.

Of the 85 bores, for which records are available and which produced water from Quaternary aquifers, 37 are less than 50 feet deep, 26 are between 50 and 100 feet deep, 12 are 100 to 150 feet deep, and 10 are over 150 feet deep. The water generally contains less than 2000 ppm total dissolved solids. A salinity of 29,000 ppm (Table 7) occurs where water in alluvium in the Finke River is contaminated by highly saline water effluent from aquifers in the Finke Group. Relatively saline water is also found in Quaternary clastic aquifers which have been contaminated by effluent water from the Bitter Springs Formation.

Tested supplies from Quaternary alluvial aquifers range up to 3000 gph in pastoral bores (Table 7), but they are generally not the maximum supplies possible. Continuous pumping at rates of over 6000 gph has been maintained for several years from some bores in the Alice Springs Town Basin.

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INDEX OF GEOGRAPHICAL PLACE NAMES

by J. SMITH & P. L. THIEME

(Not all names mentioned are necessarily marked on the map)

STRUCTURE AND MAGNETIC BASEMENT CONTOURS, AMADEUS BASIN

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

Geology compiled, 1968 by D.J.Forman
Drawn, 1968, 1969 by: G.Matveev, Miss D.M.Pillinger, Miss J.G.A.Den Hertog, Miss M. Mc Laren
Magnetic basement contours compiled by Geophysical Branch, BMR

AGE	SYMBOL	ROCK UNITS	DIASTROPHIC EVENT
CAINOZOIC	Cz		
MESOZOIC	M	Rumbalara Shale; De Souza Sandstone	
PERMIAN	Pzu	Crown Point Formation; Buck Formation; Ligertwood Beds	
CARBONIFEROUS			Alice Springs Orogeny
DEVONIAN	Pzm	Pertnjara Group (Finke Group)	Pertnjara Movement
SILURIAN		Mereenie Sandstone	Rodingan Movement
ORDOVICIAN CAMBRIAN	Pzl	Larapinta Group; Pertaoorrta Group	Petermann Ranges Orogeny
UPPER PROTEROZOIC	Eu	Pertatataka Formation; Winnall Beds	Souths Range Movement
		Areyonga Formation; Inindia Beds; Boord Formation	Areyonga Movement
		Bitter Springs Formation; Pinyinna Beds; Heavitree Quartzite; Dean Quartzite	Unnamed
YOUNGER PRECAMBRIAN	p€	Unnamed: Bloods Range Beds; Mount Harris Basalt	Unnamed; Unnamed
OLDER PRECAMBRIAN	p€n	Olia Gneiss	? Arunta Orogeny ?
	p€m	Musgrave - Mann complex	
	p€a	Arunta Complex	
	p€q	Quartzite	
INTRUSIVE IGNEOUS ROCKS			
PRECAMBRIAN	p€g	Granite	

TECTONIC UNITS

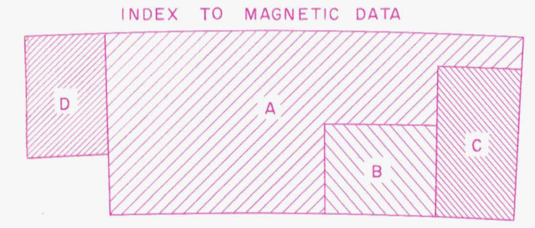
- Crystalline core of Razorback Nappe } Ormiston Nappe Complex
- Crystalline core of Ormiston Nappe } Ormiston Nappe Complex
- Crystalline core of White Range Nappe } Arltunga Nappe Complex
- Crystalline core of Ruby Gap and Trephina Gorge Nappes } Arltunga Nappe Complex
- Crystalline core of Blatherskite Nappe
- Core of Petermann Ranges Nappe (predominantly crystalline)
- Musgrave - Mann complex overlying Woodroffe Thrust

REFERENCE

- *Geological boundary, position approximate*
- *Unconformity*
- *Anticline, showing plunge*
- *Syncline, showing plunge*
- *Overturned anticline*
- *Overturned syncline*
- *Axial trace*
- *Fault*
- *Fault, showing dip of thrust plane, where approximate, line is broken; where inferred, queried*
- *Dip < 15°* } *Air-photo interpretation*
- *Dip 15°–45°* } *Air-photo interpretation*
- *Dip > 45°* } *Air-photo interpretation*
- *Trend lines* } *Air-photo interpretation*
- *Trend of lineation*
- *Strike and dip of foliation (prevailing or unmeasured)*
- *Trend of foliation (with prevailing dip)*
- *Foliation with plunge of lineation*
- *Mineral occurrence; Gp — gypsum*
- *Granulite facies of metamorphism*

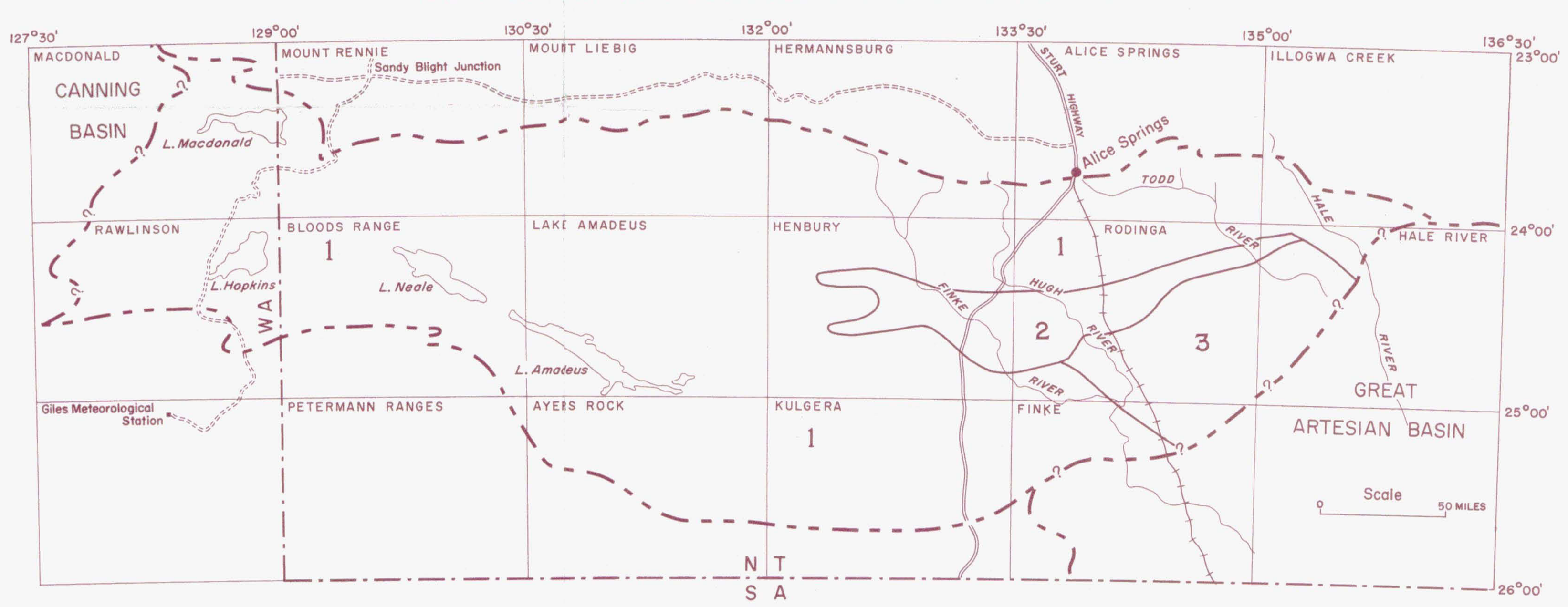
- *Basement depth corrected for magnetic strike* } *Depth in feet below sea level*
- *Basement depth uncorrected* } *Depth in feet below sea level*
- *Basement depth corrected for magnetic strike (doubtful)* } *Depth in feet below sea level*
- *Basement depth contour* } *Depth in feet below sea level*
- A *Basement zone and zone boundary*
- *Region of minor magnetic disturbance*
- *Basin boundary magnetically inferred*
- *Magnetic trend*
- *Fault*
- G2 *Magnetic basement feature*

INDEX TO MAGNETIC DATA



A Bureau of Mineral Resources
B Exoil (N.S.W.) Pty Ltd
C BMR (Aero Service Ltd)
D Australian Aquitaine Petroleum Pty Ltd

FOLD AND THRUST PROVINCES WITHIN AMADEUS BASIN



1 *Folding over decollement in Bitter Springs Formation*
2 *Zone of thrusting between upper and lower decollement*
3 *Folding over decollement in Chandler Limestone*

NT/A/297(a)

STRUCTURE AND RADIOMETRIC CONTOURS, AMADEUS BASIN

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

Geology compiled, 1968 by D.J.Forman
Drawn, 1968,1969 by: G.Matveev, Miss D.M.Pillinger, Miss J.G.A.Den Hertog, Miss M. Mc Laren
Radiometric contours compiled from Airborne Survey, 1965, by: Geophysical Branch, BMR

AGE	SYMBOL	ROCK UNITS	DIASTROPHIC EVENT
CAINOZOIC	Cz		
MESOZOIC	M	Rumbalara Shale De Souza Sandstone	
PERMIAN CARBONIFEROUS	Pzu	Crown Point Formation Buck Formation Ligertwood Beds	Alice Springs Orogeny
DEVONIAN SILURIAN	Pzm	Pertnjara Group — Finke Group Mereenie Sandstone	Pertnjara Movement Rodingan Movement
ORDOVICIAN CAMBRIAN	Pzl	Larapinta Group Pertaoorrta Group	Petermann Ranges Orogeny
UPPER PROTEROZOIC	Ꞓu	Pertatataka Formation; Winnall Beds Areyonga Formation; Inindia Beds; Boord Formation Bitter Springs Formation; Pinyinna Beds Heavitree Quartzite; Dean Quartzite	Souths Range Movement Areyonga Movement
YOUNGER PRECAMBRIAN	p€	Unnamed; Bloods Range Beds; Mount Harris Basalt	Unnamed Unnamed Unnamed
OLDER PRECAMBRIAN	p€n	Olia Gneiss	?
	p€m	Musgrave - Mann complex	Arunta Orogeny ?
	p€a	Arunta Complex	
	p€q	Quartzite	
INTRUSIVE IGNEOUS ROCKS			
PRECAMBRIAN	p€g	Granite	

TECTONIC UNITS

- Crystalline core of *Razorback Nappe*
- Crystalline core of Ormiston Nappe

} Ormiston Nappe Complex

- Crystalline core of White Range Nappe
- Crystalline core of Ruby Gap and Trephina Gorge Nappes

} Arltunga Nappe Complex

- Crystalline core of Blatherskite Nappe
- Core of Petermann Ranges Nappe (predominantly crystalline)
- Musgrave - Mann complex overlying Woodroffe Thrust

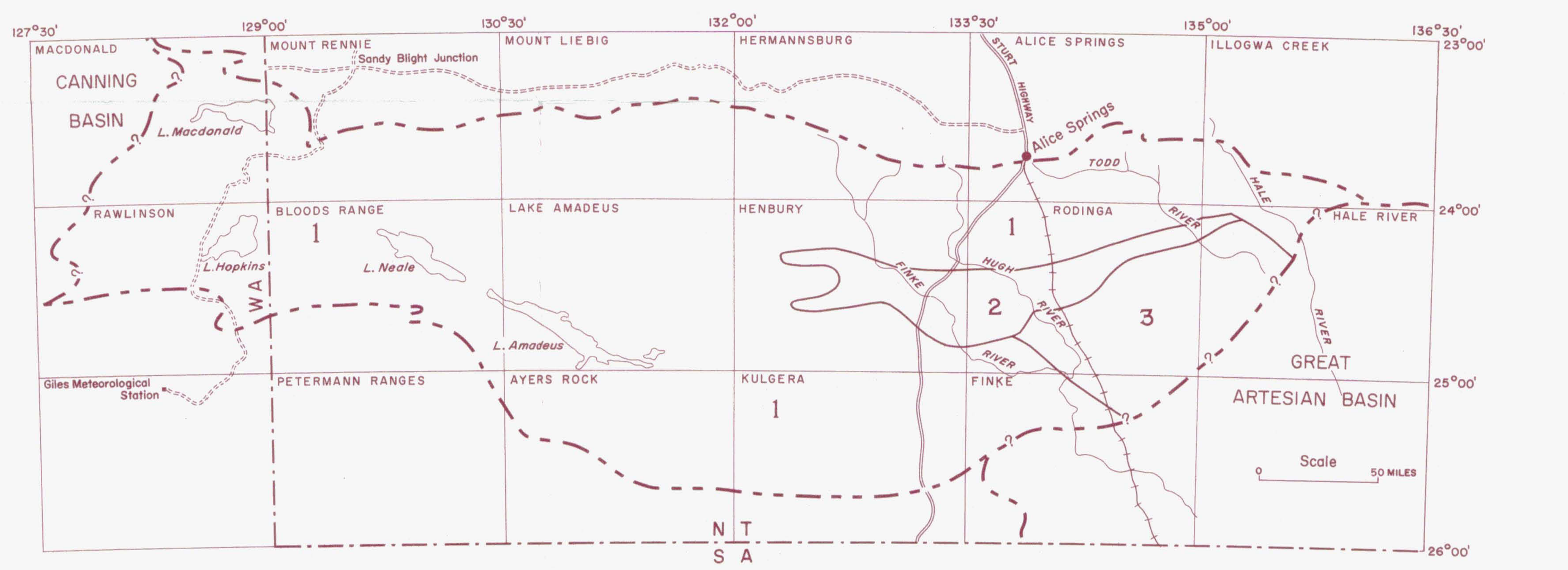
REFERENCE

- *Geological boundary, position approximate*
- *Unconformity*
- *Anticline, showing plunge*
- *Syncline, showing plunge*
- *Overturned anticline*
- *Overturned syncline*
- *Axial trace*
- *Fault*
- *Fault, showing dip of thrust plane, where approximate, line is broken; where inferred, queried*
- *Dip* $< 15°$
- *Dip* $15°-45°$
- *Dip* $> 45°$
- *Trend lines*

} *Air-photo interpretation* (dips and trend lines)

- *Trend of lineation*
- *Strike and dip of foliation (prevailing or unmeasured)*
- *Trend of foliation (with prevailing dip)*
- *Foliation with plunge of lineation*
- *Mineral occurrence; Gp — gypsum*
- *Granulite facies of metamorphism*
- *Radiometric contours, interval 25 counts per minute* (75, 100)

FOLD AND THRUST PROVINCES WITHIN AMADEUS BASIN



1 *Folding over decollement in Bitter Springs Formation*
2 *Zone of thrusting between upper and lower decollement*
3 *Folding over decollement in Chandler Limestone*

NT/A/297 (b)

STRUCTURE, BOUGUER ANOMALIES AND GRAVITY FEATURES, AMADEUS BASIN

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

Geology compiled, 1968 by D.J.Forman
Drawn, 1968, 1969 by: G. Matveev, Miss D.M. Pillinger, Miss J.G.A. Den Hertog, Miss M. Mc Laren
Gravity data, 1962; 1965. Compiled by Geophysical Branch, BMR.
Reliability: reconnaissance

AGE	SYMBOL	ROCK UNITS	DIASTROPHIC EVENT
CAINOZOIC	Cz		
MESOZOIC	M	Rumbalara Shale; De Souza Sandstone	
PERMIAN	Pzu	Crown Point Formation; Buck Formation; Ligertwood Beds	
CARBONIFEROUS			Alice Springs Orogeny
DEVONIAN	Pzm	Pertnjara Group; Finke Group	Pertnjara Movement
SILURIAN		Mereenie Sandstone	Rodingan Movement
ORDOVICIAN CAMBRIAN	Pzl	Larapinta Group; Pertaoorrta Group	Petermann Ranges Orogeny
UPPER PROTEROZOIC	Pu	Pertatataka Formation; Winnall Beds	Souths Range Movement
		Areyonga Formation; Inindia Beds; Boord Formation	Areyonga Movement
		Bitter Springs Formation; Pinyinna Beds; Heavitree Quartzite; Dean Quartzite	Unnamed
YOUNGER PRECAMBRIAN	p€	Unnamed: Bloods Range Beds	Unnamed
		Mount Harris Basalt	Unnamed
OLDER PRECAMBRIAN	p€n	Olia Gneiss	? Arunta Orogeny ?
	p€m	Musgrave-Mann complex	
	p€a	Arunta Complex	
	p€q	Quartzite	
INTRUSIVE IGNEOUS ROCKS			
PRECAMBRIAN	p€g	Granite	

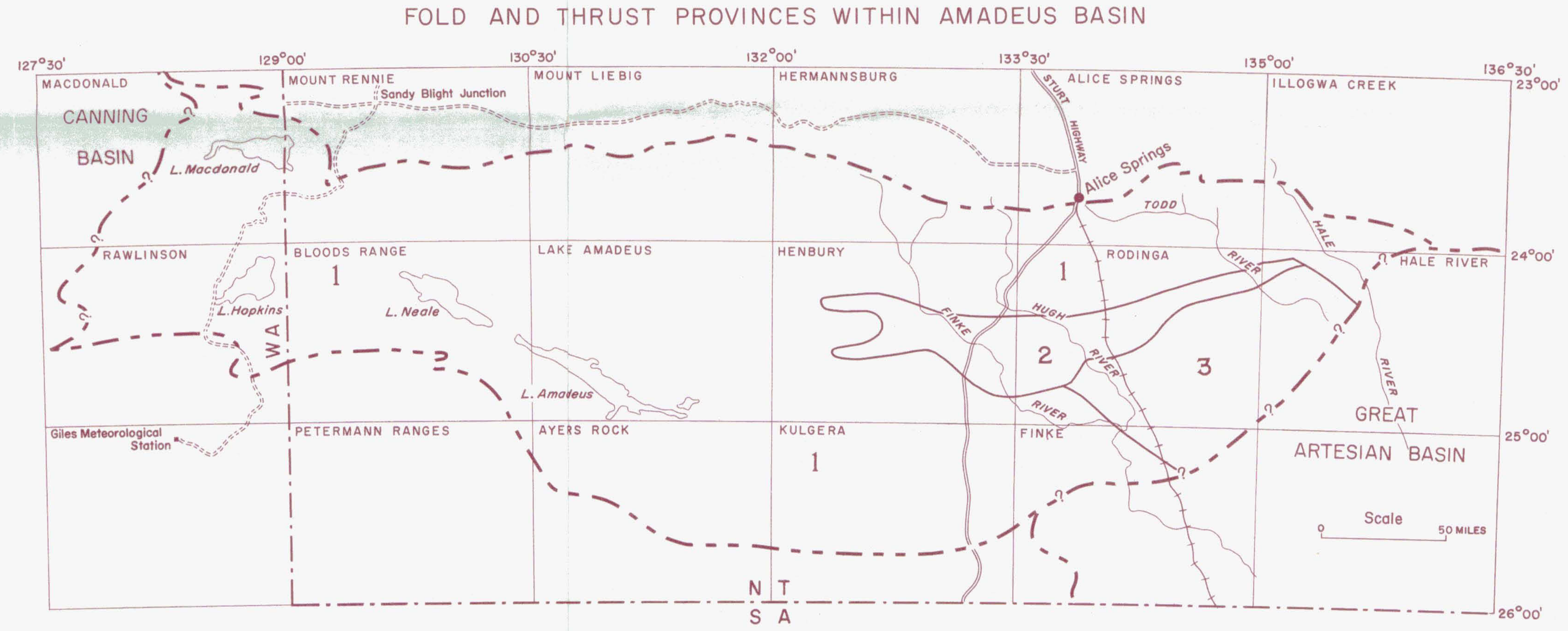
TECTONIC UNITS

- Crystalline core of Razorback Nappe; Crystalline core of Ormiston Nappe — Ormiston Nappe Complex
- Crystalline core of White Range Nappe; Crystalline core of Ruby Gap and Trephina Gorge Nappes — Arltunga Nappe Complex
- Crystalline core of Blatherskite Nappe
- Core of Petermann Ranges Nappe (predominantly crystalline)
- Musgrave – Mann complex overlying Woodroffe Thrust

REFERENCE

- *Geological boundary, position approximate*
- *Unconformity*
- *Anticline, showing plunge*
- *Syncline, showing plunge*
- *Overturned anticline*
- *Overturned syncline*
- *Axial trace*
- *Fault*
- *Fault, showing dip of thrust plane, where approximate, line is broken; where inferred, queried*
- *Dip < 15°*, *Dip 15°–45°*, *Dip > 45°*, *Trend lines* — *Air-photo interpretation*
- *Trend of lineation*
- *Strike and dip of foliation (prevailing or unmeasured)*
- *Trend of foliation (with prevailing dip)*
- *Foliation with plunge of lineation*
- Gp *Mineral occurrence; Gp — gypsum*
- *Granulite facies of metamorphism*
- *Gravity contours, interval 5 milligals*
- *Gravity anomaly, relative high*
- *Gravity anomaly, relative low*

FOLD AND THRUST PROVINCES WITHIN AMADEUS BASIN



1 *Folding over decollement in Bitter Springs Formation*
2 *Zone of thrusting between upper and lower decollement*
3 *Folding over decollement in Chandler Limestone*

NT/A/297 (c)

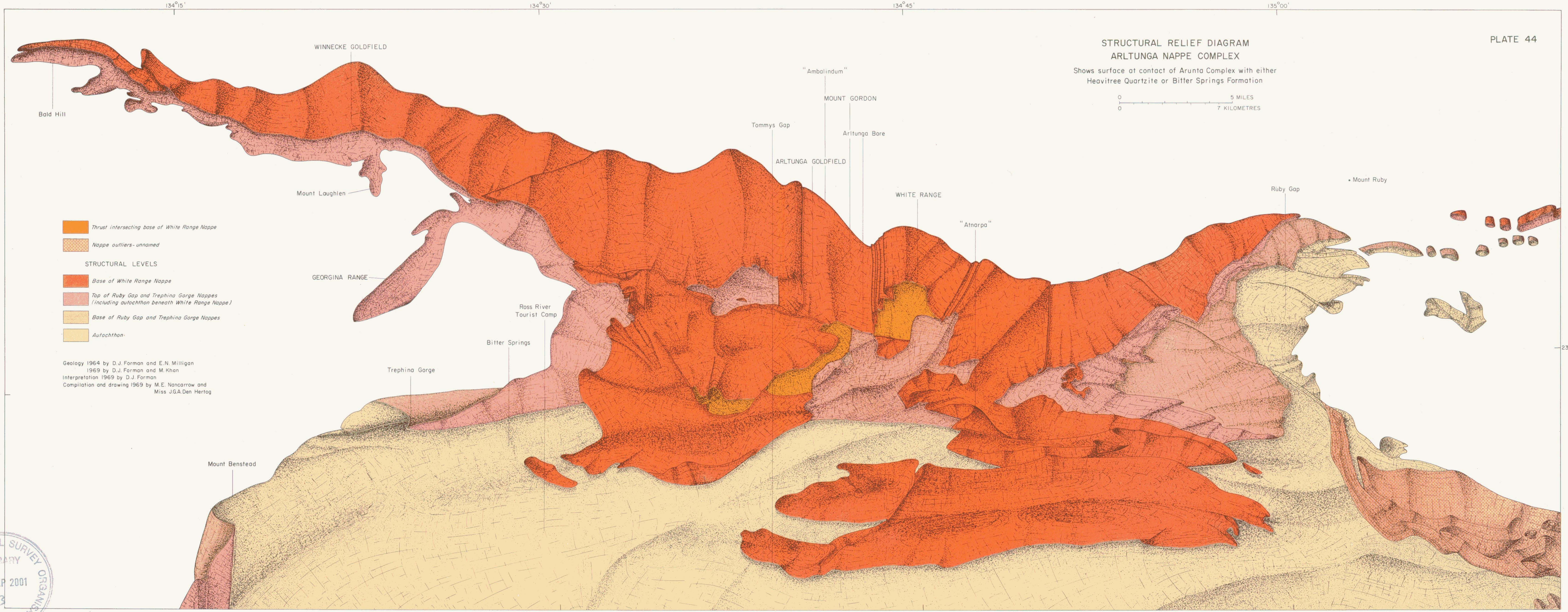


PLATE 44
STRUCTURAL RELIEF DIAGRAM
ARLTUNGA NAPPE COMPLEX
Shows surface at contact of Arunta Complex with either
Heavitree Quartzite or Bitter Springs Formation
0 5 MILES
0 7 KILOMETRES
134°15'
134°30'
134°45'
135°00'
23°30'
Thrust intersecting base of White Range Nappe
Nappe outliers - unnamed
STRUCTURAL LEVELS
Base of White Range Nappe
Top of Ruby Gap and Trephina Gorge Nappes
(including autochthon beneath White Range Nappe)
Base of Ruby Gap and Trephina Gorge Nappes
Autochthon
Geology 1964 by D.J. Forman and E.N. Milligan
1969 by D.J. Forman and M. Khan
Interpretation 1969 by D.J. Forman
Compilation and drawing 1969 by M.E. Nancarrow and
Miss J.G.A. Den Hertog
WINNECKE GOLDFIELD
Bald Hill
Mount Laughlen
GEORGINA RANGE
"Ambalindum"
MOUNT GORDON
Tommys Gap
Arltunga Bore
ARLTUNGA GOLDFIELD
WHITE RANGE
"Atnarpa"
Ruby Gap
Mount Ruby
Ross River
Tourist Camp
Bitter Springs
Trephina Gorge
Mount Benstead

GEOLOGICAL MAP
AMADEUS BASIN (WEST)
WESTERN AUSTRALIA AND NORTHERN TERRITORY
AUSTRALIA
1970

Scale 1:500,000

10 0 10 20 30 MILES

10 0 10 20 30 40 50 KILOMETRES

Geology 1956, 1963–64 by Officers of the Bureau of Mineral Resources
Compiled 1968 by A. T. Wells, D. J. Forman, A. S. Mikolajczak
Cartography by Geological Branch B M R
Drawn by A. S. Mikolajczak

Published by the Bureau of Mineral Resources, Geology and Geophysics, Department of National Development. Issued under the authority of the Hon. R. W. Swartz, M.B.E., E.D., Minister for National Development
Transverse Mercator Projection

Reference

CAINOZOIC

- QUATERNARY — Q — *Alluvium, sand, conglomerate, evaporites, travertine, gravel*
- TERTIARY — T — *Limestone, conglomerate, laterite, sandstone, siltstone*
- TERTIARY — Etingambra Formation * — Te — *Sandstone, conglomeratic sandstone, conglomerate, some siltstone*

MESOZOIC

- LOWER CRETACEOUS — Rumbalara Shale — Klr — *Siltstone, porcellanite, some sandstone. Marine fossils (Rock relationship diagram only)*
- JURASSIC ? — De Souza Sandstone — Md — *Sandstone, pebbly sandstone, some siltstone (Rock relationship diagram only)*

PALAEOZOIC

- PERMIAN — P — *Sandstone, tillitic conglomerate, shale, siltstone*
- DEVONIAN TO PERMIAN — Ligertwood Beds — Pzl — *Breccia, conglomerate, conglomeratic sandstone, sandstone*
- DEVONIAN TO CARBONIFEROUS ? — Finke Group — Pzf — *Sandstone, shale, siltstone, conglomerate (Rock relationship diagram only)*
- DEVONIAN TO CARBONIFEROUS ? — Pertnjara Group — Pzp — *Sandstone, siltstone, conglomerate, some limestone. Fish remains*
- SILURIAN ? TO DEVONIAN — Mereenie Sandstone — Pzm — *Sandstone, minor conglomerate*
- CAMBRIAN TO ORDOVICIAN — Larapinta Group — €-Ol — *Siltstone, sandstone, limestone, dolomite, phosphorite. Marine fossils*
- CAMBRIAN — Pertaoorrta Group — €p — *Sandstone, siltstone, shale, limestone, dolomite, some conglomerate. Marine fossils*
- CAMBRIAN — Cleland Sandstone — €c — *Sandstone, pebble sandstone, some siltstone*

PROTEROZOIC TO CAMBRIAN

- Mount Currie Conglomerate — Pzc — *Conglomerate; arkose at Ayers Rock*

PRECAMBRIAN

PROTEROZOIC

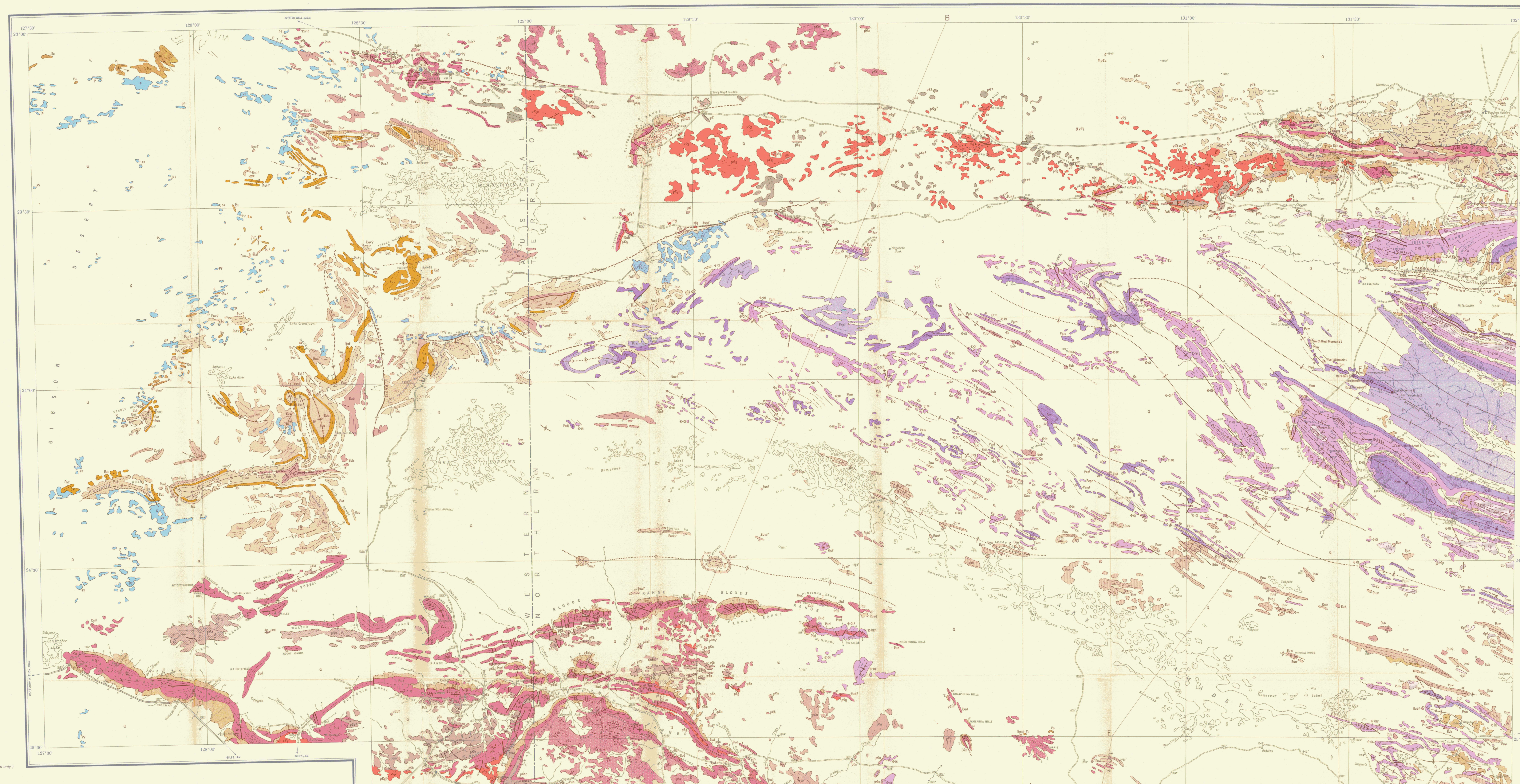
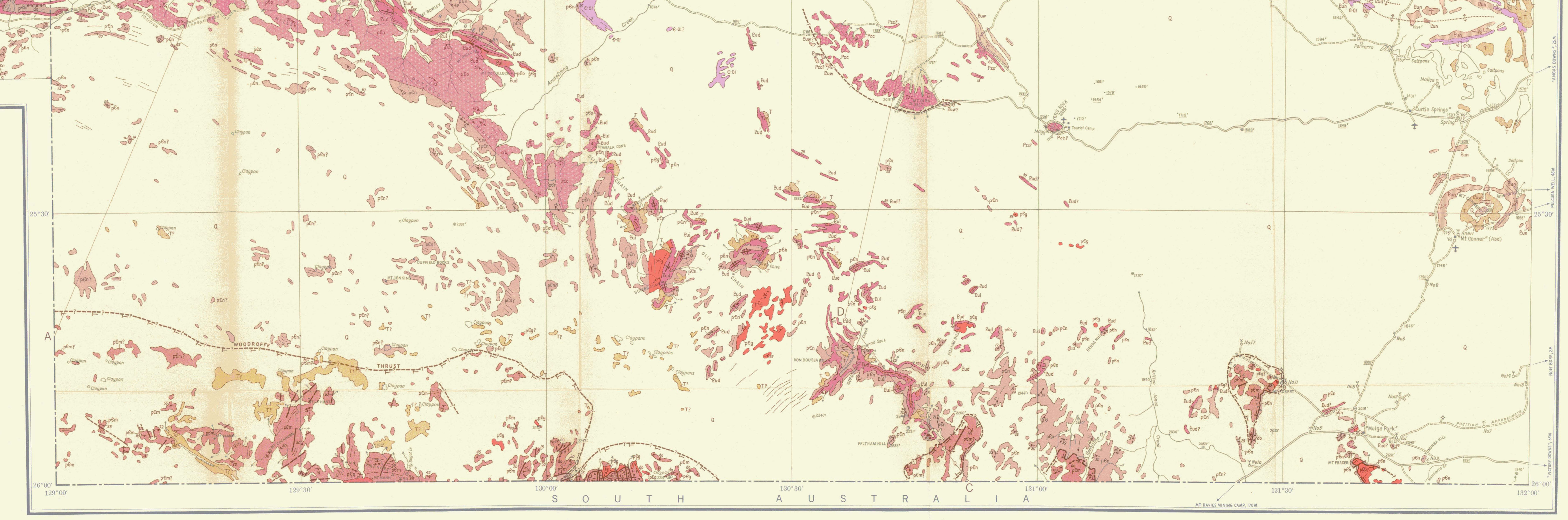
- Pu — *Sandstone, siltstone*
- Maurice Formation — Puu — *Sandstone, quartz greywacke, siltstone*
- Sir Frederick Conglomerate — Pus — *Conglomerate, some sandstone*
- Ellis Sandstone — Put — *Sandstone, siltstone, conglomeratic sandstone*
- Carnegie Formation — Puc — *Sandstone, siltstone, shale, conglomerate*
- Boord Formation — Puo — *Siltstone, calcilutite, calcarenite, tillitic conglomerate, some sandstone*
- Winnall Beds — Puw — *Sandstone, siltstone, some conglomerate*
- Inindia Beds — Pun — *Siltstone, shale, sandstone, chert, chert breccia, some dolomite and tillitic conglomerate*
- Pinyinna Beds — Pui — *Dolomite, limestone, siltstone. Metamorphosed in part to chlorite and talc schist*
- Dean Quartzite — Pud — *Quartzite, sandstone, conglomerate. Metamorphosed in part to kyanite schist and quartzite*
- Pertatataka Formation — Pup — *Siltstone, shale, limestone, calcarenite, dolomite, some sandstone and tillitic conglomerate*
- Areyonga Formation — Pua — *Siltstone and tillitic claystone, sandstone, dolomite*
- Bitter Springs Formation — Pub — *Dolomite, limestone, siltstone, sandstone, mafic volcanics Gypsum*
- Heavitree Quartzite — Puh — *Quartzite, sandstone, conglomeratic sandstone, siltstone*

- Dixon Range Beds — p€d — *Sandstone, siltstone, fine conglomerate, shale, arkose*
- Bloods Range Beds — p€b — *Sandstone, siltstone, slate, tuff, basalt and felsic porphyry and metamorphosed equivalents*
- Mount Harris Basalt — p€h — *Green schist, basalt, tuff, conglomerate, quartzite*
- p€s — *Schist, mafic volcanics, ultramafic rocks, amphibolite*
- p€l — *Mafic volcanics*
- Olia Gneiss — p€n — *Gneiss, granite, schist*
- Musgrave–Mann Complex — p€m — *Gneiss and granite*
- p€u — *Mafic and ultramafic rocks (Rock relationship diagram only)*
- Arunta Complex — p€a — *Schist, gneiss, amphibolite, marble, quartzite*
- Arunta Complex — p€q — *Quartzite and schist*
- p€ — *Metamorphic and igneous rocks*
- Pottoyu Granite Complex — p€o — *Granite* (various ages)
- p€g — *Granite* (various ages)

* Crops out on eastern sheet only.

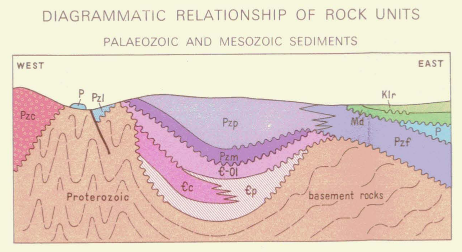
- Geological boundary
- Anticline, showing plunge
- Syncline, showing plunge
- Overturned anticline
- Overturned syncline
- Fault
- Fault, low-angle thrust (⊢ indicates upper plate)
- Where location of boundaries, folds and faults is approximate, line is broken; where inferred, queried; where concealed, boundaries and folds are dotted, faults are shown by short dashes
- 30 Strike and dip of strata
- Prevailing strike and dip of strata
- Vertical strata
- Horizontal strata
- 50 Overturned strata
- Dip < 15° (air-photo interpretation)
- Dip 15°–45° (air-photo interpretation)
- Trend lines (air-photo interpretation)
- Joint pattern (air-photo interpretation)
- 45 Strike and dip of foliation
- Prevailing strike and dip of foliation
- 35 Strike and dip of strata with trend of lineation
- 57 Strike and dip of foliation with trend of lineation
- 81 Strike and dip of foliation with horizontal lineation
- Dyke or vein, q-quartz, do-dolerite, p-pegmatite, amph-amphibolite
- Mine not worked
- Battery, smelter not operating
- • Cu Minor mineral occurrence
- Aa Asbestos (anthophyllite)
- Ag Silver
- Au Gold
- Bi Bismuth
- Cu Copper
- Mi Mica
- Mn Manganese
- Nb Niobium
- Oc Ochre
- Pb Lead
- Sn Tin
- Ta Tantalum
- Th Thorium
- U Uranium

- DD○AP4 Diamond drill hole with reference number
- Oil well
- Abandoned well with show of oil
- Dry hole, abandoned
- Gas well
- Abandoned gas well
- Abandoned well with show of oil and gas
- Bore
- Abandoned bore
- Well
- Abandoned well
- Windpump
- T Water tank
- E Earth tank or dam
- Dam on stream
- WH Waterhole
- WH Waterhole on stream
- RH Rockhole
- Sink hole
- Spring
- Swamp
- Highway
- Road
- Vehicle track
- Railway with station and siding
- Airport
- Landing ground
- "Henbury" Homestead; Abd-abandoned
- Building
- Yd Yard
- Telephone line
- State boundary
- Astronomical station
- Trigonometrical station
- •1271′ Height in feet, instrument-levelled (datum: mean sea level)
- •1722′ Height in feet, barometric (datum: mean sea level)

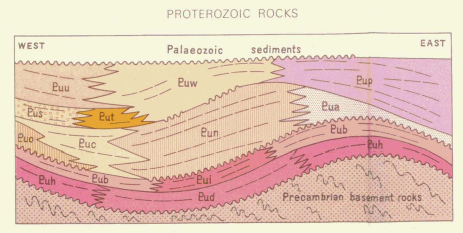



DIAGRAMMATIC RELATIONSHIP OF ROCK UNITS

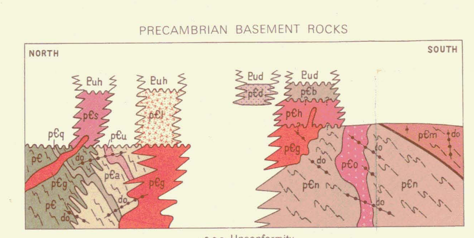
PALAEOZOIC AND MESOZOIC SEDIMENTS



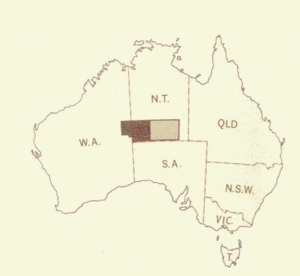
PROTEROZOIC ROCKS



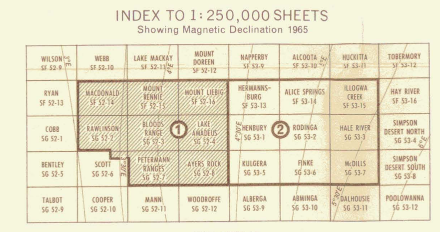
PRECAMBRIAN BASEMENT ROCKS



Unconformity

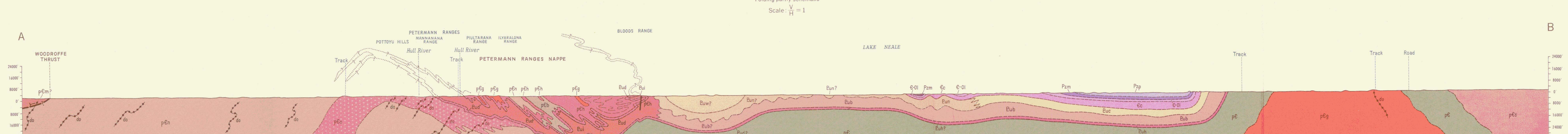


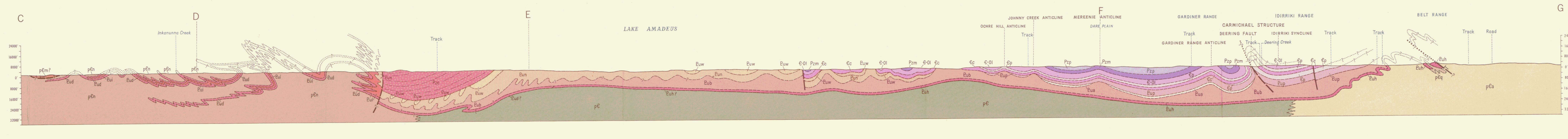
INDEX TO 1:250,000 SHEETS
Showing Magnetic Declination 1965



ANNUAL CHANGE 1′E

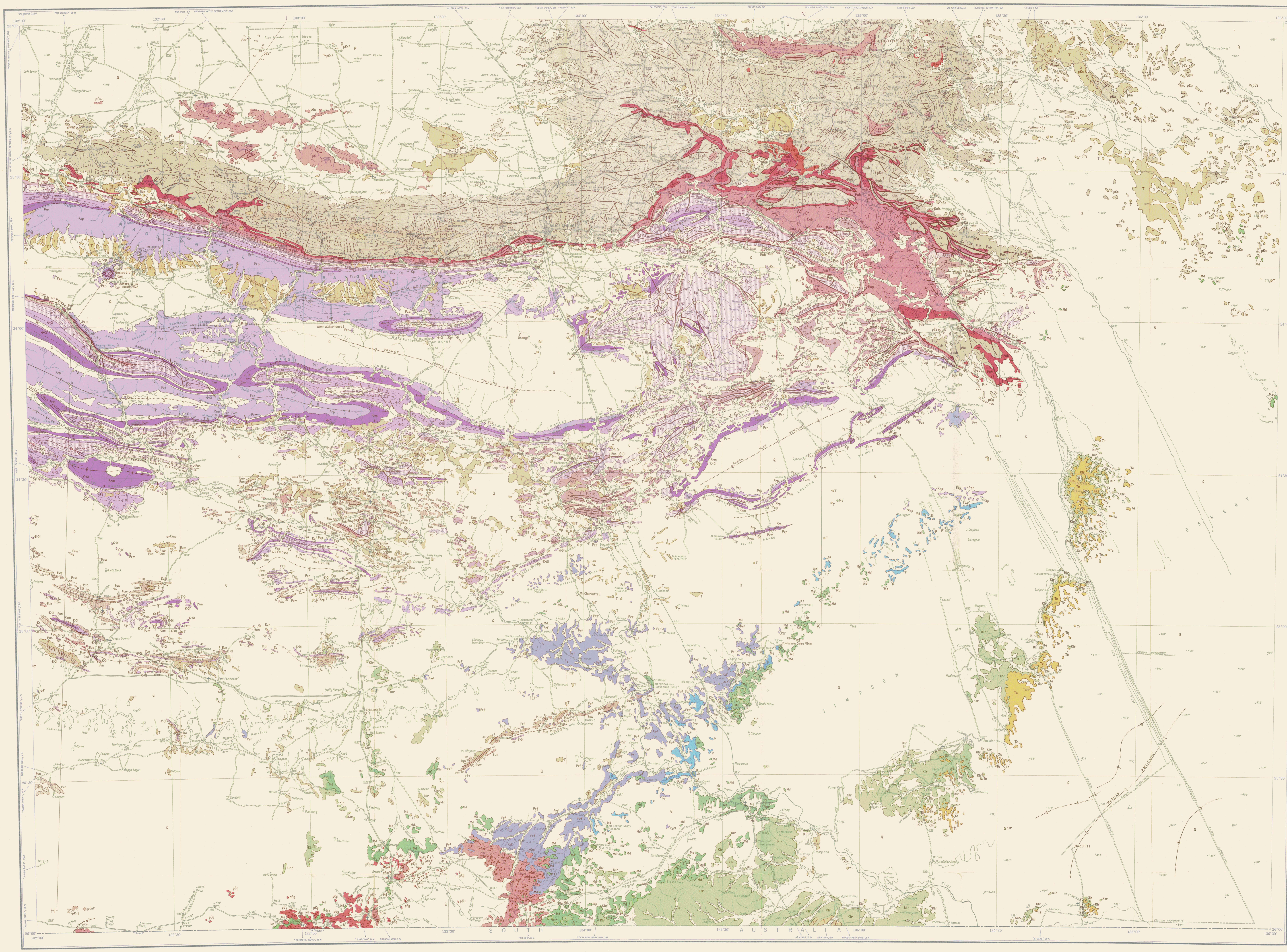
Sections
Cainozoic sediments omitted
Folding partly schematic
Scale: $\frac{V}{H} = 1$





AMADEUS BASIN (WEST)

Copies of this map may be obtained from the Bureau of Mineral Resources, Geology and Geophysics, Canberra, A.C.T., or Darwin, N.T.



GEOLOGICAL MAP
AMADEUS BASIN (EAST)
NORTHERN TERRITORY
AUSTRALIA
1970

Scale 1:500,000

10 0 10 20 30 MILES

10 0 10 20 30 40 50 KILOMETRES

Geology 1956, 1963–64 by Officers of the Bureau of Mineral Resources
Compiled 1968 by A. T. Wells, D. J. Forman, A. S. Mikolajczak
Cartography by Geological Branch B M R
Drawn by A. S. Mikolajczak

Published by the Bureau of Mineral Resources, Geology and Geophysics, Department of National Development. Issued under the authority of the Hon. R. W. Swartz, M.B.E., E.D., Minister for National Development
Transverse Mercator Projection

Reference

Era	Period	Unit		Symbol	Description
CAINOZOIC	QUATERNARY			Q	Alluvium, sand, conglomerate, evaporites, travertine, gravel
	TERTIARY			T	Limestone, conglomerate, laterite, sandstone, siltstone
		Etingambra Formation		Te	Sandstone, conglomeratic sandstone, conglomerate, some siltstone
MESOZOIC	LOWER CRETACEOUS	Rumbalara Shale		Klr	Siltstone, porcellanite, some sandstone. Marine fossils
	JURASSIC ?	De Souza Sandstone		Md	Sandstone, pebbly sandstone, some siltstone
PALAEOZOIC	PERMIAN			P	Sandstone, tillitic conglomerate, shale, siltstone
	DEVONIAN TO PERMIAN	Ligertwood Beds	*	Pzl	Breccia, conglomerate, conglomeratic sandstone, sandstone
	DEVONIAN TO CARBONIFEROUS ?	Finke Group		Pzf	Sandstone, shale, siltstone, conglomerate
		Pertnjara Group		Pzp	Sandstone, siltstone, conglomerate, some limestone. Fish remains
	SILURIAN ? TO DEVONIAN	Mereenie Sandstone		Pzm	Sandstone, minor conglomerate
	CAMBRIAN TO ORDOVICIAN	Larapinta Group		Є-Ol	Siltstone, sandstone, limestone, dolomite, phosphorite. Marine fossils
	CAMBRIAN	Pertaoorrta Group		Єp	Sandstone, siltstone, shale, limestone, dolomite, some conglomerate. Marine fossils
		Cleland Sandstone	*	Єc	Sandstone, pebble sandstone, some siltstone
	PROTEROZOIC TO CAMBRIAN	Mount Currie Conglomerate	*	Pzc	Conglomerate; arkose at Ayers Rock
PRECAMBRIAN	PROTEROZOIC		*	Pu	Sandstone, siltstone
		Maurice Formation	*	Puu	Sandstone, quartz greywacke, siltstone
		Sir Frederick Conglomerate	*	Pus	Conglomerate, some sandstone
		Ellis Sandstone	*	Put	Sandstone, siltstone, conglomeratic sandstone
		Carnegie Formation	*	Puc	Sandstone, siltstone, shale, conglomerate
		Boord Formation	*	Puo	Siltstone, calcilutite, calcarenite, tillitic conglomerate, some sandstone
		Winnall Beds		Puw	Sandstone, siltstone, some conglomerate
		Inindia Beds		Pun	Siltstone, shale, sandstone, chert, chert breccia, some dolomite and tillitic conglomerate
		Pinyinna Beds	*	Pui	Dolomite, limestone, siltstone. Metamorphosed in part to chlorite and talc schist
		Dean Quartzite		Pud	Quartzite, sandstone, conglomerate. Metamorphosed in part to kyanite schist and quartzite (Section only)
		Pertatataka Formation		Pup	Siltstone, shale, limestone, calcarenite, dolomite, some sandstone and tillitic conglomerate
		Areyonga Formation		Pua	Siltstone and tillitic claystone, sandstone, dolomite
		Bitter Springs Formation		Pub	Dolomite, limestone, siltstone, sandstone, mafic volcanics; Gypsum
		Heavitree Quartzite		Puh	Quartzite, sandstone, conglomeratic sandstone, siltstone
		Dixon Range Beds	*	pЄd	Sandstone, siltstone, fine conglomerate, shale, arkose
		Bloods Range Beds	*	pЄb	Sandstone, siltstone, slate, tuff, basalt and felsic porphyry and metamorphosed equivalents
		Mount Harris Basalt	*	pЄh	Green schist, basalt, tuff, conglomerate, quartzite
			*	pЄs	Schist, mafic volcanics, ultramafic rocks, amphibolite
			*	pЄt	Mafic volcanics
		Olia Gneiss		pЄn	Gneiss, granite, schist
		Musgrave–Mann Complex		pЄm	Gneiss and granite
				pЄu	Mafic and ultramafic rocks
		Arunta Complex		pЄa	Schist, gneiss, amphibolite, marble, quartzite
				pЄq	Quartzite and schist
				pЄ	Metamorphic and igneous rocks (Section only)
		Pottoyu Granite Complex	*	pЄo	Granite (various ages)
				pЄg	Granite (various ages)

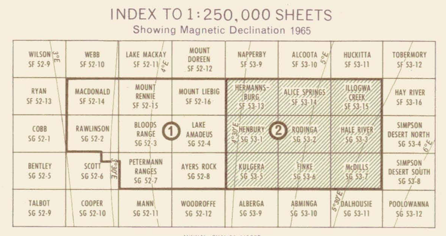
* Crops out on western sheet only.

Geological boundary
Anticline, showing plunge
Syncline, showing plunge
Overturned anticline
Overturned syncline
Fault
Fault, low-angle thrust (⊢ indicates upper plate)
Where location of boundaries, folds and faults is approximate, line is broken; where inferred, queried; where concealed, boundaries and folds are dotted, faults are shown by short dashes
Strike and dip of strata
Prevailing strike and dip of strata
Vertical strata
Horizontal strata
Overturned strata
Dip < 15° (air-photo interpretation)
Dip 15°–45° (air-photo interpretation)
Trend lines (air-photo interpretation)
Joint pattern (air-photo interpretation)
Strike and dip of foliation
Prevailing strike and dip of foliation
Strike and dip of strata with trend of lineation
Strike and dip of foliation with trend of lineation
Strike and dip of foliation with horizontal lineation
Dyke or vein, q-quartz, do-dolerite, p-pegmatite, amph-amphibolite

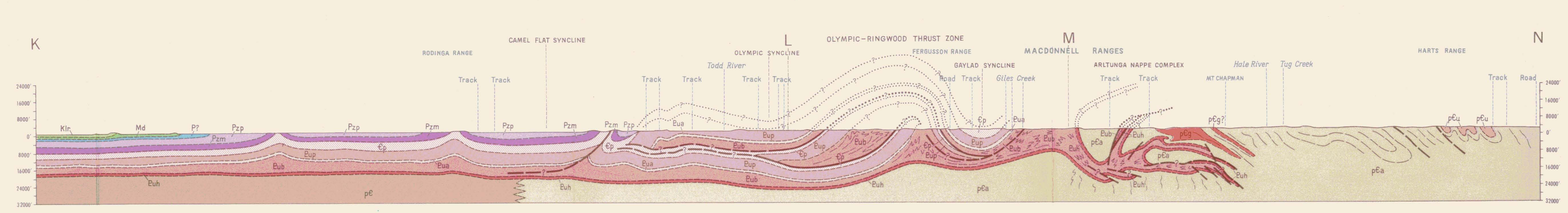
Mine not worked
Battery, smelter not operating
• Cu Minor mineral occurrence
Aa Asbestos (anthophyllite)
Ag Silver
Au Gold
Bi Bismuth
Cu Copper
Mi Mica
Mn Manganese
Nb Niobium
Oc Ochre
Pb Lead
Sn Tin
Ta Tantalum
Th Thorium
U Uranium

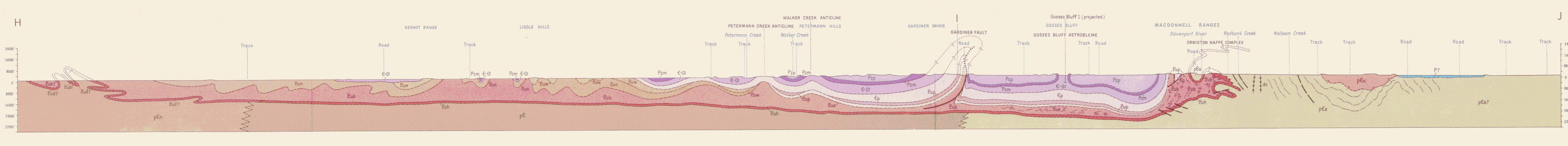
DDOAP3 Diamond drill hole with reference number
Oil well
Abandoned well with show of oil
Dry hole, abandoned
Gas well
Abandoned gas well
Abandoned well with show of oil and gas
Bore
Abandoned bore
Well
Abandoned well
Windpump
T Water tank
E Earth tank or dam
Dam on stream
WH Waterhole
WH Waterhole on stream
RH Rockhole
Sink hole
Spring
Swamp
Highway
Road
Vehicle track
Railway with station and siding
Airport
Landing ground
"Henbury" Homestead; Abd-abandoned
Building
Yd Yard
Telephone line
State boundary
Astronomical station
Trigonometrical station
1271′ Height in feet, instrument levelled (datum: mean sea level)
1722′ Height in feet, barometric (datum: mean sea level)

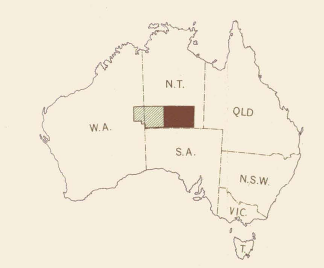
INDEX TO 1:250,000 SHEETS
Showing Magnetic Declination 1965



Sections
Cainozoic sediments omitted
Folding partly schematic
Scale: $\frac{V}{H} = 1$







AMADEUS BASIN (EAST)

Copies of this map may be obtained from the Bureau of Mineral Resources, Geology and Geophysics, Canberra, A.C.T., or Darwin, N.T.