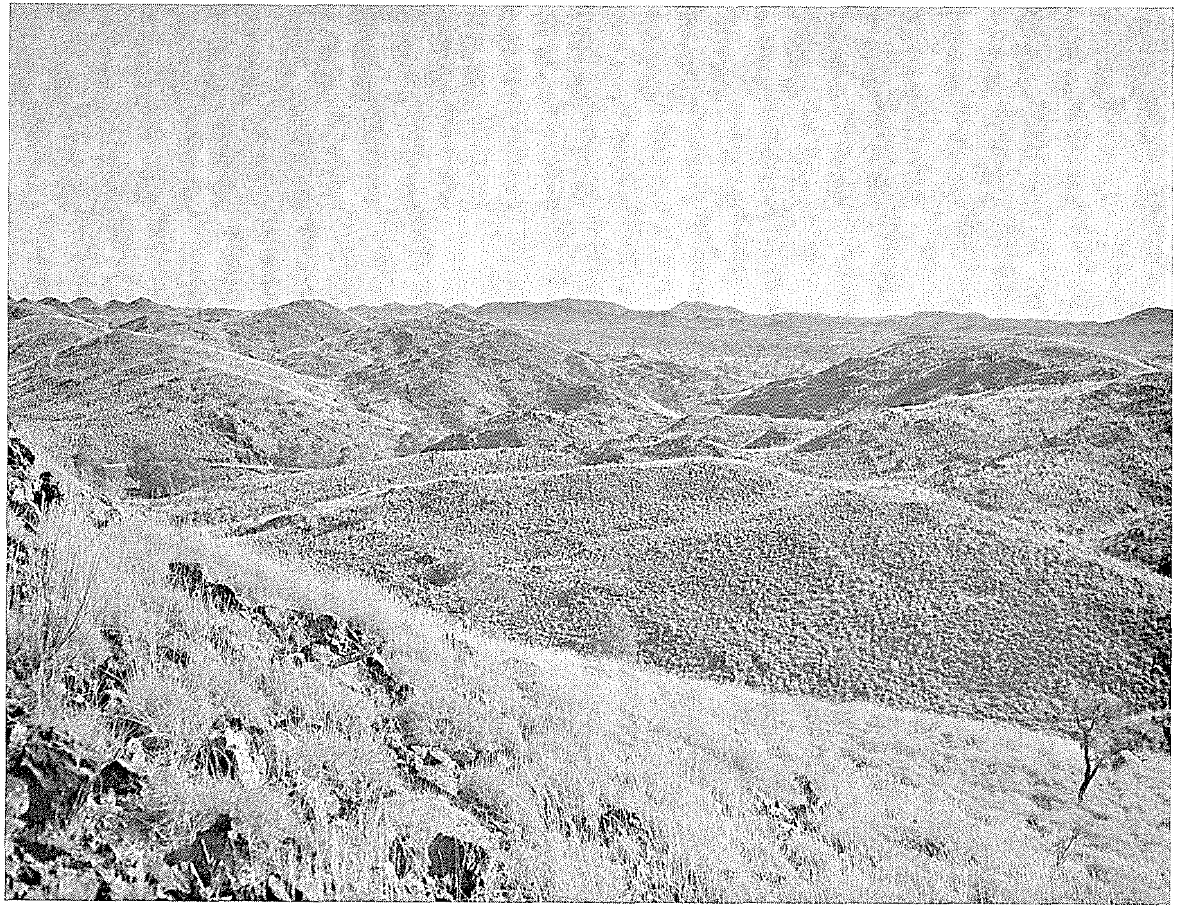
BULLETIN No. 120

GEOLOGY OF THE KIMBERLEY REGION, WESTERN AUSTRALIA: THE EAST KIMBERLEY

D. B. DOW and I. GEMUTS



Frontispiece. Lamboo Hills north of Halls Creek. (By courtesy of Australian News and Information Bureau)

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

BULLETIN 120

Geology of the Kimberley Region Western Australia The East Kimberley

by

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SUMMARY

Kimberley region is the name given to the rugged northern extremity of Western Australia, a large part of which is composed of Precambrian rocks. The area was mapped by combined teams of Bureau of Mineral Resources and Geological Survey of Western Australia geologists between 1962 and 1967: the results of the first three years' mapping—of the southeastern part of the Kimberley region—are given in this Bulletin. Isotopic age determinations were made on rocks throughout the Precambrian successions, and this has proved a valuable adjunct to the mapping.

The oldest rocks of the region are geosynclinal sediments called the Halls Creek Group. Though the record of past events affecting these rocks is now only fragmentary, sufficient rocks are now exposed to indicate that the group was laid down over the whole of the East Kimberley region, probably in Archaean time, and then tightly folded and slightly metamorphosed. At this time the Halls Creek Group was invaded by basic sills and dykes, some of which are many thousands of feet thick (Woodward Dolerite and McIntosh Gabbro), and gave rise to ultrabasic differentiates (Alice Downs Ultrabasics).

A second period of folding affected the rocks over most of the region, but it was more intense and was accompanied by high-grade metamorphism along a narrow belt extending diagonally across the map area, called the Halls Creek Mobile Zone. This more intense metamorphism formed the Tickalara Metamorphics from the Halls Creek Group, and it is believed that the Mabel Downs Granodiorite was formed at the same time by melting of the metamorphics in places. Post-tectonic granitic rocks were then intruded along the Mobile Zone as batholiths and stocks. The end product of this cycle of activity is the igneous-metamorphic complex called the Lamboo Complex.

The Tickalara Metamorphics have been subdivided into three metamorphic zones on the basis of mineralogical and textural changes in three groups of rocks—pelitic, arenaceous, and basic igneous rocks. The zones range from greenschist to granulite facies of regional metamorphism.

In early Carpentarian times, the type of deformation changed radically and the area reacted to stress during the rest of the Proterozoic almost entirely by dislocation along great faults which follow the Mobile Zone. It is possible that the displacement on these faults was predominantly horizontal. During this time the areas east and west of the Mobile Zone were tectonically competent blocks in which the only deformation consisted of broad warpings over large areas, accompanied by minor faulting.

The early Carpentarian faulting, which was accompanied by vast eruptions of acid volcanics (Whitewater Volcanics), marks a fundamental break in the tectonic activity and type of sedimentation over most of the area. To the east and west, later sediments spanning the rest of the Proterozoic were laid down in epeiric seas, and many of the formations can be recognized virtually unchanged over tens of thousands of square miles.

Only along the Halls Creek Mobile Zone did intense deformation and minor igneous intrusion continue after the early Proterozoic, and during much of this time the Mobile Zone influenced sedimentation to the east and west.

A glacial epoch towards the close of the Proterozoic (Adelaidean) has left a remarkable record of extensive ice caps, and a thick cover of glacial sediments. There were at least two major glaciations, the older of which seems to have been protracted and probably consisted of two glacial pulses.

Outpourings of basalt in the Lower Cambrian covered almost all the map area, and now cover extensive areas of the Precambrian rocks in the eastern part of the region.

Gold mining, both alluvial and lode, was an important industry before the turn of the century, but there has since been very little activity. Production of other minerals from the East Kimberley region is negligible. The region offers some promise of economic deposits of base metals, and there is a possibility that small deposits of other minerals such as nickel, tantalum and niobium, platinum, and uranium, may be found by intensive prospecting.

Groundwater is important to the major industry of the region, cattle raising, and the younger Proterozoic sediments and recent alluvium provide the most reliable sources. It is more difficult to obtain good flows of water from the crystalline rocks of the Halls Creek Mobile Zone.

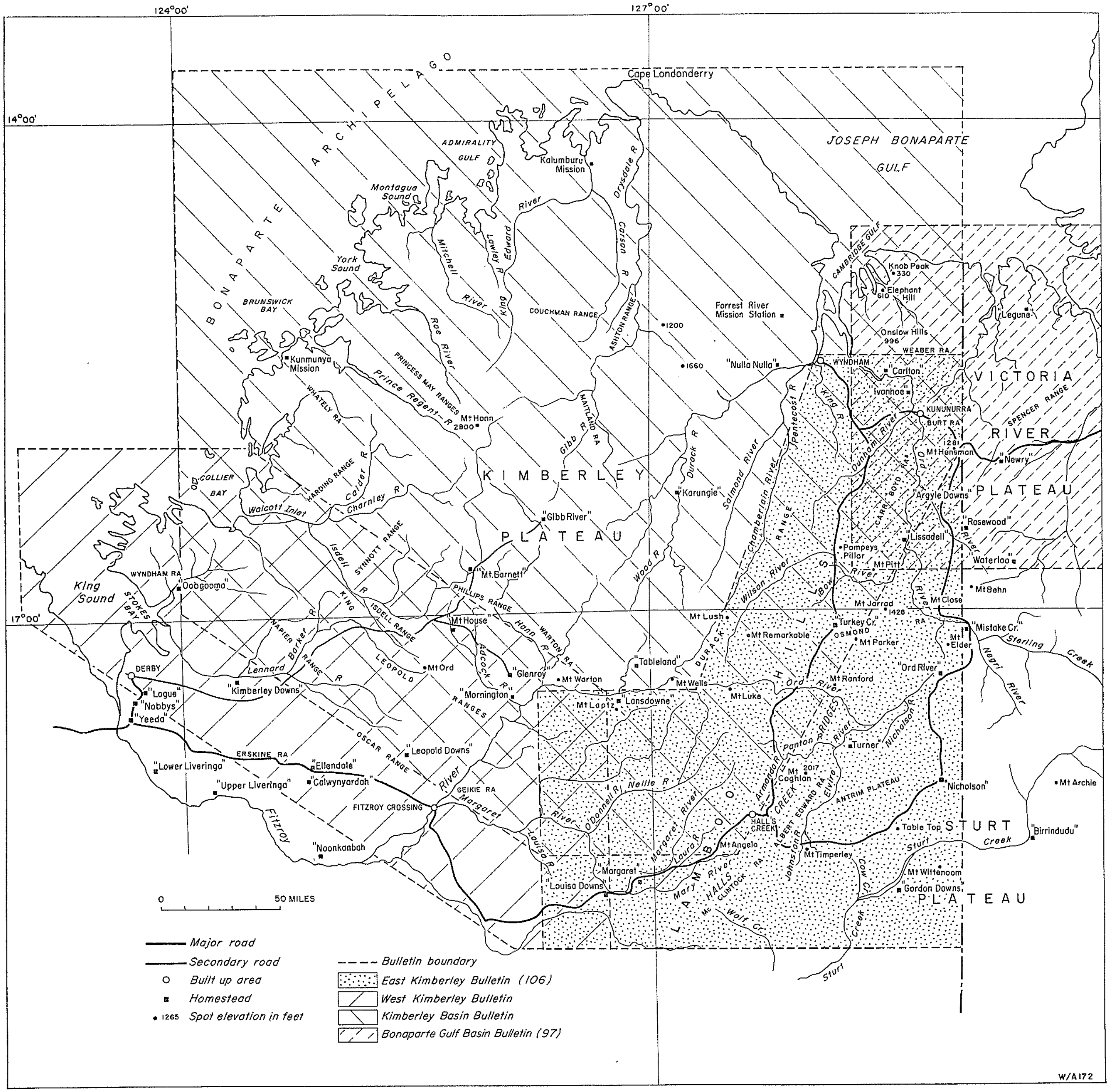


Figure 1. Locality map

INTRODUCTION

Kimberley region is the name of the rugged, and until recently isolated, northern extremity of Western Australia. This Bulletin, which deals with the southeastern part of the region, is the first of three which will describe the geology of the Precambrian rocks of the whole region—the others, which are in preparation, will cover the Kimberley Basin to the northwest, and the West Kimberley region (Fig. 1).

Cattle raising is the principal industry, but because the climate is harsh, and the soils generally poor, the region is very sparsely populated; Aborigines outnumber Europeans and most are employed as station hands. Land holdings have to be very large to be economical, and the homesteads are up to 60 miles apart.

There are only three towns in the map area: Wyndham (population 958 at June 1961), a small port on the west arm of Cambridge Gulf which has a meat-works and provides an outlet for the pastoral industry; Kununurra (population 337), about 60 miles by road from Wyndham, which is a centre for the Ord Irrigation Scheme; and Halls Creek (population 160), originally a gold-mining town, but now a small supply centre for local cattle stations and a Government administration centre.

Gold mining, both alluvial and lode, was an important industry before the turn of the century, but now the only gold won is produced by Aborigines who work small alluvial deposits during the wet season. Since 1950 there have been spasmodic attempts to reopen some of the larger lode mines, but these have not been successful. The only industry other than cattle raising is the Ord Irrigation Scheme. A dam has been constructed at a cost of $8,000,000 on the Ord River at Kununurra to provide water for irrigation of alluvial plains in the area. The scheme is in its early stages, and it is proposed to build a larger dam at a cost of about $60,000,000.

Communications and Access

Until recently, the roads linking the Kimberley region with the rest of Australia were poorly formed tracks which were impassable for weeks at a time during the wet season. Since 1960 most of the main roads have been rerouted, and though long spells of wet weather can still cause delays, they should soon be passable in all weathers.

The Great Northern Highway connecting Derby and Wyndham has a gravel surface over much of its length, and crosses the area diagonally from the south-western corner to the northern extremity. By 1966 the bridges and rerouting of the road were well advanced. Other main roads in the East Kimberley region include the Wyndham and Nicholson road in the east, which is gravelled and has several fords, and a road in the southeast which joins Halls Creek and Nicholson and continues to the Stuart Highway in the Northern Territory. In 1964, much of this road was not gravelled, and few of the rivers were bridged.

Station roads give reasonable access to much of the area: they range from well graded roads to barely discernible and washed-out tracks. Much of the Kimberley Plateau, the mountains between the Wilson River and the headwaters of the Ord River, and the Carr Boyd Ranges, are not accessible by day trips from a Land Rover, and here the mapping was done by means of a helicopter. There are almost no vehicle tracks in the belt of country between Halls Creek and the Osmond Range, but it is possible to pick Land Rover routes over most of the belt.

Wyndham and Kununurra are connected to Perth and Darwin by regular air services. Halls Creek and most of the stations in the area have airstrips from which regular connecting services are flown to Wyndham. Cessna aircraft can be chartered from Wyndham to Derby.

Climate

The region has a tropical savannah climate and a rainfall which ranges from 15 inches in the south to 35 inches in the north. Most of the rain falls between December and March, when as much as 6 inches has been recorded in one day. June to September is the dry season, but heavy winter rains have been recorded in freak seasons such as the winter of 1956. The long periods of little rain and high evaporation (100-110 in. per year) desiccate the soil, and all rivers except the lower reaches of the Ord River and spring-fed streams in the Kimberley Plateau stop flowing in the winter months. Even large waterholes and most springs are generally only semipermanent.

Day temperatures are very high throughout the year, and in summer may exceed 110°F for many consecutive days. The average daily mean temperature increases from 78°F at Halls Creek to 84°F at Wyndham, the latter figure being the highest average daily mean temperature in Australia. The average summer maximum is between 95°F and 100°F, with November the hottest month, while the average winter maximum ranges from 80°F to 90°F. Temperatures in winter can be quite low; the average minimum temperature recorded in Halls Creek for July is 45°F, and occasional frosts have been noted in the southern part of the area.

The prevailing winds are the southeast trade winds of the winter months, and the northwest monsoons. The winter winds are dry since they traverse the arid interior, and relative humidity averages about 40 percent. Summer winds are moist and bring a relative humidity of about 75 percent. August and September are the windy months, when sporadic dust storms and willy-willies occur throughout the area.

Vegetation

Most of the area is rocky or has only a thin cover of soil, and the main ground cover is spinifex, which occurs as tussocks from a few inches to 6 feet high (Pl. 1, figs 1 and 2). Each blade of spinifex is armed with a sharp siliceous point, and walking through even low tussocks can be a painful experience unless protective leggings are worn.

The trees in this country are characteristically very sparse and stunted, and large areas almost devoid of trees are not uncommon (Pl. 1, fig. 1). Watercourses generally support denser stands or larger trees, and in places there are spectacular specimens of the baobab or bottle tree. Where the rivers have cut deep gorges, small areas of dense tropical forest grow in the bottom on continually moist soil: a large variety of plants occur here, including pandanus and other types of palms.

The eastern part of the region is characterized by open plains clothed in Mitchell and Flinders grasses. Much of this country is almost treeless, but there are also large areas of savannah in which bauhinia and rosewood occur together with gum trees (Pl. 2, fig. 1).

Physiography

Most of the Kimberley region is a plateau up to 2,600 feet high, called the Kimberley Plateau (Fig. 1), while to the east, in the Northern Territory, there is a similar but lower plateau, the Victoria River Plateau. This Bulletin is concerned with the wide belt of rough mountainous country between the two.

Almost all of the East Kimberley region is drained by rivers flowing northwards to Cambridge Gulf, but there are two notable exceptions—Sturt Creek in the extreme southeastern corner, which drains south and disappears into the Canning Desert; and the headwaters of the Fitzroy River in the southwest, which flow westwards to King Sound.

Of the northerly draining rivers, the Ord River, which is by far the largest, drains about 14,000 square miles of the East Kimberley region. It is almost dry in the winter months but has an enormous flow at times in the wet season. In its middle and lower reaches it flows through gently rolling country, and is incised as much as 100 feet below plain level, but before reaching Cambridge Gulf to the north, it breaks through the Carr Boyd Range in a series of deep gorges, and it is in one of these that it is proposed to build a dam to impound water to irrigate alluvial flats to the north.

The eastern tributaries of the Ord River, with the exception of the Negri River, are short, and much smaller than the western tributaries. They rise in the northerly-trending belt of rugged country near the middle of the map area, and flow eastwards along tortuous courses before joining the main river.

The *Kimberley Plateau* is the dominant physiographic feature of the whole region, but only its margins fall within the East Kimberley region. The plateau is over 50,000 square miles in area, and has an elevation of 1,500 to 2,600 feet. It consists of flat sandstone benches many miles wide, bounded by scarps up to 250 feet high (Pl. 2, fig. 2; Pl. 3, fig. 1), and over the whole region the bedrock crops out extensively; vegetation is sparse and consists of spinifex, small pockets of grass, and scattered stunted gum trees.

The marginal ranges in the East Kimberley region are the Durack and Mueller Ranges on the west, and the King Leopold Range on the southeast. In the marginal ranges the beds dip more steeply than on the plateau, and the country consists of bold strike ridges of resistant sandstone standing up to 1,000 feet above the intervening narrow valleys. Many of the valleys are flat-floored and provide good travel for vehicles, but there are very few passes across the ridges.

The ridges are rocky and have a sparse cover of spinifex and small trees, but the valleys support reasonably good pastures and the watercourses are marked by stands of larger trees. Perennial spring-fed streams are common, and there are many permanent and semipermanent waterholes where streams have cut through the sandstone ridges in deep gorges.

The major streams on the plateau are deeply incised: valleys are as deep as 750 feet. Some, such as the Chamberlain River, which drains northwards into Cambridge Gulf, follow the structure of the underlying rocks, but others such as the O'Donnell River, which flows westwards to the Fitzroy River, are superimposed streams which transgress the geological structure. Deep narrow gorges are common where the streams cross the resistant sandstone benches.

The country to the east of the Kimberley Plateau is a complete contrast, and is characterized by chaotic rocky ridges covered by spinifex and stunted gums. We have called this belt the *Lamboo Hills* (Fig. 1), and it makes up most of the East Kimberley region.

The western side of the belt consists mainly of igneous and metamorphic rocks which have an open-textured drainage moulding low, rounded, boulder-strewn hills and subdued strike ridges (frontispiece). The area ranges from 1,000 to 2,000 feet high, and has a maximum relief of about 500 feet. Broad smooth whalebacks of granite interspersed with narrow sandy flats are common, but many of the ridges are mantled with huge boulders.

The soil cover over most of the western side of the Lamboo Hills is poor, and most grazing lands are restricted to sandy and black soil plains, or alluvial deposits along the present river channels. Wide valleys providing good pastures have been eroded on areas of intense shearing, and these provide access to the north of the map area. The hilly areas are clothed in dense spinifex and sparse eucalypts.

To the southwest, sandy plains are more extensive, and in the Margaret River headwaters only scattered tors of granite and low laterite mesas relieve the monotony of the plains. In this area, gently dipping sedimentary rocks cap the granite rocks forming the large areas of broad structural benches and subdued cuestas, characteristic of the Lubbock and Ramsay Ranges.

The southeastern part of the Lamboo Hills, from the Osmond Range to the McClintock Range, has been called the *Halls Creek Ridges*. The area consists of tightly folded sedimentary and metamorphic rocks and has a rough hilly relief of up to 500 feet. The drainage is structurally controlled, but in general it is extremely closely textured. The ridges follow the regional north-northeastern strike of the underlying rocks, and have steep flanks cut by deep gullies; they are breached every few hundred yards by cross-cutting streams (Pl. 1, fig. 1), and travel by vehicle, though possible in most places, is difficult. The runoff is fast, and there is little soil cover; consequently the main vegetation consists of spinifex and stunted eucalypts.

A feature common to the Lamboo Hills is the lack of surface water in the dry season. Almost all the streams have dry sandy beds and they flow only during wet weather; very few waterholes are permanent, and springs and soaks are rare.

Separating the Lamboo Hills from the plains to the east is the *Albert Edward Range,* which has a maximum elevation of about 1,600 feet and rises up to 500 feet above the surrounding country. It is characterized by prominent cuestas and hogbacks of sandstone, which have smooth curved dip-slopes to the east, and near-vertical scarps up to 400 feet high on the west (Pl. 3, fig. 2). The regional drainage is west to east, and the tributaries of the Ord River break through the range in deep gorges which have deep permanent pools, contrasting with the dry Lamboo Hills to the west.

The easternmost part of the map area has a low relief and there are many miles of rolling, and in places treeless, plains which extend northwards for 130 miles to Argyle Downs. They are drained by the Ord River and are about 250 feet above sea level in the north, rising gradually to 750 feet in the south. In their natural state the plains are clothed in a heavy growth of native grasses, and provide much of the best grazing in the region. However, grazing and fires have removed most of the protective grasses, and seasonal torrential rains and strong winds have swept vast areas clear of soil and vegetation. Resultant sediment loads as high as 250 tons of mud per second have been carried by the Ord River during floods.

Part of the eastern plains is underlain by flatlying volcanic rocks; this country is more rugged and consists of boulder-strewn hills up to 300 feet high. The drainage is dense, the valley walls are steep and generally broken by structural benches, and travel by vehicle is arduous. South of the Osmond Range mesas and buttes of resistant sandstone rise 200 to 600 feet above the plains (Pl. 2, fig. 1), and near Mount Buchanan erosion along joints has carved spectacular vertical-sided ravines and left spires of silicified sandstone.

To the south, the plains of gently dipping Palaeozoic limestone are cut by many narrow almost vertical-sided ravines formed by the enlargement of joints, and the area, in places, is almost impenetrable. In other localities the limestone is nearly vertical, and stands out above the surrounding country as straight walls up to 50 feet high and 100 feet across.

The *Osmond Range* is a broad massif which juts eastwards into the eastern plains from near the head of Bow River. It is dominated by a broad plateau of massive sandstone cut by mazes of deep ravines eroded along joints and faults. There is almost no soil cover and the vegetation consists of spinifex and scattered small eucalypts. The highest point of the range, Mount Parker (2,378 ft), is the culmination of one of the plateaux. The gently dipping broad cuestas flanking most of the range are drained by radial spring-fed creeks which flow down the dip-slopes. Osmond Creek is the largest stream; it rises in a large amphitheatre at the western end of the range and breaks through to the southeast in a deeply incised gorge.

The *Carr Boyd Ranges* in the north provide the most rugged country and some of the most spectacular scenery in the Kimberley region. Bulky sandstone mountains bounded by straight steep fault-scarps stand as much as 1,500 feet above the surrounding country; they are deeply dissected, and most of the watercourses are along narrow valleys or vertical-sided gorges in which waterfalls are common. The streams are mostly non-perennial, but springs are plentiful and there are many permanent waterholes. However, most of the water is of little use for stock as it is inaccessible from the pastures, which are limited to a few small valleys, the rest of the area being rocky and clothed in spinifex and small gum trees.

The rivers, like many of those on the Kimberley Plateau, are superimposed, and they cut through the Carr Boyd Ranges with scant regard for the underlying rocks. This is well illustrated by the Ord River, which leaves the eastern plains and cuts through the range by way of the Carlton Gorge (Pl. 4, fig. 2).

The *Ragged Range* is worthy of special mention. Massive red conglomerate, which forms a scarp up to 1,500 feet high, is riven by deep clefts along its length of about 20 miles, giving the ragged skyline shown in Plate 4, figure 2.

The southern part of the map area is an almost flat plain, sloping gently southwards, relieved only by sporadic low hills and mesas of sandstone. The eastern part of the plain is perched about 1,400 feet above sea level and has been called the *Sturt Plateau* (Paterson, 1954), but to the west it is much lower and merges with the plains of the Fitzroy River. It is an ancient peneplaned and lateritized surface which forms the *Canning Plain* to the south. To the north, in the Halls Creek region, it merges almost imperceptibly with the Lamboo Hills, but to the southwest and the northeast, tributaries of the Ord and Margaret Rivers have eroded well below the plain level, and the northern boundary is a deeply dissected rocky escarpment.

The plain is drained by senile streams which are marked during most of the year by braided sandy channels, or by chains of saline waterholes.

Previous Investigations

The first geological work in the Ord River Region was done in 1883 and 1884 by Hardman (1885), who was Government Geologist attached to the Kimberley Survey Expeditions. The main rock groups shown on his map are much the same as the broader divisions in this Bulletin, and his report is remarkably accurate considering the reconnaissance nature of his work. Hardman discovered gold in the region, and by 1890 considerable mining, both alluvial and lode, was taking place. Woodward (1891) and Smith (1898) reported on the geology of the goldfields.

Jack (1906) investigated the hydrology of the southwestern part of the region, but little was added to the knowledge of the geology until the discovery of a bituminous substance in the Ord and Negri Rivers in 1920 (Maitland, 1920) sparked interest in the possibility of finding petroleum in the area (Mahony, 1922). The bituminous occurrence has been described by Blatchford (1922), and Wade (1924) made a valuable contribution to the stratigraphic knowledge of the East Kimberley region, and reported on the prospects of finding commercial quantities of petroleum in the area; he subsequently made numerous contributions to the geology of the Fitzroy Basin to the southwest (Wade, 1936).

Blatchford (1928) reported briefly on gold mining at the Grants Patch centre and the occurrence of galena on Speewah station; and Finucane (1938a,b, 1939a,b,c), Finucane & Sullivan (1939), and Jones (1938) reported on the various mining areas of the region for the Aerial, Geological and Geophysical Survey of Northern Australia.

In 1945 Matheson & Teichert (1948) made a geological reconnaissance of the Cambrian rocks of the East Kimberley region, and in 1948 the Bureau of Mineral Resources began the systematic regional mapping of the Fitzroy Basin. This project was completed in 1952 (Guppy, Lindner, Rattigan, & Casey, 1958). As part of the project, the Precambrian rocks near Halls Creek were mapped by Matheson & Guppy (1949), and later the Noonkanbah and Mount Bannerman Sheet areas to the west and south were mapped (Thomas, 1958; Wells, 1962).

Probably the greatest contribution to geological knowledge of the East Kimberley region since Hardman was made by Traves (1955) who, as a member of a CSIRO Land Research and Regional Survey team in 1949 and 1952, mapped the Ord-Victoria region. His map includes all the area covered in the report. The latest work has been done by Harms (1959), who made a valuable appraisal of the whole of the Kimberley District for the Broken Hill Pty Co. Ltd, and by Ruker (1961), who mapped an area near Saunders Creek in the Gordon Downs Sheet area. Veevers & Roberts (1968) and Kaulback & Veevers (1968) have described the Palaeozoic succession of the Bonaparte Gulf Basin, which overlaps the East Kimberley in the northeast.

Present Investigation

This Bulletin describes the results of mapping done by the Bureau of Mineral Resources and the Geological Survey of Western Australia from 1962 to 1964 as part of a programme to map the Precambrian rocks of the Kimberley Region. It deals primarily with the older basement rocks of the East Kimberley region and with the overlying Proterozoic rocks on the east; the boundaries of the map area are shown in Figure 1.

Though the map area includes some of the Carpentarian rocks of the Kimberley Plateau, these are treated only very briefly in this Bulletin, and will be described in detail later (Plumb, in prep.); the basement rocks in the western half of the Kimberley region will be the subject of a third Bulletin (Gellaty, Sofoulis, & Derrick, in prep.).

Isotopic age determination has proved a valuable adjunct to the mapping of the Precambrian rocks. Sampling of suitable rocks throughout the Precambrian successions was started in 1963 by V. M. Bofinger (BMR), who continued sampling in 1964 and 1965. A total of about 150 samples have been collected.

The work on the water resources of the region has been primarily the responsibility of the Geological Survey of Western Australia: Morgan in 1962, Passmore in 1963, and Allen in 1964. The section on water supply (pp. 116-131) was written by Passmore.

Unless otherwise stated, the petrographical descriptions are by Gemuts; 800 thin sections, now stored at the Bureau of Mineral Resources and the Geological Survey of Western Australia, were examined.

Field Method. Air-photographs at a scale of approximately 1:48,000 taken in 1948 are available for the whole of the East Kimberley region. Observations were plotted directly on the photographs in the field, and the information was then transferred to transparent foil topographic maps at the same scale as the air-photographs. The maps were then reduced to the 1:250,000 scale.

Land Rovers were used for access, but most of the mapping was done on foot; areas not accessible in one day from the Land Rover were mapped with the aid of a helicopter.

Geological features of the younger Proterozoic rocks show up well on the air-photographs, and boundaries extrapolated by photo-interpretation are reasonably accurate. On the other hand, the older rocks do not show up as well, and though the traverses were in general more closely spaced, extrapolation between traverses is much less certain.

Rock exposures in the region are excellent and it was impossible to examine them all in the time available. Thus the mapping was no more than a detailed reconnaissance, and can only be regarded as a broad framework for more detailed work.

Personnel and Authorship. In a mapping project such as this it is impossible to credit individual geologists for their contributions, either for the field mapping, or for the interpretations presented in this Bulletin, which have resulted from discussions between the geologists taking part in the project. Thus the credits go, in greater or lesser part, to the following geologists:

1962: Gordon Downs Party—J. W. Smith (Party Leader) and H. L. Davies (BMR), and K. H. Morgan and I. Gemuts (GSWA)—which mapped the Gordon Downs Sheet area and the southern part of the Dixon Range Sheet area.

1963: Dixon Range Party—D. B. Dow (Party Leader), J. H. Latter, and V. M. Bofinger (BMR), and I. Gemuts (GSWA)—which mapped the Dixon Range and the southern part of the Lissadell Sheet area.

Lissadell Party—K. A. Plumb (Party Leader) and D. Dunnet (BMR) and J. R. Passmore (GSWA)—which mapped the Lissadell and Cambridge Gulf Sheet areas.

1964: Mount Ramsay Party—H. G. Roberts (Party Leader) (BMR) and I. Gemuts and R. Halligan (GSWA)—which mapped the Mount Ramsay Sheet area. D. B. Dow worked with the party for 4 months on the Mount Ramsay Sheet area, and did some remapping in the eastern Sheet areas.

Lansdowne Party—K. A. Plumb (Party Leader), D. C. Gellatly, and G. M. Derrick (BMR), and A. D. Allen (GSWA)—which mapped the Lansdowne Sheet area.

The writing of this Bulletin has been a joint effort, and the authors are in full agreement on the interpretations presented. However, as the geologist who has done more mapping on the Lamboo Complex than any other, Gemuts has written almost all the sections dealing with the Lamboo Complex, and has reported his study in more detail in another publication (Gemuts, 1969). Dow, on the other hand, has been primarily responsible for the writing of the stratigraphy.

Publications Resulting from the Present Survey. All the 1:250,000 Sheets covering the east Kimberley area, except Cambridge Gulf (that is, Lissadell, Dixon Range, Gordon Downs, Mount Ramsay, and Lansdowne) have been issued, with concomitant explanatory notes (Plumb & Dunnet, 1968; Dow & Gemuts, 1967; Gemuts & Smith, 1967; Roberts, Halligan, & Playford, 1968; Gellatly & Derrick, 1968). Only a preliminary, uncoloured, map of the Cambridge Gulf Sheet has been issued as yet, but a coloured map is in press.

Unpublished material is available in the form of Bureau of Mineral Resources Records, which can be consulted at the Bureau in Canberra, and at the Geological Survey of Western Australia, and can be borrowed on request. All are listed among the references on pages 132-6.

OUTLINE OF GEOLOGY

The following general account of the geology of the East Kimberley region should be read in conjunction with the correlation chart (Pl. 17), and the summary of stratigraphy (Tables 1 to 4). The reader is referred to pages 59-98 for a detailed description of most of the rock units and to Bulletin 107 (Gemuts, 1969) for a more comprehensive description of the Lamboo Complex. Some rock units are described in detail elsewhere and in such cases the reference containing the more detailed description appears in a footnote. A detailed account of the isotopic more detailed description appears in a footnote. Bofinger's investigations on the geochronology of the East Kimberley rocks have been presented as a doctoral thesis at the Australian National University, and will later be published as a Bulletin of the Bureau of Mineral Resources.

The oldest rocks of the region are geosynclinal sediments called the Halls Creek Group. Though the record of past events affecting these rocks is now only fragmentary, enough has been preserved to indicate that the group was laid down over the whole of the East Kimberley region, probably in Archaean times, and then tightly folded and slightly metamorphosed. At about this time the Halls Creek Group was invaded by basic sills and dykes, some of which were many thousands of feet thick, and gave rise to ultrabasic differentiates.

A second period of folding affected the rocks over most of the region, but it was more intense and was accompanied by high-grade metamorphism along a narrow belt extending diagonally across the map area, called the Halls Creek Mobile Zone (Fig. 2). This more intense metamorphism formed the Tickalara Metamorphics from the Halls Creek Group, and it is believed that gneissic granite was formed at the same time by melting of the metamorphics in places. Late-stage granites were then intruded along the Mobile Zone as batholiths and stocks.

The end product of this cycle of activity is the igneous-metamorphic complex which has been named the Lamboo Complex.

The late-stage intrusion of granite at the end of the lower Proterozoic, which was accompanied by vast eruptions of acid volcanics, marks a fundamental break in the tectonic activity and type of sedimentation over most the area. To the east and west, younger sediments were laid down in epeiric seas, and many of the formations can be recognized virtually unchanged over tens of thousands of square miles. These rocks are only broadly folded and are almost unmetamorphosed. Sedimentation was interrupted by sporadic episodes of mild tectonism, and the resulting unconformities are the basis of the major subdivisions of the rock units laid down during this period.

Only along the Halls Creek Mobile Zone did intense deformation and minor igneous intrusion continue after the lower Proterozoic, and during much of this period the Mobile Zone influenced the sedimentation to the east and west.

A glacial epoch towards the close of the Proterozoic (Adelaidean) has left a remarkable record of extensive ice caps, and a thick cover of glacial sediments. There were at least two major glaciations, the older of which seems to have been protracted and probably consisted of two glacial pulses.

Outpourings of basalt in the Lower Cambrian covered almost all of the map area, and, later, Palaeozoic sediments (with which we are not concerned in this Bulletin) were deposited in the Bonaparte Gulf Basin to the north, and over most of the map area east of the Halls Creek Fault.

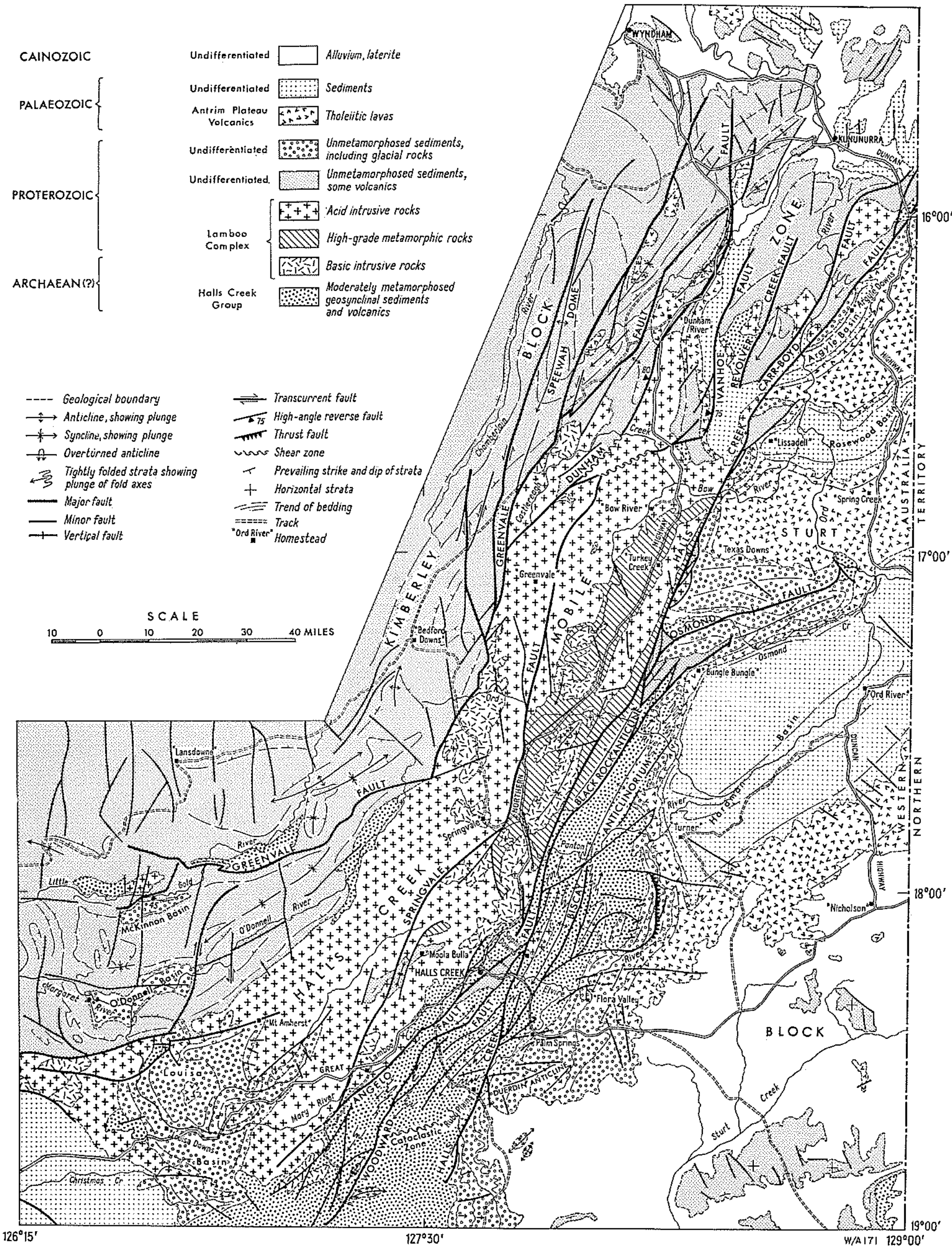


Figure 2. Structural sketch map

TABLE 1. ARCHAEAN AND EARLY PROTEROZOIC STRATIGRAPHY

Age	Group	Formation	Thickness (ft)	Rock Type	Stratigraphic Relationships	Remarks
PROBABLY CARPENTARIAN		Late dykes (Not shown on map)		Small dykes comprising dolerite, diorite, aplite, pegmatite, and quartz-feldspar porphyry	Includes dykes of several ages; all intrude Lamboo Complex	
		Acid dykes (Pbr)		Dacite, microgranite, porphyritic rhyolite	Intrude Olympio Formation	
EARLY PROTEROZOIC	LAMBOO COMPLEX	Undifferentiated (Pb)		Intimate mixture of granite, gabbro, dolerite, and some metamorphic rocks. Granite and porphyry bodies on western margin of map have been included	Granitic rocks in west belong to post-tectonic granites	Individual rock types not mappable
		Violet Valley Tonalite (Pbv)		Biotite tonalite; some granodiorite, diorite, and gabbro	Apparently intrudes Bow River Granite	
		McHale Granodiorite (Pbh)		Biotite and muscovite granodiorite and adamellite; some hornblende granodiorite	Intrudes Olympio Formation and is unconformably overlain by Red Rock beds; probably comagmatic with Bow River Granite	
		Castlereagh Hill Porphyry (Pbc)		Quartz-feldspar porphyry	Apparently intrudes, and is intruded by, Bow River Granite; comagmatic with Whitewater Volcanics	
		Bow River Granite (Pbo)		Coarse-grained, porphyritic, or even-grained biotite or hornblende granite or adamellite	Intrudes Mabel Downs Granodiorite, McIntosh Gabbro, and Whitewater Volcanics	
		Sophie Downs Granite (Pbs)		Medium-grained white granite or granophyric granite	Intrudes lower part of Halls Creek Group. Near Halls Creek is related to Bow River Granite	Stocks near Cummins Range were included on basis of rock type and field relationships, but may be older
		Mabel Downs Granodiorite (Pbt)		Foliated hornblende or biotite granodiorite and tonalite, and saccharoidal gneissic granite	Postdates McIntosh Gabbro	Probably formed by melting of Halls Creek Group at same time as formation of Tickalara Metamorphics
		Tickalara Metamorphics (Pbt)		Metamorphic rocks ranging from low-greenschist facies in south to granulite facies in north	Intruded by Mabel Downs Granodiorite and younger intrusives	Probably more highly metamorphosed equivalent of part or all of Halls Creek Group
		McIntosh Gabbro (Pbi)		Gabbro, troctolite, and dolerite; all commonly uralitized	Antedates metamorphism which formed Tickalara Metamorphics and Mabel Downs Granodiorite	
		Alice Downs Ultrabasics (Pb(a))		Pyroxenite, peridotite, anorthosite, and chlorite-tremolite schist; some gabbro	Probably a differentiate of McIntosh Gabbro	
		Woodward Dolerite (Pbd)		Dykes and sills of uralitized dolerite, gabbro, and some pyroxenite intruding Halls Creek Group	Intrudes Halls Creek Group; probably comagmatic with McIntosh Gabbro	
PROBABLY ARCHAEAN	HALLS CREEK GROUP	Undifferentiated (Ah)	At least 5,000	Schist and quartzite of the greenschist facies in southeast; inliers of sediments similar to Olympio Formation to north		
		Olympio Formation (Aho)	10,000 +	Subgreywacke, arkose, siltstone, some dolomite, and minor conglomerate. Slightly metamorphosed in most places		
		Biscay Formation (Ahr)	500 in southwest, up to 5,000 elsewhere	Basic lavas, tuffaceous greywacke, and siltstone. Prominent beds of dolomite and carbonated basic rocks. Includes dykes and sills of Woodward Dolerite too small to be mapped	Conformable Sequence	Pillow lavas found north of Sophie Downs homestead
		Saunders Creek Formation (Ahs)	0-640	Highly indurated quartz sandstone and quartz greywacke		
		Ding Dong Downs Volcanics (Ahd)	At least 1,000	Amygdaloidal basalt, basic tuff, and tuffaceous greywacke; some slate and mica schist	Oldest unit in map area	Bands of heavy minerals containing uranium and thorium

ARCHAEAN ROCKS

Halls Creek Group

The Halls Creek Group forms basement over most of the map area. It comprises very tightly folded geosynclinal sediments, which have been slightly metamorphosed over most of the area. Within the central part of the Halls Creek Mobile Zone, the sediments have been invaded by plutons and regionally metamorphosed to form the Tickalara Metamorphics of the Lamboo Complex. The Halls Creek Group is covered by later sediments, and is exposed only as isolated inliers, except for the main area of outcrop, which is a broad belt along the south-eastern margin of the Mobile Zone where the rocks are exposed between the faulted margin of the Lamboo Complex and the upturned edge of the sedimentary cover.

The Halls Creek Group is isoclinally folded, complexly faulted, and in places intruded by granite stocks and swarms of dolerite dykes; thus in many places it is impossible to establish the succession. However, in localities such as the Biscay Anticlinorium (Pl. 18), broad regional structures predominate, and though small-scale isoclinal folding complicates the picture, the broad stratigraphy has been deciphered.

The age of the Halls Creek Group is not known, but as the more highly metamorphosed equivalents, the Tickalara Metamorphics, have been reliably dated by the Rb/Sr method as 1961 $\pm$ 27 m.y., the Halls Creek Group must be older. Pegmatites intruding the group near Cummins Range have been dated less reliably as 2,700 m.y. and the group could therefore be Archaean.

Ding Dong Downs Volcanics

The basal formation of the Halls Creek Group is the Ding Dong Downs Volcanics; little is known about it because it crops out only in two small inliers and is poorly exposed. The formation comprises basic volcanic rocks and intercalated sediments; it is similar to the Biscay Formation higher in the sequence, and has been metamorphosed to the same degree. Acid rocks are exposed in places, and though some have a brecciated appearance and could be volcanic, they are more probably intrusive, and comagmatic with the much younger rhyolite dykes of the Lamboo Complex.

Saunders Creek Formation

The next unit, the Saunders Creek Formation, has a maximum thickness of about 650 feet in the type area. It consists of ubiquitously cross-bedded and indurated quartz sandstone and quartz conglomerate, which were laid down in shallow water during a pause in the vulcanism which supplied much of the detritus for the overlying and underlying formations. It is little altered, and thins rapidly to the west; near the Halls Creek Fault it is less than 50 feet thick.

The shallow-water conditions and the attenuated supply of detritus allowed considerable sorting of the sediments to take place and many beds contain a high proportion of heavy minerals. Concentrations of detrital radioactive minerals, which were tested for uranium mineralization in 1957, originated in this way; the results of the tests, however, were disappointing because thorium was found to be the element mainly responsible for the radioactivity.

Biscay Formation

The thick eugeosynclinal basic volcanic rocks and interbedded greywacke and siltstone overlying the Saunders Creek Formation are called the Biscay Formation. The basic volcanic rocks are almost completely recrystallized, and in many cases they cannot be distinguished from folded dolerite dykes (called the Woodward Dolerite where they can be mapped). However, pillow lavas have been recognized and a large proportion of the rocks exposed is volcanic. The formation is best exposed in the core of the Biscay Anticlinorium, where it is between 5,000 and 10,000 feet thick: it is much thinner to the south-west, and near Mount Cummins it is probably less than 2,000 feet thick.

Two stratigraphic horizons, composed predominantly of dolomite, have been recognized within the Biscay Formation: one marks the top of the formation over most of the Biscay Anticlinorium; the other is thinner and less extensive and occurs about half-way up the formation. Both horizons consist of banded dolomite up to several hundred feet thick, but in places the dolomite is missing and is represented by very highly carbonated basic rocks.

Several copper deposits in the Biscay Formation have been tested by diamond drilling, and though none has proved economic, it is believed that the formation offers the best hope of economic deposits of base metals in the East Kimberley region. There appears to be some stratigraphic control to the distribution of the copper mineralization in the Biscay Formation as most of the occurrences are found close to the dolomitic horizons.

Olympio Formation

The Olympio Formation is a monotonous turbidite sequence of great extent and uniformity which probably once covered the whole of the East Kimberley region. It is a sequence of interbedded subgreywacke and siltstone over 12,000 feet thick (Pl. 5), with only rare arkose and dolomite to relieve the monotony.

The only locality where mappable units were found is the northern part of the Biscay Anticlinorium, where, near the top of the formation, about 2,000 feet of massive greywacke and conglomerate are overlain by a predominantly shale sequence. However, the rocks are tightly folded, and the units could only be differentiated by more detailed mapping.

Features such as graded bedding, flute casts, load casts, and slump structures are common throughout the formation in the subgreywacke beds, and it is presumed that they were laid down by density currents. The formation is distinguished by its great lateral extent, and appears to have been deposited in a basin such as the intracratonic basin of Krumbein & Sloss (1963) (zeugogeosyncline of Kay, 1947). The sediments were supplied by an actively rising landmass of metamorphic and plutonic rocks, the location of which is not known.

Gold lodes, now worked out, occur in the basal part of the Olympio Formation, and there are rare small auriferous quartz reefs higher in the sequence; tin and niobium-bearing pegmatites are found in the formation to the south, where they have apparently been introduced by the Sophie Downs Granite. They are the only signs of metalliferous mineralization found in the formation.

Metamorphism of the Halls Creek Group

The metamorphism of the Halls Creek Group and its relationship to metamorphic zones in the Tickalara Metamorphis are discussed on pages 19-22.

The grade of regional metamorphism varies considerably over the map area: most of the rocks are, however, low-grade, and in the northern part of the Biscay Anticlinorium the alteration is little more than one would expect from diagenetic alteration.

Two distinct periods of folding which were responsible for most of the metamorphism can be distinguished in most places, and each has impressed an axial-plane schistosity (see p. 51). Zones of higher metamorphism occur near major faults and are associated with broad zones of extreme cataclasis and mylonitization.

The Halls Creek Group is highly metamorphosed near its contact with many of the granites of the Lamboo Complex. Thus, in the head of Osmond Creek, the Olympio Formation has been metamorphosed to andalusite and sillimanite schists for a quarter of a mile from the contact with the McHale Granodiorite. The metamorphic effects of the granites are generally not as pronounced, and the metamorphic rocks are generally biotite and muscovite schists.

To the southwest, near Cummins Range, a large area of Olympio Formation has been converted to high-grade biotite and muscovite schists. The metamorphism is mostly regional, but the higher grade may be partly due to thermal metamorphism by the Sophie Downs Granite. In the core of the Biscay Anticlinorium, east of Halls Creek, the Halls Creek Group are also higher in grade and belong to the low greenschist facies of regional metamorphism.

LAMBOO COMPLEX

The igneous and high-grade metamorphic rocks of the Halls Creek Mobile Zone are known as the Lamboo Complex. The complex is mainly confined to that part of the Mobile Zone between the Greenvale Fault on the west and the Halls Creek Fault on the east, but a number of granite stocks to the east have been included in the complex. The folded dolerite dykes which intrude the Halls Creek Group belong to the Lamboo Complex, but many of the smaller dykes have been mapped with the Halls Creek Group.

Hardman (1885) was the first geologist to examine the Lamboo Complex. He made only a broad reconnaissance, and was discouraged by the complexity of the rocks: 'ramifications of the different igneous and metamorphic rocks became so complicated that even on a map of a very large scale it would be extremely difficult to represent them correctly' (1885, p. 27).

Mapping of the complex is still a formidable task: the variety of rock types is so great and the structure so complex that the rocks can only be divided into broad groups. By careful study of the contact relationships the sequence of metamorphic and intrusive events in the complex has now been established, and the results of isotopic age determinations agree closely with the field relationships (Bofinger, pers. comm.).* His work has shown that the main events occurred between 2,000 and 1,750 million years ago.

Basic and Ultrabasic Intrusives

The oldest rocks of the complex are basic and ultrabasic intrusives of great extent which invaded the Halls Creek Mobile Zone more than 2,000 million years ago. The intrusions fall into two distinct groups: the first includes the sills and dykes of dolerite and gabbro (Woodward Dolerite) which intrude the Halls Creek Group. They are characteristically long and narrow, and generally tightly folded. The second group, which is found throughout the rest of the Halls Creek Mobile Zone, consists mainly of competent, broadly warped sills, thousands of feet thick, called the McIntosh Gabbro, and ultramafic rocks believed to be differentiated from it, called the Alice Downs Ultrabasics.

Woodward Dolerite

The Woodward Dolerite intrudes the Halls Creek Group throughout the map area, but is particularly well developed on the eastern side of the Halls Creek Mobile Zone south and southwest of Halls Creek township. The intrusions range from a few feet long and a few inches thick to 12 miles long and 2,000 feet thick. The smaller dykes have been included in the Halls Creek Group as they are too small to show on the map. Many of the dykes are complexly folded, especially in the area to the south of Lamboo homestead (Fig. 3).

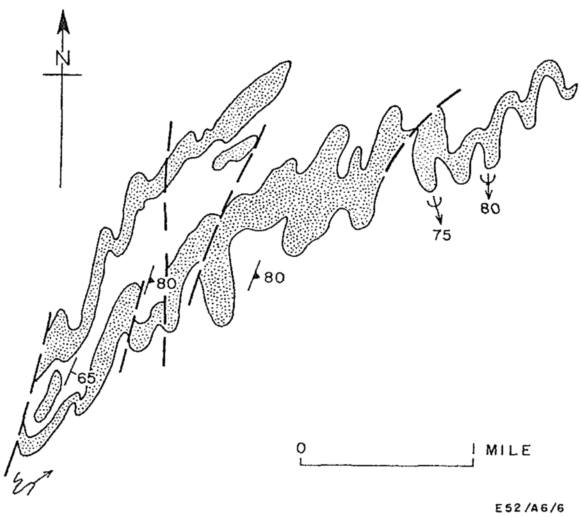


Figure 3. Folded dykes of the Woodward Dolerite

* Recent isotopic age determinations (Miss R. Bennett, BMR, pers. comm.) on rocks from the West Kimberleys indicate that the Whitewater Volcanics, Castlereagh Hill Porphyry, and Bow River Granite may be as old as late Lower Proterozoic. The data are still being evaluated.

Most of the Woodward Dolerite intrusives have been intensely uralitized, and only traces of the original minerals have been preserved. The larger intrusives are similar in composition and textures to the McIntosh Gabbro, with which they are probably comagmatic.

McIntosh Gabbro

The McIntosh Gabbro was intruded along the central part of the Halls Creek Zone, where the subsequent metamorphism and igneous intrusion were more intense, and they are either surrounded by metamorphic rocks or form large roof pendants in later intrusive granites. Some of the bodies are up to 20 miles across; they are roughly circular or elliptical in plan and sill-like in section, and are folded into shallow synclines or basins. The McIntosh Gabbro also includes many small remnants of sills such as these, and other less regular bodies.

It consists mainly of basic rocks, but some of the intrusions have ultramafic segregations near the base. The best preserved example of the larger type of sill is the *McIntosh Sill,* which crops out over an area about 9 miles long and 3 miles wide: it is about 5,000 feet thick and consists of alternating layers of altered dark and light-coloured gabbro, norite, and troctolite. Anorthosite and hypersthenite occur as lenses within the sheet, and also as separate faulted bodies, which are possibly fragments of the basal layers of the differentiated intrusion, on the north-western, western, and southern margins.

The basic rocks in the centre of the McIntosh Sill are unaltered, but on the margins they are uralitized, probably as a result of the thermal effects of the later granitic intrusions.

The sill has been folded to form a structural basin, and the poorly preserved rhythmic layering dips inwards at angles of 10° to 75°.

Alice Downs Ultrabasics

The peridotites and pyroxenites of the Alice Downs Ultrabasics represent the basal zones of the McIntosh Gabbro. They are completely or partly metamorphosed. A good example is the Panton Sill, which has been folded into a southerly plunging syncline; it is 7 miles long, 2 miles wide, and about 3,300 feet thick. It contains metamorphic rocks in the core and is broadly layered; the altered peridotite and tremolite-chlorite schist at the base grade upwards into alternating bands of light and dark-coloured gabbro towards the top of the sill. The majority of rock types in the sill contain secondary minerals derived from pyroxene and olivine during deformation and metamorphism.

Genesis of the Basic Rocks

The Alice Downs Ultrabasics and the McIntosh Gabbro were probably emplaced at considerable depth and were differentiated into a continuous sill-like body with an ultrabasic basal zone and an overlying gabbroic zone. During this stage of partial crystallization, the pluton was dismembered by faulting and folding and intruded higher into the crust. The more mobile parts of the pluton were intruded as thin sills of dolerite and ultrabasic rocks in the Halls Creek Group to

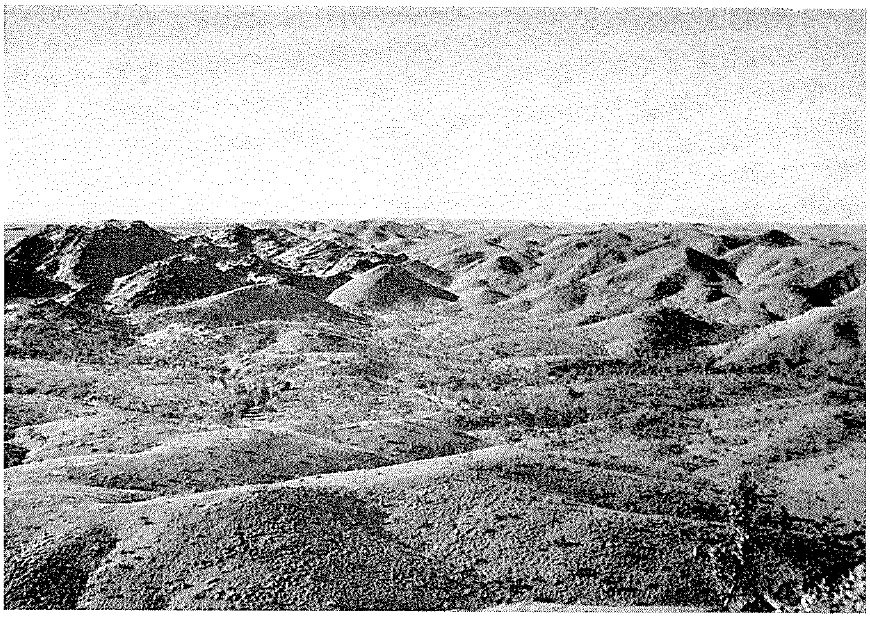


Plate 1, Figure 1. Bay of Biscay Hills 14 miles northeast of Halls Creek township. They are typical of the topography developed on the Halls Creek Group, and are characterized by a close-textured drainage and a sparse cover of spinifex and stunted gums. The dark rugged hills on the left are part of the upper carbonate horizon of the Biscay Formation.

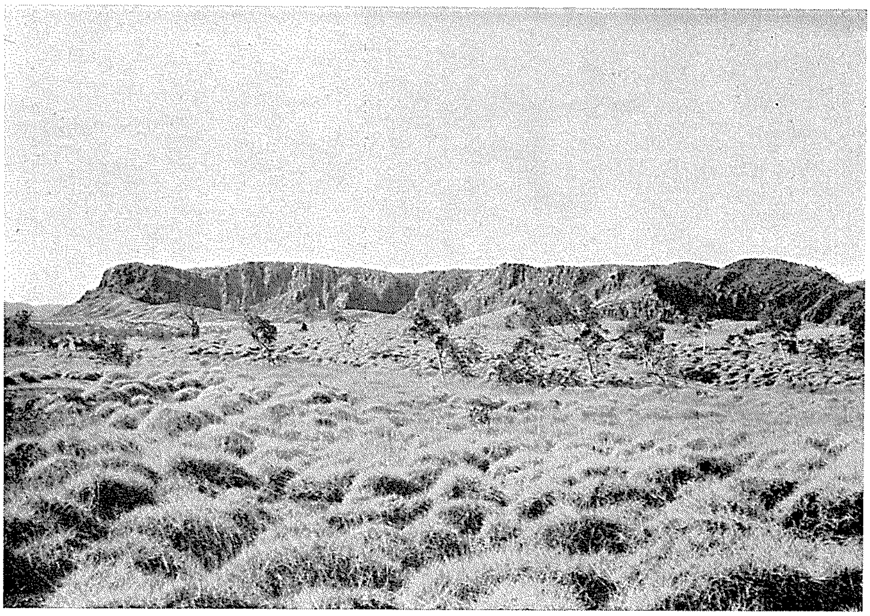


Plate 1, Figure 2. Spinifex and scattered small gum trees south of the Osmond Range. The mesa in the background is composed of Devonian Elder Sandstone.

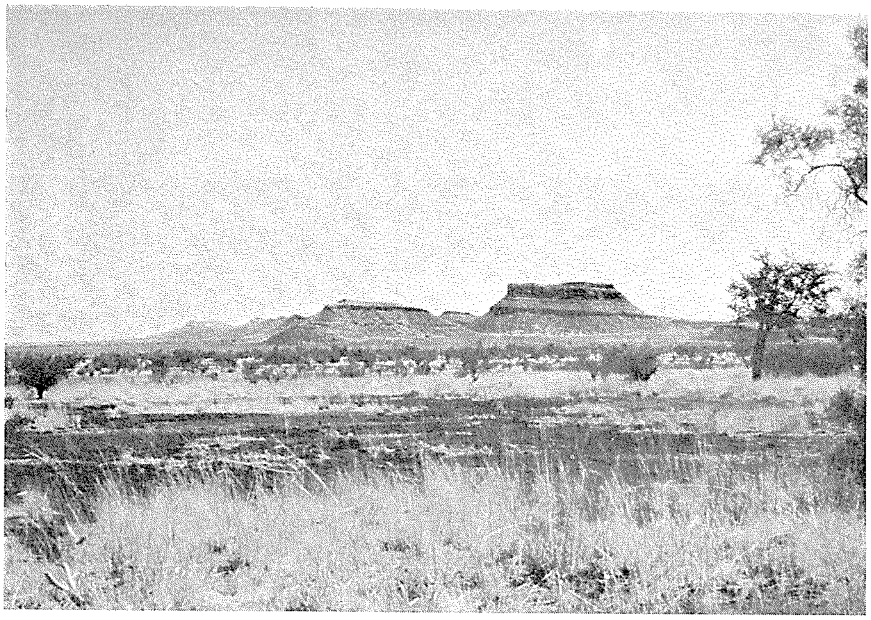


Plate 2, Figure 1. Grasslands of the eastern plains, looking south to Mount Elder. Spinifex is absent and gum trees are subordinate to bauhinia and rosewood.

Plate 2, Figure 2. Salmond River Gorge, Kimberley Plateau.

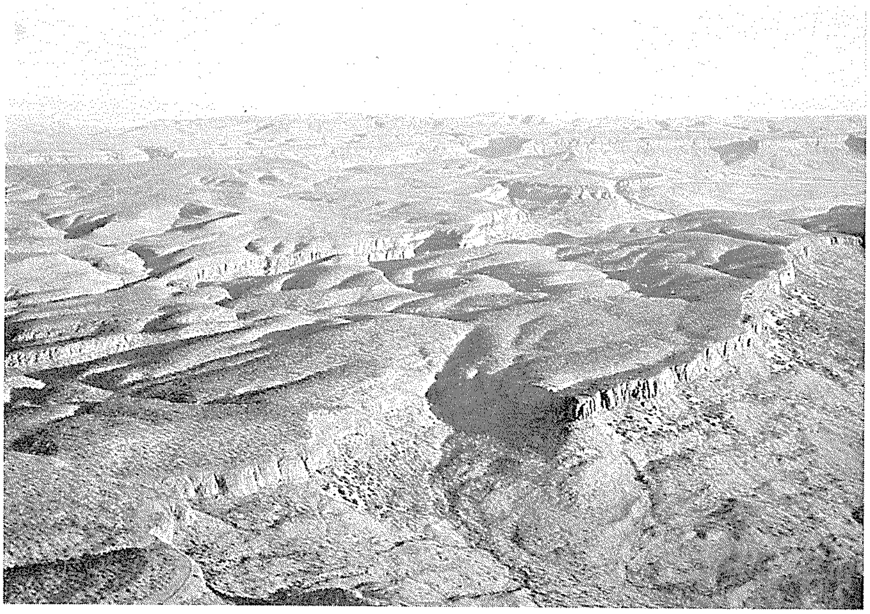


Plate 3, Figure 1. Cockburn Range looking northwest to the tidal flats of the Durack River in the extreme background. (By courtesy of Australian News and Information Bureau)

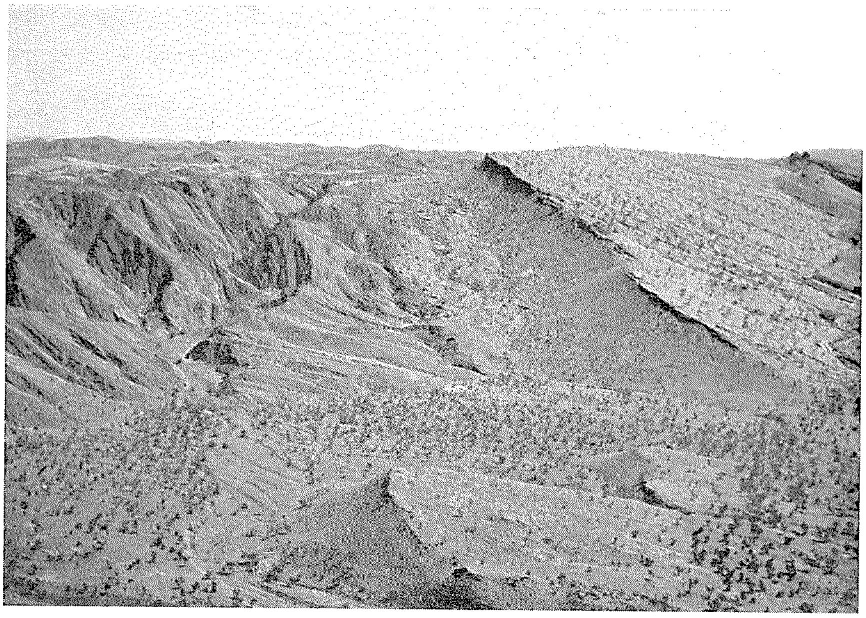


Plate 3, Figure 2. Mount Forster Sandstone unconformably overlying the Archaean (?) Olympio Formation in the Albert Edward Range. Remnants of the Moonlight Valley Tillite are found resting in places on the basement.

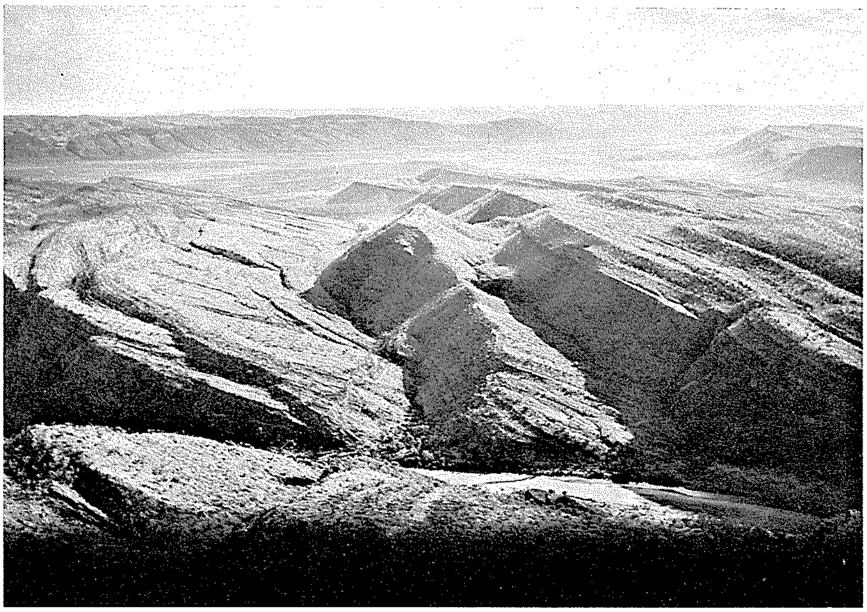


Plate 4, Figure 1. Carr Boyd Range and Carlton Gorge of the Ord River (in the foreground). Looking westwards to Dunham Valley (in background). By courtesy of Australian News and Information Bureau.

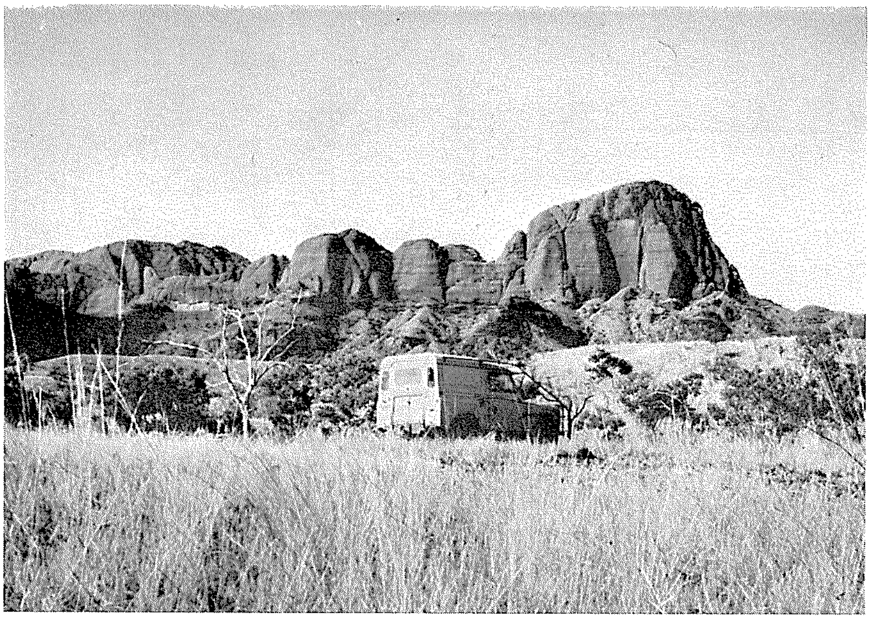


Plate 4, Figure 2. Ragged Range.

form the Woodward Dolerite. The partly solidified and differentiated portion of the magma was intruded into the hotter central part of the Halls Creek Mobile Zone to form the Alice Downs Ultrabasics and McIntosh Gabbro.

Deformation of the partly crystallized magma destroyed most of the original compositional layering of the sills, and many were completely or partly uralitized.

Tickalara Metamorphics

Along the medial part of the Halls Creek Mobile Zone, the Halls Creek Group was highly metamorphosed about 1,960 million years ago to form the Tickalara Metamorphics, which range from high greenschist facies in the south to granulite facies in the north. The Mabel Downs Granodiorite appears to have been formed by anatexis of the Tickalara Metamorphics during this period of metamorphism.

Metamorphic Zones

The Tickalara Metamorphics include a great variety of metamorphic rocks: mica schist, quartzite, paragneiss, orthogneiss, calc-silicate rocks, amphibolite, and pyroxene granulite have been recognized.

The Halls Creek Group and the Tickalara Metamorphics can be subdivided into three metamorphic zones on the basis of the mineralogical and textural changes with increasing metamorphism in the three groups of rocks—pelitic and arenaceous, calcareous, and basic igneous rocks (Fig. 4). The zones belong to the following facies of regional metamorphism (Fyfe et al., 1958):

Zone A: Greenschist facies; quartz-albite-muscovite-chlorite subfacies.

Zone B: Greenschist facies to almandine-amphibolite facies; quartz-albite-epidote-biotite, through quartz-albite-epidote-almandine, to staurolite-quartz subfacies.

Zone C: Almandine-amphibolite to granulite facies; sillimanite-almandine subfacies transitional to hornblende-granulite subfacies.

Zone A. Only rocks of the Halls Creek Group fall into this zone as it is too low-grade to include any of the Tickalara Metamorphics.

The pelitic and arenaceous rocks are slightly metamorphosed and include siltstone, shale, carbonaceous shale, subgreywacke, arkose, and subarkose. Although the rocks are tightly folded and cleaved, bedding and primary sedimentary structures are preserved. In the phyllitic siltstone and shale mica and chlorite have formed along the cleavage planes, while in the arenaceous rocks the matrix has generally been reconstituted to sericite or muscovite and chlorite. The larger detrital grains are only slightly corroded on the margins.

The calcareous rocks include limestone, dolomite, and brecciated dolomite, and their silicified equivalents. The carbonate mosaic consists of irregularly shaped grains with sutured boundaries; interstitial chlorite and sericite are common, and in some cases they form veins and clots. Rare lenses of chert and detrital quartz indicate the original bedding in the siliceous varieties.

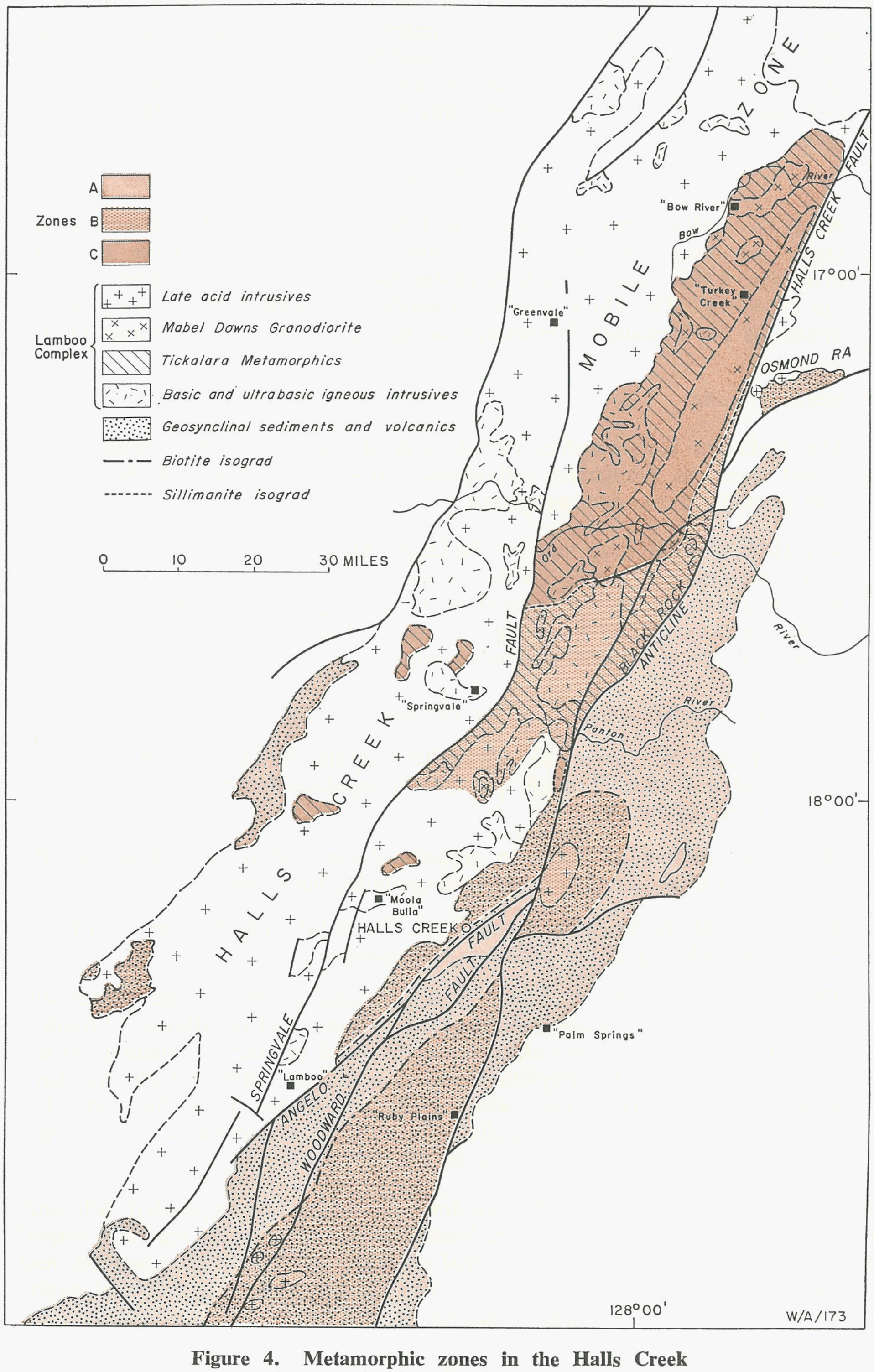


Figure 4. Metamorphic zones in the Halls Creek Group and Tickalara Metamorphics

Two types of reconstituted basic igneous rocks are present in this zone:

(i) Altered basic volcanic rocks with a decussate texture in which there is generally no relict primary fabric. They contain light green rosettes of actinolite or tremolite interfingering with chlorite, quartz, and a little carbonate. Plagioclase, ranging from primary igneous labradorite or andesine to secondary albite, is rarely present. The primary plagioclase is usually pseudomorphed by epidote and sphene.

(ii) Altered dolerite and gabbroic sills of the Woodward type, which have a relict allotriomorphic granular or ophitic texture. The light green decussate tremolite or actinolite, or more rarely hornblende, pseudomorphs of the primary ferromagnesian minerals are randomly distributed among spongy albite, epidote, and quartz crystals. In some of the rocks the primary labradorite is pseudomorphed by sericite, kaolin, and clinozoisite, or by epidote. More rarely, the secondary amphibole is replaced by chlorite, and skeletal ilmenite and sphene are abundant.

Zone B includes rocks of both the Halls Creek Group and Tickalara Metamorphics.

Entry into this zone is indicated by the presence of red-brown or brown biotite in the metamorphic derivatives of the pelitic and arenaceous rocks. The subgreywacke and siltstone of Zone A have been metamorphosed to form dominantly quartz-biotite-muscovite schists. Quartz has lost its sedimentary form and occurs as a recrystallized mosaic. Metamorphic foliations have been developed parallel to the bedding and to a steep axial-plane cleavage.

Many of the schists are garnetiferous and it appears that spongy garnet has developed in conjunction with biotite in Zone B. Some of the schists contain ovoid twinned albite porphyroblasts, and epidote is marginal to or replaces the feldspars. In rare cases incipient andalusite appears to replace biotite and muscovite. The presence of large subidioblastic flakes of chlorite which postdate the axial-plane cleavage indicate that local retrogression has occurred.

Zone B includes small areas of chloritoid schist which was probably derived from pelites containing enough iron oxide to form chloritoid.

Minor amounts of staurolite have been formed close to the Zone C isograd. It invariably occurs in association with abundant biotite and garnet. The biotite is yellow-brown or green and probably contains less iron than the red-brown variety in the quartz-biotite-muscovite schist; garnet and staurolite have taken up iron in preference to magnesia (Harker, 1939). Gneisses are associated with the staurolite-bearing schists; they contain quartz, microcline, albite, biotite, and epidote.

The calcareous rocks of Zone B comprise marble and calc-silicate rocks. No dolomitic varieties were found. The marbles consist of a calcite mosaic containing less than 5 percent of poorly formed plagioclase laths (albite?), granular epidote and sphene, and laths of tremolite or actinolite. In the calc-silicate rocks, tremolite-rich bands alternate with calcite and recrystallized quartz bands. Flakes of muscovite are widely distributed.

The basic igneous rocks of Zone B are represented by foliated amphibolites containing common hornblende. All trace of the original texture has been destroyed and they could have been derived from either intrusive dolerite or basic volcanic rocks. The amphibolites in Zone B fall into two types:

(i) Poorly foliated quartz-rich amphibolites, which have a decussate or roughly nematoblastic texture; decussate sieve-like hornblende laths are randomly oriented or form rosettes parallel to the foliation. The amphibole is pleochroic from blue-green tò dark green. A few poorly formed incipient albite grains are present.

(ii) Well foliated amphibolites in which hornblende defines a nematoblastic texture. The amphibole is pleochroic from blue-green to dark green. The abundant granular plagioclase ranges from albite to labradorite. Needles of hornblende and round granules of quartz occur as inclusions in the plagioclase.

Both types of amphibolite contain abundant sphene and epidote.

Zone C contains the highest-grade metamorphic rocks in the region. In the metamorphic derivatives of the pelitic and arenaceous rocks, entry into Zone C is indicated by the presence of fibrolitic sillimanite in place of biotite. The main rock types are banded gneiss and migmatitic gneiss, but knotted schist occurs in places. The banding is probably secondary, and it is unlikely that any trace of the primary bedding has been preserved.

The gneiss has a texture that ranges from fine-grained to coarse-grained saccharoidal. It contains varying proportions of biotite, andalusite, sillimanite, garnet, cordierite, oligoclase or andesine, and microcline. In Zone B only traces of andalusite are present, but in Zone C it is well developed and is commonly replaced by sillimanite. Cordierite has been developed in gneiss derived from chloritic sediments, probably shale and subgreywacke of Zone A.

The knotted schist contains a little staurolite and abundant garnet surrounded by fibrolitic sillimanite swirls. Kyanite and sillimanite-rich schists have been developed along the Halls Creek Fault.

The calcareous rocks of Zone C comprise marble and calc-silicate rocks. The marble is well foliated and contains bands composed of diopside, hornblende, and a little epidote. The calc-silicate rocks are commonly massive, and contain grossular garnet, green diopside, epidote, and subordinate wollastonite and scapolite. Some of them have a saccharoidal equigranular texture and these generally contain bytownite, anorthite, diopside, hornblende, garnet, scapolite, and subordinate epidote. The amphibole is pleochroic from green to green-brown, but colourless varieties are also present.

The metamorphic derivatives of basic igneous rocks in Zone C comprise foliate amphibolite, hornblende granulite, and pyroxene granulite. The zone is characterized by acicular or granular hornblende with a green-brown or brown absorption colour in the Z direction. The disappearance of the bluish green tinge marks the transition from Zone B. The hornblende granulite and pyroxene granulite contain clinopyroxene and orthopyroxene and a little cummingtonite in places. The plagioclase ranges from labradorite to bytownite. No epidote is present, but a few granules of sphene were noted in the amphibolite with greenish brown amphiboles. A little quartz is present.

Genesis of the Tickalara Metamorphics

The Halls Creek Group and some of the Tickalara Metamorphics are highly sheared and tightly folded. High shearing stress and relatively low temperatures principally controlled the crystallization of the low-grade metamorphic rocks of Zones A and B.

Turner (1938, p. 165) has aptly described the progressive steps in low-grade regional metamorphism, which can also be applied to Zone A:

'(i) Mechanical granulation, shearing out, and recrystallisation of original clastic grains.

(ii) Simultaneous growth of minute crystals of new minerals with their long axes in sub-parallel position, and subsequent increase in the size of the reconstituted mineral grains.'

The temperature gradient was slightly higher in Zone B, and minerals such as biotite, garnet, chloritoid, staurolite, and andalusite developed. Although it is generally accepted that chloritoid and staurolite are not necessarily restricted to a stress environment, it seems that stress conditions played a large part in the development of these minerals in the Tickalara Metamorphics. They always postdate or are contemporary with the development of a crenulation cleavage.

It is likely that the water content was relatively high in Zones A and B. This promoted the uralitization of basic and ultrabasic sills in both zones. The fact that the small sills are completely altered and the large sills are only altered on the margins indicates that the uralitization was not due to autometasomatism during the emplacement of the intrusions. The larger sills represent competent bodies and the central parts of the intrusions were not affected by metamorphism and water metasomatism.

In Zone C there was a further increase in temperature and a decrease in shearing stress. It is thought that the temperature rose high enough in places to melt the Tickalara Metamorphics to form the syntectonic Mabel Downs Granodiorite.

The increase in temperature brought the rocks within the sillimanite field. Sillimanite replaced andalusite in part, but generally preferred to replace biotite or nucleate within biotite. The total pressures during this stage were relatively low since sillimanite occurs with cordierite, which is known from experimental work (Halferdahl, 1956) to break down at high pressures. However, the partial pressure of water was high enough to restrict the formation of the pyroxene granulite facies in the pelitic rocks; and also high enough to partly melt the sillimanite and cordierite-rich gneiss to form migmatite and an anatectic granodiorite/tonalite magma. Von Platen (1965) has shown that cordierite and sillimanite-rich migmatites can be formed at 690°C to 730°C by melting alumina-rich gneisses at 2,000 bars water pressure.

Zone C is characterized by low shearing stresses. However, along zones of major dislocation, such as the Halls Creek Fault, kyanite and sillimanite-rich assemblages have been noted. Kyanite postdates and is derived from crenulated sillimanite in these rocks and it is likely that this reaction was accelerated by shearing; under normal temperature and pressure conditions this reaction would proceed very slowly (Verhoogen, 1951).

Mabel Downs Granodiorite

The Mabel Downs Granodiorite contains xenoliths of the Alice Downs Ultrabasics and the McIntosh Gabbro, and must postdate them: it also intrudes the Tickalara Metamorphics, but the contact is generally concordant with the foliation and there is usually a gradual transition from granodiorite to migmatite and paragneiss.

The largest granodiorite mass grades from a central zone of foliated coarsely porphyritic hornblende-rich tonalite and granodiorite, through foliated medium-grained biotite-rich granodiorite, to a marginal zone of saccharoidal medium-grained gneissic granodiorite or granite containing biotite-rich schlieren. The metamorphic rocks in its immediate vicinity include a great variety of migmatite gneiss and gneiss interfoliated with amphibolite bands.

It is thought that the Mabel Downs Granodiorite is derived from the Tickalara Metamorphics by partial melting, because:

(i) The migmatitic gneisses grade imperceptibly into the foliated Mabel Downs Granodiorite.

(ii) The granodiorite was formed at the same time as the Tickalara Metamorphics; that is, 1,961 $\pm$ 27 m.y. ago.

(iii) Individual masses of the Mabel Downs Granodiorite range from granite to tonalite; orthopyroxene-rich granodiorites are also present. The variation in composition could have resulted from the heterogeneous nature of the sedimentary pile.

The mode of occurrence of the granodiorite indicates that after formation by anatexis, some of the plutons were intruded as a mobile magma higher in the crust. In the high-grade metamorphic areas (Zone C), where migmatite is in the immediate vicinity of the granodiorite, there is no evidence of intrusion, but along parts of its margins where migmatite is absent, it has intruded calc-silicate rocks and amphibolites and enclosed xenoliths of these rocks. In the Black Rock Anticline the granodiorite has been intruded even higher into the crust and it is surrounded by metamorphic rocks of Zone B.

Post-Tectonic Granites

Most of the granitic bodies in the Lamboo Complex are post-tectonic batholiths or stocks.

Bow River Granite

The most extensive is the Bow River Granite, which is confined to the western side of the Halls Creek Mobile Zone as a single batholith, 250 miles long and up to 20 miles wide, and associated apophyses. The batholith is homogeneous in composition and texture over large areas, but in places it contains a great variety of rock types ranging from coarse-grained porphyritic granite or adamellite to even-grained granite or granodiorite. Biotite-rich varieties predominate, but close to intruded gabbro bodies hornblende is developed. Where granite intrudes gabbro, the basic rocks may be altered to diorite and granodiorite, and it is possible that most of the granodiorites in the Bow River Granite were formed by the assimilation of basic rocks by the granitic magma.

The characteristic feature of the Bow River Granite is its texture, which is dominantly porphyritic; the rock contains lath-like, ovoid, or rhombic feldspars, up to 2 inches across, set in a fine-grained groundmass of quartz and feldspar. In places the phenocrysts are aligned to form a primary foliation and lenses of feldspar-rich segregations are common.

The final phase of the Bow River Granite intrusion was marked by the development of pegmatite and aplite dykes.

Sophie Downs Granite

The Sophie Downs Granite intrudes the Halls Creek Group. It generally forms stocks in the cores of anticlines or domes on the eastern margin of the Halls Creek Mobile Zone. The name is derived from a stock east of Halls Creek township near Sophie Downs homestead, but the main group of stocks occurs to the southwest in the vicinity of Cummins Range.

All the intrusives have been included in the one unit, but isotopic age determinations indicate that while the Sophie Downs stock is similar in age to the Bow River Granite, the Cummins Range stocks may be older (about 2,100 m.y.).

The plutons consist of equigranular white granite and granophyric granite. The contacts are irregular and discordant, and there is generally a narrow contact aureole of hornfels.

Pegmatite dykes intrude the Olympio Formation around the Sophie Downs Granite stocks near Cummins Range. They occur as discontinuous randomly oriented bodies; some are concordant and some discordant with the sediments. Some of them are up to 500 feet long; the width ranges from 10 to 200 feet. They are generally composed of varying proportions of microcline, lamellar albite, quartz, greenish yellow flakes of muscovite, and crystals of black tourmaline up to 2 inches long. They commonly contain a little garnet, ilmenite, cassiterite, and minor columbite. The biotite schists on the margins of the pegmatites contain a few scattered crystals of andalusite and pyrite.

Because of their spatial association, it was thought that the pegmatites were related to the Sophie Downs Granite, but a single isotopic age determination gave an age of 2,700 m.y.

Castlereagh Hill Porphyry

The Castlereagh Hill Porphyry is a quartz-feldspar porphyry which crops out extensively in the northern part of the Halls Creek Mobile Zone. The field relationships and isotopic ages indicate a close genetic link between the Castlereagh Hill Porphyry, Bow River Granite, and Whitewater Volcanics.

The quartz-feldspar porphyries fall into two types. The first type is fine-grained, grey to black, and massive; it is similar in appearance to the Whitewater Volcanics, but lacks distinct flow foliation. Locally this type grades into coarse even-grained granite and fine to medium-grained adamellite. The second type is allied to the porphyritic Bow River Granite; it is massive and contains large phenocrysts of resorbed quartz and feldspar set in a fine-grained groundmass. The random distribution of the phenocrysts, and the nature of the groundmass, distinguish this porphyry from the normal porphyritic granite. Both types lack primary foliation, but close to large faults a secondary foliation is common and the phenocrysts are aligned in parallel planes.

The Castlereagh Hill Porphyry is similar to the massive varieties of the Whitewater Volcanics, to which it is probably genetically related. In places, it is difficult to distinguish between the quartz-feldspar porphyry dykes and the massive bedded Whitewater Volcanics, which contain many intrusive bodies. The Castlereagh Hill Porphyry may also contain some extrusive rocks, but the bulk is probably hypabyssal intrusives.

The relationship of the Castlereagh Hill Porphyry and the Whitewater Volcanics to the Bow River Granite is not so clear. Good exposures are rare, but the Bow River Granite intrudes the Castlereagh Hill Porphyry and the Whitewater Volcanics in the northern part of the region. However, north of Greenvale homestead, a dyke of the Castlereagh Hill Porphyry with chilled margins intrudes the Bow River Granite. Thus the intrusion of the Bow River Granite overlapped the igneous activity which gave rise to the Castlereagh Hill Porphyry and Whitewater Volcanics.

The isotopic ages of the Whitewater Volcanics and Castlereagh Hill Porphyry are indistinguishable, and together give an age of 1,788 $\pm$ 40 m.y. The Bow River Granite has an isotopic age of 1,854 $\pm$ 15 m.y. Acid volcanic rocks in the overlying Valentine Siltstone have an apparent age of 1,761 m.y., and it seems that the post-tectonic igneous activity of the Lamboo Complex was very protracted.

Violet Valley Tonalite

A complex series of igneous rocks ranging from gabbro to tonalite and granodiorite have been grouped under the name Violet Valley Tonalite. The rocks are generally poorly exposed and their relationships with each other have not been established. In the type area, the gabbro appears to grade into tonalite, which in turn merges with granodiorite. The Violet Valley Tonalite intrudes the Halls Creek Group and the Bow River Granite. Where it intrudes the sediments, a narrow zone of banded biotite gneiss and hornfels is developed near the contact, but where it intrudes the Bow River Granite the contact is sharp and xenoliths of country rock are absent in the tonalite.

The typical tonalite is fine to coarse-grained, non-foliated, and rich in biotite, and has an allotriomorphic granular texture.

McHale Granodiorite

Stocks of biotite-muscovite granodiorite and adamellite intruding the Olympio Formation east of the Halls Creek Fault have been called the McHale Granodiorite. They are overlain unconformably by the Carpentarian Red Rock Beds, and isotopic ages determined on two samples were similar to the Bow River Granite (about 1,850 m.y.).

Late-Stage Dykes

Late-stage basic to acid dykes intrude the Lamboo Complex. They all post-date the Bow River Granite, but their relationship to the main igneous intrusive rocks is uncertain. The dykes commonly occur in small swarms; they are generally parallel, but in some cases they intersect each other.

The dolerite and quartz-feldspar porphyry dykes in the Bow River Granite occur in small shear zones and joint planes, but the diorite, aplite, and pegmatite dykes in the Bow River Granite and Tickalara Metamorphics are not confined to zones of structural weakness.

The small stocks and thin sills of quartz-feldspar porphyry intruding the Biscay Formation of the Halls Creek Group may be comagmatic with the porphyry dykes in the Lamboo Complex. Preliminary isotopic dating indicates a minimum age of 1,500 m.y. for the porphyry intrusions in the Halls Creek Group.

Carpentarian and Early Adelaidean Rocks

The beginning of the Carpentarian epoch marked the change from tectonic and igneous activity characteristic of the early Proterozoic to the stable conditions which prevailed over most of the East Kimberley region for the rest of the Precambrian.

Whitewater Volcanics

The Whitewater Volcanics at the base of the Carpentarian* were formed at about the same time as the Bow River Granite and Castlereagh Hill Porphyry. All three formations are similar in composition, and they are probably comagmatic.

The Whitewater Volcanics, which have a maximum thickness of 6,000 to 7,000 feet, comprise rhyolite and associated intrusive rocks. Some of the Whitewater Volcanics are lavas, but many of the thick uniform extensive beds are probably ashflow tuffs. The original internal structure and texture of the ashflows have been destroyed by compaction and recrystallization.

The presence of lenses of volcanic pebble and cobble conglomerate near the top of the formation indicates that the vulcanism was punctuated by periods of erosion.

Red Rock Beds

The Red Rock Beds were laid down to the east of the Halls Creek Mobile Zone. They are generally found as thin fault wedges near the Halls Creek Fault, and though most are probably contemporaneous with the Speewah Group they could contain some younger sediments. At least 6,000 feet of predominantly

* Since the Whitewater Volcanics are intruded by most of the granites in both East and West Kimberley regions, they are no longer placed at the base of the Carpentarian, but are included in the Lamboo Complex (Gellaty et al., 1968).

TABLE 2. CARPENTARIAN STRATIGRAPHY

Age		Group	Formation	Thickness (ft)	Rock Type	Relationships to Other Units	Remarks
CARPENTARIAN			Fish Hole Dolerite (Pf)	Up to 4,000	Amygdaloidal dolerite and basalt (?). Strongly epidotized	Intrudes Red Rock Beds; Mt. Parker Sandstone unconformable above. May be equivalent to older Hart Dolerite	Small show of secondary copper minerals
			Hart Dolerite (Pdh)	Sills up to 3,000	Dolerite, fine-grained gabbro, diorite, and granophyre	Apparently 2 ages of dolerite. Most extensive probably comagmatic with Carson Volcanics. Younger sills intrude as high as Pentecost Sandstone	Granophyre differentiate at top of thick sill. Scattered grains of chalcopyrite in places
	KIMBERLEY BASIN SUCCESSION	CROWHURST GROUP	Hibberson Dolomite (Prb)	85+	Pink or yellow dolomite, oolitic dolomite, and dolomite breccia	Conformable sequence	Stromatolites common
			Collett Siltstone (Pro)	200	Laminated purple and green siltstone with minor dolomitic interbeds and lenses		
			Liga Shale (Prl)	150	Green fissile shale and micaceous siltstone		
			Hilfordy Formation (Prh)	100	Purple and white quartz sandstone with interbedded siltstone and shale	Conformably overlies Pentecost Sandstone	Sandstone glauconitic in places
		BASTION GROUP	Cockburn Sandstone (Ptc)		Massive quartz sandstone with minor interbeds of fine-grained sandstone and micaceous siltstone	Conformable sequence	
			Wyndham Shale (Ptw)	2,300	Green, grey, and black siltstone and shale with interbeds of fine-grained sandstone.		Contains oval siderite nodules up to 2 feet in diameter
			Mendena Formation (Ptm)	360	Quartz sandstone and interbedded green and purple siltstone. Dolomite, commonly oolitic, and dolomitic sandstone.	Conformably overlies Pentecost Sandstone	Contains traces of copper in northwestern part of area
		KIMBERLEY GROUP	Pentecost Sandstone (Pkp)		Quartz sandstone, pebbly in places; cross-beds, ripple marks, and mud cracks.	Conformable sequence	Divided into 3 members
			Elgee Siltstone (Pke)		Reddish brown siltstone and shale; minor quartz sandstone		
			Teronis Member (Pkt)	Up to 460	Dolomite, commonly algal or oolitic. Shale, siltstone and minor quartz sandstone		Abundant stromatolites
			Warton Sandstone (Pkw)	Up to 1,200	Quartz sandstone and feldspathic sandstone; minor purple shale		
			Carson Volcanics (Pkc)	Up to 2,000	Basalt, commonly amygdaloidal, and interbedded feldspathic quartz sandstone. Minor micaceous siltstone and basalt agglomerate		In places resembles Hart Dolerite. Minor chalcopyrite in lower flows
			King Leopold Sandstone (Pkl)	0-3,000	White to pink quartz sandstone, pebbly in places; minor feldspathic sandstone. Cross-beds and ripple marks common	Unconformable on Speewah Group in places, conformable in others	
		SPEEWAH GROUP	Luman Siltstone (Ppl)	300	Green and brown micaceous siltstone and shale; minor fine micaceous sandstone	Conformable sequence	Generally poorly exposed and invaded by Hart Dolerite
			Lansdowne Arkose (Ppo)	Up to 1,600	Feldspathic sandstone, arkose, clayey sandstone; interbedded micaceous shale and siltstone		
			Valentine Siltstone (Ppr)	100-250	Green siltstone and tuffaceous sandstone, thin beds of rhyolite ashstone and tuff		
			Tunganary Formation (Ppt)	Up to 3,500	Quartz sandstone, feldspathic sandstone, and arkose; green and brown siltstone		
			O'Donnell Formation (Ppn)	Up to 900	Subgreywacke, silty sandstone, and quartz sandstone; some shale	Unconformably overlies Whitewater Volcanics	Basal arenite is good marker bed
			Revolver Creek Formation (Pv)	Up to 4,000	Amygdaloidal basalt interbeds of pink arkose; quartz sandstone and slate	Unconformably overlies Whitewater Volcanics	
			Red Rock Beds (Pe)	7,000+	Quartzite, red siltstone, and pebble and boulder conglomerate	Rests unconformably on McHale Granodiorite	
			Moola Bulla Formation (Px)	10,000+	(1) thick basal arkose (4,500 ft), (2) Greywacke and siltstone (2,000 ft), (3) feldspathic sandstone and conglomerate (1,600 ft), (4) green siltstone and shale	Unconformable on Halls Creek Group. Relationships to other units not known	
			Whitewater Volcanics (Pw)	Up to 10,000	Porphyritic rhyolite lavas and ashflow tuffs. Minor agglomerate and volcanic conglomerate. Quartz-feldspar porphyry.	Strong angular unconformity on Halls Creek Group. Extrusive equivalent of Castlereagh Hill Porphyry	

shallow-water arenaceous sediments are preserved, but no volcanic rocks have been recognized in the succession. The type of sediments shows that the Mobile Zone was tectonically active at this time: the Red Rock Beds show extreme lateral variation and in places boulder conglomerate grades laterally into thinly bedded siltstone over a distance of less than a mile. Most of the earth movements took the form of faulting, as shown by a cliff section at the head of Osmond Creek: a prominent bed of quartzite near the base of the Red Rock Beds is displaced at least 500 feet, but an overlying boulder conglomerate is dislocated only 270 feet by the same fault. The fault had ceased movement by the time the late Carpentarian Mount Parker Sandstone was laid down, for it is unaffected where it crosses the fault.

Moola Bulla Formation

Similar sediments probably covered the whole of the Mobile Zone, but in the south only a narrow fault wedge has been preserved. The sediments, named the Moola Bulla Formation, consist of about 10,000 feet of sandstone and arkose containing a thick greywacke member which appears to have been derived from distant basic volcanic rocks.

Revolver Creek Formation

The Revolver Creek Formation is a sequence of basic volcanics overlain by marine sediments, found in the Carr Boyd Ranges at the northern end of the Halls Creek Mobile Zone. Amygdaloidal basalts near the base of the formation are interbedded with pink arkose. They are overlain by quartz sandstone and interbedded purple-brown micaceous shale and siltstone about 1,300 feet thick.

Though the formation unconformably overlies the Whitewater Volcanics and the Bow River Granite, it is intruded by late-stage microgranite dykes of the Lamboo Complex. Its stratigraphic relationship with other units is not known but it could be the lateral equivalent of the lower part of the Kimberley Group. It is unconformably overlain by the Adelaidean Carr Boyd Group.

Speewah Group †

A somewhat longer period of erosion preceded further sedimentation, initiated by mild faulting and folding. The sedimentary record is most complete along the western side of the Halls Creek Mobile Zone, where the sediments are preserved in a large structural basin, the Kimberley Basin, most of which lies to the northwest of the map area. The lower part of the Kimberley Basin succession, the Speewah Group, was laid down during a period of intermittent mild earth movements, and the sediments are characterized by disconformities, changes in thickness, and some lateral variation.

The Speewah Group is essentially an arenaceous unit. It is 3,000 to 4,000 feet thick, and is characterized by sandstone, arkose, greywacke, and siltstone. The minor acid volcanics which were extruded during this period were probably the result of the last spasms of the vulcanism responsible for the formation of the Whitewater Volcanics: isotopic age determinations show little difference in age between the various volcanics.

The Red Rock Beds and the Moola Bulla Formation were deposited in different parts of the East Kimberley region; although they cannot be correlated they were probably laid down during the same period of tectonic activity.

† The Speewah Group is described in detail in Dow et al. (1964), Gellatty et al. (1965), and Plumb (in prep.).

*Kimberley, Bastion, and Crowhurst Groups**

After the deposition of the Speewah Group the area became much more stable, and sediments were laid down very slowly in epeiric seas; sedimentation was uniform over enormous areas, and many of the formations show little change over most of the Kimberley Basin. These sediments have been divided into the Kimberley, Bastion, and Crowhurst Groups, which consist mainly of sandstone, siltstone, and shale, though dolomitic rocks are important in some units. The *Carson Volcanics* near the base of the Kimberley Group are of great extent and considerable thickness, and consist of tholeiitic basalt.

The Kimberley Group is preserved only to the west of the Mobile Zone, but probably originally extended over the whole of the East Kimberley region.

*Hart Dolerite**

The Kimberley Basin succession is intruded by dolerite sills and dykes called the Hart Dolerite, which are of enormous volume and great regional extent. It is thought that at least two ages of intrusion are represented, but the bulk of the intrusions are restricted to the Speewah Group and it seems probable that they were intruded at the same time as the extrusion of the Carson Volcanics. Isotopic age determinations on the Carson Volcanics (1,807 m.y.), and Hart Dolerite (1,800 m.y.) lend support to this argument.

Smaller sills and dykes which cannot be distinguished from the Hart Dolerite intrude sediments high in the Kimberley basin succession, and are probably much younger: it is thought that they may be correlated with the Cambrian Antrim Plateau Volcanics.

OSMOND RANGE SUCCESSION

East of the Halls Creek Mobile Zone, there is no record of Carpentarian rocks equivalent to the Kimberley Basin succession, and if these were deposited east of the Mobile Zone they must have been eroded before the deposition of the next youngest rocks which range up to Lower Adelaidean. These younger rocks are best exposed in the Osmond Range and have been informally called the Osmond Range succession (Dow et al., 1964).

They rest with extreme angular unconformity on Red Rock Beds: fault wedges of Red Rock Beds containing up to 10,000 feet of sediments were tilted nearly vertical and deeply eroded before the deposition of the Osmond Range succession.

Fish Hole Dolerite

The faulting was tensional, and was accompanied by the intrusion of the Fish Hole Dolerite, which comprises an extensive series of basic intrusions which are probably equivalent to the Hart Dolerite. The dolerite is uniform in composition and grainsize; it is generally highly epidotized and characteristically amygdaloidal. The dolerite is probably entirely intrusive, and any extrusive equivalents were probably eroded before the deposition of the Osmond Range succession.

* The Kimberley and Bastion Groups and Hart Dolerite are described in detail in Dow et al. (1964) and Plumb (in prep.). The Crowhurst Group is described in Roberts et al. (1965).

Deposition of the Osmond Range succession began probably towards the end of the Carpentarian era, during a period of mild tectonism, and the succession is punctuated by disconformities and angular unconformities. In places, the sedimentation was influenced by faulting, and it appears that there was a landmass to the west of the Halls Creek Mobile Zone which supplied detritus. The land may have been part of the Halls Creek Mobile Zone, but as the detritus has a restricted range in composition, it was most probably derived from the Kimberley Plateau.

Mount Parker Sandstone

The basal unit of the Osmond Range succession is the Mount Parker Sandstone, a thick clean quartz sandstone containing rare lenses of pebble conglomerate. Its outstanding feature, which is not always obvious on the ground, is that it is composed almost entirely of large foreset beds laid down on a platform of Red Rock Beds. This makes it difficult to determine the true thickness of the formation, but where true dips can be measured the thickness ranges from 500 feet on the northern flank of the Osmond Range to about 1,000 feet on the southern flank. The orientation of the foreset beds shows that the currents flowed from the south.

Bungle Bungle Dolomite

Overlying the Mount Parker Sandstone is a very thick dolomitic formation called the Bungle Bungle Dolomite. It is 5,000 feet thick and consists predominantly of regularly bedded dolomite or dolomitic siltstone; it is characterized by the presence of stromatolites, especially in the lower half. *Collenia frequens* Walcott 1914 is the most common, but others were noted, including *Conophyton cylindricus* (Grabau) (see Pl. 15, figs 1, 2). The fossils are generally difficult to collect because accessible outcrops of fossiliferous rocks are rare, and the best fossils can be collected from the overlying tillites which contain a great variety of stromatolites derived from the Bungle Bungle Dolomite.

There are several clean quartz sandstone interbeds in the Bungle Bungle Dolomite, and as they are thicker and more numerous close to the Halls Creek Mobile Zone they indicate a westerly provenance.

Colombo Sandstone

In the lower reaches of the Margaret River, to the west of the Mobile Zone, small remnants of Colombo Sandstone rest unconformably on the Kimberley Group. The formation consists of massive quartz sandstone up to 300 feet thick, with boulder conglomerate or breccia at the base in places. Where the Colombo Sandstone overlies dolomite, the basal bed is a chaotic mixture of angular fragments of chert which appears to be a reworked duricrust.

The original extent of the Colombo Sandstone and its age are unknown, but it is unconformably overlain by Adelaidean glacial rocks, and it could be a correlate of the Mount Parker Sandstone.

Gardiner Beds

The Gardiner Beds (Casey & Wells, 1964) crop out in the Gardiner Range to the south of the map area; they comprise 5,000 feet of pebble conglomerate overlain by quartz sandstone, shale, and minor pink and cream dolomite. In the southeastern part of the map area, the Gardiner Beds rest unconformably on the Halls Creek Group; the beds are several hundred feet thick, and consist of thin-bedded or cross-bedded quartz sandstone and minor ferruginous sandstone and pebble conglomerate. The Gardiner Beds are isolated from other Carpentarian or Adelaidean rocks, and their stratigraphic position is unknown.

ADELAIDEAN

Wade Creek Sandstone

The earliest Adelaidean rocks found to the east of the Halls Creek Mobile Zone unconformably overlie the Bungle Bungle Dolomite. The basal unit is called the Wade Creek Sandstone, a clean quartz sandstone which can generally be distinguished by its lack of bedding and uniform grainsize. It was laid down east of the Halls Creek Fault on a shallow marine shelf. For most of the time the shelf was fairly stable and the sediments fairly uniform, but where the shelf was faulted and warped the formation shows considerable lateral variation. The Wade Creek Sandstone may contain an angular unconformity (see p. 79).

The sediments deposited during the unstable periods are exemplified by the *Mount John Shale Member,* a lens of shale deposited in a basin formed on the shelf by mild warping and faulting. The basin was at least 25 miles from the Halls Creek Mobile Zone which supplied the detritus, and received fine-grained sediments while the arenites of the Wade Creek Sandstone were deposited closer to the Mobile Zone.

Plate 10 shows the Mount John Shale lensing out rapidly against faulted steps in the shelf of Wade Creek Sandstone, and that faulting was probably active during the deposition of the Mount John Shale. The lensing out of the Mount John Shale is a stratigraphic thinning; the thinning was not caused by erosion before the deposition of the overlying sandstone because the resistant bed about halfway up the shale continues to the western extremity of the shale at about the same stratigraphic horizon.

The Mount John Shale contains highly ferruginous beds which may have been deposited at the same time as the Pompeys Pillar iron ore deposits (see p. 112). The Mount John Shale has been isotopically dated by the Rb/Sr method as 1,128 $\pm$ 110 m.y., and lends support to this correlation.

It was from the lower part of the Wade Creek Sandstone that Wade (1924) found an impression thought to be fossil jellyfish, which was named *Protoniobia wadea* by Sprigg (1949). We consider that the impression is that of a plate of chert, many of which can be seen exposed on dip slopes in the type locality (see pp. 79-80).

The Wade Creek Sandstone crops out mainly in the Osmond Range, but there is a small remnant south of Palm Springs in the southern part of the map area which indicates that it was laid down over a much larger area—probably along the length of the Albert Edward Range.

Helicopter Siltstone

The Wade Creek Sandstone passes up, through a transition zone about 100 feet thick, into green or grey laminated or thin-bedded siltstone called the Helicopter Siltstone. The formation is at least 550 feet thick, and was laid down under stable conditions similar to those prevailing when the Wade Creek Sandstone was laid down, except that the western landmass was probably more remote and the depositional basin was somewhat deeper.

The Helicopter Siltstone is the last formation known to have been laid down east of the Halls Creek Mobile Zone before the deposition of the Adelaidean glacial and interglacial sediments

Carr Boyd Group

The 30,000 feet of arenites and lutites preserved in the northern part of the Halls Creek Mobile Zone have been named the Carr Boyd Group; they will be described in detail by K. A. Plumb (in prep.). Each of the constituent formations listed in Plate 17, except the Golden Gate Siltstone, has an unconformity at the base, and most of them show rapid lateral changes in lithology and thickness which testify to deposition during a tectonically active period.

The Carr Boyd Group is confined to the Mobile Zone, and there is evidence that it was deposited in a fault trough along the zone. However, it is unlikely that it was confined to the Mobile Zone, and it probably owes its absence elsewhere to erosion.

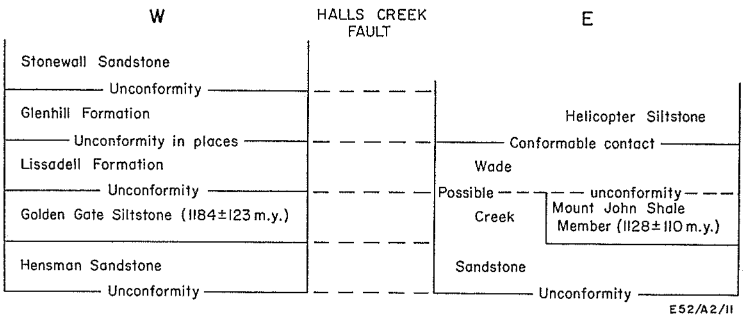


Figure 5. Correlation chart of the Carr Boyd Group and Osmond Range succession

When the Carr Boyd Group was mapped it was thought to be a lateral equivalent to the Speewah Group, but shales in the Golden Gate Siltstone have been isotopically dated and shown to be much younger (1,184 ± 123 m.y.) and about the same age as the Mount John Shale (1,128 ± 110 m.y.). The two successions are similar (Table 3), except for the differences in thickness, and the correlations shown in Figure 5 are probably correct. It is possible that the iron-rich beds near the top of the Mount John Shale Member were deposited at the same time as the iron ore beds near the base of the Golden Gate Siltstone.

Glidden Group

The Glidden Group (Roberts et al., 1965) is found only west of the Mobile Zone in two small structural basins in the southwestern part of the map area.

It consists of arenaceous sediments and interbedded shale and siltstone totalling about 1,800 feet thick which have been divided into four formations: Harms Sandstone (basal unit), Matheson Formation, Forman Sandstone, and Maddox Formation (uppermost unit). Little is known of the stratigraphic relationships of the Glidden Group except that it overlies the Carson Volcanics unconformably. Shales from the Glidden Group give a minimum isotopic age by the Rb/Sr method of 1,030 m.y. The Glidden Group is probably Adelaidean, though it could be older.

GLACIAL ROCKS

The late Adelaidean rocks of the East Kimberley region contain some of the best exposed, most extensive, and least disturbed, Precambrian glacial rocks in the world. Though partly covered by later deposits, the glacial rocks are known to have extended, more or less continuously, over an area of at least 20,000 square miles. Less is known of the extent of the ice caps which formed the glacial rocks, but the scattered outcrops of glaciated bedrock found to date indicate that most of the Kimberley Plateau and Halls Creek Mobile Zone, and some at least of the Victoria River Basin, were covered by ice at different times during the glacial maxima.

The glacial rocks were discovered by Guppy et al. (1958), and Harms (1959) later found glaciated bedrock in two localities. The glacial rocks east of the Halls Creek Mobile Zone were mapped in 1963 (Dow et al., 1964), and the evidence of glaciation was documented by Dow (1965); results of later mapping of the glacial rocks west of the Mobile Zone are given in the report by Roberts et al. (in prep.).

We believe that the glacial origin of these late Adelaidean rocks cannot be reasonably doubted (Dow, 1965), and it is evident that there were at least two glacial epochs separated by a long period of marine deposition. The older epoch, which is here named the Moonlight Valley Glaciation, consisted of two distinct glacial phases which could have been widely separated in time. The younger epoch we have named the Egan Glaciation.

TABLE 3. EARLY ADELAIDEAN STRATIGRAPHY

Age	Group	Formation	Thickness (ft)	Rock Type	Relationships to Other Units	Remarks
EARLY ADELAIDEAN OR LATE CARPENTARIAN	CARR BOYD GROUP	Stonewall Sandstone (Pcs)	2,000+	Quartz sandstone and subordinate red shale; minor subgreywacke and pebble conglomerate	Unconformably overlies Glenhill Formation	
		Glenhill Formation (Pcg)	2,000-3,000	Red and black micaceous siltstone and shale, and interbedded glauconitic fine-grained sandstone	Overlies Lissadell Formation with angular unconformity in places	
		Lissadell Formation (Pcl)	2,000-5,000	Clean well sorted quartz sandstone, interbedded with siltstone and shale; minor tuff and pyritic siltstone	Unconformably overlies Golden Gate Siltstone	
		Golden Gate Siltstone (Pcd)	800-7,000	Mostly black to purple shale and siltstone, pyritic in places. Minor quartz sandstone. To southwest, subgreywacke and micaceous shale, green tuff, and sandy hematite		Contains Pompeys Pillar Iron Ore
		Hensman Sandstone (Pch)	500-800	Massive silicified quartz sandstone	Strongly unconformable on Revolver Creek Formation	
	GLIDDEN GROUP	Maddox Formation (Pdx)	300	Black shale and micaceous siltstone; some sandstone		
		Forman Sandstone (Pdf)	220	Well sorted quartz sandstone		
		Matheson Formation (Pdm)	1,120	Laminated claystone, micaceous shale and siltstone. Subgreywacke, pyritic in part, in a quartz sandstone	Conformable sequence	Possibly equivalent to Wade Creek Sandstone and Helicopter Siltstone
		Harms Sandstone (Pda)	200	Quartz sandstone, and interbedded purple shale and siltstone	Unconformably overlies Kimberley (and Crowhurst) Group	
	OSMOND RANGE SUCCESSION	Helicopter Siltstone (Pst)	520	Laminated khaki siltstone and shale; some fine-grained quartz sandstone	Conformable	
		Wade Creek Sandstone (Psw)	1,200 (total thickness)	Clean well sorted quartz sandstone. Cross-bedding, ripple marks, and slumped beds common in upper part		
		Mount John Shale Member (Psj)	650	Khaki and some black shale and siltstone; minor quartz sandstone. Some beds highly ferruginous	Sandstone rests unconformably on Bungle Bungle Dolomite	Shale Member is lens in Wade Creek Sandstone
		Bungle Bungle Dolomite (Psb)	4,850	Dolomite and dolomitic shale. Several quartz sandstone beds up to 100 feet thick	Conformable	
		Mount Parker Sandstone (Psp)	500-1,000	Clean quartz sandstone, commonly with pebbly lenses	Strongly unconformable on Red Rock Beds	
		Colombo Sandstone (Pm)	300+	Massive quartz sandstone and chert-pebble breccia	Unconformably overlies Crowhurst Group. Probably older than Glidden Group	

TABLE 4. STRATIGRAPHY OF THE GLACIAL ROCKS

Age	Group	Formation	Thickness (ft)	Rock Type	Stratigraphic Relationships	Remarks
		Gardiner Beds (Pyd)	1,000-5,000	Quartz sandstone, ferruginous sandstone, shale, and siltstone; some algal dolomite and pebble conglomerate	Unconformable on Halls Creek Group	Stratigraphic position unknown. May contain some glacial rocks but most of formation probably older
ADELAIDEAN	ALBERT EDWARD GROUP	Flat Rock Formation (Paf)	100	Purple shale; interbedded dolomitic sandstone and quartz sandstone		Dolomitic sandstone forms extensive flagstones
		Nyuless Sandstone (Pay)	125	Quartz sandstone, feldspathic sandstone, and minor pebble conglomerate		
		Timperley Shale (Paj)	4,150	Massive grey and green shale and siltstone; interbedded dolomite near base.	Conformable sequence	
		Boonall Dolomite (Pab)	100	Yellow and grey dolomite; minor dolomite breccia, shale and siltstone		
		Elvire Formation (Pae)	200	Red-brown shale with green siltstone; minor sandstone		
		Mount Forster Sandstone (Pao)	320	Quartz sandstone; minor shale and siltstone	Unconformable on Duerdin Group	Glacial rocks apparently missing at base of group
	LOUISA DOWNS GROUP	Lubbock Formation (Pil)	6,000	Grey, green, or purple siltstone and shale and interbedded subgreywacke; some dolomite		Probably equivalent to Flat Rock Formation
		Tean Formation (Pit)	400	Feldspathic sandstone, subgreywacke; some conglomerate and dolomite	Conformable sequence	Probably equivalent to Nyuless Sandstone
		McAlly Shale (Pim)	5,000	Black, grey, green siltstone, shale		Probably equivalent to Timperley Shale
		Yurabi Formation (Piy)	100-700	Quartz sandstone and feldspathic quartz sandstone; interbedded shale and siltstone; also dolomitic beds		Probably equivalent to Mount Forster Sandstone, Elvire Formation, and Boonall Dolomite
		Egan Formation (Pie)	65-100	Tillite, conglomerate, and quartz sandstone; upper part consists of dolomite and limestone	Unconformable on Kuniandi Group	Glacial sediments deposited by Egan Glaciation
	DUERDIN GROUP	Ranford Formation (Pos)	1,850	Thinly bedded khaki siltstone and fine quartz sandstone		
		Johnny Cake Shale Member (Poj)	600	Green and red banded shale; gypsiferous and dolomitic in places	Apparently conformable on Moonlight Valley Tillite	
		Jarrad Sandstone Member (Poj)	200	Ferruginous dolomitic sandstone, bouldery lenses near base		
		Moonlight Valley Tillite (Pom)	Up to 450	Tillite, lenses dolomitic quartz sandstone and conglomerate; capped by pink and cream dolomite	Unconformable on Frank River Sandstone	
		Frank River Sandstone (Pok)	750	Dolomitic sandstone; dropped erratics and lenses of boulder conglomerate	Conformable on Fargoo Tillite	Interglacial deposit
		Fargoo Tillite (Pof)	Up to 650	Tillite with large lenses of boulder conglomerate	Unconformable on Osmond Range succession	Contains many erratics from Halls Creek Mobile Zone
	KUNIANDI GROUP	Mount Bertram Sandstone (Pnb)	400-600	Micaceous and ferruginous sandstone; minor siltstone and shale commoner towards base		
		Wirara Formation (Pnw)	1,475-1,600	Thin-bedded siltstone and shale, interbedded fine sandstone; green and red-brown banded siltstone and fine sandstone near base	Conformable sequence	
		Stein Formation (Pns)	Up to 700	Purple ferruginous greywacke	Appears to be conformable lens within the succession	Graded bedding, cross-bedding, ripple marks, slump rolls
		Landrigan Tillite (Pnl)	55-1,100	Tillite, lenses of sandstone and siltstone; capped by dolomite	Unconformable on Kimberley Basin succession	Probably equivalent to both Moonlight Valley and Fargoo Tillites

Moonlight Valley Glaciation

Sediments which were laid down during the Moonlight Valley Glaciation are preserved both east and west of the Halls Creek Mobile Zone, but none are found within the Mobile Zone. The interglacial sediments may have been deposited across the zone and later eroded, but there is evidence that the Mobile Zone formed a divide during the glaciation from which the ice flowed east and west, and if glacial rocks were deposited, they were probably thin and discontinuous.

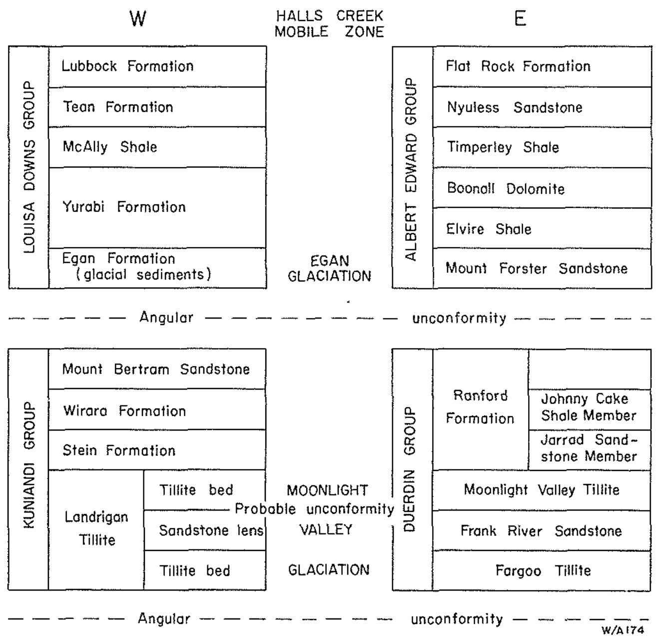


Figure 6. Correlation chart of the glacial rocks

The successions on each side of the Mobile Zone are similar, but cannot be directly correlated: they have been called the Duerdin Group on the east, and the Kuniandi Group on the west. The tentative correlations given in Figure 6, based on similarity of the constituent formations, have been confirmed by isotopic age determination of shales using the Rb/Sr method (Bofinger, pers. comm.).

There is evidence that the Moonlight Valley Glaciation consisted of two separate phases.

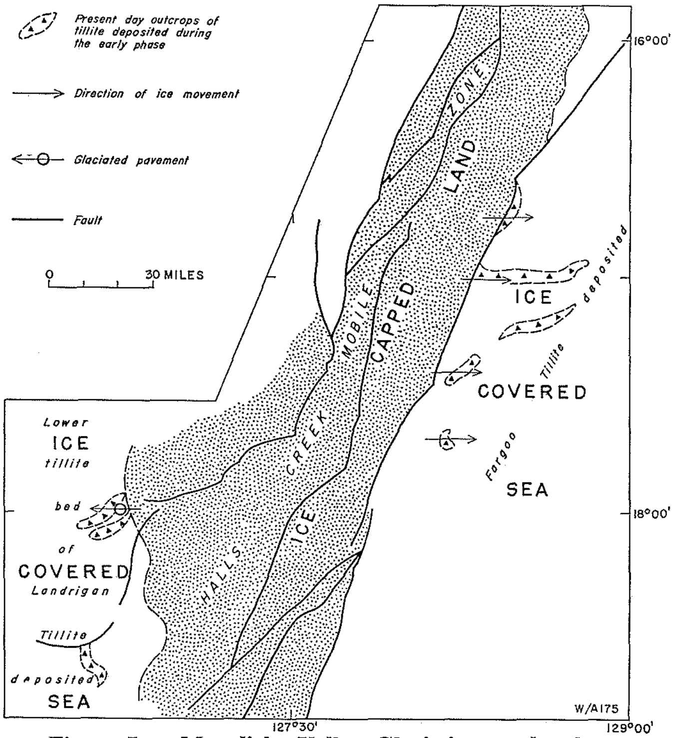


Figure 7a. Moonlight Valley Glaciation: early phase

Early Phase (Fig. 7a)

During the first phase of the Moonlight Valley Glaciation tillites were laid down each side of the Halls Creek Mobile Zone; the Fargoo Tillite to the east, and the Landrigan Tillite to the west. It has been shown that the Fargoo Tillite was deposited by ice which moved eastwards from the Halls Creek Mobile Zone (the Fargoo Tillite contains a large proportion of erratics which match exactly most of the rock types found in the Lamboo Complex), possibly from a mountain chain along the Mobile Zone.

Evidence of the direction of ice movement west of the Mobile Zone is less well documented, but it also appears to have been from west to east. This is indicated by striations on glaciated bedrock beneath the Landrigan Tillite to the north of Mount Cummins which are aligned east-west. These give no indication of the sense of the movement, but as the Landrigan Tillite contains only minor crystalline rocks which could have been derived from the Lamboo Complex, it therefore appears that the ice moved eastwards from the Kimberley basin rocks.

Before the onset of the late phase of the Moonlight Valley Glaciation there was a warmer period during which dolomitic sandstone was laid down to the east of the Mobile Zone over the Fargoo Tillite, and sandy interbeds were laid down within the Landrigan Tillite to the west. There is some evidence that glacial conditions prevailed at times during this period, for the sandstone contains lenses of conglomerate with erratics several feet across which could only have been transported by floating ice.

The tillites deposited during this early phase were probably laid down in a quiet ice-covered sea (see pp. 45-6).

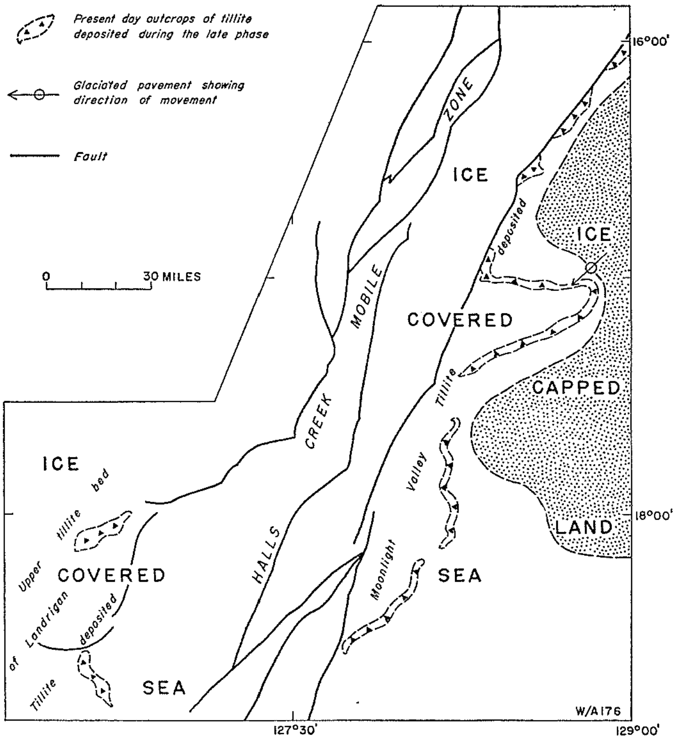


Figure 7b. Moonlight Valley Glaciation: late phase

Late Phase (Fig. 7b)

During the late phase of the Moonlight Valley Glaciation the Moonlight Valley Tillite was laid down to the east, and the upper tillite bed of the Landrigan Tillite to the west. Conditions were similar to those prevailing during the early phase, that is they were deposited in an ice-covered sea. The distribution of the land masses, however, was apparently much changed, and in the case of the Moonlight Valley Tillite the ice came from the Victoria River Plateau in the northeast. It seems unlikely that the same ice deposited the Landrigan Tillite west of the Mobile Zone, but there is no evidence to show where the ice which deposited the Landrigan Tillite came from.

Kuniandi and Duerdin Groups*

After the ice melted, normal marine sediments were laid down on each side of the Halls Creek Mobile Zone, and possibly right over it: the Duerdin Group on the east and the Kuniandi Group on the west. Initially, arenaceous rocks were deposited—purple ferruginous greywacke (*Stein Formation**) to the west and dolomitic quartz sandstone (*Jarrad Sandstone Member* of the Ranford Formation) to the east. The presence of dropped erratics in the lowermost 100 feet of the Jarrad Sandstone Member indicates that glacial conditions persisted during the deposition of the arenaceous beds.

* Described in detail by Roberts et al. (in prep.).

Distinctive green and purple shale and siltstone, up to 1,400 feet thick, called the *Wirara Formation** in the west and the *Johnny Cake Shale Member* in the east, were then laid down. The latter is poorly exposed and can seldom be recognized away from the type area. A unique type of 'zebra stone', a red shale with an unusual green mottling (Blatchford, 1927a), and fossil jellyfish (Dunnet, 1965) are both found in similar rocks at about the same horizon in the northern part of the map area. Fine-grained flaggy sandstone and interbedded siltstone were then deposited on both sides of the Mobile Zone—the *Mount Bertram Sandstone** in the west and the rest of the *Ranford Formation* in the east.

Mild folding and a long period of erosion followed the deposition of the Kuniandi and Duerdin Groups, and the sediments were stripped from large areas, leaving only small remnants preserved beneath the younger sediments.

Description of the Tillites

Fargoo Tillite

The *Fargoo Tillite,* which is up to 500 feet thick, is found only as small erosional remnants beneath the Moonlight Valley Tillite. It is the thickest and best exposed tillite in the East Kimberley region (Pl. 12, fig. 2). It has all the characteristics of tillite as described by Schermerhorn & Stanton (1963): 'unsorted, ungraded, and unbedded lithology, with haphazardly scattered poly-genetic pebbles and boulders; highly variable composition; great variation in grain-size, from the finest rock flour to very large blocks, in random proportion; angular mineral and rock grains in a structureless matrix; and the presence of faceted and striated stones'.

A characteristic feature of the Fargoo Tillite is the great variety of its megaclasts, but the greater proportion are crystalline rocks derived from the Lamboo Complex. Very large megaclasts are not uncommon: the biggest measured was 15 feet across, but many of them are between 8 and 10 feet in diameter. The most spectacular seen was an ovoid boulder of porphyritic granite, 10 feet across, which was partly exhumed from the tillite; it was polished and striated.

The Fargoo Tillite contains large lenses of conglomerate and dolomitic sandstone and was probably laid down in a tranquil ice-covered sea (see p. 46).

Frank River Sandstone

Overlying the Fargoo Tillite are remnants of dolomitic sandstone, up to 750 feet thick, which are called the Frank River Sandstone. The presence of dropped pebbles and cobbles, and lenses of boulder conglomerate, with striated boulders up to 4 feet across, in the sandstone show that glacial conditions still prevailed. However, the shoreline must have been remote. The sandstone cuts out over structural highs, and though this could be an original sedimentary feature, it is much more likely to have been caused by erosion before the deposition of the Moonlight Valley Tillite.

* Described in detail by Roberts et al. (in prep.).

Moonlight Valley Tillite

The Moonlight Valley Tillite is thinner but much more extensive than the Fargoo Tillite, and can generally be distinguished by the thin capping of dolomite which forms a persistent marker bed. The dolomite is between 6 and 30 feet thick; it ranges from pink to purple, or less commonly cream, in colour, and is invariably laminated or thinly bedded. The megaclasts in the Moonlight Valley Tillite are much less varied than those in the Fargoo Tillite. Fragments of metamorphic or igneous rocks are rare as the ice moved from the northeast over the Victoria River Plateau which was composed almost entirely of sedimentary rocks.

In the southern part of the map area the capping dolomite changes along strike into a well bedded dolomitic sandstone. The gradual increase in the proportion of sand possibly indicates the presence of a landmass to the south which supplied the coarser detritus.

*Landrigan Tillite**

The Landrigan Tillite is variable in thickness and composition, and only where it is thickest is it similar to the tillites of the Duerdin Group. It is best developed in the Kuniandi Range, where it consists of two tillite beds, each up to 500 feet thick, separated by a lens of sandstone and siltstone about 300 feet thick. The tillite beds consist of greywacke containing rounded boulders, up to 6 feet thick, of sandstone, quartzite, and dolomite derived from the Kimberley Group: a few granitic erratics were also noted.

In most places the Landrigan Tillite is capped by purple or pink laminated dolomite, up to 30 feet thick, very similar to the dolomite capping the Moonlight Valley Tillite. Also in marked similarity to the Moonlight Valley Tillite, the underlying tillite beds are missing in places, and the formation is represented only by the dolomite.

The sandstone is coarse-grained and feldspathic, and grades into pebble conglomerate: it cuts out to the north under possibly the same unconformity as that at the base of the Moonlight Valley Tillite.

Egan Glaciation (Fig. 8)

Louisa Downs and Albert Edward Groups*

Evidence of the second major ice age, called here the Egan Glaciation, is seen only west of the Mobile Zone, where tillite beds are found at the base of the Louisa Downs Group. East of the zone is a similar succession called the Albert Edward Group, which is almost certainly a correlative of the Louisa Downs Group, but no glacial beds have been recognized within it.

The tillite beds are part of the *Egan Formation**, which contains a great range of marine sediments, and shows extreme lateral variation, particularly in the lower half, which consists predominantly of boulder beds, conglomerate, and sandstone.

* Described in detail by Roberts et al. (in prep.).

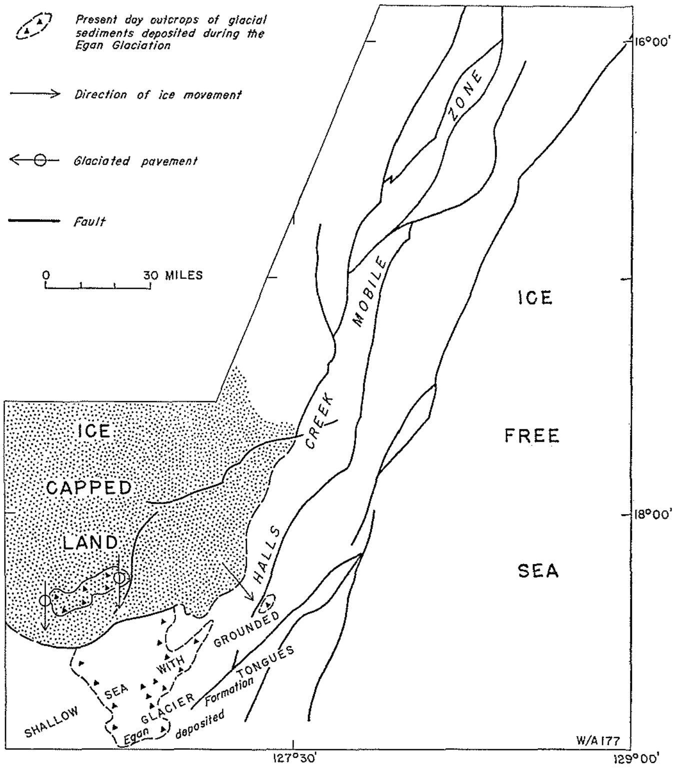


Figure 8. Egan Glaciation

The glacial origin of these beds is well authenticated: to the northeast, near Moola Bulla homestead, the tillite is mainly composed of a clay-silt matrix, and contains scattered erratics of granite and metamorphic rocks up to 10 feet across. The megaclasts comprise a great variety of rock types, and many of them are polished or striated. On the northwestern and southern margins of the O'Donnell Basin, the tillite and bouldery conglomerate rest on pavements of polished and striated quartzite bedrock in several places.

The upper part of the Egan Formation consists of a carbonate sequence up to 185 feet thick, which is regarded as the final phase of the glacial marine sedimentation (see p. 47). The beds are mostly dolomite and dolomitic sandstone and siltstone, but they also include a considerable proportion of limestone, some of which is remarkably pure.

Though no glacial beds equivalent to the Egan Formation are known east of the Halls Creek Mobile Zone, they could be concealed by the thick scree from the overlying Mount Forster Sandstone, the base of which has been seen only in two places.

Normal marine sediments were deposited in the transgressive seas which resulted from the melting of the ice caps. They are the youngest known sediments deposited before the region was inundated by enormous outpourings of basalt (Antrim Plateau Volcanics), probably in lowermost Cambrian times.

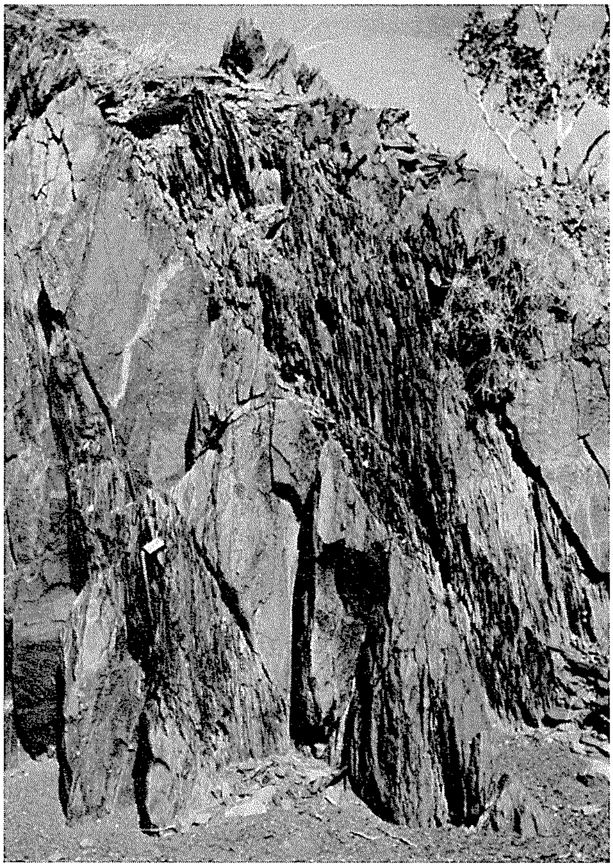


Plate 5. Recrystallized greywacke and siltstone of the Olympio Formation near the Golden Crown gold mine. The axial-plane cleavage is much more closely spaced in the siltstone and causes the typical shaly outcrop shown.

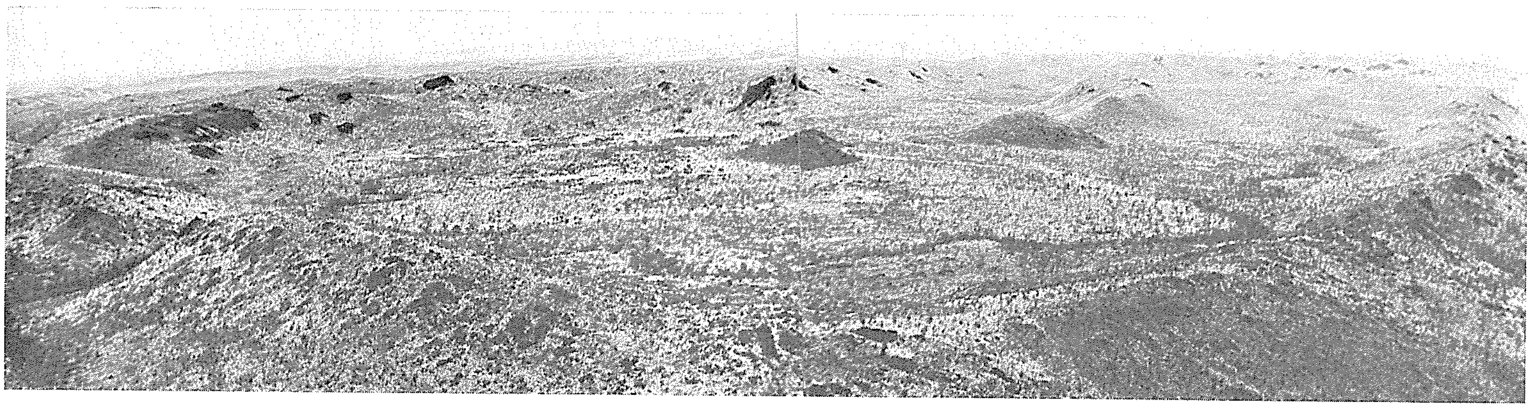


Plate 6. Panorama of the McIntosh Sill showing one of the circular ridges which define the basin.

Plate 7, Figure 1. Small scale folding in migmatite of the Tickalara Metamorphics southwest of Turkey Creek.

Plate 7, Figure 2. Dark-coloured lenses of pyroxene granulite in garnetiferous gneiss 2 miles west of Turkey Creek. Note the biotite-rich reaction rims along the contacts with the granulite.

Plate 8, Figure 1. Porphyritic Bow River Granite. The rock is finer in grain than the typical porphyritic varieties.

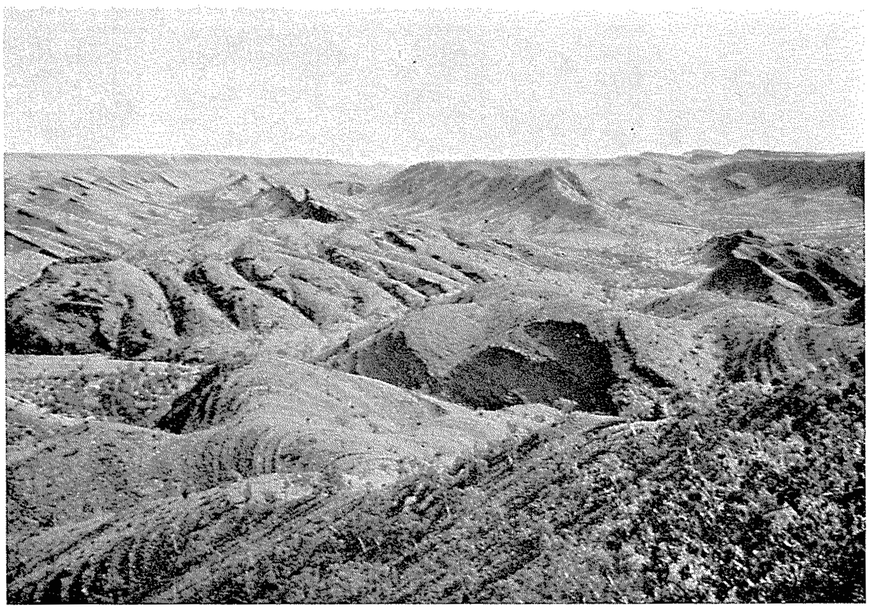
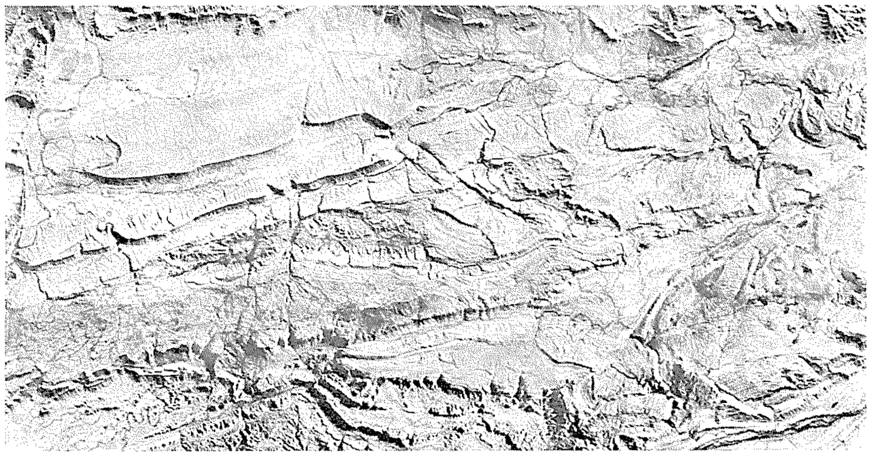


Plate 8, Figure 2. Bungle Bungle Dolomite in the Osmond Range. In the foreground the strike of the beds swings to the left. The plateau in the background on the right is composed of the underlying Mount Parker Sandstone, while the dark ridge near the centre background marks a fault which repeats the Mount Parker Sandstone in the right background.



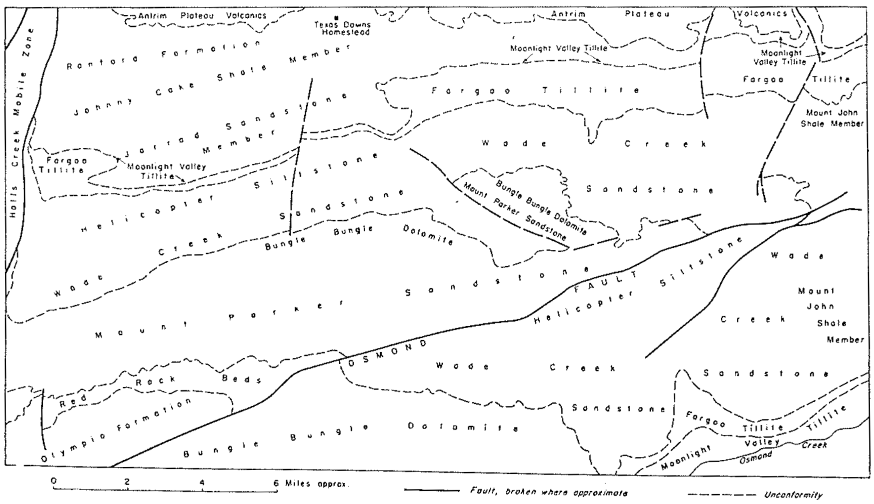


Plate 9. Photomosaic of the Osmond Range. Six unconformities can be traced on the mosaic, which was compiled from vertical air-photographs. (1) The Red Rock Beds in the bottom left hand corner unconformably overlie the isoclinally folded Olympio formation. (2) These are in turn overlain unconformably by the Mount Parker Sandstone and the Bungle Bungle Dolomite, which crop out in a belt extending across the mosaic from the bottom left hand corner. (3) The third and most extensive unconformity is at the base of the Wade Creek Sandstone: it is displaced by several faults and unconformably overlies others. The Mount John Shale Member (extreme right) is a conformable lens within the Wade Creek Sandstone; the Helicopter Siltstone (middle left) conformably overlies the Sandstone. (4) The Fargoo Tillite unconformably overlies the Helicopter Siltstone and Wade Creek Sandstone along the top third of the mosaic. (5) The Moonlight Valley Tillite, the thin band immediately overlying the Fargoo Tillite, probably has an unconformity at its base. The Ranford Formation conformably overlies the Moonlight Valley Tillite, and the Jarrad Sandstone Member can be plainly seen lensing out to the east. (6) The Antrim Plateau Volcanics unconformably overlie the Ranford Formation and Moonlight Valley Tillite along the top margin of the mosaic.

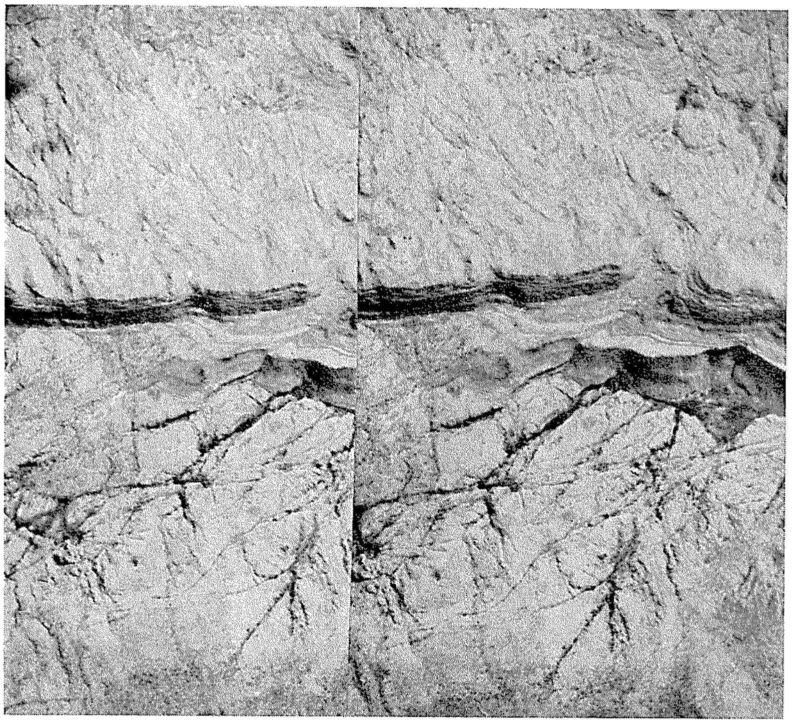


Plate 10. Stereo-pair of air-photographs showing the Mount John Shale Member (dark smooth cliff on the right) cutting out against faulted steps in the underlying Wade Creek Sandstone.

Plate 11, Figure 1. Glaciated bedrock recently exhumed from beneath the Moonlight Valley Tillite (overlying the pavement in the right top corner). The striae are aligned within a few degrees of northeast, and features such as plucking, chattermarks, etc. show that the ice came from the northeast (from right to left in the photograph).

Plate 11, Figure 2. Glacial erratic of quartzite from the Moonlight Valley Tillite. The flattened ellipsoidal shape is characteristic of the larger boulders in all tillites.

Plate 12, Figure 1. Sunlight reflecting off a highly polished cobble weathered out of the Moonlight Valley Tillite overlying the glaciated bedrock near the junction of the Ord and Negri Rivers.

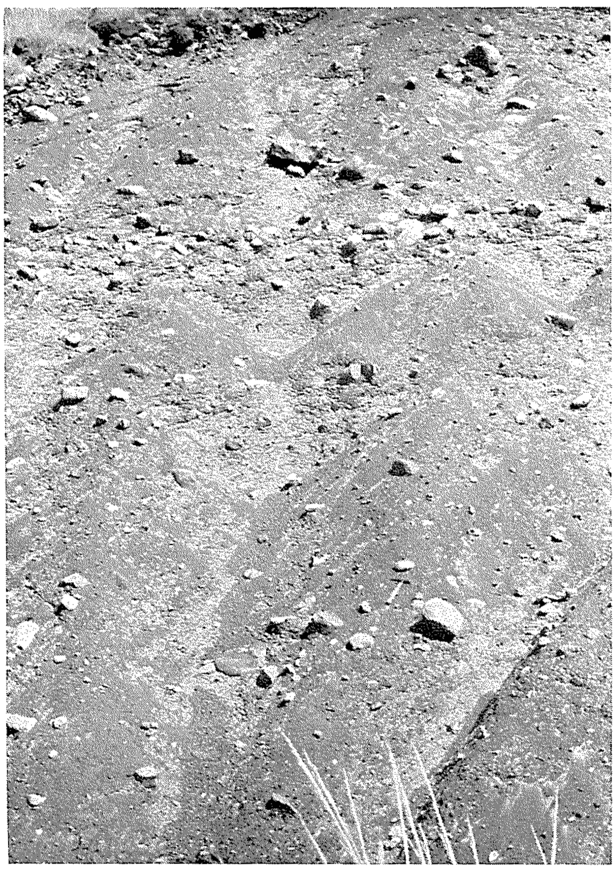


Plate 12, Figure 2. An excellent exposure of the Fargoo Tillite, 9 miles east of Turkey Creek (the photograph was taken across a steep-sided gully). Crude bedding is indicated by the concentration of boulders in a band, near the top of the exposure, which is parallel to the bedding in the overlying sediments. The hammer near the middle of the photograph indicates the scale.

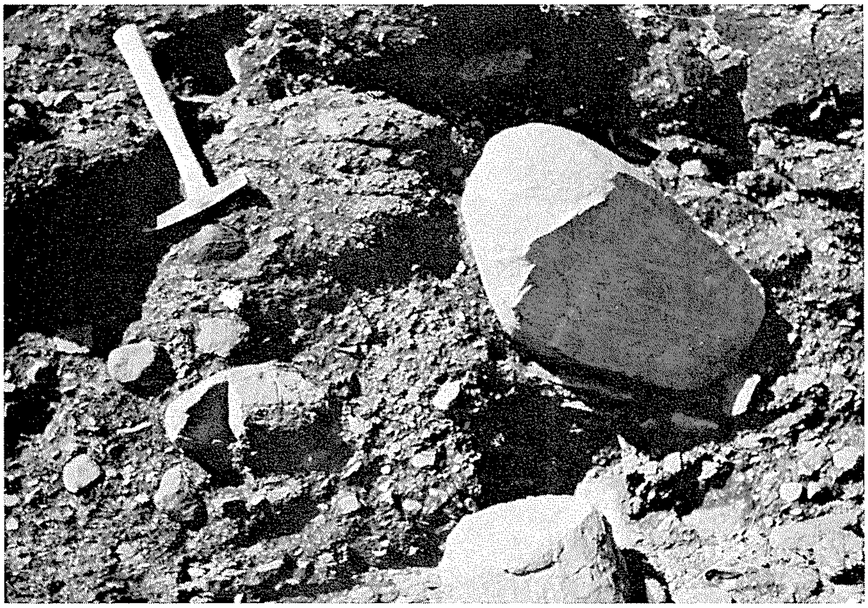


Plate 13, Figure 1. Boulder conglomerate phase of the Moonlight Valley Tillite about 4 miles south of Palm Springs. The matrix is a coarse-grained dolomitic sandstone, and the boulders are glacial erratics, many of which are striated and polished.

Plate 13, Figure 2. Dolomite-cobble conglomerate of the Moonlight Valley Tillite on the southern flank of the Osmond Range. Almost all the cobbles are dolomite and are set in a coarse-grained dolomitic sandstone matrix.

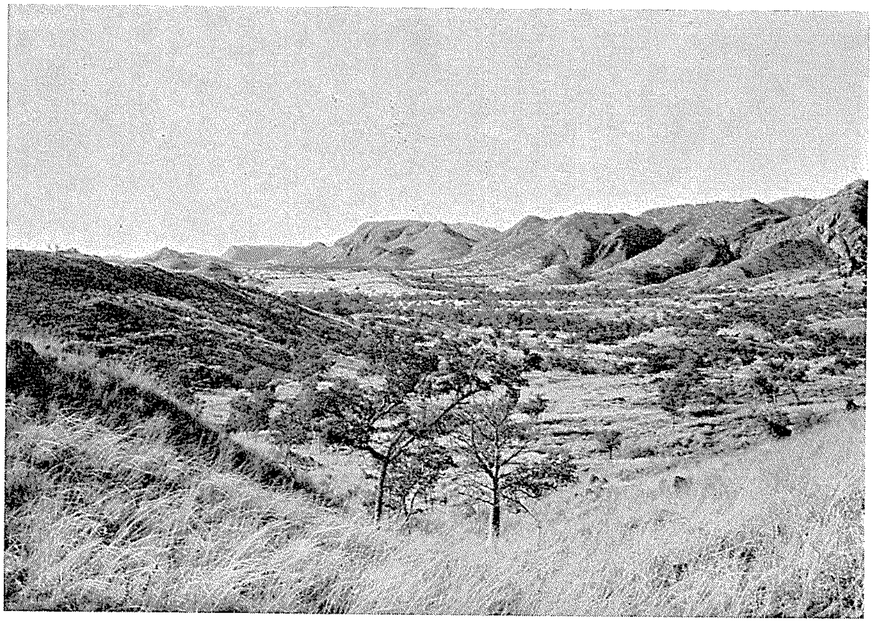


Plate 14, Figure 1. Erosion scarp marking the Halls Creek Fault near Turkey Creek (looking north). It separates the subdued hills of the Lamboo Complex in the foreground from the hills of the Carpentarian Red Rock Beds in the background on the left hand side.

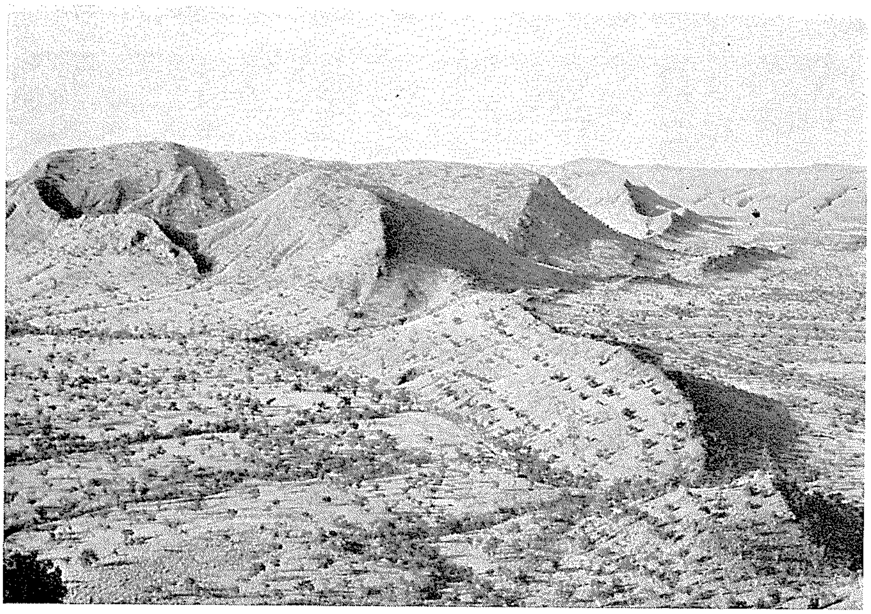


Plate 14, Figure 2. The faults as seen from the western end of Moonlight Valley (looking south) are marked by zones of silicification which stand out as sinuous ridges. The crest of the ridge in the foreground makes a splay of the Halls Creek Fault which bifurcates at the centre of the picture: one branch forms the white spur to the left of the flat-topped ridge, the other forms the low dark ridge in the plain on the right.

Plate 15, Figure 1. Horizontal section across Collenia frequens **Walcott, 1914 in the Bungle Bungle Dolomite at the head of Osmond Creek.**

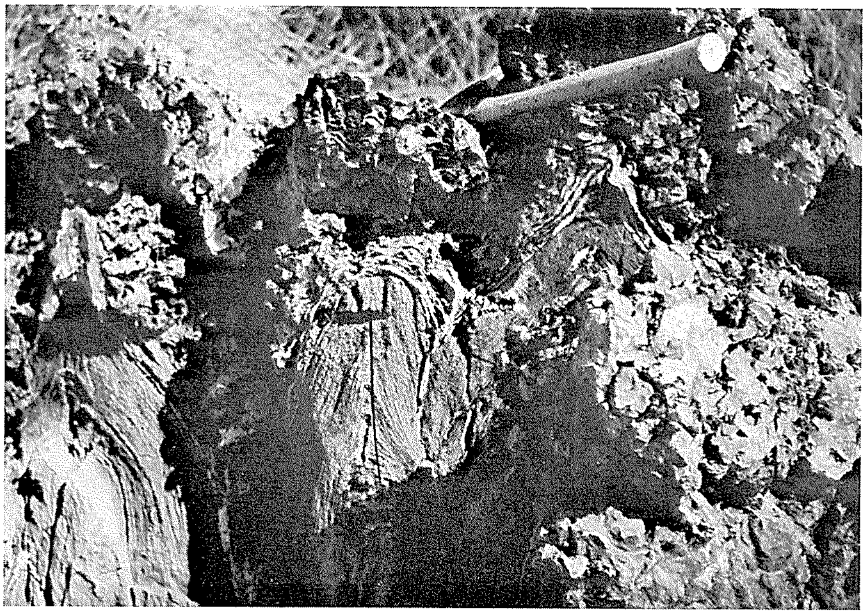


Plate 15, Figure 2. Stromatolite colony in the Bungle Bungle Dolomite 8 miles west of the junction of the Ord and Negri Rivers. It appears to consist of two colonies: the lower colony is composed of large individuals provisionally identified by Dr H. S. Edgell as Conophyton **cf.** cylindricus **(Grabau); the upper colony consists of smaller, almost completely silicified individuals, which have not yet been identified.**

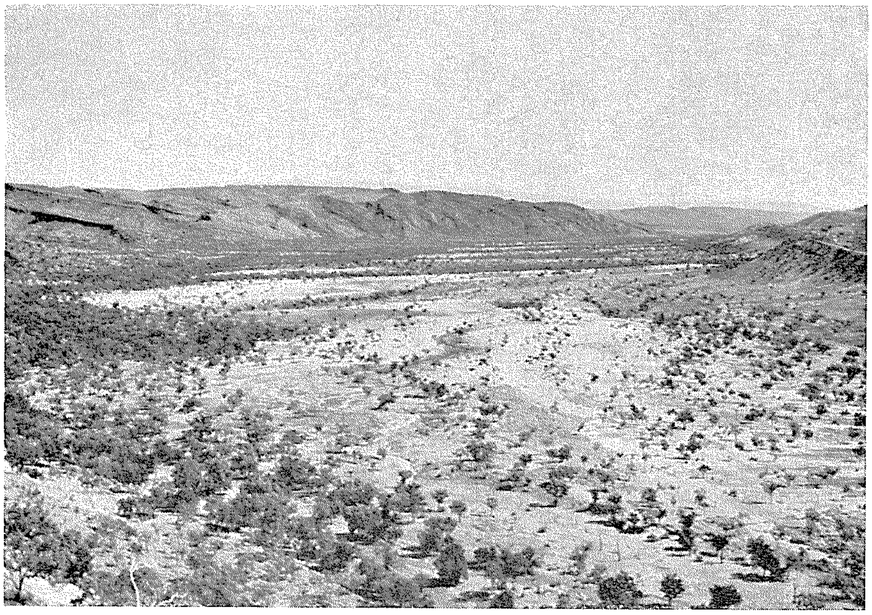


Plate 16, Figure 1. Moonlight Valley, the type area for many of the glacial rocks, looking westwards from near the Ord River. The Antrim Plateau Volcanics dip to the right, and the marker dolomite of the Moonlight Valley Tillite is exposed in the extreme lower right hand corner. Its trace can be followed as a white band along the valley. The dark beds mantling the right side of the hill in the middle background are probably Fargoo Tillite and the underlying beds shown up as gently dipping structural benches are Mount John Shale.

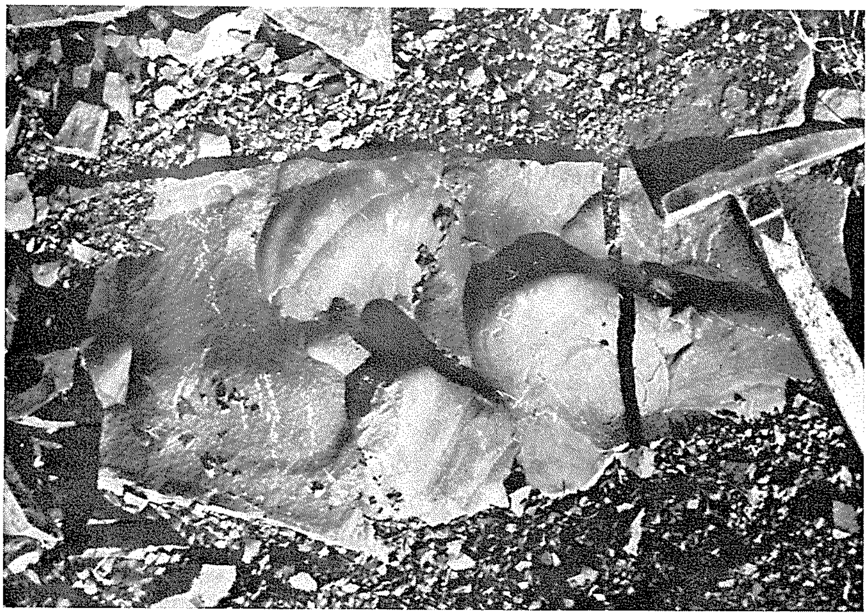


Plate 16, Figure 2. Load casts on the under surface of a thin sandstone bed in the Ranford Formation near Killarney Yard.

On the west is the *Yurabi Formation**, which overlies the Egan Formation, probably disconformably. It is characteristically arenaceous, but in the north dolomitic sediments are common in the upper part. The maximum thickness is 450 feet. It has no counterpart east of the Mobile Zone, but the overlying units can confidently be correlated across the Halls Creek Mobile Zone as shown in Figure 6. The *McAlly Shale** is a distinctive sequence of shale and siltstone about 5,000 feet thick; it is a correlative of the *Timperley Shale* on the east, which is almost identical in lithology but only 3,000 to 4,000 feet thick. The *Tean Formation** is correlated with the *Nyuless Sandstone;* both formations consist predominantly of clean arenaceous sediments 200 to 400 feet thick. The *Lubbock Formation** (possibly 6,000 feet thick) and *Flat Rock Formation* (1,000 feet preserved beneath the Antrim Plateau Volcanics) both comprise well bedded subgreywacke and alternating siltstone which are commonly dolomitic.

Age of the Glaciations

Isotopic age determinations on shales within the glacial successions (Bofinger, pers. comm.) confirm the correlations of Figures 6, which are based on the lithological similarity of some of the units on each side of the Mobile Zone.

Ages have been obtained on shales from the upper part of the Moonlight Valley Tillite and the Stein Formation (739 $\pm$ 30 m.y.), the Johnny Cake Shale Member of the Ranford Formation (685 $\pm$ 98 m.y.), the Elvire Formation (653 $\pm$ 48 m.y.), and the McAlly and Timperley Shales (666 $\pm$ 56 m.y.) (see Pl. 17).

Though the range in the ages is rather large, the results are consistent with the stratigraphy, and indicate that the Egan Glaciation occurred 600 to 700 million years ago. The late phase of the Moonlight Valley Glaciation probably occurred between 710 and 770 million years ago, but there is no direct evidence of the age of the early phase. The early phase is believed to be much younger than the Glidden and Carr-Boyd Groups, which have been dated at about 1,000 million years. Thus it appears unlikely that the early phase occurred before 900 million years ago, and it could be considerably younger.

Environment of Deposition of the Glacial Rocks

Notes on Sedimentation Under Glacial Conditions

Some of the glacial sediments of the East Kimberley region were laid down under terrestrial conditions, but most of them were probably deposited in a marine environment. Glacial marine sedimentation has been discussed at length by Carey & Ahmad (1961).

Most ice sheets (and glaciers) carry a load of sediment ranging in size from rock flour to very large boulders. The sediment is distributed throughout the ice, but is generally more concentrated near the bottom or within well defined shear zones in the ice sheet. Of prime importance is the fact that there is no sorting of the sediment, which is a chaotic mixture of all grainsizes.

The ice generally retains all this material until it enters warmer regions, where it deposits its load on melting. In a terrestrial environment, the first sediments are

* Described in detail by Roberts et al. (in prep.).

deposited under pressure directly onto bedrock as till, by melting and dissipation of interstitial ice: till is unsorted and has the same texture and size distribution as the original sediment load (Fig. 9a). Later sediments, deposited farther down the ice stream, are more variable because glacial meltwater flowing through the bottom half of the ice sheet washes out much of the finer fraction and roughly sorts some of the coarser fraction. This process of winnowing and sorting is probably dominant towards the margin of the ice sheet, and therefore most terrestrial deposits grade into stratified outwash sediments.

Where the sediment load of an ice sheet is deposited in the sea the sedimentary processes are somewhat different, and two contrasting suites of rocks are deposited, depending on whether the melting ice sheet is floating or grounded.

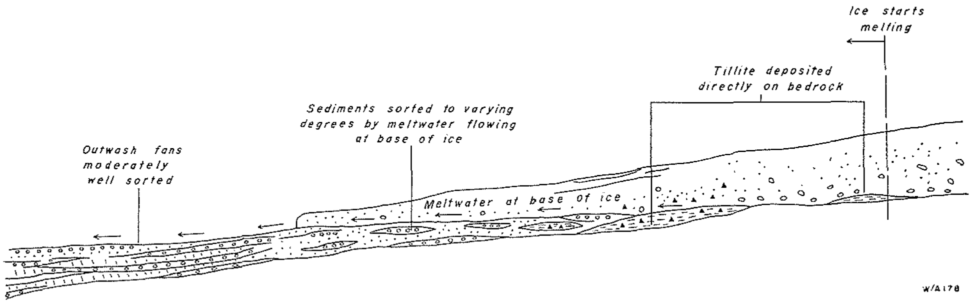


Figure 9a. Glacial sedimentation: terrestrial glacier

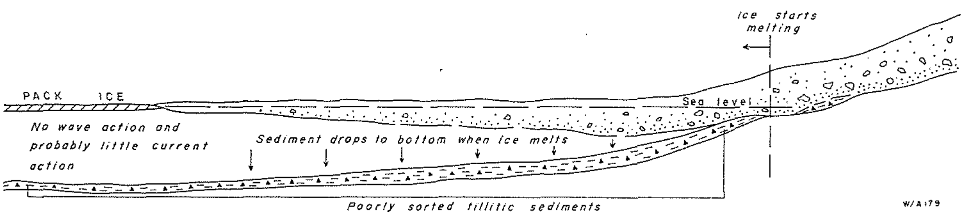


Figure 9b. Glacial sedimentation: floating glacier.

Floating Ice Sheets (Fig. 9b)

The simplest case is that of a floating ice sheet, which on melting drops its sediment load to the bottom. Under a large ice sheet this sediment is not subject to wave action, and the effect of currents is generally less than in the open sea; thus the sediments probably undergo very little sorting, and in most cases they would be indistinguishable from till directly deposited by ice. However, there is generally some sorting by current action.

Valley glaciers debouching into the sea would commonly be surrounded by pack ice and conditions of sedimentation would be similar to those prevailing under ice sheets. However, tillitic sediments would be more sporadic, and would generally be deposited only near the glaciers.

Grounded Ice Sheets

In the case of an ice sheet grounded below sea level, conditions during initial melting are much the same as for a terrestrial ice sheet, and till is deposited directly on bedrock, even at depths of many hundreds of feet below sea level.

Farther down the ice sheet, the amount of meltwater flowing along the bottom of the sheet is much less than in the case of the terrestrial glacier, because the hydraulic gradient is less, and also because much of the meltwater probably makes its way to the sea directly through the ice sheet. There is therefore less sorting of the glacial sediments under the ice, and tillitic sediments make up a greater proportion of the sediments. Sorting, however, is still an important factor in the sedimentation and can be expected to be dominant towards the margin of the ice sheet.

Secondly, previously deposited sediments may be crumpled and pushed as mudflows and submarine slides into deeper water by the bulldozing effect of the edge of the ice sheet, giving in places chaotic mixtures of contrasting sediment types.

Thirdly, a grounded ice sheet will float when its thickness has been reduced sufficiently by melting. If this stage is reached before the sheet has dropped most of its sediment load, tillitic sediments will result. The equilibrium is so delicately balanced that small changes in climate, height of sea level, or thickening of the ice sheet will result in a considerable change in the type of sediment deposited.

Thus, the sediments deposited under the ice and around the margin of a grounded ice sheet will differ from the uniform tillites deposited under a floating ice sheet, and will be an extremely variable mixture of tillite, bouldery sandstone, sandstone, and mudstone. The ratio of megaclasts to matrix will depend partly on the original sediment load of the ice sheet, and partly on the amount of subsequent sorting.

Beyond the edge of the ice sheet, the type of sediment will be controlled largely by the environment, and will generally be indistinguishable from normal marine clastics, with two probable exceptions: (i) in most cases icebergs will deposit rare erratics over large areas, and (ii) submarine slides, triggered by the moving ice sheet, will generally be more common than in marine sediments.

Environment of Deposition of the East Kimberley Glacials

In the case of the East Kimberley glacial rocks we believe that most of the sediments deposited during the Moonlight Valley Glaciation were probably laid down by a floating ice sheet, and they contrast strongly with the Egan Formation, which has the characteristics of sediments deposited in the sea by a grounded ice sheet.

Fargoo and Moonlight Valley Tillites

The Moonlight Valley and Fargoo Tillites are composed almost entirely of tillite, or of bouldery sandstone which is similar to tillite except that the fine fraction has been washed out of the matrix. These rocks could have been deposited in a terrestrial environment directly onto the bedrock, and they show many of the features of the Pleistocene tills of North America including their great extent and range of thickness (Flint, 1957). However, they also have features which are consistent with deposition from a floating ice sheet, and we believe that most of the sediments were deposited under marine conditions. Thus, the Moonlight Valley Tillite grades laterally into a massive bouldery cross-bedded sandstone (Pl. 13, fig. 1) which is extensive, only poorly bedded, and does not resemble glacial outwash deposits. The tillite also grades laterally into a distinctive dolomite conglomerate (sparagmite) as shown in Plate 13, figure 2. Both the bouldery sandstone and dolomitic conglomerate were almost certainly deposited in still water.

Other features indicating a marine or lacustrine environment are:

(1) All the tillites contain lenses, up to 20 feet thick and hundreds of yards across, of dolomitic sandstone, boulder conglomerate, and pebble conglomerate. These could conceivably have been formed by the sorting action of glacial melt-waters, but they are much more likely to have been deposited under the sea. The dolomitic sandstone lenses in particular appear to be of marine origin.

(2) In places the tillites grade upwards, without apparent break, into massive clay or shale, up to 100 feet thick, which contains scattered rare pebbles; this type of rock is almost certainly marine.

Thus the Fargoo Tillite was probably deposited by a floating ice sheet which travelled roughly in an easterly direction over the Lamboo Complex. The tillite could have been deposited directly onto bedrock as a terrestrial deposit, but the evidence available indicates that it was deposited by an extensive floating ice sheet fringing the western landmass.

The Moonlight Valley Tillite was probably deposited under similar conditions, but the ice travelled from the northeast, apparently from an ice sheet covering the (present-day) Victoria River Basin. The Moonlight Valley Tillite is generally thinner than the Fargoo Tillite and commonly occurs as discontinuous lenses in hollows in the bedrock. The tillite in the hollows was probably deposited directly on to bedrock by the ice.

Egan Formation

The Egan Formation, on the other hand, was probably laid down in the sea by a grounded ice sheet. In places, the base of the formation consists of a dolomite bed, up to 75 feet thick, which was probably laid down by a transgressive sea shortly before the glacial epoch. It is overlain by sediments many of which are characterized by the presence of megaclasts up to boulder size. The matrix of the sediments ranges from pure quartz sandstone to dolomitic sandstone, greywacke, and in extreme cases predominantly clay and silt. The megaclasts range up to 10 feet across. They may be completely unsorted and randomly distributed (thus some of the beds are true till), or they may be well sorted and consist mainly of well rounded pebbles or cobbles; they may be present as rare scattered pebbles, or they may make up the bulk of the sediment. Most of them consist of dolomite and quartzite, but in some localities a great variety of rock types is found.

The glacial sediments are poorly exposed and the relationships between the various rock types can seldom be determined. In places, there is complete lateral and vertical gradation from one rock type to the other, but elsewhere they occur as discrete lenses.

It seems therefore that the Egan Formation was laid down under shallow water near the margin, and probably underneath the ice in places, of an extensive ice sheet which capped the Kimberley Plateau to the north. The ice sheet probably did not extend far into the sea, and in most places it was grounded, thus giving the great variety of sediments characteristic of the formation.

Flint (1957) has shown that varves cannot form in salt water; and varve-like sediments are rare amongst the glacial rocks of the East Kimberley region which are believed to have been deposited in a marine environment. In shallow restricted basins, however, large volumes of meltwater could conceivably lower the salinity of the sea water sufficiently for varves to form, and such conditions probably prevailed during deposition of the Egan Formation in the O'Donnell Basin in the southwestern part of the map area (Pl. 18). On the western margin of O'Donnell Basin there are very thin regular beds of siltstone grading upwards into shale; the beds overlie the tillite, and are probably glacial varves.

Dolomite in the Glacial Environment

In the East Kimberley region the glacial rocks are invariably associated with dolomitic rocks. The widespread distribution of the dolomitic rocks over a prolonged period strongly suggests that the deposition of dolomite was a natural accompaniment of the glacial marine sedimentation, and there is little doubt that it was due to the decrease in solubility of calcium and magnesium carbonates with increasing temperature (Carey & Ahmad, 1961). Thus, if sea water is saturated with calcium and magnesium carbonates, they will be precipitated chemically or by lime-secreting organisms when the temperature rises.

In the glacial seas of the East Kimberley region the water was almost certainly saturated with calcium and magnesium carbonates. The terrain included a high proportion of carbonate rocks exposed to glacial erosion, and though much of the dolomite was present in the ice sheets as cobbles and boulders, a large proportion was present in the form of powder, and conditions were thus ideal for the meltwater to be saturated with calcium and magnesium carbonates. Sea water normally is nearly saturated with the carbonates, and it would certainly be saturated in these glacial seas.

Though dolomite is known at the base of the glacial deposits, and dolomitic lenses are common within the deposits, most of the dolomite is found immediately above the glacial sediments, and was deposited as the seas warmed after the glacial epochs.

Where there was little coarse detritus, fairly pure carbonate rocks were deposited, such as the marker dolomite above the Moonlight Valley Tillite and the carbonate rocks overlying the Egan glacials. The thin bedding in many of the carbonate rocks was probably caused by seasonal fluctuations in the temperature of the sea water. Most of the carbonates appear to have been chemically deposited (ooliths are common in places), but stromatolite colonies are not uncommon, and clearly played a part in fixing the dolomite. Roberts et al. (1965) have postulated tropical seas to account for the presence of stromatolite colonies, but such an assumption is based on the present-day distribution of stromatolites and the post-glacial temperatures in the East Kimberley region may not have exceeded those of a present-day temperate climate.

The post-glacial sediments were the last Precambrian rocks deposited in the East Kimberley region; they were broadly folded and exposed to erosion in uppermost Adelaidean or lowermost Cambrian times. They were followed by vast eruptions of tholeiitic lava which covered much of northern Australia in Lower Cambrian times; the lavas have helped to preserve this unique record of Precambrian glacial rocks.

STRUCTURE

The structure of the East Kimberley region is dominated by the Halls Creek Mobile Zone (Fig. 2), a narrow belt of intensely deformed metamorphic and igneous rocks, now partly covered by sediments, which extends from south of Halls Creek township to near Darwin in the Northern Territory (Traves, 1955). It is bounded to the east and west by faults of great magnitude, and is broken by a complex series of anastomosing faults, many of which appear to have throws comparable with the boundary faults.

The Mobile Zone is flanked by areas which have been tectonically stable since early Carpentarian times—the Sturt Block on the east, and the Kimberley Block on the west. The younger Proterozoic rocks covering the stable blocks are only slightly deformed.

Tectonism was not always confined to the Halls Creek Mobile Zone, and the oldest rocks of which we have record, the Halls Creek Group, were laid down and folded over the whole of the region. About 2,000 million years ago, deformation and igneous intrusion became localized along the middle part of the Mobile Zone where high-grade metamorphic rocks and granites were formed. Because of the high temperature within the zone, the rocks reacted to stress mainly by plastic flow, while the rocks outside the zone suffered a second widespread folding.

In early Carpentarian times, the type of deformation changed radically and the area reacted to stress almost entirely by dislocation along the great faults which follow the Mobile Zone. It is possible that the displacement on these faults was predominantly horizontal. Folding was subordinate; it consisted of broad warpings over very large areas, and only in narrow zones close to the major faults was the folding as tight as in the Halls Creek Group.

Since the Carpentarian, tectonism has followed the same pattern, with intermittent movement along pre-existing faults continuing well into the Palaeozoic and possibly even into the Mesozoic.

Since the early Carpentarian the Sturt and Kimberley Blocks reacted as competent units and the Carpentarian and younger rocks here are only gently warped and dislocated by faults of small displacement.

The following discussion of the structure is treated as far as possible chronologically.

PRE-CARPENTARIAN STRUCTURE

Deformation of the Halls Creek Group

The Halls Creek Mobile Zone is known to have been the focus of tectonism since early Proterozoic times. It was active even before this, but metamorphism and igneous intrusion dating back to 2,000 million years ago have almost completely obliterated all trace of earlier events. To find evidence of earlier tectonic events we must turn to the inliers of tightly folded Halls Creek Group which have been exposed by erosion of the younger sedimentary cover on both the Sturt and Kimberley Blocks.

The inliers show that Halls Creek Group was laid down over the whole of the East Kimberley region, and that the sediments were then tightly folded by at least two episodes of intense deformation. The first impressed a strong axial-plane cleavage over most of the area, and during the second, a strain-slip cleavage was developed which cuts across and deforms the earlier folds. The later cycle of deformation probably coincided with the major period of metamorphism which formed the Tickalara Metamorphics and Mabel Downs Granodiorite.

The folding of the Halls Creek Group is generally difficult to decipher, because of poor exposure, the lack of mappable beds at the base of the Olympio Formation, or the disruption of structures by faulting. The style of folding is well exemplified to the east of Halls Creek township, where the Halls Creek Group is folded into the Biscay Anticlinorium, and in the Garden Creek Anticline near the McClintock Range in the south.

Biscay Anticlinorium

The Biscay Anticlinorium (Pl. 18) is a complex set of folds about 20 miles northeast of Halls Creek township. It is about 70 miles long and up to 20 miles wide, and lies wholly to the east of the Halls Creek Fault. There is a large anticlinal structure to the northwest on the other side of the Halls Creek Fault, which may be the western part of the Biscay Anticlinorium which has been shifted to the southwest by transcurrent movement on the Halls Creek Fault.

The rocks in the Biscay Anticlinorium are isoclinally folded and it is almost impossible to unravel the detailed structures. By mapping the major units of the Halls Creek Group on a regional scale, and by ignoring the smaller complexities (most of the smaller folds have amplitudes of up to half a mile) the broad structure of the anticlinorium can be seen.

It is composed of two broad anticlines separated by a tight, faulted, attenuated syncline. The flanks of the anticlinorium have been faulted by two large north-northeasterly trending faults—the Halls Creek Fault on the west and an unnamed fault on the east; the anticlinorium is also dislocated by a large number of smaller faults, the largest of which are two east-northeasterly trending faults which have downthrown the northern and southern parts of the structure.

The whole structure has been domed along an east-west axis, and it plunges to the south-southwest at 30° to 50°, and to the north at about 20° to 25°. The doming was caused partly by the intrusion of the Sophie Downs Granite and partly by the intermittent tectonism which affected the Carpentarian rocks, and later the

Adelaidean rocks. At the northern end of the anticlinorium, where the Ord River cuts across it, there is a reversal of plunge and the fold axes plunge gently to the south-southwest (Fig. 2).

It was not possible to map even the core of the anticlinorium in detail in the time available, so several small areas were mapped, some on enlarged air-photographs, to try to establish the style of folding. The carbonate bands in the Biscay Formation were recognized as likely markers and attempts were made to trace them along strike, but owing to the lack of outcrop in critical areas and the presence of many small faults the beds could generally only be traced for about half a mile.

Sufficient was seen, however, to prove that the beds are isoclinally folded along axes trending parallel to the regional foliation which forms the dominant grain of the country (shown as photo-interpreted trend-lines in Pl. 18). These folds are of surprisingly large amplitude—the distance from crest to trough is up to half a mile, but the folds are only a few hundred feet across.

Throughout the Biscay Anticlinorium there is evidence that the rocks have undergone two separate periods of severe folding.

Garden Creek Anticline

The result of the two periods of folding is well demonstrated by the Garden Creek Anticline, which is one of the larger inliers of Biscay Formation, surrounded by the Olympio Formation, in the McClintock Range (Fig. 10). The structure of the anticline can be deciphered by mapping a well exposed bed of chert/dolomite which marks the top of the Biscay Formation. The rocks have been metamorphosed to the greenschist facies.

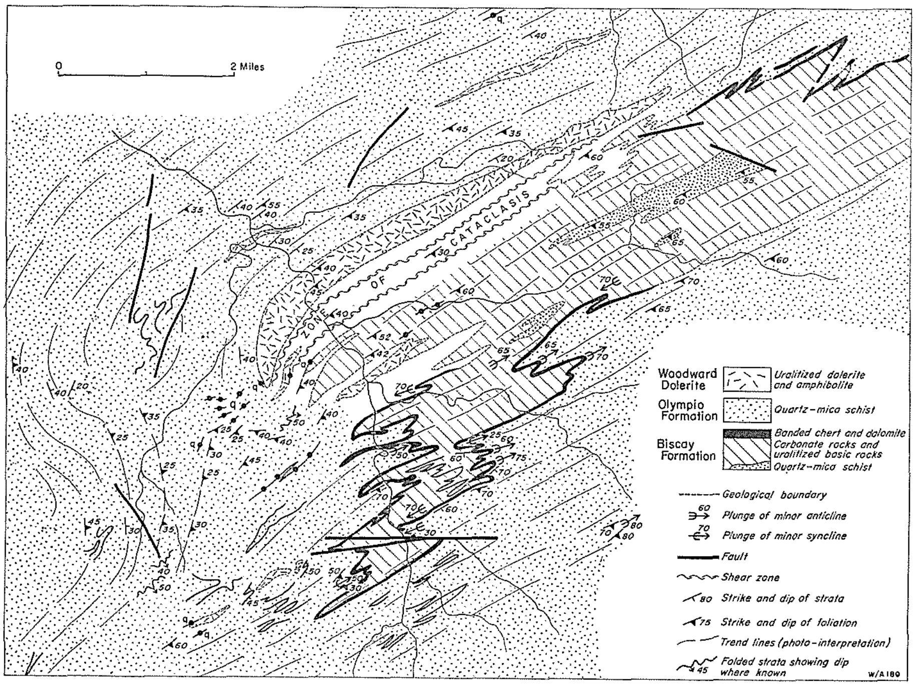


Figure 10. Garden Creek Anticline

In the northwest, the fold has been disrupted by a wide zone of cataclasis which may have been formed at the same time as the fold, or which may be the result of later faulting.

The succession was first folded into a large anticline with steeply dipping flanks. The fold now has a near-vertical axial plane, but the original plunge is unknown. During a later period of intense deformation the anticline was crumpled into a series of tight, almost isoclinal folds, the axial planes of which are at a slight angle to the original anticline. The plunges of the folds are mostly within 20° of the vertical.

A well developed cleavage was formed parallel to the second axial plane, and it is this cleavage which controls the trend-lines shown in Figure 10.

A number of thin sections of rocks from the Olympio Formation in the anticline have been examined by Dow. They comprise quartz, muscovite, and biotite schists, in which two distinct foliations can be distinguished, except where cataclastic effects have obliterated them. The first, which was apparently formed during the first period of folding, is generally parallel to the bedding, and is defined by aligned mica flakes. The earlier foliation has been crenulated by a second foliation which developed parallel to the axial planes of the crenulations by growth of a second generation of mica flakes. In the field the foliation can be seen to be parallel to the axial planes of the later folds.

The steep plunge of the secondary folds in the Garden Creek Anticline is consistent with the plunge of the folds throughout the southwestern part of the area, and in the inliers of Halls Creek Group in the Osmond Range. All the folds plunge steeply to the north and south, in marked contrast with those of the Biscay Anticlinorium, where the plunge is much less steep.

The contrasting plunges can probably be explained by the nature of the initial folding. Thus the initial folding of the Biscay Anticlinorium would have formed broad folds with moderately dipping limbs, and the subsequent folds therefore had moderately plunging axes. The other areas were probably much more tightly folded, and the later folds, formed on the steeply dipping limbs, have a steep plunge.

However, the steeply plunging folds occur in regions cut by anastomosing faults regarded as predominantly transcurrent (see p. 69), and the steep plunges could have been a direct result of this lateral displacement, by rotation of the fault wedges (Lenson, 1958). Similar steeply plunging folds occur in the Southern Alps of New Zealand, a region of strong lateral displacement, and they are regarded as having been formed by lateral displacement (Lillie & Gunn, 1964).

The dykes of Woodward Dolerite in the Halls Creek Group have also been folded and recrystallized to amphibolite, but they rarely show foliation. The complexity of the folding varies considerably and the dykes may be tightly folded (Fig. 3) or straight: the folding could have been caused by the second period of folding, but it is not known whether they were affected by the first period of deformation.

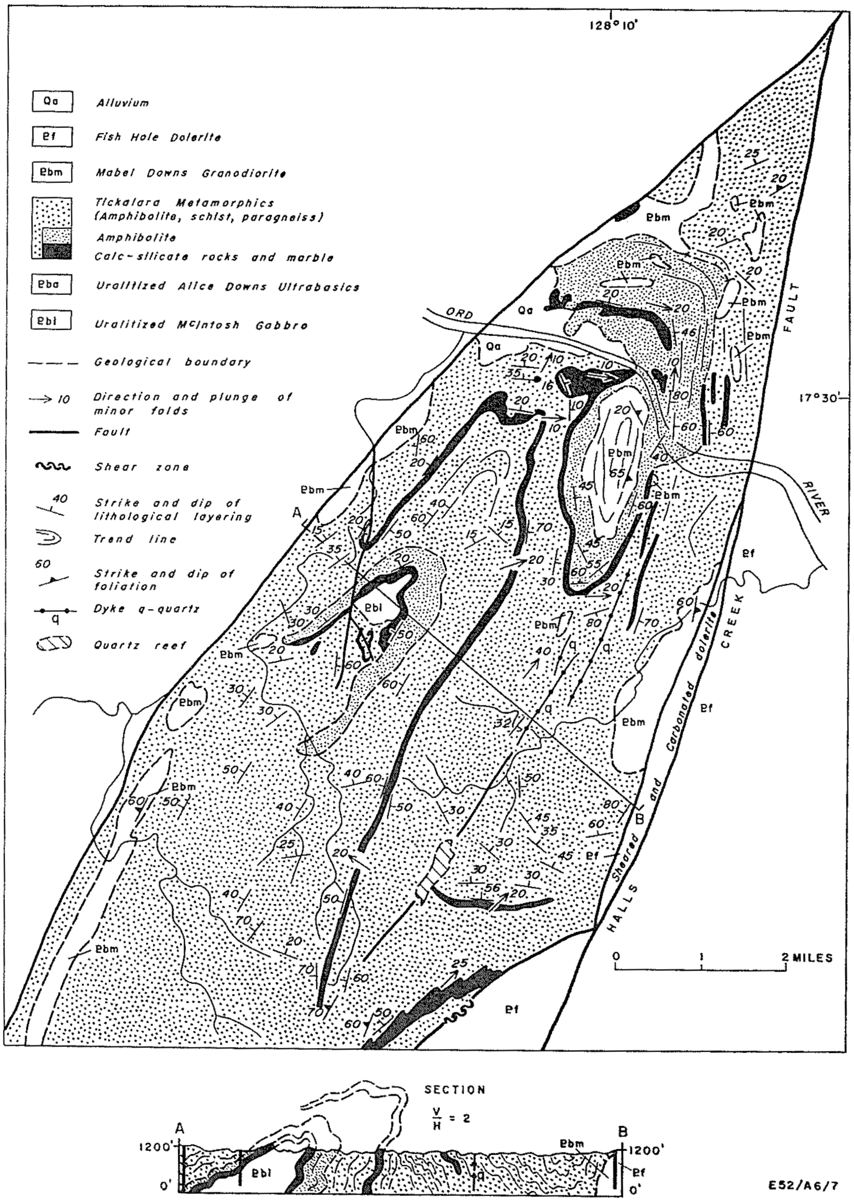


Figure 11. Black Rock Anticline

Deformation of the Tickalara Metamorphics

The Tickalara Metamorphics probably had the same tectonic history as the Halls Creek Group until their metamorphism and intrusion by granite and gabbro, but in the high-grade rocks earlier structural trends have been obliterated. The earlier structures have been preserved only in the lower-grade rocks, such as those in the Black Rock Anticline (Fig. 11) where the folding is similar to that in the Biscay Anticlinorium; it is apparent that they have undergone the same two periods of folding that affect the Halls Creek Group.

North of the Black Rock Anticline as far as the Tickalara Bore, the Tickalara Metamorphics are folded into tight northerly plunging synclines and anticlines. The major fold axes and axial planes trend north-northeast, and all minor fold axes are paralleled by steeply plunging lineations defined by oriented metamorphic minerals. The anticlines have overturned easterly limbs, and the synclines are sheared out by anastomosing faults of the Halls Creek Fault. To the west, the regional structure is disturbed by intrusive granites and numerous shear zones.

North of the Tickalara Bore, near the margins of the Mabel Downs Granodiorite, and in the migmatite gneiss near Mabel Downs homestead the structure is very complex. The folding ranges from ptygmatic to isoclinal, and the dominant processes of deformation have been transposition of folded layers and plastic flow. Flowage phenomena are particularly conspicuous in the marble bands, which have flowed like soft solids, whereas the intercalated layers of gneiss and amphibolite are shattered and dispersed.

POST-CARPENTARIAN STRUCTURE

After consolidation of the crystalline rocks of the Lamboo Complex about 1,800 million years ago, the whole region acted as a competent block, and the rocks reacted mainly by breaking along large faults which follow the Halls Creek Mobile Zone.

The Halls Creek Fault on the east and the Greenvale Fault on the west form the margins of the Mobile Zone, and they are linked by a series of large anastomosing faults (Fig. 2), the most important of which have throws comparable with those on the boundary faults.

The faults have long complex histories of intermittent movement; the smaller displacements and less intense shearing in the younger rocks indicates that faulting activity gradually diminished. The total displacement on the faults is not known; most of them have a proved vertical displacement of 5,000 to 10,000 feet, and most of them probably also have a large horizontal displacement.

Little is known about the pre-Carpentarian movement on the faults, but the evidence cited below suggests that they were probably active during the metamorphism and igneous intrusion along the Mobile Zone.

(1) In some areas, notably in the Biscay Anticlinorium and Black Rock Anticline, the grade of metamorphism is higher near some of the major faults. The higher-grade metamorphism is not superimposed, and indicates that the faults were active during metamorphism.

(2) The Bow River Granite is strongly foliated near many of the larger faults; the foliation was formed at high temperatures—probably at a late stage in the cooling of the granite. This contrasts with the effects of later faulting, when cataclasites and mylonites were formed within the granites.

(3) The Speewah and Kimberley Groups rest unconformably on the Bow River Granite and Tickalara Metamorphics, and it is clear that most of the crystalline rocks of the Lamboo Complex were exposed in earliest Carpentarian times. It is assumed that much, if not all, of the uplift was caused by movement on the boundary faults of the Halls Creek Mobile Zone before the Carpentarian.

Halls Creek Fault

The Halls Creek Fault is one of the largest structural features in northern Australia, and may be termed a 'fundamental fault' (de Sitter, 1956). It forms the eastern boundary of the Halls Creek Mobile Zone over most of its length, and brings the Lamboo Complex in contact with rocks as young as Palaeozoic. The form of the southwestern extension is uncertain, as it appears to break into a number of diverging splay faults, the most easterly of which was mapped as the continuation by Smith (1963). However, the Angelo and Woodward Faults, which diverge near Halls Creek, appear to have larger throws.

In the northeast, near Kununurra, the Halls Creek Fault forms the eastern boundary of the Palaeozoic Bonaparte Gulf Basin, and though it has not been mapped to the northeast it probably extends as far as Darwin. Over the whole of its length the Halls Creek Fault is commonly marked by a prominent scarp (Pl. 14, fig. 1), and its trace is slightly sinuous and invariably steeply dipping to the east or west. Where exposed, the fault consists of a shear zone up to a quarter of a mile wide, in which the rocks are thoroughly imbricated. Near Lissadell homestead and east of Turkey Creek, the total displacement on the fault is distributed over several faults in a zone up to 4 miles wide (Pl. 14, fig. 2).

The fault has a large vertical throw and is generally downthrown to the east, but there may be a large lateral component of which there is now little record (see below).

As the fault has had a long history of intermittent movement, and as there is some evidence that the downthrow has not always been to the east, the total vertical displacement is unknown. Thus the great thickness of Carr Boyd sediments on the west indicates that the northern part of the Halls Creek Mobile Zone was downthrown in early Adelaidean times.

The net effect of all these movements can be measured in the Osmond Range, where the Halls Creek Fault brings the upper part of the Ord Group against the Lamboo Complex: the sediments overlying are about 6,000 feet thick and there has been a net downthrow to the east of at least 6,000 feet since the Carpentarian.

The Halls Creek Fault has many of the characteristics of transcurrent faults: sinuous trace, steeply dipping fault plane, and great length (it has been mapped over a distance of 350 miles, and probably extends as far as Darwin, a further 200 miles), and therefore the horizontal displacement on the fault may be predominant; but this cannot be proved. Even in the case of faults which have undergone large horizontal movements in Recent times, such as the Alpine Fault in New Zealand (Wellman, 1956), it has not been possible to prove the total displacement, even though this is suspected to be of the order of hundreds of miles.

Evidence of horizontal movement is given by the apparent displacement of the western side of the Biscay Anticlinorium some 60,000 feet to the south by the southerly extension of the fault (Pl. 18). This extension appears to be a subordinate splay of the main fault, and the total horizontal displacement on the Halls Creek Fault farther north may be much greater.

Small lenses of quartzite, and quartz-jasper conglomerate belonging to the Red Rock Beds, are found along the Halls Creek Fault and its main splay, for up to 8 miles south of Osmond Range. They were probably formed by drag along the faults during lateral displacement.

Most of the other faults of the Halls Creek Mobile Zone have the same general characteristics as the Halls Creek Fault, and are discussed only briefly. The pattern of faulting is well exhibited in the Carr Boyd Range in the north, where the Mobile Zone is broken into an interlocking set of long fault wedges. In the south, probably only a small proportion of the faults cutting the Lamboo Complex have been mapped because there are no overlying sedimentary rocks to act as markers, and many areas of poor outcrop which could conceal large faults. Those mapped show up as strong lineations on the air-photographs and are marked in places by quartz reefs, silicified zones, or zones of cataclasis.

Carr Boyd Fault

The Carr Boyd Fault is a steeply dipping westerly splay of the Halls Creek Fault in the northeastern corner of the map area. The vertical displacement is not known because the formations dislocated change in thickness across the fault, but is of the order of several thousand feet, west block down. The fault wedge between the fault and the Halls Creek Fault has been tilted to the south, and its northern end has been upthrown several thousand feet, a rotation possibly caused by transcurrent movement along the two faults (Lensen, 1958). The intensity of folding and shearing of the rocks of the wedge increases markedly to the south towards the junction of the Carr Boyd and Halls Creek Faults.

Revolver Fault

The Revolver Fault is a westerly splay of the Carr Boyd Fault, and has similar splay faults diverging from it. The fault is an ancient one and displaces the lower part of the Carr Boyd Group, but not the upper part: vertical displacement is about 6,000 feet, east block down. To the south, the folded cleavage in Halls Creek Group adjacent to the fault indicates a large horizontal component (Dow et al., 1964).

Dunham Fault

The Dunham Fault is an easterly splay of the Greenvale Fault which forms the western margin of the Halls Creek Mobile Zone. It has a steeply dipping shear zone up to a mile wide which is marked by prominent quartz reefs or a steep scarp. The fault dips steeply to the east, and near the O'Donnell Range it is a reverse fault and the dislocated strata indicate a vertical displacement of about 8,000 feet, west block down. However, horizontal displacement of about 20,000 feet could also give the observed displacement. The fault also displaces Devonian strata, but only by small amounts.

Ivanhoe Fault

The Ivanhoe Fault consists of a steeply dipping shear zone up to three-quarters of a mile wide which displaces the Carr Boyd Group by as much as 7,000 feet vertically, west block down, and 10,000 feet horizontally, west block south. There has been considerable post-Devonian movement on the fault, and at its northern end the Devonian rocks have been displaced about 3,000 feet vertically. To the south, where Devonian rocks transgress the fault undisturbed, the displacement decreases.

Greenvale Fault

Over most of its length the Greenvale Fault trends roughly south-southwest, and forms the western boundary of the Halls Creek Mobile Zone, but near Whitewater Well it changes rather abruptly to a more westerly trend before it dies out near the western margin of the Sheet area. Though this westerly trending extension was mapped as the continuation of the Greenvale Fault it is probable that the main fault extends southwards under an alluvium-filled valley to join the Springvale Fault near Moola Bulla homestead.

North of Whitewater Well the Greenvale Fault is marked by shear zones up to 2 miles wide, and it follows a sinuous trace which is offset horizontally, west block south, by several northerly splay faults: one of these, just north of Mount Remarkable, has offset the main fault by at least 20,000 feet. Downthrow on the main fault is 6,000 to 10,000 feet to the west, and as the fault plane dips steeply east and west, so the fault is variously normal or high-angle reverse. It is suspected that the fault may have a large horizontal component, but there is no supporting evidence.

The westerly extension of the Greenvale Fault has a vertical displacement of at least 15,000 feet near Mad Gap Yard on the Watery River, but this diminishes rapidly westwards, where much of the vertical displacement has been taken up by monoclinal folding. The fault here is also either normal or high-angle reverse.

Angelo and Woodward Faults

The Angelo and Woodward Faults are splays of the Halls Creek Fault which have been traced almost to the southern margin of the map area. They traverse regions of low relief, and do not have the strong physiographic expression of the Halls Creek Fault. They can be seen as lineations on the air-photographs, and in many cases they are marked by quartz reefs which stand out as vertical walls up to 20 feet high. The faults are nowhere exposed, but as the quartz reefs marking their trace are nearly vertical, it is assumed that they are also nearly vertical. The displacement is not known, and may be relatively small. The Angelo Fault generally marks the southeasterly limit of the high-grade metamorphism and igneous intrusion of the Lamboo Complex; in this respect it is similar to the Halls Creek Fault and the displacement is probably of the same order.

Springvale Fault

The Springvale Fault is a sinuous fault in the middle of the Halls Creek Mobile Zone; it forms a belt of poor outcrop up to half a mile wide in the southern part of the map area. The fault is confined to the Lamboo Complex; it appears to displace the Bow River Granite batholith for 20 miles horizontally, west block south, but this apparent displacement may be an illusion, and the intrusion may be later than the fault, which has controlled its mode of emplacement.

The fault zone was seen only near Lamboo homestead, where it consists of a vertical zone at least 200 feet wide of mylonitized granite. In many places the Bow River Granite is foliated parallel to the Springvale Fault for distances of up to a quarter of a mile. The foliation was formed during crystallization of the granite, and it is clear that the fault was active at this time.

The fault cannot be traced to the north, but it appears to merge with the complex set of faults in the northern part of the Mobile Zone. A poorly exposed easterly splay diverges from the fault near the headwaters of the Ord River, and probably follows the belt of low relief followed by the Great Northern Highway, to join the Halls Creek Fault north of Bow River.

Sturt Block

In the east of the Halls Creek Mobile Zone the Precambrian rocks are largely covered by Palaeozoic rocks and Cainozoic alluvium, but where exposed they are horizontal or only gently folded.

Only near the Mobile Zone are the rocks greatly deformed. The Red Rock Beds are the ones most affected, and within 4 miles of the Mobile Zone they are broken into small wedges by steeply dipping anastomosing faults of the Halls Creek Fault and by divergent faults trending roughly northeast. The component rocks within the wedges are generally nearly vertical and the competent beds are tightly folded. The fault planes are invariably steep, and though the vertical displacement is known to be several thousand feet, the horizontal displacement is unknown. It could, however, be predominant.

Much of the faulting along the marginal zone postdates the deposition of the Red Rock Beds, but faulting was also active during their deposition. Cliff sections in the head of Osmond Creek give ample evidence of this: a prominent bed of quartzite and quartz-pebble conglomerate is downthrown by at least 500 feet, but the overlying boulder conglomerate is dislocated only 270 feet by the same fault, and the overlying Mount Parker Sandstone is not affected. The Red Rock Beds in this locality show great lateral variation which was probably caused by contemporaneous faulting.

There was much less tectonic activity along the edge of the Mobile Zone after the deposition of the Mount Parker Sandstone. The Osmond Range succession and the overlying glacial rocks are affected by faults, but the displacements are small. The *Osmond Fault* is an exception: it has downthrown the southern flank of the anticline forming the Osmond Range, a vertical distance of 8,000 to 11,000 feet, and though its horizontal displacement is not known it is believed to be small. The fault plane is nearly vertical and the Osmond Range succession has been dragged vertical or overturned close to the fault.

The only Precambrian rocks exposed away from the Mobile Zone in the map area are the Gardiner Beds of unknown age. They are horizontal or gently dipping and are dislocated by small faults which generally trend northwest. The type of deformation is characteristic of the rest of the Sturt Block (Traves, 1955), and it can be safely inferred that the post-Carpentarian rocks covered by the Palaeozoic sediments have a similar structure.

Other than the Osmond Fault, only one major fault is known in the Sturt Block in the map area. It is exposed at the extreme eastern end of the Osmond Range as a large northwest-trending shear zone which affects the Halls Creek Group and the Red Rock Beds. The younger Precambrian rocks are little affected by the fault, but the Cambrian rocks to the southeast near White Mountain are dislocated by a faulted monocline which was apparently formed by reactivation of the fault. It is also possible that the Tertiary sediments at White Mountain owe their elevated position to movement along this fault.

Kimberley Block

Most of the Kimberley Block falls outside the East Kimberley region, and will be described in detail by K. A. Plumb (in prep.); only a brief description is given here.

The Carpentarian rocks of the Kimberley Block are nearly horizontal, and only near the Halls Creek Mobile Zone are they deformed to any great degree. Along the northern half of the Mobile Zone, the belt of deformed rocks is about 20 miles wide, and here the rocks are broadly folded into dome or basin structures which are broken by northerly trending faults diverging from the Mobile Zone at a small angle. These faults are generally steeply dipping and have horizontal displacements up to 20,000 feet, west block south, but only minor vertical displacements. The faults are very localized, and consist of brecciated zones and quartz-filled zones up to 20 feet wide. Close to the faults the rocks are steeply dipping, and the less competent are very tightly folded in places.

The marginal zone is much wider and the structure much more complex in the southeastern part of the map area, for here the rocks are also affected by folding parallel to the King Leopold Mobile Zone (Traves, 1955). This zone is a northwesterly trending tectonic belt similar to the Halls Creek Mobile Zone, which crosses the southeastern extremity of the map area (Fig. 12). The interaction of the two trends has caused a swing from southwest to northwest in the strike of folds affecting the Halls Creek Group. The change occurs off the map area to the south, where later sediments obscure much of the geology, but from the air-photographs it appears to be a gradual swing.

On the other hand the change in the trend of folding in the Carpentarian rocks is rather abrupt: the south-southwesterly trend of the northern region continues with only a slight swing westwards almost to the western margin of the map area, where the fold axes change within a few miles to a north-northwesterly trend. The folding also changes from the broad folding characteristic of the marginal zone in the north, to tighter folding dominated by strike faults of considerable magnitude. These faults are steeply dipping and have vertical displacements of up to 3,000 feet.

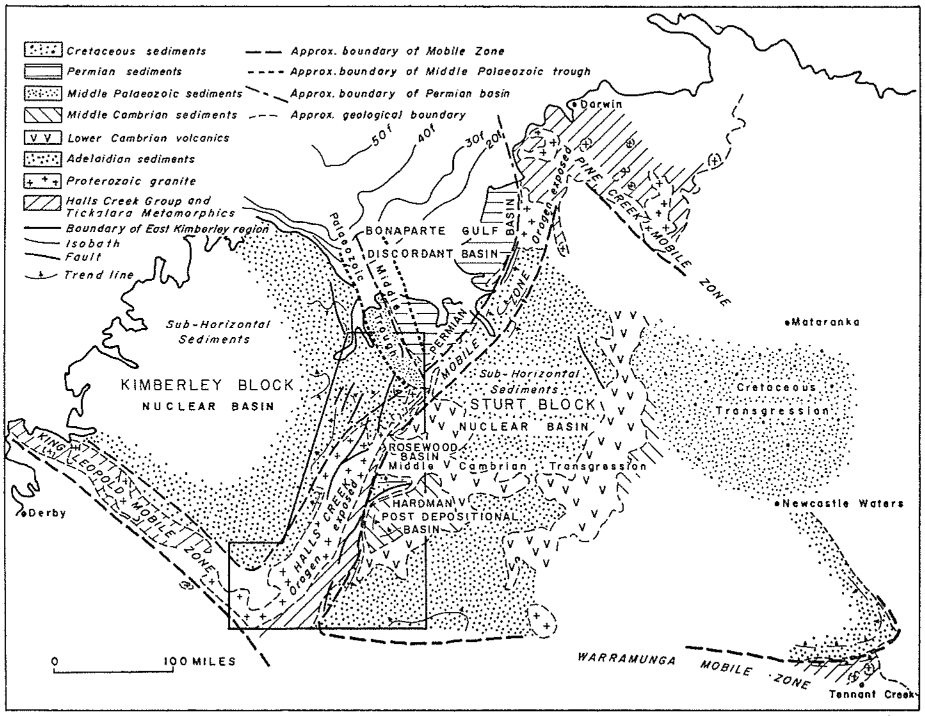


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Figure 12. Tectonic pattern, East Kimberley region

Normal faults of similar trend but much smaller vertical throw affect the Carpentarian rocks to the east. Some of them trend north-northeast, and have predominantly transcurrent displacements, west block south, ranging up to 25,000 feet, and are apparently related to the transcurrent faults described before which dislocate the marginal zone to the northeast.

Adelaidean rocks occur only east of the marked change in strike, where they are preserved in three structural basins: the MacKinnon, O'Donnell, and Louisa Basins. However, the basins were formed by the interaction of the two fold trends, and within them two sets of fold axes nearly at right angles can be seen in places.

DETAILED DESCRIPTION OF ROCK UNITS

In the following pages all the early Proterozoic and most of the Adelaidean sediments of the East Kimberley region are defined, and detailed descriptions given, but the Carpentarian rocks of the Kimberley Plateau to the northwest, and of the Carr Boyd Range to the northeast, are to be described by K. A. Plumb (in prep.).

The glacial rocks of the southwestern part of the region are to be defined and described in detail by Roberts et al. (in prep.). The igneous rock units of the East Kimberley Region are defined in Gemuts (1969).

In describing the sediments we have used the classification of sediments given by Pettijohn (1957), except for the sandstones, which we have classified according to Dapples, Krumbein, & Sloss (1953), the essential features of which are shown in Figure 13.

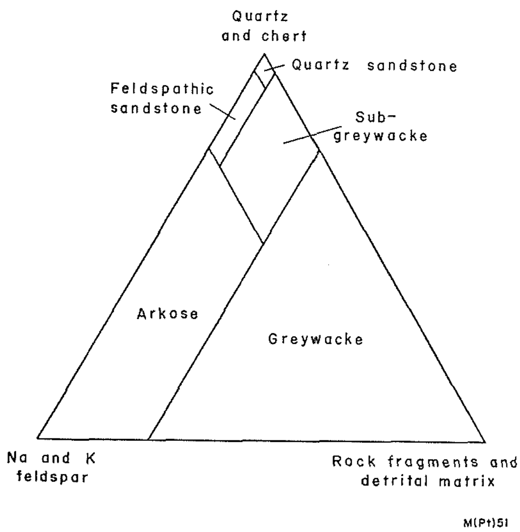

Figure 13. Classifications of sandstones

Bedding (stratification) of the sediments is described according to the present system:

Laminated	Beds up to 0.5 inch thick
Thin-bedded	Beds between 0.5 inch and 4 inches thick
Thick-bedded	Beds between 4 and 36 inches thick
Massive	Beds over 36 inches thick

The type of outcrop is an important characteristic of many of the sedimentary rocks and the following terms have been used to describe the parting intervals:

Platy	Partings up to 0.5 inch apart
Flaggy	Partings between 0.5 and 6 inches apart
Blocky	Partings between 6 and 36 inches apart
Massive	Partings over 36 inches apart

Halls Creek Group

The rocks of the Halls Creek Group are the oldest known in the map area. The name was first used by Matheson & Guppy (1949) who divided the basement rocks into the Halls Creek Group (metasediments and volcanics); the McClintock Greenstones (mainly basic lavas); and the Lamboo Complex, which they defined as an essentially granitic complex containing sedimentary relicts. Traves (1955) could not differentiate between the Halls Creek Group and the McClintock Greenstone; he included both units in the Halls Creek Metamorphics, which he defined as including all the metamorphics in the vicinity of Halls Creek and in isolated areas to the north-northeast. Because many of the sediments are little altered we have retained Matheson & Guppy's term Halls Creek Group.

Definition

Constituent Formations and Lithology: Olympio Formation (uppermost unit), turbidite sequence of alternating greywacke and siltstone; *Biscay Formation,* tuffaceous greywacke and siltstone; intercalated basalt and dolerite; *Saunders Creek Formation,* thin unit comprising quartz sandstone, quartz conglomerate, and arkosic sediments: *Ding Dong Volcanics,* basic volcanics and intrusives; minor acidic igneous and marine sedimentary rocks.

Distribution: Crops out as north-northeasterly belt from Cummins Range to Frank River, and as small inliers northwards to limit of map area; also small inliers northwards of Halls Creek.

Derivation of Name: From Halls Creek township.

Stratigraphic Relationships: Overlain unconformably by Whitewater Volcanics at base of Carpentarian sedimentary rocks; intruded by Proterozoic granite and basic rocks; bottom not exposed.

Thickness: Unknown; probably about 20,000 feet.

Age: Probably Archaean; believed to be unmetamorphosed equivalent of Tickalara Metamorphics, which have been dated as 1,960 m.y.

Ding Dong Downs Volcanics

Definition

Lithology: Basic volcanic rocks and minor intercalated sediments metamorphosed to low greenschist facies; subordinate fine-grained acidic rocks in succession may be volcanic or intrusive.

Distribution: Only in core of Saunders Creek Dome 20 miles east-northeast of Halls Creek, and in Cummins Range near southern extremity of map area.

Derivation of Name: Named Ding Dong Downs Formation by J. W. Smith after Ding Dong Downs Bore (18°02'S., 127°58'E.) As the formation is composed predominantly of volcanic rocks, we prefer the name Ding Dong Downs Volcanics.

Type Area: Area of outcrop in core of Saunders Creek Dome (18°08'S, 127°57'E.). No type section measured because formation is tightly folded and poorly exposed.

Stratigraphic Relationships: Comformably overlain by Saunders Creek Formation; boundary marked by abrupt change from volcanic rocks to quartz sandstone and conglomerate of Saunders Creek Formation; bottom not exposed.

Thickness: Not known.

Age: Early Proterozoic or Archaean.

Description

The Ding Dong Downs Volcanics consist largely of epidotized basalt. The basalt is fine-grained, of a distinctive light green colour, and in places has abundant near-spherical amygdales filled with quartz, calcite, and zeolite(?). Native copper was found near Saunders Creek uranium prospect as small crystals and aggregates in the amygdales, and thin veins of quartz and native copper have been reported from this locality (J. Carruthers, pers. comm.). The rock has a granoblastic texture, and is composed mostly of pale yellow epidote, subordinate randomly oriented actinolite, and cavity-filling calcite. Magnetite occurs as scattered crystals larger than the matrix, and a few small crystals of pyrite are present. Fine-grained basic crystal tuffs, some with relict agglomerate texture, are interbedded with the basalt.

Fine-grained acid igneous rocks constitute only a small proportion of the formation, but some occur as persistent bands which can be traced for several miles. The bands are rarely more than 50 feet thick and are mostly very fine-grained; it is not known whether they are volcanic or intrusive. Only one thin section of the rhyolite was examined. It consists of phenocrysts of microcline, partly or wholly replaced by albite, set in a fine-grained groundmass of quartz, sericite, feldspar, biotite, and chlorite. A little calcite, iron oxide, epidote, and zircon are present, and the rock commonly contains scattered octahedra of magnetite. Some of these acid rocks are probably volcanic, but some of the more massive outcrops could be intrusive, and could therefore be the same age as rhyolite porphyry intruding the Biscay Formation to the northwest. Pods of coarse crystalline calcite occur on the upper boundary of the rhyolite.

Metamorphosed sedimentary rocks are interbedded with the volcanic rocks: they include carbonaceous phyllite, quartz-sericite schist, epidotized quartz-muscovite schist, and quartz-biotite schist; sheared and recrystallized rocks, which appear to have been originally tuffaceous greywacke, are associated with the basic volcanics. All these rocks appear to have been affected by a period of later thermal metamorphism, and in places the original schistosity has been partly destroyed by the formation of randomly oriented biotite.

No pillow structures were seen in the basalt and some of the volcanics could have been laid down subaerially, but the presence of interbedded sedimentary rocks indicates that most of them were laid down under water.

Saunders Creek Formation

Definition

Lithology: Indurated quartz sandstone, quartz conglomerate, and feldspathic sandstone.

Distribution: Crops out northeast of Halls Creek around Saunders Creek Dome, and on northern margin of Sophie Downs Granite; also in Cummins Range.

Derivation of Name: Named by Ruker (1961) after Saunders Creek, 20 miles northeast of Halls Creek (180°00'S., 128°03'E.). He included greywacke and subgreywacke which J. W. Smith put in the overlying Biscay Formation.

Type Area: Saunders Creek Dome, 20 miles northeast of Halls Creek.

Type Section: 1½ miles southwest of Bulman Waterhole (18°07'S., 127°56'E.).

Stratigraphic Relationships: Conformable between Ding Dong Downs Volcanics and Biscay Formation. Lower boundary sharp; upper boundary arbitrarily placed, in 200-foot transitional zone, where greywacke (Biscay Formation) becomes preponderant.

Thickness: 640 feet in type section; thins rapidly to west, and north of Sophie Downs Granite, only 50 to 100 feet thick.

Age: Early Proterozoic or Archaean.

Description

The section measured by pacing in the type area is given in Table 5.

West and southwest of Bulman Waterhole quartz conglomerate occurs near the base of the unit as beds between 1 and 5 feet thick. The conglomerate consists of rounded to subangular fragments of quartz and rhyolite in a fine-grained quartz matrix; it contains a high proportion of radioactive heavy minerals. The sandstone is medium to coarse-grained, and almost invariably cross-bedded; it is composed of quartz, which has been mostly recrystallized to a fine-grained mosaic, minor feldspar, calcite, rock fragments, and a little magnetite, biotite, glauconite, muscovite, and zircon. The glauconite was identified by X-ray powder photography; it occurs as rounded grains, some of which partly replace feldspar. In places, the quartz sandstone grades into feldspathic sandstone.

The rapid lateral changes in lithology and thickness, and the ubiquitous cross-bedding, show that the Saunders Creek Formation was laid down in shallow water. It was laid down during a pause in the vulcanism between the eruption of the Ding Dong Downs Volcanics and the Biscay Formation.

TABLE 5. TYPE SECTION OF SAUNDERS CREEK FORMATION

	Thickness (ft)	Description
		Biscay Formation (greywacke, subgreywacke, minor quartz sandstone and shale).
		Gradational contact
	180	*Quartz sandstone,* thinly bedded, grey, fine-grained; composed of well rounded quartz grains and a little sericitic matrix. Upper part: *quartz sandstone,* thinly bedded, fine-grained; interbedded with subordinate *greywacke,* dark grey to dark blue, fine-grained.
	135	*Subgreywacke,* thinly bedded, dark blue, fine-grained; composed of well rounded quartz grains in sericitic matrix.
	5	*Quartz sandstone,* massive, cross-bedded, dark blue, fine-grained; cross-bedding shown by layers of black heavy minerals.
	70	*Greywacke,* thinly bedded, dark blue, fine-grained
	150	*Quartz sandstone,* thinly bedded, medium-grained to fine-grained, blue-grey; grading into *subgreywacke;* cross-bedding common. Upper part: mainly *greywacke,* thinly bedded, blue.
	100	*Quartz sandstone,* thinly bedded, medium-grained, white; a little sericitic matrix; some cross-bedding.
		Conformable contact
		Ding Dong Downs Volcanics (amygdaloidal basalt).
Total	640	

Biscay Formation

Definition

Lithology: Basic volcanic and intrusive rocks with intercalated sediments; generally metamorphosed to low greenschist facies.

Distribution: Crops out northeast of Halls Creek in core of Biscay Anticlinorium, and south of Halls Creek in core of same anticlinorium (?) displaced southwards by Halls Creek Fault; also in area immediately north of Halls Creek.

Derivation of Name: Named by J. W. Smith after Bay of Biscay Hills in middle reaches of Panton River about 30 miles northeast of Halls Creek (17°48'S., 128°05'E.).

Type Area: Core of Biscay Anticlinorium to north of Saunders Creek and Sophie Downs Domes.

Stratigraphical Relationship: Conformable between the Saunders Creek Formation and Olympio Formation. Upper boundary defined as top of highest basalt or dolomite bed; where dolerite intrudes contact boundary arbitrarily placed at top of uppermost extensive sill.

Thickness: Thickness not measured because formation isoclinally folded; appears to be 5,000 to 10,000 feet.

Age: Early Proterozoic or Archaean.

Description

The Biscay Formation has been metamorphosed and the rocks belong to the greenschist facies of regional metamorphism. The formation consists of recrystallized basalt and dolerite, commonly highly carbonated, schistose greywacke and siltstone, dolomite, muscovite and biotite schists, and calc-silicate rocks. Basalt and dolerite predominate. It is generally impossible to tell whether the fine-grained basic rocks are extrusive or intrusive: pillow lavas are found in Woodward Creek, but undoubted intrusives have also been seen. Fine-grained acid igneous rocks occur throughout the formation: most of them appear to be intrusive and have been dated as 1,540 m.y. old, by the Rb/Sr method, but others could be extrusive and therefore part of the Biscay Formation.

The formation is isoclinally folded, and the detailed stratigraphical succession has not been established. However, as the isoclinal folds are not of great amplitude, and as the broad pattern of the folding is fairly simple (see p. 49), four broad stratigraphic units can be distinguished:

(1) A basal unit composed predominantly of tuffaceous greywacke, siltstone, and shale with some basalt and dolerite. One thick bed of shale is predominantly carbonaceous. The more highly metamorphosed part of the unit consists of biotite schist, carbonaceous schist, and amphibolite.

(2) A thin zone of flaggy dolomite with bands of chert which grades laterally into banded jaspilite. The dolomite is commonly overlain by pyritic carbonaceous shale and siltstone which crop out as a limonitic gossan; the pyritic sediments are generally associated with fine-grained acid igneous rocks which are probably intrusive. The fine-grained micaceous quartzite and light grey subgreywacke between the Sophie Downs and Saunders Creek Domes probably belong to this horizon.

(3) A thick unit comprising tuffaceous greywacke interbedded with shale, basalt (some with pillow structures), and dolerite. Pods of carbonate, ranging from inches to hundreds of feet long, are common.

(4) The uppermost unit is a diffuse zone of carbonate-rich rocks which grade from pure dolomite or calc-silicate rocks, such as those found near Duffers mine and south of Sophie Downs Dome, to highly carbonated basalt and dolerite containing pods of dolomite up to a mile long and hundreds of feet wide. Most of the carbonate appears to be secondary and even the large dolomite bands could be intrusive, but the zone is stratigraphic, and the unit probably had a high carbonate content when it was deposited.

The top of the Biscay Formation is defined as the top of the dolomite or the carbonated basic rocks. Almost all the gold mines in the Halls Creek Goldfield are confined to the top of the Biscay Formation or the basal part of the Olympio Formation, and most of them are associated with a large dolerite sill which intrudes the contact.

The least metamorphosed basic volcanics in the Biscay Formation are dark green, fine-grained, and in some cases, porphyritic. They are completely recrystallized and few primary features have been preserved. Plagioclase is pseudomorphed by sericite, kaolin, and clinozoisite or epidote, and the ferromagnesian minerals by small tremolite laths or chlorite and epidote. Quartz is a minor constituent, and ilmenite has been replaced by leucoxene. In some of the basic intrusives relict subophitic or allotriomorphic granular textures can be discerned; the lath-like andesine has been replaced by fine-grained aggregates of epidote; the secondary hornblende is idioblastic to xenoblastic, and the grains are fractured and replaced by biotite. In the subophitic rocks the groundmass consists of fine-grained quartz and ragged feldspar.

Acid igneous rocks are common in the Biscay Formation. Most of them are intrusive (Gemuts, 1969), but some could be extrusive. They consist mainly of rhyolite, which is commonly porphyritic, and are composed of phenocrysts of quartz and feldspar and fine-grained granular quartz and orthoclase, with subordinate plagioclase and rare biotite. Where plagioclase predominates the rocks are classed as dacite.

Tuffaceous greywacke, greywacke, and shale are intercalated with volcanic rocks throughout most of the Biscay Formation, and in places they are predominant. They are all recrystallized to some extent, and are generally highly sheared. The least altered comprise well bedded green schistose greywacke and tuffaceous greywacke, and interbedded green and grey phyllite.

As the metamorphic grade increases, the rocks grade into grey to dark brown incipiently crenulated schists. The following mineral assemblages have been noted: quartz-biotite-chlorite, quartz-muscovite-biotite, and quartz-plagioclase-biotite-muscovite.

The rocks have a well developed preferred orientation, defined by small laths of muscovite and red-brown biotite; quartz has lost its sedimentary form and occurs as polygonal sutured grains; plagioclase and orthoclase occur in minor amounts, and a little sphene, tourmaline, and apatite are commonly present.

The schists were probably derived from shale and greywacke, and they grade into dark green chlorite schist and massive tremolite-rich rocks which were probably derived from marl and calcareous greywacke.

To the east of the Halls Creek Fault, the uppermost part of the Biscay Formation is composed of carbonate-rich rocks which range from almost pure dolomites and marble to calc-silicate rocks.

Quartz-calcite-chlorite schist, intercalated with tremolite-rich and epidote-rich calc-silicate rocks, are predominant. The tremolite-rich rocks consist of prismatic crystals or rosettes of tremolite, calcite, and smaller grains of chlorite and muscovite. In the more massive rocks, detrital quartz grains can still be discerned. The epidote-rich rocks consist of decussate aggregates of chlorite and zoisite, irregular sphene, and scapolite containing minute poikiloblastic crystals of green spinel.

Dolomite is common, and in places it is coloured black by manganese, or red and brown by limonite and hematite; most of it is brown to white. It consists of twinned and distorted carbonate crystals enclosing poorly sorted and sutured grains of quartz, tiny grains of graphite, quartz, muscovite, and prismatic crystals and rosettes of tremolite. In some sections the coarse-grained aggregates are surrounded by fine-grained calcite which may be an indication of tectonic brecciation.

Olympio Formation

Definition

Lithology: Monotonous sequence of subgreywacke interbedded with siltstone, shale, and subordinate feldspathic greywacke, arkose, pebble conglomerate, quartz sandstone, and rare dolomite; metamorphosed to low greenschist facies in southwestern part of map area.

Distribution: East of Halls Creek Fault, wide belt between Ruby Plains homestead and Osmond Range; west of fault, between Halls Creek and Cummins Range in southwestern part of map area. In the small inlier in the headwaters of the Osmond River the eastern part consists of almost unaltered subgreywacke which grades by increasing contact metamorphism into high-grade schist in the west.

Derivation of Name: Named Olympio Creek Formation by Ruker (1961) after Olympio Creek, 22 miles north-northeast of Halls Creek.

Type Area: Middle reaches of Panton River, north of Saunders Creek area. No type section measured.

Stratigraphic Relationships: Conformably overlies Biscay Formation and unconformably overlain by Whitewater Volcanics.
Thickness: Probably at least 12,000 feet.
Age: Early Proterozoic or Archaean.

Description

The Olympio Formation is a monotonous sequence of subgreywacke and siltstone which is probably at least 12,000 feet thick. It has not been subdivided because it generally lacks marker beds and is tightly folded. Near the top there is some variation in lithology, and it may be possible to distinguish two units by more detailed mapping:

(1) In the upper part of the formation there is about 2,000 feet of massive coarse-grained subgreywacke and conglomerate with only a small proportion of shale. There is, however, considerable lateral variation, and shale beds up to 20 feet thick are present in places.

(2) Shale is predominant near the top of the formation, and beds up to 300 feet thick were seen.

The bulk of the Olympio Formation consists of a succession of interbedded subgreywacke and siltstone, the relative proportions of which vary considerably vertically, and probably also laterally. The subgreywacke ranges from fine to coarse-grained but is predominantly medium-grained. The coarser beds are mostly subgreywacke or greywacke, but arkose, and more rarely quartz sandstone, are locally important. A few lenses of quartz-pebble conglomerate and dolomite are present.

The arenaceous beds are generally between 1 and 4 feet thick, and are mostly light-coloured; they alternate with subordinate dark-coloured shale and siltstone. Beds of greywacke up to 6 feet thick are common, and some are up to 20 feet thick. Graded bedding is common in the greywacke, and flow casts are common at the base of the coarser varieties; cross-bedding and ripple marks are rare. Laminate or thin-bedding are common in the shale, but in most outcrops the original structures have been obliterated by cleavage and schistosity (Pl. 5).

The subgreywacke is composed of subangular to subrounded grains of quartz (30-50%), feldspar, fine-grained volcanic fragments, and chert, chaotically distributed in a fine-grained matrix of sericite, chlorite, and quartz. There is little sorting except in the quartz-rich varieties, which contain more rounded grains and less matrix. The subgreywacke grades with increasing matrix into dark green to blue unsorted greywacke composed of poorly rounded to angular fragments. Many of the rocks can be classified as arkose and subarkose which are composed of quartz, plagioclase, minor potash feldspar, and rare rock fragments set in a matrix of sericite and chlorite. They are poorly sorted and those with abundant matrix are classed as feldspathic greywacke. A little tourmaline, zircon, sphene, and iron oxide are generally present.

The conglomerate is generally composed mainly of rather poorly sorted rounded to subrounded pebbles of quartz, with subordinate jasper, chert, fine-grained dolerite, feldspar, and shale set in an arkose or greywacke matrix. The shale and siltstone are grey, blue-green, or dark blue, and are commonly phyllitic. The beds of shale in the upper part of the formation are mostly purple or red in outcrop.

In the inlier of the Olympio Formation in the head of Osmond Creek, the rocks in the eastern part comprise slightly recrystallized greywacke, sericite schist, and marble, but in the west they have been intruded by granite and metamorphosed to muscovite-sillimanite schist. The rocks on the western side of the inlier dip almost vertically to the south and west, and it was originally thought that they were folded into an anticline which plunged south at nearly 90°. However, the graded bedding in the less metamorphosed rocks to the east indicates that the top of the succession lies to the north. The thickness of the sequence described in Table 6 was estimated from the air-photographs.

TABLE 6. OLYMPIO FORMATION, HEAD OF OSMOND CREEK

	Thickness (ft)	Description
		(Quartz sandstone and quartz pebble conglomerate).
		Unconformity
	3,000	*Marble* (about 50%), green or cream, rarely pink, fine-grained, invariably laminated; rare laminae replaced by dolomite or chert; beds 6 to 12 feet thick; interbedded with *sericite schist* (about 50%), fine-grained, massive, with rare interbeds of *subgreywacke,* laminated; beds up to 2 feet thick.
	800	*Quartz-sericite schist,* fine-grained; with rare graded beds of *quartz greywacke,* up to 4 feet thick.
	2,000	*Subgreywacke,* thick-bedded, medium-grained to coarse-grained; consists of rounded grains of quartz and minor feldspar in recrystallized chloritic or sericitic matrix; rare graded bedding, interbedded with up to 20 percent of *phyllite and sericite schist,* fine-grained; massive beds up to 3 feet thick.
	1,800	*Greywacke,* laminated and thin-bedded, green; composed of subangular quartz and muscovite grains in fine-grained chloritic matrix. Many large dykes of *uralitized gabbro.*
Total	7,600	
		Osmond Fault

The beds are only slightly metamorphosed and are extensively intruded by gabbro, but they can confidently be referred to the Olympio Formation which crops out 12 miles to the south.

The arenaceous beds consist mainly of schistose subgreywacke composed predominantly of embayed quartz, minor altered feldspar, and some muscovite, set in a matrix of sericite, chlorite, and more rarely carbonate. A few rock fragments and grains of tourmaline, zircon, and ironstained leucoxene are generally present. With a decrease in the proportion of matrix the rock grades into quartz sandstone.

Metamorphism of the Olympio Formation. Almost all the finer-grained beds have an axial-plane cleavage; the cleavage may not be apparent in fresh exposures, but it causes the rock to weather into blade-shaped fragments (Pl. 5). East of the Frank River, the shale has a marked lineation parallel to the steeply dipping fold axes and the outcrops consist of tightly packed angular rods of shale.

North of Saunders Creek, the Oympio Formation has been only slightly recrystallized: the matrix has generally been reconstituted to sericite and chlorite, but the large detrital grains show only slight marginal corrosion. The degree of reconstitution of the matrix could have been caused by diagenetic processes alone.

In the Gordon Downs Sheet area, the rocks have been regionally metamorphosed to low greenschist facies. The matrix has a slight foliation and much of it has been recrystallized to muscovite. The larger detrital grains are considerably corroded, or sutured where they are in contact, and commonly contain flakes of chlorite near their margins. Both thin sections examined represent the biotite grade in which the matrix has been completely reconstituted to muscovite and biotite.

Undifferentiated Halls Creek Group

The schist and quartzite cropping out in the southeastern corner of the map area are overlain unconformably by the Proterozoic Gardiner Formation, and have been mapped as undifferentiated Halls Creek Group. The following assemblages, which are higher in grade than general, have been noted: quartz-muscovite-chlorite, quartz-muscovite-hematite, and quartz-diopside-cordierite-microcline.

The first assemblage is represented by a schistose rock in which lepidoblastic flakes of muscovite are interfoliated with polygonal xenoblastic grains of quartz. The subordinate patches of sericite and muscovite may represent retrogressed aluminium silicates.

The second and third assemblages are represented by granular quartzites. In the second, idioblastic hematite is interbanded with xenoblastic quartz and rare ragged flakes of muscovite. In the third, idioblastic diopside is set in a xenoblastic granular quartz-rich base. Moderate amounts of cordierite and potash feldspar are set in sericite-rich cavities and may represent the original argillaceous matrix. A little clinozoisite, amphibole, and sphene are present.

Four miles northwest of the junction of the Ord and Negri Rivers there is an inlier of tightly folded greywacke, subgreywacke, shale, and minor dolomite, similar to the Olympio Formation in the Ord River 50 miles to the southwest. The greywacke and subgreywacke are green to dark grey, medium to coarse-grained, and consist of rounded to subangular grains of quartz and feldspar set in a green chloritic matrix. It grades into quartz-pebble conglomerate, and commonly occurs as regular beds, between 2 and 6 feet thick, in which cross-bedding can sometimes be distinguished, with interbeds of siltstone and shale from 1 to 2 feet thick. The siltstone and shale are black, or rarely green and red, and are generally laminated. Dolomite crops out in the southwestern part of the inlier as beds up to 20 feet thick.

The sediments are commonly intruded by dykes of altered gabbro, especially along a shear zone south of the Ord River. Close to the dykes the greywacke has been recrystallized to hornfels. The finer-grained rocks have been changed to phyllite.

To the north, inliers of undifferentiated Halls Creek Group crop out in the Carr Boyd Ranges, where they are unconformably overlain by the Carr Boyd succession and Revolver Creek Formation. They cannot be directly correlated with the formations in the south.

Tightly folded khaki slate and grey medium-grained feldspathic greywacke crop out *6 miles north-northeast of Mount Nyuless.* The beds are folded along axes with a very shallow plunge, and are overlain with marked angular unconformity by the Revolver Creek Formation and are intruded by Bow River Granite. The contact metamorphic aureole surrounding the granite is only 3 to 4 inches wide.

The low-grade metamorphics in the *upper Revolver Creek area* consist of subgreywacke, fine-grained feldspathic greywacke, green, grey, and red slate, sericite schist, and minor acid tuff(?). The beds are tightly folded along southerly plunging axes and are unconformably overlain by the Revolver Creek Formation

To the *east and north of Mount Hensman,* beds of red slate, quartzite, subgreywacke, and mica schist are intruded by small uralitized dolerite dykes.

In the vertical subgreywacke and minor thin beds of phyllite near the *'Ord Damsite road'* the bedding has been transposed into lenticular wedges parallel to the cleavage. They are intruded by the Bow River Granite which has a metamorphic aureole, up to 1,000 feet wide, of spotted poikiloblastic cordierite-biotite schist.

Farther north, near *Fine Springs,* a sequence of red slate, phyllite, minor subgreywacke, and a persistent 25-foot bed of conglomerate composed of pebbles and cobbles of chert, dips at about 25° to the north. The conglomerate has a black ferruginous grit at the base. The sediments are intruded by the Bow River Granite and dolerite dykes, and are overlain, probably unconformably, by the Whitewater Volcanics.

Whitewater Volcanics

Definition

Lithology: Porphyritic rhyodacite andesite ashflow tuffs and lavas; volcanic conglomerate, lapilli tuff, and sandstone near top of formation.

Distribution: Flanking Lamboo Complex from Leopold River in southwest to near Dunham River homestead in northeast; also on margins of inliers of Bow River Granite in Carr Boyd Range.

Derivation of Name: J. W. Smith named Whitewater Formation after Whitewater Well (127°33'E., 17°37'S.), but as acid volcanics predominate we prefer the name Whitewater Volcanics.

Type Area: Broad anticline north of Mount Remarkable (127°38'E., 17°12'S.). No type section measured.

Stratigraphic Relationships: Unconformably overlain by Speewah and Carr Boyd Groups; in places rest with strong angular unconformity on Halls Creek Group; intruded by Castlereagh Hill Porphyry, with which they are probably comagmatic, and by Bow River Granite.

Thickness: Apparently about 2,000 feet thick in type area and up to 9,000 feet thick to southwest (from air-photographs).

Age: Basal Carpentarian. Rb/Sr 1,823±17 m.y.

Description

The most abundant rock types in the Whitewater Volcanics are massive, red-brown, or light green volcanics ranging from porphyritic rhyodacite to porphyritic andesite. They rarely exhibit any internal structure, and are probably ashflow tuffs. The formation also includes subordinate volcanic conglomerate, siltstone, sandstone, and a little lapilli tuff and agglomerate. In the lower part of the formation, massive intermediate rocks, some of which are coarser in grain and contain phenocrysts of feldspar, amphibole, and pyroxene, predominate. No tuffaceous textures have been seen in these rocks, and it is uncertain whether they are extrusive volcanics.

The volcanics are commonly massive and structureless, and consist of phenocrysts of white and blue quartz and pink feldspar set in a dark cryptocrystalline siliceous groundmass speckled with tiny phenocrysts of quartz and feldspar. The blebs of chlorite, which are generally present, probably represent altered biotite or other mafic minerals. Flow layering is prominent on some weathered surfaces, and is outlined by parallel or subparallel lenticles of fine-grained material. In thin section, the rock consists of euhedral to subhedral phenocrysts of bipyramidal quartz and euhedral zoned crystals of plagioclase set in a cryptocrystalline groundmass of ragged feldspar, quartz, chlorite, and devitrified glass. The plagioclase ranges from albite to oligoclase and is invariably sericitized and embayed; it is commonly replaced by granular epidote. Some of the coarser rocks may be intrusive; the potash feldspar generally occurs in aggregates in association with quartz, and chlorite commonly pseudomorphs amphibole, and less commonly pyroxene.

The original texture of the volcanics has generally been destroyed by recrystallization. Glass shards are seldom recognizable, but most of the volcanics contain small elongate splinters and angular fragments of quartz and feldspar which indicate a tuffaceous origin. Most of the flows are massive, uniformly fine-grained, and very extensive; these characteristics suggest that they are ashflow tuffs.

Traves (1955) noted welded tuffs within the Whitewater Volcanics, and one thin section we examined consists of dark lenticular shards and angular fragments set in a fine-grained siliceous matrix. Fractured quartz, albite, and potash feldspar are distributed randomly throughout the rock, and flow layers or compaction bands are defined by the shards and by recrystallized bands. A. F. Trendall (Geol. Surv. W. Aust., pers. comm.) has described other aphanitic rocks from the region: 'Variations of grainsize within this mosaic define the outlines and internal structure of bands, and contorted fragments vary in size from about 2 mm. down to the smallest. Subhedral feldspars are enclosed within this matrix. The shapes and stratified arrangements of the fragments strongly suggest volcanic detritus, and there is little doubt that these rocks are thoroughly welded.'

Gellatly et al. (1965) have described the Whitewater Volcanics as follows: 'Because of the high percentage of matrix of indefinite mineralogy, the petrological classification of the Whitewater rocks is uncertain. Based on relative percentage of the various xenocrysts and phenocrysts they appear to range from rhyodacite to andesite. The majority are probably dacites.'

Lenses of volcanic conglomerate, agglomerate, sandstone, and minor siltstone and chert, occur in the upper part of the Whitewater Volcanics, particularly in the interval between 600 and 1,000 feet stratigraphically below the top of the formation. They crop out along the eastern side of the Lamboo Complex and rest on the lower part of the formation with slight erosional unconformity; they are conformably overlain by the upper part. The sedimentary and pyroclastic lenses crop out as a prominent strike ridge, which can be recognized on the air-photographs by the denser growth of stunted eucalypts. A typical section is given in Table 7.

TABLE 7. TYPICAL SECTION OF SEDIMENTARY ROCKS IN WHITE-WATER VOLCANICS

	Thickness (ft)	Description
		(Rhyolite).
		Conformable contact
	30	*Chert,* green to white, banded.
	10	*Chert breccia or agglomerate,* green, poorly sorted; composed of pebbles of chert and fragments of quartz and feldspar set in siliceous matrix.
	400	*Volcanolithic greywacke,* grey, coarse-grained, poorly sorted; contains angular to rounded fragments of chert and jasper, euhedral feldspar, quartz, and unidentified ferromagnesian minerals; matrix chloritic and commonly highly sheared. To the west, the greywacke grades into *boulder conglomerate,* dark; composed of rounded and angular boulders rhyolite in greywacke matrix.
		Erosional unconformity
Total	440	(Acid volcanics).

Red Rock Beds

Definition

Lithology: Mostly shallow-water quartz sandstone and quartz-pebble conglomerate which, in places, show extreme lateral variation.

Distribution: Well developed in type area at head of Red Rock Creek and in head of Osmond Creek. East of Halls Creek Fault, between Frank and Bow Rivers, are broken into many steeply dipping fault wedges.

Derivation of Name: From Red Rock Creek, a tributary of Osmond Creek.

Type Area: Head of Red Rock Creek where type section was measured (17°20′S., 128°18′E.).

Stratigraphical Relationships: Unconformable between Olympic Formation and Mount Parker Sandstone. Regarded as correlatives of Carr Boyd Group to north, Speewah Group to west, and Moola Bulla Formation to southwest.

Thickness: 6,000 feet measured on air-photographs in type section.

Age: Almost certainly Carpentarian.

Description

The Red Rock Beds are mostly arenaceous shallow-water sediments. In places, they show extreme lateral variation, particularly in the lower part of the unit; for this reason, and because they are generally much faulted, the beds have not been subdivided.

The lowermost part of the type section comprises about 1,500 feet of indurated quartz grit and quartz conglomerate. The grit is purple to grey, and is composed of poorly sorted angular to subrounded grains of quartz and a few scattered quartz pebbles. It is massive in outcrop, but the thin bedding is generally visible in good exposures. Cross-bedding and ripple marks are common. The sandstone grades into quartz conglomerate composed of rounded to subangular pebbles and cobbles of quartz, quartzite, and chert set in a coarse-grained grit matrix. Quartz-jasper conglomerate is common near the base of the sequence. It is composed of rounded to subangular pebbles of quartz and angular fragments of jasper set in a medium-grained orthoquartzite matrix.

In the type area, these beds are overlain by about 4,500 feet of laminated and thin-bedded orthoquartzite with rare interbeds of grit and quartz conglomerate. The orthoquartzite is white, pink, or rarely red, and is composed of well sorted rounded quartz grains with varying proportions of siliceous matrix. Rare ripple marks, cross-bedding, slump structures, and pebble casts are seen throughout the sequence.

In the head of Osmond Creek, the Red Rock Beds comprise about 600 feet of sandstone, conglomerate, and siltstone overlying the Oympio Formation and McHale Granite. A notable feature of the beds is the marked lateral variation, and in places, coarse boulder conglomerate grades into siltstone over a distance of less than a mile.

Fine-grained purple to red micaceous sandstone and interbedded red micaceous siltstone predominate in this region. The sandstone is laminated and has a platy outcrop; it is composed of well sorted and well rounded quartz grains set in a ferruginous, argillaceous matrix. The proportion of matrix ranges from almost nil to about 30 percent; in places it is highly ferruginous. Cross-bedded conglomerate is common throughout the succession and is predominant near the base. It generally consists of unsorted angular to rounded pebbles or cobbles of quartz, quartzite, and rare schist set in a quartz grit matrix. The basal beds overlying the granite are arkose or arkose conglomerate. One prominent conglomerate, about 200 feet above the base, is composed of tightly packed well rounded boulders of pink and white quartzite from 2 to 3 feet across set in a quartz sandstone matrix.

Near the Halls Creek Fault the Red Rock Beds are cut by numerous faults, and they are generally steeply dipping or tightly folded. They are also intruded by the Fish Hole Dolerite, and it is not possible to establish the succession. The best exposure, 6 miles south of Killarney Bore, was measured by Abney level. The section is given in Table 8.

TABLE 8. SECTION OF RED ROCK BEDS, SOUTH OF KILLARNEY BORE

	Thickness (ft)	Description
		Fault
	850	*Quartz sandstone,* flaggy to thinly flaggy, commonly laminated, pink or rarely white, fine-grained to medium-grained, well sorted; consists of well rounded grains of quartz and small amounts of siliceous or argillaceous matrix; ranges from highly indurated to almost friable; cross-bedding rare.
	100	*Micaceous quartz sandstone,* red and purple, fine-grained; and *micaceous siltstone,* red, flaggy to platy; rare beds contain pebble casts; some quartz grit.
	110	*Micaceous quartz sandstone,* red and purple, medium-grained, poorly sorted; contains a little ferruginous matrix; massive to blocky towards top, flaggy to platy below; generally laminated, but rarely cross-bedded.
	550	*Dolerite,* weathered; purple and brown.
	25	*Quartz sandstone,* massive, white, coarse-grained; contains scattered pebbles of quartz; some cross-bedding.
	20	*Dolerite,* brown, weathered.
	20	*Quartz sandstone,* massive, white, highly indurated.
		Angular unconformity
Total	1,675	
		McHale Granite intruding greywacke and dolomite of *Olympio Formation.*

The Red Rock Beds are about 6,000 feet thick and were laid down in shallow water, probably near the shore. Faulting took place during deposition (see p. 57) and has profoundly influenced sedimentation.

Because of their stratigraphical position, and their similar mode of deposition, the Red Rock Beds are believed to be correlatives of the Speewah Group and Moola Bulla Formation.

Moola Bulla Formation

Definition

Lithology: Upper and lower sequences of arkosic sandstone and quartz conglomerate separated by a prominent member of alternating greywacke and siltstone.

Distribution: Confined to two fault wedges west of Halls Creek Fault between Koongie Park homestead and Duffers mine.

Derivation of Name: Named by J. W. Smith after Moola Bulla homestead, about 11 miles west of Halls Creek (18°15′S., 127°40′E.).

Type Area: Fault wedge between Koongie Park and Sophie Downs homesteads. Type section measured where Halls Creek/Nicholson road crosses formation (about 18°15′S., 127°43′E.).

Stratigraphical Relationships: Unconformably overlies Olympio Formation; upper limits not known. Similar to Speewah Group, and to a lesser degree Red Rock Beds, with which it is correlated.

Thickness: At least 10,000 feet thick as measured on air-photographs.

Age: Probably Carpentarian.

Description

The Moola Bulla Formation consists of two thick sequences of cross-bedded feldspathic sandstone separated by interbedded greywacke and siltstone, and overlain by green siltstone and shale with thin interbeds of sandstone and greywacke.

The basal unit is about 4,500 feet thick and consists almost entirely of arkosic sandstone. It is commonly almost friable, and weathers cavernously to give a conspicuous hummocky outcrop with only a few scattered clumps of spinifex and rare stunted gums. The sandstone is blocky to massive, and cross-bedding is ubiquitous; it is greenish cream, predominantly coarse-grained, and composed of quartz, subordinate feldspar, and rare chert grains set in a kaolinitic or sericitic matrix. The proportions of these minerals vary randomly both laterally and vertically, and in some of the finer-grained varieties the matrix is predominant. The grains are generally poorly sorted and are angular to subangular; in the finer varieties they are subrounded.

In a few places, arkosic sandstone grades into quartz-pebble conglomerate or laminated pink or purple phyllitic siltstone.

The arkosic sandstone is overlain by about 1,900 feet of alternating greywacke and subordinate phyllitic siltstone. In contrast with the arkose, it forms subdued rounded hills covered with spinifex and scattered gums. The greywacke is medium-grained and green, and is probably composed partly of volcanic detritus. It occurs as beds from 2 to 3 feet thick, with interbeds of green phyllitic siltstone ranging from thin partings to beds up to a foot thick. Graded bedding is common throughout, and a few flow casts are present near the base of the coarser beds. Lenses of quartz-pebble conglomerate are also present near the base of the beds.

The greywacke is overlain by about 1,600 feet of light grey slightly friable feldspathic sandstone, which is similar to the lower unit. It is massive to blocky; cross-bedding is ubiquitous and is commonly picked out by dark stringers of heavy minerals. The greywacke is commonly coarse-grained, and consists of quartz, feldspar, and chert grains set in a sericitic matrix. The matrix rarely exceeds 20 percent of the rock, but in places it grades into subgreywacke. Quartz-pebble conglomerate is more common than in the bottom unit; it consists mainly of well rounded pebbles of quartz and a few fragments of greywacke, schist, and chert, set in a feldspathic sandstone matrix. Towards the top of the unit, where medium-grained quartz sandstone predominates, the sediments are more regularly bedded, finer-grained, and better sorted.

The uppermost beds of the Moola Bulla Formation are green siltstone and shale containing thin beds of greenish cream quartz sandstone and subgreywacke. The sequence is poorly exposed and was not examined in detail, but it is probably about 2,000 feet thick.

Most of the Moola Bulla Formation was laid down during a period of mild tectonism, in a predominantly shallow-water environment close to a granitic and metamorphic terrain composed of the Lamboo Complex and Halls Creek Group. There was a short period of deeper immersion, probably accompanied by distant basic volcanic eruptions, during which the basic greywacke and siltstone were laid down. There followed another period of shallow-water deposition during which the second arkosic unit was laid down. The green siltstone and shale were probably deposited in deeper water during a period of reduced tectonism which allowed greater sorting of the sediments.

Mount Parker Sandstone

Definition

Lithology: Quartz sandstone and minor quartz-pebble conglomerate.

Distribution: Forms large part of Osmond Range; also discontinuous exposures southwards along Albert Edward Range to boundary of map area, and northwards along Halls Creek Fault to near Lissadell homestead.

Derivation of Name: From Mount Parker, highest point in the Osmond Range (17°11'S., 128°18'E.).

Type Area: North of headwaters of Osmond Creek between Mount Parker and Horse Creek. No type section measured.

Stratigraphic Relationships: Unconformably overlies Red Rock Beds and conformably overlain by Bungle Bungle Dolomite; boundaries sharp and unambiguous.

Thickness: Between 500 and 1,000 feet north of Osmond Creek, but much thicker to south.

Age: Probably Adelaidean, but could be as old as Carpentarian.

Description

The Mount Parker Sandstone forms prominent escarpments, and over large areas it is seamed by numerous deep vertical-sided gullies eroded along joints and faults. The middle part of the formation is difficult to reach, and was examined at a few localities only.

The bulk of the formation has a uniform lithology, and consists of pink, salmon, or white, fine to medium-grained quartz sandstone. It is only moderately indurated, and is composed of well rounded and well sorted grains of quartz, generally with only a small proportion of interstitial siliceous material. Near the bottom of the formation, the sandstone contains a few well rounded pebbles of quartz and quartzite lenses of quartz-pebble conglomerate. A little ferruginous quartz sandstone, composed of coarse subangular grains of quartz in a ferruginous matrix, is present.

Most of the bedding consists of foreset beds between 3 inches and 1 foot thick. Smaller-scale cross-bedding and current-ripple marks, with a wavelength of 3 to 6 inches, are common. Towards the top of the formation the sandstone is finer in grain and regularly bedded, and the beds range from half an inch to 3 feet in thickness.

In the southwestern part of Osmond Range, the formation is capped by about 50 feet of flaggy ferruginous quartz sandstone, but in the northern part of the range, the uppermost beds are predominantly silicified dolomite and shale. An incomplete section measured at the head of Horse Creek is given in Table 9.

TABLE 9. SECTION OF MOUNT PARKER SANDSTONE, HEAD OF HORSE CREEK

	Thickness (ft)	Description
		Bungle Bungle Dolomite (platy dolomite and dolomitic siltstone).
		Conformable (?) contact
	30	*Quartz sandstone,* fine-grained, flaggy, indurated; well sorted and well rounded grains set in a little siliceous matrix.
	60	*Silicified dolomite,* massive, red to pink, fine-grained, cherty rock with conchoidal fracture; contains irregular concretionary structures; commonly rolled and slumped; some stromatolites probably present.
	30	*Micaceous shale,* laminated, red; rare thin *sandy beds;* thin beds, nodules, and lenses of *chert* (about 30%), commonly banded grey and pink; some probable mudcracks.
	120	*Quartz sandstone,* regularly bedded, pink or white; blocky to platy and even laminated; thicker beds more common near base; consists of well sorted and well rounded quartz grains with a little siliceous matrix; generally indurated; current ripple marks, with amplitude of 3 inches, not common. One 6-inch bed of *micaceous subgreywacke* with clay matrix stained by patches of malachite.
Total	240	
		Mount Parker Sandstone (cross-bedded quartz sandstone of unknown thickness).

The silicified dolomite probably has greater affinities with the Bungle Bungle Dolomite, but it is resistant to erosion, and its outcrop cannot be distinguished on the air-photographs from the Mount Parker Sandstone. Thus the base of the carbonate rocks has been taken as the bottom of the Bungle Bungle Dolomite.

The Mount Parker Sandstone appears to have been laid down in shallow water as foreset beds on a gently dipping shelf of Red Rock Beds. The attitude of the foreset beds indicates a source to the south; the apparent thickening of the formation in the southern part of the Osmond Range also indicates a southerly provenance.

The overlying units in the Osmond Range were derived from the Halls Creek Mobile Zone and it is possible that the Mount Parker Sandstone was derived from the same source, the sediment being supplied by a large river draining the Mobile

Zone. The Mount Parker Sandstone in the Osmond Range is probably an old delta composed of southerly foreset beds formed by a strong southerly current.

Because most of the bedding is foreset, the thickness of the formation was not measured, but the few dips measured and the width of outcrop on the air-photographs indicate that the thickness is between 500 and 1,000 feet in the northern part of Osmond Range. Exposures are poor at the southern end of the Albert Edward Range, but there seems to be a progressive thinning southwards and on the southern margin of the map area only about 200 feet of sandstone is exposed.

Bungle Bungle Dolomite

Definition

Lithology: Mainly dolomite, dolomitic shale, and minor limestone; quartz sandstone beds, up to 100 feet thick, locally important.

Distribution: Crops out widely in Osmond Range, and as almost continuous belt along Albert Edward Range between Mount Forster and Ruby Plains homestead.

Derivation of Name: From Bungle Bungle outcamp on Turner station near head of Red Rock Creek (17°21'S., 128°21'E.).

Type Area: Southern part of Osmond Range where Osmond Creek cuts through formation. Composite type section measured at four localities in type area.

Stratigraphic Relationship: Conformably overlies Mount Parker Sandstone and overlain unconformably by Wade Creek Sandstone; boundaries sharp and unambiguous.

Thickness: About 4,200 feet in type section, which is truncated by Wade Creek Sandstone; elsewhere, only thinner erosional remnants preserved.

Age: Probably Adelaidean, but could be as old as Carpentarian.

Description

Four incomplete sections of Bungle Bungle Dolomite were measured in the Osmond Range. A generalized composite section is given in Table 10.

TABLE 10. GENERALIZED SECTION OF BUNGLE BUNGLE DOLOMITE

	Thickness (ft)	Description
		Wade Creek Sandstone (clean quartz sandstone).
		Unconformable contact
	230	*Quartz sandstone,* cross-bedded; and minor *dolomitic shale,* thin-bedded.
	700	*Dolomite,* medium-bedded, pink and cream.
	80	*Dolomite and limestone,* thin-bedded, grey.
	530	Upper part: *sandstone,* laminated and thin-bedded, silicified, medium-grained; lower part: *dolomite,* laminated, grey; and *shale,* silicified.
	390	*Dolomite,* laminated and thin-bedded, pink.
	150	*Sandstone,* massive, calcareous; contains lenses of *dolomite.*
	300	*Shale,* thin-bedded and laminated, green; with interbeds of *siltstone,* red and grey, siliceous.
	90	*Limestone breccia,* grey.
	100	*Quartz sandstone,* thin-bedded to medium-bedded, fine-grained; contains minor interbeds of *shale;* ripple marks and load casts common.
	200	*Shale,* thin-bedded, dark; and minor *quartz sandstone.*
	240	*Limestone,* thin-bedded, grey; and minor *calcareous shale,* grey.
	190	*Dolomite,* thin-bedded, pink and cream; with some interbeds of *shale.*
	420	*Dolomite,* thick-bedded, massive, cream, pink, and brown.
	450	*Shale,* thin-bedded, khaki and green; with interbeds of *dolomite,* pink.
		Conformable contact
Total	4,170	
		Mount Parker Sandstone (ferruginous quartz sandstone).

Sandstone interbeds are thinner and less common to the east; some of the thicker sandstone beds can be seen on the air-photographs to thin markedly over a distance of about 10 miles.

The northernmost exposure of the Bungle Bungle Dolomite, 8 miles west of the junction of the Negri and Ord Rivers, grades northwards into platy to flaggy siliceous siltstone and chert. The silicification was probably associated with deep weathering, possibly accentuated by silicification along the fault zone which bounds the eastern side of the exposure.

Stromatolite colonies are common, especially towards the top of the formation. Two types have been distinguished: the more common, shown in Plate 15, figure 1, has been identified by Dr H. S. Edgell (Geol. Surv. W. Aust., pers. comm.) from photographs as *Collenia frequens* Walcott, 1914. This form is found throughout the upper half of the formation. The second type of colony, found only in one locality 8 miles west of the junction of the Negri and Ord Rivers, is shown in Plate 15, figure 2. It appears to consist of a smaller variety encrusting an earlier variety. The larger colony, which has been identified by Edgell as probably *Conophyton* cf. *cylindricus* (Grabau), is mostly dolomite, and only rarely have the laminae been replaced by chert. The encrusting colony is composed of individuals of circular cross-section which are about an inch across; they consist of laminae up to a quarter of an inch thick, gently domed upwards. In contrast with the lower colony, the upper one is almost completely altered to chert.

Several different, less well preserved forms of stromatolite were seen in outcrop, but could not be photographed, and as they occur in inaccessible localities, they were not collected. A great variety of stromatolites which were almost certainly derived from the Bungle Bungle Dolomite can be seen in the dolomite boulders weathered out of the tillites in the overlying Ord Group.

Colombo Sandstone

Definition

Lithology: Massive silicified quartz sandstone, commonly with conglomerate or sedimentary breccia at base.

Distribution: Small area northwest of junction of O'Donnell and Margaret Rivers near western margin of map area.

Derivation of Name: From Colombo Hill, a newly named feature 3 miles north of junction of O'Donnell and Margaret Rivers (18°17'S., 126°37'E.).

Type Area: Colombo Hill, which is capped by the formation; no type section measured.

Stratigraphic Relationships: Lies unconformably between Crowhurst and Louisa Downs Group; relationship with Glidden and Kuniandi Groups not known.

Thickness: Greatest thickness preserved about 300 feet.

Age: Probably Carpentarian, but may be as young as early Adelaidean.

Description

The Colombo Sandstone consists almost entirely of massive medium to coarse-grained quartz sandstone; it is generally silicified, and forms distinctive rounded rugged outcrops. It is generally white or cream or purple, and consists of poorly sorted quartz grains, and some chert and jasper fragments, set in a fine-grained siliceous matrix which constitutes up to 10 percent of the rock.

Bedding is generally not prominent, and weak partings give a thick-bedded or massive outcrop. Cross-bedding is commonly present, and in thin section some of the rocks can be seen to be made up of graded laminae.

In places, the base of the formation consists of boulder conglomerate or breccia which grades laterally and vertically into the silicified sandstone. The conglomerate is commonly composed of rounded to angular boulders of quartzite, chert, and jasper, set in a coarse-grained quartz sandstone matrix, but where the formation overlies the Hibberson Dolomite, the basal bed consists of a distinctive breccia which appears to be a reworked duricrust. It is composed of a chaotic mixture of angular fragments of chert, up to 18 inches across, set in a siliceous sandstone matrix.

The Colombo Sandstone could be a correlative of the Mount Parker Sandstone.

Gardiner Beds

The Gardiner Beds were named by Casey & Wells (1964) from the Gardiner Range south of the map area, where about 5,000 feet of sediments crop out. The sequence comprises pebble conglomerate overlain by quartz sandstone, shale, and minor pink and cream dolomite.

In the map area, the Gardiner beds are nearly flatlying, and only a small thickness is exposed. The thickest section seen is about 100 feet thick, and consists of quartz sandstone and minor pebble conglomerate.

In the map area quartz sandstone predominates. It is clean, well sorted, medium-grained, and white to pink, and in places contains clay pebble casts and scattered pebbles of quartz and chert. The sandstone is generally massive, but in places the outcrops are flaggy or blocky; cross-bedding and ripple marks are common in places. The sandstone grades into coarse quartz grit and quartz-pebble conglomerate containing well rounded to subangular pebbles of quartz and chert in a quartz sandstone matrix.

Quartz sandstone, with up to 20 percent feldspathic or kaolinitic matrix, is common, and probably gives rise to the brown ferruginous sandstone which is seen in many of the lateritized outcrops.

Wade Creek Sandstone

Definition

Lithology: Predominantly medium-grained clean quartz sandstone; includes thick shale lens, Mount John Shale Member.

Distribution: Throughout Osmond Range as broad dip slopes; small exposure of sandstone unconformably overlying Bungle Bungle Dolomite, 9 miles south of Palm Springs on Gordon Downs Sheet area, is probably Wade Creek Sandstone.

Derivation of Name: From Wade Creek in Osmond Range.

Type Area: Osmond Range. Composite section assembled from incomplete sections in type area.

Stratigraphic Relationships: Unconformably overlies Bungle Bungle Dolomite and conformably overlain by Helicopter Siltstone; grades into Helicopter Siltstone over stratigraphic interval of about 100 feet; boundary arbitrarily placed where siltstone becomes preponderant.

Thickness: From about 400 feet east to about 1,200 feet at western end of Osmond Range.

Age: Adelaidean. Mount John Shale Member dated as 1,128±110 m.y. by the Rb/Sr method.

Description

The Wade Creek sandstone forms broad dip slopes in the Osmond Range area and is similar in outcrop and photo-pattern to the Mount Parker Sandstone.

It can be divided into two parts: the lower consists of medium-grained sandstone which crops out in the western half of the Osmond Range, and an upper arenaceous unit which extends the full length of the Osmond Range. The lower unit contains a lens of shale, the Mount John Shale Member, which grades eastwards into fine-grained sandstone and siltstone.

The formation rests unconformably on a soil profile on the Bungle Bungle Dolomite; the profile consists of a highly ferruginous zone between 2 and 5 feet thick, or a zone of silicified dolomite up to 30 feet thick.

The lower unit is 1,000 feet thick near Mount John, where the section given in Table 11 was measured, but it thins rapidly to the west and cuts out against a pre-existing topographical high north of the headwaters of Osmond Creek.

TABLE 11. SECTION OF LOWER PART OF WADE CREEK SANDSTONE AT MOUNT JOHN

	Thickness (ft)	Description
	30	*Ferruginous sandstone and siltstone,* flaggy; limonitic and hematitic cement.
	60	*Quartz sandstone,* flaggy, white, medium-grained, clean.
	20	*Ferruginous quartz sandstone,* flaggy; abundant limonitic and hematitic cement; interbedded with *ferruginous sandstone.*
	90	*Quartz sandstone,* flaggy, medium-grained; composed of well rounded quartz grains and minor amounts of sericitic matrix; with thin interbeds of highly *ferruginous siltstone.*
	270	*Mount John Shale Member. Shale,* laminated and thin-bedded, black and grey; with thin interbeds of *cherty siltstone.*
	140	*Quartz sandstone,* green and brown; flaggy to platy outcrop; bedding planes have surface of green chloritic material.
	390	*Quartz sandstone* grading into *orthoquartzite,* white, medium-grained; consists of well rounded and well sorted grains of quartz and a little siliceous matrix; generally massive, but current ripple marks and cross-bedding can sometimes be distinguished; *Protoniobia wadea.*
Total	1,000	

The basal part of the lower unit has a uniform lithology and can generally be distinguished from other sandstone units by its lack of bedding and uniform grain-size. The basal sandstone is thickest at Mount John and thins to the north and west.

It was from the lower unit that Wade (1924) collected the supposed jellyfish named by Sprigg (1949) *Protoniobia wadea.* Wade thought the sandstone was Lower Cambrian, and Sprigg correlated the beds with the basal Cambrian of Ediacara in South Australia, but they are of course much older. We could not find Wade's locality, but in Wade Creek there is a platform on which are exposed hundreds of small chert plates consisting of a number of concentric rings, very similar to Wade's supposed jellyfish. Many of these are single plates, between half an inch and 2 inches across, but a large proportion consists of two to three individuals of various sizes fused together. In some cases, small nodules are fused to the margin of a larger one, giving the appearance of the budding appendages described by Sprigg. Under these circumstances there is some doubt that Wade's jellyfish is of organic origin, a doubt previously expressed by Harrington & Moore (Moore, 1956).

The highly ferruginous sandstone overlying the Mount John Shale is known only near Mount John: to the north there is a similar thickness of flaggy quartz sandstone and minor quartz siltstone, but the ferruginous beds are missing.

The sandstone lying unconformably between the Bungle Bungle Dolomite and the Moonlight Valley Tillite 8 miles south and southwest of Palm Springs is probably the basal part of the Wade Creek Sandstone. It is similar to the Wade Creek Sandstone in the type area, but it is brown to cream in colour and is more highly silicified, probably as a result of lateritization, and forms a distinctive bouldery outcrop.

The upper unit, which was originally called the Boll Sandstone (Dow et al., 1964), is more extensive than the lower unit, and overlaps onto the Bungle Bungle Dolomite and Mount Parker Sandstone to the west. This appears to be an onlap caused by a rising sea level, but it is possible that the lower unit was eroded in the western part of the Osmond Range before the upper unit was deposited.

The upper unit consists of blocky to massive clean quartz sandstone. It is mostly medium-grained, and consists of well rounded to subrounded quartz grains which are generally not as well sorted as in the lower unit. Many of the beds lens out rapidly, and in some places they are highly convoluted, probably as a result of submarine slumping. Ripple marks and cross-bedding are common.

The thickness of the upper unit has not been measured, but it is between 250 and 300 feet. It is overlain by a transition zone, 50 to 100 feet thick, of platy to laminated fine-grained quartz sandstone and interbedded quartz siltstone. The boundary with the Helicopter Siltstone is arbitrarily placed where siltstone becomes predominant.

Mount John Shale Member

Definition

Lithology: Black, green, or grey shale containing thin beds of siltstone and cherty siltstone.

Distribution: Eastern end of Osmond Range within 12 miles of Mount John.

Derivation of Name: From Mount John at eastern end of Osmond Range (17°8′S., 128°42′E.).

Type Area: Type section measured at Mount John.

Stratigraphical Relationships: A conformable lens in Wade Creek sandstone; upper and lower boundaries sharp; changes laterally to west into fine-grained quartz sandstone.

Thickness: 270 feet in type section; to north, near Moonlight Valley, maximum thickness 450 feet.

Age: Adelaidean. Rb/Sr age 1,128±110 m.y.

Description

The Mount John Shale Member is easily eroded, but has been protected by the overlying Wade Creek Sandstone, which caps the spectacular buttes and mesas in the eastern half of the Osmond Range. The slopes of the buttes and mesas are covered by talus and outcrops are rare.

The type section at Mount John consists of 720 feet of laminated and thin-bedded black and grey shale containing thin interbeds of cherty siltstone and minor thin beds of fine-grained micaceous quartz sandstone near the base. The thickest sequence is in a prominent mesa at the southeastern end of Moonlight Valley, where the section was measured by Abney level up a cliff section (Table 12).

TABLE 12. SECTION OF MOUNT JOHN SHALE MEMBER IN MOONLIGHT VALLEY

	Thickness (ft)	Description
		Wade Creek Sandstone (flaggy fine-grained quartz sandstone).
		Conformable contact
	85	*Shale,* laminated, whitish grey; and subordinate *quartz siltstone.*
	50	*Quartz siltstone,* platy to laminated, white; with partings, up to half an inch thick, of *chloritic shale,* green.
	100	*Quartz siltstone,* laminated, grey or white.
	5	*Quartz sansdtone,* medium-grained; composed of well rounded grains of quartz with no matrix; completely cross-bedded; beds picked out by ferruginous laminae.
	115	*Shale,* laminated, dark olive-green; subvitreous lustre on freshly broken surfaces.
	30	*Quartz siltstone,* thin-bedded, micaceous, khaki-green; with a few interbeds of *shale,* laminated, khaki-green.
	45	*Shale,* laminated, cream, grey, or white, subvitreous; no outcrop.
		Conformable contact
Total	450	
		Wade Creek Sandstone (medium-grained clean quartz sandstone).

The Mount John Shale Member was probably deposited in a basin formed by warping and minor faulting of the shallow shelf on which the late Proterozoic sediments were being deposited. The basin was at least 25 miles from the Halls Creek Mobile Zone, which was the source of the detritus, and received fine-grained sediments while the arenites of the Wade Creek Sandstone were deposited closer to the Mobile Zone.

Plate 10 shows that the Mount John Shale lenses out rapidly against upfaulted Wade Creek Sandstone, and indicates that faulting was active during the deposition of the shale. The thinning of the Mount John Shale to the west appears to be a stratigraphic thinning and was not caused by erosion before the deposition of the overlying sandstone. This is shown on the air-photographs, by a resistant bed about halfway up the shale, which continues to the western extremity of the shale in the same stratigraphic position.

Helicopter Siltstone

Definition

Lithology: Mostly platy to laminated siltstone and shale; thin beds of fine-grained quartz sandstone throughout, and massive bed of resistant quartz sandstone near top.

Distribution: Narrow belt along northern edge of Osmond Range.

Derivation of Name: From Helicopter Springs, 10 miles southwest of Texas Downs homestead (17°07′S., 128°22′E.).

Type Area: Near eastern extremity of formation where Horse Creek cuts across it. No type section measured.

Stratigraphical Relationships: Conformably overlies Wade Creek Sandstone and unconformably overlain by Fargoo Tillite; grades downwards into Wade Creek Sandstone over about 100 feet; boundary placed where sandstone becomes predominant.

Thickness: About 550 feet.

Age: Adelaidean.

Description

The Helicopter Siltstone crops out south of Fargoo Creek (Pl. 9) in the scarp of a prominent cuesta formed by a resistant bed of quartz sandstone near the top of the formation. The overlying beds, also mapped as Helicopter Siltstone, form the broad alluvium-filled valley of Fargoo Creek, and are known only from rare outcrops in creek beds.

The Helicopter Siltstone consists mainly of green and grey micaceous quartz siltstone and some shale; the shale is laminated or thin-bedded and has a distinctive platy outcrop. Beds of pink or grey fine-grained quartz sandstone, generally from 2 to 6 inches thick, are rare in the lower half of the formation, but constitute about 30 percent of the upper part. The sandstone which forms the cuesta is lenticular and massive, and consists of fairly well rounded quartz grains and minor kaolinitic matrix.

The sediments overlying the resistant sandstone appear to be mostly green or grey siltstone and shale similar to the underlying rocks, but there are several beds of flaggy quartz sandstone forming subdued strike ridges along the valley floor.

A thickness of 460 feet was measured in Horse Creek, but the section is not complete; the total thickness preserved beneath the Fargoo Tillite is estimated to be at least 550 feet.

Duerdin Group

Definition

Constituent Formations and Lithology: Ranford Formation (uppermost unit), siltstone, shale, and fine-grained dolomitic sandstone; *Johnny Cake Shale Member,* green and purple banded shale; *Jarrad Sandstone Member,* dolomitic sandstone; *Moonlight Valley Tillite,* tillite capped by a thin dolomite marker bed; *Frank River Sandstone,* dolomitic sandstone and rare greywacke and builder beds; *Fargoo Tillite,* tillite and bouldery dolomite conglomerate.

Distribution: Crops out sporadically along Ord River, east of Halls Creek Fault, from near Kununurra in northeast to near Beaudesert Bore in extreme south of map area.

Derivation of Name: From Duerdin Creek (18°30′S., 127°55′E.).

Type Area: Moonlight Valley (17°03′S., 128°33′E.), where greatest thickness preserved. The type sections measured in Moonlight Valley (Pl. 16, fig. 1), except for Frank River Sandstone, measured in headwaters of Frank River (17°23′S., 128°17′E.).

Stratigraphic Relationships: Rests with major unconformity on Helicopter Siltstone, and overlain unconformably by Albert Edward Group.

Thickness: 2,100 feet thick in type area.

Age: Adelaidean.

Fargoo Tillite

Definition

Lithology: Massive tillite with large patches of dolomitic boulder conglomerate.

Distribution: Only along south side of Moonlight Valley (Pl. 9) and in watershed of Frank River.

Derivation of Name: From Fargoo Creek, a newly named feature on north flank of Osmond Range (17°06'S., 128°25'E.).

Type Area: Between Fargoo and Horse Creeks, south of Moonlight Valley. Type section measured at excellent exposure in steep bluff half a mile north of Horse Creek (17°04'S., 128°31'E.).

Stratigraphic Relationships: Unconformably overlies Helicopter Siltstone and conformably overlain by Frank River Standstone; upper boundary sharp.

Thickness: About 140 to 450 feet.

Age: Late Proterozoic.

Description

Outcrops of the Fargoo Tillite are rare, and the formation generally forms low rounded ridges covered by cobbles and boulders weathered out of the tillite. Where a considerable area of tillite is exposed, it has a distinctive dendritic drainage pattern which can generally be recognized on the air-photographs (Pl. 9).

The formation comprises tillite, boulder conglomerate, and dolomitic sandstone. The type section which was measured by Abney level is given in Table 13.

TABLE 13. TYPE SECTION OF FARGOO TILLITE

	Thickness (ft)	Description
		Tillite.
		Probable angular unconformity
		Frank River Sandstone (quartz sandstone, massive beds, 6 feet thick: medium-grained, cream to greenish grey; with thin partings of *siltstone,* green).
		Conformable contact
	25	*Clay* (about 66%), massive, grey, stiff; contains beds of *quartz sandstone,* up to 2 feet thick; load casts at base; and lenses of *dolomite sandstone,* rolled and slumped.
	15	*Shale,* thin-bedded, grey; contains rare rounded pebbles of quartz and quartzite.
	50	*Clay,* grey; contains scattered rounded pebbles; rolled and slumped dolomitic beds, and concretionary masses of dolomite (Pl. 12, fig. 2).
	10	Lenses of *quartzite-pebble conglomerate,* consisting of well rounded quartzite pebbles in dolomite sandstone matrix.
	150	*Tillite,* composed of stiff grey to green clay containing unsorted fragments ranging from sand size to boulders several feet across (Pl. 13, fig. 1).
		Angular unconformity
Total	250	
		Helicopter Siltstone (laminated siltstone and shale).

The tillite ranges in thickness from 140 to about 450 feet. The contact with the underlying siltstone, seen only in the type section, is sharp and conformable with the bedding of the siltstone over a distance of about 10 feet. However, on a larger scale, the siltstone beds are inclined at an angle of about 3° to the tillite which progressively truncates them. Farther east, the siltstone is missing and the tillite rests on the Wade Creek Sandstone. In this locality, there is a lens of thin-bedded dolomite and cross-bedded medium-grained dolomitic sandstone over a mile long at the base of the tillite. The sandstone grades into pebble and cobble conglomerate composed of well rounded fragments of grey limestone, chalcedony, quartz, agate, and a variety of rocks derived from the Lamboo Complex, set in a matrix of dolomitic quartz sandstone.

Indurated grey siltstone and clay forms about 90 percent of the tillite. The remainder consists of scattered unsorted fragments ranging from sand size to boulders up to 18 feet in diameter. In places, the matrix is calcareous and the pebbles and boulders have a calcareous coating up to one-sixteenth of an inch thick.

No particle-size analysis has been made of the tillites and only two thin sections have been examined, both from the Fargoo Tillite. The outstanding textural characteristic is the imperceptible gradation in grainsize of the mineral fragments down to the limit of resolution of the microscope.

Sand-size grains form 25 to 50 percent of the matrix; the larger grains are almost all very well rounded. It seems unlikely that they were rounded so well by glacial abrasion, and they were probably derived from the Proterozoic sandstones. The smaller grains are commonly subangular to angular and were probably formed by granulation of larger grains. The grains are mostly quartz (60-85%) and carbonate (40-15%), but a great variety of other minerals and rock fragments, derived from igneous and metamorphic rocks, is present in small amounts.

About half of the finer fraction is composed of mineral fragments (predominantly quartz and carbonate) ranging in size down to the limits of resolution of the microscope. Very fine-grained mica is common; some grains could be detrital, but most seem to be authigenic. The remainder of the fine fraction is indeterminate under the microscope.

The tillite is invariably massive, and the only signs of bedding are the rare concentrations of boulders in zones parallel to the bedding of the overlying sediments. Most of the larger components are well rounded and many are roughly ovoid in shape: the flattened ovoid shape seen in Plate 11, figure 2 is characteristic of the larger boulders. Polished and striated boulders are not common, except in restricted localities, and though references to the faceted pebbles are common in the literature on Australian tillites, no genuine faceted pebbles were seen. Fragments which have had a broken face striated by later abrasion can easily be mistaken for faceted pebbles, but even these are rare.

Quartzite, yellow dolomite, and grey limestone are the most common rock types found in the tillite, but almost every rock type from the Lamboo Complex, the Halls Creek Group, and the Osmond Range succession is represented. Angular fragments of chert, chalcedony, and agate are seldom seen in the tillite, but they constitute a large proportion of the surface rubble. Judging by the great number of chips and partly formed spear heads composed of these materials, the Aboriginals used the tillite as a source of chert for artefacts.

Boulders are rare towards the top of the tillite and are succeeded by lenses, up to 30 feet long and 6 feet thick, of dolomite, dolomitic sandstone, and pebble conglomerate. Most of the lenses slumped before consolidation, and in extreme cases they consist of rolled masses of dolomite and dolomitic sandstone.

In the middle reaches of the Frank River the Fargoo Tillite is about 200 feet thick; about half the formation is similar to the type section, but the megaclasts are smaller and much more restricted in composition, and fewer of them show evidence of glacial abrasion. The largest boulder seen was 4 feet across, and the bulk of them consist of quartzite and dolomite; rocks derived from the Olympio Formation are not common and rocks from the Lamboo Complex are rare.

The tillite grades, both laterally and vertically, into boulder conglomerate consisting of boulders randomly distributed in a coarse-grained dolomitic sandstone matrix. The conglomerate is rarely cross-bedded, and the boulders are less abundant and generally smaller than in the tillite.

The southernmost exposure of the Fargoo Tillite, 5 miles west of the Dixon Range, is much thinner and contains no true tillite; the section measured is given in Table 14.

TABLE 14. FARGOO TILLITE, 5 MILES WEST OF DIXON RANGE

	Thickness (ft)	Description
		Moonlight Valley Tillite (tillite)
		Unconformity
	100	*Frank River Sandstone.* Beds of *quartz sandstone,* up to 2 feet thick; purple, argillaceous; with interbeds of *shale* and *siltstone.*
	20	*Dolomitic sandstone,* dark brown, laminated and cross-bedded, fine-grained.
		Conformable contact
	30-40	*Fargoo Tillite. Boulder conglomerate,* composed of well rounded boulders of quartz, quartzite, dolomite, and chert, which are rarely polished and striated, set in matrix of dolomitic sandstone; lenses of *dolomitic conglomerate.*
	10	*Quartz sandstone,* medium-grained, well sorted, almost friable.
		Angular unconformity
Total	160-170	
		Olympio Formation (greywacke and siltstone).

Frank River Sandstone

Definition

Lithology: Dolomitic arenite and interbedded siltstone; rare bouldery sandstone containing glacial erratics.

Distribution: In watershed of Frank River, along south flank of Osmond Range, and north of Fargoo Creek.

Derivation of Name: From Frank River (17°23'S., 128° 17'E.).

Type Area: Between Mount Ranford (in middle reaches of Frank River) and locality 7 miles southwest of Bungle Bungle, where type section was measured.

Stratigraphic Relationships: Conformably overlies Fargoo Tillite and overlain, probably unconformably, by Moonlight Valley Tillite; boundaries sharp and unequivocal.

Thickness: 810 feet at type section.

Age: Late Proterozoic.

Description

Only small remnants of the Frank River Sandstone are preserved beneath the Moonlight Valley Tillite. It is characteristically dolomitic and generally occurs as massive recessive beds 10 to 20 feet thick capped by more resistant flaggy beds which form subdued structural benches. The dominant rock is a light-coloured dolomitic subgreywacke which grades into dolomitic greywacke, similar to the matrix of the underlying Fargoo Tillite, or into dolomitic orthoquartzite.

The type section, which was measured about 7 miles southwest of Bungle Bungle, is given in Table 15.

Five specimens of arenite from the type section were examined in thin section; all were found to contain appreciable amounts of carbonate, most of which is probably dolomite.

The greywacke is similar in composition to the matrix of the underlying Fargoo Tillite, but it contains a greater proportion of sand-size grains. As in the tillite, the larger grains are well rounded and the smaller grains are subangular. The grains consist predominantly of strained quartz (80-95%) and carbonate (20-5%) with a little chert, microcline, metamorphosed greywacke, schist, tourmaline, and sphene. About half the matrix is carbonate (partly detrital and partly interstitial), and half is a mixture of very fine small angular grains of quartz, sericite, some of which appear to be detrital, and a little hydrated iron oxide. There is a complete gradation from greywacke to dolomitic subgreywacke, which

TABLE 15. TYPE SECTION OF FRANK RIVER SANDSTONE

	Thickness (ft)	Description
		Moonlight Valley Tillite (tillite capped by marker dolomite).
		Probable unconformity
	60	*Dolomitic sandstone,* thick-bedded; beds 5 to 10 feet thick; flaggy towards top.
	5	*Quartz siltstone,* greenish grey; grading upwards into *shale;* platy outcrop.
	180	*Dolomitic quartz sandstone,* grey, medium-grained; weathers readily; occurs as massive beds, 5 to 10 feet thick, capped by resistant beds of flaggy dolomitic quartz sandstone which form structural benches (thin section 4). Towards top, finer in grain and more thinly bedded with intercalations of *micaceous siltstone.*
	200	*Dolomitic sandstone,* weathers brown, medium-grained to fine-grained; bedding mostly massive; beds from 5 to 10 feet thick; thinly flaggy towards top; 5-foot pebbly bed about middle.
	10	*Quartz sandstone,* prominent resistant bed; creamy brown, medium-grained to coarse-grained; composed of subangular to rounded quartz grains and about 5 percent kaolinitic matrix; probably originally dolomitic; massive.
	40	*Quartz sandstone,* pink, fine-grained; composed of well rounded quartz grains set in porous ferruginous matrix which was probably originally dolomitic; mostly flaggy, but becomes platy near top.
	5	*Subgreywacke,* coarse-grained; contains cobbles and boulders up to 3 feet across; some of the megaclasts have a high polish.
	175	*Dolomitic subgreywacke,* massive, readily weathering, medium-grained; beds 15 to 20 feet thick; grades upwards into more resistant *dolomitic quartz sandstone,* thinly flaggy; forms benches.
	60	*Dolomitic subgreywacke,* grey to dark grey, medium-grained to coarse-grained; beds about 4 feet thick; separated by readily weathering beds of *dolomitic quartz sandstone* up to 1 foot thick. Towards top, thin interbeds of *siltstone,* khaki-green; and *quartz sandstone,* very fine-grained.
	25	Mostly *dolomitic subgreywacke,* medium-grained; grading into *greywacke.* Subgreywacke composed of well rounded quartz grains in ferruginous and argillaceous matrix. Beds are flaggy near bottom, but grade at top into *dolomitic quartz sandstone,* thinly flaggy, grey-green.
		Conformable contact
Total	760	
		Fargoo Tillite (siltstone and shale with rare scattered pebbles).

is generally coarser and better sorted, and has only about 10 percent matrix, and also to dolomitic orthoquartzite with very little matrix. The composition of the detrital grains and the matrix is very similar in all these rocks.

Along Moonlight Valley the Frank River Sandstone changes laterally in lithology and thickness. Near the mouth of Fargoo Creek it consists of poorly sorted cross-bedded quartz sandstone containing dropped erratics up to cobble size. It is more regularly bedded towards the top, where it is generally flaggy; it contains lenses of poorly sorted pebble conglomerate which is composed of subangular pebbles of quartz, quartzite, and chert, set in a grit matrix. The whole formation in this area is friable and porous, and there is a considerable amount of kaolinitic matrix which indicates that the rocks were probably originally dolomitic.

Moonlight Valley Tillite

Definition

Lithology: Tillite capped by distinctive and persistent dolomite between 6 and 20 feet thick; some dolomite-cobble conglomerate.

Distribution: Discontinuous exposures preserved beneath younger rocks east of Halls Creek Fault, from near Kununurra in northeast to near Ruby Plains, a distance of 200 miles.

Derivation of Name: From Moonlight Valley, a wide open valley along northern flank of Osmond Range (17°03'S., 128°33'E.) (Pl. 16, fig. 1).

Type Area: Moonlight Valley. Type section measured in steep bluff about 1 mile south of Killarney Yard (17°05'S., 128°31'E.).

Stratigraphic Relationships: Overlies, probably unconformably, Frank River Sandstone and conformably overlain by red shale of Ranford Formation or by Jarrad Sandstone Member; boundaries sharp and unambiguous.

Thickness: Deposited in basement hollows; from about 6 to 450 feet.

Age: Late Proterozoic.

Description

The formation is generally thinner than the Fargoo Tillite, but is much more extensive. It was deposited on a surface which had a relief of at least 100 feet, and the tillite has a maximum thickness of about 450 feet where it was deposited in hollows. It thins or cuts out over rises in the basement, but the capping dolomite generally continues unbroken. To the south along the Albert Edward Range, the basement ridges were apparently more extensive, and the tillite occurs as thin discontinuous lenses, except south of Palm Springs, where it thickens markedly.

In most places, the Moonlight Valley Tillite is almost indistinguishable from the Fargoo Tillite, but it can generally be recognized in the field by its stratigraphical position and by the thin band of dolomite which almost invariably caps it. In contrast to most of the Fargoo Tillite, few Archaean or early Proterozoic rocks are found in the Moonlight Valley Tillite: most of the components larger than pebble size are quartzite and, less commonly, dolomite. They are all well rounded and commonly striated and polished (Pl. 11, fig. 2; Pl. 12, fig. 1), and in general they are not as big as those in the lower tillite: the largest seen was 8 feet in diameter.

The type section (Table 16), chosen because it is the only complete exposure of the formation so far found, is atypical, in that it does not contain any large glacial erratics.

TABLE 16. TYPE SECTION OF MOONLIGHT VALLEY TILLITE

	Thickness (ft)	Description
		Ranford Formation (red shale with interbedded platy pink dolomite).
		Conformable contact
	10	*Marker dolomite,* laminated, pink; with thin partings of *shale,* green.
	115	Mostly *shale,* dark olive-green; contains scattered pebbles and cobbles of indurated micaceous quartz sandstone, many of which are striated; grades upwards into *shale,* red; rare scattered pebbles; and rare lenses of slumped *dolomitic sandstone,* green.
		Probable unconformity
Total	125	
		Frank River Sandstone (flaggy dolomitic quartz sandstone).

South of Palm Springs, the Moonlight Valley Tillite shows extreme lateral variations: the most common rock (Pl. 13, fig. 1) is a coarse-grained quartz sandstone, which generally contains scattered boulders, up to 12 feet across, of quartzite, dolomite, and greywacke. The sandstone matrix is very poorly sorted, and consists of rounded quartz grains and very minor amounts of matrix. In places, the boulders are closely packed, but elsewhere erratics are rare.

The bouldery sandstone grades laterally into medium-grained better sorted quartz sandstone, which is commonly calcareous or dolomitic, and into boulder tillite. Towards the top of the tillite there are lenses of dolomitic sandstone up to 10 feet thick and hundreds of feet long. In places, they are highly convoluted; they were probably deformed while the sandstone and clay were still plastic (Fig. 14). The deformation could have been caused by overriding of glacial ice, or by subaqueous slumping.

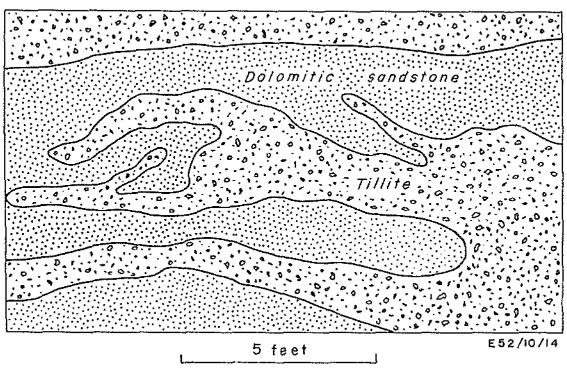

Figure 14. Plastically deformed tillite of the Moonlight Valley Tillite

The capping dolomite, though only 6 to 20 feet thick, is a distinctive and persistent indicator of the Moonlight Valley Tillite. It is pink or rarely yellow, and is invariably laminated or thin-bedded. The laminae in places are less than one-tenth of an inch thick and are very regular; they are possibly varves. It grades laterally into an unusual rock, found in the Frank River area, the southern flank of Osmond Range, and near the junction of the Ord and Negri Rivers, which consists of nearly spherical cobbles of dolomite of similar size, set in a dolomitic sandstone matrix (Pl. 13, fig. 2).

Glaciated pavement is exposed near the junction of the Ord and Negri Rivers, and areas of up to 250 square feet are exposed over a distance of about a mile. The pavement consists of quartzite and indurated micaceous sandstone which have been polished, grooved (Pl. 11, fig. 1), striated, and plucked. Some poorly preserved rounded forms, up to 6 feet long and 2 feet high, could be small roches moutonnées. These features show that the ice came from the northeast, and as the nearest older Precambrian rocks are in the Katherine-Darwin region, this probably explains the absence of metamorphic and igneous rocks in the Moonlight Valley Tillite.

Ranford Formation

Definition

Lithology: Mostly thin-bedded siltstone and fine-grained quartz sandstone containing thin beds of dolomitic sandstone and dolomite. The *Jarrad Sandstone Member* near the base of the formation consists of dolomitic sandstone, and the *Johnny Cake Shale Member* is a distinctive red and green shale overlying the Jarrad Member in places.

Distribution: East of Halls Creek Fault between Mount Brooking in northeast and Beaudesert Bore in south.

Derivation of Name: From Mount Ranford (17°28′S., 128°12′E.).

Type Area: Moonlight Valley. Composite type section measured between Killarney Yard and Texas Downs homestead.

Stratigraphic Relationships: Conformably overlies Moonlight Valley Tillite and unconformably overlain by Albert Edward Group; lower boundary defined as top of marker dolomite of Moonlight Valley Tillite; south of Palm Springs, where marker dolomite is missing, boundary defined as base of dolomitic sandstone overlying Moonlight Valley Tillite.

Thickness: 2,140 feet (including both members) at type section.

Age: Late Proterozoic.

Description

The lower half of the Ranford Formation has been divided into two members —the Jarrad Sandstone Member and the Johnny Cake Shale Member. The upper part of the formation crops out poorly, and in most places only thin platy beds of khaki-green siltstone capping subdued structural benches are seen. In creek exposures, the resistant siltstone beds are seen to constitute only about 20 percent of the outcrop; the rest consists of massive beds, up to 2 feet thick, of dark purple-brown or khaki-green quartz siltstone which weather recessively.

Load casts, generally smaller than those pictured in Plate 16, figure 2, are common at the bottom of the beds, and are characteristic of the formation, except the uppermost part.

A summary of the type section is given in Table 17.

TABLE 17. SUMMARY OF TYPE SECTION OF RANFORD FORMATION

	Thickness (ft)	Description
		Antrim Plateau Volcanics (tholeiitic basalt overlying thin patches of aeolian sand).
		Unconformity
	60	*Quartz sandstone,* massive, greenish grey, highly indurated, fine-grained; small round cavities; rare hematite-jasper veins up to half an inch wide.
	500	Mostly *quartz sandstone,* very fine-grained; and *micaceous quartz siltstone;* khaki-green, platy or laminated; no load casts.
	540	*Quartz siltstone* (about 80%), dark purple-brown, less commonly khaki-green, fine-grained, massive; weathers recessively. *Micaceous quartz siltstone* and *micaceous shale* (20%), khaki-green; resistant to weathering; platy outcrop. Almost all beds have load casts at base.
	600	*Johnny Cake Shale Member. Shale,* green and reddish purple, banded (see p. 92).
	210	*Jarrad Sandstone Member.* Mostly *dolomitic sandstone* (see p. 91).
	230.	*Shale,* massive reddish brown; and interbeds of *dolomite* (20%), cream and green; 2 to 6 inches thick; well developed load casts at base.
		Conformable contact
Total	2,140	
		Moonlight Valley Tillite (*dolomite,* laminated, cream; beds up to 2 inches thick, separated by thin partings of *shale,* red-brown). *Pebble tillite.*

No dolomitic rocks were seen in the type section above the Johnny Cake Shale Member. The four thin sections examined show little variation, and range from siltstone to fine-grained sandstone. They are composed of subangular grains of quartz and abundant flakes of mica, set in a chloritic or sericitic matrix: the reddish brown beds owe their colour to the abundance of hydrated iron oxide in the matrix. A little zircon and apatite were noted.

At Mount Brooking, 70 miles southeast of Wyndham, fossil jellyfish have been found in the Ranford Formation (Dunnet, 1965). The fossils are well preserved and very abundant in the fine-grained rocks capping Mount Brooking and the surrounding hills. Some of the forms are similar to the Ediacara fauna of South Australia (Sprigg, 1949), but some new forms are also present (Dunnet, 1965).

The sequence in the Mount Brooking area differs slightly from the type section of the Ord Group and is given in Table 18.

TABLE 18. SEQUENCE AT MOUNT BROOKING

Thickness (ft)	Description
150	*Ranford Formation. Siltstone,* laminated and thin-bedded; and *quartz sandstone,* fine-grained, micaceous; jellyfish in upper part; 'Zebra-stone' in lower part.
10-30	*Subgreywacke,* red-brown, ferruginous, fine-grained.
200	*Claystone, siltstone, and shale,* white to mauve; some *micaceous siltstone,* and *kaolinitic sandstone,* fine-grained.
350	*Jarrad Sandstone Member. Ferruginous subgreywacke,* massive, red-brown; with large proportion of silt matrix containing plentiful mud pellets; probably dolomitic.

TABLE 18. SEQUENCE AT MOUNT BROOKING (Cont.)

Thickness (ft)	Description
	Conformable contact
2-10	*Moonlight Valley Tillite. Dolomite,* laminated, pink.
150	*Tillite.*
25	*Subgreywacke,* dark purple-brown; composed of small quartz grains in purple siliceous dolomitic (?) matrix; blocky rounded outcrop.
150	*Shale,* khaki-green to greenish grey; weathers into small pieces; and rare beds of *quartz sandstone,* up to 3 inches thick; laminated, khaki-grey, fine-grained.
200	*Shale and siltstone* (about 50%), khaki-green; weathers readily; beds up to 1 foot thick. *Quartz sandstone* (about 50%), fine-grained to very fine-grained; platy outcrop.
250	*Quartz sandstone,* grey to greenish grey, medium-grained to fine-grained; with interbeds of *micaceous siltstone,* khaki-green; proportion of siltstone increases upwards to about 40 percent.
400	Upper part; *quartz sandstone,* pink to pinkish brown, fine-grained to medium-grained; composed of rounded quartz and chert grains in pink siliceous matrix (about 5%); large flakes of detrital muscovite on bedding planes in places; blocky; grades into *pebble conglomerate,* fine-grained; blocky outcrop; rare load casts, up to 3 feet long and 1 foot across, at base of some beds. Lower part: *quartz sandstone,* medium-grained to coarse-grained; composed of well rounded quartz grains in about 10 percent kaolinitic matrix; slightly porous in outcrop, and may have been originally dolomitic; blocky to massive outcrop.
50	*Quartz sandstone,* dark brown to light brown, fine-grained; composed of well rounded quartz grains in about 10 percent brown siliceous matrix; coarsely flaggy, but rarely laminated or thin-bedded.
	Conformable contact
35	*Moonlight Valley Tillite. Marker dolomite,* laminated or platy, cream.
Total 1,972-2,000	

Jarrad Sandstone Member

Definition

Lithology: Mostly dolomitic sandstone containing rare glacial erratics.

Distribution: Along Moonlight Valley, between Killarney Yard and Horse Creek Well; and in northeast, between Mount Evelyn and Mount Brooking.

Derivation of Name: From Mount Jarrad (17°01'S., 128°30'E.) near Texas Downs homestead.

Type Area: Moonlight Valley. Type section measured south of Killarney Yard where Fargoo Creek cuts the member (17°05'S., 128°20'E.).

Stratigraphic Relationships: Conformable lens within Ranford Formation; thins eastwards and cuts out within 25 miles of Halls Creek Fault; boundaries sharp and unequivocal.

Thickness: About 200 feet near Halls Creek Fault.

Age: Late Proterozoic.

Description

The Jarrad Sandstone Member is resistant and forms a spectacular cuesta on the south side of Moonlight Valley (Pl. 9).

The member consists mainly of an even-grained pink or cream dolomitic sandstone, which weathers to a dark purple-brown ferruginous sandstone. It consists of resistant beds, up to 4 feet thick, which crop out strongly, alternating with beds of flaggy sandstone of similar thickness which have a recessive outcrop. Near the bottom there are lenses of sandstone containing erratic cobbles, some of which are striated, and also beds of platy to flaggy fine-grained dolomitic sandstone with well developed load casts at their base. The dolomitic sandstone beds are pink or green, and weather recessively.

In thin section, the sandstones are seen to range from dolomitic quartz sandstone containing about 10 percent carbonate to sandy dolomite containing about 70 percent carbonate. The sediments are well sorted, fine to medium-grained, and consist of well rounded to subrounded grains of quartz, and minor chert and carbonate, set in a granular carbonate matrix. A little muscovite, tourmaline, sphene, and apatite, and a few fragments of shale are present.

In the type area the resistant sandstone beds have unusual markings resembling worm burrows. In the vertical plane the markings have slightly curved traces up to 8 inches long and a quarter of an inch wide, which project downwards from the top of the bed. Their trace in a horizontal plane is shorter, and is generally more sharply curved, and rarely contorted. The markings are composed of slightly coarser sandstone.

Johnny Cake Shale Member

Definition

Lithology: Green and reddish purple banded shale, partly gypsiferous or dolomitic.

Distribution: Crops out very poorly; in Moonlight Valley known only between Halls Creek Fault and Horse Creek Well; also small outcrops along southern flank of Osmond Range and in watershed of Frank River about 6 miles southwest of Bungle Bungle.

Derivation of Name: From Johnny Cake Creek near Horse Creek Well in Moonlight Valley.

Type Area: Moonlight Valley. No complete section could be measured, for lack of exposure.

Stratigraphic Relationships: Conformable within Ranford Formation.

Thickness: About 600 feet, measured on air-photographs in type area; thinner to south.

Age: Late Proterozoic.

Description

The Johnny Cake Shale Member weathers readily, and generally forms flat sand-covered areas. Exposures are rare, and are found only in creek banks, but where it dips gently, as in Moonlight Valley, the member shows up well on the air-photographs as white flat areas.

The Johnny Cake Shale Member consists predominantly of green and reddish purple regularly banded shale; it contains a small proportion of white micaceous material which appears to be authigenic mica. The bands are generally between half an inch and 1 inch thick, but range up to 3 inches. In places, the shale is gypsiferous. Rare beds of pink or cream dolomitic subgreywacke, up to 3 inches thick, crop out as subdued structural benches. They have well developed load casts at the base. The dolomitic subgreywacke is very fine-grained, and consists of poorly sorted, subangular grains of quartz and carbonate, set in a matrix of carbonate and a fine-grained mixture of sericite and chlorite. The matrix generally forms from 10 to 15 percent of the rock. A few grains of muscovite and some biotite, chert, zircon(?), and fragments of chlorite were noted.

The 200 feet of banded mauve and white shale and siltstone above the Jarrad Sandstone Member near Mount Brooking (Dow et al., 1964) probably belong to the Johnny Cake Shale Member, but the beds have been mapped as part of the Ranford Formation.

In this area the well known 'zebra-stone' or 'ribbon-stone' of Argyle Downs (Larcombe, 1927; Blatchford, 1927a; Hobson, 1930), is found about 100 feet below the jellyfish. It consists of white siltstone or claystone which contains abundant red or purple laminae, rods or ellipsoidal structures. Apart from their colour, they are indistinguishable from the enclosing white siltstone, and the colour is probably due to leaching (Hobson, 1930).

V. M. Bofinger (BMR) has made a preliminary Rb/Sr age determination on a sample of the Johnny Cake Shale Member from near the Moonlight Bore. He gives a tentative age of 685 $\pm$ 98 m.y. (late Adelaidean), which agrees with the field relationships.

The small remnants of the Ranford Formation preserved under the Albert Edward Group along the Albert Edward Ranges are more massively bedded, and are generally coarser in grain than the beds in the type area. The upper part of the unnamed basal sandstone member shown on the Gordon Downs Sheet area is probably the lateral equivalent of the Jarrad Sandstone Member, but the lower part was laid down before the marker dolomite, and is therefore older than the Jarrad Member.

A section measured 2 miles south of Palm Springs is given in Table 19.

TABLE 19. RANFORD FORMATION, 2 MILES SOUTH OF PALM SPRINGS

	Thickness (ft)	Description
		No outcrop (scree derived from overlying Mount Forster Sandstone).
	65	*Shale and siltstone* (about 50%), khaki-green to greenish grey, massive. *Quartz sandstone* (about 50%), purplish brown, very fine-grained; probably originally dolomitic; massive; contains rare beds of *sandstone*, medium-grained, up to 3 feet thick.
	5	*Quartz sandstone,* fine-grained, purple, massive.
	50	*Shale and siltstone,* banded red and green; with subordinate *subgreywacke,* dark brown to purple, platy.
	100	*Subgreywacke,* purple; beds about 4 feet thick; and about 30 percent *shale,* banded green and grey, generally micaceous.
	10	*Shale* interbedded with *siltstone,* purple and green, platy.
	100	*Subgreywacke,* fine-grained, purple, blocky; and subordinate *siltstone,* purple to greenish grey; beds up to 3 inches thick; load casts common.
Total	330	
		No outcrop.

Albert Edward Group

The Albert Edward Group is late Adelaidean in age and is regarded as a correlative of the Louisa Downs Group to the west.

Definition

Constituent Formations and Lithology: Flat Rock Formation (uppermost unit), calcareous and dolomitic ferruginous sandstone alternating with ferruginous siltstone; *Nyuless Sandstone,* medium-grained clean quartz sandstone and feldspathic sandstone; *Timperley Shale,* grey and green shale and siltstone, rare dolomite and quartz sandstone; *Boonall Dolomite,* grey or yellow dolomite and dolomitic breccia; *Elvire Formation,* brown to maroon shale and siltstone; *Mount Forster Sandstone,* clean resistant quartz sandstone.

Distribution: Crops out along Albert Edward Range from Bungle Bungle to southern limit of map area, and up to 20 miles east of range. The quartz sandstone cropping out near the Halls Creek Fault south of the Bow River has been referred to the Mount Forster Sandstone, and is the most northerly exposure of the group.

Derivation of Name: Named by J. W. Smith after Albert Edward Range.

Stratigraphic Relationships: Unconformably overlies Duerdin Group and overlain unconformably by Lower Cambrian Antrim Plateau Volcanics. Correlative of Louisa Downs Group to west.

Thickness: Between 4,000 and 6,000 feet: thickest unit, Timperley Shale, very poorly exposed.

Age: Late Adelaidean.

Mount Forster Sandstone

Definition

Lithology: Fine to coarse-grained clean quartz sandstone and some pebble conglomerate. Forms bold cuestas along Albert Edward Range.

Distributions: As for Albert Edward Group; small inlier also exposed near Halls Creek Fault northwest of Texas Downs homestead.

Derivation of Name: Named by J. W. Smith after Mount Forster 12 miles southwest of Hardman Range (17°58'S., 128°12'E.).

Type Area: Albert Edward Range between Palm Springs and Mount Kinahan. Type section measured in gorge of Brim Creek (18°15'S., 128°00'E.).

Stratigraphic Relationships: Unconformably overlies Ranford Formation and conformably overlain by Elvire Formation.

Thickness: 320 feet in type section.

Age: Late Adelaidean.

Description

The Mount Forster Sandstone is the basal unit of the Albert Edward Group. It is composed of resistant quartz sandstone, which, with the Mount Parker Sandstone, forms bold cuestas dominating the Albert Edward Range. The abundant blocky scree from the Mount Forster Sandstone effectively masks the contact with the underlying units, and the contact was seen only in two places where slips have removed the scree. The Egan Glacials were probably being deposited to the west at the same time as the basal beds of the Albert Edward Group, and it is possible that there are lenses of tillite at the base of the Mount Forster Sandstone.

The formation is composed of white or cream fine to medium-grained orthoquartzite with abundant ripple marks and almost ubiquitous cross-bedding. It is generally blocky or massive, or less commonly flaggy, and contains lenses of coarser sandstone and scattered quartz pebbles. A distinctive and extensive bed of quartz-pebble conglomerate near the base is composed of well rounded small pebbles of quartz and chert in a coarse-grained sandstone matrix. Towards the top of the formation there are several beds, up to 10 feet thick, of less resistant grey siltstone. The type section is given in Table 20.

In thin section, the Mount Forster Sandstone is a medium-grained orthoquartzite composed of a mosaic of quartz grains, some carbonate, and a few fragments of rock and feldspar; a little zircon, tourmaline, and iron oxide are present.

TABLE 20. TYPE SECTION OF MOUNT FORSTER SANDSTONE

	Thickness (ft)	Description
		Elvire Shale (chocolate-brown fissile shale).
		Conformable contact
	135	*Quartz sandstone* (orthoquartzite), white, grey, and light brown, flaggy, generally fine-grained and clean; with rare interbeds of *siltstone,* grey.
	25	No outcrop.
	60	*Orthoquartzite,* white, blocky, medium-grained to coarse-grained, similar to basal sandstone, but contains more argillaceous material; scattered pebbles of quartz and chert and many impressions of clay pellets.
	35	No outcrop.
	55	*Orthoquartzite,* white, blocky, medium-grained to coarse-grained; generally clean; cross-bedding ubiquitous; includes distinctive *conglomerate,* fine-grained; composed of well rounded black and brown and white pebbles of quartz and chert in coarse-grained sandstone matrix.
		Unconformity
Total	305	
		Ranford Formation (very fine-grained khaki-green quartz sandstone).

Elvire Formation

Definition

Lithology: Maroon and chocolate-brown shale and siltstone, with rare beds of medium-grained quartz sandstone.

Distribution: As for Albert Edward Group.

Derivation of Name: Named by J. W. Smith after Elvire River.

Type Area: Albert Edward Range between Palm Springs and Panton River. Type section measured in Brim Creek gorge (18°15'S., 128°00'E.).

Stratigraphic Relationships: Conformable between Mount Forster Sandstone and Boonall Dolomite. Upper and lower contacts gradational over about 20 feet; boundaries placed where shale becomes subordinate.

Thickness: 200 feet in type section; little variation in thickness throughout Albert Edward Range.

Age: Late Adelaidean.

Description

The Elvire Formation is easily eroded and outcrops are rare. Fresh exposures are maroon or chocolate-brown in colour and consist of 6-inch beds of shale interbedded with beds of siltstone up to 4 inches thick. Quartz sandstone beds several feet thick are common near the base, and the formation grades into the underlying Mount Forster Sandstone. The Elvire Formation generally has interbedded dolomite near the top and the contact with the Boonall Dolomite is gradational over about 20 feet.

Boonall Dolomite

Definition

Lithology: Fine-grained grey or yellow dolomite with minor dolomite conglomerate and dolomite breccia.

Distribution: As for Albert Edward Group.

Derivation of Name: Named by J. W. Smith after Boonall Yard 26 miles northeast of Flora Valley homestead (18°02'S., 128°15'E.).

Type Area: Albert Edward Range between Palm Spring and Panton River. Type section measured in Brim Creek gorge (18°15'S., 128°00'E.).

Stratigraphical Relationships: Conformable between Elvire Formation and Timperley Shale.

Thickness: 100 feet in type section; up to 200 feet in places.

Age: Late Adelaidean.

Description

The Boonall Dolomite is more resistant than the enclosing formations and crops out as subdued cuestas along the eastern side of the Albert Edward Range.

It consists almost wholly of dolomite, which is generally uniformly fine-grained, pink-cream or grey when fresh, but mostly weathers yellow or brown. It has a blocky or massive outcrop near the base, but is flaggy in the middle; laminae and thin-bedding can generally be distinguished on weathered surfaces, but are commonly contorted or broken by intraformational slumping.

Fine-grained dolomite conglomerate, composed of rounded to subangular pebbles of dolomite in a sandy dolomitic matrix, is common near the base. Many of the beds have an oolitic matrix, and there are beds up to 6 inches thick throughout the formation which are composed almost entirely of ooliths. Stromatolites have been recorded from the Boonall Dolomite.

Three of the thin sections examined consist of fine-grained recrystallized dolomite containing scattered grains and small patches and lenses of detrital quartz sand; the fourth is a pelletoid conglomerate composed of rounded fragments of carbonate rocks set in a fine-grained matrix of carbonate with scattered large rounded grains of detrital quartz sand. The carbonate mineral has been identified as dolomite by the Australian Mineral Development Laboratories.

Timperley Shale

Definition

Lithology: Thick, uniform, green or dark grey shale and siltstone.

Distribution: East of Albert Edward Range, between Duerdin Anticline and Boonall Yard on Gordon Downs Sheet area.

Derivation of Name: Named by J. W. Smith after Mount Timperley, 10 miles south of Flora Valley homestead (18°29'S., 128°00'E.).

Type Area: Middle reaches of Johnston River, south of Flora Valley. Type section measured 14 miles south of Flora Valley (18°30'S., 127°58'E.).

Stratigraphic Relationships: Conformable between Boonall Dolomite and Nyuless Sandstone.

Thickness: Estimated to be between 3,000 and 5,000 feet.

Age: Late Adelaidean.

Description

The Timperley Shale is similar to the McAlly Shale to the west of the Halls Creek Mobile Zone, and is tentatively correlated with it. It is easily eroded and invariably forms soil or sand-covered plains; exposures are found only in the banks of incised streams. As the outcrops are invariably small and sporadic, our knowledge of the formation is very limited.

The thickness of the type section was measured as 4,000 feet by tape and Abney level, but as the dip of the beds is not known over much of the section, the thickness must be regarded as approximate only. Measurement on air-photographs in other localities indicates that the formation is probably not less than 3,000 feet thick and that it could be up to 5,000 thick, in places.

The bulk of the Timperley Shale consists of interlaminated shale and siltstone in about equal proportions. Both invariably contain small flakes of detrital muscovite, and some diagenetic illite (V. M. Bofinger, pers. comm.). Unlike the McAlly Shale, which commonly shows fine cross-bedding, the laminae in the Timperley Shale are generally very regular and very thin, although they range up to one-quarter of an inch thick. No graded bedding was noted, and cross-bedding is rare.

The upper few hundred feet of the formation is coarse in grain and consists of siltstone and interbedded flaggy quartz sandstone. The sandstone is green or brown, fine-grained, and rarely calcareous. In thin section the rock is seen to be a fine-grained subgreywacke composed of quartz, carbonate, feldspar, rock fragments, and a little iron oxide.

Towards the bottom of the type section there are several prominent bands of light-coloured fine-grained calcareous quartz sandstone up to 50 feet thick, interbedded with the green shale; these bands do not appear to be present to the north.

The formation is remarkably similar to the McAlly Shale which crops out west of the Halls Creek Mobine Zone about 32 miles away, and the two are almost certainly correlatives. The McAlly Shale is possibly thicker, though this is hard to prove on the available information; and it contains black carbonaceous, and in places pyritic, shale which has not been seen in the Timperley Shale.

Nyuless Sandstone

Definition

Lithology: Fine to medium-grained clean quartz sandstone.

Distribution: As for Timperley Shale.

Derivation of Name: Named by J. W. Smith after Nyuless Creek 10 miles east-north-east of Flora Valley homestead.

Type Area: East and southeast of Flora Valley homestead. Type section measured 12 miles south of homestead (18°30'S., 128°00'E.).

Stratigraphic Relationships: Conformable between Timperley Shale and Flat Rock Formation. Upper and lower boundaries gradational over about 100 feet; boundaries placed where quartz sandstone becomes preponderant.

Thickness: About 125 feet.

Age: Late Adelaidean.

Description

The Nyuless Sandstone is much more resistant than the enclosing formations, and forms bold ridges up to 150 feet high in the otherwise monotonous plains.

The formation consists entirely of sandstone except for the top and bottom few feet. The sandstone is fine to medium-grained, and consists of well rounded grains of quartz and iron oxides coated with minor amounts of fine-grained siliceous material, which when ferruginous imparts a pink colour to the normally grey rock. Clay pellets are common throughout the formation. The formation has a flaggy outcrop in the bottom half which grades into blocky or massive outcrop near the top. Laminae or thin bedding can commonly be distinguished in good exposures, and cross-bedding is common near the top.

Flat Rock Formation

Definition

Lithology: Mainly fine-grained ferruginous and generally dolomitic sandstone, which crops out as large flatlying slabs, with interbeds of siltstone.

Distribution: Restricted to area east and southeast of Flora Downs homestead.

Derivation of Name: Named by J. W. Smith after Flat Rock Yard 12 miles south of Flora Valley homestead (18°28'S., 128°5'E.).

Type Area: Area of outcrop. No type section measured.

Stratigraphic Relations: Conformably overlies Nyuless Sandstone and overlain with angular unconformity by Lower Cambrian Antrim Plateau Volcanics.

Thickness: Greatest thickness preserved beneath Antrim Plateau Volcanics about 1,000 feet.

Age: Late Adelaidean.

Description

The Flat Rock Formation, as its name implies, generally crops out as broad structural benches capped by extensive slabs of resistant sandstone separated by areas of sandy alluvium covering less resistant and finer-grained beds.

The sandstone is purple or purple-brown, fine-grained, ferruginous, and commonly dolomitic or calcareous. The beds are generally less than 1 foot thick and are mostly massive, though laminae can sometimes be seen on freshly broken surfaces; ripple marks are common, but cross-bedding was not seen. The intervening beds are rarely seen, so little is known of them, but they appear to be mostly shale and siltstone.

ECONOMIC GEOLOGY

Gold is the only mineral which has been produced in quantity from the East Kimberley region. Records of the Mines Department of Western Australia show that over 29,000 fine ounces of gold were produced up to 1963 (Table 21), but the returns to the Royal Mint (Traves, 1955) indicate that the total output was over 38,000 ounces. Most of the gold was produced before the turn of the century, and since then only small quantities have been produced by European and Aboriginal fossickers, and by spasmodic attempts at lode mining. There seems to be little prospect of large lodes or alluvial deposits being discovered.

Small deposits of many metallic minerals, particularly copper, are known throughout the region, most of which have been discovered by prospectors or cattlemen. Though there has been a little production from some of the deposits, no large orebodies have been found, and until 1964 only a few of the known deposits had been tested. In 1964, Pickands Mather and Company International started a programme of stream sediment sampling covering 30,000 square miles of potential mineral-bearing country in the Kimberley region. The area examined includes the Halls Creek Mobile Zone, where several promising geochemical anomalies have been found.

One of the most interesting areas is the Sophie Downs/Saunders Creek region, where several new shows of copper minerals were found in the Biscay Formation during the present survey. Though Peko Mines N.L. drilled the most promising of these, Ilmars prospect, without striking significant grades of mineralization, much more work needs to be done before the potential of the region, and particularly the Biscay Formation, can be assessed.

Traces of nickel and platinum have been found in serpentinized peridotite of the Alice Downs Ultrabasics, and in spite of the poor surface indications, these rocks are worthy of detailed investigation.

Asbestos

Ramifying lenticular seams of asbestos occur 6 miles north of Lamboo homestead in a sill of serpentinized peridotite of the Alice Downs Ultrabasics, but the mineral has been identified as a fibrous variety of anthophyllite (C. D. Branch, BMR, pers. comm.), which is of little commercial value.

The asbestos is of the cross-fibre type and is generally straight, though bent fibres are not uncommon. Most of the veins have a fibre length of less than half an inch, but there are pods of brittle fibre up to 6 inches long. The asbestos is confined to a zone about 20 feet thick near the margin of the sill, and can be traced most of the way round the sill over a distance of several miles. The fibres generally appear to constitute a small proportion of the rock.

Bands of magnetite up to half an inch thick commonly line the contact between the asbestos and serpentinite; blades of magnetite project from the bands into the asbestos parallel to the fibre, and in places the magnetite constitutes up to 20 percent of the seam by volume. Vugs lined with small quartz crystals are commonly associated with the magnetite.

Disseminated garnierite is present in the lateritized ultramafic rocks, and there is a possibility of finding concentrations of secondary nickel silicates in the area.

A small uneconomic deposit of chrysotile occurs north of the junction of the Ord and Negri Rivers in serpentinized dolomite overlying the Moonlight Valley Tillite (Harms, 1959). The chrysotile occurs as numerous lenticular seams of small extent, and fibres are up to 1 inch long. The dolomite is overlain by Antrim Plateau Volcanics, and the deposit is believed to have been formed by contact metamorphism.

Chromium

Chromite has been found in the Alice Downs Ultrabasics north of Lamboo homestead, and in the Panton Sill about 32 miles north of Halls Creek.* The deposit in the Panton Sill consists of disseminated grains, primary segregated bands, and secondary veins. One zone, which is up to 30 feet wide and over a mile long, consists of steeply dipping bands of chromite up to 1 inch thick intercalated with altered ultrabasic rocks. In addition, secondary chromite veins, up to 300 feet long and 2 feet wide, occur in magnesite within the Panton Sill. Assays of samples from the deposits gave the following results:

Cr (%)	*Fe* (%)	*Ni* (%)	*Pt* (dwt/ton)
	Primary Band		
11.5	20.1	—	—
12.5	—	0.15	0.4
	Secondary Veins		
19.47	22.3	—	—
22.3	—	0.12	—
21.7	—	0.2	2.0
19.5	—	0.09	1.5

The Lamboo deposit is about 6 miles north of the homestead, near the base of a body of serpentinized peridotite. The chromite occurs in a zone, about 20 feet wide, which can be traced around most of the peridotite body; it occurs as bands up to 6 inches thick, which may have resulted from gravity differentiation. The deposits are too small and low in grade, and contain too high a proportion of iron, to be a source of chromium, but they deserve prospecting for their platinum content (see p. 114).

* Chromite has also been found about 5 miles south of Mt Bertram (Gellaty & Soufoulis, in prep.).

Copper

Copper minerals are widespread in the East Kimberley region in rocks of many ages, but most owe their discovery to the extensive staining of the secondary copper minerals in even the smallest deposits. Almost all the known occurrences are of no economic interest, but three deposits in the Biscay Formation have been tested by diamond drilling: Ilmars prospect, Angelo prospect, and a prospect at Saunders Creek.

Ilmars prospect, 16 miles northeast of Halls Creek, was discovered in 1963 by Gemuts (1963). The gossan crops out 200 yards from the road to Saunders Creek, near the crest of a sharp ridge about 50 feet high. The host rocks are the isoclinally folded lower carbonate horizon of the Biscay Formation (see p. 64).

The gossan occurs in two bands of thin-bedded dolomitic shale which are generally separated by a leached zone, commonly heavily impregnated with limonite, cuprite, malachite, minor azurite, and rare smithsonite and cerussite. The gossan strikes north and dips 65° west. It is 850 feet long and averages about 60 feet wide, but over most of its length it is split by a horse, about 15 feet wide, of unmineralized tremolite-bearing calc-silicate rock. The footwall gossan is 25 feet wide and contains abundant secondary copper minerals in bands and small lenses. A sample assayed by the Bureau of Mineral Resources was found to contain 19.1 percent copper, 0.34 percent lead, and 1.0 percent zinc. The hangingwall lens is up to 34 feet wide, and consists mainly of limonite-impregnated dolomitic rocks containing patches of cuprite and malachite.

The mineralization follows a shear zone trending about 5° northwest of the regional strike. The prospect appears to be confined to the carbonate rocks which have been folded into an isoclinal syncline plunging north at about 18°, and as the keel of the syncline would be at no great depth below the prospect ridge, the copper mineralization could be shallow. Any extension of the lode would be to the north in the direction of the plunge of the folds, and the presence of two shear zones, about 1,000 and 3,000 feet to the north-northeast of the prospect, may represent an extension of the lode. The shear zones are impregnated with limonite and stained with malachite; one is 700 feet long and the other 100 feet long, and both are a few feet wide.

Peko Mines N.L. put down several diamond drill holes in 1963, most of them directly below the gossan, apparently without striking any worthwhile mineralization. Little drilling has been done to test the possible northerly extension of the lode.

The *Angelo prospect,* 20 miles southwest of Halls Creek, occurs in basic volcanic(?) rocks, greywacke, and intercalated dolomite pods which probably belong to the Biscay Formation. The area is poorly exposed and structurally complex and the relationship with the surrounding Olympio Formation is uncertain.

The prospect consists of two gossans composed of limonite with small patches of hematite, cuprite, malachite, and azurite; the larger gossan is over 200 feet long by about 60 feet wide, and the smaller is 200 feet by about 40 feet. The copper minerals are not visible on the surface, but they can be found in most places by breaking the gossan.

Following a geophysical investigation of the prospect, Peko Mines N.L. put down several diamond drill holes in 1962-63; they proved reserves of 500,000 tons comprising 200,000 tons of primary ore (2.3% Cu), 200,000 tons of secondary ore (2-4% Cu), and 100,000 tons of pyritic ore (0.5% Cu) (McNeil, 1966).

Saunders Creek Copper Prospect: Showings of copper minerals north of Saunders Creek uranium prospect have been known for many years, and a strong self-potential anomaly was located nearby by Peko Mines N.L. in 1962. The anomaly was drilled in the same year, but it is reported that only disseminated pyrite in shale was encountered.

The Biscay Formation offers the best prospects for economic concentrations of base metal mineralization. The dolomitic rocks in particular are favourable host rocks and deserve detailed geophysical or geochemical prospecting. In 1964 and 1965 Pickands Mather & Company International conducted a reconnaissance stream sampling programme over almost the whole of the East Kimberley region, and the most promising geochemical anomalies have been found in the lower half of the Biscay Formation, including the lower dolomite horizon (R. Schmidt, Pickands Mather & Co. Int., pers. comm.).

Copper mineralization was noted during the present survey in dolomitic rocks of the Biscay Formation about 3 miles northwest of Mount Coghlan, but the extent of the mineralization is not known. Two small shows of copper minerals occur in similar dolomite 1½ miles northwest and about 2 miles north of Halls Creek; they were investigated by Peko Mines N.L., but apparently proved of little interest as no further work was done.

About a mile southwest of Ilmars prospect there is a siliceous gossan, discovered during the present survey, about 1,300 feet long and up to 75 feet wide; it strikes north and dips steeply to the west. It forms a razor-backed ridge cut about midway by a small westerly flowing stream. The gossan occurs in sheared dolomite and is heavily impregnated with limonite and cryptocrystalline quartz. It contains patches of secondary copper minerals, but these are small and sporadic and the deposit does not appear to be of economic value.

Several large gossans rich in iron and manganese were found in carbonate rocks on the northern end and western flank of the Black Rock Anticline. The host rocks are part of the Tickalara Metamorphics, which are regarded as the more highly metamorphosed counterpart of the Biscay Formation. Despite an extensive search, no trace of base metals was found in the gossans, but samples of the stream sediments in the vicinity were found to contain anomalous molybdenum values, and grab samples of the more highly manganiferous lodes were found to contain 800 parts per million of molybdenum and anomalous copper values. This area needs detailed prospecting.

All other known copper deposits are small, and only a few have been tested by pits or trenches. The known deposits are listed below in order of the decreasing age of the host rocks. Most of the occurrence were located during the current survey, but information on those not visited has been extracted from the comprehensive unpublished report by Harms (1959).

Ding Dong Downs Formation: Native copper has been recorded in quartz-calcite amygdales in the highly epidotized basalt of the Ding Dong Downs Formation 2 miles south-southwest of Bulman Waterhole. The mineralization is near the contact with the Saunders Creek Formation, and consists of scattered crystals of pyrite and altered magnetite surrounded by a halo of malachite staining. The known mineralized area is only about 20 feet by 10 feet, and one sample of the basalt without amygdales assayed only 0.07 percent copper. The deposit is of no commercial significance, but as thin persistent veins of quartz and native copper, up to an inch wide, are known in the basalt in the same locality (J. Carruthers, pers. comm.), we consider that the Ding Dong Downs Formation warrants further prospecting.

Biscay Formation: See pages 100-101.

Olympio Formation: Most of the gold lodes in the Biscay Formation and the basal part of the Olympio Formation contain subordinate sulphides, including some chalcopyrite.

Disseminated copper minerals are known in greywacke south of *Hangmans Creek Bore,* and a small lode of high-grade secondary copper minerals, about 100 feet long and up to 3 feet wide, is exposed west of the road to Cummins Range, about 5 miles south of *Mount Dockerell.* Copper minerals were found in Olympio Formation sediments three-quarters of a mile south of *Koongie Park homestead* during well sinking, but there is no information on the size or depth of the deposit. About 4 miles south-southwest of this locality there is a small deposit of copper minerals. All these deposits are too small to be of economic importance.

Lamboo Complex: The numerous small deposits of copper minerals in the Lamboo Complex are listed below; the mineralized zones are confined to small shear zones and are rarely over 50 feet long or 2 feet wide.

The largest is an iron-rich gossan, containing abundant secondary copper minerals, 4½ miles southeast of *Margaret River homestead;* it occurs in a small inlier of amphibolite of the McIntosh Gabbro exposed beneath Tertiary limestone. The gossan extends discontinuously over a strike length of 260 feet and is up to 30 feet wide. No work has been done on this deposit, which appears to warrant some trenching to determine the size of the gossan, much of which is covered by thin travertine.

Copper mineralization about 3 miles southwest of the Mount Angelo prospect was prospected under option by Conzinc Riotinto of Australia Ltd. The host rocks are amphibolite and probably some greywacke, intruded by granite, all now highly sheared, and though the mineralization is extensive, it appears to be very low grade.

Matheson & Guppy (1949) reported the finding of a boulder containing good copper mineralization along the telegraph line southwest of the outlier of Kimberley Group rocks, to the southwest of *Moola Bulla homestead.*

Minor shows of secondary copper minerals occur in granite about a mile northeast of *New Lamboo homestead* (B. Taylor, pers. comm.).

Small quartz veins containing chalcopyrite are common near *Me No Savvy Yard* near the junction of the Margaret and Glidden Rivers, but all of them are only a few inches wide and a few feet long. A trace of disseminated chalcopyrite is found in a dolerite dyke about 4 miles east-northeast of *Mount Amherst out-station.*

A grab sample from a large gossanous quartz reef adjacent to the road 9 miles northeast of *Mount Angelo* was found to contain 100 ppm Ni, 40 ppm Co, 2,000 ppm Cu, 600 ppm Pb, 4 ppm Ag, 50 ppm Mo, 200 ppm Sn, and 1,400 ppm Zn. The reef warrants further prospecting.

Small shears containing low-grade chalcopyrite, the largest about 100 feet long by about 2 feet wide, are common in the dolomitic rocks of the Tickalara Metamorphics east of the Mabel Downs Granodiorite between the *Ord River* and *Turkey Creek.* Those encountered during the present survey are shown on the map, but others have been reported, many near Corkwood Bore (Harms, 1959); none appear to offer any prospect of economic concentrations.

Two small copper-bearing shears in Tickalara Metamorphics occur near the Great Northern Highway south of *Mabel Downs homestead,* one near Tickalara Bore and the other near Froghollow Spring. Both are in Tickalara Metamorphics.

Harms has reported surface stainings of copper minerals, assaying up to 1.7 percent copper, in dolerite about 4 miles northeast of the *Fourteen Mile Bore* at approximately 17°40′S., 128°00′E., and a small quartz copper carbonate vein about 4 miles northeast of Roses Bore at 17°44′S., 127°50′E. Neither of the deposits was located during the present survey.

McHales copper prospect occurs in sheared granite about 7 miles southeast of Turkey Creek. Some trenches have been dug across the lode which consists of small lenticular bodies of malachite and chalcocite.

Whitewater Volcanics: Small amounts of copper mineralization were noted in two localities in the Whitewater Volcanics: (i) carbonate stains on the surface of a waterfall in a creek 5 miles south of the Dunham River Jump Up; (ii) 6 miles northeast of Moonlight Valley Yard (16°26′30″S., 128°7′E.) there is a thin isolated vein of quartz, arsenopyrite, and minor chalcopyrite. The vein could only be traced for a few inches in the acid volcanics adjacent to the basic dyke, and in neither of the localities is the mineralization of commercial significance.

Fish Hole Dolerite: Small shows of malachite and azurite have been known in the Fish Hole Dolerite for many years, and several new occurrences were found during the current survey, but none of them is over 50 feet long or 2 feet wide. Samples of sediment from streams draining the area were found to have a high content of copper and nickel, but it seems unlikely that economic concentrations are present in the volcanics. The dolerite of the Ding Dong Downs Formation, which contains copper mineralization, may be intrusive, and may be of the same age as the Fish Hole Dolerite. This would explain the similarity in the proportion of the trace elements present in the stream sediments draining the Ding Dong Downs Formation (R. Schmidt, pers. comm.).

Older Dolerites Intruding the O'Donnell Formation: Malachite and azurite coat joints in uralitized dolerite intruding the O'Donnell Formation 1½ miles southwest of Moonlight Valley Yard in the Lissadell Sheet area (16°30′30″S., 128°02′30″E.).

Carson Volcanics: Traces of secondary copper mineral and disseminated chalcopyrite were noted in amygdales in many localities throughout the map area, most commonly in the lowermost lava flows of the volcanics. A little disseminated chalcopyrite is common in other parts of the formation . No prospecting has been done on these rocks, but the grade of the deposits examined was always very low.

Elgee Siltstone: Small flakes of azurite coat the bedding planes of the Elgee Siltstone west of the Chamberlain River at 16°57′S., 127°38′20″E., but the occurrence is of no economic significance.

Mendena Formation: Harms (1959) has recorded 'minor veinlets of copper carbonate, oxides and chalcocite in a siltstone a few chains south' of Plants homestead. The veins range up to 4 feet long and 3 inches wide. Only flakes of carbonate on joints were seen during the present survey.

Hart Dolerite: Traces of copper carbonate have been recorded in the Speewah Sill: (i) Martins silver-lead prospect (16°12′S., 127°58′E.) contains scattered patches of azurite and malachite in quartz (Harms, 1959), and (ii) azurite was noted in a shear zone associated with epidote and quartz about 5 miles north of the Speewah homestead. Traces of disseminated chalcopyrite are common in the Hart Dolerite throughout the map area.

Antrim Plateau Volcanics: Small occurrences of copper minerals have been reported from widely separated localities in the Antrim Plateau Volcanics. Most of them consist of carbonates, chalcocite, and cuprite: native copper is also found, either as vesicle fillings or as sparse disseminations. The basalt immediately underlying Headleys Limestone in the Rosewood Wall area contains no visible copper minerals, but channel samples 6 feet long across it assayed about 0.6 percent copper (Harms, 1959). Other samples from the same horizon a short distance away showed no significant copper content, but the possibility of finding economic low-grade copper bodies in the Antrim Plateau Volcanics cannot be discounted.

Headleys Limestone: Minor copper stains are found in the Headleys Limestone in widespread localities in the map area. The largest are found in the Rosewood Wall, near Old Lissadell homestead, and south of Bungle Bungle outcamp, but all are of small extent and low grade.

The mineralization in the Rosewood Wall consists of disseminated and nodular chalcocite and associated secondary carbonates which are generally concentrated near the base of the formation. Discontinuous patches of mineralization occur over a distance of 3 miles, and assays from two shallow trenches gave the following results (Harms, 1959):

Costean 1	0.18 percent Cu over 11 feet
Costean 2	5.82 percent Cu over 6 feet

The values are consistently low except for 30 inches of 11.5 percent copper in costean 2 which have unduly weighted the results.

Matheson & Teichert (1948) have suggested that the copper has been leached from the volcanics by surface waters and fixed by the limestone. Alternatively, it may have been deposited in the sediments from water enriched in copper by the volcanic rocks.

Small very low-grade patches of secondary copper minerals are widespread in the uppermost limestone of the *Hudson Formation* near Mount Elder, and north of Mistake Creek homestead; these are almost certainly of sedimentary origin. Minor copper carbonates also occur in joints in Cambrian limestone underlying the Ragged Range Conglomerate on the western scarp of the Ragged Range, but the occurrences are of no economic significance.

Gold

Gold was discovered in the Kimberley region in 1884 by Hardman (1885) during a geological reconnaissance of the area. He reported promising alluvial prospects over a large area of metamorphic rocks, and in the ensuing rush large quantities of gold were quickly won. However, the auriferous gravels, though mostly rich, were thin and of small extent, and the field was rapidly worked out. By 1890, when Woodward (1891) visited the field, there were very few alluvial miners still working.

Most of the alluvial gold was readily traced to its source, and by the time of Woodward's visit, all the reefs known today had been discovered, partly developed, and abandoned. Few of the mines were profitable, and the history of the Mount Bradley mine as related by Attwater (1900) is typical:

'The history as read in the Warden's "Register" is one continuous series of liens, claims, caveats, and transfers, until in August 1892, the whole property, then vested in the name of Duncan Buchanan, was sold to the notorious Jacksons Reefing Company. The work up to this time consisted mainly of the two southerly shafts and the eastern tunnel. The Jacksons Reefing Company soon afterwards went hopelessly bankrupt, and W. J. Coleman, then the store and hotel keeper at Brockman (the Mount Bradley township), lodged a claim for £300 due for stores and obtained judgement, in spite of the fact that a large sum was owing for wages. The property was sold by the Sheriff and bought in by Coleman for £300. Coleman abandoned all the claims, leases, etc., except the Mount Bradley, removed the 10 head Mill and Machinery from the Caroline pool, three miles from Halls Creek, to the 5 acre Machinery Area, which he took up for the purpose, and let the Mine on tribute to one Esau, an Afghan, and Simon de Putz, a mechanic. These two worked the Mine energetically and, for a time, profitably, during which period Coleman gathered in most of the batteries and plants in the district for debts. Finally the good ore became exhausted, and de Putz cleared out leaving Esau in debt to Coleman. The Afghan worked off the debt and was given a half interest in the Mine on condition of his working it. Coleman offered the Mine for sale in London.'

The small size of the reefs, remoteness of the area, lack of water and fuel, and in some cases, the mineralogy of the ores, all contributed to the failure of the mines (Woodward, 1891). Since Attwater's time spasmodic attempts have been made to reopen the larger mines, but all were apparently unprofitable, and there appears to be no prospect of a sizeable orebody being found. The following comment made by Smith (1898) is still pertinent: 'The past history of this field will, I think, be the future history of the field. Patches of alluvial gold, and small veins of uncertain continuance, will be found at rare intervals, which will pay working shareholders well for a few months.'

The gold mines were reported on by Woodward (1891), Smith (1898), and Blatchford (1928), but the only systematic work was done by Finucane and Sullivan in 1937-38. Their findings were published in the AGGSNA series of reports and are a valuable reference (Finucane, 1938a; Finucane, 1939a,b,c; Finucane & Sullivan, 1939).

TABLE 21. MINERAL PRODUCTION
(up to December 1963)

		GOLD			
				Reef Gold	
Name of Mine (No. of claim)	Year	Alluvial Gold (oz)	Dollied Gold (oz)	Ore Treated (tons)	Output (oz)
Mary River Goldfield (Total production—1,312.23 oz)					
Reform (60)	Before 1897			399	210.03
Newlook (119)	Before 1897	82.66	951.52		
PA99	1940-41			46.85	53.66
PA151	1950		14.36		
Mount Dockerell Goldfield (Total production—1,358.4 oz)					
Lady Hopetown (47)	Before 1897			40	322.77
Victoria (7)	Before 1897			4	113.16
PA59	1935			36	25.24
(?)	1935				25.89
Mount Miniard (81)	1935-36			184	169.71
Western Lead (85)	1935-42			216	75.53
Irish Lass (95)	1937-43	9.17	13.66	341	266.75
Old Mac (103)	1938-40			235	179.66
Erin-Go-Bragh	1939-41			61	53.32
PA75	1938		20.03		
PA102	1940			26	11.37
PA101	1940-41			82	24.18
(?)	1941			16	2.96
Old Golden Dream (112)	1941-42			92	25.19
PA137	1949	18.89	11.28		
Sundry claims	(?)			160	89.64
Halls Creek Area (Total production—685.06 oz)					
Jubilee (43)	Before 1897			23	450.23
Lady Broome (1)	Before 1897			400	27.53
(?)	Before 1928			94.6	62.68
PA84	1938-39			10	14.14
PA112	1941			9	15.27
PA118	1942			10	15.51
PA108	1942	27.72			
PA115	1943			81	52.08
PA158	1953			9	16.33
PA 161	1953			3.5	3.56
Brockman Area (Total production—3,327.55 oz)					
Afghan (48)	Before 1897			94	68.37
Brockman King (40)	Before 1897			85.3	35.89
Faugh-A-Ballagh (30)	Before 1897			15	15.96
Golden Crown (53)	Before 1897			1,153.5	1,281.20
Southern Cross (10)	Before 1897			5	2.98
Mount Bradley (109)	Before 1928			2,462	1,820.33
Mount Bradley (109)	1940-42			193	50.94
PA78	1938-39	7.62			
PA93	1939				0.98
PA97	1940		7.62	7.0	13.92
New Golden Crown (124)	1963			120	21.64
Grants Patch (Total production—435 oz)					
Lone Hand (?)					260.00
Comet (54)	Before 1897			28.7	147.23
Star of Kimberley (59)	Before 1897			1.0	0.73

TABLE 21. MINERAL PRODUCTION
(up to December 1963) (Cont.)

GOLD

Name of Mine (No. of claim)	Year	Alluvial Gold (oz)	Dollied Gold (oz)	Reef Gold Ore Treated (tons)	Reef Gold Output (oz)
Perseverance (58)	Before 1897			5.0	2.75
(?)	Up to 1928			3.0	15.01
PA96	1940			3.15	3.00
PA162	1955		6.28		
Ruby Creek (Total production—11,567.32 oz)					
North Ruby Queen (44)	Before 1897			191	186.08
Rising Sun (42)	Before 1897			577	491.27
Sunny Corner (31)	Before 1897			22	59.27
West and Left (24)	Before 1897			679.5	948.91
St Lawrence (61)	Before 1902			377	89.00
Ruby Queen (61)	Before 1908			9,678	6,216.22
(?)	Before 1928			151	127.28
PA79	1938			92	22.98
St Lawrence (100)	1938			10	11.32
West and Left (96)	1938-41			10	5.30
Goliath (98)	1938-42			120.7	103.72
PA91	1939			12	4.25
PA93	1939		11.51		
PA96	1939			11.8	4.02
(?)	1939		1.05		
Shorts Hope (108)	1940			50	3.09
Goliath (98)	1940			6.5	6.18
Darcys mine (111)	1941-42		16.05	78	61.26
PA124	1947	12.71		8	6.03
Ruby Queen (97)	1897-1963		4.49	3,069.3	1,731.05
Other Returns (Total—11,042.8 oz)					
(Reported by banks and gold dealers up to December 1963)		8,973.1	2,057.06	0.75	12.64

Total Recorded Gold Production for the East Kimberley Region: 29,783.98 oz

TIN CONCENTRATES

	Year	Quantity Treated (tons)	Metallic Content (units)	Value (A£'s)
Mount Dockerell Area (Total—86.31 units valued at £598.38)				
PA120	1943	0.60	40.0	143.0
Crown Lands	1951	0.17	12.0	116.87
Crown Lands	1952	0.06	4.0	42.56
Sundry Leases	1962	0.46	30.31	295.95

LEAD CONCENTRATES

	Year	Quantity Treated (tons)	Lead (tons)	Value (A£'s)
Mount Amherst (Total—6.24 tons valued at £647.61)				
PA127	1948-49	6.53	4.51	356.62
Crown Lands	1952	2.73	1.73	290.99

SILVER

Total Production: 162.38 oz

The economic gold mineralization is confined to four auriferous belts: the Halls Creek/Ruby Creek area (by far the most important), Grants Patch centre, Mount Dockerell, and the headwaters of the Mary River; the latter was only a very small field, even by East Kimberley standards. The total recorded production from the field up to 1963 was 29,718 ounces of gold. By far the greater proportion was alluvial, and though the production figures given in Table 21 are the complete records of the Mines Department of Western Australia, probably only a small proportion of the gold mined last century was recorded.

The mineralization is identical in the four areas, and consists of steeply dipping small quartz fissure veins containing pyrite and small amounts of galena, sphalerite, and chalcopyrite; most of them are concordant with the foliation and bedding, and are commonly folded. As all the ore was recovered by amalgamation, the mines were worked only in the oxidized zone, where most of the gold occurred as finely divided free gold. However, coarse specimen stone was not uncommon, and it is still possible to find good samples in pillars left in some of the mines. Evidence of primitive smelting around the mines is common, but most appears to have been experimental as none of the reefs were large enough or rich enough to warrant cyanide treatment of the ore.

There is a strong stratigraphic control of the mineralization, and without exception the economic mines are confined to a narrow zone along the boundary between the Biscay and Olympio Formations. Large dolerite sills have also been intruded along this boundary, but they are older than the gold mineralization and do not appear to be genetically related to the gold: the boundary of the two formations was probably a favourable horizon for both the intrusion of the dolerite and the permeation of the mineralizing solutions. The origin of the mineralizing solutions is not known, but the association of base metal sulphides with the gold indicates a magmatic origin, possibly the Sophie Downs Granite.

Halls Creek/Ruby Creek Area (Finucane, 1939a)

By far the most important auriferous area in the East Kimberley region lies to the southeast of Halls Creek. Almost all the mines had been worked out by the turn of the century, and since then only a little gold has been won spasmodically by prospectors or small syndicates working the old mines. The most recent work was done on the Golden Crown mine by a small syndicate in 1962-63. The syndicate carried out considerable development work, including the sinking of a shaft about 100 feet deep and cross-cutting a similar distance to the lode, but the lode at depth was found to be very small and highly pyritic. Only 120 tons of ore were crushed for a return of 21.6 ounces of gold.

The original township of Halls Creek was situated 8 miles east of the present township, on the northern extremity of the auriferous area, but it was shifted to the present, more convenient location near the airstrip shortly before 1960. Now only the roofless remains of the more substantial rammed-earth buildings can be seen at the old site.

Most of the mines are confined to a narrow southwesterly trending belt, 12 miles long by about 5 miles wide, southwest of the old township. The most northerly mine is the Faugh-A-Ballagh; it is small and consists of a few pits and shallow shafts. Other mines of note, listed in order to the southeast, are: the Golden Crown, an open cut and minor underground workings on a small quartz reef intruding dolerite; the Lady Margaret, consisting of pits and shallow shafts on small quartz veins cutting across a dolerite dyke; and Mount Bradley, which was one of the largest and most productive mines in the area (see p. 105). The southern limit of the belt is marked by a complex series of folded reefs, the largest of which are the St Lawrence and Ruby Queen; the latter was the most productive mine in the East Kimberley region.

A short distance southwest of the old township there is a narrow belt, 1½ miles long, of small irregular quartz reefs on which many pits and shallow shafts have been sunk: the Jubilee mine at the southern end of the belt is the only mine of note.

The gold in the Halls Creek/Ruby Creek area occurs in small steeply dipping quartz reefs intruding the Halls Creek Group. The largest and most productive reefs occur in the basal sediments of the Olympio Formation, and most are near the large dolerite dyke which marks the top of the Biscay Formation: shale appears to be a favourable host, and the reefs are smaller and lower in grade in the arenaceous beds, though the Mount Bradley mine is a notable exception. The reefs are generally concordant with the bedding and foliation, and they commonly follow folded strata, but it is not known if they were intruded after or prior to the folding.

Some of the auriferous reefs occur in volcanic rocks near the top of the Biscay Formation, or in the prominent dolerite dyke at the top. These reefs are generally small and cut across the host rocks.

Only small portions of the reefs were auriferous, but some were very rich: in the larger mines the economic gold values occurred in steeply plunging shoots of ore. Most of the auriferous quartz of the area is smoky blue, and the gold occurs free; specimen stone containing scattered grains and thin stringers of gold can still be found in small pillars left in the Mount Bradley mine, and in dumps at the Ruby Queen. The unoxidized ore in most of the mines contains pyrite and galena, and some contains chalcopyrite.

The *Ruby Queen mine* is situated on a fairly well defined steeply dipping quartz reef intruding greywacke and shale of the Olympio Formation. The reef is about 1,100 feet long and forms the crest of a prominent strike ridge, which is breached by a steep gully near the southern end. The reef has been driven both north and south from the gully for a total distance of 585 feet, giving backs of 160 feet in places. A shaft which was sunk with government assistance reached 190 feet below the adit, but appears to have found little ore. The recorded production of the mine is 7,947 ounces of gold from 12,747 tons of ore, almost all of which was mined before 1908.

The *St Lawrence mine* worked a sinuous quartz reef about 500 feet long and 1 to 2 feet wide, which follows the structure of the host greywacke and shale of the Olympio Formation. The lode has been driven about 300 feet from an adit, and it has been stoped to the surface, up to 60 feet above. A winze was sunk 57 feet below the main drive, and some ore was stoped from this level, but the lode at depth seems to have been small and low grade (Smith, 1898). The reef was rich, and 1,599 ounces of gold were won from 1,387 tons of ore, but of this only 11 ounces were won after 1902.

The *Mount Bradley* reef crops out along the crest of a prominent ridge, and is visible from the Halls Creek/Flora Valley road. The reef is about 600 feet long and 4 to 12 feet wide, but the economic gold was confined to two steeply plunging shoots, each about 50 feet long and 120 feet deep. The development work on the mine includes two long adits, one from either side of the mine ridge, and a shaft which was sunk to about 180 feet below ground level. Total production is recorded as 1,871 ounces of gold from 2,655 tons of ore, almost all of which was mined before 1897.

Grants Patch Centre (Finucane, 1939b)

The Grants Patch centre is located near the middle reaches of the Panton River about 32 miles northeast of Halls Creek. The field was almost worked out when Woodward (1891) visited the area in 1890, and there were only three men working in the area. All the reefs now known had been found, and some development had been done, including the erection of a five-head battery, but the ore proved to be unsuitable for amalgamation, and lode mining had been abandoned by 1890. Finucane reported that the area was deserted in 1939, and little work has been done in the intervening years. The recorded production of the centre is 435 ounces of gold, of which 6 ounces was alluvial.

Although the auriferous reefs of the Grants Patch centre are narrow, they are longer and better defined than elsewhere in the East Kimberley region. Six of the reefs are between 450 and 700 feet long, but they rarely average more than 2 feet in width. The quartz is dark blue or dark grey, and glassy; it generally contains abundant pyrite, some galena, and rare chalcopyrite as disseminated grains, or more commonly as irregular patches. Boxworks and limonite patches and small gossans are common in the oxidized ore, but the oxidized zone is shallow over most of the field and sulphides can generally be found within a few feet of the surface.

The reefs occur within the Biscay Formation, mostly in greywacke or shale. They are concordant with the foliation, and commonly follow shears, rather than tension cracks as in other centres.

The gold is mostly associated with the sulphides, and values are very patchy (Finucane, 1939b). The sulphides inhibit the recovery of gold by amalgamation and tests done on the ore from the Star of Kimberley show that only 16 percent is recoverable by this method (Finucane, 1939b). This no doubt accounts for the very low tonnage of ore treated in the field. Cyanidation gives good recovery in some cases, but even with this method, the copper content of the ores would probably cause difficulties.

The field has no prospects because: (i) only by mining all the larger reefs would sufficient tonnage be available to justify the erection of a costly cyanide plant; (ii) gold values are low; samples collected by Finucane ranged from nil to 38 dwt of gold per ton, but the average of all the gold-bearing samples was only 5.5 dwt over an average width of less than 3 feet.

The Mary River Centre (Finucane & Sullivan, 1939)

The Mary River centre is located about 20 miles south-southwest of Halls Creek. Though 1,312 ounces of gold were recorded from this centre, all but 82 ounces from lodes (Table 21), the auriferous veins are very small. The returns show that most of the gold was dollied, and undoubtedly came from small rich shoots of which there is now no trace.

The veins are composed of quartz with minor pyrite, galena, and arsenopyrite. They occur in the Biscay Formation and are roughly concordant with the foliation. There are several large white quartz reefs in the area, mostly following faults, but they are not auriferous.

The largest workings are called the Reform mine. The reef is about 300 feet long, but is generally only a few inches wide: the auriferous shoot was confined to a section about 70 feet long which appears to have been a stockwork rather than a defined reef. It has been mined out by a shallow open cut.

A small stamp 'battery' (or mechanical dollypot), constructed of parts gleaned from the rest of the area, is the only sign of recent activity in the fields, but this is now abandoned. The area has been thoroughly prospected and provides no encouragement for future work.

Mount Dockerell Area (Finucane, 1938a)

The Mount Dockerell area, about 55 miles southwest of Halls Creek, is the most remote of the four auriferous belts in the East Kimberley region. Even now it is difficult of access and this is probably why it is the only centre where appreciable mining has taken place this century. The field was worked before 1891, and by 1897, 436 ounces of gold had been won, but by 1898 the field had been abandoned. Between 1935 and 1943, the field was revived and 902 ounces of gold were mined, but there has been almost no activity since then, apart from desultory alluvial mining by Aborigines during the wet season.

The auriferous reefs are found close to the contacts of a thick dolerite dyke of Woodward Dolerite which intrudes the Olympio Formation. Most of the reefs lie within the dolerite, but some are in greywacke and shale of the Olympio Formation intercalated with the dolerite. The stratigraphic position of the dyke is not known exactly because it is faulted on its western side, but it is thought to be near the base of the formation, and therefore on nearly the same horizon as the large dyke that intrudes the Olympio Formation in the Halls Creek/Ruby Queen area.

The auriferous veins are rarely over 100 feet long or 2 feet wide, and commonly contain a little galena, pyrite, and arsenopyrite in addition to free gold. Smith (1898) mentions that in one mine the quartz contained abundant galena which assayed 9 ounces of silver per ton and a trace of gold. The productive parts of the reefs were generally less than 30 feet long; economic gold values did not persist below a depth of 30 feet, though the deepest shafts are between 50 and 70 feet deep.

It is evident that a large amount of prospecting has been done in the field and there is little hope of other workable reefs being discovered. The only other lode mines known are: the *Duffers mine,* which consists of surface workings on a small reef in the basal part of the Olympio sediments, and was worked until recently; and small quartz reefs in Bow River Granite 6 miles north-northeast of Mount Amherst station from which small parcels of high-grade ore have been mined by pits. There is no record of production from these mines.

In addition to alluvial gold mined in the four auriferous belts already described (Finucane, 1939c), alluvial gold was also mined in the Black Elvire River to the northeast of Mount Coghlan. The workings were not located during the present survey, and no gold lodes are known in the area. During the present survey, a few prospecting pits on small quartz reefs were observed in the Olympio Creek Formation 6 miles south of the Ord River. Alluvial gold has been reported from Prospect Creek west of Argyle station in the Carr Boyd Range, and in the Golden Gate area southeast of Kununurra, but none was found in these areas by Harms (1959) or during the present survey.

Iron

Beds of low-grade siliceous hematite crop out for 10 miles along the crest of a high cuestal range, a few miles east of Pompeys Pillar, about 80 miles south of Wyndham. They have been examined by Harms (1959) and MacLeod (1963).

Only two deposits approach ore grade: the *Pompeys Pillar* deposit about 4 miles east of Pompeys Pillar and the *Matsu deposit* about 9 miles to the southeast. Both deposits occur near the base of the Golden Gate Siltstone, but they are separated by the Ivanhoe Fault, which has displaced the Matsu deposit about 10,000 feet to the east of the Pompeys Pillar deposit. The larger Matsu deposit is lower in grade and more difficult of access.

The deposits cap the dip slope of the cuestal range, and the iron-rich zone, which is up to 35 feet thick, consists of beds of massive sandy hematite, and hematitic sandstone, interbedded with ferruginous shale and quartz sandstone. The presence of cross-bedding in the massive hematite indicates a clastic origin, and the associated sandstone shows abundant shallow-water sedimentary features. Superficial pisolitic and botryoidal goethite occurs on weathered surfaces.

Pompeys Pillar Deposit

The ferruginous beds of Pompeys Pillar have been repeated by strike faulting and are known as the 'western' and the 'eastern' deposits.

The *western deposit* is accessible by four-wheel-drive vehicle; it was tested by drilling in 1962, and more exhaustively in 1963-64, but the results are not available for publication. The deposit is about 9,000 feet long, 15 to 35 feet thick, and up to 400 feet wide (MacLeod, 1963). From a brief study of the surface outcrops, MacLeod estimated that 3 to 5 million tons of ore containing over 60 percent iron could be selectively mined. Silica is the main impurity. The *eastern deposit* is much smaller and the total reserves were estimated by MacLeod as 2.2 million tons.

Matsu Deposit

The Matsu deposit caps a gentle dip slope for a width of several hundred feet; it crops out over a strike length of about 4 miles and is 35 feet thick. Individual beds contain up to 60 percent iron (Harms, 1959; MacLeod, 1963), but numerous intercalations of sandstone and shale make it unlikely that ore in excess of 50 percent iron could be mined by conventional techniques. Up to 20 million tons of iron-rich material is indicated, but only a small fraction of this can be considered as possible ore (MacLeod, 1963).

The overall low grade and limited extent of the deposits make it unlikely that they could be mined economically to provide direct shipping ore, but as the ore is coarsely granular it could conceivably be upgraded by beneficiation.

There are other iron-rich beds in the East Kimberley region, but none approaches ore grade. Five widely spaced beds, up to 20 feet thick, of hematitic sandstone, and minor sandy hematite and botryoidal hematite, crop out along the crest of the Bandicoot Range, 2 miles west of the Ord River Diversion Dam. They occur within the Bandicoot Range Beds of the Carr Boyd Group, and can be traced for 2 miles along strike. The deposits have not been tested or assayed, but visual examination indicates that the material probably contains less than 45 percent iron. Silica is the main impurity. The beds dip steeply and the deposits cannot be considered to be of economic importance.

Beds of hematitic sandstone up to 20 feet thick, and small bodies of massive hematite adjacent to dolerite intrusions, occur within the O'Donnell Formation between Dunham River homestead and the headwaters of the Wilson River. None of the deposits is of economic significance.

Two beds of ferruginous sandstone and siltstone, between 20 and 30 feet thick, crop out over a distance of about 9 miles on the southern side of the Osmond Range. They cap the Mount John Shale Member and consist of sand and silt cemented by limonite and hematite. Representative samples assayed less than 25 percent iron and the deposits have no commercial potential. The hematite fragments mantling the ground 4 miles west-southwest of Bungle Bungle in the Osmond Range have been derived from high dolomite hills containing pods up to several feet thick of siliceous hematite. They are associated with pods and veins of chert and probably result from weathering of the dolomite. The total iron content is small.

Lead

A small amount of lead and silver has been won from the Mount Amherst lead mine, about 6 miles north-northwest of Mount Amherst homestead.

The mine was examined in 1937 by Jones (1938), but up to that time no lead had been produced: it was worked in 1948 and 1952 when the price of lead was high, but the total output was only 6 tons of lead.

The lode consists of several quartz-carbonate veins in a zone about 350 feet long and up to 12 feet wide. The veins contain both galena and cerussite, and samples taken by Jones assayed up to 15.3 percent lead and 2.34 ounces of fine silver, over a width of 52 inches. The present state of the workings shows that only small high-grade patches were mined, and the deposit holds no promise of further production.

Similar but smaller quartz-carbonate veins occur to the south and east of the homestead and near Me No Savvy Yard, but they are of no economic significance. Small amounts of galena are generally found in the auriferous quartz reefs in the East Kimberley region (see pp. 107-112).

A little galena was found in 1964 by geologists of Pickands Mather International in sheared dolomitic siltstone and sandstone of the Lubbock Formation near Louisa Downs.

Nickel

The possibility of finding economic concentrations of nickel in the Alice Downs Ultrabasics cannot be discounted, although only traces of nickel have been found on the surface. The only nickel minerals seen were flakes of garnierite in asbestos minerals 6 miles north of Lamboo homestead.

The asbestos occurs in serpentinized peridotite, and the present land surface coincides with the base of an ancient laterite profile, and there is little doubt that the garnierite was formed by the concentration of nickel during lateritic weathering.

Economic concentrations of nickel may occur as lateritic concentrations in soils or as veins of nickel silicate in the zone of weathered rock (de Vletter, 1955). There is a possibility of economic concentrations of nickel in the zones of deeper weathering in the ultramafic rocks north of Lamboo homestead.

Nickel in ultramafic rock can also be mobilized by heat and pressure, and deposited in favourable structural environments such as faults and shatter zones. The Bow River Granite intrudes the ultramafic rocks north of Lamboo homestead, and it could conceivably have caused the concentration of nickel sulphide mineralization. Though no primary nickel sulphides were seen, any such mineralized zones would almost certainly be areas of no outcrop, and could probably only be detected by geophysical means.

Petroleum

Precambrian sediments are regarded unfavourably as source rocks for petroleum accumulations, and there is very little chance of commercial accumulations being found in the East Kimberley region.

After the discovery in 1920 of asphaltite in the Antrim Plateau Volcanics near the junction of the Ord and Negri Rivers, the Oakes-Durack Kimberley Oil Company drilled on an anticline in the Cambrian Negri Group near White Mountain. No indications of oil were found, and Wade (1924) stated that it was impossible that oil was present in commercial quantities in the East Kimberley region. Blatchford (1927b) and Hobson (1936) also reported unfavourably on the prospects of finding oil accumulations.

However, the source of the asphaltite is not known, and it could be the underlying Albert Edward Group. Certainly, in younger rocks the Timperley Shale would be regarded as a favourable source rock, and there are a number of dome structures in the Albert Edward Group capable of forming reservoirs.

Platinum

Grab samples from chromite bands in the Panton Sill assayed up to 2 pennyweights of platinum per ton (see p. 99). The Panton Sill has not been systematically prospected, but the presence of platinum in randomly chosen samples should encourage detailed mapping and sampling of the sill.

Silver

A few ounces of silver have been produced from the Mount Amherst lead mine, and a small amount has been produced as a by-product of the gold from the East Kimberley region.

Tin, Niobium, and Tantalum (Finucane, 1939b)

Cassiterite and columbite occur in pegmatites in the Mount Dockerell region, together with albite, muscovite, tourmaline, and minor spessartite. Tantalite has been reported from the area (Simpson, 1951), but there is no other record of its occurrence. Pegmatites which cut calcareous country rock commonly contain small amounts of fluorite and apatite.

The pegmatites may be irregular, tabular, or thin reef-like bodies. The dykes range up to 500 feet long and from 10 to 200 feet wide.

The alluvial deposits shed from the pegmatites have been worked from time to time. Total production from the field was 86.31 units of tin metal valued at £598/10/- (see Table 21).

Finucane (1938b) sampled the alluvial deposits of Columbium Creek, but there is only a small volume of gravel available; the deposits average less than half a pound of concentrate per cubic yard. The concentrates contain cassiterite and subordinate columbite.

The pegmatite lodes do not appear to have been adequately prospected, and there could be economic enrichments of cassiterite, columbite, and possibly tantalite. Some prospecting was done on the pegmatites by a private company in 1964, but the results of their work are not available.

Uranium

Uranium has been found in two localities in the East Kimberley region, and though some development work was done neither proved to be economic.

Saunders Creek prospect is situated about 20 miles northeast of Halls Creek on the western limb of a tight anticline in the Halls Creek Group. It was discovered late in 1954 by prospectors of United Uranium N.L., but little work was done until 1957. It was reported on by Walpole & Prichard (1958) and Ruker (1961). One diamond drill hole was put down in 1959, but no economic mineralization was found (Mercer, 1961).

The radioactivity is due mostly to sedimentary concentrations of thorogummite, which are confined to the basal quartz-pebble conglomerate, quartz sandstone, and subgreywacke of the Saunders Creek Formation. The drill hole was 734 feet long, and intersected the radioactive beds between 520 and 618 feet, or 400 to 450 feet below the surface, in unoxidized material. Assay results were disappointing, and the best values were 0.16 percent eU_3O_8 from 543 feet to 543 feet 4 inches, and 0.04 percent eU_3O_8 from 538 feet to 539 feet 4 inches. The most radioactive mineral from the core was identified by X-ray diffraction as thorogummite with a thorium/uranium ratio of 3:1 to 2:1. As the uranium values are low, the prospect was abandoned.

Dunham River Prospect. Uranium was discovered 5 miles south of Dunham River homestead by United Uranium N.L. in 1954. It is situated close to the Dunham Fault near the Dunham Jumpup.

The northern mineral leases (MC 39, 42; de la Hunty, 1955) cover a basic dyke intruding sheared granite. The radioactivity is caused by autunite lining joints in the dyke, but only a very small patch of mineralization was found and most of this was removed by a 15-foot prospecting shaft. The radioactivity of the dyke was tested for a distance of 4,000 feet, but only the prospect area gave anomalous readings.

The second prospect straddles the Great Northern Highway. To the north of the highway, several costeans cut the contact between sheared granite and the basal quartz sandstone of the O'Donnell Formation. Torbernite occurs as a band up to 4 inches wide, in sheared granite close to the sandstone. During 1963 the Department of Main Roads constructed a new road which passes immediately south of the prospect, but no further mineralization is visible in the road cutting.

To the south, other claims along the Dunham Fault, held by United Uranium N.L., were reported on by de la Hunty (1955). They were not located during the 1963 survey, but are apparently less important than the claims to the north.

WATER SUPPLY

by R. Passmore*

Previous Work

Observations on the hydrology of the East Kimberley region were first made in 1885 when Hardman recognized the principal drainage divide between the Ord and Margaret Rivers. Jack (1906) made an appraisal of the artesian groundwater prospects at Wyndham and other parts of the Kimberley region. He recommended deep drilling at Wyndham to intersect sandstone (Proterozoic) cropping out to the northwest, and predicted the water-bearing potential of basalt, limestone, and sandstone formations from the presence of springs. Some drilling results were reported by Maitland (1903, 1908, 1913). Matheson & Teichert (1948) noted the control exercized by faults and gentle folds on the occurrence of springs and lagoons in the Palaeozoic structural basins, and considered the fragmental and vesicular layers on the Antrim Plateau Volcanics to be useful aquifers. Similar conclusions were reached by Traves (1955), who also reported the production of usable water supplies from early and late Proterozoic rocks.

In 1950, the Western Australian Government introduced the Kimberley Water Supply Subsidy Scheme, designed to increase the number of permanent watering points. Under the scheme, the Government reimburses leaseholders for approved drilling operations which fail to produce useful supplies. To the end of 1965 about 60 sites had been drilled under the scheme in the East Kimberley region, and subsidy was paid on 21 of these. Most sites are inspected by geologists of the Geological Survey of Western Australia; reports on each inspection are filed by the Geological Survey and copies are sent to leaseholders. Berliat (1954, 1956) reported on prospective bore sites in the East Kimberley region and gave a general account of the water-bearing potential of some rock types. Ellis (1953) described conditions of occurrence and methods of exploitation of water supplies in some early Proterozoic crystalline rocks. Descriptions of the hydrogeology of parts

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of the area covered by this Bulletin are contained in unpublished Records of the Geological Survey of Western Australia (Morgan, 1963; Passmore, 1964; Allen, 1965, 1966a,b).

Drainage

The four main river basins—the Ord, Pentecost, Fitzroy, and Keep Rivers (Fig. 15)—drain to the sea, while Sturt Creek carries water inland to an unco-ordinated drainage area. Just over half of the map area lies within the Ord River

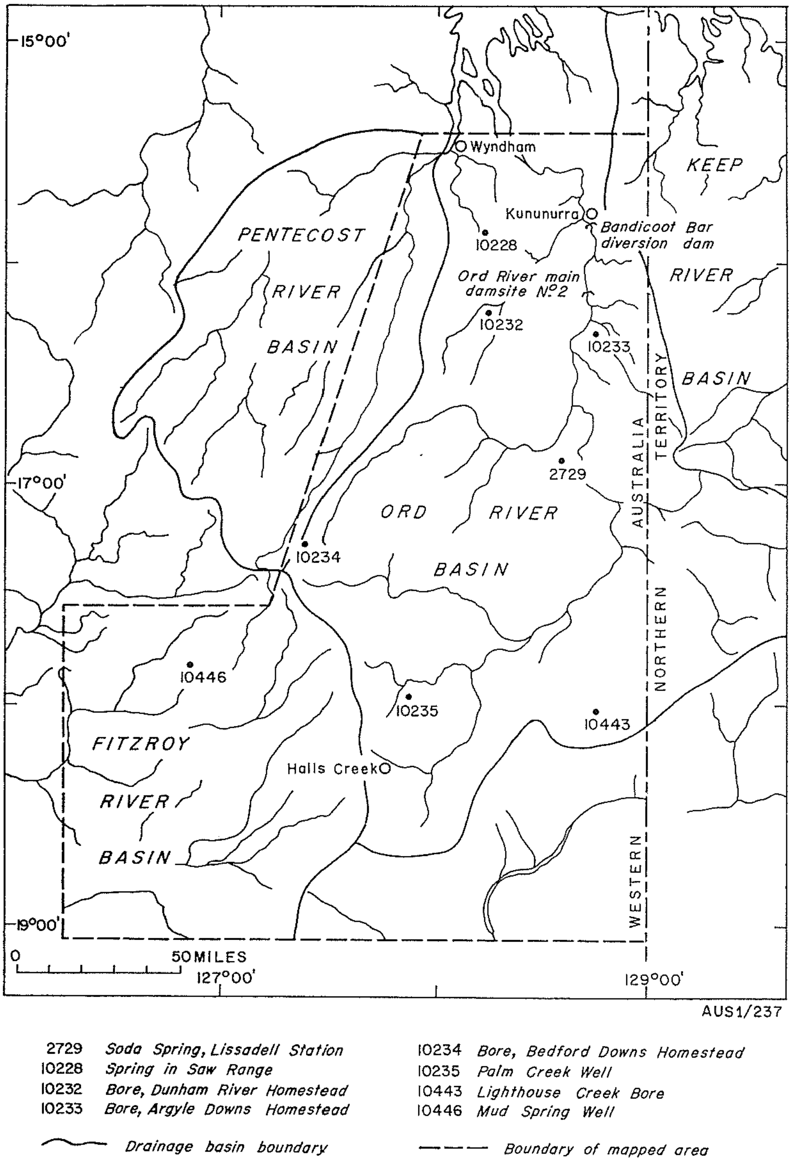

Figure 15. Drainage basins and water sampling points

Basin (about three-quarters of the total basin area of 21,000 square miles). The Fitzroy River Basin covers just over a quarter of the area, and the other three smaller basins cover the remainder.

A river gauging station at the Ord River main dam site No. 2 (Fig. 15) is operated by the Public Works Department of Western Australia to provide a measure of river flow from 17,800 square miles of catchment. Records since 1944 (P.W.D., W.Aust., 1964) indicate the average annual flow to be approximately 2,450,000 acre-feet. The river usually flows between the months of December and April. An approximate relationship between monthly percentage runoff (P) and effective rainfall (R_e, weighted mean of 10 measuring stations, adjusted for time-lag) was determined from the river flow figures to be $P = 1.44\ R_e^{1.5}$. From this, an effective rainfall of 5 inches in a month would yield 16 percent runoff. The remaining water is ponded or added to soil and aquifer storage, but much of the surface-stored and soil water is lost by evaporation (estimated at 90-100 in. per year).

The Ord River Basin encompasses a variety of rocks which differ in porosity, permeability, and runoff characteristics. The rainfall is generally unevenly distributed over the basin so that more rain falls on one rock type than another, and there are large variations from the calculated relationship ($P = 1.44\ R_e^{1.5}$) between runoff measured in the Ord River and rainfall measured at 10 localities in the basin. The capacity of rocks and soil cover to absorb rainfall increases in the general order: metamorphic and igneous rocks, limestone and shale, silicified sandstone, basalt and dolerite, lightly cemented sandstone, sandy soil, and alluvium. This has produced drainage patterns of increasingly open texture in about the same order.

During the dry season, permanent and semipermanent pools of water exist in many of the watercourses, and surface flow takes place in the lower reaches of the Pentecost River, Osmond Creek, and for short distances along others. The pools are maintained by groundwater flow from permeable and jointed rocks in localities where the watertable is higher than the river bed. Some of the pools are associated with faults and major joints which represent zones of increased permeability, and allow more ready intake and transmission of rainfall and shallow groundwater, or the release of pressure water from confining beds.

Alluvial deposits along most of the watercourses are restricted to the vicinity of the present channels, except in the lower reaches. In the upper reaches many creeks traverse bare rock or contain too little alluvium to provide storage for more than small quantities of groundwater, which in most cases is dissipated by evaporation and transpiration during the dry season. Permanent storage may exist in the thicker deposits of alluvium, such as those along the greater part of the Ord River. At the Ord River main dam site No. 2 the alluvium is 96 feet thick (Gordon, 1965), and capable of retaining large quantities of water as underflow.

Surface Storage

There is one major dam in the area, the Bandicoot Bar Diversion Dam on the Ord River at Kununurra. It was constructed in 1960-61, and has a capacity of 80,000 acre-feet; it is used to irrigate farms for cotton growing. Investigations for the foundations of the dam were reported by Wyatt (1960).

A larger dam to supply up to 1,250,000 acre-feet of irrigation water is designed for the Ord River main dam site No. 2. The engineering geology of the proposed dam site has been described by Wyatt (1960, 1962a,b), Gordon (1963, 1965), and Swarbrick (1965), and the results of engineering investigations have been summarized by the Public Works Department of Western Australia (1964).

Artificial surface storages are used very little by the pastoral industry, because of the high evaporation rate, and the intense and unreliable rainfall. There are probably fewer than 25 dams in the whole area. Springs and pools of water in watercourses are utilized to some degree, although many dry up during the year.

Town Water Supplies

Of the three townships in the area, Halls Creek and Kununurra utilize groundwater, whereas Wyndham obtains surface water from pools in the King River. At Halls Creek there are six bores supplying the town with 400 to 2,000 gallons per hour (gph) each, and five privately owned bores. They draw from volcanic rocks and metamorphosed sediments of the Halls Creek Group. The water is of low salinity and low hardness; a sample from one bore had 170 parts per million (ppm) dissolved solids and 50 ppm total hardness (as $CaCO_3$).

The Kununurra water supply has been produced from two of the six bores in the township, pumping from coarse alluvium of the Ord River valley. It is hard water, containing 270 ppm total hardness (as $CaCO_3$), but the soft water from the alternative source, the Bandicoot Bar Diversion Dam, is very turbid in the wet season. Two new bores drilled near the river in an attempt to find softer water yield large quantities of water with a total hardness of 200 ppm.

Water is piped 16 miles to Wyndham from natural pools in the King River with a capacity of 26 acre-feet. Exploration for underground supplies has been unsuccessful; some bores and wells sunk into shales near the township were low-yielding or saline (Maitland, 1903, 1908, 1913; Jack, 1906), and recent drilling into the Antrim Plateau Volcanics and Pentecost Sandstone has failed to produce large enough supplies. A dam site on Moochalabra Creek, 11 miles south of the town, is being investigated. The completed dam is expected to have a capacity of about 1,000 acre-feet.

Hydrogeology

In the East Kimberley region about 260 bores and wells provide water for stock or domestic use. Six groundwater provinces, based on the main lithological groups and the major structural elements, can be delineated (Fig. 16). They coincide with the Palaeozoic sedimentary basins (Ord and Bonaparte Gulf Basins), the Proterozoic sedimentary basins (Ord and Bonaparte Gulf Basins), the Proterozoic sedimentary rocks (Kimberley, Musgrave, and Osmond Range Provinces), and the Halls Creek Group and Lamboo Complex (Halls Creek Province). With the exception of the small Osmond Range Province they were defined by Mackay (1963). Each contains aquifers with characteristic hydrological properties, although the rocks typical of one province may be found in small areas of another. The aquifers and some of the provinces were described by Morgan (1963), Passmore (1964), and Allen (1966b) and the present description draws on these unpublished works.

Bore and well locations shown on the geological map, and data such as depth, supply, and water quality, were collected during the field seasons 1962 to 1964.

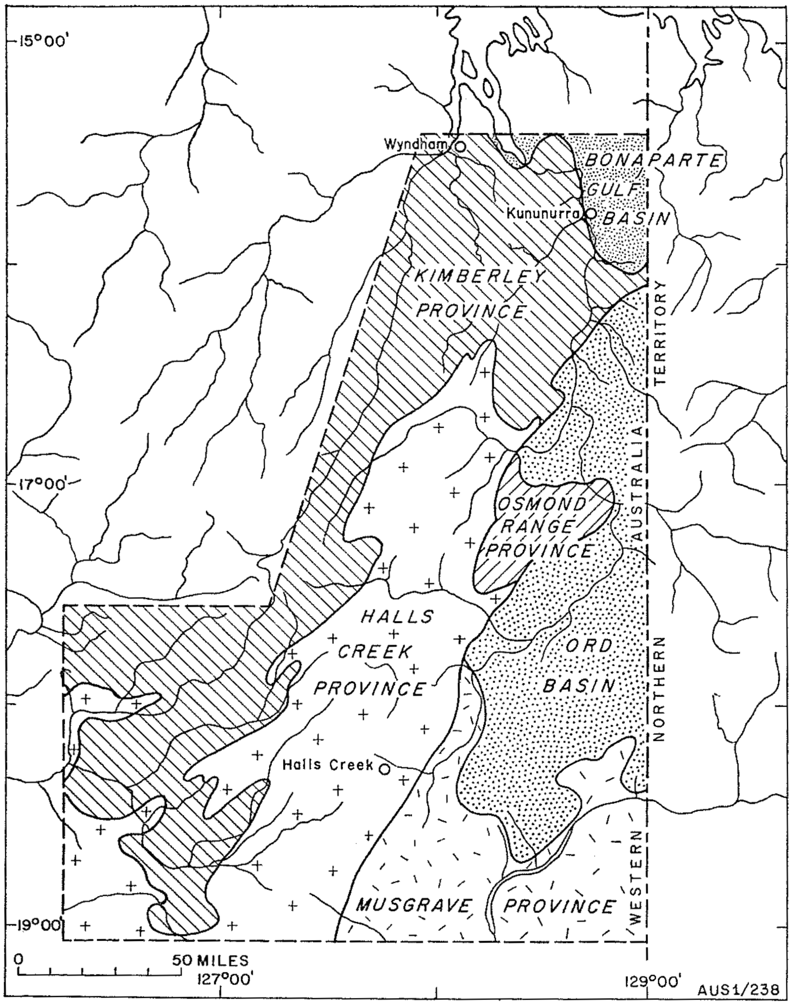

Figure 16. Groundwater provinces

The rates of supply are those reported by drillers, and the figures are of variable reliability. A bore under the subsidy scheme is considered to be successful if it produces over 500 gph, but on some stations bores yielding less than 1,000 gph are abandoned. The rate of production at cattle watering points depends on demand, but the average rate is probably less than 10,000 gallons per day.

Kimberley Province

The Kimberley Province has an area of about 53,000 square miles; it comprises the Kimberley and Mount Cumings Plateaux, their folded margins, and the Carr Boyd Ranges. Only 11,000 square miles along the eastern and southern margins of the province are included in the map area. Carpentarian sedimentary rocks (sandstone, siltstone, and shale), dolerite, and basic volcanic rocks predominate, but small areas of older crystalline rocks and Cambrian sediments and volcanics, mainly around the Carr Boyd Ranges, are included in the province.

TABLE 22. BORE DATA

	Kimberley Province				Musgrave Province				Osmond Range Province				Halls Creek Province				Ord Basin Province				Bonaparte Gulf Basin Province			
	O	AD	A	Sal	O	AD	A	Sal	O	AD	A	Sal	O	AD	A	Sal	O	AD	A	Sal	O	AD	A	Sal
Alluvium	5	40		low-high									13	30		low	1	20		low-med.	6	100		low-high
Laterite, soil, and Lawford Beds	1	10		low									2	—		low	1	30	2	low-med.				
Palaeozoic sandstone	2	300		low or med.													2	90	2	low	5	140	4	low
Palaeozoic limestone and shale																	22	240	2	low-med.				
Antrim Plateau Volcanics	7	60	4	low	5	270	4	low									51	70	19	low	3	190		low
Proterozoic sandstone	10	120	4	low-high	17	120	36	low-high	3	110		low												
Proterozoic shale	5	150	5	med.-high																				
Hart Dolerite	21	40	3	low-med.																				
Lamboo Complex (total)													53	60	14	low								
Lamboo Complex (granite and porphyry)													8	70	8	low								
Lamboo Complex (basics)													8	50	5	low								
Lamboo Complex (Tickalara Metamorphics)													22	50	1	low								
Whitewater Volcanics													2	140		low								
Halls Creek Group													23	80	5	low-med.								

O No. of bores in operation.
AD Average depth of operating bores
A No. of abandoned bores.
Sal Salinity of groundwater.

There are 51 known operating bores in the province; water is obtained from the rock types listed in Table 22. Sixteen abandoned bores are known, but there may be more than three times this number, because many are unrecorded. The groundwater salinities (T.D.S.) indicated in Table 22 are based on measured and reported values, and the following code is used: low, up to 1,000 ppm; medium, 1,000 to 6,000 ppm; high, over 6,000 ppm.

The Hart Dolerite has been drilled more often than the other rocks, partly because its weathering products give rise to fertile black soils. It can be drilled (with some difficulty) by percussion cable-tool rigs. The dolerite is usually sufficiently well jointed to yield supplies of about 1,000 gph from bores 25 to 60 feet deep, although several bores of insufficient supply are known. Water from the Hart Dolerite is used domestically at the homesteads on Bedford Downs and Lansdowne stations. It is suitable for domestic purposes in most places, as the salinity ranges from 280 to 1,400 ppm T.D.S. and averages about 440 ppm. The more highly saline waters have probably been in contact with shale and siltstone intruded by the dolerite. Similar groundwater conditions to those in the Hart Dolerite exist in the Carson Volcanics, which have been successfully drilled in parts of the province outside the present area.

The sedimentary rocks yield variable quantities of water with a wide range of salinity. The salinity ranges from 20 ppm in a spring in the Saw Range to over 6,000 ppm in some coastal areas. Near the estuarine part of the Ord River on Ivanhoe station, 3 bores yielded salt water which had penetrated into the sandstone from the estuary. Although the rocks are indurated and have low primary porosity, many of the formations are well jointed and have high fracture porosity and permeability. A bore 190 feet into the Pentecost Sandstone on Ivanhoe station is reported to yield 7,400 gph and smaller supplies are generally available in other bores. The presence of springs shows that most of the sandstones contain groundwater, but apart from the Pentecost Sandstone and Mendena Formation, they have not been drilled because they are hard and abrasive, and can normally only be drilled by rotary-percussion rigs which are more expensive to operate than the more common cable-tool rigs. Because of the rugged stony country, poor soils, and the existence of springs, water supplies are seldom sought in these areas.

The shale and siltstone are more easily drilled and have been prospected in spite of their poor potential. The McAlly and Wyndham Shales have yielded small supplies of fresh to saline water, probably from thin beds of more permeable siltstone. In parts of the province outside the map area, water has been obtained from the Elgee Siltstone.

The alluvium along many rivers contains groundwater, although in most places it is only thick enough to contain permanent supplies in the present river channel. At some localities the groundwater is maintained by springs issuing from the bedrock. Especially where derived from sandstone, alluvium is sandy and permeable and yields good supplies of water. Five bores and wells draw from it in this province, including the Margaret River homestead well, which obtains good-quality water from a depth of 20 to 27 feet.

Musgrave Province

The Musgrave Province comprises 4,000 square miles in the map area and is characterized by Adelaidean sedimentary rocks partly covered by soil and laterite. The Albert Edward Group and Gardiner Beds underlie the greater part, while the Ord Group and Mount Parker Sandstone occupy a narrow area along its western border. They comprise mainly shale and siltstone, with subordinate sandstone, and dolomite. Some Antrim Plateau Volcanics, typical of the adjoining Ord Basin Province, are included in this province. Boundaries are partly obscured by soil cover.

Groundwater may be confined or unconfined, in joints and fractures in the dolomite and indurated sandstone, and possibly in solution cavities in the dolomite. Perennial and intermittent springs, such as Blue Hole and Fish Hole on Flora Valley station, may arise where the rocks are cut by deep gorges. The shale and siltstone are relatively impermeable and their small yields are usually insufficient for stock-watering points. At least 36 bores in the sedimentary rocks have been abandoned because supplies are insufficient, but some were not completed because the sandstone was too hard.

The 17 bores drawing on the Proterozoic rocks yield between 500 and 2,500 gph, and generally less than 1,500 gph. Most are between 50 and 500 feet deep, with static water levels at 20 to 300 feet below surface.

The Antrim Plateau Volcanics yield water supplies of a little over 1,000 gph from 5 bores between 90 and 560 feet deep. Two of the bores are reported to flow. Laterite and soil are at a higher elevation than most of the groundwater, but may contain some perched water, e.g. the seepage issuing from beneath the laterite at Horse Spring. Alluvium in the bed of the Elvire River probably contains permanent groundwater, but has not been developed.

The salinity of the groundwater ranges from less than 100 ppm in jointed rocks and alluvium to over the 6,000 ppm limit for stock, in some shales. It is reported to fluctuate throughout the year in the shale supplying the Flora Valley homestead well, in response to recharge of fresher water from the Elvire River.

Osmond Range Province

The Osmond Range Province is a small area (740 square miles) of rugged country between the Ord and Halls Creek Provinces. The main rock types are late Proterozoic to Adelaidean indurated sandstone, dolomite, siltstone, shale, and tillite; they comprise the Red Rock Beds and the formations between the Mount Parker Sandstone and Duerdin Group. There are small outliers of crystalline rocks typical of the Halls Creek Province. The range rises 1,000 feet above the surrounding country and consists mainly of exposed rock cut by several deep gorges. It is unfavourable for grazing except along the northern margin. There are three known watering points, reported to be capable of producing 900 to 3,600 gph from less than 210 feet, in jointed sandstone of the Duerdin Group.

The sandstone and dolomite formations maintain numerous waterholes in gullies cutting them. Underflow in creeks draining the range to the south contributes water to Osmond Creek, which in its lower reaches flows for all or nearly all the year.

Osmond Creek and waterholes in the Osmond Range contain fresh water, and no salty water was reported in bores. The groundwater in the province should be of domestic quality, except in the shales and siltstones.

Halls Creek Province

Ten thousand square miles of the Halls Creek Province, about two-thirds of its total area, lies within the map area. The province comprises the crystalline rocks of the Halls Creek Mobile Zone and is typified by closely spaced drainage yielding high runoff. Much of it consists of bare or boulder-strewn hills, although in the southern part there is an extensive cover of soil and laterite, and thick alluvium in watercourses.

The province comprises the Halls Creek Group, the Lamboo Complex, and the Whitewater Volcanics, which include igneous, metamorphic, and indurated sedimentary rocks with varying degrees of secondary permeability along joints, fractures, and cleavage planes. Basic volcanics and intrusives, quartzites, greywackes, and high-grade metamorphics appear to be more jointed than the granites and acid volcanics. The joints are stronger than the cleavage planes in the slates and schists. Rock fracturing is increased near faults and may provide storage for useful supplies of water in otherwise unproductive rocks. Several bores are located along the Halls Creek Fault; they include two bores at the Alice Downs homestead which are 69 and 103 feet deep, and yield good-quality water at 1,800 and 720 gph respectively. However, some of the faults are cemented with secondary silica and have low permeability.

Ninety-three productive bores are known. Of these 23 obtain water from the Halls Creek Group, 53 from the Lamboo Complex, 2 from the Whitewater Volcanics, and 15 from alluvium and soil. A more detailed breakdown is given in Table 22.

The Halls Creek Group gives rise to rough country which is mainly unproductive agriculturally, and in which there is no large demand for groundwater. Small water supplies of 500 to 1,000 gph and in some places as much as 2,000 gph are obtained from bores in the basic volcanics, greywacke, and quartzite of the Biscay and Olympio Formations. These formations provide the Halls Creek town supply. The dolomite and marble may have solution cavities containing groundwater, although the one bore known to penetrate these rocks was reported to be dry. Slate and schist can be expected to yield small supplies from cleavage planes.

Igneous and high-grade metamorphic rocks of the Lamboo Complex underlie the greater part of the province, and give rise to useful pasture land. There are more bores in the high-grade metamorphics and basic igneous rocks than in the granites and porphyries, relative to their areal extent. This reflects the greater intensity of grazing over the basic and metamorphic rocks, as well as their greater water-bearing capacity. In places, the granitic rocks form rounded hills in which sheet jointing, parallel to the rock surface, is the only common form of jointing. In the absence of interconnected water-bearing joints, the weathered zone may be impermeable because clay decomposition products remain *in situ*. Some seepages and springs arise at the contacts between the basic or metamorphic rocks and the granites. The seepages and springs apparently result from the change in permeability, and several bores have been sited along these lithological boundaries.

The Whitewater Volcanics yield good-quality groundwater at a few springs and two bores. They underlie rather poor pastoral country, and in the vicinity of the more productive Hart Dolerite they have been relatively unprospected.

In the southwestern part of the province, in the upper catchment of the Margaret River, the alluvium, soil, and laterite are thick enough to contain permanent supplies of groundwater; the bores range up to 40 feet in depth. Elsewhere, the alluvium is thin, except along rivers such as the Ord and Bow. At the Bow River station homestead, water is pumped from alluvium which is 50 feet thick, but where the alluvium is restricted to the river beds the pumping installations may be damaged during river flow.

The groundwater from both bedrock and alluvium is generally of good quality; it is suitable for domestic and stock purposes, and contains less than about 500 ppm dissolved solids. Some saline water has been encountered in schists.

Ord Basin Province

The Ord Basin Province is defined by the Palaeozoic volcanics and sediments of the Ord Basin, and covers an area of 6,000 square miles in Western Australia. In its three component basins—Hardman, Rosewood, and Argyle—the synclinal sedimentary rocks form separate subprovinces from the surrounding Antrim Plateau Volcanics. All are drained by the Ord River, to which seepage provides permanent underflow in alluvium. In many places along the Ord and Negri Rivers waterholes are maintained by the underflow.

Prospecting for groundwater has been more concentrated in the productive black soil plains of this province. However, groundwater is available in most parts of the basin. There are 77 known operating bores, of which 51 produce from the volcanics, 24 from the Palaeozoic sedimentary rocks, 1 from the Tertiary Lawford Beds, and 1 from alluvium. Depths range from 8 to 680 feet and water levels from 0 to 550 feet. Supplies of up to 3,000 gph are reported, with an average about 1,500 gph.

The presence of springs arising in the volcanics suggested to Jack (1906) that the volcanics contain pressure water, as for example at their contact with the overlying Negri Group. Matheson & Teichert (1948) and Traves (1955) have described occurrences of groundwater in springs and bores in the volcanics; the water is contained in joints, faults, and cracks, and may be confined in agglomerate layers by fine-grained basalt or the basal limestone of the Negri Group.

One artesian bore is known at Napoleon Spring, on Argyle Downs station, and subartesian water has been encountered in many bores; the water is confined in well jointed layers by less permeable layers. Three bores obtain subartesian water from the contact between the volcanics and the Negri Group. Faults and large joints give rise to springs and seepages in localities where the piezometric surface is above ground level. Elsewhere, they allow additional access for recharge and may maintain seepages of unconfined groundwater at intersections with drainage lines.

In the sediments of the structural basins, groundwater is obtained from limestone, sandstone, and possibly some zones within the shales. The distribution of water-bearing cavities in the limestone is variable; there may be no useful supply for more than 150 feet below the first occurrence of water, or large quantities may be present at several levels. The Panton Formation supplies three bores, 130 to 315 feet deep, in the centre of the Argyle Basin. The bore logs are not available, but the aquifers are probably beds of limestone and siltstone within the shales. In places, there are sufficient intergranular pore spaces in the Buchanan Sandstone and sandstones in the Elder Formation to store usable supplies of water, such as those obtained from the Turner River homestead and Eagle Hawk Bores, which are 72 and 226 feet deep respectively. At Dry Swamp Yard on Turner River station two bores sunk into these formations were abandoned at 80 and 160 feet with only small supplies from silt and sandstone.

Alluvium occurs in the beds and in places on the banks of the major rivers; groundwater enters the alluvium from aquifers cut by the rivers. Large supplies of water could be drawn from the alluvium, but supplies are generally available from the permanent pools in the rivers. The well at Bungle Bungle outcamp on Turner River station obtains groundwater from alluvium in Red Rock Creek.

The salinity of the groundwater from the Antrim Plateau Volcanics ranges from 300 to 850 ppm, while the most saline water known from bores in the Negri Group, at Argyle Downs homestead, is 1,130 ppm, which is slightly above the limit recommended for drinking water. The presence of salty water (3,000 ppm in September, 1963) in pools in the Negri and Ord Rivers near their junction indicates that more saline groundwater exists in parts of the Negri Group. The salty water seeps from the Panton Formation, Nelson Shale, and limestone. The high concentration of salts in the pools is partly due to evaporation, and Hardman (1885) has described salt encrustation on their margins.

Bonaparte Gulf Basin Province

The Bonaparte Gulf Basin Province covers an area of 1,500 square miles in the map area. Palaeozoic sediments crop out in low fault-block hills which rise above the alluvial and soil cover. They contain lightly cemented sandstones which hold usable quantities of groundwater and supply several springs, such as Hart and Point Springs. Some of the sandstone has a low permeability and yields little water; 2 bores at Kununurra were abandoned for this reason. The limestone and dolomite may contain useful supplies if they have open joints or solution cavities, but no bores are known to produce from them. The shale in the sequence would probably be unproductive.

Of the 14 known operating waterbores in that part of the province in the map area 5 obtain groundwater from the Palaeozoic sediments. The water is reported to be of good quality and in sufficient supply for stock watering. An oil exploration well, Alliance Oil Development Bonaparte No. 1, drilled in the northern part of the province, encountered fresh water to a depth of 1,600 feet in Carboniferous sandstone and carbonate rock (Le Blanc, 1964). Three watering points are supplied by the Antrim Plateau Volcanics, which underlie the sediments around the margins of the basin at least.

The thick alluvial deposits along the Ord River contain groundwater, but in the lower reaches the water is salty because of tidal movement of sea water up the river to Tarara Bar, about 15 miles downstream from Kununurra. At the township, 6 bores within a mile of the Ord River obtained fresh confined water from alluvial 'sand and shingle' interbedded with clay. Most of the bores yielded between 1,000 and 2,000 gph, but one close to the river supplied 20,000 gph from coarse-grained alluvium. The water in the alluvium at Kununurra has a relatively low salinity (60 ppm NaCl), as it is recharged from the diversion dam.

Quality of Groundwater

The groundwater is generally of good quality, and is suitable for domestic use (salinity less than 1,000 ppm) as well as for stock, but in the poorly drained southeastern area, in the lower reaches of Sturt Creek, the groundwater is saline.

Some of the schists in the Halls Creek Province and some shales in other provinces contain water of high salinity. In these fine-grained and finely cleaved rocks, the movement of water is slow, and the dissolution of rock minerals produces high concentrations of dissolved solids in the groundwater. In places along the tidal flats bordering Cambridge Gulf, the alluvium and other rocks have been invaded by sea water. Local recharge conditions determine whether usable water can be produced.

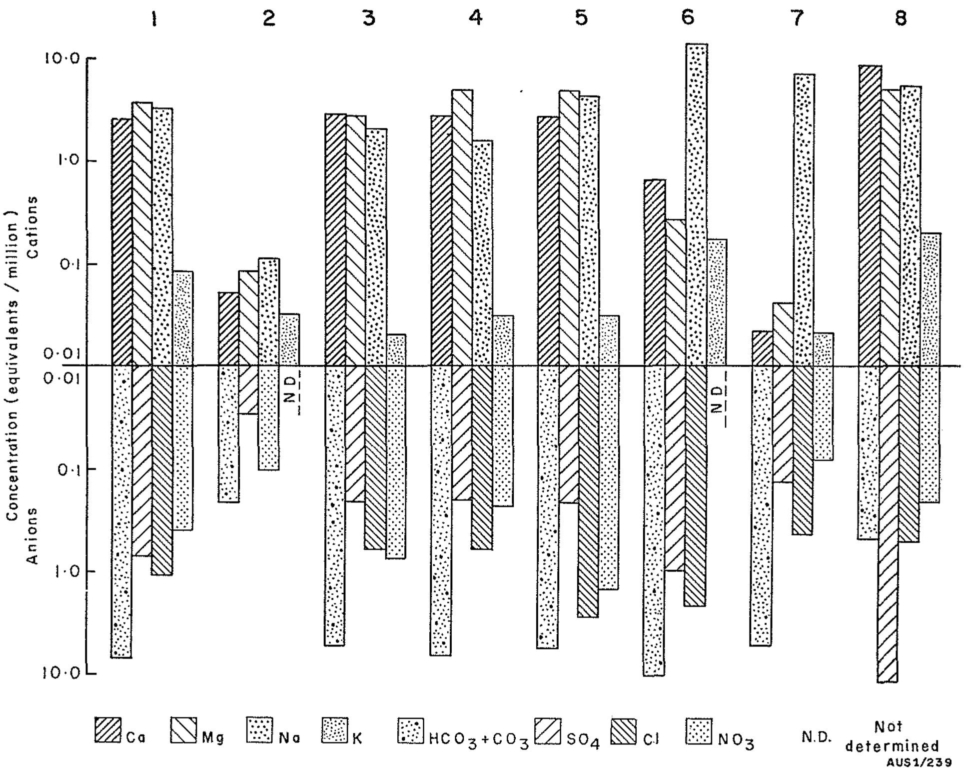

Figure 17. Ionic concentrations in groundwater

TABLE 23. ANALYSIS OF GROUNDWATER

Source	Palm Creek Well	Spring in Saw Range	Bedford Downs Homestead Well	Mud Spring Well Lansdowne Station	Dunham River Homestead Bore	Nicholson Station Lighthouse Creek Bore	Soda Spring Lissadell Station	Argyle Downs Homestead Bore
Aquifer	Tickalara Metamorphics	Pentecost Sandstone	Hart Dolerite	Hart Dolerite	Antrim Plateau Volcanics	Antrim Plateau Volcanics	Antrim Plateau Volcanics	Negri Group (Panton Formation)
GSWA No.	10,235	10,228	10,234	10,446	10,232	10,443	2,729	10,233
Specific conductivity at 20°C. (micromhos)	690	24	575	670	910	1,220	n.d.	1,370
pH	8.0	6.6	8.0	7.8	7.8	8.8	9.4	7.6
Mineral Matter (ppm)								
Calcium	47	1.	51	47	49	11	1	157
Magnesium	41	1	31	50	52	4	1	55
Sodium	70	3	44	32	81	294	145	110
Potassium	3	1	1	1	1	6	1	7
Carbonate	415	1.2	320	406	351	573	223	278
Bicarbonate	nil	nil	nil	nil	nil	36	63	nil
Sulphate	35	2	11	15	8	49	6	552
Chloride	32	4	21	21	101	78	15	37
Nitrate	26	u.d.	59	17	92	n.d.	1	13
Iron	0.1	0.9	0.1	0.3	0.1	2.1	u.d.	0.1
Total (by conductivity)	480	17	400	620	630	800	u.d.	960
Total (by evaporation)	490	20	460	430	560	850	390	1,130
Hardness (calc. as ppm $CaCO_3$)								
Total	286	6	255	324	336	44	1	618
Bicarbonate	286	6	255	324	288	44	u.d.	228
Non-carbonate	nil	nil	nil	nil	48	nil	u.d.	390
Calcium	117	2	127	118	122	28	u.d.	392
Magnesium	169	4	128	206	214	16	u.d.	226

Analyses by the Western Australian Government Chemical Laboratories of 8 samples from bores and springs in 5 formations are listed in Table 23 (from Passmore, 1964; Allen, 1965, 1966a). The sample localities are shown in Figure 15, and the analyses are illustrated in Figure 17. The silica content was not determined.

The groundwater from the gneissic rocks of the Tickalara Metamorphics in the Palm Creek Well on Alice Downs station is typical of the water from the basic to intermediate crystalline rocks. About equal amounts (in equivalents per million) of calcium, magnesium, and sodium are derived from the breakdown of feldspars and ferromagnesian minerals. The major anion is bicarbonate, which is a product of the weathering of these minerals and the solution of carbon dioxide.

Very fresh water, of 20 ppm salinity, was sampled from a spring issuing from the Pentecost Sandstone near Saw Range, about 40 miles southeast of Wyndham. It is typical of the groundwater from jointed siliceous sandstones, except near the coast where the salinity is higher. Concentrates of all ions are low, and the dissolved solids are in similar proportion to rainwater, except for the higher content of bicarbonate formed by the solution of carbon dioxide produced biologically at the spring.

The Hart Dolerite at Mud Spring Well on Lansdowne station and at Bedford Downs homestead yields groundwater of similar chemical composition to that from the Tickalara Metamorphics and other basic to intermediate crystalline rocks. At Bedford Downs homestead there is a larger than normal concentration of nitrate (59 ppm).

Most of the groundwater from the Antrim Plateau Volcanics is similar to that from the Hart Dolerite, as indicated by the sample from the Dunham River homestead bore. Water of similar composition (not shown) was sampled from Spring Creek station. In Lighthouse Creek bore on Nicholson station and Soda Spring on Lissadell station the water has an abnormally high proportion of sodium, which has been concentrated by base exchange reactions between groundwater and zeolites. The process of absorption of calcium and magnesium from the water into the zeolites—in exchange for sodium—is near completion in the Soda Spring water, which contains less than 1 ppm of calcium and magnesium. There is a high proportion of bicarbonate because of the greater solubility of sodium carbonate than calcium or magnesium carbonates.

The shale and limestone of the Negri Group at the Argyle Downs homestead yield water with a higher proportion of sulphate and calcium than usual for shales, and a low concentration of bicarbonate. Such an effect would be produced by the dissolution of gypsum, a mineral known to be present in some of the Negri Group shales.

Most of the groundwaters are hard. Of the eight samples analysed, the exceptions are the low-salinity water from the Pentecost Sandstone and those waters from the Antrim Plateau Volcanics which are rich in sodium. The hardness values listed in Table 23 show that, except for the sulphate-rich water from the Negri Group, the hardness is almost all caused by bicarbonates of calcium and magnesium. It is therefore temporary, and can be removed by boiling.

Nitrate concentrates in two of the water samples are higher than the 45 ppm limit suggested by the U.S. Department of Public Health (1962) for drinking water. At Bedford Downs homestead its concentration is 59 ppm, and at Dunham River homestead it is 92 ppm, sufficient to be injurious to children. The nitrate is probably derived from organic matter around the homesteads, or from leguminous vegetation.

Movement of Groundwater

Rain falling on bare rock infiltrates or runs off in proportion to the permeability of the rock. The cover of soil, alluvium, or weathered material over the rock requires wetting before recharge, and the amount of rainfall consumed depends on the thickness, permeability, and porosity of the cover rocks. The black clayey soils on many basic rocks and some shales are impermeable when wet, but recharge takes place through desiccation cracks before they close after a few inches of rain (Allen, 1966a). In the upper reaches of the drainage system, creeks concentrate runoff, store it temporarily in the thin alluvium, and provide additional recharge to the underlying rocks.

The larger, more deeply incised, rivers act as groundwater drains, and groundwater movement appears to coincide approximately with the surface drainage, although only a few relative water levels have been measured. Allen (1966a) found that in the Antrim Plateau Volcanics of the Gordon Downs Sheet area, a divide between groundwaters moving northwest towards the Ord River and southeast towards Sturt Creek coincided approximately with the drainage divide. Conditions are probably similar in other areas. In jointed rocks, the depth of water penetration below ground level ranges from 200 to 300 feet; below this level joints are infrequent or closed. Regionally, the shape of the groundwater body is controlled by the topography. Locally, such as in the sedimentary basins, groundwater may be confined in specific aquifers, extend to greater depth, and have piezometric levels dependent on the particular conditions of recharge and water movement. In some areas of poorly jointed rocks the groundwater probably does not form a continuous body, but moves along unconnected channels.

With the regional movement of groundwater following the surface topography, there would be southerly and westerly flow in the southern region, but a predominantly northerly flow towards Cambridge Gulf over most of the area.

Additional Water Supplies

The water-bearing properties of the major rock units have been outlined in the descriptions of the groundwater provinces, and some indication of the likelihood of obtaining useful supplies is given by the number of successful and unsuccessful bores drilled in the various rocks (Table 22). However, the amount of drilling in a formation has depended on the hardness of the rock and the need for water supplies, which in turn depends largely on the type of soil and the presence or absence of permanent surface water. Little information is available on abandoned bores.

In the provinces of Proterozoic and Palaeozoic sedimentary and volcanic rocks, bores can be successfully sited to intersect prospective formations below the expected water level, at localities with favourable recharge conditions. But in places—for instance, much of the Musgrave Province—the rocks are of low permeability and yield insufficient supplies of saline water. In the crystalline rocks of the Halls Creek Province the occurrences of usable supplies of groundwater are less predictable, as water-bearing joints at depth cannot be predicted from the surface. Possible favourable sites are the contacts between different types of rock, pegmatite dykes, and large joints and faults. Some granitic hills have well developed sheet jointing which may permit intake of rainfall, and sites near the base of such hills could be productive. Some springs and seepages have been successfully developed, usually as wells. Sites near watercourses are often more favourable than those on the divides because of the lesser depth to water and better recharge conditions.

Until recently drilling has been restricted by the capabilities of cable-tool percussion rigs, which are inefficient in hard rocks. Down-the-hole hammer drills have penetrated granite and hard sandstone to greater depths, but drilling costs are higher and good access tracks are required.

Alluvium is a useful aquifer where it is thick enough to contain permanent groundwater, and in the Ord River, for example, very large supplies would be available. The best method of pumping water from the alluvium would be from collector wells on the banks of rivers, with horizontal screens projecting under the river beds. A typical collector well is illustrated by Todd (1959, p. 145) who reports yield of 168,000 gph per well in permeable aquifiers. Supplies of this order would be useful for irrigation.

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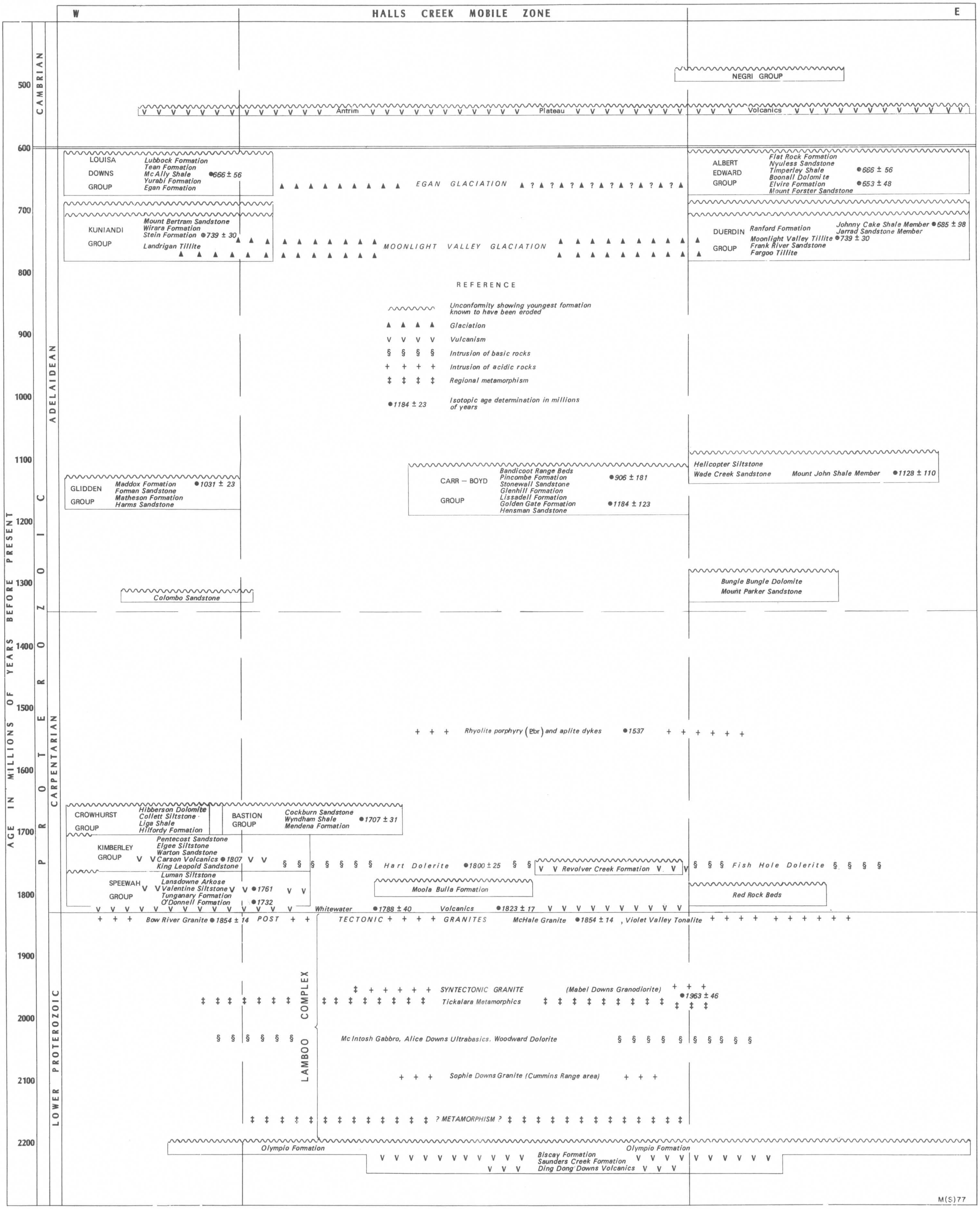


W
HALLS CREEK MOBILE ZONE
E
AGE IN MILLIONS OF YEARS BEFORE PRESENT
CAMBRIAN
ADELAIDEAN
CARPENTARIAN
LOWER PROTEROZOIC
PROTEROZOIC
NEGRI GROUP
Antrim Plateau Volcanics
LOUISA DOWNS GROUP
Lubbock Formation
Tean Formation
McAlly Shale
Yurabi Formation
Egan Formation
666 ± 56
EGAN GLACIATION
ALBERT EDWARD GROUP
Flat Rock Formation
Nyuless Sandstone
Timperley Shale
Boonall Dolomite
Elvire Formation
Mount Forster Sandstone
666 ± 56
653 ± 48
KUNIANDI GROUP
Mount Bertram Sandstone
Wirara Formation
Stein Formation
739 ± 30
Landrigan Tillite
MOONLIGHT VALLEY GLACIATION
DUERDIN GROUP
Ranford Formation
Johnny Cake Shale Member
Jarrad Sandstone Member
685 ± 98
Moonlight Valley Tillite
739 ± 30
Frank River Sandstone
Fargoo Tillite
REFERENCE
Unconformity showing youngest formation known to have been eroded
Glaciation
Vulcanism
Intrusion of basic rocks
Intrusion of acidic rocks
Regional metamorphism
1184 ± 23 Isotopic age determination in millions of years
GLIDDEN GROUP
Maddox Formation
Forman Sandstone
Matheson Formation
Harms Sandstone
1031 ± 23
CARR – BOYD GROUP
Bandicoot Range Beds
Pincombe Formation
Stonewall Sandstone
Glenhill Formation
Lissadell Formation
Golden Gate Formation
Hensman Sandstone
906 ± 181
1184 ± 123
Helicopter Siltstone
Wade Creek Sandstone
Mount John Shale Member
1128 ± 110
Colombo Sandstone
Bungle Bungle Dolomite
Mount Parker Sandstone
Rhyolite porphyry (Pbr) and aplite dykes
1537
CROWHURST GROUP
Hibberson Dolomite
Collett Siltstone
Liga Shale
Hilfordy Formation
BASTION GROUP
Cockburn Sandstone
Wyndham Shale
Mendena Formation
1707 ± 31
KIMBERLEY GROUP
Pentecost Sandstone
Elgee Siltstone
Warton Sandstone
Carson Volcanics
1807
King Leopold Sandstone
Hart Dolerite
1800 ± 25
Revolver Creek Formation
Fish Hole Dolerite
SPEEWAH GROUP
Luman Siltstone
Lansdowne Arkose
Valentine Siltstone
1761
Tunganary Formation
O'Donnell Formation
1732
Moola Bulla Formation
Red Rock Beds
Whitewater
1788 ± 40
Volcanics
1823 ± 17
Bow River Granite
1854 ± 14
POST TECTONIC GRANITES
McHale Granite
1854 ± 14
Violet Valley Tonalite
LAMBOO COMPLEX
SYNTECTONIC GRANITE
(Mabel Downs Granodiorite)
1963 ± 46
Tickalara Metamorphics
McIntosh Gabbro, Alice Downs Ultrabasics, Woodward Dolorite
Sophie Downs Granite (Cummins Range area)
? METAMORPHISM ?
Olympio Formation
Olympio Formation
Biscay Formation
Saunders Creek Formation
Ding Dong Downs Volcanics
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
M(S)77

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

GEOLOGICAL MAP

EAST KIMBERLEY REGION

WESTERN AUSTRALIA

1967

Scale 1:500,000

10 5 0 10 20 30 40 MILES

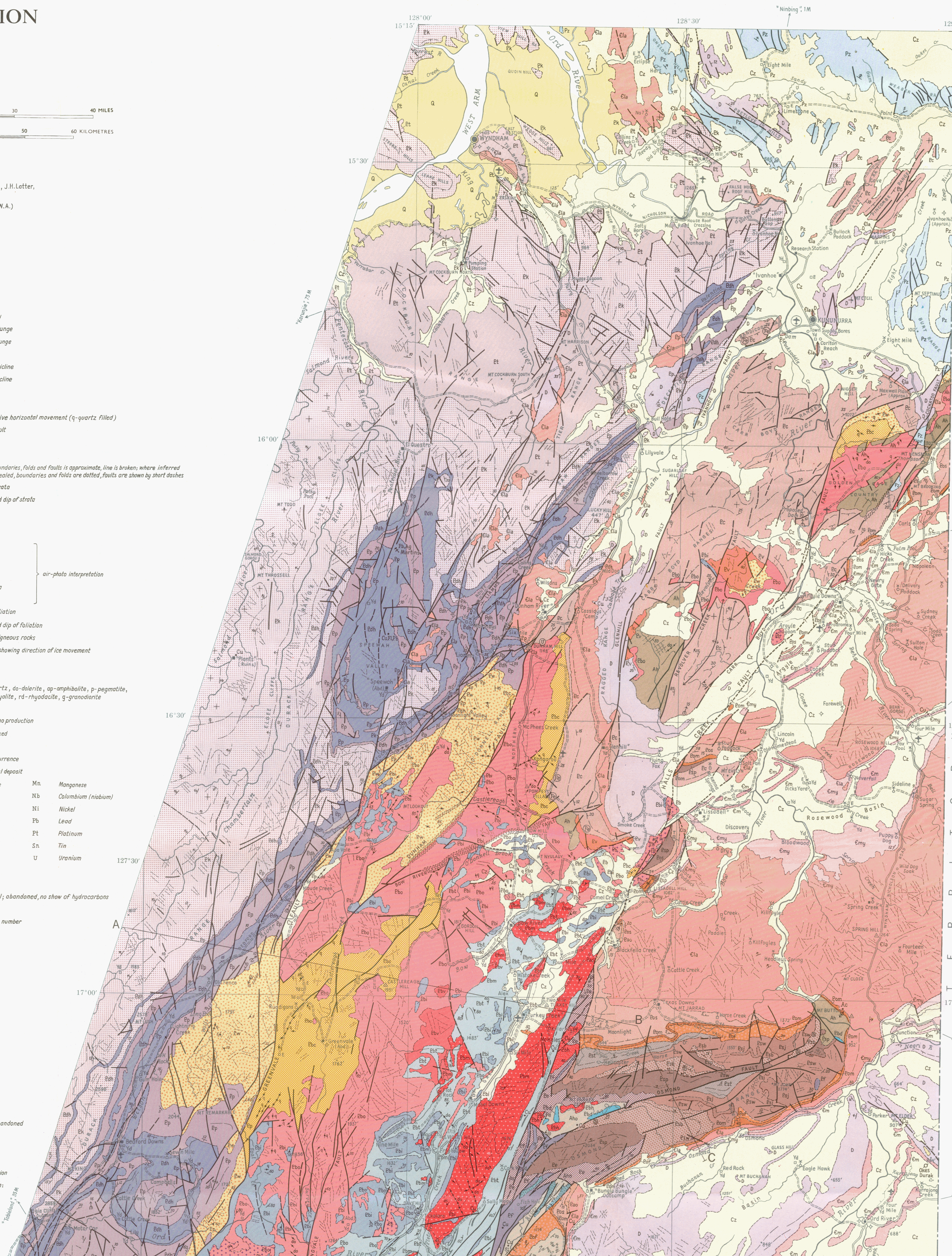
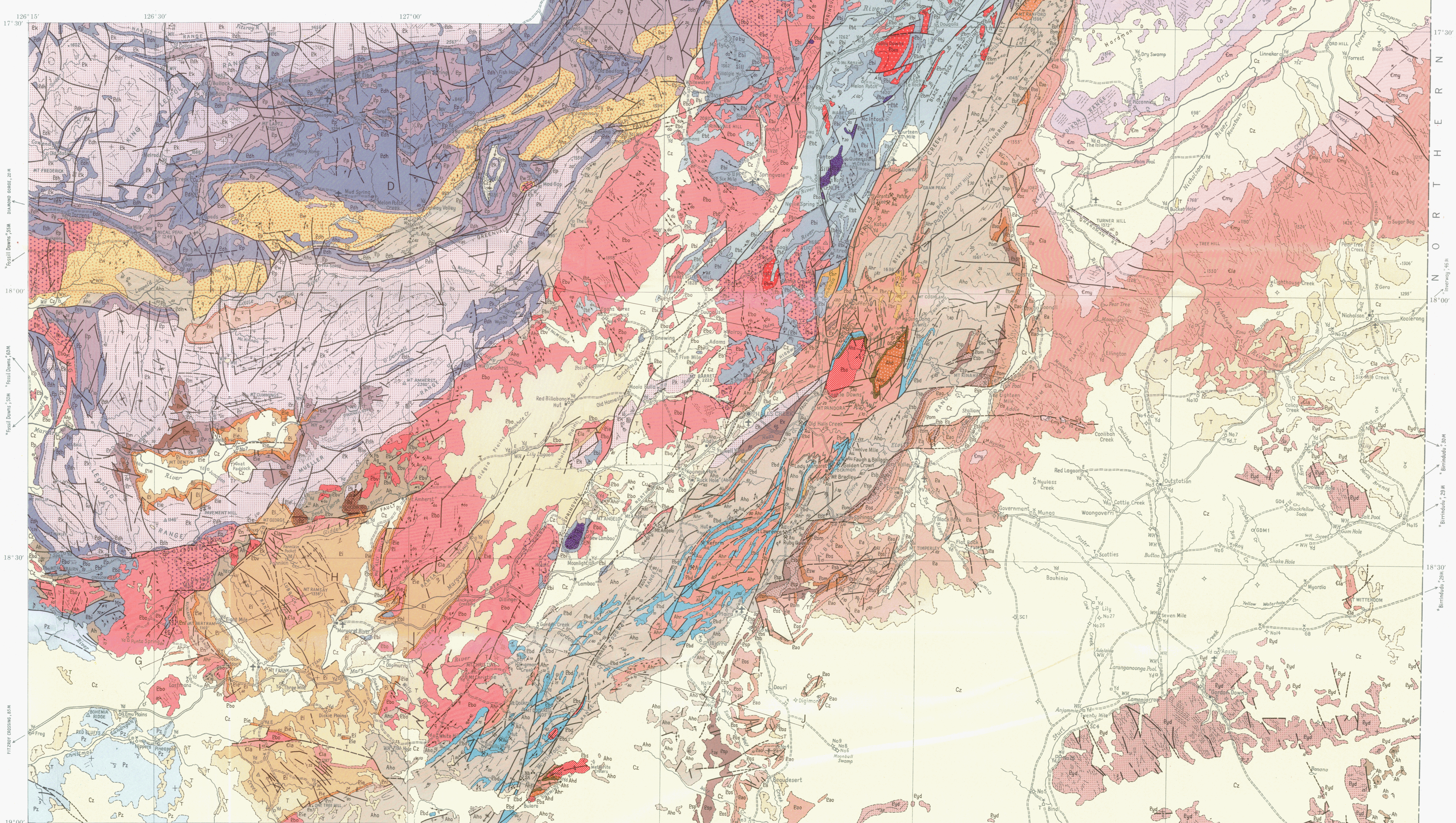
10 5 0 10 20 30 40 50 60 KILOMETRES

Geology, 1962-64, by: D.B. Dow, J.W. Smith, H.L. Davies, K.A. Plumb, H.G. Roberts, D. Dunnet, J.H. Latter, V.M. Bofinger, D.C. Gellatly, G.M. Derrick (B.M.R.) I. Gemuts, R. Halligan, A.D. Allen, J.R. Passmore, K.J. Morgan (G.S.W.A.)

Compiled, 1966, by: D.B. Dow, I. Gemuts, A.S. Mikolajczak

Cartography by: Geological Branch, B.M.R.

Drawn by: A.S. Mikolajczak

CAINOZOIC — QUATERNARY		Q	Coastal alluvium, minor evaporite deposits
CAINOZOIC — UNDIFFERENTIATED		Cz	Sand, soil, gravel, alluvium, travertine
CAINOZOIC — TERTIARY	Undifferentiated	T	Laterite, alluvium, chalcedonic limestone
PALAEOZOIC — UNDIFFERENTIATED		Pz	Sedimentary rocks of Bonaparte Gulf Basin
PALAEOZOIC — DEVONIAN		D	Friable quartz sandstone, some conglomerate
PALAEOZOIC — CAMBRIAN	Negri Group: Undifferentiated	€n	Siltstone, shale, limestone
	Headleys Limestone	€ng	Fine-grained grey limestone, some chert nodules
	Antrim Plateau Volcanics	€la	Tholeiitic basalt, minor agglomerate. Includes Lolly Conglomerate at base in west
PROTEROZOIC — ADELAIDEAN (UPPER PROTEROZOIC / UNDIFF.*)	Gardiner Beds	Ꝑgd	Quartz sandstone, ferruginous sandstone, pebble conglomerate, algal dolomite
	Albert Edward Group: Flat Rock Formation	Ꝑa	Fine-grained ferruginous sandstone, commonly dolomitic
	Nyuless Sandstone		Quartz sandstone
	Timperley Shale		Green and grey shale and siltstone
	Boonall Dolomite		Dolomite, minor dolomitic conglomerate and breccia
	Elvire Formation		Shale, siltstone
	Mount Forster Sandstone	Ꝑao	Quartz sandstone, pebble conglomerate
	Louisa Downs Group: Lubbock Formation	Ꝑl	Siltstone, shale, sub-greywacke, partly dolomitic
	Teas Formation		Feldspathic sandstone, sub-greywacke, pebble conglomerate
	McAlly Shale		Shale, siltstone; rare fine-grained quartz sandstone
	Yurabi Formation		Quartz sandstone, feldspathic sandstone, some siltstone, shale and dolomitic rocks
	Egan Formation	Ꝑle	Tillite, pebbly sandstone, dolomite, limestone, and dolomitic sediments
	Ranford Formation	Ꝑlr	Micaceous quartz siltstone, very fine-grained quartz sandstone, red and green shale, dolomitic sandstone
	Duerdin Group: Moonlight Valley Tillite	Ꝑom	Tillite, minor dolomite-cobble conglomerate, dolomite
	Frank River Sandstone	Ꝑof	Dolomitic sandstone and greywacke
	Fargoo Tillite		Tillite, boulder conglomerate
	Kuniandi Group: Mount Bertram Sandstone	Ꝑn	Micaceous, ferruginous quartz sandstone, minor shale, siltstone
	Wirara Formation		Green and red siltstone and shale, some quartz sandstone
	Stein Formation		Coarse-grained purple greywacke
	Landrigan Tillite	Ꝑnl	Tillite, sandstone lenses, minor dolomite
PROTEROZOIC — CARPENTARIAN (MIDDLE PROTEROZOIC)	Helicopter Siltstone	Ꝑst	Laminated siltstone and shale
	Wade Creek Sandstone	Ꝑsw	Quartz sandstone
	Mount John Shale Member	Ꝑsj	Shale, siltstone, minor ferruginous sandstone, chert
	Glidden Group: Maddox Formation	Ꝑd	Black shale and siltstone, feldspathic sandstone
	Forman Sandstone		Fine-grained quartz sandstone
	Matheson Formation		Claystone, shale, siltstone, sub-greywacke
	Harms Sandstone		Quartz sandstone, minor shale and siltstone
	Carr Boyd Group: Bandicoot Range Beds	Ꝑc	Quartz sandstone, partly ferruginous; conglomerate, siltstone
	Pincombe Formation		Siliceous siltstone, quartz sandstone
	Stonewall Sandstone		Friable quartz sandstone
	Glenhill Formation		Shale, siltstone; quartz sandstone, rarely glauconitic
	Lissadell Formation		Quartz sandstone, siltstone
	Golden Gate Siltstone		Black pyritic shale; siltstone, sandstone, rhyolite tuff
	Hensman Sandstone		Quartz sandstone
ADELAIDEAN OR CARPENTARIAN (UNDIFFERENTIATED)	Bungle Bungle Dolomite	Ꝑsb	Dolomite, dolomitic shale, minor limestone
	Mount Parker Sandstone	Ꝑsp	Quartz sandstone, minor pebble conglomerate
	Colombo Sandstone	Ꝑm	Quartz sandstone, chert pebble breccia and conglomerate
	Hart Dolerite	Ꝑdh	Tholeiitic dolerite, gabbro, some pyroxene granophyre differentiates
CARPENTARIAN			Dolomite of unknown origin, mostly intrusive
	Fish Hole Dolerite	Ꝑf	Highly epidotized vesicular dolerite
(LOWER & MIDDLE PROTEROZOIC)	Crowhurst Group: Hibberson Dolomite	Ꝑr	Massive dolomite, dolomitic breccia and sandstone
	Collett Siltstone		Purple and green siltstone, rarely pyritic; dolomite
	Liga Shale		Green shale, minor micaceous siltstone
	Hilfordy Formation		Quartz sandstone, ferruginous siltstone, shale
	Bastion Group: Cockburn Sandstone	Ꝑt	Quartz sandstone, minor micaceous siltstone, green shale
	Wyndham Shale		Green and grey shale, fine-grained sandstone
	Mendena Formation		Quartz sandstone, green and purple siltstone, dolomite
(LOWER PROTEROZOIC)	Kimberley Group: Pentecost Sandstone	Ꝑk	Quartz sandstone, minor glauconitic sandstone, siltstone
	Elgee Siltstone		Red-brown siltstone and shale. Dolomite member
	Warton Sandstone		Quartz sandstone
	Carson Volcanics		Tholeiitic basalt, rare agglomerate, feldspathic sandstone
	King Leopold Sandstone		Quartz sandstone, pebbly sandstone, conglomerate
	Speewah Group: Luman Siltstone	Ꝑp	Siltstone, shale, fine-grained sandstone
	Lansdowne Arkose		Feldspathic and quartz sandstone, arkose, siltstone. Rare glauconitic arkose
	Valentine Siltstone		Green siltstone, rhyolitic ashstone and tuff
	Tunganary Formation		Quartz sandstone, feldspathic sandstone, green siltstone
	O'Donnell Formation		Sub-greywacke, quartz sandstone, green shale
	Revolver Creek Formation	Ꝑv	Amygdaloidal basalt, arkose, quartz sandstone, siltstone
	Red Rock Beds	Ꝑe	Quartz sandstone, quartz conglomerate, siltstone
	Moola Bulla Formation	Ꝑx	Arkosic sandstone, quartz conglomerate; greywacke and siltstone
	Whitewater Volcanics	Ꝑw	Porphyritic acid and minor intermediate volcanic rocks. Minor sedimentary rocks
PROTEROZOIC (LOWER PROTEROZOIC)	Lamboo Complex: Undifferentiated Lamboo Complex	Ꝑbr	Rhyolite, dacite, microgranite
		Ꝑb	Intimate mixture of granite, gabbro, and metamorphic rocks. Granitic rocks in north-western corner
	Violet Valley Tonalite	Ꝑbv	Biotite-rich tonalite; some granodiorite, gabbro
	McHale Granodiorite	Ꝑbh	Hornblende biotite granodiorite, adamellite
	Castlereagh Hill Porphyry	Ꝑbc	Quartz feldspar porphyry, adamellite
	Bow River Granite	Ꝑbo	Coarse-grained granite and granodiorite, porphyritic to even-grained
	Sophie Downs Granite	Ꝑbs	Granite, granophyric granite, some microgranite
	Mabel Downs Granodiorite	Ꝑbm	Foliated hornblende granodiorite and tonalite; some biotite granite, orthopyroxene granite, and migmatite
	Tickalara Metamorphics	Ꝑbt	Schist, paragneiss, orthogneiss, migmatite, amphibolite. Calc-silicate rocks
	McIntosh Gabbro	Ꝑbi	Gabbro and dolerite, mostly uralitised; amphibolite, basic granulite
	Alice Downs Ultrabasics	Ꝑba	Pyroxenite, peridotite, chlorite-tremolite rock
	Woodward Dolerite	Ꝑbd	Basic and ultrabasic sills and dykes
ARCHAEAN OR PROTEROZOIC (ARCHAEAN OR LOWER PROTEROZOIC)	Halls Creek Group: Undifferentiated	Ah	Sub-greywacke, siltstone, mica schist, some conglomerate and dolomite
	Olympio Formation	Aho	Sub-greywacke, greywacke, siltstone, shale, some arkose, conglomerate, and rare dolomite
	Biscay Formation	Ahr	Basic volcanics and intrusive rocks, greywacke and siltstone. Limestone, dolomite, carbonated basic rocks
	Saunders Creek Formation	Ahs	Indurated sandstone and quartz conglomerate
	Ding Dong Downs Volcanics	Ahd	Basic volcanic rocks, minor greywacke and siltstone; rhyolite, probably intrusive

* Subdivisions of the Precambrian time-scale used by the Geological Survey of Western Australia, shown in grey

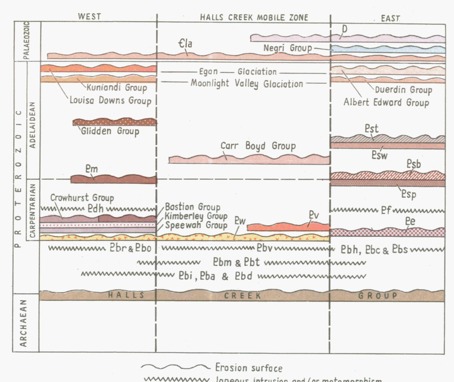
Geological boundary
Anticline, showing plunge
Syncline, showing plunge
Overturned anticline
Plunge of minor anticline
Plunge of minor syncline
Plunge of drag fold
Plunge of fold axis
Fault, showing relative horizontal movement (q-quartz filled)
Low-angle thrust fault
Inclined fault
Shear-zone
Where location 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 < 5°
Dip > 5°
Trend lines — air-photo interpretation
Tightly folded strata
Joint pattern
Strike and dip of foliation
Prevailing strike and dip of foliation
Inclined banding in igneous rocks
Glaciated bedrock, showing direction of ice movement
Macrofossil locality
Dyke or vein; q-quartz, do-dolerite, ap-amphibolite, p-pegmatite, rh-rhyolite, rd-rhyodacite, g-granodiorite

Prospect: little or no production
Mine not being worked
Alluvial workings
Minor mineral occurrence
Unexploited mineral deposit

Ac	Asbestos-chrysotile	Mn	Manganese
Ag	Silver	Nb	Columbium (niobium)
Au	Gold	Ni	Nickel
Cr	Chromium	Pb	Lead
Cu	Copper	Pt	Platinum
Fe	Iron	Sn	Tin
Fl	Fluorite	U	Uranium

Diamond drill hole
Oil exploration well, abandoned, no show of hydrocarbon
Bore with reference number
Abandoned bore
Well
Windpump
Water tank
Earth tank or dam
Irrigation dam
Dam on stream
Waterhole
Spring
Highway
Road
Vehicle track
Airport
Landing ground
Homestead; Hut; abandoned
Yard
Telephone line
State boundary
Trigonometrical station
Height in feet, datum mean sea level

DIAGRAMMATIC RELATIONSHIP OF ROCK UNITS



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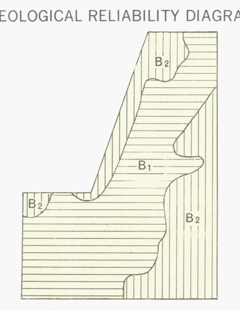
GEOLOGICAL RELIABILITY DIAGRAM

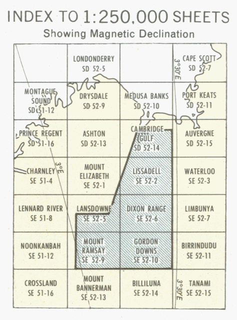


B_1 Detailed reconnaissance - numerous traverses and air-photo interpretation

B_2 Reconnaissance - some traverses and air-photo interpretation

INDEX TO 1:250,000 SHEETS

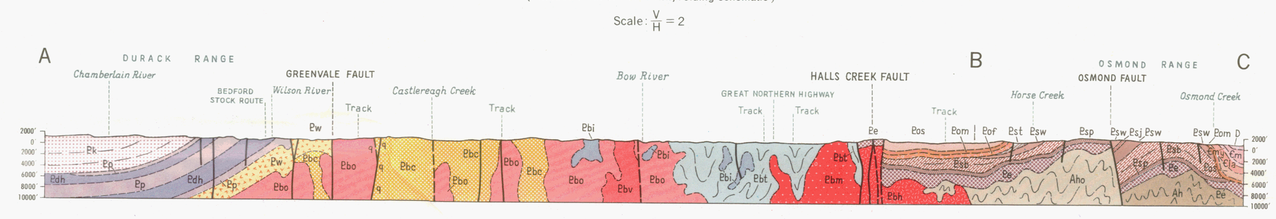
Showing Magnetic Declination

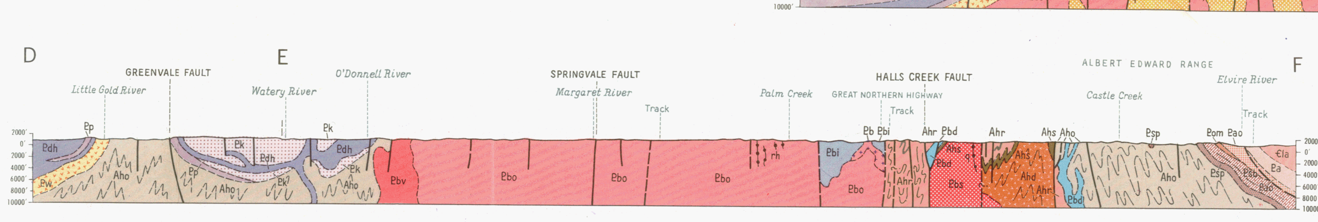


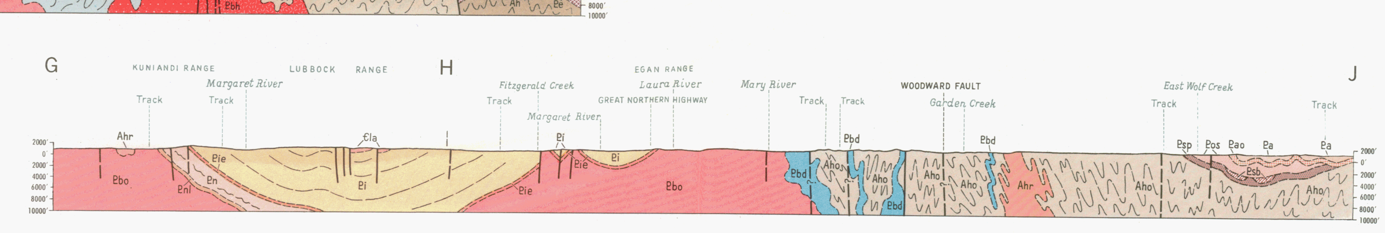
Sections

(Cainozoic sediments omitted from section)

(Attitude of faults not known; folding schematic)







EAST KIMBERLEY REGION

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