COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

REPORT No. 109

Cambrian and Ordovician Geology of the Southern Part of the Bonaparte Gulf Basin, Western Australia

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J. A. KAULBACK AND J. J. VEEVERS

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DEPARTMENT OF NATIONAL DEVELOPMENT

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SUMMARY

The Cambrian and Ordovician rocks in the southern part of the Bonaparte Gulf Basin, and the Cambrian and Devonian outliers, crop out over an area of about 500 square miles; they have an aggregate thickness of about 5000 feet. The Cambrian and Ordovician rocks rest unconformably on Precambrian sediments and are unconformably overlain by Upper Devonian and Lower Carboniferous sediments.

The base of the sequence consists of an unmeasured thickness of Lower Cambrian Antrim Plateau Volcanics, mainly basalt flows, unconformably overlain by about 400 feet of late Lower Cambrian dolomitic quartz sandstone, siltstone, and dolomite (Blatchford Formation) in the Ragged Range, and by 200 feet (and possibly as much as 1300 feet) of early Middle Cambrian shale, sandstone, and dolomite (Tarrara Formation) in the Bonaparte Gulf Basin.

The Tarrara Formation is overlain by a conformable sequence of 1200 feet of Middle Cambrian red quartz sandstone (Hart Spring Sandstone), 200 feet of Middle and Upper Cambrian dolomite and sandstone (Skewthorpe Formation), 400 feet of Upper Cambrian white quartz sandstone (Pretlove Sandstone), 750 feet of Upper Cambrian glauconitic sandstone and white quartz sandstone (Clark Sandstone), and, finally, 600 feet of Lower Ordovician dark glauconitic sandstone (Pander Greensand).

Except for the Hart Spring Sandstone and the Pretlove Sandstone, which are sparsely fossiliferous, the sedimentary sequence contains abundant fossils, mainly trilobites, which provide a basis for local and regional correlation.

In all the outliers, the Antrim Plateau Volcanics are succeeded by Lower or Middle Cambrian red sandstone and dolomite (the Blatchford Formation or the Tarrara Formation). At Gap Point and Mount Rob, the sequence continues upward into Upper Cambrian Sandstone and possibly into Lower Ordovician sandstone; the aggregate thickness of Cambrian sediments here is about 2700 feet. The Cambrian rocks in the outliers are unconformably overlain by white and red quartz sandstone (Cockatoo Sandstone) and in the Ragged Range by conglomerate and conglomeratic sandstone (Ragged Range Conglomerate). Pelecypods in the sandstone of the Ragged Range and Dillon outlier probably indicate an Upper Devonian age, equivalent to part of the Cockatoo Sandstone of the Bonaparte Gulf Basin. The thickest Devonian sequence is 3000 feet at Gap Point.

The rhythmically deposited quartz sandstone, sandy dolomite, and stromatolitic dolomite in the Skewthorpe Formation are strand, lagoonal, and algal reef deposits of successive transgressions.

The rapid replacement of one fauna by another in the Clark Sandstone is another instance of the widespread faunal crisis that took place in the Upper Cambrian.

Differential movement, probably along faults, during the Upper Cambrian is indicated by rapid changes in thickness and by faunal breaks in the Pretlove Sandstone. The Cambrian-Ordovician sequence was uplifted and warped before deposition was renewed in the Upper Devonian; the main diastrophism (tilting, large-throw profound faulting) that affected the Cambrian, Ordovician, and Upper Devonian rocks took place in the early Lower Carboniferous. This diastrophism and consequent erosion broke up the continuous sheet of Cambrian, Ordovician, and Devonian rocks that extended for an unknown distance to the southwest to form the present pattern.

The petroleum prospects of the severely faulted exposed Cambrian and Ordovician sedimentary rocks are poor. If, as is expected, less deformed equivalents of these rocks extend northeastward under the younger rocks, they would provide an attractive target for drilling.

INTRODUCTION

The Bonaparte Gulf Basin is a structural basin whose limits are shown in Figure 1. The Palaeozoic outliers of the Bonaparte Gulf Basin comprise the Cambrian and Devonian sediments of the Ragged Range, Mount Rob, Gap Point, and Dillon Spring areas.

Location and Access

Most of the rocks described in this Report lie within the Cambridge Gulf 1:250,000 Sheet area; the Ragged Range is in the Lissadell 1:250,000 Sheet area, and intermittent outcrops of the Antrim Plateau Volcanics lie on the southeastern edge of the Bonaparte Gulf Basin in the Auvergne 1:250,000 Sheet area. The outcrops described cover an area of about 500 square miles. No bores in the Bonaparte Gulf Basin have penetrated Cambrian or Ordovician rocks.

The port of Wyndham is a centre for the cattle-raising industry, and Kununurra is the centre of the Ord River irrigation scheme. Both towns are linked with Perth and Darwin by regular air services, and Wyndham by regular shipping services. The Great Northern Highway and the Wyndham-Nicholson road cross the area, and there are numerous tracks to the cattle stations.

Climate

The area has a warm monsoonal climate with a short rainy season and a long dry season. The annual rainfall is about 30 inches, and, compared with areas farther inland, is reliable. Temperature and humidity are high throughout the year, and Wyndham's mean temperature (84°F) is the highest recorded in Australia. Further details are provided by Traves (1955).

Acknowledgments

Acknowledgments are due to Dr M. Zimmermann, and Messrs P. Michoud, A. Duchemin, and M. Eyssautier, of Australian Aquitaine Petroleum Limited, for co-operation and hospitality in the field, and for valuable discussions; and to Mr W. Dunn and Mr R.H. Otway, who collected many of the fossils.

Previous Work

Of the pioneer geologists who have carried out regional studies in the East Kimberleys (Hardman, 1885; Wade, 1924; Matheson & Teichert, 1947; and Reeves, 1948), only Matheson & Teichert and Reeves described rocks considered in this Report. Reeves was the first to record Cambrian fossils (determined by Teichert) from the Carlton Hill area and from the Ragged Range; Matheson & Teichert worked in the Argyle, Rosewood, and Hardman Basins, but they described only a few outcrops (at Martins Bluff and near Tarrara Bar on the Ord River) in the area described here.

Noakes, Opik, & Crespin (1952) reviewed earlier work, and introduced new information on the Cambrian and Ordovician rocks of the Carlton area. As part of a reconnaissance of the Ord-Victoria region, Traves (1955) mapped the Bonaparte Gulf Basin. Since 1963, oil company studies have been concentrated on the Devonian or younger sediments, as was Drummond's report of 1963.

Ruker (1963) prepared a photogeological map of the Cambridge Gulf Sheet area, and later that year a Bureau geological party spent 6 months mapping the area (Veevers et al., 1964). Kaulback mapped the main area of Cambrian and Ordovician outcrop in the Bonaparte Gulf Basin, at Gap Point and south of Mount Rob, and Veevers mapped the outliers at Dillon Spring and Ragged Range. P.J. Jones spent a week with Kaulback collecting fossils from some of the important localities found by Traves and Opik (Traves, 1955). A.A. Opik has made a preliminary study of the fossils (App. 3), and is responsible for the division of the Cambrian/Ordovician sequence into faunal units, and for the palaeontological

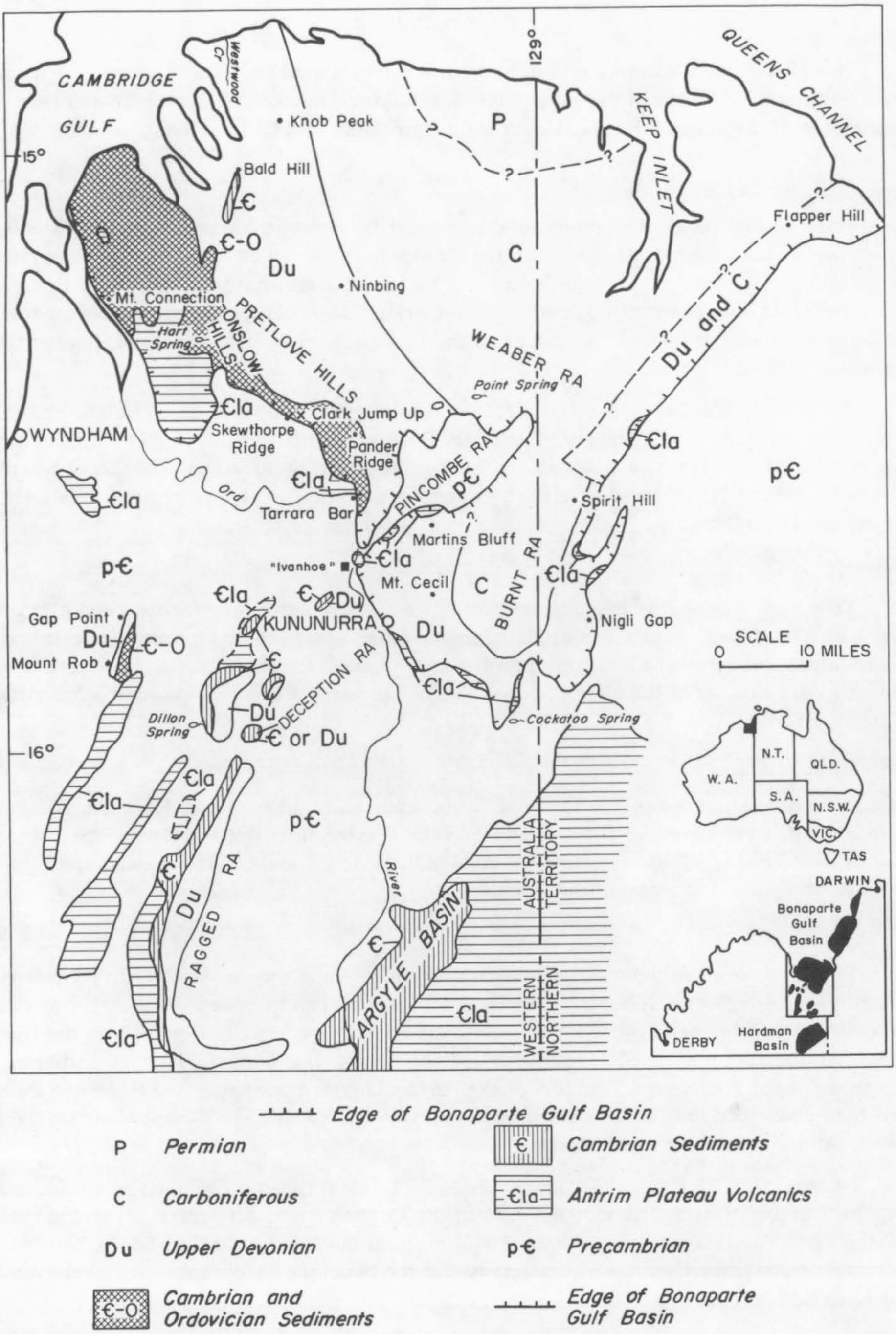

Fig. 1 Locality Map

correlations. The work and first writing of this Report were completed in 1964: since then (see Veevers & Roberts, 1968) the nomenclature of the Upper Devonian has been slightly amended, so that there is a slight discrepancy between Map 1 and the legend of a few figures.

Distribution

Cambrian and Ordovician sedimentary rocks crop out in two principal areas; the main area along the southwestern margin of the Bonaparte Gulf Basin; and the outliers of Gap Point, Mount Rob, Dillon Spring, and Ragged Range (Fig. 1). To the south and east, in the Lissadell and Dixon Range 1:250,000 Sheet areas, there are three large structural basins of Cambrian sediments - the Argyle, Rosewood, and Hardman Basins. The Cambrian sediments overlie the Lower Cambrian Antrim Plateau Volcanics, which crop out almost continuously from the Flora Valley, south of the Hardman Basin, to the Bonaparte Gulf Basin, and thence northeastward to the Katherine-Darwin region. To the north Cambrian sediments reappear in the Litchfield area and Daly River Basin.

Topography

The Cambrian and Ordovician rocks of the Bonaparte Gulf Basin underlie part of the 'Cambridge Gulf Lowlands' (Traves, 1955, Fig. 6; and see Cambridge Gulf 1:250,000 Sheet), a large area of sandy lowlands, grass-covered black-soil, and sandstone ranges up to 1000 feet high, transected by watercourses and salt-arms. A belt of relatively high hills (Onslow and Pretlove Hills), 600 to 1000 feet high and about 20 miles long, and elongated along the northwest strike, constitutes the main Cambrian and Ordovician outcrop of the Bonaparte Basin. Two dendritic drainage basins - Sandy Creek, draining to the northeast and east, and Reedy Creek, draining into the Ord River to the southwest - have cut back on either side of this belt of hills, almost to the watershed, so that the belt is divided into two parts: the Onslow Hills to the northwest, and the Pretlove Hills to the southeast. The only planed and deeply weathered surface seen in the area is at locality 236, in the Onslow Hills.

Within the Bonaparte Gulf Basin, most of the Cambrian and Ordovician outcrops owe their eminence to faults, along which the originally friable sediments have been silicified into resistant exposures; thus, virtually all the prominent exposures within the Bonaparte Basin are bounded by faults.

The Cambridge Gulf Lowlands are bounded to the north by swampy salt-flats and the sea, to the southwest by the dissected Precambrian Kimberley Plateau, to the east by the dissected Victoria River Plateau, and to the south and southeast by the Carr Boyd Ranges and Burt Range, which, together with the Pincombe Range, mark the northeastern limit of a belt of highlands.

The Palaeozoic outliers southwest of the Bonaparte Gulf Basin lie within the Kimberley Plateau, with its high strike-ridges and mesas of Precambrian rocks. Within this province, and with the exception of the Ragged Range, the low strike-ridges of soft Palaeozoic sediments occupy broad valleys. The Ragged Range, with its impressive west-facing Blatchford escarpment, is a cuesta, 25 miles long and 4 miles wide, situated between hills of Proterozoic rocks.

STRATIGRAPHICAL SUCCESSION

In 1963, Veevers, Roberts, Kaulback, & Jones (1964) found Cambrian fossils in the sediments at Mount Connection, the westernmost known outcrop of Cambrian rocks in the Bonaparte Gulf Basin, the Mount Rob outlier, the Gap Point outlier, and in the bed of the Ord River from Tarrara Bar 3 miles upstream, all of which had previously been regarded as Precambrian. Other outcrops, which had been hitherto mapped as Devonian, have been found to contain Cambrian fossils; they include a line of outcrops extending from 5 miles north of Hart Spring to Bald Hill, two hills 5 miles southwest of Point Spring, the basal part of the Dillon Spring outlier, and Biconulites dolomite, 7 miles southwest of Ivanhoe homestead.

Most of the Pretlove Hills and the Ragged Range, which had hitherto been mapped as Cambrian, were found to contain Devonian fossils; no fossils were found in the Elder Sandstone of the Hardman Basin, but all except the basal part of it is thought to be Devonian on other evidence.

General Succession

Precambrian. The following notes on the Precambrian rocks bordering the Bonaparte Gulf Basin have been supplied by K.A. Plumb.

The Palaeozoic rocks in the Bonaparte Gulf Basin are enclosed by Precambrian rocks to the east, south, and west; the Precambrian rocks also form the basement to the basin. They consist of an ancient complex of plutonic and metamorphic rocks, unconformably overlain by a younger relatively undeformed succession of sedimentary rocks.

The plutonic rocks cropout in the Halls Creek Mobile Zone, a belt about 30 miles wide which extends north-northeast from Halls Creek to near the Ord River dam and beyond into the Northern Territory, roughly along the eastern margin of the Bonaparte Basin. The rocks comprise metasediments and volcanics ranging from the greenschist to the granulite facies, and associated granite gneisses, gabbros, ultrabasic rocks, and massive granites. A wide range of mineral assemblages is represented.

The younger undeformed sediments cropout extensively in the Kimberley Basin to the west and Victoria River Basin to the east. Smaller outliers occur in the Carr Boyd Ranges, south of Kununurra, and in the Osmond and Albert Ranges farther south towards Halls Creek. Well sorted quartz sandstone predominates, with subordinate siltstone and shale, and minor acid and basic volcanics and carbonate rocks. Basic intrusives are common in the west.

The Precambrian sandstones tend to form the highest topographic features, and Palaeozoic sediments in the Bonaparte Gulf Basin were probably largely derived from this source.

Cambrian and Ordovician. Before 1963, the Cambrian and Ordovician rocks of the Bonaparte Gulf Basin and outliers were known from isolated fault blocks only. Traves (1955, p. 48) wrote '... the sediments are strongly strike-faulted, so that, without detailed work, it is impossible to obtain a complete sequence. The strike faults, marked only by small quartz veins and some slickensides, are very hard to discern; but the displacement may be over 1000 feet, and within a few yards, the section may change from Middle Cambrian to Upper Cambrian or even Ordovician in age'.

During 1963 three unbroken sequences were found in the Bonaparte Gulf Basin and near Mount Rob, which, together with smaller sections, indicate an aggregate thickness of 4500 feet of Cambrian and Ordovician sediments overlying the Antrim Plateau Volcanics. If the Blatchford Formation is added, the total is 4900 feet.

In the Bonaparte Gulf Basin these sediments were collectively called the Carlton Formation by Noakes et al. (1952) and the Carlton Group by Traves (1955). They consist of a sandstone/dolomite sequence divided into seven formations (Fig. 2), all of which, except the Tarrara and Blatchford Formations (new names), were defined by Traves (1955). In descending order, the formations are:

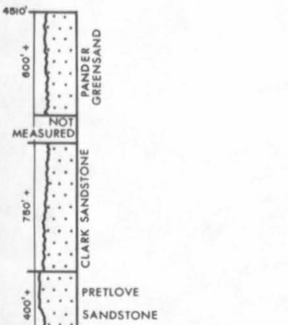

Fig. 2. Composite stratigraphical section

	Maximum Thickness (feet)
Pander Greensand	600+
Clark Sandstone	750+
Pretlove Sandstone	400+
Skewthorpe Formation	200
Hart Spring Sandstone	1260
Tarrara Formation	1300
Blatchford Formation	390
Total	4900+

Except for the new formations and a few stratigraphical corrections, this sequence is the same as that established by Traves and Opik (in Traves, 1955) on fossil evidence alone, from isolated fault blocks.

MEASURED SECTIONS

The thickness of the well exposed sections was measured with an Abney level and a 5-foot Jacob staff (Lahee, 1961, p. 455). Only rough estimates of thickness, based on horizontal distance and isolated dips, are available for sections in which the beds are poorly exposed.

Owing to the faulted and scattered nature of the outcrops, about 40 stratigraphical sections were studied to determine the Cambrian and Ordovician stratigraphy. The thickest and most useful sections are described below. The measured columnar sections are given in various figures and in the correlation charts, Figures 8 and 18.

The lithology of the Palaeozoic sediments is monotonous, and some of the sandstones belonging to different units are indistinguishable. Strike faulting is common and correlation and identification based on lithology alone are unreliable; fossils are the only means of correlating isolated outcrops.

Southern Pretlove Hills; Sections 232 and 245 (Map 1; Figs 3, 4)

Section 232 was measured along a creek bed in the sandy plain about 2 miles south of Skewthorpe Ridge. Combined with section 245 it provides an unbroken sequence from the lower Middle Cambrian to the Lower Ordovician. At the base of the section the Antrim Plateau Volcanics (fine-grained dark amygdaloidal basalt weathering red-brown, in thin layers, with a northeast dip of 14°, overlying vesicular brecciated basalt) are underlain by micaceous green and grey shale and mudstone indurated by silica, interbedded with poorly outcropping medium-grained quartzite. The shale and quartzite are probably Proterozoic, and dip northeast at 20° to 25°. Farther downstream (to the southwest) are poor exposures of shale and basalt. If this basalt is the same as that found upstream, its outcrop here indicates either the uneven erosional surface over which it flowed, or faulting.

Upstream, overlying an estimated 150 feet of Antrim Plateau Volcanics, are exposed about 40 feet of interbedded green and brown soft shale and mudstone, containing white veins of rubbly travertine (Pl. 1, fig. 1). The shale and mudstone are separated from the basalt by about 100 feet of poorly exposed sand-covered green shale, and are succeeded upstream by about 430 feet of no outcrop. This gap, which, it is inferred, indicates a continuation of the soft shale, is followed by 680 feet of fairly well exposed fine-grained laminated red silty quartz sandstone with abundant mudflakes. Above the sandstone are 38 feet of prominently bedded grey algal dolomite with Biconulites and fragments of brachiopods and an

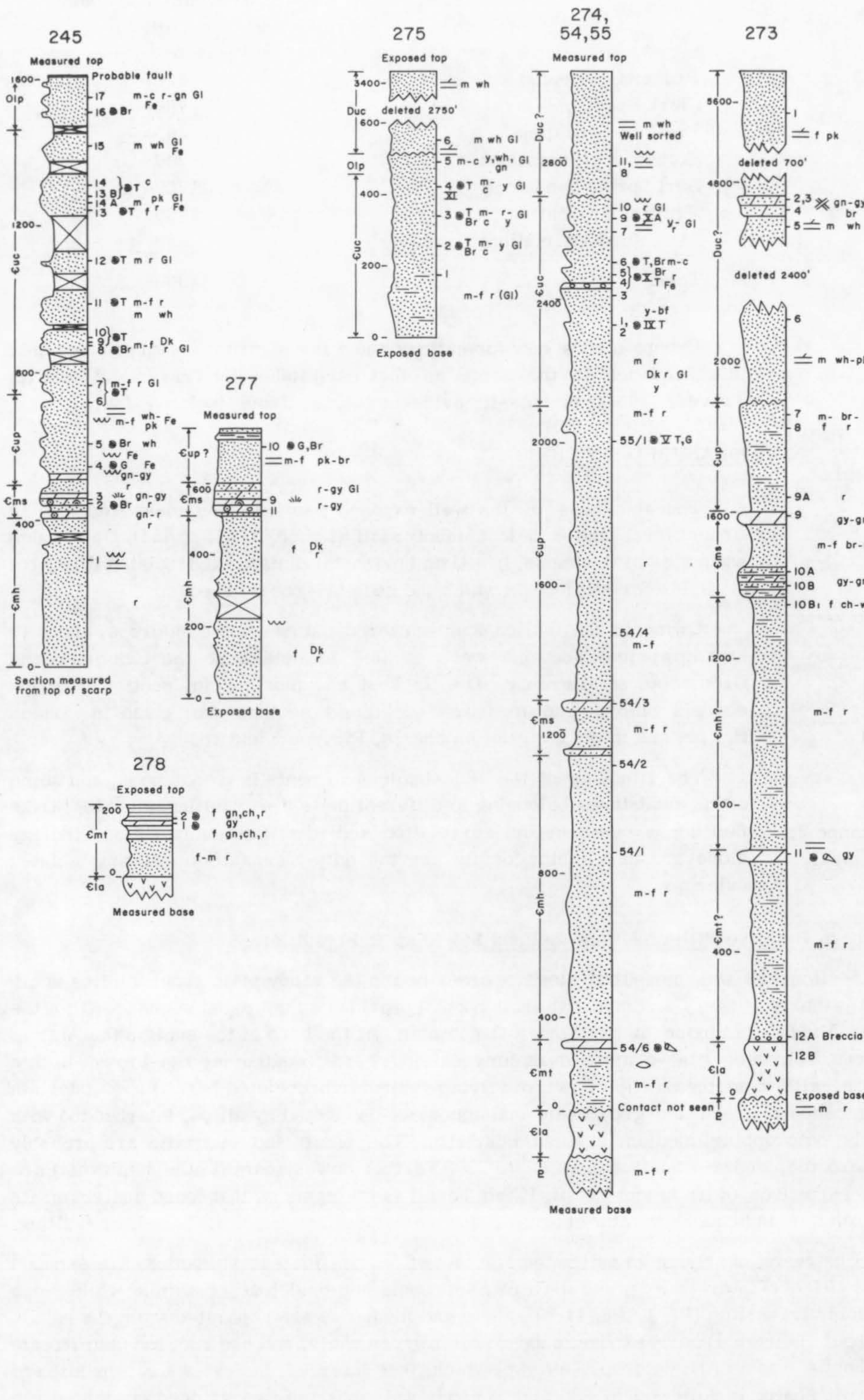

Fig. 3. Columnar sections

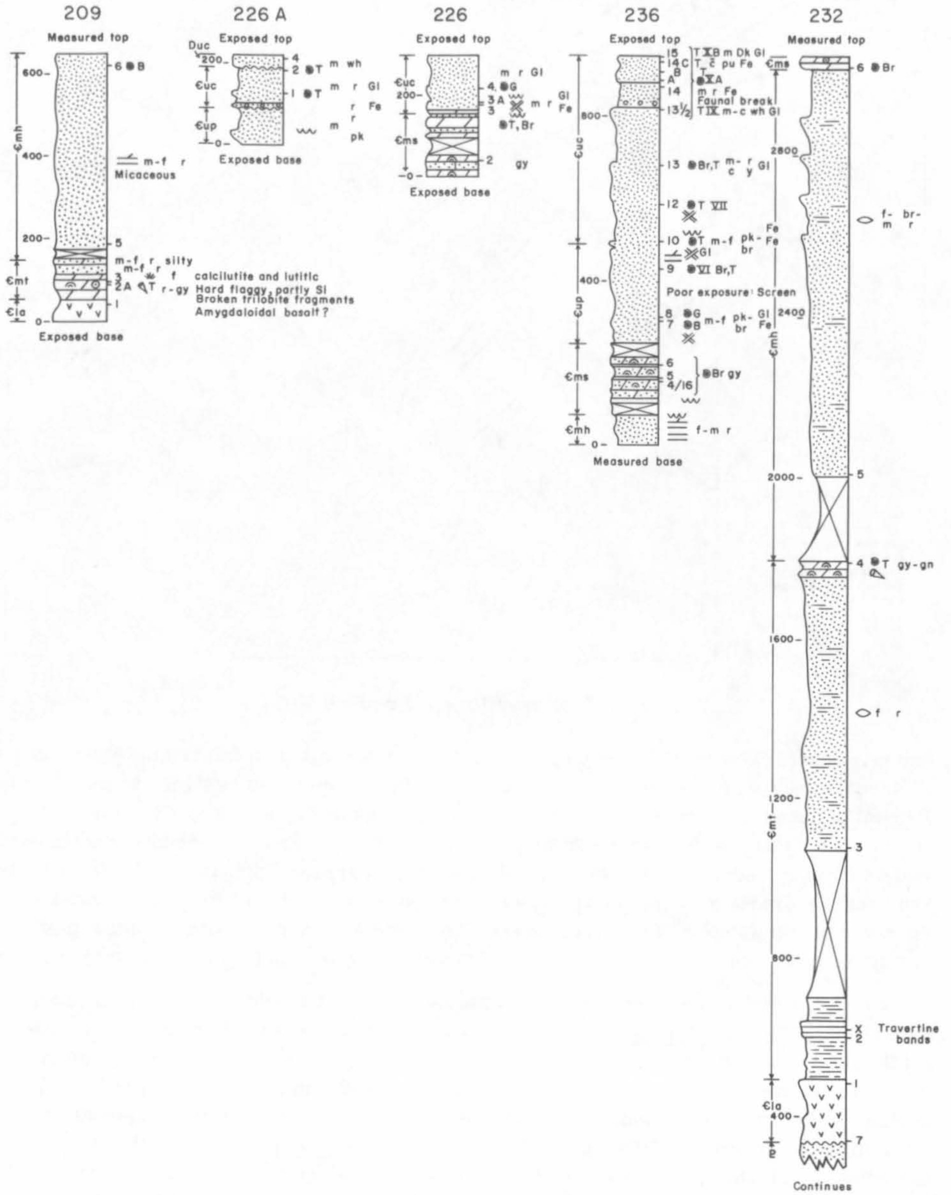

Fig. 3. Columnar sections

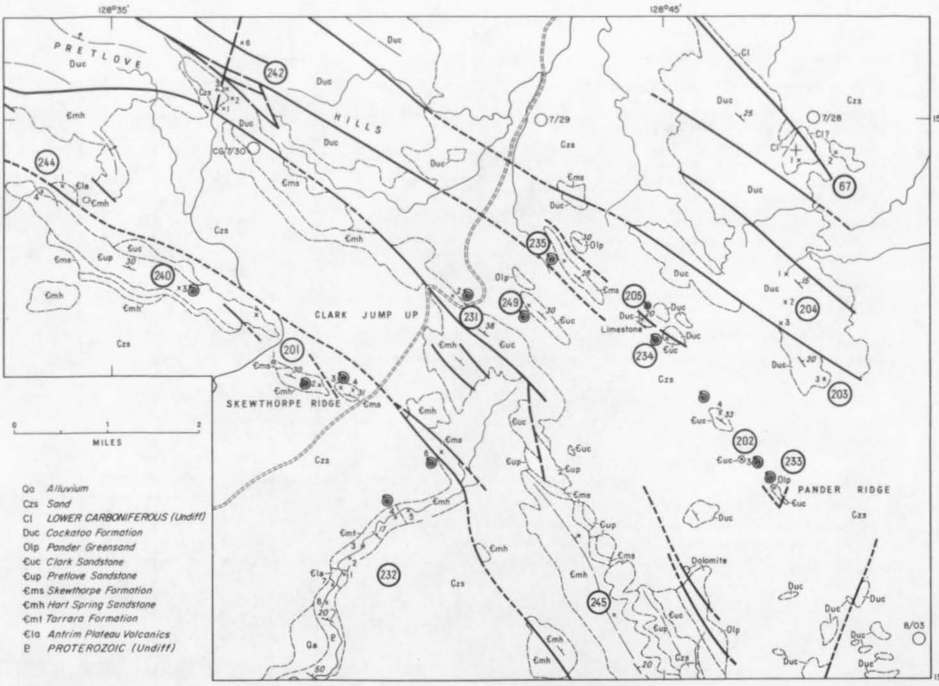

Fig. 4. Geological map, Pretlove Hills

indeterminable species of Redlichia. This part of the section, underlain by the Antrim Plateau Volcanics, and extending up to the top of the dolomite, is assigned to the Tarrara Formation. Farther upstream, and overlying the dolomite, are about 1230 feet of Hart Spring Sandstone, a fine to medium-grained red-brown silty thin-bedded quartz sandstone with mudflakes, similar to the sandstone of the Tarrara Formation. The Hart Spring Sandstone is overlain by the Skewthorpe Formation, which is cut off by a strike fault which throws the Skewthorpe Formation down into renewed contact with an outcrop of Hart Spring Sandstone to the north. The section is assumed to be uninterrupted by major faults.

Section 245 was measured across a ridge southwest of Pander Ridge. On the southern side of the ridge, the Hart Spring Sandstone rises from the sandy plain in a steep 500-foot southwest-facing scarp of barren fine to medium-grained cross-bedded and ripple-marked silty red-brown quartz sandstone with scattered mudflakes. About 400 feet of Hart Spring Sandstone were measured from the top of the scarp, and the total thickness exposed is estimated to exceed 1000 feet. The Skewthorpe Formation overlies the Hart Spring Sandstone, and its grass-covered subdued yellow and grey outcrop contrasts with the ridged spinifex-covered red and black scarp of the thinly bedded Hart Spring Sandstone (Pl. 1, fig. 2). The Skewthorpe Formation consists of 135 feet of well bedded oolitic and stromatolitic dolomite with some thin flaggy silty dolomite beds, interbedded with poorly outcropping scree-covered medium to fine-grained quartz sandstone (Fig. 5), some of which is dolomitic. The sandstone makes up about one third of the Skewthorpe Formation. Phosphatic brachiopod shells occur throughout the dolomite, and most abundantly in the silty dolomite.

Overlying the Skewthorpe Formation, and extending down the dip-slope to the north-east, almost to the plain at the foot of the hills, lies the Pretlove Sandstone, 200 feet of white, pink, or yellowish locally ironstained well sorted medium-grained flaggy quartz sandstone, which contains sparsely fossiliferous beds with brachiopods, gastropods, and trilobite fragments, and is characterized by ferruginous and ripple-marked bedding planes.

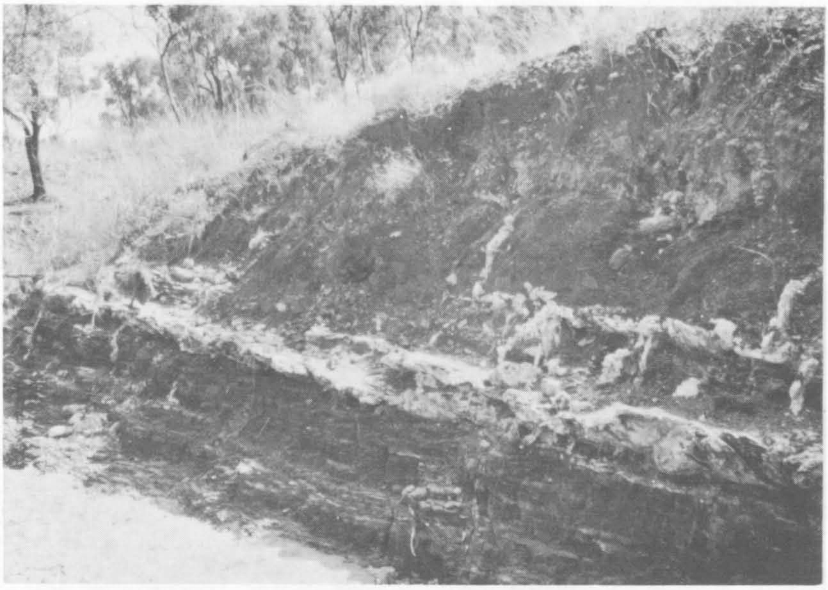

PLATE 1, fig. 1 Shale and mudstone, Tarrara Formation, section 232. The white veins are travertine

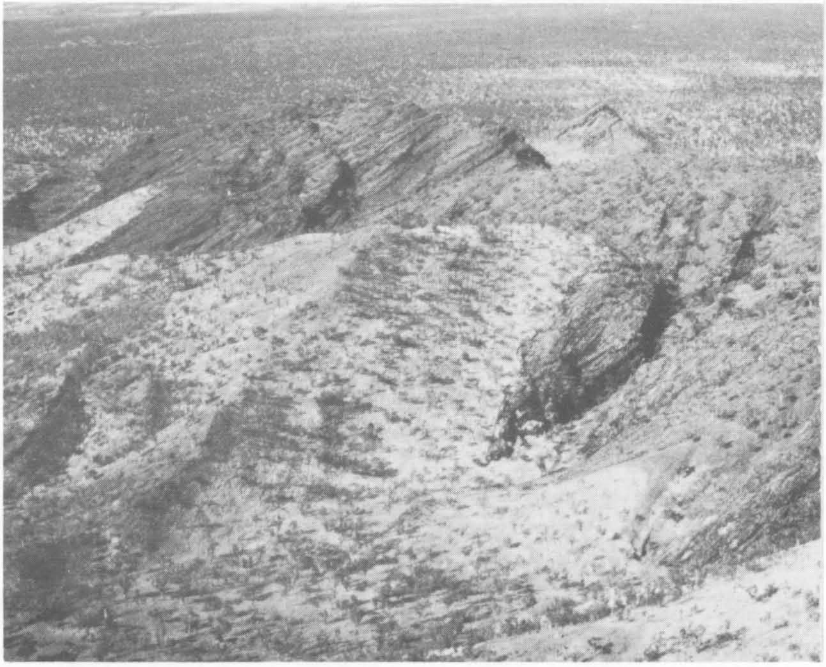

PLATE 1, fig. 2 Aerial view of Skewthorpe Formation (light-coloured) overlying Hart Spring Sandstone at locality 245 (looking southeast). Precambrian Cave Range in the background

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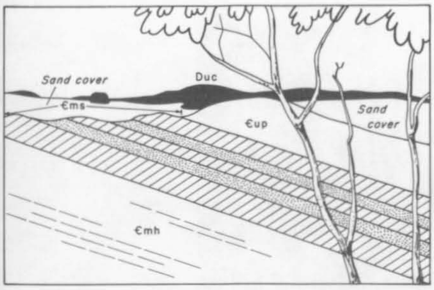

Fig. 5. Sketch of sandstone interbeds, Skewthorpe Formation, Locality 245

About 720 feet of greenish to reddish medium-grained glauconitic and friable red quartz sandstone of the Clark Sandstone overlie the Pretlove Sandstone in low ribbed ridges which become isolated in the plain to the northeast. The Clark Sandstone contains abundant glauconite in its upper half, except for a few interbeds with no glauconite; the lower half is mainly of non-glauconitic quartz sandstone, yellow, sugary white, or red, with a few glauconite sandstone beds, such as the very dark glauconitic sandstone with phosphatic brachiopod shells in the creek bed at the foot of the dip-slope on the side of the hill.

Compared with the Pretlove Sandstone, the lower beds of the Clark Sandstone are more feldspathic, friable, darker, more ferruginous, comparatively poorly sorted, richly fossiliferous, and more variable in lithology from bed to bed. The Clark Sandstone weathers black in rounded lumps which disintegrate at the blow of a hammer; outcrops are characteristically low ribbed strike-ridges. In contrast, the Pretlove Sandstone is pink or yellowish, except where locally ironstained, generally harder, partly silicified, well sorted, and poorly fossiliferous; it contains little or no feldspar and has a uniform lithology. It crops out in pinkish brown angular strike-ridges and (in other sections) in indurated high scarps and cliffs which break up readily into scree.

The Upper Cambrian Clark Sandstone is overlain by the Lower Ordovician Pander Greensand. The contact is obscured by sand, on both sides of which the dip is 25^{o}; elsewhere the Clark Sandstone passes without a break into what is tentatively regarded as the Pander Greensand.

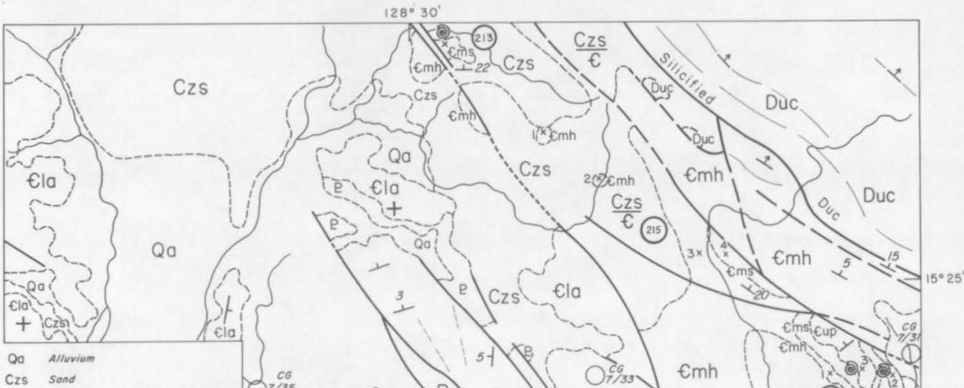

Fig. 6. Geological map, northern Pretlove Hills

The Pander Greensand consists mainly of highly glauconitic, poorly cemented quartz sandstone with numerous fragments of white phosphatic fossils. Some of the glauconite grains have broken down to iron oxides, giving a red, green, and white speckled appearance to the rock. In places, where the glauconite is not altered, the rock is dark green. Elsewhere, there are interbeds and bands of medium-grained ironstained quartz sandstone.

No determinable trilobites or brachiopods were found in the Pander Greensand, but some beds contain conodonts, which are visible under a hand-lens, and a few with the unaided eye (specimen CG245/17). From a preliminary examination, P.J. Jones (pers. comm.) determined the conodonts as Ordovician, including the forms recorded by Opik (in Traves, 1955).

The 150 feet of Pander Greensand measured in this section are cut off by poor outcrop, and probably by strike-faults, indicated by scree of slickensided silicified sandstone. To the northwest of the inferred fault are exposed 15 feet of fine-grained reddish brown quartz sandstone with mudflakes and, in a ridge, about 60 feet of hard silicified thinly bedded fine to medium-grained reddish quartz sandstone. Overlying this, in a low hill, are about 100 feet of pink and brown dolomite and dolomitic sandstone, dipping at 15° to the northeast. At the foot of the hill were found a loose block of glauconitic dolomite with indeterminate obolid phosphatic brachiopods and a loose block of red sandstone containing poorly preserved Crustacea, probably phyllocariids. Fragments of obolid brachiopods were also found in situ in a dolomite bed. These brachiopods are not known to range beyond the Cambrian and Ordovician, and as Ordovician dolomite is not known in the Cambridge Gulf area, this dolomite outcrop is probably a down-faulted block of the Skewthorpe Formation. The presence of slickensides and quartz veins indicates the presence of faults; and numerous strike faults, with a displacement of up to 2000 feet, have been proved in the board valley to the northwest and elsewhere in Lower Palaeozoic rocks.

Hart Spring and the Onslow Hills:Sections 209 and 236 (Map 1, Figs 3, 7)

Between locality 245 and the Onslow Hills, numerous incomplete sections of Cambrian and Ordovician rocks have been measured at outcrops isolated and disrupted by faults. These sections confirm the succession shown in sections 232 and 245, and indicate lateral changes in individual formations. Some outcrops (localities 240 and 243, Figs 4, 6) are relatively large, extending over three or four formations; others are little more than hillocks (e.g. Pander Ridge, Clark Jump Up), which contain incomplete sections only. The first complete section north of locality 245 was found near Hart Spring in the Onslow Hills.

Hart Spring: Section 209. At localities 208 and 209 (Figs 3, 7), a cliff of thin-bedded Hart Spring Sandstone overlies about 100 feet of dolomite and dolomitic sandstone of the Tarrara Formation, which is well exposed in two long benches, each capped by resistant dolomite, and separated from each other by about 40 feet of poorly exposed fine-grained red sandstone. The lower bench is capped by a distinctively weathering 6-inch oncolite (algal ball) bed which contains, besides Biconulites, trilobite fragments (Redlichia) similar to those found in the equivalent dolomites of section 232 (specimen CG232/4). No outcrop was found below the Tarrara Formation dolomite at localities 208 and 209, but in the creek bed in the valley immediately to the southwest were found poor outcrops of basalt, which are probably the Antrim Plateau Volcanics.

Section 209 continues upward into 520 feet of Hart Spring Sandstone with a northeasterly dip of 5° to 12°. The section was measured to a point at the foot of a small hill at locality 220 (Fig. 7), where measured section 220 showed a further 85 feet of Hart Spring Sandstone which is overlain by the basal beds of the Skewthorpe Formation.

Section 236. At locality 236, about 3 miles east of Hart Spring, the Cambrian succession is continuous from the Hart Spring Sandstone to the middle of the Clark Sandstone (Figs 3, 7, 8, 9). The Cambrian sediments crop out as a chain of hills trending approximately

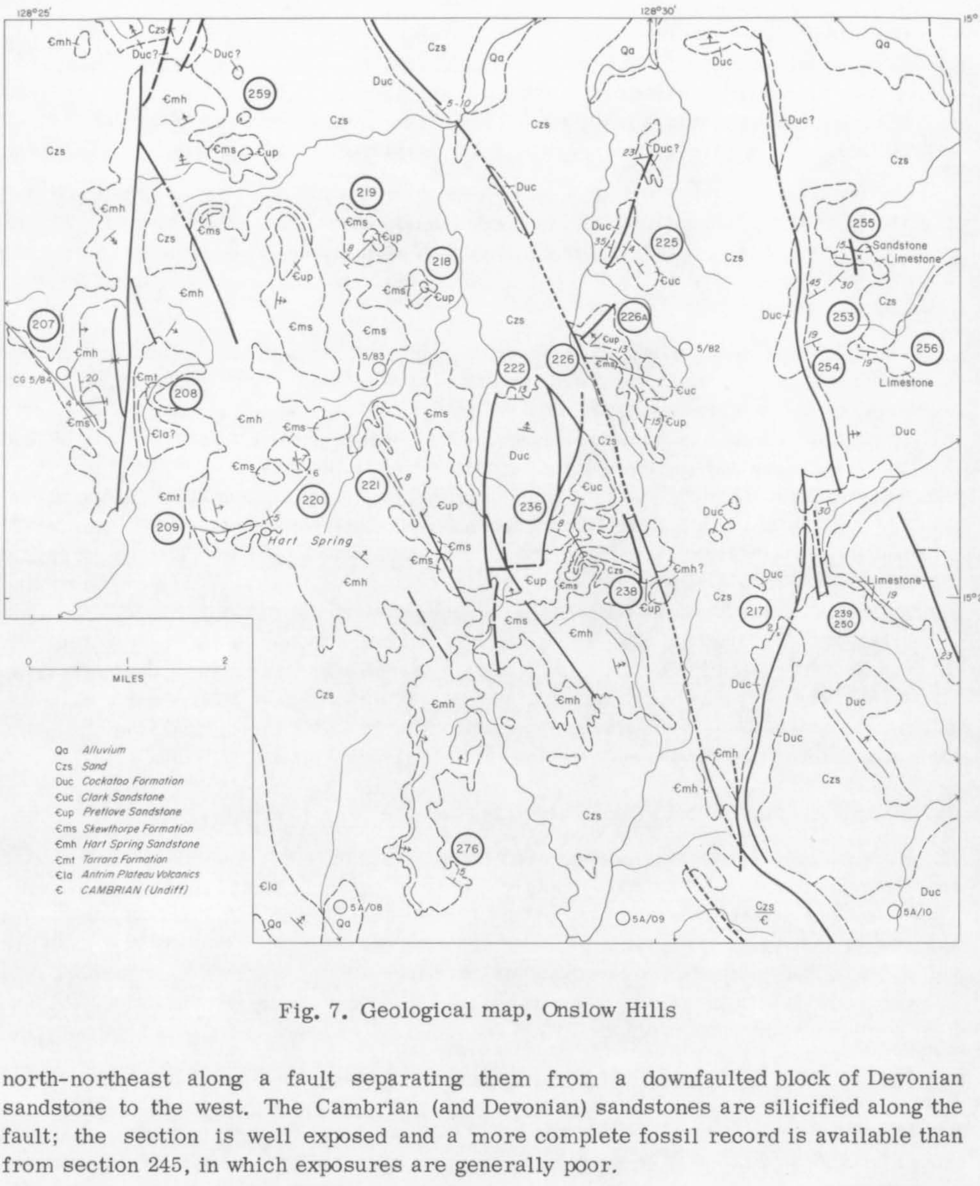

Fig. 7. Geological map, Onslow Hills

north-northeast along a fault separating them from a downfaulted block of Devonian sandstone to the west. The Cambrian (and Devonian) sandstones are silicified along the fault; the section is well exposed and a more complete fossil record is available than from section 245, in which exposures are generally poor.

The formations are readily distinguishable in section 236 (Figs 3, 8, 9). The rounded, locally rubble-covered slopes of the thin-bedded Hart Spring Sandstone (of which only about 100 feet are exposed in the valley in which the section was measured) are overlain by the Skewthorpe Formation, which forms cliffs. The Skewthorpe Formation can be followed round the curve of the valley to its northern flank, where 150 feet of it are impressively exposed in a south-facing cliff (loc. 238). The Skewthorpe Formation here consists predominantly of 5 to 10-foot beds of buff-grey, frequently ironstained, hard sandy dolomite, which is partly stromatolitic and partly oolitic, and is rhythmically interbedded with soft brown friable sandstone. Further details are given later (Fig. 21).

Above the Skewthorpe Formation lie 250 feet of Pretlove Sandstone, the lower two-thirds of which are in places almost obscured by scree. The upper part is exposed in a cliff of brown-weathering flaggy white to pink medium to fine-grained ironstained quartz sandstone which contains numerous ferruginized and ripple-marked planes.

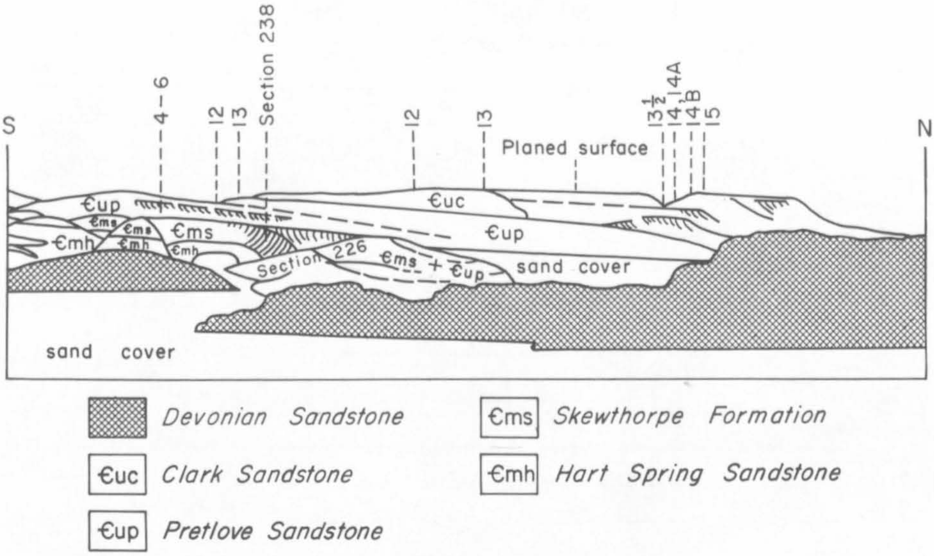

Fig. 8. Sketch of section 236

Above the Pretlove Sandstone, 450 feet of Clark Sandstone extend to the top of the ridge (fossil locality CG236/13), where they overlook the downfaulted Devonian sandstone to the west. Along the top of the ridge is a hard horizontal ferruginized platform up to 2 feet thick, which cuts across the gentle dip of the Cambrian beds. This is probably an old landsurface (Fig. 8). To the north of fossil locality CG236/13 is a steep-sided narrow east-west valley, on the north side of which the section is continued (fossil localities CG236/13½-15) to the top of the northernmost ridge of the Cambrian outcrop. Here again the horizontal ferruginized plane truncates the gently dipping Clark Sandstone.

The lower third of the Clark Sandstone exposed consists of a dark red medium-grained glauconitic quartz sandstone with a ferruginous cement, similar to the equivalent part of the Clark Sandstone in section 245. This is succeeded by a sugary friable well sorted medium-grained white quartz sandstone with rare glauconite (CG236/13½) and scattered small quartz pebbles at its top, which forms the middle part of the Clark Sandstone. It is overlain conformably by a red glauconitic medium-grained quartz sandstone with an iron-oxide cement, which becomes increasingly ferruginous towards the top of the outcrop. The glauconite is altered to iron oxide, except in a few beds. Opik (App. 3) finds a sharp break between the faunal assemblage at the top of the sugary white sandstone (faunal unit IX, Fig. 9) and that collected from the ferruginous red sandstone only a few feet above it (faunal unit X). The fossils in the upper red sandstone are fragmented (CG236/14, 15), whereas fossils in the underlying white sandstone are comparatively intact (taking into account the common preservation of trilobites as glabellae or pygidia only). These observations, together with the difference in lithology between the two sandstones, and the presence of scattered pebbles along their contact, suggest an abrupt change in some important factor or factors controlling sedimentation at the end of the deposition of the white sandstone.

Ord River: Tarrara Bar: Section 278; and Little Tarrara Bar: Section 277 (Figs 3, 10)

Tarrara Bar: Section 278. The Antrim Plateau Volcanics form a bar across the river (Fig. 10) which gives its name to this locality and to the Tarrara Formation. The well layered amygdaloidal violet volcanics dip 30° in the direction of 70°. Overlying them, and upstream along the northern bank of the river, are exposed about 200 feet of the Tarrara

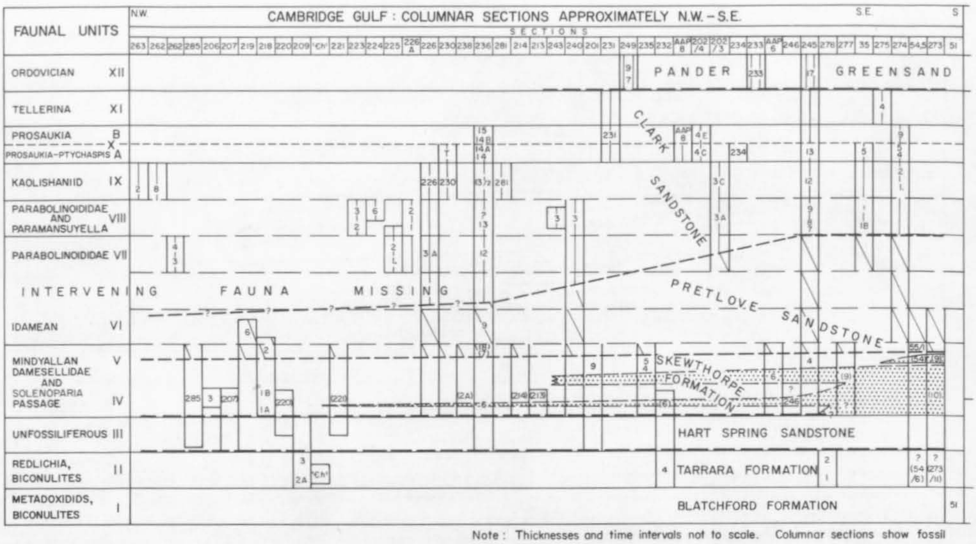

Fig. 9. Correlation chart

Formation. The exposed section consists of poorly outcropping fine-grained red micaceous silty quartz sandstone (105 ft), overlain by about 100 feet of red, green, and chocolate mudstone and shale, in the middle of which is a 20-foot bed of green and grey silicified dolomite containing Biconulites and fragments of an indeterminable Redlichia. The shale above the dolomite bed contains abundant Biconulites.

Little Tarrara Bar: Section 277. Almost 2 miles farther upstream (to the south), at Little Tarrara Bar, 510 feet of dark red fine-grained ripple-marked silty micaceous quartz sandstone are exposed along the eastern bank of the Ord River. They dip at 20° to 45° to the southeast and are overlain by about 85 feet of reddish dolomite. The dolomite contains beds of oolite, stromatolites, and quartz sandstone, and a dolomitic breccia (sample CG277/11, see App. 2), and a few glauconitic dolomite bands with phosphatic brachiopods similar to those found in the Skewthorpe Formation in most localities farther north. This dolomite is identified as the Skewthorpe Formation, and the underlying sandstone as the Hart Spring Sandstone. The Skewthorpe Formation dolomite is overlain by 150 feet of flaggy white to red ironstained medium-grained quartz sandstone with silty shale bands at its top, which contains poorly preserved gastropods and brachiopods. This is probably the Pretlove Sandstone. Outcrop continues sporadically upstream on both sides of the river, but is complicated by faults.

Palaeozoic Outliers west and southwest of Kununurra

Seven areas of outlying Palaeozoic rocks have been found west and southwest of Kununurra (Fig. 1). The localities are Ragged Range (Cambrian and Devonian), Mount Rob (Cambrian and probable Devonian), Gap Point (Cambrian, probable Ordovician, and Devonian), Dillon Spring (Cambrian and Devonian), Deception Range (probable Cambrian and Devonian), an area 10 miles northeast of Dillon Spring (Cambrian), and an area 7 miles southwest of Ivanhoe homestead (Cambrian and probable Devonian). The Dillon Spring, Deception Range, and Ivanhoe outliers were first described by Traves (1955, pp. 60-61, pl. 1), who regarded the outliers as entirely Devonian; fieldwork in 1963 has shown that the basal parts of the Dillon and Ivanhoe outliers are Cambrian. The outliers of Mount Rob and Gap Point were discovered in 1963, following the air-photograph interpretation of Ruker (1963). Reeves (1948) and Traves (1955) regarded the entire Ragged Range as Cambrian; fieldwork in 1963 showed that the upper conglomeratic part of the Range is Devonian.

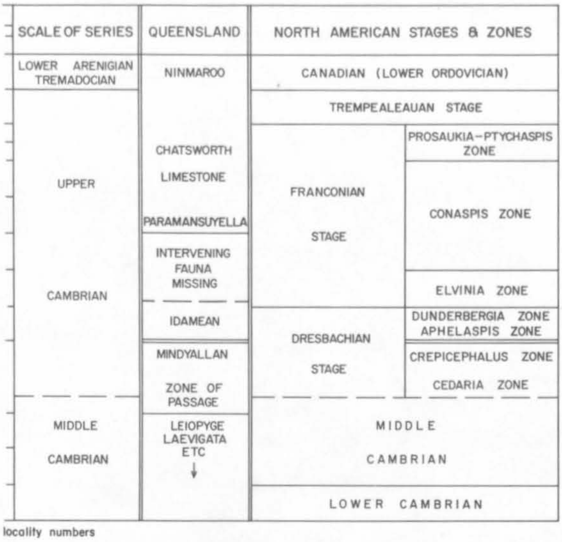

Fig. 9. Correlation chart

Gap Point; Section 275 (Figs 3, 11, 13)

About 2 miles south of Gap Point, and on either side of the Great Northern Highway where it crosses one of the upper tributaries of Parry Creek, lies a graben within the Precambrian terrain, consisting of 500 feet of fossiliferous Upper Cambrian and probably Lower Ordovician sediments which dip 25^{o} to the southeast, unconformably overlain by an estimated 3000 feet of probable Devonian Cockatoo Sandstone, which dips at 15^{o} to the southeast.

The basal 200 feet of the Cambrian outcrop is a barren red medium to fine-grained quartz sandstone with mudflakes, similar to the Hart Spring Sandstone. This is overlain, apparently conformably, by a medium to coarse-grained quartz sandstone which ranges from yellow to red and becomes increasingly glauconitic towards its top. This sandstone contains trilobites and brachiopods (specimen CG175/4) which indicate the uppermost time unit of the Upper Cambrian (unit X, Fig. 9); this and the lower sandstone are identified as the Clark Sandstone. The overlying 50 feet of sandstone immediately below the unconformable Devonian Cockatoo Sandstone contains abundant glauconite and fragments of phosphatic brachiopods, and has the speckled green, yellow, and white colour of the Pander Greensand, but in the absence of microfossils and of diagnostic macrofossils, the identification of these beds as Pander Greensand remains tentative.

Using the potassium/argon method on glauconite, V.M. Bofinger (pers. comm) has determined the minimum age of these beds as 470 m.y., or Lower Ordovician.

Mount Rob: Section 274 (Figs 3, 12, 13)

An estimated 2700 feet of Cambrian sediments crop out south of Mount Rob (which itself is Precambrian). They probably form a continuous succession from the Antrim Plateau Volcanics to the Clark Sandstone, and are unconformably overlain by Devonian sediments about 3000 feet thick. The Palaeozoic rocks are faulted down to the west against the Proterozoic. To the east, the Antrim Plateau Volcanics unconformably overlie the Proterozoic. Along the unconformity the Devonian sediments generally dip at about 5^{o} less than the Cambrian.

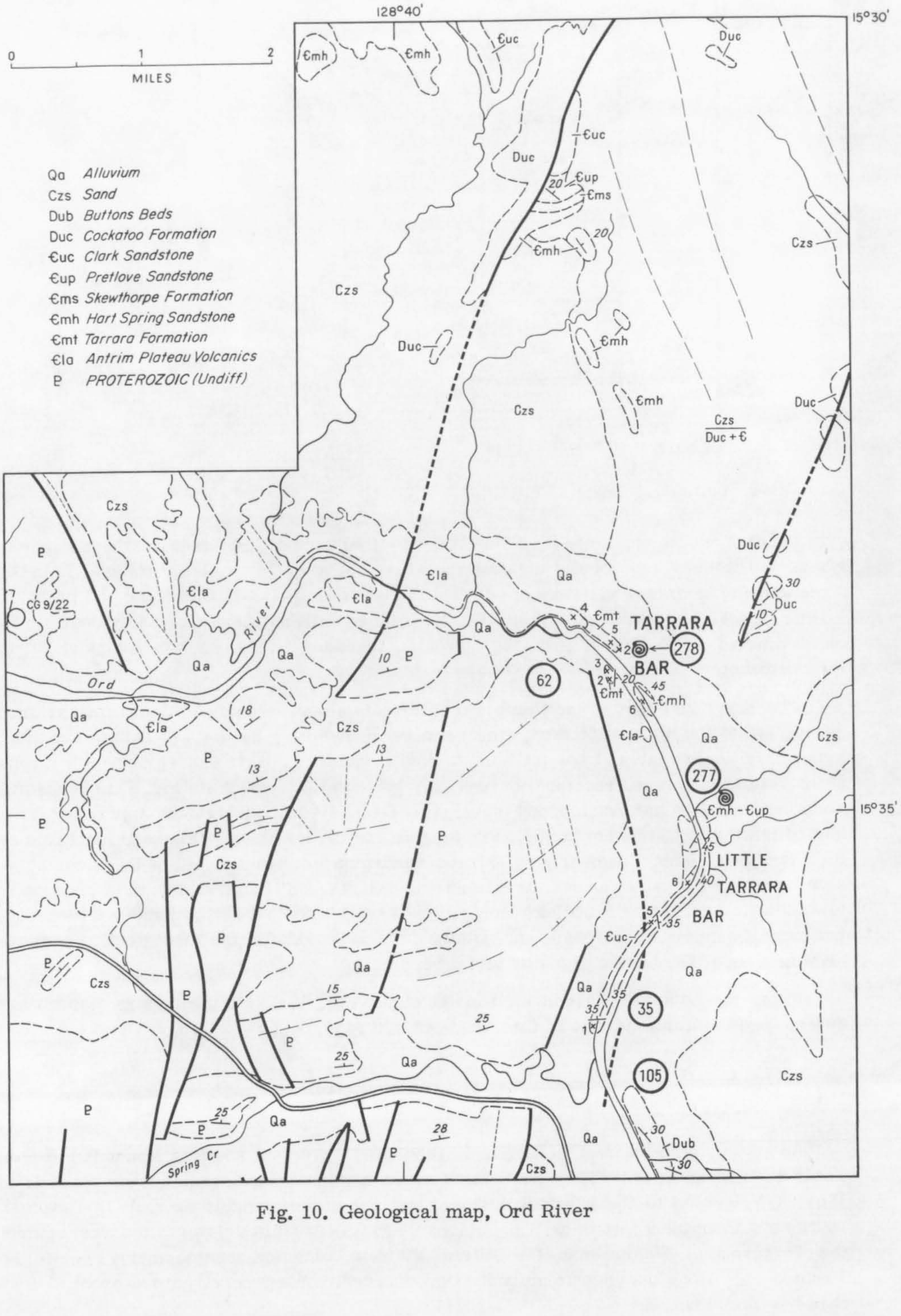

Fig. 10. Geological map, Ord River

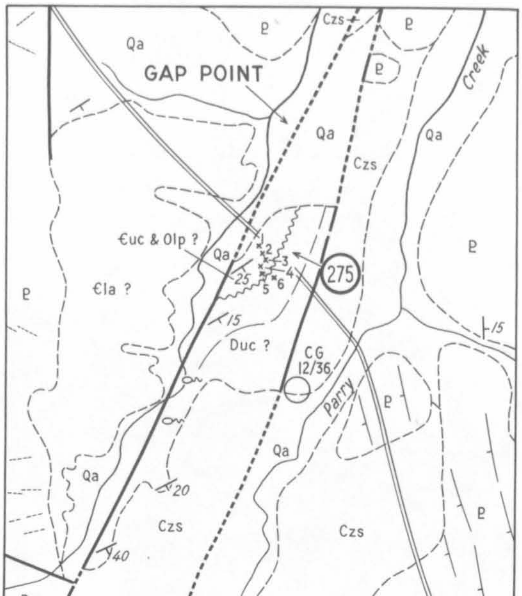

Fig. 11 Geological map, Gap Point

The Antrim Plateau Volcanics cover large areas, but are generally obscured by soil and rubble; only 150 feet were measured in this section. The Cambrian sediments crop out in low ribbed strike-ridges with a general westerly dip of 25° to 35°. Overlying the basalt in section 274 (which included sections 54 and 55) are 175 feet of fine to medium-grained silty red quartz sandstone with mudflakes, which are overlain by 20 feet of grey Biconulites dolomite, exposed in the creek bed at CG54/6 and in several localities farther south. These beds are identified as either the Blatchford Formation or the Tarrara Formation, and for simplicity of presentation, and without prejudice, are denoted on the map as Tarrara Formation. The contact between them and the underlying Antrim Plateau Volcanics is concealed in Section 274, but farther south, in section 273 (Fig.3), it is marked by a thin bed of brecciated sandstone and siltstone, with rare basalt clasts (specimen CG273/12). In section 273 the sandstone member of the Tarrara Formation is 500 feet thick.

Eight hundred feet of barren fine to medium-grained red silty quartz sandstone with mudflakes overlies the dolomite of the Tarrara Formation. These beds have been placed in the Hart Spring Sandstone because of their lithology and position overlying the Biconulites dolomite. They are overlain by a 10-foot bed of dolomite, another 100 feet of similar red medium to fine-grained silty quartz sandstone, and a second 30-foot dolomite bed (locality CG54/3). No fossils have been found in the dolomites or in the sandstone between them: the dolomites are pink, vuggy, and locally flaggy, and are interbedded with thin dolomitic sandstone beds. The dolomites and the intervening sandstone are tentatively identified as the Skewthorpe Formation; they lack fossils, oolites, and stromatolites, and are closest in lithology to the Skewthorpe Formation exposed at Little Tarrara Bar (section 277).

Overlying the dolomite beds are about 830 feet of sandstone very similar (but containing slightly larger quantities of glauconite) to the quartz sandstone between the Skewthorpe Formation dolomites, and to the Hart Spring and Tarrara Formation sandstones in this section. Towards the top of this sandstone, at locality CG55/1, trilobites belonging to faunal unit V (Mindyallan) indicate correlation with the Pretlove Sandstone (Fig. 10). The three prominent dolomite marker beds in this section provide the only means of dividing the 200 feet of lithologically homogeneous sandstone below locality CG55/1 into formations.

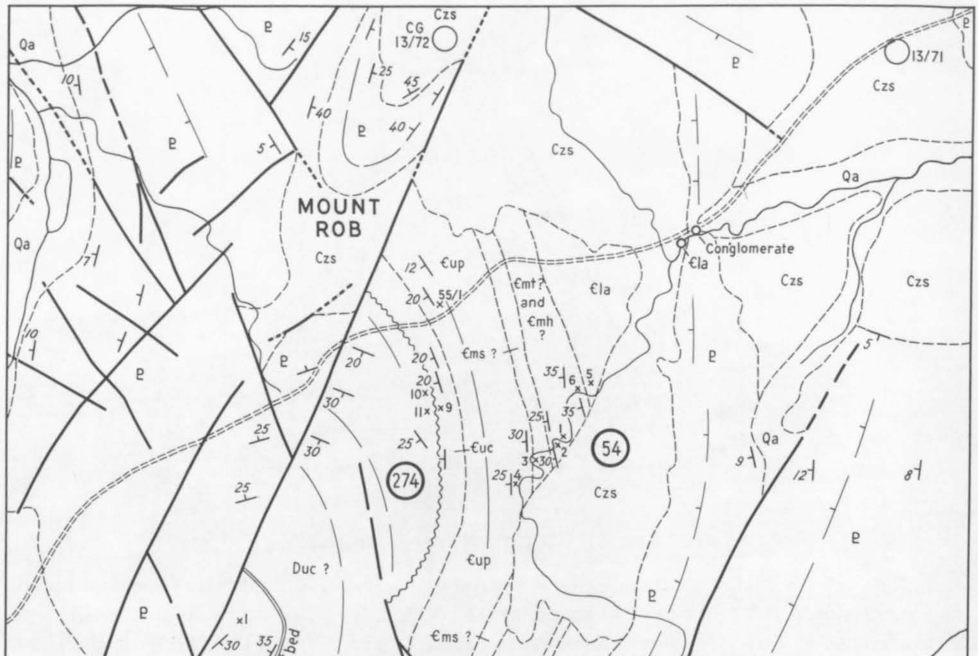

Fig. 12. Geological map, Mount Rob

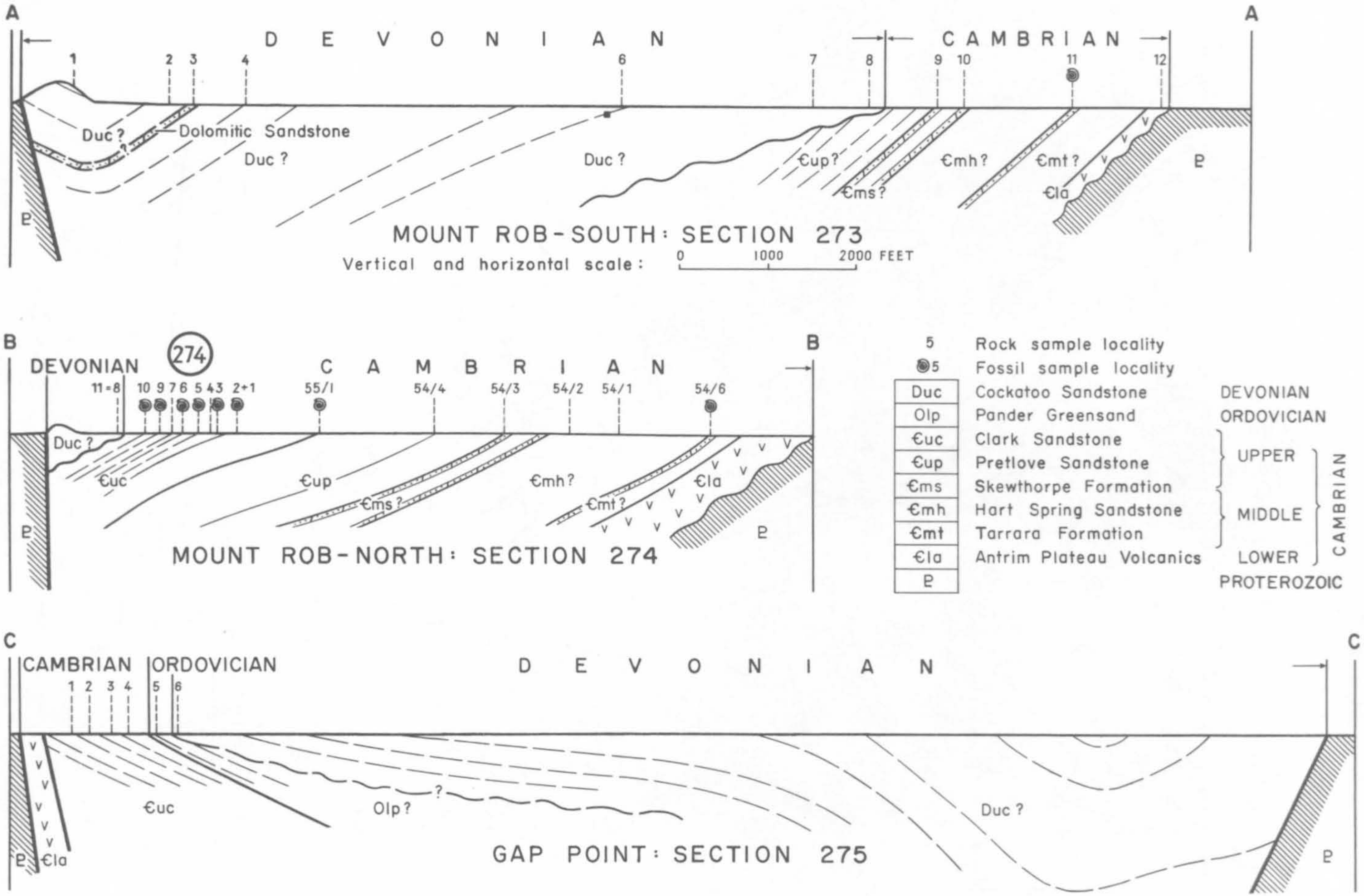

Fig. 13. Cross-sections, Gap Point and Mount Rob

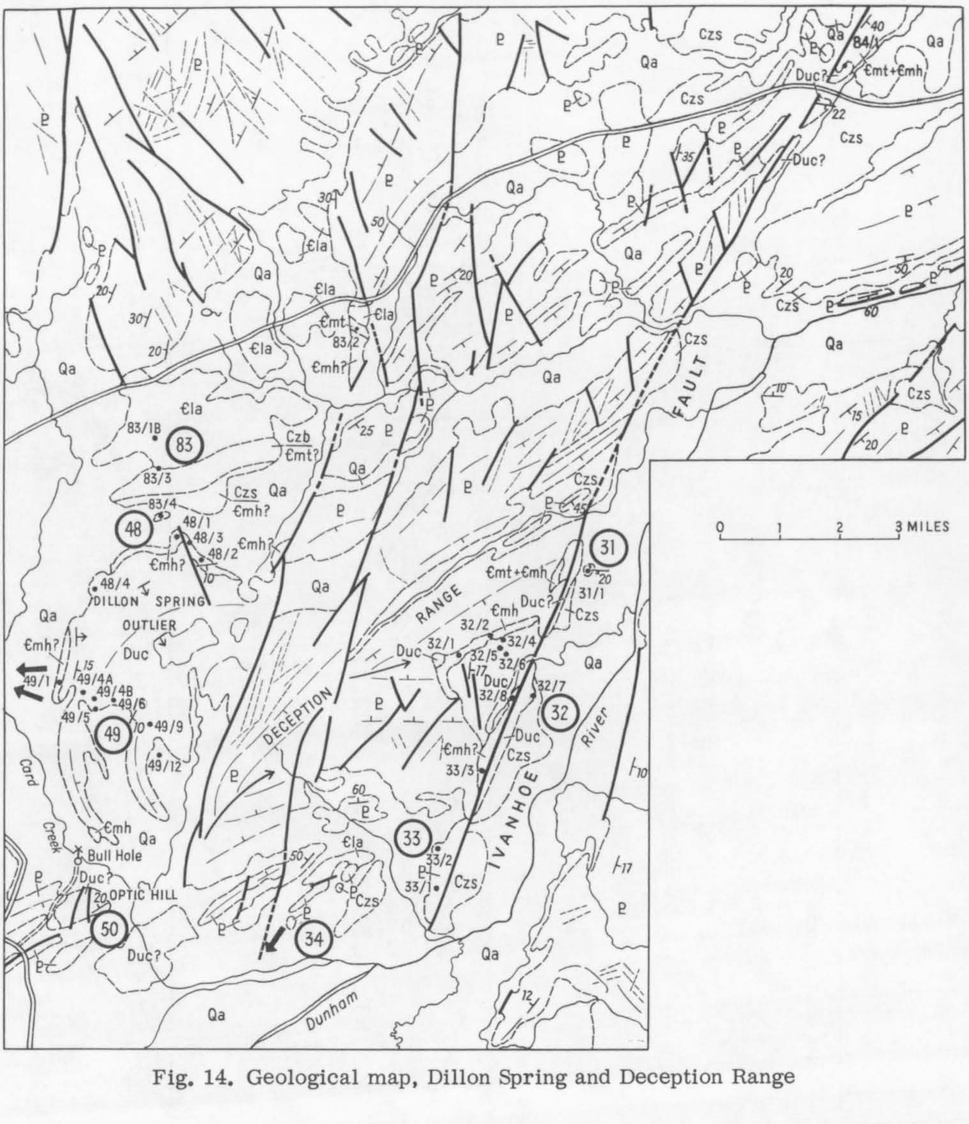

Fig. 14. Geological map, Dillon Spring and Deception Range

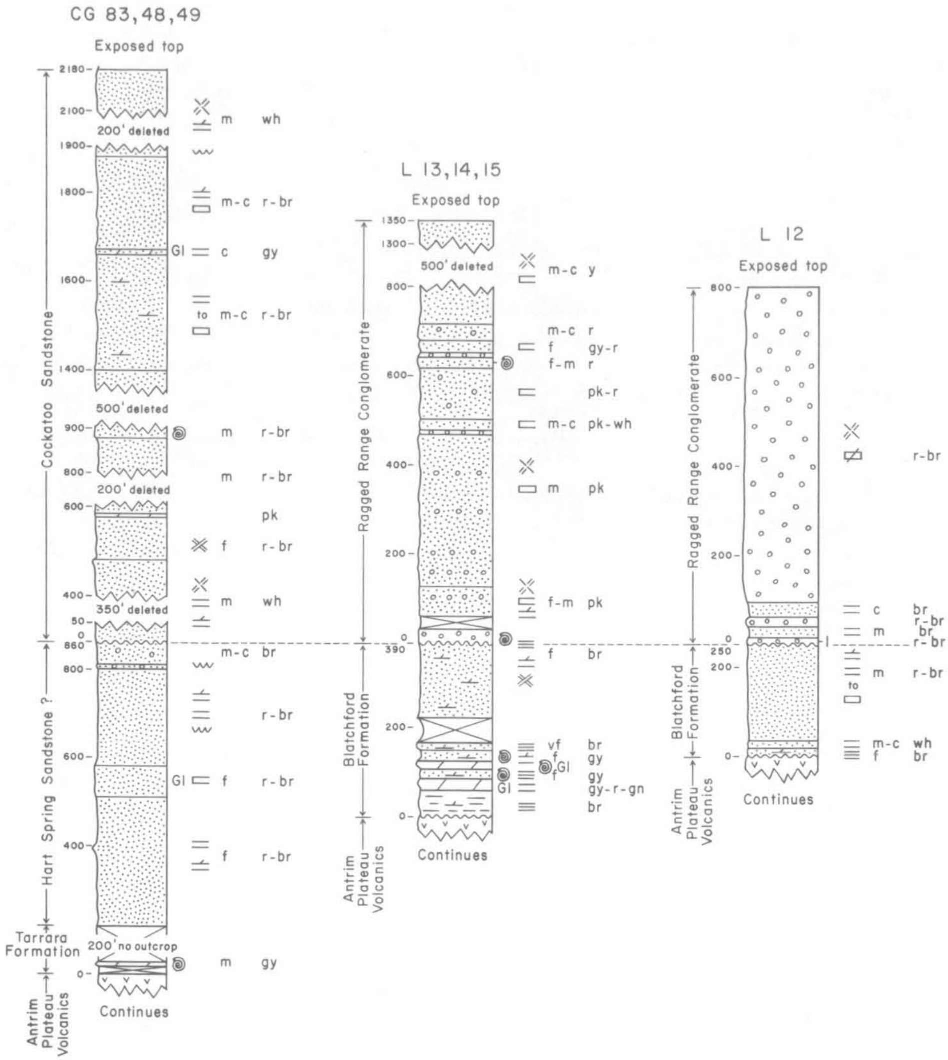

Fig. 15. Columnar sections in the Dillon Spring outlier and Ragged Range

A distinct lithological change marks the boundary between the Pretlove Sandstone and the overlying 560 feet of Clark Sandstone, which contains diagnostic trilobites and brachiopods. The lower third of the Clark Sandstone consists of fossiliferous red, dark red, and yellow medium-grained quartz sandstone with some white phosphatic brachiopod fragments, and differs from the underlying Pretlove Sandstone mainly in its high glauconitic content. The upper two-thirds are medium to coarse-grained red, yellow, and buff, dark-weathering ripple-marked and cross-bedded glauconitic quartz sandstone, with interbeds containing abundant white phosphatic brachiopods (usually fragmented). In the middle of the formation is a 3-inch ferruginized quartz-pebble band, which marks the break between faunal unit IX (specimen CG274/2) below it, and faunal unit X (specimen CG274/4) above it. This is the same break which is found in the equivalent part of the Clark Sandstone in sections 236, 245, and 202/4, and it is characterized here, as in the other sections where it has been observed, by fragmented fossils in the overlying beds.

DEVONIAN (?)

No fossils have been found in the rocks that unconformably overlie the Cambrian and probable Ordovician rocks at Gap Point and Mount Rob: so the identification of the overlying rocks as the Upper Devonian Cockatoo Sandstone is tentative. It is based on similarities with the Cockatoo Sandstone exposed 12 miles eastward in the Dillon outlier, which comprises 2400 feet of white, red-brown, and yellow quartz sandstone, with minor dolomitic beds, and one sandstone bed containing pelecypods.

The Cockatoo Sandstone (?) at Gap Point and Mount Rob is poorly exposed in low strike-ridges, and continuous sections cannot be measured. Sufficient dips, however, were measured to provide a basis for constructing the cross-sections shown in Figure 13. The Devonian (?) sequence at Mount Rob is an estimated 3000 feet of quartz sandstone with interbedded dolomitic sandstone beds at the top, and at Gap Point an estimated 3000 feet of quartz sandstone.

The lower part of the sequence is friable buff to pink medium-grained quartz sandstone (specimen 273/7A, B, 274/8, 11). The grains (predominantly quartz, with minor chert and feldspar) are coated with overgrowths, and weakly cemented with films of limonite. At Gap Point, the basal sandstone (275/6) contains rare grains of glauconite.

The dolomitic sandstone in the upper part of the sequence (273/2, 3) also contains rare glauconite, and is interbedded with green biotitic siltstone. Tubes, possibly worm tubes, are found in these rocks. The youngest preserved beds (273/1) consist of pink fine-grained quartz sandstone, which is a mosaic of overgrown quartz grains. As in the Cockatoo Sandstone of the Dillon outlier, tourmaline is a common accessory.

Dillon Spring Outlier (Figs 14, 15)

The Palaeozoic outlier at Dillon Spring is a structural half basin with its original eastern part cut off by a major, unnamed, fault. Excluding the Antrim Plateau Volcanics, which occupy an unmeasured thickness at the base, the Palaeozoic rocks have an estimated thickness exceeding 3000 feet, comprising an estimated 860 feet of Cambrian red-brown quartz sandstone, with a thin bed of fossiliferous dolomite near the base, unconformably overlain by 2180 feet of Devonian (probably Upper Devonian) white and red-brown sandstone, with minor dolomite bands, and one pelecypod-bearing bed.

Broad areas of black soil in the northern part of the basin, and three isolated areas in the northwest and west, are underlain by Antrim Plateau Volcanics. Outcrop is poor, and no estimate of thickness was made. Two specimens were collected; 83/1A is deeply weathered basalt with laths of plagioclase, irregular masses of hematite, and amygdales of quartz, hematite, and magnetite; 83/1B is a tholeiitic basalt with phenocrysts of plagioclase and augite. The volcanics occupy the floor of the basin; but a possible exception is on the southern edge, at Optic Hill, where silicified closely jointed quartz sandstone overlies Proterozoic quartzite. The sandstone is probably Devonian Cockatoo Sandstone, and the junction is probably an unconformity and not a fault, so that in the southern part of the Dillon outlier, the Cambrian basalt and sediments are overlapped by Devonian sandstone. Another outcrop of sandstone, 1 mile southeast of Optic Hill, is also regarded as probably Cockatoo Sandstone.

Cambrian sedimentary rocks (Fig. 15) comprise a poorly exposed basal unit, with a 6-inch bed of Biconulites dolomite (83/3) near the junction with the Antrim Plateau Volcanics, overlain by an estimated 650 feet of thin-bedded fine to coarse-grained red-brown quartz sandstone. Biconulites is the only fossil so far found in this sequence, which may be closely compared, on the one hand, with the Tarrara Formation and the overlying Hart Spring Sandstone of Cambridge Gulf, and, on the other, with the Blatchford Formation of the Ragged Range. For simplicity of presentation, and without prejudice, we designate the unit at the base of the sedimentary succession of the Dillon outlier as Tarrara Formation, and the overlying red-brown sandstone as Hart Spring Sandstone. This uniformly thin-bedded sandstone contains rare beds with ripple marks, tabular cross-bedding, and mud pellets, and, 60 feet beneath the unconformity, pebbles of quartz and quartzite; specimen 48/1 contains rare glauconite. In the sandstone, quartz grains have been enlarged by secondary growths of quartz over well rounded grains coated with hematitic clay. The sandstone lacks cement except for small areas cemented by hematite, and is consequently friable and highly porous.

The boundary between the Hart Spring Sandstone and the overlying Cockatoo Sandstone is an erosional unconformity, without visible angular discordance. The erosional unconformity is best seen 4 miles north of Optic Hill, at the base of section 49, where 230 feet of Hart Spring Sandstone are exposed in the scarp, and are overlain by white quartz sandstone of the Cockatoo Sandstone. One mile north of 49/1, the Hart Spring Sandstone gives way laterally to Cockatoo Sandstone, which occupies the whole scarp. The Devonian rocks are not faulted, and the relief on the unconformity (at least 230 feet) indicates the minimum erosional relief that existed before Devonian deposition.*

The Devonian succession of the Dillon outlier exceeds 2000 feet of quartz sandstone, white at the base and top, elsewhere red-brown and yellow, with minor dolomitic beds, and one sandstone bed containing pelecypods. Traves (1955) overlooked the unconformity at the base of the Devonian succession, and grouped with the Devonian what is now regarded as the Hart Spring Sandstone.

The several subdivisions of the succession are readily visible on the air-photographs. The basal unit (interval 0 to 480 feet) and the topmost unit (1880 to 2180 feet) consist of strongly jointed friable white sandstone, indistinguishable from parts of the Cockatoo Sandstone east of Kununurra. The interval between these units (480 to 1880 feet) is red-brown to pink friable quartz sandstone with minor beds of grey glauconitic sandy dolomite and dolomitic quartz sandstone. Throughout the Devonian section, the quartz sandstone lacks cement; the original rounded quartz grains are now angular with secondary overgrowths.

Dickins (in Traves, 1955, p. 61) identified pelecypods from 880 feet above the base as Parallelodontidae gen. cf. Leptodesma sp., and says (pers. comm.) that they are indistinguishable from forms collected from the Cockatoo Sandstone at Mount Cecil and from the Ragged Range Conglomerate.

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* The section through the Cockatoo Sandstone was measured above the outcropping Hart Spring Sandstone at locality 49, and the thickness was found to be 2180 feet. The Cockatoo Sandstone is at least 230 feet thicker 1 mile north of locality 49/1, to give a total thickness of 2410 feet.

Deception Range Outliers

The outlying Palaeozoic rocks of the Deception Range lie west of a zone of intensely sheared and silicified rocks cut by the Ivanhoe Fault. At locality 32 (Fig. 14), discovered following Ruker (1963), a sequence of 220 feet of red and grey quartz sandstone and 530 feet of white quartz sandstone occupy a structural half basin which is a copy, on a smaller scale, and without fossils, of the nearby Dillon outlier. This basin unconformably overlies Proterozoic sandstone. The basal 220 feet of grey-green chalcedonic quartz sandstone and red-brown quartz sandstone are tentatively identified as Hart Spring Sandstone, and are overlain, probably at an erosional unconformity, by 530 feet of white sandstone, tentatively identified as Cockatoo Sandstone, which on the south side of the basin rests direct on Proterozoic rocks. Lying close to the Ivanhoe Fault, the entire section is affected by close joints and small faults. No fossils were found.

A few miles to the south at locality 33, vertical dolomitic quartz sandstone lies on the western side of the Ivanhoe Fault; 2 miles to the west at locality 34, the Palaeozoic rocks are less obviously affected by the fault, and the steepest dip is 15^{o}. Forty feet of medium-bedded pink sandy dolomite overlain by 100 feet of quartz feldspathic sandstone are faulted down against basalt. The dolomite in a micrograined mosaic contains 15 percent of poorly sorted angular quartz grains, and small amounts of mica, tourmaline, and glauconite, and is indistinguishable from specimens from locality 49/11, in the Devonian part of the Dillon outlier. At locality 34/1, the overlying sandstone contains abundant ripple marks, and $1\frac{1}{2}$ miles to the southwest at locality 34/4, abundant tabular cross-beds. Measurements of these sedimentary structures are summarized in Table 1 and Figure 16; the directions of the ancient currents are shown in Figure 14.

No fossils were found at localities 33 and 34, and these rocks are regarded as undifferentiated Palaeozoic, probably Cambrian Tarrara Formation and Hart Spring Sandstone, or Devonian Cockatoo Sandstone, because of their similarities with parts of both the Cambrian and Devonian successions of the Dillon outlier. Traves (1955, pl. 1) mapped these localities as Cockatoo Sandstone, heedless of the warning expressed in the name of this area.

Localities 83/2 and 84/1

At locality 83/2, 10 miles northeast of Dillon Spring (Fig. 14), basalt of the Antrim Plateau Volcanics is overlain by a thin bed of grey glauconitic dolomite with Biconulites (tentatively identified as Tarrara Formation) in turn overlain by red-brown glauconitic dolomitic quartz sandstone with clay pellets (Hart Spring Sandstone). These rocks are affected by the same fault that cuts the Dillon outlier, and some beds are overturned.

At locality 84/1, 7 miles southwest of Ivanhoe homestead, and immediately east of the Ivanhoe Fault (Fig. 14), glauconitic dolomite with Biconulites (probably Tarrara Formation) is succeeded by red-brown quartz sandstone (Hart Spring Sandstone) and white quartz sandstone (Cockatoo Sandstone). These rocks are locally silicified and sheared, and no estimate of their thickness can be made. Traves (1955, p. 61) doubtfully referred the dolomite and the brown sandstone to the Cockatoo Sandstone.

Directional Sedimentary Structures

Measurements of directional sedimentary structures in the Dillon and Deception Range areas, corrected for secondary tilt, are summarized in Table 1, and those with significant means in Figure 16; the distribution of ripple-mark azimuths at locality 34/1, with an insignificant mean, is also given for comparison.

Localities 49/2 and 49/3 lie within the basal 200 feet of the Cockatoo Sandstone of the Dillon outlier, and the difference between their mean dip azimuths is insignificant. In turn, the mean dip azimuths of 270^{o} and 285^{o} at these localities do not differ significantly from

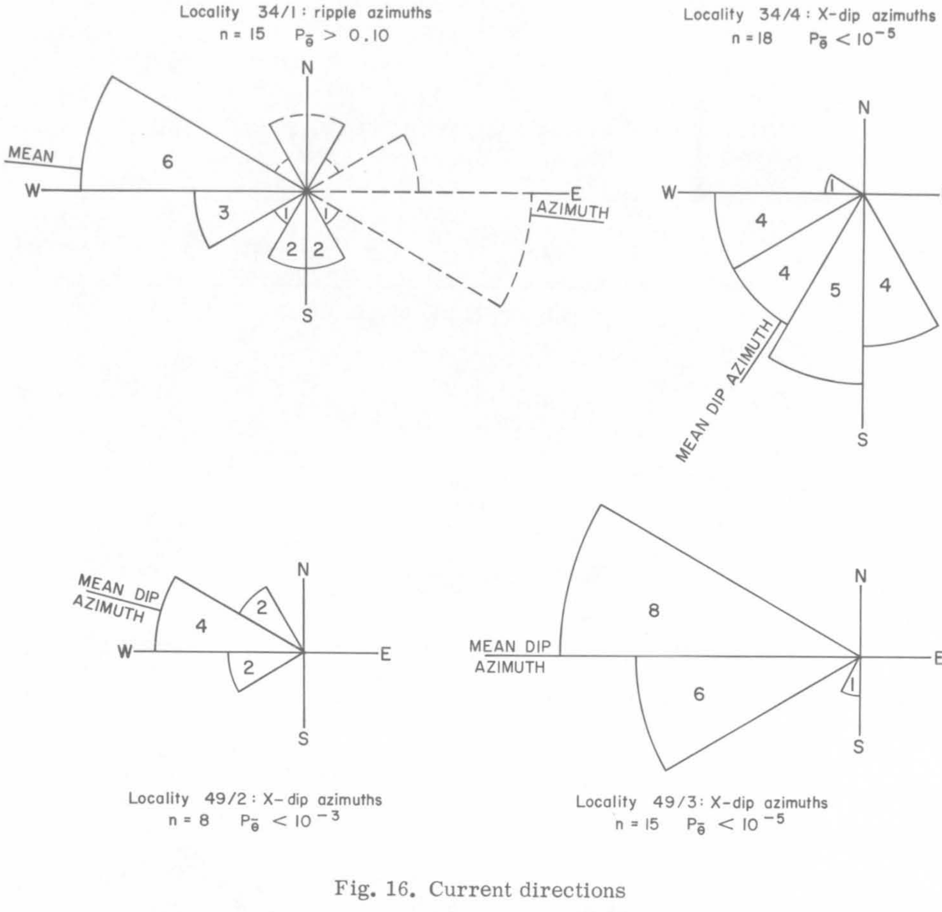

Fig. 16. Current directions

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the dip azimuth of 268° at locality L14, 100 feet above the base of the Ragged Range Conglomerate. This dip azimuth is not general in the Ragged Range, as is shown by measurements on the same bed at 53/1, 3/4 mile north of L14, which have a mean of 200°, showing that the depositing currents shifted from south-southwestward to westward. Nevertheless, the agreement between one of the mean dip azimuths of the Ragged Range and the mean of corresponding beds in the Dillon outlier indicates that at least some of the basal beds of the Cockatoo Sandstone at the Dillon outlier and of the Ragged Range Conglomerate were deposited from dominantly westward currents.

The mean dip azimuth at locality 34/4 (Palaeozoic, probably either Cambrian or Devonian) of 213° lies within the range 200° to 268° found near the base of the Ragged Range Conglomerate, but the precise age of the rocks at 34/4 is unknown, and as yet this azimuth cannot be related to azimuths of coeval rocks.

TABLE 1

STATISTICS OF DIRECTIONAL SEDIMENTARY STRUCTURES
DILLON SPRING AND DECEPTION RANGE AREAS

Locality	n	$\bar{\theta}$	$P_{\bar{\theta}}$	s^2	$s^2_{\bar{\theta}}$	Difference between means	Significance (p)
			Tabular Cross-bedding				
34/4	18	213°	$<10^{-5}$	-	-		
48	9	312°	> 0.05	-	-		
49/2	8	285°	$<10^{-3}$	286	36		
						15°	> 0.10 N.S.
49/3	15	270°	$<10^{-5}$	639	43		
49/10	11	4°	> 0.1	-	-		
			B. Ripple Mark				
34/1	15	95° (275°)	> 0.10	-	-		
			C. Current Lineation				
49/7	7	49° (229°)	> 0.05	-	-		

NOTE: For explanation of symbols, see Table 2.

Ragged Range (Fig. 17)

Cambrian dolomitic quartz sandstone and siltstone and glauconitic dolomite (the Blatchford Formation) crop out in the Blatchford escarpment of the Ragged Range; they unconformably overlie the Antrim Plateau Volcanics, and are overlain with angular unconformity, and in the southern part of the Ragged Range overlapped, by the Devonian Ragged Range Conglomerate.

Blatchford (1928) recorded observations on the sandstone and conglomerate of the Range; failing to find fossils, he left open the question of the age of the conglomerate. Reeves (1948, p. 7) found that the conglomerate is underlain by 'about 300 feet of red sandstone and sandy shale in which there are thin beds of grey siliceous limestone, containing the Lower Cambrian pteropod (Salterella hardmani). The red sandstone conglomerates overlying these 300 feet of sandstone and shale, we concluded are equivalent to the Mount Elder Series, Middle Cambrian in age according to Teichert and Matheson'.

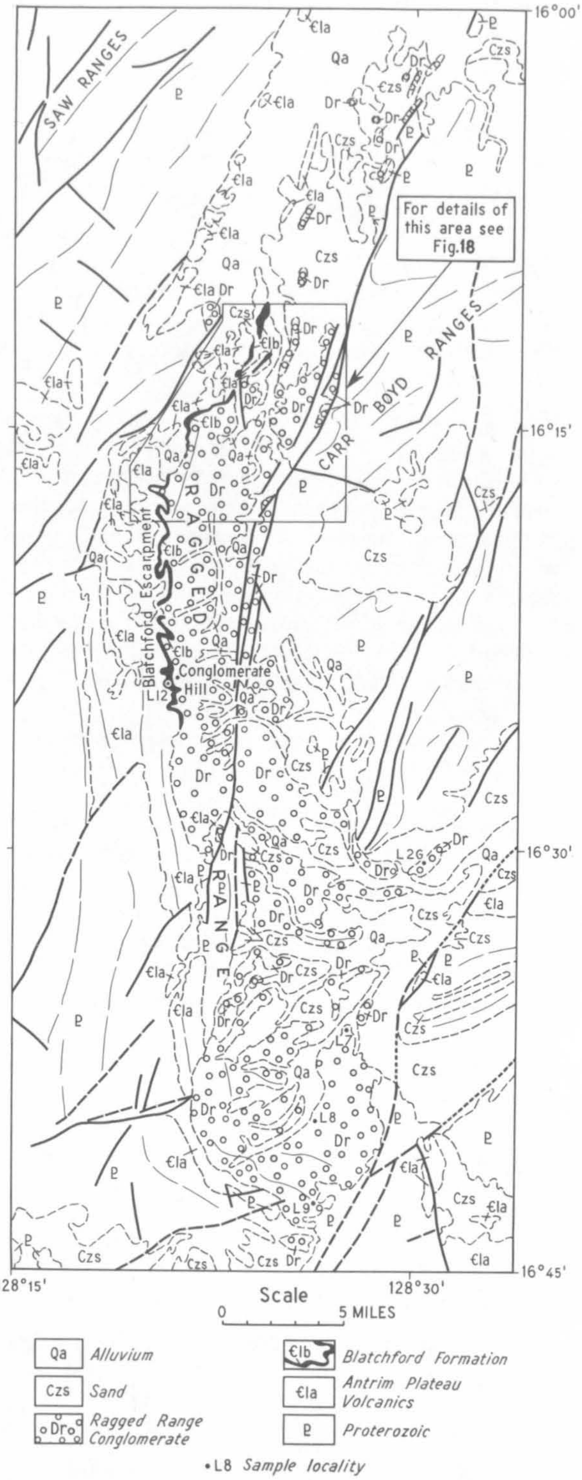

Fig. 17. Geological map, Ragged Range

Traves (1955) identified the shale and limestone as part of the Middle Cambrian Negri Group, and dated the overlying conglomerate as Middle Cambrian also, on the basis of its 'rapid transition from shales of the Negri Group'.

In 1963, K.A. Plumb and J.J. Veevers discovered trilobites (subsequently dated by A.A. Opik as possibly late Lower Cambrian) in brown siltstone overlying the Biconulites dolomite, an angular unconformity between the Cambrian dolomitic sandstone and the Ragged Range Conglomerate, and fossils in the conglomerate that indicate a probable Upper Devonian age.

The outcrop of the Blatchford Formation extends for 20 miles along the Blatchford Escarpment from a point 4 miles south of the confluence of Cabbage Tree Creek and the Dunham River to a point 9 miles north of Glenhill homestead. Most of the outcropping Blatchford Formation dips gently eastward, but at locality L13 ($16^{o}14\frac{1}{2}$'S, $128^{o}22$'E) (Fig. 18), chosen as type locality, the formation dips east at up to 25^{o}.

Two measured sections, L12 (Fig. 15) situated immediately west of Conglomerate Hill, and L13, 12 miles north of L12, show the range of lithology. The grey-green silty dolomite (specimen L13/2) that occupies the interval 60 to 70 feet in section L13 consists of dolomite (70 percent) in a fine crystalline mosaic, angular silt and sand grains of quartz (25 percent), and small amounts of glauconite, biotite, and muscovite, and is probably a dolomitized silty calcite mudstone. The glauconitic dolomite is a mosaic of fine-grained dolomite (95 percent), with rare patches of rhombs, with large grains (up to 3 mm long) of glauconite (4 percent), possibly as replacements of echinoderms, and rare angular silt grains of quartz. The fine-grained dolomitic quartz sandstone (as represented by specimen L14/1 from a nearby section) consists of fine angular sand-sized grains of quartz (60 percent), some with secondary overgrowths, set in a mosaic of fine dolomite, and rare muscovite, and with narrow calcite veins along the bedding.

The only fossils found in section L13 are Biconulites and probable worm tracks, but at locality 51/1, 5 miles southwest of L13 (Fig. 18), trilobites were found in a brown siltstone 20 feet above a glauconitic dolomite with Biconulites. According to A.A.Opik, the trilobites possibly indicate late Lower Cambrian, so that the Blatchford Formation is regarded as older than the Cambrian sedimentary succession of the Cambridge Gulf area to the north, and the Negri Group to the east and southeast.*

The shape of the surface separating the Antrim Plateau Volcanics and the Blatchford Formation is not precisely known. That it is a structural unconformity is seen at locality 51 (Fig. 18), where faulted volcanics are overlain by undeformed Blatchford Formation. Immediately south of locality L13, a fault with a similar trend cuts all three formations, but the more intense deformation of the volcanics indicates that the fault was probably initiated before the deposition of the Blatchford Formation and Ragged Range Conglomerate, and was later reactivated. Evidence that the unconformity represents a period of erosion has yet to be found.

The discovery of probable Upper Devonian pelecypods and gastropods in the Ragged Range Conglomerate, and the recognition of an angular unconformity between the Blatchford Formation and the Ragged Range Conglomerate, have led to the removal of the Conglomerate from the Cambrian, and point to the possibility that at least part of the Elder Sandstone of the Hardman Basin, with which Reeves (1948) and Traves (1955) identified the Conglomerate, is itself Devonian. This possibility is recognized by Dow et al. (1964), who have split off an upper unit from the Elder Sandstone.

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* Matheson & Teichert (1948) regarded the Negri Group as late Lower Cambrian; Opik (in Traves, 1955) revised the age to Middle Cambrian.

Fig. 18. Geological map, northern Ragged Range

Unless viewed from favourable points, such as the one from which the photograph of Plate 2, figure 1 was taken, the junction between the Blatchford Formation and the Ragged Range Conglomerate appears to be merely an erosional unconformity of low relief. In fact, despite the appearance of conglomerate immediately above the unconformity, first impressions lead one to group the lower part of the Conglomerate with the Blatchford Formation, and to subdivide the overlying part of the Conglomerate into various units separated by conspicuous erosional unconformities (in effect, large-scale cut-and-fill structure). About 9 miles north of Glenhill homestead, the Conglomerate overlaps the Blatchford Formation to rest directly on the volcanics, and, east of the Ragged Range, near the southwest tip of the Carr Boyd Range, the Conglomerate rests directly on Precambrian rocks.

Ragged Range Conglomerate. Devonian pebble, cobble, and boulder quartzite conglomerate and quartz sandstone, up to 1350 feet thick, crop out in the Ragged Range and a short distance to the south (Fig. 17). The Conglomerate unconformably overlies Precambrian rocks in the southeast, and the Antrim Plateau Volcanics and Blatchford Formation in the west. The northeast and southwest parts of the Conglomerate are faulted down against Precambrian rock.

PLATE 2, fig. 1 Looking northeast at the unconformity between the Blatchford Formation below and the Ragged Range Conglomerate above.
Section L13 is on the left slope of the hill and L14 and L15 in the near and middle distance on the extreme right

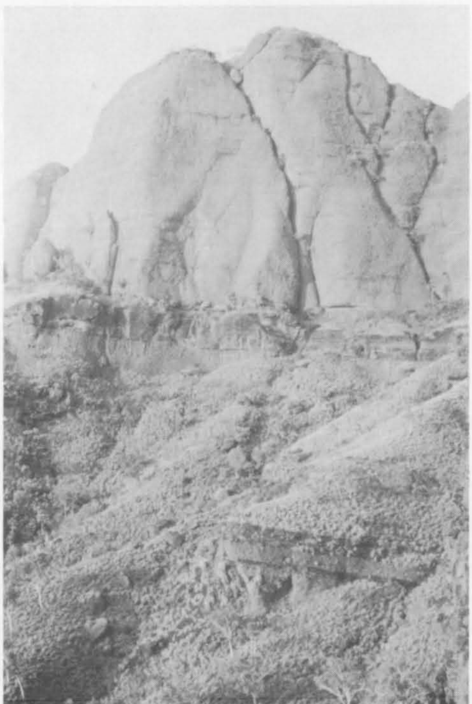

PLATE 2, fig 2 Conglomerate Hill, from a point 2 miles westward (point L11), showing horizontal Ragged Range Conglomerate unconformably overlying broadly folded Blatchford Formation and Antrim Plateau Volcanics

PLATE 3 Air-photograph of the northern part of the Ragged Range. Conglomerate and conglomeratic sandstone passing northward into closely jointed sandstone.

Blatchford (1928) noted the lateral passage of conglomerate through alternating conglomerate and sandstone to sandstone, the crumbly nature of the sandstone, the quartzite composition and perfect rounding of the phenoclasts and, failing to find fossils, left open the question of age. Reeves (1948) and Traves (1955) regarded the Conglomerate as Cambrian.

The Ragged Range Conglomerate is a sequence, up to 1350 feet thick, of red pebble, cobble, and boulder quartzite conglomerate and yellow, pink, and red quartz sandstone. The length of outcrop is 36 miles, and its width ranges from 4 to 11 miles. The Ragged Range is a cuesta with gentle easterly dip; the northeast part is bounded by faults of the Ivanhoe Fault system, which continue south across the range to the Glenhill station area, where the faults mark the western limit of the Conglomerate. Between Flying Fox Bore and the southernmost outcrop, the Conglomerate is poorly exposed in a gentle northeast slope. The easternmost outcrop mapped is situated 5 miles northeast of Flying Fox Bore. Gentle dips prevail except in the central-eastern part of the range, where dips of 25^{o} are common, and locally along faults.

The proportions of conglomerate and sandstone change markedly from place to place, as seen by a comparison of sections L14-L15 (Fig. 15), which is dominantly sandstone, and section L12 at Conglomerate Hill (Pl. 2, fig. 2), 13 miles to the south, which is dominantly conglomerate. The variation in lithology is indicated in the air-photograph patterns (Pl. 3); for example, in the composite section across the northern part of the range (L14-L15) (Fig. 18), the conglomeratic sandstone parts of the section (intervals 0 to 100 feet, 465 to 475 feet, 640 to 650 feet) underlie smooth barely dissected cuesta surfaces, and the sandstone parts underlie deeply and minutely etched hills criss-crossed with numerous joints. The conglomeratic sandstone thickens to the south and is dissected into smooth rounded spurs by a medium-textured trellis pattern of watercourses. South of locality 51, the minutely etched and jointed sandstone wedges out entirely to give way to a monotonous conglomeratic sandstone terrain in which the only variety is provided by the nearly vertical bluffs of conglomerate in the Conglomerate Hill area. These bluffs, which rise to heights of 700 feet above the underlying conglomeratic sandstone, are deeply dissected along joints into beehive shapes, with smoothly sculptured sides (Pl. 3, fig. 2). In the southern part of the Conglomerate, south of Flying Fox Bore, the higher ground in the west underlain by small rounded hills of conglomeratic sandstone passes eastward into scree-covered foothills crossed by broadly spaced tree-lined watercourses cut in alluvium.

Throughout most of the outcrop, the phenoclasts in the conglomerate consist of quartzite and the matrix of quartz sandstone, to the virtual exclusion of other rock types. Traves (1955) noted pebbles and boulders of strongly weathered granite in the northwestern part of the range, and the southern part of the outcrop includes fine pebble arkose conglomerates. The sandstone is everywhere crumbly; thin sections show a pressure solution fabric of quartz grains coated with a film of red-brown clay.

Pelecypods and gastropods were found at localities 52/1 and 53/2. The fossils are poorly preserved as impressions in medium to coarse-grained laminated red and brown quartz sandstone. According to J.M. Dickins (pers. comm.), the pelecypods at 52/1 are Parallelodontidae gen. cf. Leptodesma sp., which is found also in the Cockatoo Sandstone of the Dillon Spring area and at Mount Cecil.

The dips of tabular cross-beds were measured at three localities, corrected stereographically for secondary tilt, and the corrected values analysed to determine the mean azimuth and its statistical significance. The results are given in Table 2. The method of analysis follows Curray (1956), and the statistical significance of the difference between means was tested by Student's t-test. A significance level of 5 percent ($p < 0.05$) was adopted.

TABLE 2

STATISTICS OF DIRECTIONAL SEDIMENTARY STRUCTURES IN RAGGED RANGE CONGLOMERATE

Locality	n	$\bar{\Theta}$	$P_{\bar{\Theta}}$	s^2	$s^2_{\bar{\Theta}}$	Difference between means	Significance (p)
L2G	10	278°	>0.05	-	-		
L14	12	268°	<0.02	3464	287	68°	0.01
53/1	12	20°	$<10^{-3}$	1438	120		

n = Number of dip measurements

$\bar{\Theta}$ = mean azimuth

$P_{\bar{\Theta}}$ = probability that the mean azimuth could be obtained by chance from a random distribution

s = standard deviation of azimuth distribution

$s_{\bar{\Theta}}$ = standard error of the mean azimuth

Since the probability that the value of $\bar{\Theta}$ at locality L2G could have arisen by chance from a random distribution exceeds 5 percent, this value is rejected as insignificant. The mean azimuth values from localities L14 and 53/1 are significant, and the differences between these means is also significant. In other words, at localities L14 and 53/1, which are situated only 3/4 mile apart on the same bed, the directions of the depositing currents shifted from south-southwest to west. Many more measurements at numerous localities would be required to map the variable pattern of the depositing currents, but the available evidence indicates that west or southwest currents were important depositing agents at least in the basal part of the Conglomerate. These currents flowed across or counter to the local depositional slope, which, as indicated by the change from conglomerate to sandstone, contained a northward component.

THE FORMATIONS

Antrim Plateau Volcanics (Traves, 1955)

The Antrim Plateau Volcanics are a discontinuous sheet of basalt and minor interbedded agglomerate and tuff, up to 3000 feet thick, that covers large areas in northwestern Australia. In the area described in this Report, exposures are poor, and the basalt is generally considerably altered.

Along the southwestern margin of the Bonaparte Gulf Basin (Fig. 1), the Antrim Plateau Volcanics crop out intermittently between the Cambrian sediments, and disappear beneath Recent coastal deposits a few miles northeast of Mount Connection. The scattered outcrops of the Volcanics between Wyndham and Ragged Range lie at the base of the Palaeozoic outliers. Isolated outcrops of the Volcanics at Martins Gap, at Kununurra and south-southeastward, north of Cockatoo Spring, and south-southeast and north-northeast of Spirit Hill, are the only Cambrian rocks recorded on the southern and southeastern margin of the Bonaparte Gulf Basin. The thickness of the Volcanics was not measured, but it is estimated that it does not exceed 500 feet, and along the southeastern margin is probably less than 100 feet.

Morgan (App. 4) studied a small suite of specimens. The rocks contain a few phenocrysts of plagioclase and augite, and the texture of the groundmass is intersertal. Morgan points out that the altered basalts resemble spilite, and that their general similarity to a relatively unaltered specimen of tholeiitic basalt suggests that most of the basalt was altered after extrusion, possibly by a combination of metasomatism and diagenesis.

No trace of asphaltite, which is associated with the Antrim Plateau Volcanics in the Negri River area, was found.

A marked erosional and angular unconformity separates the Antrim Plateau Volcanics from the underlying Proterozoic rocks.

In the Ragged Range the Volcanics and the overlying late Lower Cambrian Blatchford Formation are separated by a low-angle unconformity indicated by certain faults in the Volcanics which do not affect the Blatchford Formation. The Volcanics were deposited, weathered, and locally faulted before the late Lower Cambrian. In the Hardman Basin, Dow et al. (1964) have recorded thick profiles of deep weathering at the top of the Volcanics, which are overlain by early Middle Cambrian sediments.

Along the southern and southeastern margins of the Bonaparte Gulf Basin the Antrim Plateau Volcanics and the overlying Upper Devonian Cockatoo Sandstone are separated by a low-angle unconformity. A few miles north of Cockatoo Spring (locality 81/7), the Volcanics are overlapped by the Cockatoo Sandstone, which rests direct on Proterozoic rocks.

Blatchford Formation (new name)

The Blatchford Formation is a sequence, at least 390 feet thick, of grey-green and brown dolomitic siltstone interbedded with fossiliferous glauconitic dolomite, overlain by cross-bedded fine-grained brown dolomitic quartz sandstone. The formation unconformably overlies the Antrim Plateau Volcanics, and is overlain with angular unconformity by the Devonian Ragged Range Conglomerate.

The outcrop extends for 20 miles along the Blatchford Escarpment of the Ragged Range. Most of the beds dip gently to the east, but at locality L13 (lat. $16^{o}14\frac{1}{2}$'S, long. $128^{o}22$'E), chosen as the type section, the formation dips to the east at up to 25^{o}.

The only fossils known in the formation are metadoxidid trilobites, which possibly indicate lowest Middle Cambrian (Opik, App. 3), and Biconulites.*

Further details are given under the description of the Ragged Range, which is the only known locality.

Tarrara Formation (new name)

The Tarrara Formation is a sequence, at least 700 feet thick and possibly as much as 1300 feet thick, of red micaceous silty quartz sandstone, green, chocolate, and red shale and mudstone, and grey or red fossiliferous dolomite. The formation overlies the Antrim Plateau Volcanics apparently conformably, and is conformably overlain by the Hart Spring Sandstone. The type section is the right bank of the Ord River at Tarrara Bar (section 278: lat. 15^{o} 4'S., long. $128^{o}41$'E.). The only other occurrences are section 232 south of Clark Jump Up, and section 209 near Hart Spring. Section 232 contains an estimated 1300 feet of Tarrara Formation, half of which is obscured by sand. The upper part consists of 680 feet of red laminated silty quartz sandstone with mud flakes, capped by 38 feet of grey-green fossiliferous sandy and oncolitic dolomite; the lower part consists of a single outcrop composed of 40 feet of shale and mudstone, but the estimated thickness of the unit is at least 700 feet. The Tarrara Formation in section 209, near Hart Spring, includes 65 feet of red-grey fossiliferous dolomite, overlain by 40 feet of red quartz

* Later work by Opik (see App. 3, p. 75, footnote) calls into question the separation of his divisions I and II. If they should prove to be identical, the Blatchford Formation, which is lithologically similar to the Tarrara Formation, could reasonably be assumed to be synonymous with it, and the name and definition would become redundant. Dr Opik (pers. comm.), however, thinks it likely that further collecting will show the Blatchford Formation to belong to an earlier zone of the Ordian Stage than the Tarrara Formation.

sandstone interbedded with dolomite at the top. The dolomite in both section 232 and section 209 contains fragments of an indeterminable species of Redlichia first recorded by Opik (1957, p. 83), which indicates faunal unit II (Opik, App. 3). Other fossils are fragmented brachiopods, stromatolites, and Biconulites cf. hardmani, which also occurs in silty shale above the dolomite at Tarrara Bar (locality 278/2).

In the Blatchford Formation in the Ragged Range, the Biconulites dolomite is overlain by siltstone containing metadoxidid trilobites, possibly indicating lowest Middle Cambrian (Opik, 1968). In the Mount Rob and Dillon outliers no other fossils were found in association with Biconulites, and it is uncertain whether the Biconulites dolomites occur in the Blatchford or the Tarrara Formation. For simplicity of presentation, and without prejudice, we designate the unit at the base of the Cambrian sedimentary succession in the Mount Rob and Dillon outliers as Tarrara Formation, and the overlying red-brown sandstone as Hart Spring Sandstone, although they may belong to the Blatchford Formation.

The lateral variation of the Tarrara Formation is illustrated by the dolomite which ranges from 20 feet thick at Tarrara Bar, 38 feet in section 232, to 65 feet near Hart Spring. There is an increase in the content of fragmental trilobites in the thicker section, and from section 232 to Hart Spring there is an increase in the content of oncolites, which indicate deposition in very shallow water. Oolites also occur near Hart Spring. The lineation of Biconulites shells, in places telescoped into one another, was also noted by Wade (1924, pl. IV) and by Teichert (1946) in the Negri Series of the Hardman Basin, and indicates deposition in turbulent water.

The contact of the Tarrara Formation with the underlying Antrim Plateau Volcanics is poorly exposed, but as the dips in the two formations are roughly parallel it appears that they are conformable. A basalt breccia occurs at the base of the probable Tarrara Formation in the Mount Rob outlier (locality 273/12A).

Hart Spring Sandstone (Traves, 1955) (re-defined)

Traves defined the Hart Spring Sandstone as 'the sandstone with some impure limestone and shale, which crops out in the vicinity of Hart Spring ...'. The 'impure limestone and shale' have been named above as the Tarrara Formation, and the Hart Spring Sandstone is accordingly re-defined as the fine to medium-grained red micaceous quartz sandstone that conformably overlies the Tarrara Formation and is conformably overlain by the Skewthorpe Formation. A complete section has not been measured. Strike faults interrupt the section at Hart Spring. The thickness of the measured section is 1020 feet (1220 feet, if a covered interval estimated to represent 200 feet is included) in section 232, south of Clark Jump Up. The Hart Spring Sandstone has also been seen at Mount Connection, the northernmost known outcrop (section 285, 500 feet exposed); in several faulted sections in the Onslow Hills (sections 220, 221); along the southwest margin of the Pretlove Hills (section 240, locality 243); at Skewthorpe Ridge, locality 201; southwest of the fault at Clark Jump Up (section 231); south of the Pretlove Hills (section 245, 650 feet); and at Little Tarrara Bar (section 277, 510 feet). In the outliers the red sandstone overlying the Biconulites dolomite is either Hart Spring Sandstone or the upper part of the Blatchford Formation, and for simplicity of mapping, we have tentatively identified this red sandstone as Hart Spring Sandstone. About 650 feet of red sandstone is preserved in the Dillon outlier, and 800 feet of red sandstone, conformably overlain by dolomite beds tentatively identified as Skewthorpe Formation, in the Mount Rob outlier.

The Hart Spring Sandstone is uniform reddish fine-grained silty quartz sandstone which commonly contains mud pellets and flakes. Towards its top, particularly in the northern outcrops (section 207, specimen CG207/4), it contains beds of white quartz sandstone with a calcareous or dolomitic cement, and rarely red silty shale bands (section 236). Glauconite grains are sparse, and are visible only under the microscope. Ripple marks, sun cracks, mud pellets, worm burrows, and sole and flute marking are common. It is prominently cross-bedded in the northern outcrops; tabular cross-bedding is common at Hart Spring (Traves, 1955, Fig. 21), and large-scale trough cross-bedding at locality 276 about 3 miles to the southeast (Pl. 6, fig. 2), which is very similar in scale (and lithology) to some of the cross-bedding structures in the Cockatoo Sandstone. All these sedimentary structures are common in shallow-water deposits.* The red colour of the Hart Spring Sandstone is due to a coating of hematite around the original grains, and to the hematite cement between the grains enlarged with quartz overgrowths. The only fossils found in 1963 in the Hart Spring Sandstone are small phosphatic brachiopods from a loose rock in the valley northeast of Hart Spring (fossil locality CG209/6), and hyolithids, collected from many widely scattered outcrops. Traves also records a probable Billingsella. The fossil association and the position of the formation between the fossiliferous Skewthorpe and Tarrara Formations indicate that the Hart Spring is Middle Cambrian.

Skewthorpe Formation (Traves, 1955)

The Skewthorpe Formation is the name given by Traves to the sediments which crop out at Skewthorpe Ridge, where fossiliferous oolitic and sandy dolomite is interbedded with friable brown-red quartz sandstone.

The Skewthorpe Formation conformably overlies the Hart Spring Sandstone, and is conformably overlain by the Pretlove Sandstone.

From north to south the known localities of the Skewthorpe Formation are: Locality 262, about 10 miles southwest of Bald Hill (the northernmost known outcrop); locality 285 (Mount Connection); locality 218 (Traves' locality 11); localities 219, 221, 226, 238, 236, 213, 214, 240 and 201 (Traves' locality 13, Skewthorpe Ridge); locality 235 (Traves' locality 38); and localities 245, 246 and 277 (Little Tarrara Bar). Parts of sections 273 and 274, in the Mount Rob outlier, are tentatively identified as Skewthorpe Formation.

According to Opik (App. 3), the trilobites and brachiopods indicate that the top of the formation belongs to the Mindyallan stage of the Upper Cambrian (faunal unit V), and the base to the Middle-Upper Cambrian zone of passage (faunal unit IV, Fig. 9).

Lithology. The Skewthorpe Formation consists of dolomite, sandstone, and some shale, and is characterized by oolitic and, to a lesser extent, stromatolitic dolomite. Mud pellets, ripple marks, cross-bedding, and worm burrows are found at most outcrops.

In the northern outcrops (north of locality CG236, and Mount Connection) dolomite predominates, and quartz sandstone is subordinate. The sediments are arranged in rhythmic units consisting of quartz sandstone at the base, sandy dolomite with oolitic dolomite in the middle, and algal dolomite at the top (see sections 236 and 238). Most of the northern outcrops occur in cliffs or steep scarps, as at Mount Connection and at section 238 in the Onslow Hills (Fig. 19). The rhythms are not so well developed in some of the sections in the Onslow/Pretlove Hills area; and in the sections south of the Pretlove Hills they appear to be absent. The northern sections are abundantly fossiliferous. Stromatolitic dolomite predominates and is most abundant in the upper part of each rhythm; oolitic dolomite is present, but is not as abundant as in the central sections. The number of oolitic and algal dolomite beds, both of which predominate south of the Onslow Hills (section 214), and the abundance of trilobites and brachiopods decrease to the south. The dolomite changes from grey in the north to red in the south; the northern outcrops usually contain a large proportion of detrital quartz sand (often up to 50 percent), but lack finer terrigenous material.

* None of the directional structures appears to be polarized, and the current directions are unknown.

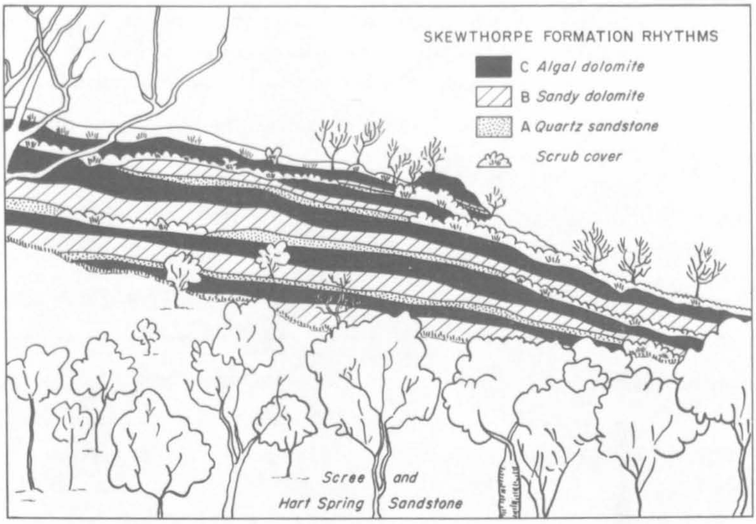

Fig. 19. Sketch of outcropping rhythms in Skewthorpe Formation

In the central parts of the Bonaparte Gulf Basin (the Onslow and Pretlove Hills, Figs 3, 6) the sandstone content increases to the south at the expense of dolomite (sections 214, 240, 201, 235, 245, from north to south).

At Little Tarrara Bar, the formation contains only 85 feet of reddish sandy dolomite, with a few oolitic and rare algal dolomite beds, interbeds of quartz sandstone, and a distinctive dolomitic solution breccia (specimen CG277/11, see App. 2). A few crystalline glauconitic dolomite bands contain brachiopods. This is the southernmost recorded outcrop of the Skewthorpe Formation.

The part of the Mount Rob section tentatively identified as Skewthorpe Formation is predominantly reddish brown quartz sandstone with mud pellets. The red colour is due to a hematite cement. The thin dolomite members consist of microgranular pink to reddish silty rarely glauconitic dolomites, dolomitic mudstones, and quartz sandstones with dolomitic cement (specimens CG273/9, CG273/10B). No fossils have been found in them.

Thickness. At Little Tarrara Bar (section 277) the dolomite is 85 feet thick. Forty-five miles to the northwest (sections 245, 246, 235, 201 and 240) the dolomite sequence is much thicker (140 to 235 feet), and is interrupted by two beds of quartz sandstone (Fig. 5). Farther to the northwest the dolomite contains only one major sandstone bed (sections 236, 226, 221), which disappears northwestwards and is absent in the dolomite beds in sections 218, 219, and 285 at Mount Connection.

In the Bonaparte Gulf Basin, the sections of the Skewthorpe Formation near the northeast margin of the main Cambrian outcrop (section 218, 240 feet; section 219, 270 feet) contain a greater thickness of dolomite than the sections on the southwest margin (section 221, 135 feet; section 245, 140 feet). The thickness of the dolomite sequence in a small area of the Onslow Hills (section 236, 130 feet, section 238, 150 feet; section 226, 180 feet), and between Skewthorpe Ridge (section 201, 150 feet) and Clark Jump Up (section 235, 210 feet) increases to the northeast.

The interpreted relationship between the major sandstone interbeds in the various measured sections of the Skewthorpe Formation are shown in Figure 9.

The intertonguing of the Skewthorpe Formation dolomite with quartz sandstone to the south and southeast (Fig. 9), and the thickening of the dolomite sequence to the north, suggest an influx of terrigenous material from the southeast and south.

If the intervals in the Mount Rob sections 273 and 274 have been correctly assigned to the Skewthorpe Formation, then the dolomitic sequence in the northern sections at Mount Rob is almost entirely represented by sandstone with thin dolomite beds at the top.

The differences in lithology and thickness of the Skewthorpe Formation from north to south are summarized in Table 3.

TABLE 3

LITHOLOGICAL VARIATION IN SKEWTHORPE FORMATION

Lithological Character	Southern: Mount Rob+	Southern: Little Tarrara Bar	Central	Northern
Presence of quartz as 'wedge' in formation	Almost wholly	Almost wholly	Common	None
Thickness of dolomite member (feet)	10	85	210	270
Colour of dolomite	Red	Red-grey	Grey	Grey
Silt content of dolomite	Very abundant	Abundant	Rare	Very rare
Proportion of sandstone in dolomite member	Sandstone predominant	Sandstone predominant	Dolomite exceeds sandstone	Dolomite predominant
Oolite	Not seen	Rare	Very abundant	Abundant
Current cross-bedding in dolomite beds	Not seen	Rare	Present	Abundant
Stromatolites	Not seen	Rare	Present	Predominant
Fossils	Not seen	Present	Abundant	Very abundant

+ The identification of the Skewthorpe Formation in the Mount Rob section is tentative only.
Note: Glauconite occurs in all areas.

Environment of Deposition. The presence of cross-bedding, oolites, and ripple marks indicates that the Skewthorpe Formation was deposited in shallow water and the presence of stromatolites (cf. Logan, Rezak, & Ginsburg, 1964) probably indicates an intertidal environment. The terrigenous components of the Skewthorpe Formation decrease to the north even if the evidence from Mount Rob is disregarded. This, together with the red colour due to oxidation in the southern sediments, indicates a nearby shoreline in the south.

Fossils are rare in the south, and organic activity may have been inhibited by the dilution of the marine waters by continental drainage (sandstones and silty dolomites), or by increased salinity due to evaporation, caused by a combination of shallowing and warm climate (Opik, 1956). That the climate was at least warm enough to allow evaporation in shallow areas is indicated by the presence of abundant oolitic beds.

The Skewthorpe Formation sediments correspond laterally to three palaeogeographic zones of depositional environment within the shallow shelf province:

(a) A relatively shallow southern zone, where oxidizing conditions prevailed and high salinities due to evaporation probably inhibited life and where terrigenous material predominated, possibly the result of continental drainage which may have diluted the marine waters just sufficiently to prevent the deposition of evaporites.

(b) A central zone, within the influence of marine currents, where the water was clearer, undiluted by continental drainage, and where conditions were favourable for oolitic formation and protected enough to harbour a living population.

(c) The northern zone, where the clarity of the water and the supply of oxygen and nutrients by marine currents, and probably also by wave action, provided conditions suitable for the support of an abundant living population.

This threefold environmental division is supported by the distribution of stromatolite types in the Skewthorpe Formation. In the central part of the Bonaparte Gulf Basin only stromatolites of laterally-linked hemispheroid type (App. 1, Fig. 2B) have been found. This type of stromatolite, referred to by Logan, Rezak, & Ginsburg (1964) as 'type LLH', is probably characteristic of the 'marine, intertidal mud-flat environment, mainly in protected locations of re-entrant bays and behind barrier islands and ridges where wave action is usually slight'.

In the north, the Skewthorpe Formation contains stromatolites composed of discrete vertically-stacked hemispheroids (type SH of Logan et al., 1964), which are characteristic of 'reef developments on exposed intertidal headlands and localities with moderate sea waves'. Oncolites are known in the north only. Logan et al. (1964) regard oncolites (their type SS) as characteristic of 'agitated lower intertidal conditions'.

The Rhythms. The sedimentation rhythms of the Skewthorpe Formation are best exposed in section 238 (Figs 20, 21), which contains 13 complete rhythms.

The ideal rhythm (Pl. 5, fig. 2) consists of three units:

C. Stromatolitic dolomite;

B. Sandy crystalline and oolitic dolomite;

A. A basal friable quartz sandstone.

Unit A (Specimen CG238/2a) is frequently eroded away, and locally contains dolomitic sandy shales in the lower part of the formation. Unit B (Specimen CG238/2b) is progressively less siliceous and more dolomitic upwards; it passes from medium-grained dolomitic sandstone at its base through current-bedded sandy dolomite to crystalline dolomite at the top. There are numerous oolitic beds in this unit. Unit C consists of dolomitic stromatolites (specimen CG238/2C) with thin interbeds, lenses, and pockets of oolitic dolomite between the stromatolites. Frequently the stromatolites are capped by a breccia consisting of oval rounded pebbles up to 4 inches long, locally imbricated, of the same stromatolites in a matrix of sandy and oolitic dolomite.

Each rhythm is generally less siliceous and more dolomitic towards the top, as is the whole sequence; in the lower part of the formation the quartz sandstone (unit A) is well developed in each rhythm; in the middle part, the quartz sandstone beds are thin (Fig. 21; Pl. 5, fig. 2) and in the upper part quartz sandstone is absent. The dolomite, sandy dolomite, and dolomitic sandstone of unit B become proportionately thicker higher in the sequence. The dolomitic stromatolites of unit C, with their characteristic domed, laminated, and undulose structures, are absent in the lower part, and increase in number and thickness towards the top of the formation, where they are up to 5 feet thick. The dolomitic breccia capping the algal beds has the same distribution.

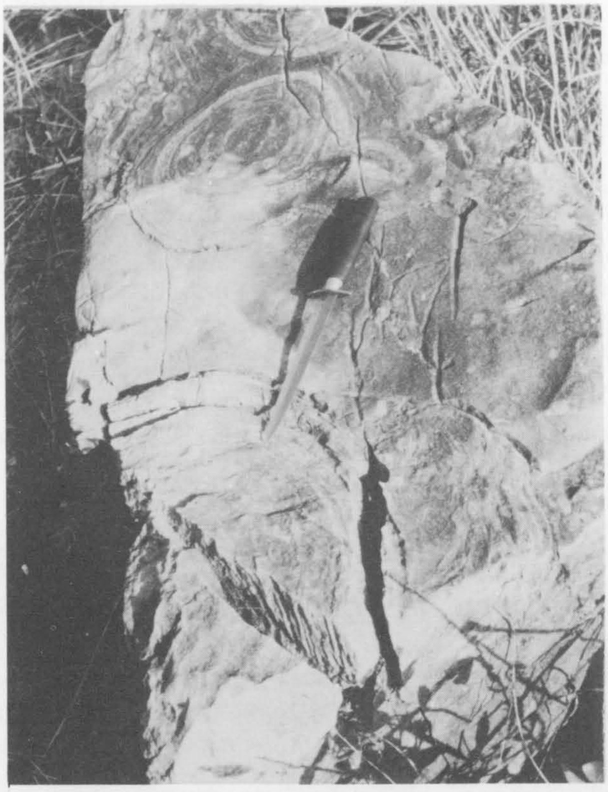

PLATE 4, fig. 1 Planed stromatolite bed (unit C) in rhythmic beds of Skewthorpe Formation. Locality CG238.

PLATE 4, fig. 2 Dolomitic algal breccia round stromatolites in Skewthorpe Formation. Locality CG238.

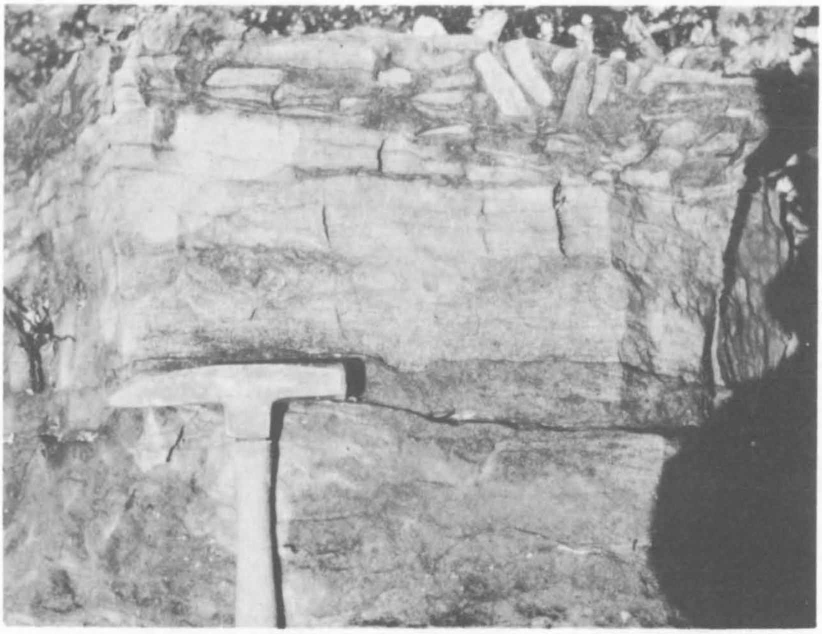

PLATE 5, fig. 1 Imbrication in dolomitic algal breccia overlying stromatolite bed: Skewthorpe Formation. Locality CG238.

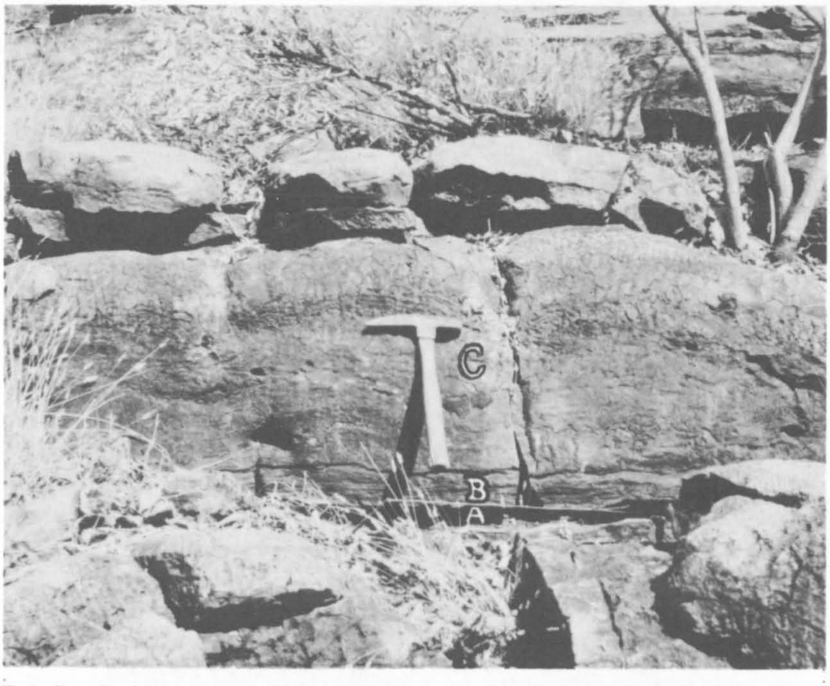

PLATE 5, fig. 2 A typical sedimentation rhythm in the upper part of the Skewthorpe Formation, where the lower sandstone Unit A is very thin. Locality CG238.

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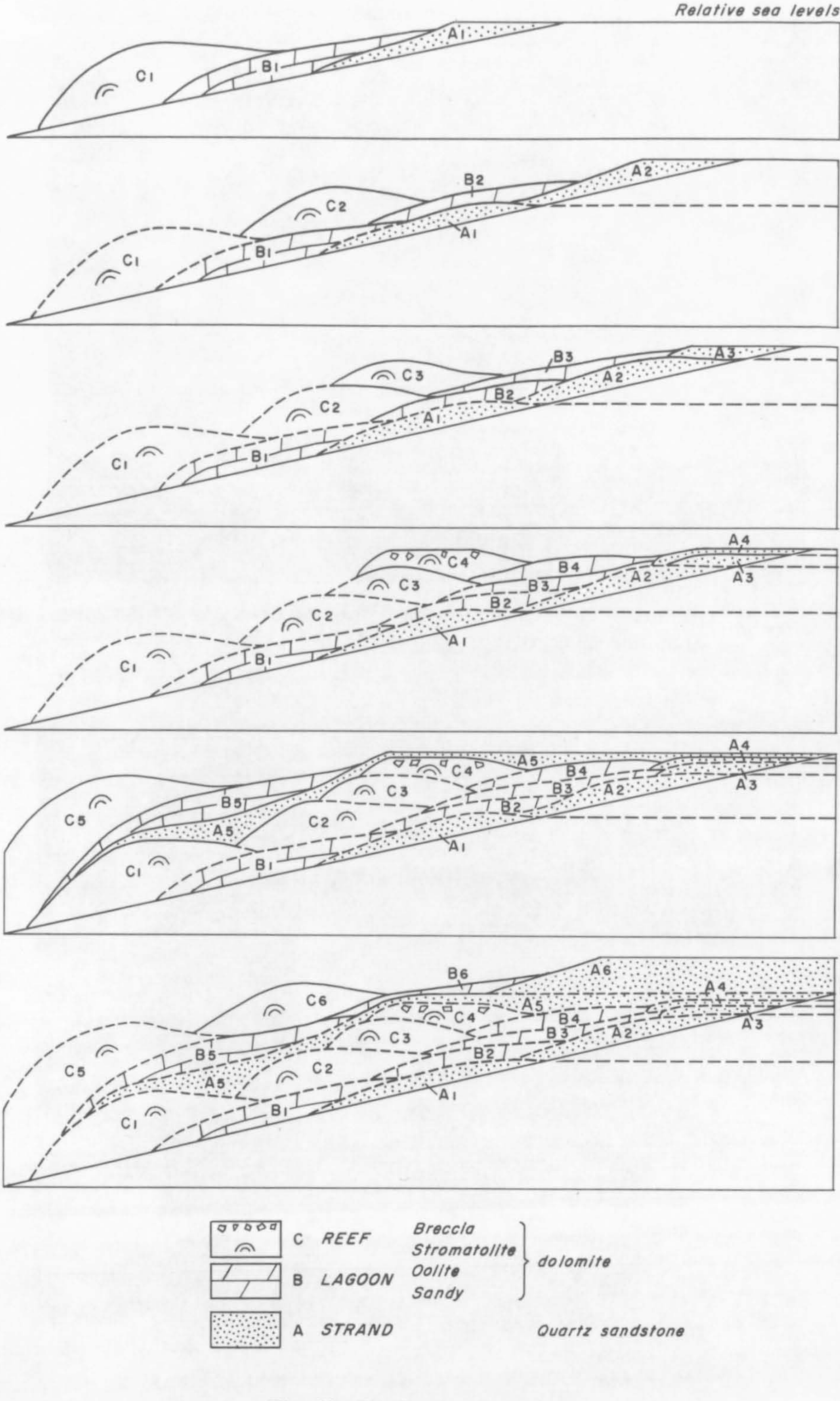

Fig. 20. Rhythmic sedimentation

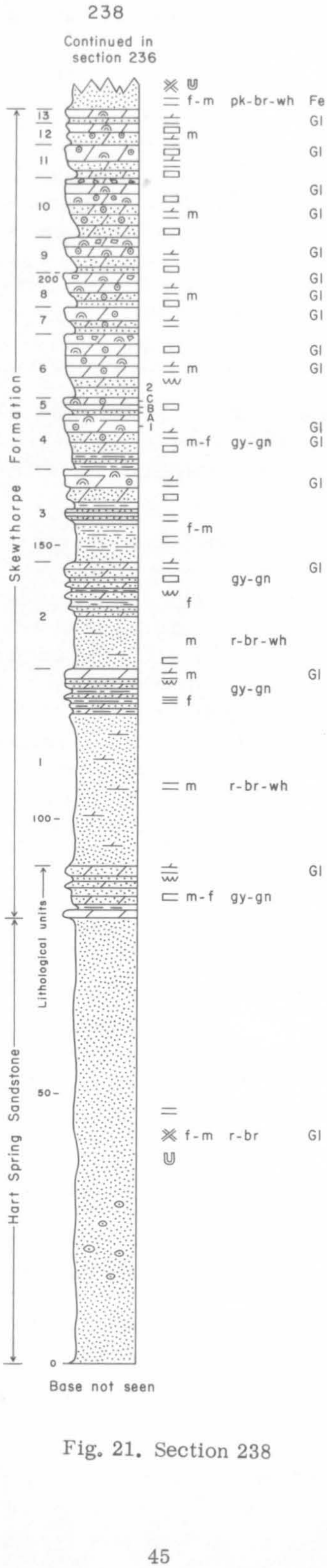

Fig. 21. Section 238

The rhythms progressively thin towards the top of the formation. They stand out well in outcrop, and the different units are readily distinguished; the top of most rhythms is a planed undulating bench and the base is frequently marked by a cleft where the weathered quartz sandstone of unit A has been cut back.

Discussion. The three units of each rhythm probably represent different depositional environments similar to the southern, central, and northern facies of the Skewthorpe Formation. Unit A probably represents terrigenous deposits near the shore; the carbonate and oolite of unit B were probably deposited in clear-water lagoons in which trilobites and brachiopods flourished; unit C was probably deposited on reefs on the seaward side of the lagoons; the sediments were probably trapped by algae and bound into stromatolitic banks, providing a barrier against waves for the lagoon. The presence of a planed surface at the top of each stromatolitic unit and the presence of stromatolitic breccias filling local troughs between the stromatolitic domes (Pl. 4, fig. 2; Pl. 5, fig. 1) indicate that the stromatolitic banks periodically emerged above the water.

In each rhythm, the terrigenous content decreases towards the top, probably indicating a shifting locus of deposition landward. Similarly, the terrigenous content progressively decreases upward in the Skewthorpe Formation, probably in response to a progressive advance of the sea.

This rhythmic succession can probably be best explained as the result of movement of the shoreline caused by fluctuations in the supply of sediment (Richards, 1962), in conditions of uniform subsidence and major transgression. The primary condition is the subsidence of the basin or shelf. With the resulting marine transgression the environments represented by the rhythmic units A (strand), B (lagoon), and C (reef) all migrated landward with the retreating shoreline, so that the lagoon sediments advanced diachronously across the strand sediments, and similarly the reef sediments advanced across the lagoon deposits (Fig. 20). When the algal reef deposits had migrated shorewards over the lagoon and strand deposits and reached sea level, it is possible that a temporary base-level of erosion in the hinterland may have been attained, causing the sediment supply to decrease, and allowing subsidence to overtake deposition, so that the sea could advance again. With the renewed subsidence, the rate of deposition accelerated, and on top of the planed reef surface sediments of the strand facies were deposited and a new cycle of sedimentation began. The deposition of the rhythms required a delicate balance between the supply of sediment, relative sea level, and the subsidence of the basin.

Pretlove Sandstone (Traves, 1955)

Traves defined the Pretlove Sandstone as the Upper Cambrian white sandstone that crops out in the Pretlove Hills. He found no complete sequence, and did not designate a type section. During 1963, several complete sections were found and section 245, 4 miles southwest of Clark Jump Up, is here designated as the type section. Much of the area mapped by Traves as Pretlove Sandstone is now known, on palaeontological evidence, to be Cockatoo Sandstone.

The Pretlove Sandstone is the white, pink, and red fine to medium-grained quartz sandstone that conformably overlies the Skewthorpe Formation and is conformably overlain by the Clark Sandstone. The Pretlove Sandstone ranges in thickness from 210 feet in section 245 to 250 feet in section 236; 830 feet of sandstone has been tentatively identified as Pretlove Sandstone at Mount Rob. The type section is 205 feet thick. The chief sections measured are 218, 219, 226, 236, 240, 245; and, in the Mount Rob outlier, 273 and 274.

The correlation diagram (Fig. 18) shows that the upper boundary of the Pretlove Sandstone and the Clark Sandstone is diachronous from the Mindyallan (faunal unit VI) in the north to the middle Franconian (top of faunal unit VII) in the south. There is possibly an overall corresponding increase in thickness towards the south, from 250 feet in section 236 in the Onslow Hills to 830 feet in section 274 near Mount Rob.

In the Bonaparte Gulf Basin the lithology of the Pretlove Sandstone is uniform; it is characterized by a meagre fauna and by numerous ferruginized ripple-marked planes (e.g. section 236). In the southernmost outlier of Mount Rob, however, it resembles the Hart Spring Sandstone, and is darker, more ill sorted, and more silty than in the north. At Little Tarrara Bar it is more silty and darker than in the type section.

The Pretlove Sandstone is much thinner in sections 225, 226, and 226A than in section 236, only about a mile to the south (see Fig. 22). In section 226A fossils of faunal unit VII were not found. Faunal unit VII in section 226 is represented by a ferruginous pebble conglomerate (App. 3); the beds below contain fossils of faunal unit V, and the beds above belong to faunal unit VIII. This conglomerate is present at the same horizon in section 225, where the Pretlove Sandstone is slightly thicker. It appears that there was an interval of non-deposition during part of the periods represented by faunal units VI and VII. The abruptness of the variation in thickness of the Pretlove Sandstone between sections 236 and 226 over a distance of 1 mile suggests that the non-deposition may have been due to local faulting. The comparatively thick sediments of section 236 were probably deposited on the downthrown side of the fault, and the conglomerate, and the thin sediments of sections 226, 226A, and 225, on the upthrown side. The movements did not affect the Skewthorpe Formation, which is of uniform thickness.

Clark Sandstone (Traves, 1955)

Traves defined the Clark Sandstone as 'the sandstone which crops out on the eastern side of the fault at Clark Jump Up on the track from Carlton to Legune'. At this locality (Traves' locality 36, our locality 231) the dark green to red medium-grained glauconitic sandstone and friable red sandstone contain abundant trilobites, brachiopods, and gastropods. The type section is isolated by faults and by sand; in section 245, 4 miles to the southeast, the Clark Sandstone conformably overlies the Pretlove Sandstone, and is thought to be conformably overlain by the Pander Greensand. The Clark Sandstone has been identified in the following sections and localities (from north to south): locality CG262/1 (Traves' locality 1), locality CG263/3 (Traves' locality 2), and section 262/8, in the line of outcrops to the south of Bald Hill; Sections 225, 226A, 226, and 236 (450 feet) in the Onslow Hills; section 240, northwest of Clark Jump Up, and section 231 at Clark Jump Up; section 202/4 in a ridge about 1 mile northwest of Pander Ridge; section 245 (720 feet) in the south of the Pretlove Hills; section 35 on the bank of the Ord River south of Little Tarrara Bar; section 275 at Gap Point and section 274 near Mount Rob. It crops out also in numerous isolated localities in the Pretlove and Onslow Hills. About 7 miles southwest of Point Spring, at locality CG281, an isolated outcrop of Clark Sandstone is unconformably overlain by the Cockatoo Sandstone: this is the easternmost outcrop of known fossiliferous Cambrian sediments in the Bonaparte Gulf Basin. Complete sections of the Clark Sandstone are exposed at localities 236 (Onslow Hills) and 245 (southern Pretlove Hills); the section at locality 274 (Mount Rob) is unconformably overlain by Devonian sandstone, and at Gap Point the base of the Clark Sandstone is not exposed. In section 236 the fossils (Opik, App. 3) indicate that the top of the section has been eroded to a level slightly below the junction of the Clark Sandstone and the Ordovician Pander Greensand in section 245. The Clark Sandstone is probably at least as thick in the south as it is in the north (450 feet).

The lithology of the Clark Sandstone and a comparison with that of the Pretlove Sandstone have already been described. Little lateral variation in lithology was seen.

The distinctive interbeds of dark reddish grey glauconitic feldspathic sandstones with a crystalline dolomitic or calcareous cement at the type locality and at locality CG202/4 cannot be traced from one section to the next. They may represent brief periods of waning terrigenous influence during deposition, or they may be due to postdepositional diagenetic

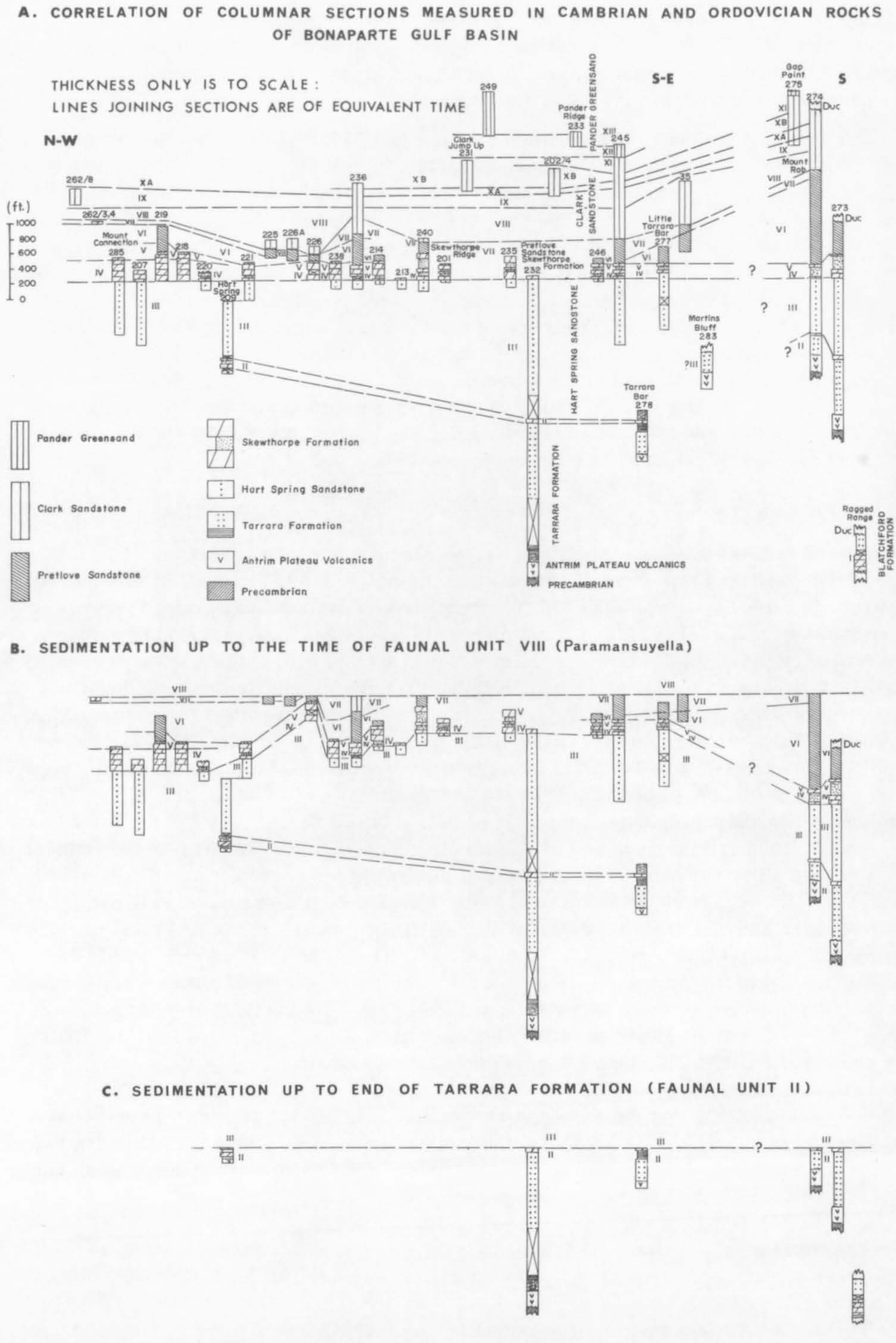

Fig. 22. Correlation of sections

changes (see App. 2). The two sections lie to the centre and east of the main Cambrian outcrop, where the possibility of embayment and flexure has already been pointed out (in connexion with the Skewthorpe Formation) and where sedimentation may have been of more marine type.

The faunal break in the Clark Sandstone (between faunal units IX and X, see Figs 22, 9), together with very minor lithological variations, indicates an abrupt change of conditions of deposition at this time.

In section 245 the faunal break and minor lithological differences similar to those in section 236 are found between two conformable beds of sandstone (specimens CG245/12 and CG245/13) which contain fossils of equivalent age to those from localities CG236/13, and CG236/13½. The same break was found in section 274 near Mount Rob and section 202/4 at a low ridge about a mile northwest of Pander Ridge: it is accompanied by minor lithological differences (small quartz pebbles in the underlying white sandstone, and broken fossils in the overlying red sandstone). This break was detected in detailed sections only: it is not visible on the air-photographs, and the sediments above and below the break have been included in the Clark Sandstone. Other detailed work may indicate that the Clark Sandstone should be split into two formations.

The fossils in the Clark Sandstone indicate that it belongs to the Franconian and Trempealeauan stages of the Upper Cambrian, as shown in Figure 9.

The passage into the overlying Ordovician Pander Greensand is obscured by sand cover. According to Opik (pers. comm.), the Cambrian-Ordovician contact is marked by a distinctive leached bed of pipe-rock in an outcrop to the north of the Carlton Ningbing track, north of Clark Jump Up.

Pander Greensand (Noakes, Opik, & Crespin, 1952; Traves, 1955)

Traves defined the Pander Greensand as 'the glauconitic sandstone which forms Pander Ridge'. The poorly cemented medium-grained highly glauconitic quartz sandstone contains numerous white phosphatic fossil fragments. 'Some of the glauconite grains have broken down to iron oxides, giving a red, green and white speckled appearance to the rock. In places where the glauconite is not altered to iron oxides, the rock has a dark green colour' (Traves, 1955). Elsewhere there are interbeds and bands of medium-grained ironstained quartz sandstone with well rounded grains. Glauconite commonly constitutes up to 60 percent of the rock.

The Pander Greensand probably overlies the Clark Sandstone conformably and its top is everywhere eroded.

The Pander Greensand crops out in the following localities: locality CG249 (Traves' locality 37), where a 400-foot section was measured, the lower 50 feet of which may belong to the Clark Sandstone; a small ridge 1 mile to the north (Traves' locality 39); Pander Ridge (locality CG233, Traves' locality 8; 130 feet); locality CG245 (150 feet); and, tentatively, the top of section 275 at Gap Point. A potassium/argon age determination on the glauconite from Gap Point indicated a minimum Lower Ordovician age (V.M. Bofinger, pers. comm.).

Opik (in Traves, 1955) discovered conodonts and other fossil fragments of Ordovician age in specimens collected in 1949 from Pander Ridge, and pointed out that the lithology is identical with that of the Upper Tremadocian Baltic 'Glauconite Sandstone' from which Pander, more than a century ago, discovered and described the first known assemblage of conodonts. On the basis of the conodonts, the approximate position of the Cambrian-Ordovician boundary was determined in the field. The tentative correlation of the measured sections 233, 245, 249 of the Ordovician sediments in the Bonaparte Gulf Basin is based on trilobites (Figs 9, 22; Opik, App. 3). This correlation, and the stratigraphic position of the

Pander Greensand above the Upper Cambrian Clark Sandstone at locality CG245 in the southern Pretlove Hills, indicates that the maximum preserved thickness of the Pander Greensand is about 600 feet.

The Pander Greensand is the youngest exposed Lower Palaeozoic formation in the Bonaparte Gulf Basin and its outliers.

STRUCTURE

The Cambrian and Ordovician rocks have been tilted, faulted, and uplifted. The only folds occur in the Devonian sediments, but they probably continue into the Cambrian and Ordovician rocks below. The folds are caused by reversals of dip in the graben at Mount Rob and Gap Point.

The Tarrara Bar area, the Onslow Hills, and the area to the north are cut by long faults with a north to north-northeasterly strike. The Pretlove Hills are cut by strike faults with a west-northwesterly trend.

The Precambrian, Cambrian, Ordovician, and Devonian rocks are all affected by both sets of faults. The major faults have throws measured in thousands of feet. A few of the fault zones exceed 100 yards in width, but most are less than 10 yards wide, and most of them are heavily silicified. No drag, except the reversals of dip at Mount Rob and Gap Point, was seen along faults.

Detailed mapping in the Pretlove Hills (Fig. 23) has revealed a set of horsts and graben bounded by high-angle normal faults.

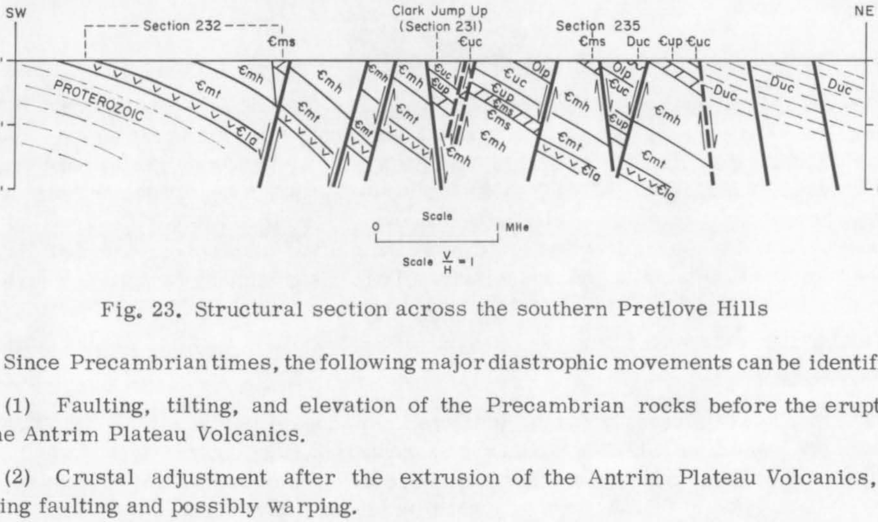

Fig. 23. Structural section across the southern Pretlove Hills

Since Precambrian times, the following major diastrophic movements can be identified.

(1) Faulting, tilting, and elevation of the Precambrian rocks before the eruption of the Antrim Plateau Volcanics.

(2) Crustal adjustment after the extrusion of the Antrim Plateau Volcanics, involving faulting and possibly warping.

(3) Subsidence of the basin during the Lower Cambrian to Lower Ordovician.

(4) Uplift some time between the Lower Ordovician and Upper Devonian, probably at the end of the Lower Ordovician, and erosion to various levels.

(5) Subsidence and deposition in the Upper Devonian and early Lower Carboniferous, followed by

(6) Major faulting of the early Lower Carboniferous and older units, including the Precambrian, Cambrian, Lower Ordovician, and Upper Devonian.

Minor movements during the Upper Cambrian are indicated, during the interval represented by faunal unit VII (the conglomerate and interval of non-deposition in section

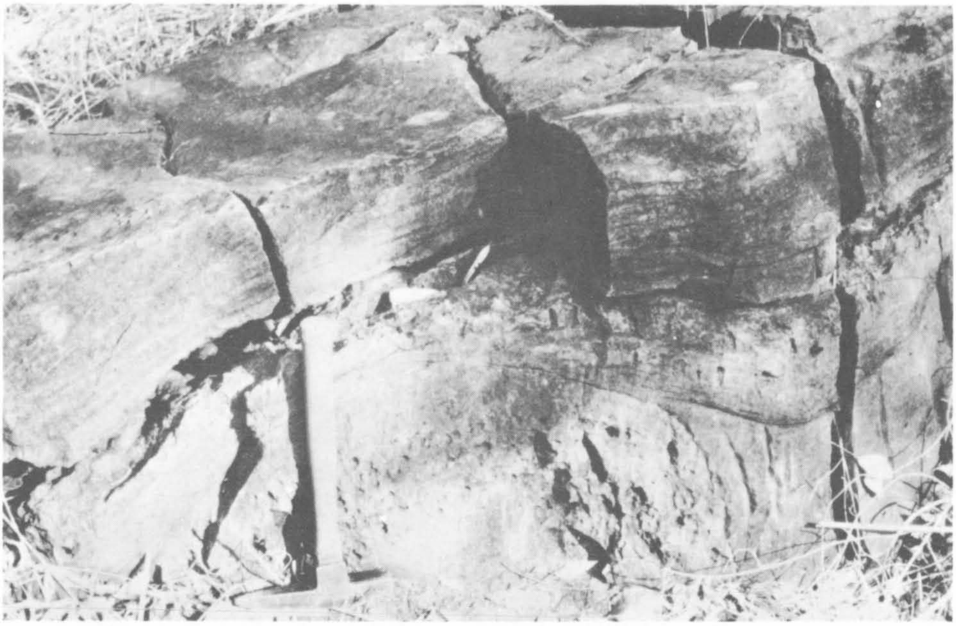

PLATE 6, fig. 1 Upwardly-convex stromatolite hemispheroid in Skewthorpe Formation (Locality CG238) with younger beds deposited round it. This is in the upper rhythmic beds of Section 238, and the algal unit (C) is overlain directly by sandy cross-bedded dolomite (Unit B), without intervening quartz sandstone (Unit A), present in lower rhythms.

PLATE 6, fig. 2 Large-scale trough cross-bedding in Hart Spring Sandstone locality CG276, 3 miles southeast of Hart Spring

226) and at the end of the interval represented by faunal unit IX (the faunal and minor lithological break in the Clark Sandstone).

A period of non-deposition may have been responsible for the gap in the fauna between faunal units VI and VII in the Upper Cambrian.

DEPOSITIONAL HISTORY

At some time during the late Proterozoic, the area was elevated and dissected. In the Lower Cambrian, the Antrim Plateau Volcanics were extruded, locally faulted, and warped; in the Ragged Range area, the Volcanics subsided in the late Lower Cambrian and were covered by the marine Blatchford Formation. The area north of the Ragged Range was probably land or an area of marine non-deposition before the Middle Cambrian. In the early Middle Cambrian, marine deposition spread at least as far southwest as the Mount Rob area, and as far southeast as the Hardman Basin, and in the area of the Bonaparte Basin and its outliers marine deposition continued, with a few minor breaks only, at least to the end of the Lower Ordovician. The eastern limit of deposition is not known.

Sand and minor carbonate rocks were deposited in a shallow slowly subsiding basin. The two dolomite horizons indicate intervals of reduced terrigenous sand supply.

It is inferred that the dolomite and oolite of the Skewthorpe Formation indicate deposition in warm water. According to Opik (1957, p. 265), in the Cambrian, 'the climate of the western half of Australia was still arid, but to a lesser degree than in recent time, and the mean temperature of the air and sea was markedly lower'. In this general setting, the Skewthorpe Formation possibly represents a warm interlude.

There is no record of deposition between Lower Ordovician and Upper Devonian; during this interval the Bonaparte Gulf Basin was probably a land-surface, and in some places the whole column of sediments was eroded to various depths, locally to the Antrim Plateau Volcanics, before the Upper Devonian transgression.

ECONOMIC GEOLOGY

Surface water. The area is drained by the lower parts of the Ord and Dunham Rivers, which carry enormous volumes of water in the wet season, and are reduced to a chain of waterholes in the dry season. Tributary watercourses are almost completely dry in the dry season.

Numerous springs issue from faults cutting the Cambrian sedimentary rocks south of Bald Hill, at Leichhardt Spring, and northwest of Hart Spring.

Underground water. No bores or wells have been sunk in the area.

Phosphate. Certain beds in the Pander Greensand contain concentrations of phosphatic brachiopods and conodonts. Two samples from Pander Ridge were found to contain less than 1 percent $P_2 0_5$.

Petroleum. We concur with Traves (1955, p. 104) in regarding the severely faulted outcropping Cambrian and Ordovician sedimentary rocks as poor prospects for petroleum. If, as is expected, less deformed equivalents of these rocks extend northeastward under younger rocks, they would provide an attractive target for the drill. The only deep test yet made of the Bonaparte Gulf Basin was abandoned at a depth of 10,530 feet in Upper Devonian shale.

No trace of asphaltite, which is associated with Cambrian rocks in the Negri River area, was found.

Glauconite. The Pander Greensand locally contains up to 60 percent glauconite. The Clark Sandstone is glauconitic, particularly in the upper part; both the Pretlove Sandstone and the Skewthorpe Formation contain minor amounts of glauconite.

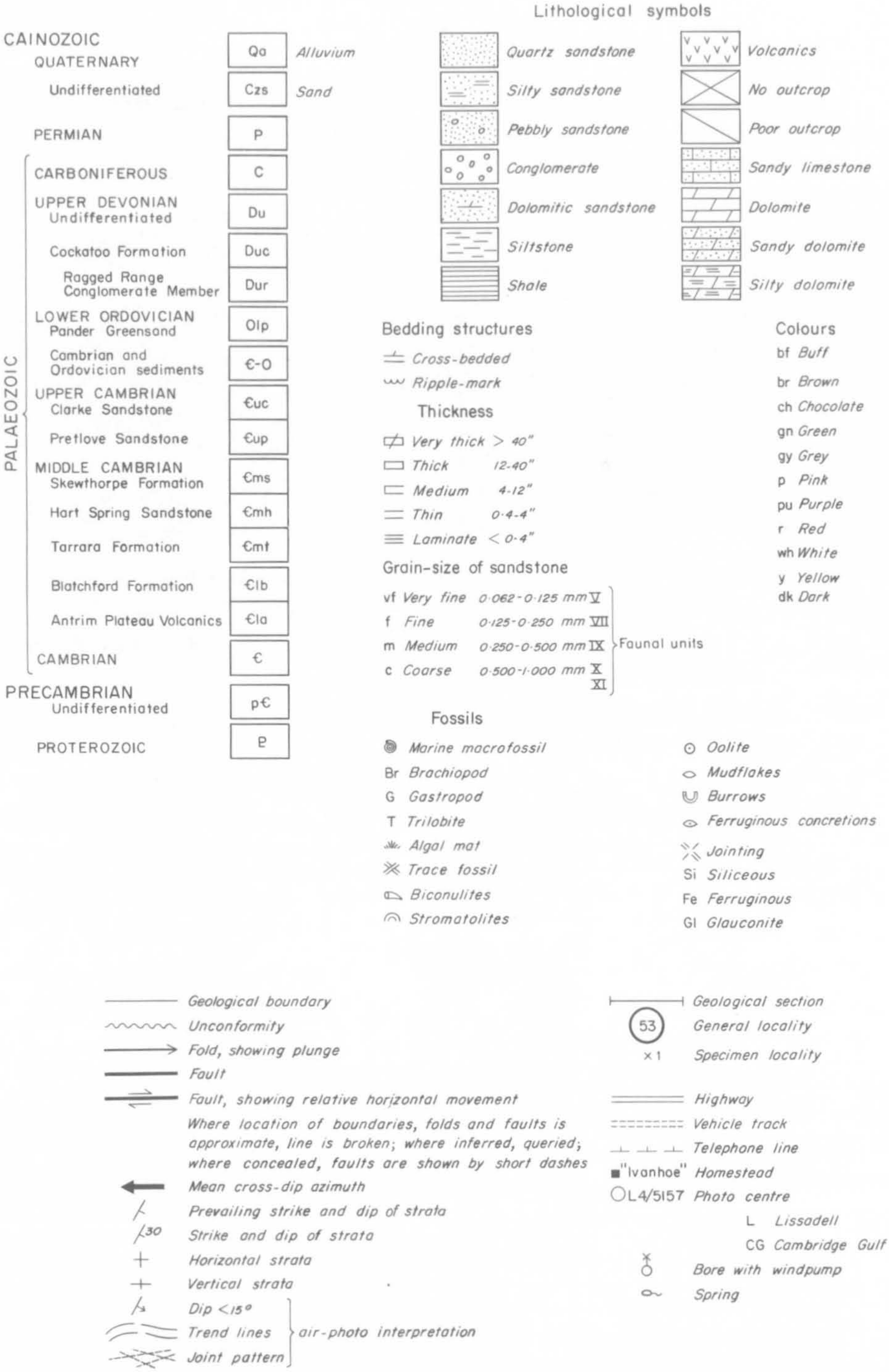

Fig. 24. Symbols used in illustrations

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APPENDIX 1

STROMATOLITES FROM THE SKEWTHORPE FORMATION

by

J.A. Kaulback

The specimens described were collected during 1963 from dolomitic algal dolomite of the Cambrian Skewthorpe Formation in the Bonaparte Gulf Basin. They are associated with brachiopods and trilobites belonging to the Middle to Upper Cambrian passage zone (Opik, App. 3). Few algae have been described from the Cambrian of Australia: Chapman (1907) described Girvanella from the Silurian limestones of Victoria, and (1911) from the Upper Cambrian of Gippsland; Etheridge (1917) described Girvanella from the Cambrian of northwest Australia. More recently, Robertson (1960) has described some Precambrian stromatolites.

Algal stromatolites are found throughout the Skewthorpe Formation, and are the predominant component in the northern outcrops, at Mount Connection, and in the Onslow Hills. The stromatolites occur in many types of external form, but only the two which have been found to contain microscopic structures are described. Because of the lack of comparable forms and the restricted nature of the specimens, a formal taxonomic nomenclature is inappropriate at this stage, and the two types have been designated Type A (CG213/15) and Type B (CG238/20).

Locality and Stratigraphy

The stromatolites are found only in the Skewthorpe Formation, which includes 200 feet of algal and oolitic dolomites, in a predominantly arenaceous 4900-foot sequence of Cambrian and Ordovician sediments. Specimen CG213/15 (Type A) was collected from section 213 in the northwest Pretlove Hills, where stromatolites are prominent. Specimen CG238/2C (Type B) was collected from section 238, in the Onslow Hills, where the largest stromatolites were found. The stromatolites occur in the upper members of the rhythmic units, which are particularly well exposed in a cliff face at locality 238. Each rhythm consists of a basal quartz sandstone, overlain by sandy and oolitic dolomite and oolitic dolomite, and an upper zone of dolomitic stromatolites, which are commonly capped by a thin dolomitic breccia containing clasts of oolitic dolomite and stromatolites.

Alteration

The stromatolites consist of aphanitic dolomite or ferroandolomite. They were probably originally deposited as calcium carbonate with a subordinate magnesia content and were subsequently recrystallized. The lack of porosity, the lack of any trace of calcite, and the fine grainsize suggest that the rock was recrystallized penecontemporaneously or shortly after deposition.

Description

TYPE A (Specimen CG213/15): distinguished by microscopic spherules along the laminae.

Structural formula: Discrete, vertically stacked hemispheroids composed of closely linked hemispheroidal laminae on a microscopic scale (Fig. A). The basal radius of the larger hemispheroid is variable. ($\frac{\text{SH-V}}{\text{LLH-C}}$: Logan, Rezak, & Ginsburg (1964) formula).

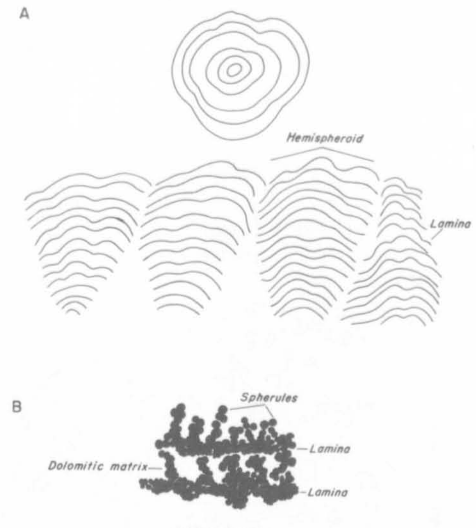

Figure A

Diameter of hemispheroids: range, 1-3 cm; approximate average, 2 cm

Distance between centres of hemispheroids: approximate average, 2 cm.

Number of hemispheroids per 10 cm^2: 40-70

Thin section: CG213/15

Diameter of spherules: average, 45μ ; range, 30-100 μ

Distance apart of spherules: average, 50μ

Vertical height of largest columnar aggregation of spherules: about 200μ

Number of spherules per mm^2: 300-400

Vertical distance apart of laminae: 200-300 μ

Observations

The spherules frequently occur in a roughly spherical colony with a wall composed of a thick network of smaller spherules; inside the wall, the spherules are bigger and are arranged in clusters, set in a matrix of microgranular or microcrystalline dolomite. The spherules are not distinct over a large enough area to enable an estimate of the variation of their number within a cluster or of the number of clusters within a colony. Spherules are of ferroandolomite, which appears darker than the dolomitic matrix; no signs of internal structure have been observed.

TYPE B (Specimen CG238/2c); distinguished by microscopic tubules along the laminae.

Hand specimen

Structural formula: Spheroidal, with small-scale component laminae of laterally linked hemispheroidal type, with close lateral linkage (Fig. B).

Diameter of spheroids: 8-24 inches.

Thin Section (Fig. B)

Vertical distance apart of laminae; average, 500μ ; range, 330-670μ

Diameter of tubules: average, 100-150μ ;range, 100-200μ

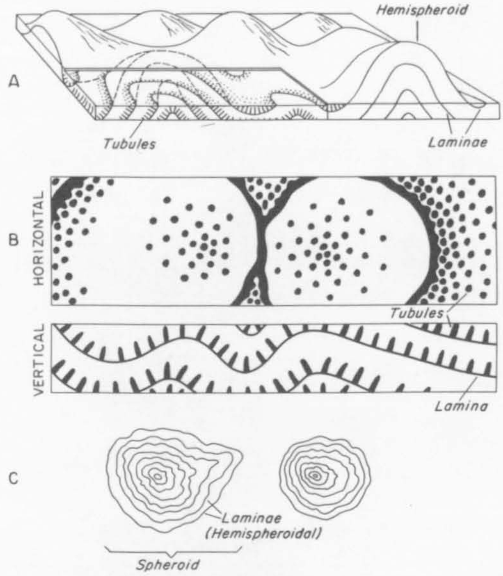

Figure B

Distance apart of tubule centres: average, 130 μ

Vertical length of tubules: range, 200-400 μ

Number of tubules per mm^2: average, 76; range, 60-100

Observations

The tubules are approximately circular in section; diameter varies within and between the tubules. They are composed of microgranular dark ferroandolomite. No internal structures have been observed. The intertubule matrix is of clear microgranular or microcrystalline dolomite. The tubules and matrix have been partly replaced by a mosaic of finely crystalline dolomite. In horizontal section, the tubules are frequently arranged in circular 'colonies', with alternating concentric rings of clear microcrystalline or microgranular dolomite and tubule-containing areas. This circular organization is thought to be due to the angle at which the section is cut across the undulating laminae.

Ecology and Environment of the Skewthorpe Formation

The ecology of the stromatolites can be deduced from a study of both recent and ancient algal deposits.

Controlling factors in algal growth are sufficient light for photosynthesis, clarity of water, and moderate water turbulence, where sedimentation is slow enough for them to avoid burial (Robertson, 1960, p. 8). Algae grow in warm or cool, fresh or salt water and require a shallow shelf or lake environment (Cloud, 1942), though Recent blue-green algae have been found at great depths (Marshall, 1954).

The depositional environment of the Skewthorpe Formation is discussed above. Ripple marks, cross-bedding, oolites, and round-pebble breccias are all indicative of shallow-water deposition. Logan, Rezak, & Ginsburg (1964) relate the varying external forms of the stromatolites to subdivisions of the intertidal or near-intertidal zones in which it is thought they were deposited; the laterally linked hemispherical stromatolites (Type B) indicate a protected intertidal mudflat, and those exhibiting discrete hemispheroids indicate a more exposed intertidal headland (Type A). The environment described only applies to the horizon in which the specimen is found, and only to a restricted area within it, for differences in lithology and related microfacies are abrupt and considerable both vertically and horizontally within the Skewthorpe Formation. In locality 238, where Type B was found, spherical stromatolites are abundant, distributed vertically through the column, which indicates an overall increase in local agitation, and less protected, more permanently submerged conditions (Logan et al., 1964). Many stromatolites exhibit a compound external form: the stromatolite from which Type B was collected is of the laterally-linked hemispheroid type, enclosed in a spherical structure. This is taken to indicate a change in conditions from 'protected intertidal mudflats' to 'agitated lower intertidal'. This corresponds to the observed indications of increasing marine influence upward within each rhythm.

There is a relation between the microstructures and external structure of the stromatolites which may have a genetic significance. Type B, which has a primary external form of laterally-linked hemispheroids, contains delicate microscopic vertical tubules which probably required relatively protected conditions in order to survive. Type A, which has an external structure of discrete hemispheroids, contains no vertical tubules, and its spongy matted microstructure appears admirably suited to withstand more exposed conditions. The fact that the microscopic structures are related to the external form may mean that they were developed as a result of adaptation to local conditions. This suggests that the generic nomenclature should be abandoned in favour of a nomenclature based on morphology, even in cases where microstructures are present.

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APPENDIX 2

PETROGRAPHY OF THE CAMBRIAN AND LOWER ORDOVICIAN SEDIMENTS OF THE BONAPARTE GULF BASIN AND ITS OUTLIERS

by

J.A. Kaulback

One hundred acetate peels and about 100 thin sections were prepared from a large number of specimens collected in 1963 or by Traves and Opik in 1949 or 1952.

The nomenclature used is based on the descriptive classification of carbonate rocks of Leighton & Pendexter (1962), with slight modifications. A limestone with 50 to 90 percent skeletal material and the rest micrite is classified as a 'micritic skeletal limestone', whereas under Leighton & Pendexter's classification it would be called a 'skeletal-micritic limestone'. The modified classification is in accordance with modern usage.

Folk's (1960) scale (fine, medium, or coarse) is used for the size of carbonate crystals and the scale of Wentworth & Udden (1922) is used for detrital grainsizes.

Glover's (1963) classification of diagenetic textures has been used.

The acetate peels of the carbonates were made in accordance with the method described by McCrone (1963) with modifications to suit the comparatively insoluble dolomite. The specimens were cut, polished, and etched with dilute hydrochloric acid; acetone was then applied to the etched specimen, and a piece of acetate paper (Kodatrace produced best results) quickly placed, matte side down, on the wet surface, with a rolling motion to eliminate air bubbles. The acetate paper with the impression of the etched rock on it was peeled off the sample after 15 minutes. An average etching time of 3 to 5 minutes with a 10 percent or 25 percent solution of hydrochloric acid was necessary to produce a good peel of the dolomites. The few limestone specimens required only 1 minute's etching with 10 percent hydrochloric acid. The peels were placed between glass plates and photographed through an enlarger. All photographs of acetate peels made in this way are therefore negatives; a clear calcite crystal appears black and the ferruginous dolomitic rings of ooliths appear white.

In the differentiation of the carbonate minerals alizarin red S and potassium ferricyanide were used as stains (Warne, 1962).

Specimens of which an acetate peel or a thin section have been made are marked 'P' or 'TS' respectively.

Diagenesis in the Oolitic Beds of the Skewthorpe Formation

Many of the ooliths in beds not heavily recrystallized are composed of aphanitic or microgranular dolomite, which suggests that the original composition was dolomitic or that the original magnesium-rich calcite was replaced by dolomite at an early stage (Schlanger et al., 1963). Reorganization to rhombic crystals or a euhedral mosaic took place at a later stage. There is no evidence of compaction due to solution of the original cement or matrix before the influx of dolomite-rich solutions. There was probably no change in volume, and recrystallization was purely a process of reorganization of existing material: the aphanitic and microgranular dolomite and ferroandolomite of both matrix and ooliths were recrystallized into rhombs in which the more ferruginous material remained as inclusions or was concentrated in zones. The unrelated axial orientation of the concentric zones of the rhombs in some oolites may indicate that there was still some motion of the ooliths during recrystallization, and it appears that the recrystallization was probably a syndepositional or early postdepositional process. In some specimens (CG201/4E, Pl. 11, fig. 3), where the primary ferroandolomite in the ooliths contained so much iron that it was unstable, the dolomite became separated from the excess iron and formed large rhombs, around which the iron oxides were concentrated in a granular mass. This process would have taken place before consolidation of the rock, as later reorganization would probably have resulted in rhombs of ankerite rather than a separation of the dolomitic and ferruginous components of the primary composition, which would have been more feasible in a relatively fluid medium.

The fact that some oolitic dolomite beds are recrystallized, while others of practically identical lithological and chemical composition are virtually not, also indicates an early and possibly preconsolidation recrystallization. If diagenesis were due to some late post-consolidation process there is little reason to suppose that beds of a similar chemical and lithological composition would not have been similarly affected by it.

Diagenesis in the Upper Cambrian and Lower Ordovician Sandstones

The history of the formation of the Upper Cambrian and Lower Ordovician sandstones is summarized as follows;

1. Deposition of feldspathic quartz sandstone in a matrix of ferruginous silt or clay, and formation of glauconite pellets.

2. Authigenic growth of secondary quartz and feldspar.

3. Replacement of the original matrix by a crystalline dolomitic cement.

4. Solution of the dolomitic cement and alteration of glauconite to iron oxide.

Dolomitic members of the Tarrara Formation

Specimen CG208/1 (TS): Glauconitic recrystallized oolitic dolomite, with skeletal fragments.

Locality: West of Hart Spring, at base of section 209.

Hand specimen: Red, fine-grained, with prominent skeletal fragments.

Texture: Completely recrystallized in subhedral dolomite mosaic, which does not completely obscure the relict original skeletal and oolitic texture. Ooliths show cerebroid, radial, and concentric structures.

Specimen CG273/11 (P): Microgranular and microcrystalline dolomite and calcite.

Locality: Mount Rob outlier (probably Tarrara Formation)

Hand specimen: Very fine-grained, banded dark and pale grey.

Texture: Recrystallized, reorganization and replacement texture.

Composition: Alternating bands of dolomite and limestone (largest dolomite rhomb 200μ).

Alteration: Slightly silicified, partly desilicified and dedolomitized by weathering.

Specimen CG T.E., (P) (Pl. 10, fig. 2): Skeletal micritic limestone.

Locality: This sample is a glacial erratic in Keep Inlet Beds (Permian). Its original locality in the Lower or Middle Cambrian is unknown. The description is included here because it resembles parts of the Tarrara Formation more closely than any other formation within the Bonaparte Gulf Basin.

Hand specimen: Grey, shelly, sparsely glauconitic, with prominent silicified Biconulites tests.

Texture: Original; parts recrystallized to calcite mosaic.

Composition: 7 percent microgranular limestone with minute quantities of ferroan-dolomite. Skeletal fragments, 25 percent; mostly Biconulites tests. Abundant brachiopod fragments and trilobite fragments. Some of the shell fragments are of calcite; most are silicified. Their interiors are filled with aphanitic dolomite. Five percent quartz.

Hart Spring Sandstone

Specimen CG207/4 (TS) (Pl. 10, fig. 3): Fine to medium-grained quartz sandstone with dolomite cement.

Locality: West of Hart Spring, section 207.

Hand specimen: White, friable.

Texture: There are prominent secondary overgrowths on both the quartz and feldspar grains. Many feldspar overgrowths are moulded on the quartz overgrowths, which were the first to form. Intergranular spaces are filled with euhedral dolomite rhombs and a sub-hedral dolomite mosaic, which formed after the secondary overgrowths on the quartz and feldspar grains. Some lenses of mudstone also present.

Composition: Grains: 5-10 percent feldspar (mostly microcline); 60 percent quartz; and 5 percent quartzite and chert. The grains range from 0.25-0.05 mm in diameter. Dolomitic cement: 25-40 percent euhedral to subhedral mosaic.

Specimen CG235/1, (TS) (Pl. 10, fig. 1): Quartz sandstone with abundant quartzite grains and iron oxide cement.

Locality: Northeast of Clark Jump Up.

Hand specimen: Fine to medium-grained, reddish brown, friable.

Texture: Both the quartz and feldspars have secondary overgrowths.

Composition: Quartz grains, 60 percent, well rounded prior to secondary enlargement; potash-feldspar, 5 percent (microcline and orthoclase); quartzite, 30 percent; iron oxide cement, 5 percent; accessory tourmaline, apatite, and muscovite.

Alteration: Secondary overgrowths round and between the grains of feldspar and quartz. Original grains are coated with a film of iron oxide, and a thicker layer of iron oxide coats the overgrowths or intergranular cement, indicating two different periods of iron oxide deposition. The reddish colour of the Hart Spring Sandstone is due to original ferruginous coatings on the grains, and to secondary iron oxides.

Skewthorpe Formation

(a) Oolites and pisolites

Specimen CG201/5, (P) (Pl. 11, fig. 2): recrystallized pisolitic dolomite.

Locality: Skewthorpe Ridge.

Hand specimen: Buff-yellow pisolites protrude from a grey matrix.

Texture: Originally oolitic and pisolitic, with microgranular matrix. Matrix and pisolites are partly recrystallized in fine rhombohedral texture, which does not obscure the original texture. Some of the groundmass is reorganized to medium-grained crystalline rhombs. Pisolites grade from many-coated at the top to single-coated (pseudo-pisolites) at the base. Stylolites occur preferentially in the many-coated pisolites. Many-coated pisolites have smaller nuclei than those with fewer coats.

Composition: Pisoliths: 80 percent, 2.5-5 mm diameter. Ferroandolomite concentric coatings. Nuclei consist of microgranular or shelly fragments. Cement: microcrystalline or microgranular. Some rhombs, averaging 0.2 mm across.

Alteration: Partial rhombic recrystallization. Stylolites were formed by solution of ferroandolomite.

Specimen CG218/1 (P): Glauconitic detrital pisolitic dolomite.

Locality: Northwest of Pretlove Hills, section 218.

Hand specimen: Protruding pisolites prominent. Grey-green.

Texture: Partial rhombic recrystallization texture (medium crystalline) in pisolitic nuclei. Otherwise original texture. Imbrication in oval pisolites.

Composition: Pisolites: 50 percent up to 4 mm across of ferroandolomite. Many have skeletal nuclei. Grains: 40 percent, quartz and feldspar, subrounded; 0.15-0.3 mm. Cement: 5 percent, microgranular. Glauconite: 5 percent, pelletal.

Alteration: Partial rhombic recrystallization of feroandolomite in pisolitic nuclei.

Specimen CG201/4G (P): Glauconitic, partly recrystallized oolitic dolomite.

Locality: Skewthorpe Ridge.

Hand specimen: Grey-green ooliths faintly visible.

Texture: Oolitic texture obscured partly by rhombohedral reorganization texture.

Composition: Ooliths: 60 percent nuclei of dolomite and coatings of ferroandolomite to ankerite. Many flattened, and truncated by stylolites parallel to bedding plane. Many nuclei are flattened, while outer rings are successively less so. The orientation of the axes of flattened nuclei is haphazard in relation to the bedding plane. This can be observed in both vertical and horizontal sections. Many ooliths are penetrated by quartz grains and by each other. Grains: 25 percent detrital quartz, 0.1-0.4 mm, well rounded. Cement: 15 percent microgranular dolomite.

Specimen CG285/4, (TS) (Pl. 11, fig. 1): Aphanitic recrystallized dolomite (originally oolitic dolomite).

Locality: Mount Connection.

Hand specimen: Ooliths weather out clearly. Grey.

Texture: Completely recrystallized into crystalline mosaic but relict texture shows original ooliths. Crystals do not cross the original outer boundary of the individual ooliths. The outline of the original oolitic nucleus also survives in the same way, and within it the crystals are often comparatively small.

Composition: Ooliths: 70 percent maximum diameter 1.3 mm; of dolomite; well packed. Cement: subhedral mosaic cement of dolomite. Crystals reach 0.4 mm across. Grains: 8 percent; quartz, 0.05-0.2 mm.

Specimen CG245/3 (TS): (Pl. 12, fig. 1): Detrital oolitic dolomite.

Locality: South of Pretlove Hills, section 245.

Hand specimen: Grey-buff.

Texture: Original oolitic texture completely replaced by rhombic dolomite; arrangement of quartz grains round the original ooliths (1.1 mm across) reveals the original texture. Typically there is a large dolomite rhomb (up to 0.5 mm) in the centre of the oolith. Many rhombs zoned, with areas containing minute inclusions of ferruginous material alternating with areas without inclusions. Round the central large rhomb the subhedral mosaic is of smaller crystals, which cross the original external oolith boundary.

Composition: Dolomite: 75 percent, rhombic, and subhedral mosaic, with ferruginous inclusions and zones. Grains: 25 percent, quartz, subrounded before secondary outgrowths.

Specimen CG201/4E (TS) (Pl. 11, fig. 3): Medium-grained quartz sandstone, with ooliths, and dolomitic cement.

Locality: Skewthorpe Ridge.

Hand specimen: Pinkish grey.

Texture: Ooliths and dolomitic cement partly recrystallized.

Composition: Grains: 60 percent, quartz, with some quartzite; attain 0.4 mm. and average 0.3 mm; poorly rounded. Ooliths: 25 percent, dolomite and ferroandolomite. Cement: 15 percent, aphanitic dolomite, with some rhombs.

Specimen CG201/6 (TS) (Pl. 12, fig. 2): Aphanitic dolomite.

Locality: Skewthorpe Ridge.

Hand specimen: Grey-green, visibly crystalline.

Texture: Completely replaced by subhedral dolomite mosaic. Relict ferruginous circular or oval line shows original oolitic texture.

Composition: Dolomite.

Alteration: Complete recrystallization. Relict ooliths often have an inner concentric line within their external form. Rhombic and euhedral crystals frequently cut across the outer line, but never the inner line, within which they are smaller. The inner ring of the photomicrograph of specimen CG201/6 shows an elongated off-centred shell-fragment as a nucleus. There is a bipartite division of the inner ring; crystals in one division are relatively smaller than those in the other.

(b) Sandstones

Specimen CG238/2: Medium-grained quartz sandstone with dolomite.

Locality: Onslow Hills.

Hand specimen: Friable, grey-buff.

Texture: Secondary outgrowth of quartz grains. Cement is fine-grained subhedral mosaic of rhombic dolomite. Circular grouping of grains suggests relict outlines of ooliths, completely recrystallized.

Composition: Grains: 60 percent quartz, subrounded; 10 percent quartzite and rare potash-feldspars, 0.2-0.25 mm. Cement: 30 percent, dolomite.

Similar rocks: Specimen CG240/2 has laminae and bands of crystalline dolomite. Specimen CG262/1 has no dolomitic cement but a ferruginous cement.

Specimen CG277/1, (P): Oolitic solution breccia.

Locality: Little Tarrara Bar.

Hand specimen: Purplish grey. Clasts difficult to distinguish from matrix.

Texture: Angular clasts of fine bedded oolite (3 mm-25cm or more) in a fine-grained feruginous sandstone. Top and base of brecciated beds are straight. Brecciation extends along whole of bed; interbedded with non-brecciated beds. No ooliths in non-brecciated beds. Complete recrystallization of ooliths, which are distinguishable only by circular arrangement of grains round their original outline. Clasts are corroded and dissolved round their edges.

Composition: Clasts: glauconitic detrital oolitic ferroandolomite, layered. Made up of ooliths, 40 percent; glauconite, 8 percent; microgranular cement, 22 percent; quartz, 30 percent. The matrix is a ferruginous sandstone.

(b) Stromatolites

Specimen CG214/13 (Pl. 13, figs 1 and 2): Fine to medium-grained quartz sandstone, with dolomitic cement.

Locality: South Onslow Hills.

Hand specimen: Grey-green-brown.

Texture: Subangular grains. Cement is euhedral and often rhombic. Scattered ooliths and spherical algal pellets.

Composition: Grains: 50 percent quartz, with secondary outgrowths; 10 percent potash-feldspar with secondary overgrowths, and 5 percent quartzite; accessory tourmaline. Cement: dolomite, whose crystals have grown round the secondary outgrowths of the grains. Ooliths: scattered, showing radial and concentric structure. Algal pellets: scattered, consisting of aggregations of small quartz grains and dolomite rhombs bound together by fine ferruginous threads and branching filaments. Algal pellets often act as nuclei for ooliths.

Specimen CG214/6 is essentially the same, but has more algal structures. The algae binding the sediment consist of crenulated horizontal branching threads, which are frequently gathered up in spheres, which may be unattached in areas where detrital grains are most numerous.

Logan, Rezak, & Ginsburg (1964) relate the spherical shape of algal structures to a more turbulent depositional environment than that of horizontally layered or hemispherical structures.

(c) Dolomitic breccias

Specimen CG262E (P): Dolomitic breccia.

Locality: North of the Onslow Hills.

Hand specimen: Grey-green, with prominent clasts.

Texture: Rounded, oval clasts from a few millimetres to about 7.5 cm in a matrix of medium-grained quartz sandstone with dolomitic cement. The matrix contains scattered ooliths. Oval clasts show imbrication.

Composition: Matrix: grains, 70 percent; quartz and feldspar, subangular, in a euhedral mosaic cement of dolomite. Scattered ooliths of feroandolomite or ankerite. Clasts: ferruginous oolitic quartz sandstone with ferroandolomite cement; ferruginized algal stromatolitic dolomite; and oolitic dolomite.

Similar specimens: CG214/15, CG262

Observations: The dolomitic breccias mark the transition between the more continental and the marine parts of the Skewthorpe Formation sedimentary rhythms, and indicate very shallow (beach) deposition.

Upper Cambrian and Ordovician Sandstones

Specimen CG226/3 (TS): Medium-grained feldspathic quartz sandstone, with weak ferruginous cement.

Locality: Section 226, Onslow Hills.

Age: Clark Sandstone, Upper Cambrian.

Hand specimen: Reddish brown, friable. Contains trilobites and brachiopods.

Composition: Grains: quartz, 50 percent; potash-feldspar, 35 percent; glauconite, 10 percent; pelletal, green; accessory chert, quartzite, and tourmaline. Grainsize 0.05-0.2 mm. Cement: hematite, very little.

Specimen O & T (TS) (Pl. 13, fig. 3): Medium-grained glauconitic feldspathic sandstone with dolomitic cement.

Locality: A few hundred yards northwest of Clark Jump Up.

Age: Ordovician (Pander Greensand).

Hand specimen: Green and red speckled.

Composition: Grains: potash-feldspar, 25 percent; quartz, 20 percent; quartzite, 5 percent; glauconite (pellets), 25 percent. Cement: dolomite, 25 percent.

Specimen CG233A (TS) (Pl. 13, fig. 4): Medium-grained glauconitic quartz sandstone, with hematite cement.

Locality: Pander Ridge.

Age: Ordovician (Pander Greensand).

Hand specimen: Dark red to purple, with green and white specks.

Texture and alteration: Quartz and feldspar grains have secondary overgrowths. Glauconite pellets are fresh, but many are mechanically compressed and distorted by compaction, and frequently altered to iron oxide at pressure points.

Composition: Grains: quartz, 50 percent; quartzite and chert, 10 percent; feldspar, 5 percent; phosphatic shell fragments, 3 percent; glauconite (pelletal), 20 percent. Cement: hematite. Often as coating round original grains, between the grain and its authigenic rim.

Similar rocks: CG233G, Pander Greensand (TS), has well developed secondary overgrowth of quartz, with a hematite coating round the original grain as well as in intergranular spaces (Pl. 13, fig. 5). In CG233D, Pander Greensand (TS), some of the glauconite pellets are altered to iron oxide at pressure points (Pl. 14, fig. 1). In CG231A, Clark Sandstone (TS), some of the glauconite pellets have yielded to pressure from secondary overgrowth of grains by splitting along microfaults within the pellets. One glauconite grain shows parallel cleavage, similar to that of biotite (Cf. Hodgson, 1962) (Pl. 13, fig, 6).

In CG202/3A, Clark Sandstone (TS), authigenic growth of quartz has stopped where the quartz grain penetrates a glauconite pellet, which shows that quartz secondary overgrowth was subsequent to compaction (Pl. 14, fig. 2). In CG202/4D, Clark Sandstone (TS), many glauconite pellets are completely replaced by a rhombic mosaic of dolomite, in which only the relict outline and a few green traces of pigment remain (Pl. 14, fig. 3). In CG202/41, Clark Sandstone (TS), quartz grains are partly replaced by dolomite, which is rhombic and has ferruginous inclusions, indicating a probable original matrix of ferruginous clay (?) or silt (Pl. 15, fig. 1). In CG202/3A, Clark Sandstone (TS), glauconite pellets contain outlines of rhombic dolomite. The original dolomite has been dissolved, the only traces of it being etched quartz grains (Pl. 15, fig. 2).

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See references in main report.

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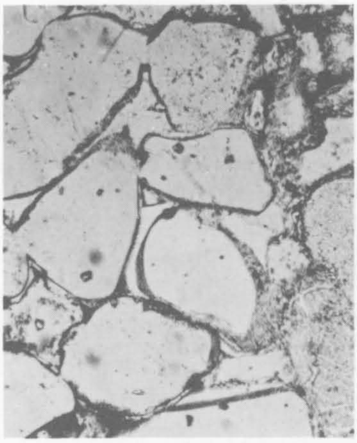

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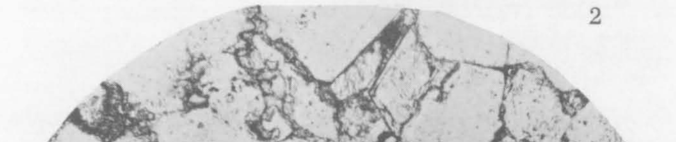

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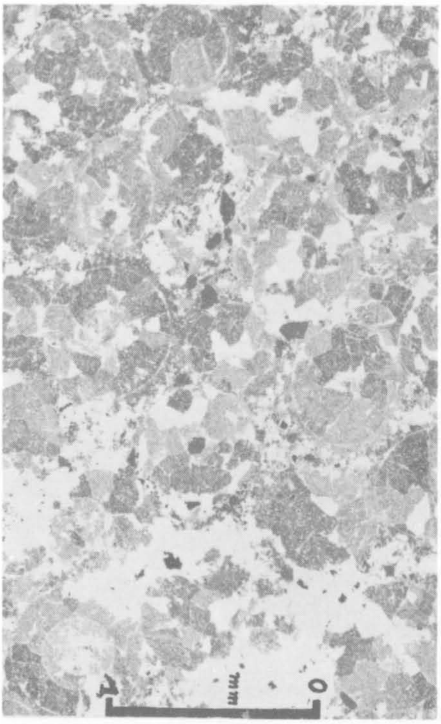
PLATE 7, fig. 1 Specimen CG235/1. Ordinary light, x90. Hart Spring Sandstone Mosaic of quartz grains rimmed with iron oxide, all overgrown by secondary silica, in turn rimmed with iron oxide.

PLATE 7, fig. 2 Specimen CGTE. Peel print, x4. Glacial erratic in Permian Keep Inlet Beds, original locality in Lower or Middle Cambrian unknown. Biconulites in a micrite matrix.

PLATE 7, fig. 3 Specimen CG 207/4. Ordinary light, x90. Hart Spring Sandstone. Overgrown quartz (Q) and feldspar (F) grains in a dolomite matrix.



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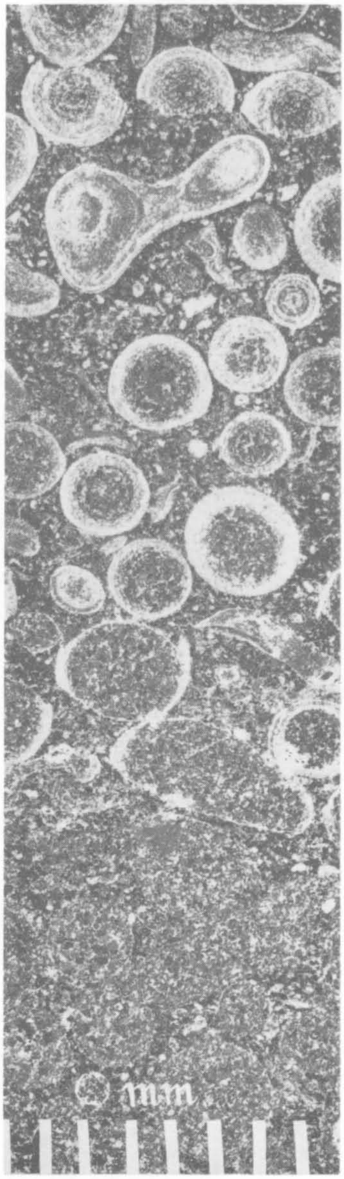

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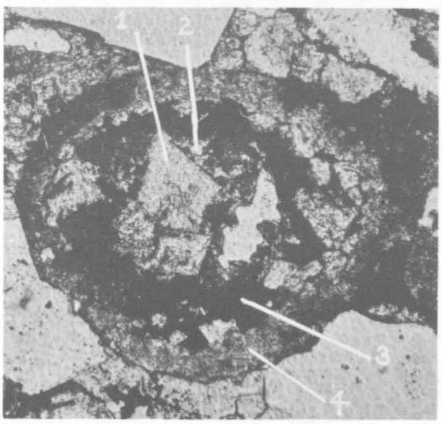


3

PLATE 8 — Skewthorpe Formation

PLATE 8, fig. 1 — Specimen CG 285/4. Peel print, x30. Dolomitized oolite.

PLATE 8, fig. 2 — Specimen CG 201/5. Peel print, x6. Dolomitized pisolite.

PLATE 8, fig. 3 — Crossed nicols, x90. Recrystallized dolomitized oolith. The large central dolorhomb (1) is enclosed in a matrix of microcrystalline dolomite (2), surrounded by iron oxide (3). The outer shell of the oolith (4) consists of minute ferroandolomite rhombs.

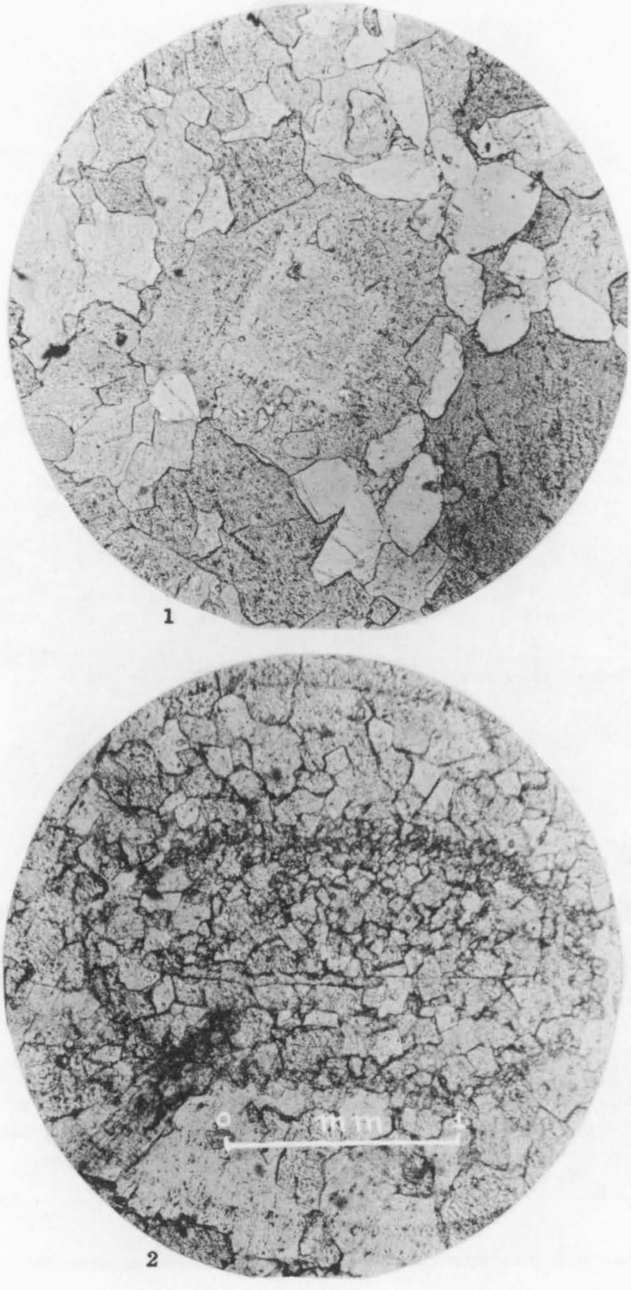
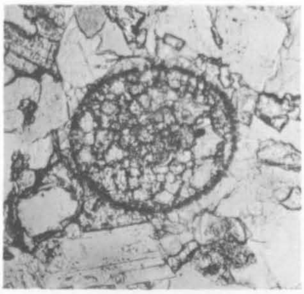


PLATE 9	Skewthorpe Formation
PLATE 9, fig. 1	Specimen CG 245/3. Ordinary light, x40. Quartz grains (clear) around dolorhomb replacing oolith.
PLATE 9, fig. 2	Specimen CG 201/6. Ordinary light, x40. Relict oolith structure in dolomite.



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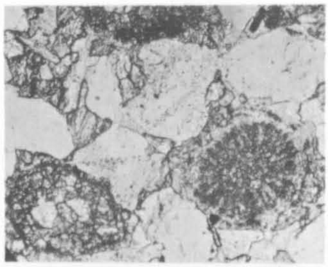

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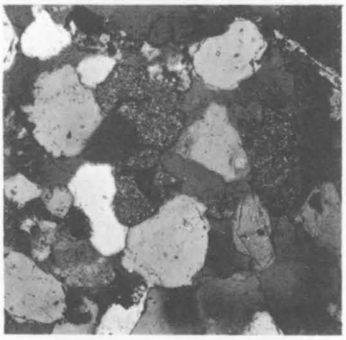

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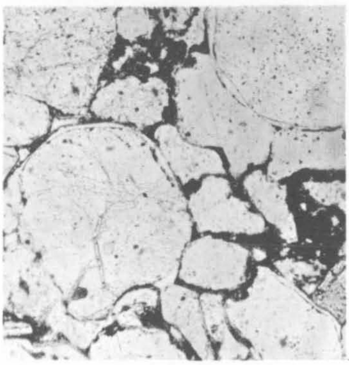


5

6

PLATE 10, fig. 1 Specimen CG 214/3. Ordinary light, x70. Skewthorpe Formation. Algal (?) pellet in feldspathic quartz sandstone with dolomite cement.

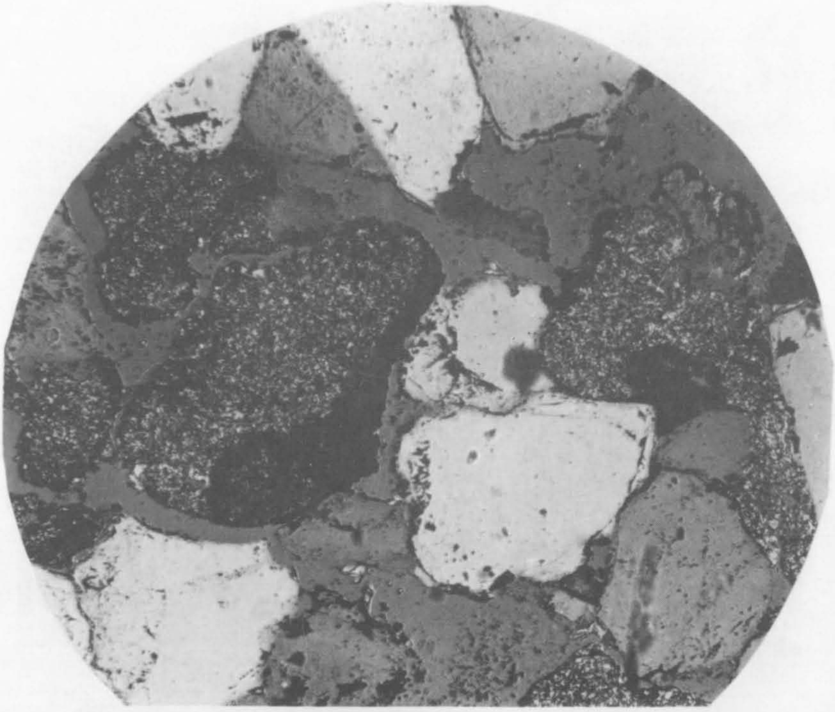
PLATE 10, fig. 2 Ordinary light, x70. Same as above, showing an algal pellet with strong radial structure.

PLATE 10, fig. 3 Specimen CG-OT. Crossed nicols, x40. Pander Greensand. Glauconitic feldspathic sandstone.

PLATE 10, fig. 4 Specimen CG 223A. Crossed nicols, x50. Pander Greensand. Glauconitic quartz sandstone.

PLATE 10, fig. 5 Specimen CG 233G. Ordinary light, x50. Pander Greensand. Quartz overgrowths and hematite cement.

PLATE 10, fig. 6 Specimen CG 231A. Ordinary light, x90. Clark Sandstone. Glauconite after biotite (?)



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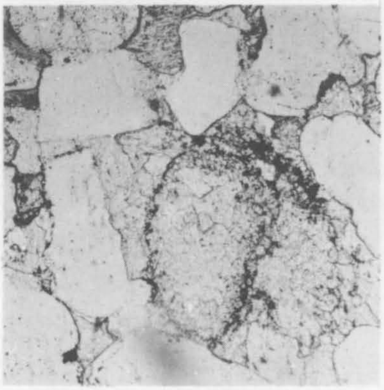


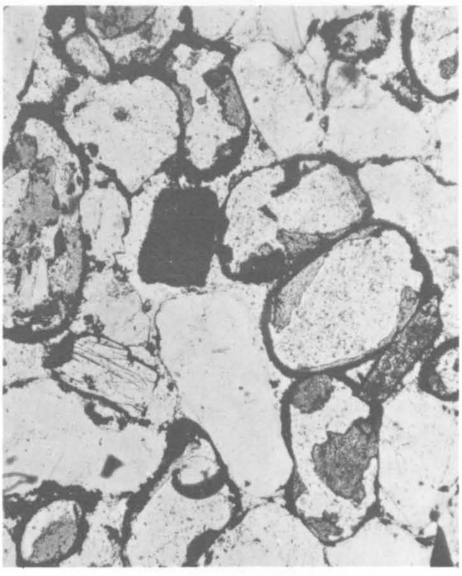
3

PLATE 11, fig. 1 Specimen CG 233D. Crossed nicols, x90. Pander Greensand. Alteration of glauconite to iron oxide.

PLATE 11, fig. 2 Specimen 202/3A. Ordinary light, x90. Clark Sandstone. Quartz overgrowths.

PLATE 11, fig. 3 Specimen CG 202/4D. Ordinary light, x45. Clark Sandstone. Glauconite pellets replaced by dolorhombs.

1



2

PLATE 12 Clark Sandstone

PLATE 12, fig. 1 Specimen CG 202/4I. Crossed nicols, x90. Quartz partly replaced by dolomite.

PLATE 12, fig. 2 Specimen CG 22/3A. Ordinary light, x90. Glauconite filling cavities in quartz.

APPENDIX 3

THE CAMBRIAN AND ORDOVICIAN SEQUENCE, CAMBRIDGE GULF AREA.

by

A.A. OPIK

The geographic designation 'Cambridge Gulf Sequence' is applied here for the sake of continuity with earlier published accounts (Opik, 1956, 1957) regarding the same sequence and region. Other designations are 'Joseph Bonaparte Gulf' and the colloquial 'Bonaparte Gulf' (for example, in Noakes, Opik, & Crespin, 1952).

The collection in hand (by J.J. Veevers and Party, 1963) is rather voluminous. The extraction of all fossils and their adequate study is a project of several years; hence, the present account is based on a preliminary study of selected material.

The larger part of the earlier collection by D.M. Traves and A.A. Opik was destroyed by fire before it was examined, and the account by Opik (1956) refers essentially to palaeontological field observations.

Friable sandstone is the matrix of the fossils, and tests of trilobites and calcareous brachiopods are not preserved. Special care is therefore needed in extracting and conservation of the specimens; furthermore, large numbers of specimens are needed for an adequate description of species and even genera to ensure that features approaching the size of sand grains and interspaces between the grains may not escape observation and conservation.

Stratigraphic Designations and Palaeontological Nomenclature

Twelve stratigraphic entities can be recognized in the Cambrian and Ordovician sequences of the Cambridge Gulf area; they are enumerated by Roman numerals I to XII, in ascending order. These entities are based on fossils, and on trilobites in the first place. Fauna I is isolated, and is nowhere in contact with the Redlichia-bearing sequence (II). Division III, covering the larger part of the Middle Cambrian is, however, unfossiliferous on available evidence, but its age is evident from the interpolation between divisions II (below) and IV (above). Division X is composite, with XA (below) and XB (above); these subdivisions are apparent from the distribution of different species of common genera of common subfamilies.

The names of trilobites used in the description of the stratigraphic subdivisions are given in a form not affecting the existing taxonomic nomenclature. Designations like 'metadoxidids' and 'kaolishaniid' are references to the 'nearest family' in the sense of current classifications; the formal names of families (e.g. Saukiidae, Parabolinoididae) and of genera (Prosaukia, Ptychaspis, Paramansuyella) are used in their definite taxonomic meaning.

Corrections

The corrections that follow below (in ascending order) are needed to maintain the continuity passing from the earlier publications (Traves, 1955; Opik, 1956, 1957) to the present account. Amplified discussions of the corrected stratigraphic and palaeontological data are given below.

(1) The limestone - siltstone sequence in Ragged Range (Traves, 1955, p. 47, text-fig. 20) designated as 'Negri Group' belongs to a different unit probably older than the Negri Group.

(2) The fossiliferous part of the Skewthorpe Formation dated by Opik (1956, 1957, p. 53) as nathorsti or Leiopyge laevigata Zone is even younger than that (Middle Cambrian/ Upper Cambrian passage and early Upper Cambrian).

(3) The 'not yet properly correlated locality containing "Idahoia" associated with dikelocephalids and a probably olenid trilobite' (Opik, loc. cit) represents division VII. Dikelocephalids, however, are absent and the 'Olenids' belong now to the Parabolinoididae (this family was established in 1956).

(4) The 'middle Dresbachian' sandstone with Crepicephalus (loc. cit) represents division IX. This 'Crepicephalus' is a kaolishaniid (probably a new genus).

The Faunal Sequence

I. (Metadoxidid): This division contains Biconulites and a Metadoxidid trilobite; Redlichia is absent. Biconulites occurs in the early Middle and apparently in the late Lower Cambrian, and the Metadoxididae are believed to be lower Middle Cambrian in age. This sequence is therefore regarded as of lowest Middle Cambrian age.

II. (Redlichia): The Redlichia is known from fragments only and cannot be determined specifically; it is associated with Biconulites cf. hardmani. The age is early Middle Cambrian, and, probably, older that the Xystridura-bearing upper part of the Negri Group*.

III. This part of the sequence is unfossiliferous, but represents the larger part of the Middle Cambrian.

IV. Passage: The fossils in this part of the Skewthorpe Formation are the agnostids Peronopsis, Grandagnostus, and Ptychagnostus, and the polymerid trilobite hitherto regarded, and referred to, as Solenoparia; it belongs, however, to a new and apparently local genus of the Ptychopariacea of an unknown family affiliation. The agnostids were formerly believed to occur in the Middle Cambrian only, but are now known to pass into the early Upper Cambrian in Queensland as well. In the same division, fragments of Damesellidae (but not of Damesella) have been recorded, which are even better represented higher up in this division. These trilobites belong to Blackwelderia, and another unpublished genus, both known from the early Upper Cambrian Mindyallan Stage (Opik, 1963) of Queensland. Hence, division IV represents the Middle Cambrian/Upper Cambrian passage and also the earliest part of the Upper Cambrian, which, however, are inseparable from each other in the collections from the Cambridge Gulf area.

V. Mindyallan: Mindyallan is the initial Upper Cambrian stage (Opik, 1963, 1966): in the lower (in parts dolomitic/calcareous) levels of this division the 'Solenoparia' (see under IV) and the unpublished form of the Damesellidae are well represented; in the sandstone that follows above sinistral gastropods occur; undescribed as yet, these are recorded in the Mindyallan faunas of Queensland and central Australia. Hence, division V wholly belongs in the Mindyallan Stage, and it is correlated with the Kushanian of China and the lower Dresbachian of North America.

VI. Idamean: The part of the sequence referable to the Idamean Stage of the Upper Cambrian (Opik, op. cit.) is poor in fossils. Gastropods and phosphatic brachiopods occur sporadically; trilobites referable to the Aphelaspidinae are present in specimen 245/7, but are inconclusive as regards their position within the stage.

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* More detailed later investigation indicates that Divisions I and II cannot readily be separated in age, and that they both belong to the newly-named Ordian stage. This is equivalent to the 'post-Olenellus pre-Paradoxides' stage of Europe and is placed by the author in the lowest Middle Cambrian (see Opik, A.A., Bur. Miner. Resour. Aust. Bull. 92, 1968).

Owing to the scarcity of fossils, the Idamean and the Mindyallan parts of the sequence cannot be separated. Even more obscure is the upper extent of the Idamean because a fauna is missing which should intervene between the Idamean and division VII (Parabolinoididae). The missing fauna is expected to correspond to the zone of Irvingella tropica and Agnostotes inconstans of the Queensland scale of zones (below) followed above by an equivalent of the American Elvinia Zone. It is possible that in the Cambridge Gulf sequence the Parabolinoididae had already appeared in Elvinia time, i.e. one zone earlier than in America. It should be noted also that in Queensland (Opik, 1963, p. 22) a barren sequence covers the interval between the Irvingella tropica/Agnostotes Zone of the Idamean and the strata containing Paramansuyella. Consequently, equivalents of the Elvinia fauna and of division VII (Parabolinoididae) are not evident in Queensland.

The following three faunal divisions, the VII (Parabolinoididae), VIII (Parabolinoididae and Paramansuyella) and IX (kaolishaniid), cannot be separated sharply from each other because the Parabolinoididae extend apparently even into the base of division IX; nevertheless the faunal contrast between the earliest (VII) and the latest (IX) divisions prevents any confusion, and Paramansuyella (of VIII) and the kaolishaniid (of IX) have not as yet been found together.

VII. (Parabolinoididae): Three genera of Parabolinoididae Lochman, 1956, occur in the Cambridge Gulf sequence. Parabolinoides itself is absent, but affiliates of Taenicephalus and, apparently, of Croizana (forms with obsolete or partly obsolete frontal marginal cranidial furrow) are present.

VIII. (Parabolinoididae and Paramansuyella): The Parabolinoididae in division VIII are referable to the genera of the earlier division VII; the species of Paramansuyella, however, is confined to division VIII. It is very close to the undescribed species from the Chatsworth Limestone of Queensland (Opik, 1960, p. 107; 1963, locality D124, p. 22).

IX. (Kaolishaniid): The trilobite is recognizable from the pygidium, cranidium, and free cheeks and belongs to an undescribed genus tentatively placed in the family Kaolishaniidae. Division IX with the Kaolishaniid is a valuable stratigraphic marker. Above it, and quite abruptly, a different fauna, beginning with Ptychaspis, gains with the advance in time in diversity and abundance of forms.

X. Ptychaspis/Prosaukia: This unit is divisible into a lower (XA) and an upper (XB) part. The lower part contains, among other trilobites, Tsinania and an asaphiscid which has been compared with Maryvillia (Opik, 1956, p. 53); these disappear in subdivision XB, in which a saukiid appears, distinguished by a long frontal spike.

As a whole, unit X contains several undescribed and some known genera of the Saukiidae. Prosaukia is represented by some three species and Sinosaukia probably by two. Ptychaspis is also well represented and a form intermediate between a Saukia and a Ptychaspis occurs frequently. Deserving of mention also is an affiliate of Prosaukia whose cranidia are some 3 cm long and are distinguished by very long (transversely) posterolateral limbs.

XI. (Tellerina): Only one collection (275/4) is referable to this division. It contains a Tellerina-like pygidium and fragmentary cranidia of Saukiidae reminiscent of Saukia and/or Saukiella. The occurrence of cranidia cf. Tellerina was mentioned by Opik (1956, p. 53).

Unit XI represents the top of the Upper Cambrian (i.e. of the Cambrian) and should be examined in the field once more.

XII. (Ordovician): Within section 249, bed 249/9 contains fragments of asaphids and cystid plates with pore rhombs. Above it, Richardsonellidae, Leiostegiidae, and protopliomerids indicate a late Tremadocian to early Arenigian age for bed 249/11.

Provincial Affinities and Zone Correlation.

The fossil record in the Cambridge Gulf sequence is continuous beginning with unit VII, whose Parabolinoididae indicate marine connexion with North America (e.g. Minnesota), whereas Paramansuyella and the Kaolishaniid are of a southeast Asian affinity. Units VII to IX together can be correlated roughly with the Conaspis Zone of the Franconian of North America. The fauna of unit X is also a blend of North American and southeast Asian forms on a background of a probably endemic Australian population of trilobites. It correlates well with the American Upper Franconian Zones with Ptychaspis and Prosaukia. Unit XI, finally, represents the Trempealeauan Stage.

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APPENDIX 4

PETROGRAPHY OF THE ANTRIM PLATEAU VOLCANICS AND ASSOCIATED ROCKS FROM THE BONAPARTE GULF BASIN AND OUTLIERS

by

W.R. Morgan

The specimens described are:

Specimen No.	Locality
R15308	Ord River, 1 mile west of Kimberley Research Station
R15320	8 miles southeast of 8-mile Creek Bore
R15352	Martins Gap
R15353	Martins Gap
R15865	Ord River, near Tarrara Bar
R15866	Ord River, near Tarrara Bar
R15867	Ord River, near Tarrara Bar
R15876	5 miles south of 8-mile Creek Bore
R16901	5 miles south-southeast of Mount Rob
R16915	Martins Gap
R16951) R16952)	7 miles north-northeast of Dillon Spring
R16956	Northern tip of Carlton Range
R16988	Northern part of Ragged Range
TS.14,440	Martins Bluff
TS.14,441	Martins Bluff
TS.14,442	4 miles north of Nigli Gap
TS.14,443) TS.14,444)	8 miles south of Spirit Hill
TS.14,445	9 miles northeast of Spirit Hill

All the specimens represent the Antrim Plateau Volcanics except R16901, TS14,440, and TS14,441, which are specimens of conglomeratic and brecciated material which overlies the volcanics.

Antrim Plateau Volcanics

All the specimens, except R16952, TS14,443 and TS14,444 are strongly altered.

R16952 is a moderately porphyritic basalt; about 10 percent of the rock consists of phenocrysts ranging from 0.3 to 2.8 mm in diameter. Most of the phenocrysts consist of tabular, commonly clustered, crystals of sericitized plagioclase, with a composition of about An_{55} to An_{60}. A few small phenocrysts of augite and altered olivine (?) are present. Specimens TS14,443 and TS14,444 are sparsely porphyritic rocks with plagioclase phenocrysts, up to about 1 mm across, forming less than 1 percent of the rocks.

In all three specimens, the groundmass has an intersertal texture. The plagioclase laths average 0.1 mm long and 0.03 mm wide. In specimen R16952 the plagioclase is strongly sericitized, but in the others it is only slightly altered. The composition of the plagioclase is about An_{50}. Augite is slightly chloritized in specimen R16952; in specimens TS14,444 and TS14,445, it is partly ferruginized and altered to smectite. Augite forms granular to prismatic crystals about 0.03 mm across. The iron oxide crystals, 0.02 to 0.1 mm across, are octahedral. Interstitial chlorite and devitrified glass (R16952) are present. Some vein quartz is present in specimens R16952 and R14445. Small amounts of fox-brown biotite form poikilitic flakes, about 0.1 mm diameter, in specimen TS14444.

In the strongly altered specimens, the phenocrysts form less than 1 percent of most rocks; specimen R15876 contains about 5 percent of phenocrysts. The porphyritic crystals commonly range up to about 1 mm long, although in specimens R15865 and R15876 they are about 3 mm long. Most of the phenocrysts consist of tabular crystals of moderately to strongly sericitized albite. In specimen R16951, in addition to plagioclase, a few chloritized phenocrysts of pyroxene, and a pseudomorph of serpentine and ferruginous material after olivine are present.

In all except three of the specimens, the groundmass consists of a meshwork of moderately to strongly sericitized plagioclase laths, and ferruginous chlorite pseudomorphs after pyroxene, set in a highly ferruginous and chloritic material, much of which possibly represents altered glass. Probable pseudomorphs after olivine are present in specimens R15308, R15320, R15866, and R15867. The average grainsize ranges from 0.01 to 0.2 mm. Three specimens, R15353, R16951 and TS 14445, appear to consist mostly of highly ferruginized altered glass.

Most of the specimens are amygdaloidal; the amygdales commonly contain quartz and in a few specimens there is a thin rim of chlorite. Specimen R16988 contains calcite and quartz. In specimen R15867, the amygdales are filled with smectite and chlorite; in specimen R15320, clay minerals; and in specimen TS14445, smectite and chalcedony.

Specimen TS14442 contains some xenoliths of inequigranular fine-grained sandstone, in which the grainsize ranges from 0.03 mm to 0.15 mm. The grains are angular to subrounded; they consist mostly of quartz, but chert, albite, microcline, and ferruginous material are also present. The ferruginous material is much more common close to the margins of the xenolith, and appears to have been introduced from the basalt. The abundant matrix in the xenoliths is formed of zeolitic material and crystalline quartz.

Conglomeratic and Brecciated Rocks

The two specimens of conglomeratic rocks (TS14,440 and TS14,441) consist of rounded granules and pebbles ranging up to 6 mm in diameter. The granules and pebbles consist of ferruginized, chloritized, and carbonated basalt. They are embedded in a matrix composed of crystalline calcite enclosing a few clastic grains of quartz.

The breccia (R16901) consists of angular to subrounded fragments ranging up to about 7 mm in diameter. The fragments are mostly of ferruginous siltstone and sandstone and some slightly feldspathic sandstone; a few consist of layered ferruginous siltstone/sandstone. One fragment has a texture that suggests it is a strongly silicified acid tuff.

The matrix is feldspathic sandstone; a few grains of sodic plagioclase and microcline are present; the shape of the grains and general appearance of the plagioclase is unlike that in the basalts. In places, however, the matrix contains a few grains of strongly altered basalt similar to the underlying basalt flows. The matrix grains are enclosed in a silica cement; some cavities are filled with crystalline calcite.

The altered basalts are probably spilites, formed by the alteration of basic lavas (Hopgood, 1962; Dickinson, 1962; Nicols, 1958). Some believe that autometasomatism is responsible for the alteration (e.g. Nicols, op. cit); others believe that the alteration is due to diagenesis and possibly burial metamorphism (e.g. Dickinson, op. cit). A.J.R. White (pers. comm) believes that many spilitic rocks in strongly folded geosynclinal regions represent metamorphosed basalts and dacites belonging to the greenschist facies.

The spilitic rocks of the Antrim Plateau Volcanics are similar to the relatively unaltered specimen (R16952), which is probably a tholeiitic basalt. This suggests that they were altered after extrusion. The Antrim Plateau Volcanics are only slightly folded, and the alteration is possibly due to a combination of autometasomatism and diagenesis.

The relatively unaltered basalts are generally similar to those described from the Antrim Plateau Volcanics by Glover (in Traves, 1955), except that they contain fewer phenocrysts. The specimens, however, do not resembly closely any of the groups described by Edwards (in Edwards & Clarke, 1940), but there is a general similarity.

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JOSEPH BONAPARTE GULF
CAMBRIDGE GULF
QUEENS CHANNEL
GEOLOGICAL MAP
SOUTHERN PART
BONAPARTE GULF BASIN
WESTERN AUSTRALIA AND NORTHERN TERRITORY
1968
Scale 1:250,000
15 MILES
25 KILOMETRES
CROWN COPYRIGHT RESERVED
Geology, 1966, by: J. J. Veevers, J. Roberts, J. A. Kaulback.
Compiled, 1966, by: J. J. Veevers, J. Roberts, A. S. Mikolajczak, F. J. Roberts.
Cartography by: Geological Branch, B.M.R.
Drawn by: Austral Cartographic Service, Canberra, A.C.T.
Printed by: Mercury Press Pty. Ltd., Hobart
Compiled and published by the Bureau of Mineral Resources, Geology and Geophysics, Department of National Development. Issued under the authority of the Hon. David Fairbairn, Minister for National Development.
Transverse Mercator Projection.
CAINOZOIC
QUATERNARY
Qac Coastal alluvium
Qa Alluvium
UNDIFF.
Czs Sand
Czb Black soil
PALAEOZOIC
PERMIAN
Keep Inlet Beds Pk
UPPER CARBONIFEROUS
Border Creek Formation Cub
LOWER CARBONIFEROUS
Tanmurra Formation (In section only) Clt
Point Spring Sandstone Clp
Burvill Beds Clr
Utting Calcarenite Clu
Waggon Creek Breccia Clw
Milligans Beds Clm
Zimmermann Sandstone Clz
Septimus Limestone Cls
Enga Sandstone Cle
Burt Range Formation Clb
UPPER DEVONIAN TO LOWER CARBONIFEROUS
Bonaparte Beds (In section only) D-Cb
UPPER DEVONIAN
Buttons Beds Dub
Ningbing Limestone Dun
Cockatoo Formation Duc
Jeremiah Member Duj
Cecil Sandstone Member Due
Abney Sandstone Member Dua
Kununurra Member Duu
Kellys Knob Sandstone Member Duk
Westwood Member Duw
Hargreaves Member Duh
Ragged Range Conglomerate Member Dur
LOWER ORDOVICIAN
Pander Greensand Olp
UPPER CAMBRIAN
Clark Sandstone €uc
Pretlove Sandstone €up
MIDDLE CAMBRIAN
Skewthorpe Formation €ms
Hart Spring Sandstone €mh
Tarrara Formation €mt
LOWER CAMBRIAN
Blatchford Formation €lb
Antrim Plateau Volcanics €la
CAMBRIAN
Undifferentiated €
PRECAMBRIAN
Undifferentiated p€
Geological boundary
Anticline, showing plunge
Syncline
Fault
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
Horizontal strata
Dip <15°
Trend lines
Joint Pattern
air-photo interpretation
Oil exploration well: St — stratigraphic hole
Oil exploration well: abandoned, dry
Oil exploration well with show of gas: abandoned
Mine
Bore
Windpump
Waterhole
Spring
Highway
Road
Vehicle track
Airport
Landing ground
Homestead
State boundary
Margin of Bonaparte Gulf Basin
INDEX TO ADJOINING SHEETS
Showing Magnetic Declination
Sections
Cainozoic sediments omitted from sections
Attitude of faults not known
Scale: V/H = 2
A
B
C
D
A.O.D. Bonaparte No 2 (projected)
A.O.D. Bonaparte No 1 (projected)
BONAPARTE GULF BASIN
Copies of this map may be obtained from the Bureau of Mineral Resources, Geology and Geophysics, Canberra, A.C.T., or Darwin, N.T. or the Geological Survey of Western Australia, Perth