EXPLANATORY NOTES
2nd Edition

HELEN SPRINGS
SE 53-10

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Helen Springs SE 53-10; explanatory notes (second edition)

(1:250 000 geological map series, ISSN 0814-7485)

Bibliography

ISBN 0 7245 7010 1 (Hard copy)
ISBN 978-0-7245-7139-0 (CD version)


559.429 21

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ABSTRACT

HELEN SPRINGS is bounded by latitudes 18º00’ S and 19º00’ S and longitudes 133º30’ E and 135º00’ E and is situated in the northern Tennant Inlier and western Georgina Basin. It features Proterozoic units of the Ashburton province that form three deformed, predominantly shallow marine (and fluvial) sedimentary successions bounded by unconformities; the Tomkinson Creek, Namerinni and Renner Groups. These Groups have a maximum composite thickness of 16.5 km and were deposited in a series of overlapping basins that probably extended across most of the North Australian Craton.

The Tomkinson Creek Group comprises six formations (Hayward Creek and Morphett Creek Formations, Short Range Sandstone and Attack Creek, Bootu and Carmilly Formations) that outcrop in southern HELEN SPRINGS and reach a maximum thickness of 10.5 km. These units were probably deposited under fluvial to shallow marine conditions. An extensive continental flood basalt is included in the lower part of the succession (Whittington Range Member, top of Hayward Creek Formation). The Tomkinson Creek Group was folded about northwest trending fold axes prior to deposition of the Namerinni Group.

The Namerinni Group overlies the Tomkinson Creek Group with a subtle angular unconformity. It comprises about 2800 m of mostly shallow water, cyclic siliciclastic and mixed carbonate/siliciclastic units and is divided into the Jeromah, Carruthers, Shillinglaw and Willieray Formations. These units contain slightly less compositionally mature siliciclastic successions compared to the upper Tomkinson Creek Group. A 1639 ± 27 Ma date from a tuffaceous unit within the Shillinglaw Formation (Nunn 1997) suggests that the Namerinni Group is a chronostratigraphic equivalent of the McArthur Group of the McArthur Basin. The Namerinni Group is separated into an eastern and western succession by relatively down-faulted Renner Group rocks. Subtle lithological and thickness differences distinguish each succession.

The Renner Group unconformably overlies the Namerinni and Tomkinson Creek Groups and consists of about 3500 m of predominantly shallow water siliciclastic rocks. It is divided into five formations (Gleeson, Baralandji, Powell, Wierny and Jangirulu Formations) plus an uppermost unit, the Lake Woods beds, the top of which is not exposed in HELEN SPRINGS. Stratigraphic relationships imply significant restructuring of fault blocks prior to deposition of the Renner Group, suggesting a significant time break. This contrasts with subtle angular relationships beneath the Namerinni Group.

Up to 500 m of relatively flat-lying Cambrian units of the Georgina and Wiso Basins overlie the Proterozoic Ashburton province to the east and west, respectively. Geophysical data indicate that rocks similar to those of the Ashburton province underlie these younger successions across most or all of HELEN SPRINGS. Areas in northern HELEN SPRINGS and palaeovalleys within the ranges also preserve eroded remnants of the Lower Cretaceous Dunmarra Basin. These strata include less than 50 m of undifferentiated, fossiliferous shallow marine to fluvial and lacustrine sedimentary rocks. A thin veneer of Cenozoic rocks and unconsolidated deposits covers the majority of HELEN SPRINGS.

Although no significant deposits have been identified to date, HELEN SPRINGS is considered prospective for base metals, hydrocarbons and diamonds. Manganese appears to be present in economic-sized deposits, particularly in the Bootu Creek area where several small deposits have been mined in the past. Significant groundwater resources occur in the Georgina Basin.

* Names of 1:250 000 and 1:100 000 map areas are given in large and small capitals respectively, eg HELEN SPRINGS, MUCKATY.
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INTRODUCTION

These explanatory notes summarise the results of geological investigations in HELEN SPRINGS by the Northern Territory Geological Survey (NTGS) during 1995-1997. As part of this project, Proterozoic rocks in ELLIOTT and NEWCASTLE WATERS were also mapped. HELEN SPRINGS is bounded by latitudes 18°00' S and 19°00' S and longitudes 133°30' E and 135°00' E and covers an area of more than 17 500 km² in the north-central Northern Territory (Figure 1).

The First Edition geological map and explanatory notes of HELEN SPRINGS were published in 1969 (Randal and Brown 1969) following field mapping by the Bureau of Mineral Resources (BMR) in 1965. Gravity data were collected on a regional 11 km grid by BMR between 1960 and 1965. Airborne magnetic and radiometric data (500 m spaced east-west lines, 100 m terrain clearance) were acquired over the entire sheet in 1993, and can be obtained from NTGS in digital format.

Locations referred to in this text are based on Australian Map Grid zone 53 coordinates and the AGD 84 map datum, and are accurate to within about 50 m. The Universal Grid Reference style is used as explained on the map face (eg Renner Springs at AMG 372500 E and 7974000 N is represented by LV725740).

Figure 1  Location of HELEN SPRINGS

Terminology and classification

Quoted bed/lamination thickness follows Blatt et al (1980). Grain size terminology of clastic rocks follows Wentworth (1922). In these notes and on the accompanying geological map, the term sandstone principally refers to grainsize; litharenite, sublitharenite and quartz arenite refer to sandstone composition where differentiated (Folk 1974). The term mudstone refers to fine clastic rocks containing silt- and clay-sized grains. Mudstone is used as a general classification term and includes claystone, siltstone, shale and argillite. Mudstone is used in this sense because the proportions of its components often can not be precisely determined. Siltstone is defined as a mudstone containing predominantly silt-sized, usually quartzo-feldspathic grains. The classification of carbonate rocks is often problematical in a mixed clastic/carbonate environment; here, it principally follows Wright (1992). The term quartzic dolostone as used here refers to dolostone in which quartz is a significant siliciclastic component. These rocks often also contain quantities of feldspars, micas and lithic grains. The description of igneous rocks follows the IUGS terminology in Le Maitre (1989).

Common indicators of marine versus non-marine depositional settings of Proterozoic rocks are glauconite and tidal facies associations (eg Miall 1990). Unfortunately, glauconite is scarce in HELEN SPRINGS and therefore recognition of the latter is taken as the best indicator of a marine environment.
Location and access

The Stuart Highway runs north-south through the Ashburton Ranges in western HELEN SPRINGS. An underground Alice Springs to Darwin gas pipeline roughly parallels the Stuart Highway on the western side of these ranges. The highway and access tracks linking it to the pipeline provide good access to western HELEN SPRINGS. Renner Springs roadhouse, located about 160 km north of Tennant Creek on the Stuart Highway in northern HELEN SPRINGS, is the only service station and accommodation in this region. The Barkly Stock Route, a formed gravel road, passes near the northern edge of the map sheet. Several pastoral properties and a few isolated Aboriginal communities are located in HELEN SPRINGS and unsealed tracks servicing these populations provide access to the remainder of the map area. Access to the black soil regions is often impossible during the wet season. Roads are limited in southwestern HELEN SPRINGS in the area of the Karlantijpa North Aboriginal Land Trust.

Climate

Climate in this region is semi-arid subtropical, with long hot summers and sporadic monsoonal rains and mild dry winters. Maximum temperatures average about 38°C in summer and about 27°C in winter. Average annual rainfall for this region is approximately 400-450 mm, with most falling in the period November to March. The annual evaporation rate is nearly 3.5 m.

All watercourses in HELEN SPRINGS are intermittent and only flow after significant rains. Several waterholes and rockholes in this region retain water for extended periods, although only a few could be considered as permanent. Lake Woods, which partly extends into northwestern HELEN SPRINGS, may contain water or be dry for a number of years. This region supports a cattle industry relying on groundwater supplies principally derived from aquifers in the Georgina Basin.

Physiography

Randal and Brown (1969) recognised three main physiographic divisions in HELEN SPRINGS. They described the eastern half of the sheet area as the downs country and this represents all of the areas locally known as black soil, including intermittent lakes or depressions, the low lying floodouts of internally draining creeks and those creeks draining the ranges in the northwest. The sand plains predominantly result from fluvial and colluvial transport of sand weathered from the ranges. These appear to be younger than the black soils and are prograding over them, but as discussed later, relationships are more complex. The sand plains continue westwards and merge with vegetated and stabilised longitudinal sand dunes in the eastern Tanami Desert in southwestern HELEN SPRINGS.

The Ashburton and Whittington Ranges consist of dissected sandstone ridges and plateaux. The highest plateaux in the ranges are remnants of an ancient weathering surface, the Ashburton Surface (Hays 1967). According to Stewart et al (1986), this surface formed prior to the Cambrian, at least in the Davenport province in the southern Tennant Inlier, and has remained essentially unchanged since then. A younger weathering surface, the Tennant Creek Surface (Hays 1967) corresponds to the uppermost extent of the Cretaceous sediments in HELEN SPRINGS and nearly coincides with the Ashburton Surface. Both surfaces are variably eroded and their remnants can be seen throughout the Tennant Inlier.

The lowest point in HELEN SPRINGS, 198 m above sea level (ASL), occurs in the northwest on the margin of Lake Woods. The black soils, at about 200-230 m ASL, are gently undulating and in general the lowest parts of HELEN SPRINGS. The Ashburton Surface represents the highest topography, gradually sloping in the ranges from an unnamed hill at 405 m ASL in southern HELEN SPRINGS to about 280 m ASL at the northern sheet boundary. Topographic relief in the ranges is typically less than 30 m although it can reach about 50 m to the south.


Previous investigations

Randal and Brown (1969) described previous studies in HELEN SPRINGS and a brief summary is presented here. The explorer John McDouall Stuart named a number of the creeks draining the Ashburton Ranges. Brown (1895) found the first recorded Cambrian fossils on the Barkly Tablelands between Powell Creek and Alexandria station. Woolnough (1912) and Jensen (1914) commented on the Cambrian rock units and groundwater resources, and Ward (1962) selected water bore sites. Chewings (1931) reported on the geology of the Ashburton Ranges and the Barkly Tableland. Noakes and Traves (1954) described the geology of the region, naming the Barkly Group and the Ashburton Sandstone (these names are invalid in the sense of Staines (1985) and are no longer in use). They noted that the Helen Springs Volcanics were deposited on topography controlled by the “Ashburton Sandstone”. Hossfeld (1954) also briefly commented on the geology of this area and Öpik (1956) collected and documented fossil specimens. Jones (1955) and MacKay (1956) investigated the Bootu Manganese deposits and found that they did not extend to any great depth. BMR commissioned a regional gravity survey over the area (Flavelle 1965) and an aeromagnetic survey over BRUNETTE DOWNS, which also covered the eastern portion of HELEN SPRINGS (Howe and Faessler 1963).

Investigations since the release of the First Edition geological map have principally concentrated on exploring the manganese and base metal potential of the Proterozoic rocks and the diamond potential of the region. These efforts are summarised below under ECONOMIC GEOLOGY. Probably of most significance is the work of Ward (1983), who mapped a large region of the Ashburton Province in western HELEN SPRINGS as a consultant for Key Resources, Clifford Minerals, Hunter Resources and Esso. He suggested a correlation between the Tomkinson Creek beds and the McArthur River region sediments, described them as “most comparable” and assigned mapped units with names from the latter.
PROTEROZOIC STRATIGRAPHY

TOMKINSON CREEK GROUP

The Tomkinson Creek Group is a succession of shallow marine and continental sedimentary rocks that contains mafic volcanic rocks in the lower part. Most stratigraphic units are laterally persistent and conformable. They reach a maximum composite thickness of almost 11 km in HELEN SPRINGS, where they are usually identical to those described in FLYNN by Donnellan et al (1995). Sparse outcrop and geophysical (TMI) data indicate that the group extends into northeastern GREEN SWAMP WELL and southeastern SOUTH LAKE WOODS. A summary of the Tomkinson Creek Group is given in Table 1 and the distribution of the group in HELEN SPRINGS is shown in Figure 2.

The base of the group is not exposed in HELEN SPRINGS. In TENNANT CREEK, Donnellan et al (1995, 1999) reported a transitional lower contact with the underlying Brumbreu Formation of the Flynn Group, although geochronological data indicate that there is a substantial discontinuity of 35 Ma at this level. The Namerinni and Renner Groups unconformably overlie the Tomkinson Creek Group.

The Tomkinson Creek Group is dominated by thick siliciclastic units that alternate with six mixed siliciclastic-carbonate intervals. The carbonate units of the lowermost mixed siliciclastic-carbonate interval are localised and poorly developed in HELEN SPRINGS. This interval has been mapped as part of the Whittington Range Member of the Hayward Creek Formation. The five other mixed siliciclastic/carbonate intervals are widespread.

Hayward Creek Formation (Pth)

Ridge-forming sandstone units of the Hayward Creek Formation form extensive high ranges in HELEN SPRINGS. These upstanding outcrops of moderately to subvertically dipping sandstone are mainly confined to two regions in southwestern HELEN SPRINGS, in the axes of northerly and northwesterly plunging, faulted anticlines.

Mendum et al (1978) originally defined the formation and named it after Hayward Creek in TENNANT CREEK. Donnellan et al (1995) subsequently included the overlying Whittington Range Volcanics of Mendum et al (1978) as the Whittington Range Member. Donnellan et al (2001) formally defined three mappable sandstone units, which were described in Donnellan et al (1995) as lower, middle and upper sandstone members as, in ascending order, the Manga Mauda, Meerie and Coodna Members. The four members have a maximum exposed composite thickness of greater than 3.5 km in HELEN SPRINGS.

The base of the Manga Mauda Member does not crop out in HELEN SPRINGS and the Meerie and Coodna Members...
Quartz grains appear to be free from prior overgrowths and quartz cemented, although there is also some interstitial clay. They are variably rounded and sorted and are generally quartz cemented, although there is also some interstitial clay. Quartz grains appear to be free from prior overgrowths and are therefore probably first cycle. Variable, though typically minor polycrystalline quartz, chert and lithic grains of metasedimentary and probable volcanic origin are present, as are trace amounts of zircon and white mica. Intense silicification and generally poor outcrop have precluded any change to previously interpreted depositional

<table>
<thead>
<tr>
<th>Unit</th>
<th>Lithology</th>
<th>Stratigraphic Relationships</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carmilly Formation</td>
<td>Laminated to thinly bedded silicified dolostone; laminated to thinly bedded siltstone, and mudstone; mostly fine to medium sandstone; silicified cryptomicrobial boundstone, stromatolites, evaporite pseudomorphs, enterolithic and nodular chert.</td>
<td>Conformably overlies Bootu Formation (sharp to transitional contact). Subdivided into informal lower, middle and upper lithofacies. Unconformably overlie by undivided Cretaceous rocks.</td>
<td>Restricted shallow marine with minor terrigenous input; peritidal environs including intertidal and hypersaline; possibly lacustrine in lower part.</td>
</tr>
<tr>
<td>~750 m (min)</td>
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<tr>
<td>Bootu Formation</td>
<td>Thinly to very thickly bedded, medium to very coarse sandstone and pebbly sandstone; minor thinly bedded siltstone and mudstone; calcareous siltstone and sandstone; minor carbonaceous shale and manganiferous sandstone, stromatolites and halite pseudomorphs.</td>
<td>Disconformably to conformably overlies Attack Creek Formation. Unconformably overlie by Gleeson Formation and undivided Cretaceous rocks.</td>
<td>Protected shallow marine with periodic exposure (supratidal) upward to intertidal and subtidal open marine upward to shallow marine with minor fluvial and continental? red beds.</td>
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<td>~1800-2200 m</td>
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<tr>
<td>Attack Creek Formation</td>
<td>Massive to laminated dolostone and limestone?; laminated to thinly bedded siltstone and mudstone; chert; thinly bedded quartzic dolostone; laminated cryptomicrobial boundstone, thin to medium beds of intraformational conglomerate</td>
<td>Disconformably to conformably overlies Short Range Sandstone (sharp to transitional contact). Unconformably overlie by Gleeson Formation.</td>
<td>Shallow marine, open tidal flats protected from significant terrigenous input; periodic exposure.</td>
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<td>~330-400 m</td>
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<tr>
<td>Short Range Sandstone</td>
<td>Thinly to very thickly bedded, fine to coarse sandstone; minor thinly bedded micaceous fine sandstone and siltstone, and lesser laminated mudstone; some pebbly sandstone and conglomerate lags; rare halite pseudomorphs.</td>
<td>Disconformably to conformably overlies Morphett Creek Formation. Subdivided into Deagan Member and informal middle and upper lithofacies. Unconformably overlie by Gleeson Formation.</td>
<td>Predominantly shallow marine littoral to subtidal, minor fluvial or deltaic.</td>
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<td>650-850 m</td>
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<tr>
<td>Morphett Creek Formation</td>
<td>Thinly to occasionally very thickly bedded fine to very coarse sandstone and pebbly sandstone; very thinly to medium bedded fine to medium sandstone and siltstone; thin to medium beds of graded intraformational conglomeratic sandstone; laminated chertified dolostone and cryptomicrobial boundstone; stromatolites; pebble to cobble conglomerate (metasedimentary clasts and less common white vein quartz clasts); evaporite pseudomorphs; enterolithic and nodular chert.</td>
<td>Disconformably overlies Whittington Range Member of Hayward Creek Formation. Consists of Kuerschner and Mitty Members. Unconformably over lain by Gleeson Formation and undivided Cretaceous rocks.</td>
<td>Fluvial to shallow marine. Continental red beds to marginal shallow marine including peritidal flats and sabkha. Some shallow marine channels.</td>
</tr>
<tr>
<td>~3000-3200 m</td>
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<tr>
<td>Hayward Creek Formation</td>
<td>Thinly to very thickly bedded medium to very coarse sandstone and pebbly sandstone; minor pebble to cobble conglomerate (clasts of white vein quartz and white to pinkish cream quartz arenite); minor thinly bedded fine to medium sandstone, siltstone, mudstone and intraformational conglomerate; basaltic lava.</td>
<td>Disconformably? overlies Flynn Group in TENNANT CREEK. Subdivided into Manga Mauda, Meerie, Codna and Whittington Range Members.</td>
<td>Fluvial to shallow marine, intertidal, periodic subaerial exposure.</td>
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<td>~3500 m</td>
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Table 1  Stratigraphic units of the Tomkinson Creek Group in HELEN SPRINGS

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<td>Thinly to very thickly bedded, medium to very coarse sandstone and pebbly sandstone; minor thinly bedded siltstone and mudstone; calcareous siltstone and sandstone; minor carbonaceous shale and manganiferous sandstone, stromatolites and halite pseudomorphs.</td>
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form the majority of the exposed Hayward Creek Formation. In contrast with TENNANT CREEK, an upper sandstone lithofacies of the Coodna Member is mappable throughout most of HELEN SPRINGS.

Abundant medium to very coarse siliciclastic rocks dominate the Hayward Creek Formation. These are typically quartz arenite and in the Manga Mauda and Coodna Members, sublitharenite is also prevalent. Quartz grains are predominantly fairly clear and free from undulose extinction.
environments (Donnellan et al 1995, 1999, 2001). Manga Mauda Member lithofacies are interpreted as largely fluvial. The overlying Meerie Member is interpreted as predominantly shallow marine. The lower sandstone lithofacies of the Coodna Member is considered to be mainly fluvial, whereas the upper sandstone lithofacies was probably deposited in very shallow water environments that may have been locally intertidal. The environment of the basal lithofacies of the Whittington Range Member is interpreted as marginal very shallow water to supratidal.

A transgression and regression is particularly noticeable in MUCKATY, where facies deepen from very shallow water marine/fluviatile environments in the uppermost Manga Mauda Member to open marine, higher energy subtidal facies in the middle of the Meerie Member. Depositional settings then return to shallow water intertidal and ultimately fluvial in the basal and middle parts of the Coodna Member.

The Coodna Member is slightly coarser and less compositionally and texturally mature in MUCKATY than in BRUNCHILLY and northern FLYNN, although exposures are still comparable to those in a large part of SHORT RANGE and east of the Stuart Highway in FLYNN. The Coodna Member also appears to have a higher pebble content than usual in MUCKATY and in this respect, resembles the Manga Mauda Member in TENNANT CREEK. In contrast with TENNANT CREEK, exposures of the Manga Mauda Member in MUCKATY appear to be more mature than those of the Coodna Member, although the basal parts of the Manga Mauda Member do not outcrop in MUCKATY.

SHRIMP U-Pb dating of detrital zircons from Meerie Member sandstone in FLYNN indicates a maximum age of 1784 ± 9 Ma (Compston 1995). This date is considered to be a very good approximation of the depositional age, given that some sandstone units from the Hayward Creek Formation in FLYNN were clearly derived from contemporaneous felsic pyroclastic rocks and were rapidly deposited with limited reworking.

**Manga Mauda Member (PTh_m)**

Siliciclastic rocks of the Manga Mauda Member are confined in outcrop to central MUCKATY, where the member is at least 600 m thick. They represent an overall fining-upward (pebbly to fine-grained) and thinning-upward (very thickly to thinly bedded) sedimentary succession. Finer sandstone and siltstone are cross-laminated and some contain ripple marks and desiccation features. Graded beds and pebble lags are present near the base of the succession and trough or tabular cross-stratification is common. The widespread siltstone interval in the middle part of this member in TENNANT CREEK, as well as its coarse basal sandstone, do not crop out in MUCKATY. The absence of these units suggests that outcrops in MUCKATY are equivalent to the second major fining-upward cycle of the Manga Mauda Member in TENNANT CREEK (units 1d and 1e of the type section in FLYNN; Donnellan et al 1995).

**Meerie Member (PTh_h)**

The Meerie Member consists of fine to coarse, moderately to very well sorted and rounded, grainsize-laminated quartz arenite. Typically, the cream to tan to pink sandstone has laterally persistent, predominantly thin to medium beds and low to high angle, bidirectional, tabular cross-stratification. Minor intervals of medium to granular and pebbly, current rippled sandstone are associated with slight depressions filled with gravel lags. Towards the top of this member, thinly bedded sandstone intervals with slightly asymmetric, straight crested and bifurcating ripple marks, and in places desiccation features, are extensive (eg LV784136). The thickness of the Meerie Member is about 900 m in central MUCKATY and 700 m in BRUNCHILLY. However in BRUNCHILLY, the thickness of the unit may be similar to that in FLYNN (about 1000 m) given that the contact with the underlying Manga Mauda Member is not exposed.

In MUCKATY, the base of the member consists of a 3-10 m thick unit of poorly to moderately sorted, medium to very thickly bedded, cross-stratified, medium to very coarse sandstone, and granule and pebble conglomerate, which is well exposed near LV712192. As in central SHORT RANGE (Donnellan et al 2001), this unit has a sharp and locally erosive contact with the Manga Mauda Member, whereas elsewhere throughout the Ashburton province, the contact usually appears to be transitional.

**Coodna Member (PTh_h)**

The Coodna Member is lithologically very similar to the Manga Mauda Member and virtually identical to that mapped in TENNANT CREEK. A slightly different geomorphic expression is mappable throughout most of the member in HELEN SPRINGS and distinguishes an upper and lower sandstone lithofacies. The Coodna Member is only about 420 m thick in BRUNCHILLY and this is substantially thinner than the corresponding interval to the south in TENNANT CREEK. It is considerably thicker in MUCKATY where it reaches about 1300 m and this is comparable to, or thicker than most sections in TENNANT CREEK. The upper sandstone lithofacies of the Coodna Member is about 150 m thick in MUCKATY and 100-120 m thick in BRUNCHILLY.

Despite intense silicification, the upper sandstone lithofacies of the Coodna Member forms a slightly recessive bench in comparison with the lower sandstone lithofacies. Both sandstone lithofacies are repeatedly grainsize-laminated, but medium to massive bed sets in the lower lithofacies contrast with thin to medium bed sets in the upper lithofacies. The upper lithofacies also tends to be slightly finer and better sorted than the lower lithofacies. It is likely that the upper sandstone lithofacies of the Coodna Member is distinct from the sedimentary lithofacies that were included in the overlying Whittington Range Member in FLYNN (Donnellan et al 1995). This is particularly evident near LV848023 in MUCKATY where a transitional relationship is apparent.

As in TENNANT CREEK, Coodna Member sandstones are repeatedly thinly to thickly bedded and grainsize-laminated. Variably orientated, medium to very thick trough cross-strata with gravel lags and graded beds are common and are often associated with thinly to medium bedded, cross-laminated and current rippled, and rarely desiccated sandstone (eg LV805101).

The boundary between the Meerie and Coodna Members is transitional and is marked by a change to thicker bedded, coarser and less compositionally mature sandstone. Locally, the base of the Coodna Member is marked by heavy mineral-laminated sandstone (eg MV063000) and also by a change from flaggy to massive or boulder-forming outcrop.
characteristics. Elsewhere, for example in central Muckaty, it is represented by a sudden increase in bedding thickness and the onset of large-scale, trough cross-bedded, pebbly immature sandstone (Figure 3). An intensely lateritised interval at the contact between the Meerie and Coodna Members in the extreme south of Brunchilly is interpreted as intensely weathered volcanic rock and is probably a dolerite sill. Fine sandstone and mudstone are usually mapped at this stratigraphic level to the south in Flynn.

Whittington Range Member (Plthw)
The Whittington Range Member overlies the Coodna Member and is an interval of mafic volcanic rocks, thinly bedded sandstone and mudstone, and locally evaporitic and cryptomicrobial laminated carbonate rocks. It typically forms a recessive valley in the Whittington and Short Ranges in southern Helen Springs. Several small outcrops of weathered, amygdaloidal to massive basaltic lava. The lowermost ~400 m of Whittington Range Member is best exposed along a creek section, nominated as a reference section, in southeastern Muckaty from LV847023 to LV837017. This section provides the most complete exposure of the 550-600 m thick unit in Helen Springs, albeit deeply weathered and partly capped by ferricrete. It contains about 150 m of well exposed sedimentary rocks overlain by about 400-450 m of volcanic rocks consisting almost entirely of coherent amygdaloidal to massive basaltic lava.

The sedimentary rocks at the base of the member represent a cyclic fining- and thinning-upward sand-silt succession. The lowermost parts of this succession contain a few medium to thickly bedded, coarser sandstone units. In the upper part, rippled sandstone becomes progressively finer and thinner upward and has an increased proportion of leached mudstone. Thinly bedded to flaggy, tan coloured, extremely micaceous fine sandstone is common in the upper interval. Abundant ripples, desiccation features, tabular mudstone clasts and halite pseudomorphs are common sedimentary structures, along with some convolute laminations and small sand volcanoes. Silicified boundstone and small domical stromatolites occur at this stratigraphic level in Brunchilly (near MV040023).

Outcrops of volcanic rocks are often reddish-brown (to dark greenish-grey) and are deeply weathered. In places, small feldspar phenocrysts weathering to white clay are preserved and quartz-filled amygdales are locally abundant and very distinct (eg LV874096). Mendum and Tonkin (1976) described this unit as consisting of amygdaloidal basalt of tholeiitic affinity and also reported a few spherulitic rhyolite flows from drillcore in Flynn (BMR 3; MU078929).

The basalt is in sharp contact with the underlying sedimentary lithofacies near LV845022 in the reference section. The coherent amygdaloidal nature of the basalt along with the absence of pillow lava suggests it is mostly a subaerial lava flow. The base of the basalt in the valley near LV871098 varies from conformable to intrusive where it is locally peperitic. This strongly supports the interpretation that the dolerite sills in the Hayward Creek Formation are associated with the extrusion of basalt in the Whittington Range Member.

Morphett Creek Formation (Ptcm)
The Morphett Creek Formation is a succession of ridge-forming sandstone and recessive siltstone and carbonate rocks that was named by Mendum and Tonkin (1976) after Morphett Creek in Helen Springs and defined by Mendum et al (1978). Donnellan et al (1995) estimated its thickness to be about 2500 m in Flynn and suggested that an apparent increase in thickness to the north in that area was due to faulting. The thickness is estimated to be about 3000 m in Brunchilly and at least 3000-3200 m in central Muckaty, where the base of the formation is not exposed.

Basal sandstone and conglomerate units of the Morphett Creek Formation sharply overlie the volcanic unit of the Whittington Range Member of the Hayward Creek Formation. Dips within the sedimentary units above and below the

Figure 3 Typical example of thickly bedded, large-scale, low angle trough cross-bedded pebbly sandstone from Coodna Member in Muckaty (LV750156).
volcanic unit are the same. This suggests a concordant relationship between the two formations, despite an inferred period of erosion following extrusion of the volcanic lava.

Four distinct lithofacies were recognised in the Morphett Creek Formation in FLYNN and TENNANT CREEK by Donnellan et al (1995, 1999) but were not individually shown on maps. These lithofacies are similarly recognised throughout HELEN SPRINGS. Although all lithofacies and associations are clearly widespread throughout the Ashburton province, poor outcrop and structural complications typically frustrate efforts to map them in detail. However a mappable contact marked by a distinct morphological change is usually discernible between the second and third lithofacies, approximately in the middle of the formation in HELEN SPRINGS. The lower two distinct sandstone lithofacies are included in the Kuerschner Member (new name; see Appendix). The overlying Mitty Member (new name; see Appendix) consists of a lower mixed siliciclastic-carbonate lithofacies, and an upper predominantly fine to medium sandstone and mudstone lithofacies (the latter was referred to as ‘siltstone lithofacies’ in FLYNN by Donnellan et al 1995).

The Morphett Creek Formation is interpreted as representing a transgression from fluvial to very shallow marginal marine settings in the Kuerschner Member to shallow water intertidal and marginal marine to sabkha environments in the overlying Mitty Member. This formation probably represents more or less steady subsidence, following the widespread extrusion of continental flood basalts in the Whittington Range Member at the top of the Hayward Creek Formation.

Kuerschner Member (Ttmn)
The Kuerschner Member (new name, see Appendix) usually forms upstanding, dissected strike ridges, typically of slightly lower relief than those of the underlying Hayward Creek Formation. The lower lithofacies of the Kuerschner Member is estimated to be about 500 m thick in both MUCKATY and BRUNCHILLY, and is overlain by about 1000 m of the upper lithofacies. The aggregate thickness of the member in HELEN SPRINGS closely approximates the 1600 m estimated in FLYNN (Donnellan et al 1995).

The lower lithofacies of the Kuerschner Member is predominantly red-brown to cream coloured sandstone but also includes minor siltstone and at least locally, a basal conglomerate or pebbly sandstone. Basal conglomerate and pebbly sandstone are generally not well developed in BRUNCHILLY but are prevalent in MUCKATY (eg LV771119) where conglomerate and gravel lags are associated with medium to very thick tabular and trough cross-bedded, red-brown, poorly to moderately sorted sandstone and pebbly sandstone. Conglomerate clasts are predominantly of sandstone but also include white vein? quartz and red-brown jasper clasts.

A flaggy, granule-bearing, grainsize-laminated, current rippled, laterally persistent sandstone unit forms the base of the Kuerschner Member at MV038018 in BRUNCHILLY. Abundant float of rounded sandstone pebbles attests to the probable local occurrence of conglomerate or pebble-bearing sandstone at this level. The basal sandstone has a lower, lithic-rich sandstone interval that is medium bedded, grainsize-laminated and tabular cross-bedded. This is interbedded with siltstone and fine sandstone with desiccation features. The lithic and mica content of the lowermost sandstone increases upward in association with dark, heavy mineral-laminated sandstone.

The upper lithofacies of the Kuerschner Member is typically of well sorted, cream to tan quartz arenite that has well rounded grains, mostly thin to medium beds, well developed grainsize laminations and a typical sugary weathering texture. This sandstone tends to gradually fine and thin upward and is typically much better sorted and compositionally more mature than that of the lower lithofacies. Quartz granules and pebbles are rare. Bidirectional tabular or planar cross-bedding is common throughout and most bed sets display a good lateral persistence. Ripple marks are also typically well developed, and reactivation surfaces are locally recognisable (eg MV025052), indicating a high energy environment.

Finer sandstone and minor green-grey or red-brown mudstone occur near the top of the Kuerschner Member (Figure 4). These are particularly well exposed in MUCKATY at LV380076 where several fining- and thinning-upward cycles are evident in a creek section. Current ripple marks are abundant, as are desiccation features and intraformational tabular shale clasts. The uppermost interval of the Kuerschner Member commonly forms a series of benched sandstone ridges separated by narrow, recessive finer intervals.

The contact between the two sandstone lithofacies of the Kuerschner Member is transitional (eg LV055304). The lowermost quartz arenites of the upper sandstone lithofacies are thinly bedded and flaggy in outcrop. The lower sandstone lithofacies has darker weathering characteristics, darker brown airphoto tones and a more rounded, dissected topography than the markedly benched quartz arenites of the upper lithofacies. These features enable the two lithofacies to be readily differentiated.

Mitty Member (Ttmn)
The Mitty Member (new name, see Appendix) generally forms a wide dissected valley between the upstanding Kuerschner Member and the overlying, ridge-forming Short Range Sandstone. It is usually poorly exposed although some intervals form discontinuous, low, rounded and undulating strike ridges of intensely silicified or highly leached outcrop. The most intensely silicified exposures typically protrude above the topographic height of undifferentiated Cretaceous valley fill, and in places have been previously mapped as Cretaceous units in both HELEN SPRINGS and TENNANT CREEK. Conversely, the most leached outcrops of the Mitty Member tend to occur below this topographic level.

The type section for the lower lithofacies of the Mitty Member contains a cyclic succession of thinly to medium bedded sandstone, laminated mudstone and green and blue-grey chert (silicified cryptomicrobial mat), and domical stromatolites. This mixed siliciclastic-carbonate lithofacies occupies an approximately 700 m thick stratigraphic interval from LV964054 to LV967905, and is probably much more areally extensive and continuous than apparent in outcrop. The interval corresponds to the ~500 m thick recessive siltstone/carbonate lithofacies mapped in FLYNN by Donnellan et al (1995).

Sandstone in the lower part of Mitty Member is typically cream or white and well sorted. It has planar or tabular cross-
bedding and is in places intensely ripple marked. Trough cross-bedding is not common. The sandstone intervals are mostly upstanding and are cyclically associated with recessive intervals of mudstone and carbonate rocks that are less common in outcrop. Minor, laterally discontinuous, lenticular conglomerate units are also present in the sandstone intervals. Sandstone often has desiccation features and abundant intraformational tabular mudstone clasts. Halite pseudomorphs are common but tend to be restricted to certain stratigraphic horizons (eg LV894219 and LV992052) and nodular voids, possibly after anhydrite, also occur.

Stromatolitic carbonate rocks, now totally silicified and dark blue-grey in colour, are well exposed in the vicinity of MV039089. At MV040089, stromatolite domes 0.5 m in diameter and height together form bioherms about 3-4 m in diameter. These bioherms are associated with coarse to granular sandstone, which has abundant, tabular weathered-out shale clasts. Elsewhere in this area (eg MV041086) are silicified, grey-black domical stromatolites about 10 m in diameter. A stromatolitic aggregation or bioherm structure about 100 m in diameter is preserved at MV030080. It is likely that these stromatolites sustained rapid growth rates to avoid being buried by clastic material. Ribbon chert, possibly replacing cryptomicrobial mats, is also well developed throughout this area. The stratigraphic relationships of this carbonate dominated interval are equivocal. However, it is interpreted as a local variant of the mixed siliciclastic-carbonate lithofacies, as it occupies essentially the same stratigraphic level elsewhere in Flynn. Comparable stromatolitic units and associations are found in the Carruthers Formation (Namerinni Group) to the north in HELEN SPRINGS.

Nodular chert (cauliflower chert) is well developed locally at LV968049 in close association with a probable stromatolitic bioherm about 100 m in diameter. In this area, silicified stromatolitic aggregations form individual low relief hills surrounded by more recessive sandstone and siltstone. Nodular chert and voids after probable evaporite minerals are also well preserved at LV956150. They are associated with a cyclic succession of sandstone, siltstone, ribbon chert and intensely silicified conical and domical stromatolites that extends to the contact with the unconformably overlying Gleeson Formation (Renner Group) at LV965162. Stromatolites in this interval range from isolated 4-5 cm high cones to 10-12 cm high domes.
that form aggregations. Locally, conical forms are found preserved between domical stromatolites. This cyclic interval of sediment is correlated with that described above.

Laterally discontinuous, 10-50 cm thick layers of white to grey enterolithic nodular chert up to tens of meters in length are notably common between LV935175 and LV895195. They are typically associated with laminated to thinly bedded dolomitic mudstone, cryptomicrobial boundstone and stromatolites, and minor fine sandstone. Smaller, lower relief and bulbous stromatolitic bioherms tend to occur in this interval (eg LV628292). A distinctive quartzic dolostone is found in the vicinity of Kuerschner Creek (eg MV055225) and is correlated with similar rocks at MU054929 in FLYNN. This unit contains ooids at the Kuerschner Creek locality.

The upper lithofacies of the Mitty Member is predominantly of thinly bedded siliciclastic units. These transitionally overlie the lower lithofacies and may in part be a lateral facies equivalent. A nearly complete section through the upper lithofacies is located between LV948094 and LV925073. The main rock types are thinly to medium bedded, parallel- and cross-laminated, fine to medium sandstone and micaceous mudstone. These rocks in places exhibit excellent parting lineations, current lineations and tool marks. The sandstone is locally rich in lithoclasts, probably from intraformational sources, and also carries distinct rip-up clasts and weathered-out shale clasts. Sandstone composition varies from quartz arenite to lithic arenite and most contain abundant detrital mica. Mudstone may be fissile and is purple to cream or white when weathered, whereas sandstone tends to be a distinct orange to reddish-brown or cream to green-grey colour.

Sandstone of the upper lithofacies typically has abundant ripple marks including current, oscillation and interference ripples. Some units are normally graded intraformational conglomerates with coarse to granular sandstone bases that contain tabular mudstone clasts. These units are mostly thinly to medium bedded and generally seem to be associated with intervals of sandstone that contain abundant intercalated mudstone units and desiccation features. Halite pseudomorphs and nodular chert are common in these intervals but are not restricted to them.

Ribbon cherts are sometimes associated with the upper lithofacies of the Mitty Member (eg LV983908) and are interpreted as having replaced cryptomicrobial mats. This suggests that cryptomicrobial dololaminite probably remains a component throughout the Mitty Member and that the distinction between the lower and upper lithofacies is essentially one of relative proportions of siliciclastic versus biogenic material (microbial mat and stromatolitic carbonate). The relative proportions of these facies appear to vary from place to place suggesting a depositional environment containing local shoals and banks.

The Mitty Member is similar to other lithostratigraphic units in HELEN SPRINGS, particularly the Attack Creek and Carmilly Formations (Tomkinson Creek Group), and Carruthers and Shillinglaw Formations (Namerinni Group), and can be difficult to differentiate. This is particularly so in southeastern HELEN to the northeast and east of Ladabah Bore where outcrops of Morphett Creek Formation and probable Carruthers Formation are in close proximity. In the absence of diagnostic features, intensely weathered rocks portrayed on HELEN SPRINGS as probable Carruthers Formation to the northeast of Ladabah Bore might be part of the Mitty Member of the Morphett Creek Formation. In this case, it is also possible that rocks mapped as Powell Formation might be Short Range Sandstone.

Short Range Sandstone (Ets)

The Short Range Sandstone in southern HELEN SPRINGS usually outcrops in bevelled strike ridges dissected by crosscutting creeks that expose almost continuous stratigraphic sections. Outcrops on ridgetops tend to be intensely silicified or are often covered by ferruginous sandy soils and poorly exposed. The Short Range Sandstone was named by Mendum and Tonkin (1976), defined by Mendum et al (1978) and subdivided by Donnellan et al (1995). The lower and upper sandstone lithofacies of the Short Range Sandstone as defined by Donnellan et al continue into HELEN SPRINGS, but the boundary between them is only locally recognisable and differentiation is not made on the map face.

A thin sandstone unit at the base of the formation in FLYNN that is laterally persistent and much thicker in HELEN SPRINGS is now mapped as the Deagan Member (see Appendix). The remainder of the former lower sandstone lithofacies is now referred to as the middle sandstone lithofacies. As described in FLYNN (Donnellan et al 1995), the Short Range Sandstone is predominantly white, well sorted, fine to coarse, thinly to very thickly bedded quartz arenite. A unique feature of the formation is the presence of minor (<2%) well rounded red chert grains.

Deagan Member sandstone tends to be less texturally and compositionally mature than that of the middle and upper sandstone lithofacies. This corresponds to increased sorting, grain roundness and sphericity upward throughout the Short Range Sandstone. Dispersed, rounded granules and pebbles of quartz and cream to pinkish sandstone occur throughout the formation except in the uppermost units.

Monocrystalline quartz is the principal constituent of Short Range Sandstone rocks. Most quartz grains are relatively clear and undulose extinction is minor, but some grains exhibit polygonal recrystallised domains and others have strain lamellae or a sutured recrystallised tectonic fabric. The Deagan Member has rare, euhedral, embayed quartz grains within recrystallised quartzofeldspathic matrix. Minor amounts (<~2%) of similar quartzofeldspathic grains are present throughout the remainder of the formation and suggest a contribution from a felsic volcanic provenance. Haematitic chert grains, which are characteristic of this formation, are completely recrystallised and are of unknown origin. Trace amounts of well rounded tourmaline, rounded elongate grains of zircon and detrital white mica are present throughout the unit.

Near Gap Bore in BRUNCHILLY, a 750 m reference section is exposed between MV032293 and MV053298. The best exposures of the base and top of this section are along strike to the northwest near MV003330 and MV028317, respectively. The Deagan Member occupies the lower 150 m interval and is overlain by about 150 m of middle sandstone lithofacies from MV031299 to MV036297 and by about 450 m of upper sandstone lithofacies thereafter.

The thickness of the formation in HELEN SPRINGS ranges from a minimum of about 650-700 m in the
Whittington Ranges near Mitty Waterhole in western MUCKATY to a maximum of almost 850 m in central MUCKATY. The Deagan Member represents the lowermost 80-120 m in both of these regions.

In TENNANT CREEK, Donnellan *et al* (1995) reported a total thickness of 1025 m in the type section. This appears to be the maximum thickness of Short Range Sandstone in the Ashburton province although a comparable thickness is estimated in southeastern SOUTH LAKE WOODS.

**Deagan Member (P Ltsd)**

The Deagan Member is an interval of thinly to thickly bedded medium to coarse sandstone that is overlain by a recessive interval of finer and more thinly bedded sedimentary rocks. This Member forms a prominent paired strike ridge and valley at the base of the Short Range Sandstone ([Figure 5](#)), and is readily identifiable on aerial photographs in HELEN SPRINGS.

Upstanding sandstone at the base of the Deagan Member is composed of grainsize-laminated quartz arenite and sublitharenite. It is characteristically bidirectionally cross-stratified and bed sets are nearly planar, although some beds and sets lens out and are channel-like. Large-scale, medium to very thick beds and trough cross-beds are common at or near the base in some areas (eg LV925061 and MV003331). Locally, basal sandstones contain angular to well rounded sedimentary pebble clasts that appear to have been derived from the underlying Morphett Creek Formation (eg LV925061).

Some sandstone units in this interval also show reactivation surfaces, overturned cross-beds, convolute bedding and dewatering features indicative of energetic and rapid sedimentation (eg MV003331 and LV923168). Thinly to medium bedded sandstone, which is variably and intensely ripple marked or planar laminated, is commonly observed in a cyclic association above these thicker bedded sandstones. Desiccation features are occasionally present in this interval.

The contact between white, thickly bedded, clean sandstone of the Deagan Member and underlying orange-brown, thinly to medium bedded sandstone and mudstone of the Morphett Creek Formation appears to be concordant. In most localities in HELEN SPRINGS, the contact to covered by scree. Where exposed, it is sharp, and the presence of brown sandstone clasts in the overlying white sandstone is indicative of erosion, at least locally. In some regions, as in TENNANT CREEK, the contact appears to be transitional over a short interval.

The basal sandstone fines and thins upward into a recessive interval of very thinly to medium bedded, fine quartz arenite and siltstone. Thinning- and fining-upward cycles 2-5 m thick are typical, together with sandstone that is often extensively and variably ripple marked and parallel- or cross-laminated (eg LV926058). Typically, the uppermost fine sandstone contains moulds after weathered-out shale clasts, desiccation features and layers rich in halite pseudomorphs (both hopper and cubic forms up to 2 cm across). This sandstone is locally interbedded with commonly micaceous (eg LV931176) siltstone and green-grey to red-brown to maroon shale.

**Middle and upper sandstone lithofacies**

The Deagan Member is sharply overlain by about 20-50 m of cyclic, medium to very thickly bedded, trough or tabular cross-bedded sandstone in the Whittington Ranges (eg near LV923169). Similar strata occur at the base of the middle sandstone lithofacies in the reference section near Gap Bore. In both regions, the sandstone contains tabular shale clasts up to 4 cm across, as well as subangular to rounded granules and pebbles of vein quartz and pink or cream sandstone. The sandstone is typically well grainsize-laminated and commonly shows reactivation surfaces, overturned cross-bedding and convolute laminations, indicative of energetic and rapid sedimentation. Individual sandstone units often vary in thickness along strike and occasionally pinch out. They also show local erosional relationships and are channel-like, particularly in the northern Whittington Ranges.

The basal sandstone of the middle lithofacies locally erodes into the uppermost Deagan Member (eg LV923169 and LV922094) and a disconformity is therefore evident at this stratigraphic level. The relationship is analogous to that at the base of the Deagan Member and suggests that a stepped transgression is expressed in the Short Range Sandstone.

The remainder of the middle lithofacies sandstone is similar to that of the lower sandstone lithofacies described in *FLYNN* (Donnellan *et al* 1995), which consists of cyclic, thinly...
to medium bedded, fine to coarse quartz arenite. Oscillation and current ripple-marked intervals are common, as are planar, and simple or tabular cross-beds.

The upper sandstone lithofacies is a cyclic, fining- and thinning-upward succession of mainly medium to coarse, thinly to thickly bedded sandstone. The sandstone is often colour laminated (pink, cream and grey) and has large tabular to asymptotic, low angle bidirectional cross-beds. Thiny to medium bedded ripple marked intervals occur throughout this succession and are common near the top. With the exception of the uppermost ~50-100 m of section, discontinuous lenticular beds of pebbly and granular sandstone are present throughout this lithofacies.

The middle lithofacies is interpreted as predominantly shallow water intertidal facies though locally it may be deltaic or even fluvial given the presence of deformed (overturned) cross-bedding (eg Miall 1990). A gradual deepening is envisioned for the upper sandstone lithofacies but intertidal to subtidal conditions still prevailed. Shallow environments were occasionally repeated throughout the deposition of the Short Range Sandstone as interpreted from the cyclic nature of the succession. The uppermost Short Range Sandstone probably represents shallower tidal flats which served as barriers to the superseding, quieter lagoonal settings of the Attack Creek Formation.

**Attack Creek Formation (Rta)**

Exposures of the Attack Creek Formation are generally restricted to carbonate rocks and siltstone in isolated silicified knolls or leached creek embankments. The best outcrops are located in the vicinity of the Bootu manganese mine. Although both the carbonate and siltstone lithofacies of Donnellan *et al* (1995) in FLYNN are recognised in HELEN SPRINGS, the poor quality of outcrop precludes any subdivision.

Mendum and Tonkin (1976) defined the formation in TENNANT CREEK where it is best exposed. Donnellan *et al* (1995) mapped this formation in FLYNN, and subdivided it into a lower, dominantly dolomitic siltstone/calcimudstone unit and an upper sandstone package that is now part of the overlying Bootu Formation (new name, see Appendix). The lower contact with the Short Range Sandstone is conformable and a transitional relationship between sandstone and calcareous siltstone is exposed at MV0288317. This contact appears to be sharp and is usually mapped at the base of a dip slope formed by upstanding Short Range Sandstone.

In HELEN SPRINGS, the Attack Creek Formation is about 330 m thick in the vicinity of the Bootu mine and about 425 m thick in the Whittington Ranges. In FLYNN, Donnellan *et al* (1995) recorded a thickness of 375 m.

Surface alteration of all exposures has been extensive. Carbonate rocks are intensely silicified, particularly in central MUCKATY. Outcrops are dominated by thinly to thickly laminated and, less commonly, massive dolostones and dolomitic intraclast breccias. These are typically green or grey and are predominantly neomorphosed to microsparites and intrasparites. Parallel or wavy laminations are the most common sedimentary feature, which near the top of the formation are interpreted as cryptomorphic laminites. Very thin beds of ripple cross-laminated, fine to very fine sandstone and laminated siliclastic siltstone occur in places within the dolostones. Intraformational conglomerate, rip-up clast breccias and slump breccias commonly form laterally persistent thin beds.

The contact with the overlying Bootu Formation is placed at the base of the first laterally persistent sandstone in an upward dolostone to sandstone transition. In BRUNCHILLY, the boundary is sharp and concordant. To the south of the Bootu manganese mine, the base of a laterally persistent, thinly to thickly bedded, medium to granular sandstone interval (well exposed at LV999361) marks the top of the Attack Creek Formation. This sandstone is up to about 5 m thick and displays a locally erosive base on underlying carbonate rocks. With the exception of outcrops near LV887188, it does not crop out in MUCKATY or FLYNN. The base of the Bootu Formation is represented by thin to medium ripple marked sandstone in FLYNN.

Several thin beds of green friable siltstone occur within the carbonate lithofacies. These were interpreted as possible tuffs, although zircon separated from one of these siltstone intervals in drillcore varied from euhedral, magmatic growth-zoned grains to clear rounded grains that are probably detrital. Despite Pb-loss, all zircons appear to be older than about 1700 Ma and represent a heterogeneous population. Armstrong (1998) quoted an imprecise pooled SHRIMP U-Pb age of 1757 ± 52 Ma for this sample, but has since revised the age to 1752 ± 26 Ma, which is the age of the youngest zircon (pers comm, 1998). This represents the best estimate of the maximum depositional age of this rock.

The Attack Creek Formation was probably deposited in a protected shallow marine environment starved of significant siliclastic input. There is evidence for intertidal settings and the presence of intraclast breccias, pisolithes and oncolites may indicate reworking after periodic exposure and consolidation. The occurrence of intraformational slump breccias and rip-up clast breccias probably indicates occasional more energetic conditions.

**Bootu Formation (Ptb)**

The Bootu Formation is an upstanding unit dominated by a relatively homogeneous succession of sandstone that includes intervals of granular to pebbly sandstone and conglomerate, and minor amounts of siltstone, mudstone and carbonate rocks. The most distinguishing feature of this formation is the apparent homogeneity and extensive thickness of uniformly medium to very thickly bedded sandstone (Figure 6).

The exact thickness of the Bootu Formation is unknown but is inferred to be greater than 1800 m in BRUNCHILLY. An approximately 1350 m thick reference section near Looa Creek includes the majority of the sandstone lithofacies that form the middle to upper parts of this formation. A nearly continuous and complete, though poorly exposed section southeast of Carmilly Waterhole is estimated to be at least 2000 m thick.

Outcrop of Bootu Formation is mainly confined to a faulted, northwest trending synclinal structure about 13 km northeast of Banka Banka homestead, where it forms an extensive low relief plateau. Rock units on this plateau tend to be intensely silicified and are often covered by ferruginous sandy soils. As a result, there is typically only limited exposure.
of the middle to upper parts of the formation. Two smaller regions of outcrop occur in synclinal axes in MUCKATY.

The lowermost 150-250 m of the Bootu Formation is variably exposed and typically forms a series of lower relief strike ridges below the main area of outcrop. The lowermost units form a distinct lower lithofacies and host the abandoned Mucketty manganese mine and other manganese occurrences in HELEN SPRINGS and TENNANT CREEK. This lower lithofacies is a cyclic, mixed siliciclastic-carbonate succession that represents the transition from the underlying, carbonate dominated Attack Creek Formation to the sandstone lithofacies of the Bootu Formation.

The base of the Bootu Formation is placed at the base of the first laterally persistent sandstone in a cyclic, dolostone to sandstone transition. This sandstone is poorly to moderately well sorted, medium to granular and locally pebbly, and is about 5 m thick near LV999361. It ranges from calc-litharenite or sublitharenite to quartz arenite. The sandstone has a sharp discordant and locally erosive contact with underlying carbonate lithofacies of the Attack Creek Formation and is planar, tabular or trough cross-bedded (eg near LV9444557). It also exhibits localised overturned cross-bedding and convolute laminations (eg near LV9455558 and LV9545561). Most sandstone towards the base of the Bootu Formation contains tabular shale clasts and subangular to rounded metasedimentary clasts. The latter are predominantly of sandstone but also include minor amounts of siltstone and carbonate. Graded bedding is sometimes present.

In BRUNCHILLY, a manganese-enriched interval of laminated to thinly bedded siltstone and mudstone occurs just below a laterally persistent sandstone unit, which is about 50 m above the base of the Bootu Formation. The manganese enrichment is at a similar stratigraphic level throughout BRUNCHILLY, MUCKATY and FLYNN and appears to be stratiform. In BRUNCHILLY, manganese stained domical and bulbous stromatolites occur about 3 m above the main Bootu mine manganese mineralisation. Overlying manganese stained, thinly bedded sandstone and siltstone exhibit shallow water ripple marks, desiccation features and halite pseudomorphs (Figure 7).

The upper 100-150 m of the lower lithofacies contains two major coarsening- and thickening-upward sandstone cycles. The sandstone consists mostly of thinly to medium bedded sublitharenite to quartz arenite that has planar, tabular, trough and ripple cross-strata. It also has locally abundant desiccation features and halite pseudomorphs, and rare domical stromatolites in the lower parts. Some siltstone and fine sandstone interbeds exhibit current lineations and tool marks, and the more recessive intervals may be due to a higher mudstone and/or lithic content. The contact with the overlying dominant sandstone lithofacies is placed where bedding becomes medium to thick and units are medium to coarse. This contact is transitional, coincides with the appearance of scattered pebbles and cobbles and approximates the beginning of the upstanding low relief plateau.

The remainder of the formation is dominated by thinly to very thickly bedded, fine to very coarse, moderately to well sorted quartz arenite and sublithic arenite. Although not mapped, it can be differentiated into a middle and upper lithofacies. The middle lithofacies forms the majority of the unit and is at least 1350 m thick in the vicinity of Looa Creek. Minor granular to cobble conglomerate and poorly sorted sublithic arenite are also present in the middle lithofacies. Most conglomerate clasts are of well rounded cream to pinkish quartzite and less common white vein quartz. Ripple marks are present in some intervals throughout and are very common in the upper lithofacies sandstones. Most cross-bedding is bidirectional, simple or tabular and concave upward. Some meter-thick, concave cross-beds with large tabular weathered-out mud clasts that are indicative of rapid sedimentation are present in the middle lithofacies.

In general, most sandstone is finer and more thinly bedded in the upper lithofacies of the Bootu Formation. The finer sandstone is usually interbedded with red-brown mudstone and siltstone and is typically well rippled. Desiccation features are common. The remaining sandstone appears to be a lateral equivalent and consists of planar or tabular cross-bedded, medium-bedded quartz arenite, or medium to thick trough cross-bedded pebbly sublitharenite. The upper lithofacies is about 100-200 m thick.

The contact with the overlying Carmilly Formation is gradational. Sandstone units fine and thin upward to be sharply overlain by laminated mudstone and dolostone, which contain thin intervals of thinly bedded sandstone in their lower part.

Typically, sandstone of the Bootu Formation consists of >90% monocrystalline quartz, <10% chert and <5% lithic.

Figure 6 Medium to very thickly bedded sandstone from creek section of Bootu Formation in BRUNCHILLY (LV966509). Exposure has approximately 8-10 m of relief.
grains. Most quartz grains are milky. Some quartz shows deformation lamellae or recrystallised domains indicating a metamorphic provenance. Other quartz grains contain green, brown and blue-grey tourmaline, muscovite or fluid inclusions that are indicative of a high-level igneous or hydrothermal origin (Folk 1974, Morton 1991). Rounded to fractured euhedral tourmaline and zircon are common accessory heavy minerals.

While there is obvious supergene enrichment of manganese in the lower Bootu Formation (Jones 1955), the occurrence and close association of manganese and graphitic units is noteworthy and may be related to the shallow water saline depositional environments of the Bootu Formation. Hypersaline brine pools can result in decaying organic matter and reducing conditions. This may have led to primary manganese precipitation. Alternatively, manganese-enriched, oxidised basin fluids may have migrated along Bootu Formation sandstone units and reacted with reduced units (graphitic shales).

Carmilly Formation (Pty)

The Carmilly Formation (new name; see Appendix) is the uppermost unit of the Tomkinson Creek Group, and is a recessive, mixed siliciclastic and carbonate sequence that conformably overlies the Bootu Formation. It is approximately 750 m thick in northwestern Brunchilly near the headwaters of Carmilly Creek, after which it is named, but the exact thickness of the formation in this region is uncertain due to fault complications. The preserved stratigraphic level at the top of the unit also varies due to an angular unconformity between the Carmilly Formation and the overlying Jeromah Formation. The youngest stratigraphic units of the Carmilly Formation appear to be in the southern parts of the type area. Probable Carmilly Formation also occurs in Helen.

Three distinct lithofacies are identified in the type area. The lower lithofacies (Lty1) is a recessive, mixed siliciclastic-carbonate interval that is transitional with the overlying middle lithofacies (Lty2). The middle lithofacies is a 70-150 m thick upstanding sandstone interval, which typically forms a prominent strike ridge in the middle of the formation near LV953475. This is overlain by another recessive, mixed siliciclastic-carbonate interval (Lty3), which is distinct from the lower lithofacies.

The Carmilly Formation consists of cream to maroon siliciclastic mudstone, greenish grey and cream to white or pinkish-tan, predominantly fine to medium sandstone, and variably silicified dolostone and chert. The carbonate lithofacies is of thinly bedded dolostone that ranges from predominantly laminated to massive. It typically forms distinct cryptomicrobial dolostone intervals, which contain biohermal stromatolites and wavy- or parallel-laminated boundstone and dololaminites. These are locally associated with evaporite pseudomorph-bearing sandstone units and chertified evaporite ‘beds’.

The base of the Carmilly Formation is exposed along several kilometers strike length near LV970474. Basal units are typically of recessive chert, laminated dolostone or cream to maroon mudstone.

The lower lithofacies consists of thinly bedded and laminated silicified dolostone (chert) and cream to green-grey or maroon mudstone and sandstone. Chert and fine to medium sandstone intervals form small, low relief rises or rounded strike ridges whereas the siltstone/mudstone-dominated intervals are more recessive. Intervals of chert, dololaminite, and domical and bulbous stromatolites (Figure 8a) are interbedded with minor, well sorted, current and oscillation ripple marked, very fine to medium sandstone in the lower parts (eg near LV958497). These units pass upward into a more siliciclastic succession comprising intercalated planar bedded, parallel- and cross-laminated sandstone and mudstone. This interval is often prolifically ripple marked and desiccated. Most sandstone units at this level (eg LV956476) have a distinctive grey appearance when weathered.

The contact between the lower and middle lithofacies of the Carmilly Formation occurs near LV947489. The relationship is transitional and the boundary is placed at the base of a relatively homogeneous succession of well sorted, thinly to medium bedded quartz arenite, which is prolifically ripple marked.

The middle lithofacies of the Carmilly Formation is mostly composed of cream to white or pinkish-tan sandstone. This
Figure 8  Carmilly Formation in Brunichly;
(a) low relief domical stromatolite from lower lithofacies at LV992381;
(b) rippled, well sorted, fine to medium sandstone from middle lithofacies at LV953472 (note different ripple orientations);
(c) nodular chert (anhydrite?)-rich mudstone interval from upper lithofacies near LV957461.
sandstone consists mostly of intensely ripple marked, well sorted, thinly to medium bedded, fine to medium quartz arenite (Figure 8b). Current and interference ripple marks are common throughout. Several slightly less resistant intervals of finer and more thinly bedded quartz arenite occur in this lithofacies. Desiccation features are abundant in some horizons, as are intraformational tabular shale clasts. Evaporite pseudomorphs (mostly after halite) are present in some intervals, particularly near the top. Voids after probable nodular anhydrite pseudomorphs occur in the uppermost part near LV947489. This upstanding sandstone interval displays gradational contacts with adjacent units and separates an underlying predominantly fine siliciclastic succession from an overlying more dolomitic (microbial/evaporitic) succession.

Upstanding sandstone that forms the lower exposed part of the Burke Creek Dome in central HELEN is very similar to this member and has been mapped as probable Carmilly Formation middle lithofacies. Rocks typical of the upper and lower lithofacies of the Carmilly Formation are generally not exposed in this region. However, a thin, poorly exposed interval of recessive fine sandstone and mudstone occurs above the probable middle lithofacies sandstone, but below trough cross-bedded and pebbly sandstone of the Jeromah Formation in the Burke Creek Dome. These strata may be referable to the upper lithofacies.

The upper lithofacies is dominated by cream to buff-weathering, laminated to thinly bedded mudstone, calcareous siltstone and minor dolostone (eg LV946486). Thin layers of nodular chert (Figure 8c), enterolithic chert (anhydrite) and pseudomorphs after halite and probable gypsum (now replaced by silica) are also present. The stromatolitic bioherms and boundstones that occur in the upper lithofacies tend to show a cyclic relationship with ripple cross-laminated, evaporite pseudomorph-bearing sandstone and planar laminated mudstone. These bioherms tend to be of lower relief and are more domical in character (eg LV946488) than those in the lower lithofacies, suggesting slightly more energetic shallow environments.

Carmilly Formation sediments conformably overlie shallow marine to deltaic or fluvial facies of the uppermost Bootu Formation and represent a gradual, though in part cyclic, shift to lower energy, protected lagoonal and marginal marine settings. Relatively energetic intertidal settings are common throughout. Several slightly less resistant intervals of finer and more thinly bedded quartz arenite are common.

The contact with the overlying Jeromah Formation is sharp and erosional (eg LV940521, LV942528 and LV947497). A subtle regional angular relationship is evident between these formations through the midwestern BRUNCHILLY and there is typically a sudden change in lithology and bedding characteristics, although locally, this is not obvious and the contact can be difficult to distinguish. The units above the unconformity are typically medium to thick, tabular or trough cross-bedded sandstones, pebbly sandstones and conglomerate.

**Namerinni Group**

The newly defined Namerinni Group is an alternating sandstone, siltstone and carbonate succession with a maximum total thickness of about 2800 m in HELEN SPRINGS. This Group is named after Namerinni Waterhole and is divided into, in ascending order, the Jeromah, Carruthers, Shillinglaw and Willieray Formations (Table 2). The Mesoproterozoic Renner Group unconformably overlies all formations of the Namerinni Group.

Rocks now mapped as Namerinni Group were formerly included in the undifferentiated Tomkinson Creek beds of Randal et al (1966) and Randal and Brown (1969). A subtle angular unconformity with the underlying Tomkinson Creek Group is now recognised in HELEN SPRINGS. This unconformable relationship is best expressed in the eastern succession where the Namerinni Group is underlain by various units of the Carmilly Formation. Namerinni Group rocks are in general finer and the sandstones are less mature and more lithoclast-rich than those in the upper Tomkinson Creek Group.

The eastern and western successions of the Namerinni Group outcrop in two main regions of the Ashburton Ranges in central western HELEN SPRINGS (Figure 2). These are geographically separated by the relatively down-faulted Muckaty-Renner Block. The Muckaty-Renner Block contains mostly Renner Group rocks, but there are at least two small regions of Namerinni Group against its faulted margins.

The largest area of exposed Namerinni Group outcrop is the succession on the western side of the Muckaty-Renner Block in central and southern HELEN and northern MUCKATY. In this region, the Namerinni Group is typically more flat lying, its stratigraphy is generally less complicated by faults and access is generally easier. Two small inliers of upper Namerinni Group are exposed north of the main area of outcrop in HELEN.

The other major area of exposed Namerinni Group occurs to the east of the Muckaty-Renner Block in northeastern MUCKATY and northwestern BRUNCHILLY. These outcrops form an elongate linear belt that contains typically moderately dipping strata. The stratigraphy of the eastern succession is complicated by numerous subvertical faults at a low angle to bedding. There are subtle differences between some lithofacies of the eastern and western successions.

**Jeromah Formation (Emj)**

The newly defined Jeromah Formation (see Appendix) is at the base of the Namerinni Group and is best exposed in the eastern succession near the headwaters of Jeromah Creek, after which it is named. It also outcrops in two separate localities in the western succession. Typically, exposures form variably upstanding and sometimes bevelled strike ridges that are often more dissected and less prominent in the middle and uppermost parts of the formation. Intervals that are predominantly of sandstone are upstanding relative to more recessive intervals of interbedded sandstone, siltstone and mudstone. In the eastern succession, the thickness of the formation varies from about 350 to 700 m, with the thicker strata in the south.
Table 2  Stratigraphic units of the Namerini Group in HELEN SPRINGS.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Lithology</th>
<th>Stratigraphic relationships</th>
<th>Depositional environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Willieray</td>
<td>Thin to medium bedded sandstone and siltstone; minor pebbly sandstone,</td>
<td>Transitional and conformable contact with underlying Shillinglaw Formation. Unconformably</td>
<td>Continental red beds to shallow</td>
</tr>
<tr>
<td>Formation</td>
<td>conglomerate and mudstone; minor quartzic dolostone and dolostone.</td>
<td>overlain by Gleeson Formation and undifferentiated lower Cretaceous rocks. Thickest and</td>
<td>marine.</td>
</tr>
<tr>
<td>~70-400+ m</td>
<td></td>
<td>uppermost units are exposed in the eastern succession.</td>
<td></td>
</tr>
<tr>
<td>Shillinglaw</td>
<td>Very thin to medium bedded dolomitic mudstone and dolostone; very thin to</td>
<td>Transitional and conformable contact with underlying Carruthers Formation. Individual</td>
<td>Peritidal with aeolian</td>
</tr>
<tr>
<td>Formation</td>
<td>medium bedded sandstone and siltstone; quartzic dolostone, dolostone;</td>
<td>units show complex facies associations in the western succession. Unconformably overlain by</td>
<td>contribution, fluvial.</td>
</tr>
<tr>
<td>~500-650 m</td>
<td>stromatolitic bioherms, evaporite pseudomorphs, angular solution breccia;</td>
<td>Gleeson Formation and undifferentiated lower Cretaceous rocks.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>minor conglomerate.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carruthers</td>
<td>Thin to medium bedded sandstone, siltstone, quartzitic dolostone,</td>
<td>Transitional and conformable contact with underlying Jeromah Formation. Upper lithofacies</td>
<td>Peritidal, hypersaline to</td>
</tr>
<tr>
<td>Formation</td>
<td>dolostone; stromatolitic bioherms, cryptomicrobial boundstone, evaporite</td>
<td>is notably thicker in eastern succession. Unconformably overlain by Gleeson</td>
<td>intertidal.</td>
</tr>
<tr>
<td>~800-1100 m</td>
<td>pseudomorphs, nodular and enterolithic chert.</td>
<td>Formation and undifferentiated lower Cretaceous rocks.</td>
<td></td>
</tr>
<tr>
<td>Jeromah</td>
<td>Thin to thickly bedded sandstone, pebbly sandstone, thinly bedded siltstone and mudstone; minor conglomerate, halite pseudomorphs.</td>
<td>Overlies Carmilly Formation with angular unconformity. Comprises two upward fining and</td>
<td>Fluvial to deltaic and shallow</td>
</tr>
<tr>
<td>Formation</td>
<td></td>
<td>thinning successions with local disconformity between them. Thicker in eastern</td>
<td>marine, locally hypersaline.</td>
</tr>
<tr>
<td>~350-700 m</td>
<td></td>
<td>succession.</td>
<td></td>
</tr>
</tbody>
</table>

The type section is located in the northern part of the eastern succession from LV940526 to LV934526, where two fining-upward cycles are clearly distinguished. A north-northwesterly trending fault with only minor apparent displacement occurs near the middle of this section and precludes an accurate thickness measurement. A second, approximately 450 m thick reference section that has similar stratigraphic relationships occurs in the western succession from LV645652 to LV644642. This and all other sections through this formation are faulted.

The base of the Jeromah Formation is located along strike to the south of the type section, and is part way up a slope near LV940521 and also near LV947498. The contact is sharp and erosive in both localities but the angular relationship is subtle and difficult to determine in outcrop. The Jeromah Formation clearly overlies different units of the Carmilly Formation (Tomkinson Creek Group) along the mapped contact.

The topmost units of the Jeromah Formation are obscured by scree in the type section and are best exposed about 2 km along strike near LV932502. Tabular to blocky rubble of the Jeromah Formation contrasts with more competent and silicified outcrop of the overlying more thinly bedded Carruthers Formation.

The Jeromah Formation consists primarily of red-brown to orange-tan or creamy-grey to red-purple sandstone of sublitharenite, quartz arenite and rarely litharenite composition. The sandstone is typically poorly to moderately well sorted and is grain-size-laminated. Bedding is generally of medium thickness but there are intervals in which it varies from medium to very thick and from very thin to thin. Thicker beds usually contain scattered pebble clasts and have associated granule and pebble lags and pebble to cobble conglomerates that form gross fining-upward packages.

Conglomerate clasts are granule to cobble size, polymictic, predominantly subrounded and vary from clast to matrix supported. Clasts are mostly of pinkish or white sandstone or white vein quartz. Sandstone clasts tend to dominate in the eastern succession whereas white vein quartz clasts are more abundant in the western succession. Finer, angular chertified dolostone and mudstone clasts up to pebble size occur throughout this formation but are coarsest and most common in the lower parts of the eastern succession. Pebbles of stromatolitic carbonate are present in the eastern succession and were probably derived from the underlying Carmilly Formation.

Bidirectional, low to high angle tabular or trough cross-beds are common in Jeromah Formation sandstones. Bedding is generally planar and laterally persistent but lensing is evident in some units. Medium to thickly bedded sandstones are usually normally graded and have coarse to granular bases, locally abundant reactivation surfaces and overturned cross-bedding. Ripple marks are prolific in some intervals, and range from forms with low amplitudes and wavelengths to high energy duneforms (megaripples). A characteristic feature of sandstone in the lower parts of the formation is the presence of angular to subangular white or black chert clasts. Intraformational tabular mudstone clasts or moulds occur throughout the formation but are most common in the upper part. Variably micaceous fine sandstone and siltstone also occur and are sometimes interbedded with subordinate mudstone.

In the type section, the lower fining-upward cycle commences with basal pebble and cobble horizons. These are interbedded with, and overlain by medium to very thickly bedded, tabular or trough cross-bedded, medium sandstone to granule conglomerate. Dewatering structures and convolute laminations are sometimes present in this interval, as are rare...
The Carruthers Formation comprises interbedded dolostone (including silicified dolostone or chert, dolomitic mudstone, quartzic dolostone, and laminated stromatolithic boundstone and bafflestone), shale, mudstone and sandstone. Evaporite pseudomorphs are common and include: nodular chert and moulds after anhydrite; hopper and cube casts and moulds after halite; and rare bladed or disc shapes probably after gypsum. This formation is also characterised by abundant stromatolites with diverse geometries, intense surface silification of carbonate rocks, and a distinct upstanding sandstone interval in the uppermost part.

The Carruthers Formation displays a conformable and transitional relationship with the underlying Jeromah Formation. It is divided into three informal lithofacies in HELEN SPRINGS. The lower recessive part comprises two consecutive and generally distinct, mixed siliciclastic-carbonate successions that are referred to the lower and middle lithofacies. These are overlain by a ridge-forming, predominantly siliciclastic upper lithofacies. The combined thickness of the lower and middle lithofacies is greatest in the western succession whereas the upper lithofacies is much thicker in the eastern succession.

Poor exposures typically prevent the mapping of boundaries between lithofacies in the eastern succession. Although these units are recognisable and are comparable to their equivalents in the western succession, subtle lithological variations are apparent. Firstly, the lower and middle lithofacies in the eastern succession locally contain more mudstone and show minor differences in the character of their stromatolitic units. Secondly, sandstone intervals of the middle lithofacies are thinner and less abundant in the eastern succession. Finally, the upper lithofacies is much thicker, slightly coarser, more thickly bedded, and has fewer evaporitic pseudomorphs in the eastern succession.

The Carruthers Formation outcrops as recessive, low relief rises punctuated by upstanding strike ridges in the lower and middle lithofacies. Carbonate rocks typically outcrop as low relief, undulose rubbly rises, characterised by subtle benches of silicified, stromatolitic dolostone cyclically interbedded with sandstone. Stromatolitic boundstone and bafflestone commonly form discontinuous outliers of higher relief. Siltstone and mudstone intervals are typically recessive.

Sandstone is predominantly sublitharenite or quartz arenite and mostly contains poorly to moderately well sorted, subangular to rounded quartz grains with subordinate chert. Accessory minerals include muscovite, angular, euhedral to well rounded blue-green tourmaline and zircon. In places, haematite overgrowths enclose grains and authigenic quartz is common in at least two generations of overgrowth. Haematite also occurs as a cement in laminations, usually supporting primary grains. Some sandstones contain grains of low to moderate sphericities indicating that they are texturally submature despite being relatively quartz-rich. This is supported by the

Overturned cross-beds. South of the type section, the lowermost units vary from medium to very coarse sublitharenite to thinly bedded, ripple marked quartz arenite. These grade upward into tabular or trough cross-bedded sandstones which are more typical of the basal Jeromah Formation.

In the type section, the lower units grade upward into a recessive succession of thinly bedded, red-brown to tan fine sandstone and subordinate mudstone. This interval is variably micaceous and commonly contains intensely ripple marked and planar- or cross-laminated horizons. Halite pseudomorphs and desiccation features occur locally throughout this recessive interval. These units are interpreted as lateral facies variants of a thinly bedded, fine to medium, moderately well sorted sandstone interval that occurs elsewhere at this stratigraphic level in HELEN SPRINGS.

The contact between the lower and upper fining-upward cycles may be sharp and locally erosive (eg LV937520) but usually the relationship is transitional. The two cycles are similar, although the upper cycle is typically finer and more compositionally mature. It is also characterised by more numerous, tabular weathered-out mudstone clasts and desiccation features, and by abundant ripple marks and small halite pseudomorphs, particularly in the upper beds.

Most Jeromah Formation sandstone is sublitharenite or quartz arenite and consists of poorly to well sorted, subangular to rounded quartz grains with subordinate chert, sedimentary and rare metamorphic lithoclasts. Monocrystalline quartz of low to high sphericity is dominant. Some quartz grains are recrystallised and either contain deformation lamellae, microlites (muscovite and tourmaline) and vacuoles, or display undulose extinction. Sedimentary clasts are mainly of sandstone and siltstone (rarely veined by quartz) and chert. Accessory minerals include muscovite, angular, euhedral to well rounded blue-green tourmaline and zircon. In places, haematite overgrowths enclose grains and authigenic quartz is common in at least two generations of overgrowth. Haematite also occurs as a cement in laminations, usually supporting primary grains. Other cement or matrix components include sericite, clay (kaolinite?) and fine-grained arenaceous material.

The favoured depositional setting for the Jeromah Formation is a marginal shallow marine environment, possibly a deltaic setting where channelised units with high sedimentation rates and intertidal to supratidal units are intimately associated. A fluvial setting is possible for some lower parts of the formation.

The angular unconformity at the base of this formation may correlate with the unconformity between the Tawallah and McArthur Groups in the southern McArthur Basin. This suggests that the Jeromah Formation has possible equivalents at the base of the McArthur Group.

Carruthers Formation (Pmc)

The newly defined Carruthers Formation (see Appendix) is named after Carruthers Creek in HELEN. Poor exposure, especially in the lower parts of the formation prevents the measurement of detailed sections. The formation has a minimum thickness of approximately 1100 m in the western succession where it is generally better exposed and is about 800-1000 m thick in the eastern succession.
presence of a minor matrix component, typically <5% (up to about 10%) and by the interbedded association of sandstone and mudstone.

Finer, evaporite pseudomorph-bearing lithologies are extensively chertified and contain abundant dissolution textures. Some are layered, with discontinuous laminations, and consist of mixed fine to medium sandstone, quartzic dolostone and dolomitic mudstone. These layers contain quartz grains (mostly monocrystalline), muscovite and chaledony infilling voids possibly after evaporite minerals, and dolomite crystals replaced by quartz. They are farruginous and often contain minor limonite and clay minerals. Intraformational siltstone and boundstone clasts (possible oncoktes or infillings of desiccation cracks) also occur, but are rare.

Sedimentary and diagenetic structures in the Carruthers Formation indicate a marginal marine setting with occasional emergence, possibly in a coastal to continental supratidal sabkha environment, although alternative environments such as intertidal lagoonal or lacustrine settings are plausible.

The lower lithofacies generally lacks coarse elastic detritus and appears to have been deposited in a protected, very shallow intertidal to supratidal setting. The middle lithofacies has increased proportions of higher energy well sorted sandstone compared to the lower lithofacies. This probably indicates a greater marine influence during deposition, and the sandstone may represent sandbars or channels migrating across more stable, relatively low energy, peritidal carbonate deposits. Both of these lithofacies contain intervals of intercalated sandstone and mudstone that have sedimentary structures indicative of shallow marine mudflats and tidal rhythmites. The depositional environment for the upper lithofacies is locally variable. The lower intervals were probably deposited in a relatively protected, shallow marine environment, whereas the upper intervals are probably representative of higher energy, dominantly intertidal and less commonly supratidal conditions.

Lower lithofacies
The lower lithofacies is best exposed at the type locality on the southern flank of Burke Creek Dome (LV636402) where the minimum thickness is estimated to be 50-100 m. Ward (1988c) suggested that this interval may exceed 350 m a few kilometres to the south. In general, the contact with the underlying Jeromah Formation is identified by a change in relief at the base of interbedded, very thinly to thinly bedded sandstone, siltstone and mudstone. At the eastern succession reference locality (LV932502), the lower lithofacies is about 50 m thick and the transitional contact with the Jeromah Formation is placed at the base of the first maroon mudstone interval.

The basal units of the lower lithofacies consist of silified, interbedded, pinkish-tan to red-purple sandstone and mudstone. Minor cream to maroon or black mudstone and chertified dolomitic mudstone are locally present. The sandstone is mostly quartz arenite or sublitharenite and has planar to undulose tabular bedding that ranges in thickness from very thin to thin (rarely medium). Parallel, streaky, flaser and wavy or lenticular laminations occur throughout this interbedded interval and rip-up intraclasts and clast impressions occur in sandstone beds. Other primary bedding structures include low angle cross-stratification, faint planar laminations, ripple cross-laminations, interference and asymmetric current ripples (some with symmetrical rounded crests) and rare desiccation cracks. Halite pseudomorphs are locally common.

Transitionally overlying the basal siliciclastic units is a cyclic succession of laminated to thinly bedded dolostone (commonly stromatolitic), dolomitic mudstone and chert with minor mudstone, sandstone and quartzite dolostone. Intense silification and leaching have destroyed many fabrics and primary sedimentary structures in the carbonate rocks.

Nodular chert is common and characteristic of this interval and massive enterolithic chert (probably after gypsum/anhydrite) is present in some intervals as discontinuous thin to medium beds. Large, irregularly shaped bodies of massive, randomly orientated anhydrite? pseudomorphs occur near LV637546. Clusters of probable pseudomorphs after gypsum also occur in stromatolitic bioherms and adjacent dolostone near LV647552. Rare small (approximately 1-2 cm) bladed chert pseudomorphs that show tapered ends are probably also gypsum pseudomorphs.

Stromatolite morphologies are variable and include planar laminites, and domical/hemispheroidal (some linked), columnar, conical (with cylindrical cores), tabular and fungoid forms (Figure 9).

Other sedimentary structures in this lithofacies include: teepee structures; thinly bedded, tabular, intraformational pebble conglomerates; discontinuous, crinkled microbial laminations; rip-up clasts; lenticular, wavy and possibly flaser bedding; rare desiccation cracks; fenestrae; and diagenetic chert nodules.

In the western succession, the uppermost beds of the lower lithofacies are apparently less stromatolitic and intercalated sandstone, dolomitic mudstone, chertified dololaminites and other dolostone types are the dominant lithologies.

Middle lithofacies
The middle lithofacies of the Carruthers Formation is best exposed immediately south of Burke Creek Dome near Carruthers Creek where it has an estimated thickness of 150-200 m. It is similar to the lower lithofacies but typically contains more extensive and thicker sandstone intervals. The upper boundary of this member is exposed only in the eastern succession on the east side of a small ridge near LV930502 and is conformable and transitional.

This lithofacies contains two, broadly related interbedded facies. The dominant facies consists of intercalated dolomitic mudstone, dololaminites, siltstone, calc-dolostone, quartzic dolostone and sandstone. Interbedded with this predominantly carbonate facies at various stratigraphic levels, probably near the bottom and middle? of the unit, are intervals of relatively homogeneous well sorted sandstone and minor interbedded siltstone. The interbedded relationship between carbonate and sandstone facies appears less obvious where the sandstone intervals are thicker and more widespread in outcrop (eg north of Burke Creek Dome and in central-southern Helen). In the eastern succession, this sandstone facies forms much thinner units.

The carbonate rocks locally contain diagnostic 2-10 m thick cycles of stromatolitic dolostone overlain by evaporite pseudomorph-bearing sandstone and mudstone units. Some
stromatolites have a characteristic rusty red and dark grey colour. Bedding ranges from very thin to thick and although relationships are not always apparent, lenticular, wavy, continuous and discontinuous intercalated mudstone and sandstone are present. Nodular chert (mostly elliptical and up to 10 cm in diameter) is abundant near LV648626, but is scarce elsewhere. Disseminated, tabular pseudomorphs after gypsum occur on parting lineations at LV661670 and were possibly replaced by barite that in places forms disrupted, very thin to thin intraformational beds.

Stromatolitic boundstone and bafflestone are predominantly medium to thickly bedded and are steel gray with a milky white weathering patina. Stromatolite shapes are outlined by dark, curved discontinuous laminations which are often distorted by fenestrae and possible dissolution textures. Stromatolite forms include planar laminites, domical (including some linked hemispheroidal types), bulbous, conical (linked and dendroidal varieties), and columnar (including some branching) types. In places they form aggregations, with some bulbous, domical and conical forms up to 70 cm high. Some have weathered-out cylindrical cores. Occasionally, nodular chert has grown in the cores of stromatolite heads and in buttress positions between heads. In thin section, gypsum blades can be observed to cut stromatolitic laminae.

The interbedded, typically more recessive non-stromatolitic units comprise dolomitic mudstone, quartzic dolostone, calci-dolostone (near LV570736), siltstone and sandstone. Sandstone may have scoured bases, fluid escape structures, mudflakes and small-scale trough cross-beds. Siltstone is locally micaceous and commonly leached. Other sedimentary structures include ripple cross-laminae, discontinuous planar (streaky) and wavy laminations, fenestrae and intraclast flat-pebble breccias.

Siliciclastic intervals in the middle lithofacies are distinct and typically crop out as low rises of homogeneous, blocky-weathering, silicified pink, purple or tan sandstone with oxidised rust-red coatings. Most units are of thinly to medium bedded (rarely very thinly bedded), faintly laminated, very fine to medium, well sorted sandstone. They contain tabular mudclasts and impressions, quartz vugs and moulds (probably after anhydrite), asymmetric sinuous ripples with rounded crests, rare red lithic grains and disseminated black heavy minerals. The sandstone beds have bidirectional, low angle, simple or tabular cross-stratification. At least two prominent intervals of sandstone are present in the eastern succession and are between 5 and 50 m thick.

Upper lithofacies

The upper lithofacies of the Carruthers Formation is predominantly sandstone, which contains some interbedded mudstone and minor chertified and, in places, stromatolitic dolostone. It is between 40-120 m thick in the western succession and is approximately 600 m thick in the eastern succession. Outcrops are typically resistant and upstanding. Some sandstone contains evaporite pseudomorphs after anhydrite (nodular gypsum?) and/or halite. Ferricrete is commonly developed on mudstone rich intervals.

This lithofacies is a coarsening-upward unit. It can be divided into a lower 0-30 m thick, very thinly to thinly bedded, fine sandstone and mudstone interval, and an upper, thinly to medium bedded, slightly coarser and more competent sandstone interval, which forms the majority of the lithofacies. The base of the upper lithofacies is placed at the first occurrence of a very thinly to thinly bedded sandstone that has interbedded red-purple ferruginised mudstone units (near LV644642).

The lower interval of the upper lithofacies is commonly obscured by tabular rubble from the overlying sandstone. It is most prevalent in the western succession and consists of red-purple or tan intercalated sandstone and mudstone with subordinate chertified dolostone that locally contains microbial laminations, small domical and columnar stromatolites, fenestrae and teepee structures. Isolated chertified dololaminite interbeds occur at LV589652 and some of these contain bulbous stromatolites. Some of the interbedded sandstone units have scoured and peneplaned the dolomitic units and weathering? dissolution textures are common.

The sandstone and mudstone of this basal interval is typically laminated and micaceous in part. Sandstone contains bidirectional, low angle tabular (or less commonly trough) cross-beds and ripple cross-laminae. Some sandstone beds are wavy or lenticular and very thin interbeds contain mud
drapes and minor flaser bedding. Other sedimentary structures include mud clast impressions, mud flakes, desiccation features, and undulatory laminations and rare wrinkle marks (runzel marks).

The upper interval consists of resistant (silicified), light pink to purple or tan sandstone and minor red-brown or maroon mudstone. Sandstone is fine to very coarse and is predominantly thinly to medium bedded. It has bidirectional, low angle, tabular or trough cross-beds and may have lenticular bed sets that in places exhibit a pinch and swell geometry. Some intervals contain abundant intraformational mud clasts, mud galls, desiccation cracks, pseudomorphs after halite (casts and moulds), flaser bedding, normally graded beds, synaeresis cracks and scattered quartzite pebbles. Sandstone beds may have scoured bases infilled by discontinuous intraformational siltstone breccia. Ripple marks are prolific and include symmetric, asymmetric and less common interference and linguoid varieties. Nodular chert or moulds after nodular chert are also diagnostic. These are common in the eastern succession and forms an upstanding strike ridge with a high point at Mount Shillinglaw. To the east and northeast of Mount Shillinglaw in HELEN, this formation is poorly exposed in the eastern succession. It is divided into two subunits, informally referred to as the lower and upper lithofacies. This subdivision was not mapped in the eastern succession due to poor exposure; however, a transitional contact between the lower and upper lithofacies occurs at LV913476.

The lower lithofacies is typically intensely silicified in the type section and forms an upstanding strike ridge with a high point at Mount Shillinglaw. To the east and northeast of that ridge, outcrop is leached and less silicified, and forms dominantly recessive undulose hills of low to moderate relief. Leached units are commonly tabular or blocky whereas silicified units are blocky in outcrop. Lateritic profiles are often developed on leached rock types (eg in northwestern MUCKATY) whereas manganiferous or ferruginous deposits tend to develop on more silicified units (eg near Mount Shillinglaw). Silcrete is common to both silicified and leached units.

The base of the Shillinglaw Formation is best observed on the western flank of Mount Shillinglaw at LV576718. The contact with the underlying Carruthers Formation is conformable and transitional, and is placed at the base of a succession of very thin to medium interbedded sandstone (containing pseudomorphs after halite), mudstone, microbial dolostone (containing aggregations of bulbous stromatolites), and red to maroon chertified dololaminites. This succession contains a variety of facies that may vary considerably along strike but generally become more arenaceous up-section.

Sandstone of the Shillinglaw Formation is mostly of well sorted quartz arenite or sublitharenite, which contains subangular to subrounded, very fine to medium grains of monocrystalline quartz, minor polycrystalline quartz, chert, sedimentary lithic grains and accessory muscovite, zircon and tourmaline. Quartz overgrowths and cement are common, although a muddy ferruginous matrix is in places evident where quartz cement is absent. Less mature sandstone is of a similar composition but has a larger matrix component and may contain accessory ooid clasts.

Quartzic dolostone in the Shillinglaw Formation is composed mainly of subangular to subrounded monocrystalline quartz. It also contains minor chert, polycrystalline quartz (some sutured varieties), plagioclase, and silicified, fine, rounded, dolomitic lithoclasts. Accessories include muscovite, tourmaline and zircon. Most grains have low sphericities and are set in a dolomitic and less common microcrystalline calcite matrix/cement that is variably iron stained and contains microstylolites. Laminations and dissolution textures are common in microcrystalline calcite varieties and are possibly replacing evaporite minerals.

The composition of the sedimentary rocks indicates that they were dominantly reworked from previously deposited sediments, possibly from chertified underlying units and intraformational sources. The dominance of undeformed monocrystalline quartz and less common feldspar throughout this formation may indicate a predominantly plutonic or volcanic provenance whereas tourmaline may indicate a pegmatitic source. Greenish chert units are interpreted to have a felsic volcanic component from the presence of clear quartz and euhedral, magmatically zoned zircon.

**Shillinglaw Formation (Ems)**

The Shillinglaw Formation is a newly defined, 550-700 m thick, mixed siliciclastic-carbonate unit (see Appendix), named after Mount Shillinglaw in HELEN. This formation is best known from outcrops in the western succession and, apart from outcrops near Mount Hawker in northwestern MUCKATY, is poorly exposed in the eastern succession. It is divided into two subunits, informally referred to as the lower and upper lithofacies. This subdivision was not mapped in the eastern succession due to poor exposure; however, a transitional contact between the lower and upper lithofacies occurs at LV913476.

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**Lower lithofacies**

The lower lithofacies of the Shillinglaw Formation is about 250-350 m thick in the western succession and about 300 m thick near Mount Hawker in the eastern succession. It comprises interbedded sandstone, mudstone and dolostone and is often characterised by distinct cream to rusty-tan and less common red tonal variations on aerial photos. These denote bedding trends, especially in central HELEN. Several greenish chert horizons occur near the top of this unit in the western succession (eg LV587745) and are interpreted to be tuffaceous units. Zircons from one of these units have yielded a rather poorly constrained SHRIMP U-Pb date of 1639 ± 27 Ma (Nunn 1997) and this provides a maximum depositional age.

Cream to red or mauve, chertified, domical and columnarstromatolitic boundstone and dololaminites is diagnostic of the lower lithofacies, especially in the western succession (eg northern parts of Mount Shillinglaw). Stromatolitic units are less abundant in the exposed parts of the eastern succession. Silicified, evaporite pseudomorph-bearing dolostone, quartzic dolostone and sandstone are also characteristic rock types.

Fine to medium, slightly micaceous sandstone occurs intermittently throughout this lithofacies and outcrops as laterally continuous units up to 10 m thick, but usually less than 2 m thick. Sandstone units are usually thinly to medium bedded, display low angle, bidirectional, simple or tabular cross-bedding, and contain current ripple marks
and ripple cross-laminations. Desiccation cracks, rare scoured bases, angular to rounded mud clasts, chert and ferruginous mud flake intraclasts are also present. Some lenses contain medium bedded, fine to very coarse, poorly sorted quartz arenite, discontinuous granular lags and silicified sedimentary pebble lithoclasts (eg LV596685). These probably represent palaeochannel deposits.

Sandstone units in the lower lithofacies commonly grade upward to mudstone or very thinly to thinly bedded dolomitic mudstone and dololaminite. Sandstone and mudstone are commonly interbedded and form streaky, lenticular, wavy and flaser laminations (Figure 10) and beds (eg LV617750). Other sedimentary structures in sandstone include scoured bases, intraclastic flat pebble breccias, mud clast impressions and rip-up clasts (mud galls and chert clasts), load structures, graded beds, diagenetic chert nodules, mud drapes, ripple cross-laminations, ripple marks with both rounded and truncated crests (asymmetric, symmetric, linguoid, interference, linear to bifurcating), desiccation cracks and rare fluid escape and convolute bedding structures. Pseudomorphs after halite are present but mainly occur in the basal parts.

Interbedded, very thinly to thickly bedded, laminated dolomitic units are both stromatolitic and non-stromatolitic and are variably micaceous. Stromatolitic units are more prevalent in the western succession and comprise domical, columnar, conical (up to 1 m high), bulbous and planar forms, as well as ‘sausage-like’ stromatolites that occur between large probable mudcracks at LV589703. Stromatolite aggregations up to 20 m across and with a few meters of relief occur at LV588704. Sedimentary structures common to this facies include tepees, ripple cross-lamination, cryptomicrobial lamination, fenestrae, intraclast breccias and rare elliptical, laminated, diagenetic nodules (found as float only). Solution breccia is common at LV586737 and is associated with possible slump folding of beds at LV589703. It is also common near faults.

The poorly exposed uppermost intervals of the lower lithofacies near Mount Shillinglaw are composed of interbedded, locally calcareous quartzic dolostone, dolostone, sandstone and siltstone. These strata also contain thinly bedded dolostone with radiating acicular crystal clusters (some of which are vertically stacked or intergrown) orientated approximately perpendicular to bedding. SEM analyses indicate that these crystals have pseudo-hexagonal cross sections with blocky and feathery terminations, as is characteristic of neomorphosed aragonite (P Winefield pers comm 1997).

The lower lithofacies of the Shillinglaw Formation lithologically resembles the lower and middle lithofacies of the Carruthers Formation and was probably deposited in a similar marginal marine to continental sabkha environment. Stromatolitic dolostone and interbedded sandstone and mudstone units, interpreted as tidal rhythmites, indicate shallow water deposition in the photic zone throughout the lower lithofacies. Evaporitic pseudomorphs, intraformational breccia, ripple marks and desiccation cracks also indicate periodic emergent or supratidal settings. Solution breccias may have formed by dissolution of evaporite-rich facies, causing the collapse and fragmentation of overlying beds.

**Upper lithofacies**

The upper lithofacies is predominantly a succession of calcareous and quartzic dolostone. It contains minor thinly to medium bedded dolostone, dololaminites, dolomitic mudstone, breccia, sandstone, conglomerate and mudstone, and becomes progressively coarser and more siliciclastic up-section. The type section in central HELEN has a minimum thickness of 300-400 m and outcrops as low to moderate relief undulose hills with subtle benching. The upper lithofacies has characteristic red to dark purple aerial phototones that highlight gentle folding in HELEN and distinguish it from other mixed siliciclastic-carbonate lithofacies in HELEN SPRINGS.

The contact with the lower lithofacies in the western succession is sharp and conformable to possibly disconformable. It separates thinly bedded, chertified, laminated dolostone and mudstone of the lower lithofacies from thinly to medium bedded quartz arenite and sublithic arenite containing metasedimentary lithic clasts, and is placed at the base of the first thin sandstone unit at LV585738. The basal sandstone unit is thin, laterally persistent, micaceous in part, silicified, medium to coarse, thinly to medium bedded and faintly laminated. It contains low angle cross-beds, some

![Figure 10 Typical example of thinly interbedded fine sandstone and dolomitic mudstone showing planar and flaser bedding characteristics, from lower lithofacies of Shillinglaw Formation at LV617750.](image-url)
localised small trough cross-beds, desiccation cracks, tabular mudclast impressions (up to 2 cm) and occasional pebble clasts of laminated dolostone. In the eastern succession (eg at LV913476), the contact with the lower lithofacies is transitional and the base of the upper lithofacies is mapped at the onset of slightly coarser sandstone.

A red to purple and light grey intercalated lithofacies of quartzite dolostone, dolomitic mudstone, dolostone, sandstone, siltstone and rare conglomerate overlie the basal sandstone. The thin interbedded rock types are laminated (discontinuous, wavy and undulose) and contain ripple cross-laminations and rip-up clasts. Some beds are graded. Quartzite dolostone is the dominant rock type and is thinly to massively bedded, fine to coarse and in places intensely fractured and fissile. Locally, these units contain detrital muscovite and some frosted, well rounded quartz grains, indicating a possible aeolian contribution. Granules and small pebble clasts occur in thinly to thickly bedded fine dolostone near LV594767.

Sandstone, including the basal facies, is poorly to well sorted, fine to coarse, and contains some discontinuous granular laminations and pebbles (mainly quartzite and chert) up to 5 cm in diameter. It forms light cream to tan, thin to medium beds that are low angle bidirectionally cross-stratified. Sedimentary structures include ripple cross-laminations, scoured bases, tabular mudclast impressions, and rare fluid escape structures. Some beds are lenticular, and laminations or very thin interbeds of dolomitic mudstone and dololaminate may be present.

Dolostone and quartzite dolostone have karstic weathering surfaces and are thinly to thickly bedded. They are variably calcareous and silicified and may contain discontinuous, undulose and sandy ripple cross-laminations. Locally, these rock types contain secondary barite, subangular quartz and lithic pebbles, granular laminations, possible desiccation cracks and solution seams.

Pebble to cobble conglomerate is clast supported, cross-stratified and medium to thickly bedded. It contains imbricated, subangular to subrounded quartzite clasts and minor tabular dolomitic mudstone clasts in an arenaceous matrix. Conglomerate is interbedded with red to purple, medium bedded, micaeous quartzite dolostone containing silicified dolostone rip-up clasts.

The upper lithofacies depositional environment is somewhat equivocal but is interpreted to be dominantly shallow to subtidal marine. The relatively higher energy basal sandstone interval is indicative of a shallow water environment whereas the overlying units were deposited in dominantly quiescent conditions. The lack of evaporites and stromatolites suggests a deeper water environment to that of the lower lithofacies, but the red to dark purple colour of these rocks could also indicate lacustrine redbed facies. The transitional relationship with overlying sandstone of the Willieray Formation favours a shallow water environment, at least for the upper parts of the Shillinglaw Formation.

**Willieray Formation (P. Lmw)**

The newly defined Willieray Formation (see Appendix) forms the uppermost part of the Namerinni Group and is predominantly a siliciclastic unit with subordinate carbonate rocks. It conformably overlies the Shillinglaw Formation and is best exposed in the western succession about 10 km north of Mount Shillinglaw (LV580795). Good exposures also occur about 5 km north-northwest of Mount Willieray, and in the vicinity of Mount Hawker in the eastern succession. The Willieray Formation typically forms discontinuous low to high relief hills, in which benched outcrop typically weathers to tabular or blocky rubble and commonly has a characteristic red-brown to orange-tan colour. Outcrops are usually leached and silicified, and are locally covered by laterite, ferricrete or undifferentiated Cretaceous rocks.

The preserved thickness of this formation varies considerably beneath an angular unconformity with the overlying Gleeson Formation of the Renner Group, and locally, the unit is completely removed by erosion. The formation is up to 120 m thick in the western succession and up to at least 400 m thick in the eastern succession, where most exposed sections are incomplete and structurally complicated.

The basal unit of the Willieray Formation is typically less than 20 m thick and consists of an overall coarsening- and thickening-upward package of interbedded dolomitic mudstone, quartzite dolostone and sandstone in thin to medium beds. It is commonly poorly exposed and is possibly absent in places. Bedding is typically planar or wavy and some sandstone beds pinch out. Sedimentary structures include parallel, wavy and streaky lamination, ripple marks and ripple cross-lamination, desiccation cracks, mudclast impressions and mud galls. Some low angle tabular cross-bedded sandstone within this basal interval has an off-white matrix and is notably micaceous.

The basal unit is overlain by typically fine to medium (less commonly up to very coarse) red-brown to purple and tan sandstone and minor mudstone. This constitutes the majority of the Willieray Formation although some recessive, more mudstone dominated intervals are apparent. Minor pebbly sandstone and conglomerate form thin to thick cross-beds and lags throughout. Intervals dominated by thick red-brown to cream mudstone (mostly siltstone) are present in the eastern succession.

Sandstone is predominantly of thinly to medium bedded quartz arenite or sublitharenite with low angle cross-beds and in places, discontinuous coarse laminations that contain higher proportions of muscovite and rare quartzite pebble clasts. Other sedimentary structures include abundant ripple marks (symmetric and asymmetric, parallel-crested to bifurcated, and linguoid and interference ripples), planar and ripple cross-laminations, rare graded beds, undulose bedding, mudclast impressions (up to 5 cm), white dolostone rip-up clasts, reactivation surfaces, desiccation cracks, scour and fill structures and rare pseudomorphs after halite.

Sandstone contains subangular to subrounded, poorly to well sorted grains that consist predominantly of monocrystalline quartz with minor polycrystalline quartz, chert, and metamorphic and sedimentary lithoclasts (some laminated). Detrital muscovite, blue-green tourmaline and rounded zircon are common accessory grains. Authigenic quartz, haematite, clays and sericite constitute varying proportions of the cement and matrix. Monocrystalline and polycrystalline quartz probably indicate a plutonic and less significant metamorphic provenance whereas sedimentary lithoclasts indicate the intraformational reworking of quartz-rich sedimentary rocks.
The Willieray Formation is a transgressive, sandstone-dominated unit that was probably deposited in an intertidal to supratidal environment. The close association of localised high energy channels, prolifically ripple marked sandstone intervals, evaporite pseudomorphs and desiccation features, and intervals of interbedded sandstone and mudstone that appear to be analogous to tidal rhythmites favours a marginal shallow marine environment and suggests either a tidal flat or deltaic setting.

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**Table 3** Stratigraphic units of the Renner Group in HELEN SPRINGS

<table>
<thead>
<tr>
<th>Unit</th>
<th>Lithology</th>
<th>Stratigraphic relationships</th>
<th>Depositional environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Woods beds</td>
<td>Sandstone, siltstone, and shale; chertified dolostone and chertified probable stromatolitic bioherms; minor granular conglomerate; poorly to well sorted quartz arenite; laminated or thin to medium beds; some graded beds; some grainsize-laminated units; dominantly very fine- to medium-grained; ripple marks; desiccation features; nodular chert.</td>
<td>Conformable on the Jangirulu Formation. Intruded by dolerite sills in HELEN SPRINGS and BEETALOO. Top is unknown, but appears to be unconformably overlain by Middle Cambrian Montejinni Formation in SOUTH LAKE WOODS.</td>
<td>Shallow marine to supratidal.</td>
</tr>
</tbody>
</table>

| Jangirulu Formation      | Well sorted, fine to very coarse but mostly medium sandstone; minor granule to pebble conglomerate; typically homogeneous and faintly laminated; thinly to very thickly, but mostly medium bedded; bidirectional simple to tabular cross-bedding, some trough cross-bedding; well ripple marked in parts; desiccation features near top. | Sharp to transitional contact with underlying Wiemery Formation. Locally intruded by dolerite sills. Top contact is transitional but sharp with Lake Woods beds. | Shallow marine; subtidal to intertidal (high energy); minor subaerial exposure. |

| Wiemery Formation        | Laminated to medium-bedded, very fine to medium micaceous sandstone; minor coarse to very coarse sandstone and granular conglomerate; siltstone, shale, chertified dolostone; ripple marks, desiccation features, halite pseudomorphs and nodular chert; horizons with abundant shale clasts. | Conformable transitional contact with underlying Powell Formation. Locally intruded by dolerite sills. Sharp to transitional contact with underlying Jangirulu Formation. Unconformably overlain by Muckaty Member of Helen Springs Volcanics and undifferentiated Lower Cretaceous rocks. | Shallow marine to supratidal, fluvial in part; minor subaerial exposure. |

| Powell Formation          | Quartz arenite, granular to small pebble quartz conglomerate, minor siltstone and mudstone, and fine-grained, angular sedimentary clast-bearing quartz arenites; moderate to very well sorted; medium to very thickly bedded; pinching and swelling of beds common in lower part; ripple marks to dune-forms; tabular to bidirectionally low angle cross-beds; intervals with desiccation features and halite pseudomorphs, some horizons with abundant shale clasts on parting surfaces. | Subdivided into informal lower, middle and upper lithofacies. Conformable transitional contact with underlying Wiemery Formation and underlying Baralandji Formation. Unconformably overlain by Muckaty Member of Helen Springs Volcanics and undifferentiated Lower Cretaceous rocks. | Shallow marine subtidal (to open marine shelf) to supratidal; tidal? channels. |

| Baralandji Formation      | Varibly micaceous siltsite and sandstone; minor feldspar content; glauconitic in upper part; granular to pebbly sandstone and polymeric conglomerate; ferruginous siltsite and fine sandstone; shale; laminated to thinly bedded shale, siltstone and fine sandstone; medium to thickly bedded sandstone and granule to pebble conglomerate; planar, tabular and trough cross-bedding; parallel laminated; hummocky cross-stratification; ripple marks and megaripples; gutter casts; desiccation features; halite pseudomorphs, Fe-oxides after pyrite/ glauconite. | Subdivided into lower Sweetwater Member and upper Grayling Member. Conformable transitional contact with underlying Gleeson Creek Formation and overlying Powell Creek Formation. Unconformably overlain by Muckaty Member of Helen Springs Volcanics and undifferentiated Lower Cretaceous rocks. | Shallow marine; fluvial to supratidal mudflats at base deepening upwards to subtidal. |

| Gleeson Formation         | Sandstone, typically medium to very coarse, varibly micaceous lithic arenite to quartz arenite with minor feldspar component; pebbly sandstone; pebble to cobble conglomerate, metasedimentary clasts dominant with lesser white vein quartz clasts; minor well laminated siltstone and mudstone; extreme variations in sorting and textural maturity; thin to very thick beds; graded to faintly laminated beds, cross-beds, ripple marks and megaripples, desiccation features. | Unconformably overlaps Namerinini and Tomkinson Creek Groups. Conformable transitional contact with overlying Baralandji Formation. Unconformably overlain by Muckaty Member of Helen Springs Volcanics, Anthony Lagoon beds and undifferentiated Lower Cretaceous rocks. | Fluvial to shallow marine; subaerial exposure; rapid sedimentation; minor relict topographic relief on unconformity surface. |

The Renner Group (new name, see Appendix) is a predominantly siliciclastic succession comprising five newly defined formations, in ascending order the Gleeson, Baralandji, Powell, Wiemery and Jangirulu Formations, plus a topmost informal unit, the Lake Woods beds (Table 3). All five formations were originally included within the former Tomkinson Creek Beds (Randal et al 1966, Randal
Table 4  Proposed correlations of Mesoproterozoic units. Roper Group stratigraphy is described in Abbott et al 2001.

<table>
<thead>
<tr>
<th>Renner Group</th>
<th>Depositional environment in Ashburton province</th>
<th>Roper Group</th>
<th>Depositional environment in southern McArthur Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Woods beds</td>
<td>shallow marine?</td>
<td>middle Velkerri Formation</td>
<td>Marine</td>
</tr>
<tr>
<td>Jangurulu Formation</td>
<td>intertidal and subtidal</td>
<td>lower Velkerri Formation</td>
<td>Marine</td>
</tr>
<tr>
<td>Disconformity</td>
<td></td>
<td>Bessie Creek Sandstone</td>
<td>intertidal and subtidal</td>
</tr>
<tr>
<td>upper Powell Creek Formation</td>
<td>intertidal to supratidal, fluvial?</td>
<td>Corcoran Formation</td>
<td>intertidal and subtidal</td>
</tr>
<tr>
<td>middle Powell Creek Formation</td>
<td>intertidal</td>
<td>Hodgson Sandstone</td>
<td>marine</td>
</tr>
<tr>
<td>Disconformity</td>
<td></td>
<td>Jalb0 Formation</td>
<td>intertidal and subtidal</td>
</tr>
<tr>
<td>lower Powell Creek Formation</td>
<td>subtidal and intertidal</td>
<td>Arnold Sandstone</td>
<td>intertidal and subtidal</td>
</tr>
<tr>
<td>Grayling Member</td>
<td>subtidal open marine</td>
<td>Crawford Formation + Mainoru Formation</td>
<td>subtidal open marine</td>
</tr>
<tr>
<td>upper Sweetwater Member</td>
<td>intertidal to subtidal</td>
<td>Limmen Sandstone</td>
<td></td>
</tr>
<tr>
<td>lower Sweetwater Member</td>
<td>fluvial?, supratidal</td>
<td>Mantungula Formation</td>
<td></td>
</tr>
<tr>
<td>disconformity? to conformity</td>
<td></td>
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<tr>
<td>Gleson Formation</td>
<td>fluvial to shallow marine</td>
<td>Phelp Sandstone (or absent)</td>
<td>fluvial</td>
</tr>
<tr>
<td>Angular unconformity</td>
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(1983) also recognised this angular unconformity in central Renner Group was first identified by Randal et al (1966) and subsequently reassigned to the Montejinni Limestone (Kennewell and Huleatt 1980). Two new members are also defined within the Baralandji Formation, namely the Sweetwater and Grayling Members. Although other divisions can be identified in this group and are described below, they are not differentiated on HELEN SPRINGS.

The Renner Group displays extensive lateral continuity in the northern part of the Ashburton province, and is now recognised in HELEN SPRINGS. Two isolated inliers of Gleeson Formation are distributed throughout BEETALOO and TANUMBIRINI (Lanigan et al 1994). Figure 2 shows the distribution of the Renner Group in HELEN SPRINGS.

In the Ashburton province, the Renner Group unconformably overlies the Palaeoproterozoic Namerinni and Tomkinson Creek Groups, and is unconformably overlain by the Early Cambrian Muckaty Member of the Helen Springs Volcanics. Younger Phanerozoic sedimentary rock units also unconformably overlie the Renner Group. A maximum composite thickness of greater than 3500 m is preserved in HELEN SPRINGS.

The angular unconformity at the base of what is now the Renner Group was first identified by Randal et al (1966) and subsequently reassigned to the Montejinni Limestone (Kennewell and Huleatt 1980). Two new members are also defined within the Baralandji Formation, namely the Sweetwater and Grayling Members. Although other divisions can be identified in this group and are described below, they are not differentiated on HELEN SPRINGS.

The Renner Group displays extensive lateral continuity in the northern part of the Ashburton province, and is now recognised in HELEN SPRINGS. Two new members are also defined within the Baralandji Formation, namely the Sweetwater and Grayling Members. Although other divisions can be identified in this group and are described below, they are not differentiated on HELEN SPRINGS.

The Gleson Formation (new name, see Appendix) is a predominantly upstanding sandstone or pebbly sandstone unit at the base of the Renner Group. It also contains minor interbedded conglomerate, siltstone, mudstone and shale. Gleson Formation sandstone is typically more micaceous and is compositionally and texturally less mature than most other sandstone units in the Ashburton province. Extreme variations in grainsize, sorting and textural maturity, and dramatic facies variations are also conspicuous characteristics of the formation.

The Gleson Formation generally forms low relief strike ridges with exposures that are either indurated, rounded, and boulder-strewn, or friable and bencheted. Friable sandstone is deeply weathered and supports a residual deposit of distinctive iron-stained quartzitic and micaceous red sandy soil (or scree).

Outcrops of Gleson Formation are distributed throughout the northern parts of the Ashburton Ranges in HELEN SPRINGS and continue as far south as Morphett Creek in BRUNCHILLY, and northwards into BEETALOO and NEWCASTLE WATERS. Two isolated inliers of Gleson Formation sandstone about 25 km northeast of Renner Springs probably represent remnant topographic highs as they are...
The thickness of the Gleeson Formation ranges from about 30 m to about 650 m. It is approximately 525 m thick in the type section in central Helen (Figure 11), but thickly bedded conglomerate units, occurring to the north and south, are absent in the measured section. A second, approximately 600 m thick reference section is located in southwestern Monmoota between LV790555 (the actual base is seen at LV794536) and LV893554. In this section, the rocks exhibit more pronounced grain size variations, particularly in the upper lithofacies, than those within the type section.

The Gleeson Formation is divided informally into a lower, middle and upper lithofacies in Helen Springs (Figure 11). Each has a distinct geomorphological expression and is readily identifiable on aerial photographs. The lower lithofacies is largely recessive and forms a distinct horizon that often highlights the unconformity below. It typically grades upward into the more upstanding middle lithofacies, which displays a relatively uniform geomorphic expression, albeit variably dissected. In contrast, the upper lithofacies sharply overlies the middle lithofacies, particularly in northern Helen Springs, and is benched in appearance. It is composed of several fining-, maturing- and thickening-upward intervals.

Outcrops of the lower lithofacies are generally 20-40 m thick. They consist mostly of distinct orange-tan to red-brown, very fine to medium micaceous sandstone and siltstone (Figure 12a) with minor amounts of thinly interbedded red-brown mudstone or shale, and thin to thick beds of coarse to pebbly sandstone. Rare conglomerate lags and normally graded, thinly to medium bedded pebbly sandstone intervals also occur in this lithofacies. Most sandstone is of litharenite or sublitharenite composition.

Typically, the rocks are well planar laminated, thinly bedded and often exposed in decimetre-scale to metre-scale tabular outcrop on scree slopes. Parallel lamination is typical and very low angle, climbing and leeward dipping cross-laminations are also present. Other sedimentary features include tool marks, minor low amplitude current ripple marks, desiccation features, local convolute laminations and sand volcanoes. Detrital coarse white mica content is extremely variable and individual laminations may contain as much as 40-50% mica.

Locally, the lower lithofacies is very thin or absent (eg in southeastern Helen). In central-eastern Muckaty (eg near LV882211), this unit is represented only by trough cross-bedded sandstone or conglomerate, which contains pebbles and cobbles.

Typically, the middle lithofacies contains medium to very coarse sandstone (eg Figure 12b) and pebbly sandstone, along with minor conglomerate and rare siltstone. Upstanding thin to medium beds of medium sandstone form the base of this unit (eg at LV553793 and LV755356). Despite variations in grainsize and bedding thickness, it remains relatively uniform in composition throughout Helen Springs and together
Figure 12 Typical examples of units from Gleeson Formation;
(a) planar laminated to thinly bedded micaceous fine sandstone and mudstone of lower lithofacies at LV602828;
(b) trough cross-bedded, medium to very coarse sandstone from upper lithofacies at LV620859;
(c) metasedimentary (predominantly quartzite) clast-rich pebble and cobble conglomerate from upper lithofacies at LV943222.
with the lower lithofacies, represents a single coarsening- and thickening-upward succession.

The upper lithofacies is highly variable in texture and composition and consists of several fining-, maturing- and thickening-upward sedimentary intervals. The number of cycles appears to vary from region to region, but generally decreases to the south. In some areas (eg in southwestern MUNMOONA), individual cycles, which are up to 100 m thick, thin and vanish over several kilometres of strike length. In northern HELEN and further to the north in ELLIOTT, the rocks are compositionally and texturally more mature than those in southern HELEN SPRINGS, although the provenance remains the same.

The middle and upper lithofacies consist of weakly graded to massive sandstone or pebbly sandstone that is grey, orange-tan, or cream to red-purple. Beds are typically medium to thick and are low angle cross-stratified. Although most are tabular in appearance, pinching and swelling is relatively common. Minor very thickly bedded sandstone (about 1-2 m thick) occurs at intervals throughout the Gleeson Formation and is relatively common in the upper lithofacies. Sandstone composition is mostly sublitharenite or quartz arenite in the middle lithofacies and varies between litharenite and quartz arenite in the upper lithofacies. Conglomerate beds and lenses are common in the middle and upper lithofacies and locally are more than 20 m thick, particularly in the upper lithofacies in MUCKATY (Figure 12c).

Simple and tabular trough cross-bedding is very common throughout the Gleeson Formation. Most troughs are typically metre-scale or greater, with open basin shapes and low angle cross-stratification. High angle cross-stratification is not common. Laminations are mostly asymptotic. Reactivation surfaces are common, and convolute and overturned laminations are locally abundant throughout all lithofacies (eg at MV017461). Erosional U-shaped troughs up to 3 m deep occur in eastern MUCKATY (near LV882211), and in central eastern MUCKATY (near LV888220), broader channel-like structures tens of metres across contain imbricated pebbles and cobbles.

Straight crested, bifurcating, linguoid and cuspat ripples as well as dunes (megaripples) are prevalent in various intervals, often near the tops of individual cycles in the upper lithofacies. Sandstone in these intervals is typically a thinly to medium bedded, fine to medium, well sorted quartz arenite that contains intraclasts of siltstone, mudstone and shale, as well as desiccation features.

The Gleeson Formation is broadly comparable with, but less mature than other Renner Group units. The presence of biotite and feldspars as well as coarse zircon and tourmaline is characteristic of less mature units throughout the Renner Group. Most of the sandstone units, including the quartz arenites, contain detrital muscovite (albeit typically less than 10%).

Sandstone of the Gleeson Formation is variably sorted and mostly has a low matrix component. The principal constituent grain type is quartz (between 80% and 98%), in both monocrystalline and polycrystalline forms. Angular to subangular quartz grains with low sphericities are common and in some sandstones, grains are both rounded and angular.

Some quartz grains contain inclusions of tourmaline, muscovite and biotite and are probably derived from a granitic provenance. Other constituent grains include variable amounts of chert, microcline (microperthite), oligoclase-andesine feldspar, muscovite, green to brown biotite, blue-green tourmaline, zircon and probable Fe-Ti oxides. Metasedimentary lithic and probable granite grains (quartz containing mica and/or tourmaline microlites) are locally abundant (up to about 15%). Grains of tourmaline and zircon that are close to the actual framework grain size are common.

The feldspar content is generally low (less than 5% and typically less than 1%) in coarser sandstone units, but less mature, finer sandstone and siltstone intervals often have elevated feldspar contents up to 10%. Several different types of cement including thin rims of clear quartz, pinkish kaolinite and greenish chlorite? (or clay?) are present. The degradation of biotite to chlorite, and feldspar to a quartz, sericite and clay mosaic is common, even in core samples from significant depths.

Up to 99% of the clast types in conglomerates of the Gleeson Formation are of quartz-rich metasediments. This feature distinguishes the formation from the Hayward and Jeromah Formations, which are the basal units of the Tomkinson and Namerinni Groups respectively. The highest modal proportion of conglomerate clasts is of medium to coarse quartzite and this is similar to that of conglomerates in the Short Range Sandstone and Bootu Formation. Other components include minor quantities of quartz-veined metasediments, white vein quartz, white chert and jasper. Rare pebbles of phylite and mafic igneous rocks also occur in MUCKATY. Most clasts are equivalent to rocks of the underlying Tomkinson Creek and Namerinni Groups. The absence of immature volcanic debris and presence of only minor amounts of white vein quartz in the Gleeson Formation distinguish it from the Hayward Creek Formation. The lack of abundant chert clasts distinguishes it from the Jeromah Formation.

The unconformity between the Gleeson Formation and most of the underlying Palaeoproterozoic formations in HELEN SPRINGS is well exposed. Minor palaeotopographic relief of about 5-10 m is recognised from detailed mapping of the unconformity surface in MUCKATY where it overlies intercalated sandstone and siltstone packages of the Morphett Creek Formation. However for the most part, the unconformity surface appears to be relatively planar, especially in northern HELEN SPRINGS. The upper boundary with the overlying Baralandji Formation is transitional and typically covered by scree. It is defined in the type section at the top of a fining-upward cycle (Figure 11).

Most of the Gleeson Formation was probably deposited in moderate to very high energy shallow water environments, although lower energy environments were also present. Sedimentary components were most likely derived from a rejuvenated nearby granitic provenance as well as a more obvious metasedimentary provenance. The lower lithofacies most likely represents fluvial overbank deposits given the close association of fine sandstone and mudstone with localised high energy channels and the absence of tidal, evaporitic and carbonate facies. The coarsening-upward, predominantly trough cross-bedded, texturally immature sandstone and pebbly sandstone of the middle lithofacies were probably also deposited in a fluvial setting. The numerous
large-scale channel deposits and ripple marked intervals of the upper lithofacies may be fluvial in part, but a prograding marine delta or marginal marine setting is favoured.

Lithostratigraphic correlatives of the Gleeson Formation do not occur in the Abner Range in MOUNT YOUNG of the southeastern McArthur Basin. However, recent mapping in other parts of the McArthur Basin (URAPUNGA and ROPER RIVER; Abbott et al. 2001) has identified a relatively thin unit, the Phelp Sandstone, which may be a correlative.

**Baralandji Formation (Erb)**

The Baralandji Formation (new name, see Appendix) is a 100-700 m thick unit composed predominantly of very fine to medium sandstone, siltstone and shale with minor amounts of coarse to very coarse sandstone and conglomerate. Compositionally, the formation differs conspicuously from the overlying Powell Formation, but it is, at least in its lower part, similar to the underlying Gleeson Formation. It is in large part recessive. The top of an upstanding sandstone unit marks the boundary between two distinct members with notably different lithofacies: the lower, Sweetwater Member, (Erbs) and the upper, Grayling Member, (PLrb).}

**Sweetwater Member (PLrbs)**

The Sweetwater Member (new name, see Appendix) is a coarsening-upward siliciclastic succession occupying the lower part of the Baralandji Formation. It is conformable with the underlying Gleeson Formation and overlying Grayling Member. The 50-300 m thick member thickens notably to the north and displays considerable east-west thickness variations in HELEN SPRINGS.

The lower recessive and upper ridge-forming intervals of the Sweetwater Member provide a distinctive geomorphological expression. The upper interval forms a prominent dome about 2 km east of Renner Springs in central and northern HELEN. It also occurs in BEETALOO and NEWCASTLE WATERS but does not outcrop in southeastern HELEN, nor in southwestern MONMOONA and northwestern BRUNCHILLY.

The nearly complete type section, albeit poorly exposed in parts, is located in ELLIOTT about 9 km southwest of Sweetwater Bore, after which this unit is named. The Sweetwater Member is almost 300 m thick in this section and the upper interval reaches its maximum known thickness (about 225 m).

Moderate to good exposures of the member flank an anticline between LV547831 and LV568807 and good exposures of the lower unit occur in MUCKATY near LV915240. In a reference section between LV606936 to LV609942 in HELEN, the upstanding sandstone lithofacies is 100 m thick and the underlying recessive unit is estimated to be also about 100 m thick.

The lower unit consists dominantly of fine, variably micaceous sandstone and minor interbedded red-brown to green-grey siltstone and shale. Exposures are typically tabular to blocky and are often benched. Sandstone is well laminated to thinly planar bedded and commonly contains intraformational, tabular shale clasts and rare laminated granular horizons. The siltstone and shale units are poorly expressed. Typical sedimentary structures include ripple marks, low angle bidirectional cross-stratification, locally abundant desiccation features and halite pseudomorphs. Tool marks and current lineations are commonly developed on bedding surfaces. Current ripple marks are dominant over oscillation forms that are in places bevelled. Some of the ripple marked intervals include distinct low amplitude and low wavelength, lower energy forms.

Elongate gutter casts are well exposed in the lower Sweetwater Member in eastern MUCKATY near LV915240, and are 20-30 cm deep and up to 50 cm wide. The channels form in thinly bedded mudstone and fine sandstone and typically contain graded coarse to fine immature sandstone and imbricated flat pebble breccia infills. Current lineations often cross the gutter casts at high angles suggesting periods of inundation and desiccation (ie intertidal mudflats).

Sandstone of the upper interval of this member is typically thinly to medium bedded and very fine to medium in the lower parts, but coarsens upward into medium to thickly bedded, granule- to pebble-bearing, medium to very coarse sandstone and minor conglomerate. The sandstone has a distinct air photo expression and consists mostly of well indurated sublitharenite and quartz arenite. Most is pinkish-tan but at the top of the unit, the sandstone is lighter cream or grey. This uppermost interval consists of poorly to moderately sorted, graded conglomerate and medium to very coarse litharenite to quartz arenite. It contains well developed parallel, sinuous and bifurcating current dune forms (Figure 13) with consistent palaeocurrent directions. Trough or tabular cross-beds are common.

Conglomerate clasts include white vein quartz pebbles, subangular to rounded pebbles and cobbles of siltstone and sandstone, and angular to subangular stromatolitic carbonate, silicified dololaminite and chert. The carbonate and chert clasts may have been derived from carbonate rocks of the Namerinni or Tomkinson Creek Groups, but their angularity and localised abundance in this unit indicates that they may be intraformational.

Sedimentary structures and grainsize characteristics are consistent with an upward increase in depositional energy and water depth. The lower interval was probably deposited in a periodically exposed, locally saline shallow water environment. The depositional environment changes up-section through intertidal, to a high energy subtidal setting in the upper part.

Quartz is the dominant component of the Sweetwater Member. Up-section, there is an increase in the amount of polycrystalline quartz and metasedimentary lithic grains. Tourmaline and zircon are common accessories throughout.

The lower conformable contact with the Gleeson Formation is well exposed in a valley near LV564815. The contact is placed at the base of a very micaceous fine sublitharenite containing siltstone and shale interbeds that overlies thinly bedded quartz arenite of the Gleeson Formation. The basal sandstone is cream to greenish when silicified, or tan when weathered and leached, and has tabular, planar laminated beds. It also contains abundant angular chert clasts, flat silt and shale pebbles, and tabular moulds on some bedding planes. The underlying quartz arenite is cream to pinkish, well sorted, ripple marked and desiccated.
The Sweetwater Member resembles the Gleeson Formation, both lithologically and in general outcrop appearance. However, the upper lithofacies of the Gleeson Formation consists of fining- and maturing-upward cycles in contrast to the coarsening- and thickening-upward Sweetwater Member. There is also a striking lithostratigraphic similarity between the Sweetwater Member in HELEN SPRINGS and the Mantungula Formation and Limmen Sandstone of the Roper Group in MOUNT YOUNG.

The upper contact with the typically recessive, lowermost Grayling Member is rarely exposed. However, a sharp and conformable relationship occurs near LV630899. The Sweetwater Member is also flanked by the unconformably overlying Helen Springs Volcanics to the east of Renner Springs and is unconformably overlain by undifferentiated Lower? Cretaceous rocks near LV630890.

North-northwesterly and north-northeasterly trending faults may have been active during deposition. The northward thickening and east-west thickness variation of the upper unit suggests a wedge shaped geometry. Furthermore, the dune form palaeocurrent directions are remarkably uniform over a strike length of over 10 km and roughly parallel these faults, suggesting that the Sweetwater Member may have been deposited in a half graben under the influence of northward trending currents parallel to the long axis of the basin.

Grayling Member (Plb)
This newly defined member (see Appendix) is named after Mount Grayling in HELEN and is readily identified by its red-brown to red-purple or cream to green-grey, well laminated micaceous sandstone or siltstone. The upper units typically form rounded or benched, sparsely vegetated strike ridges whereas the remainder of the member tends to be recessive. The type section is located 10-15 km north of Mount Grayling between LV630890 (base) and LV645880 (top).

The upper units of the Grayling Member are usually subtly benched and this reflects several fining-upward cycles in an overall, slightly coarsening-upward succession, which is mostly composed of interbedded siltstone and fine to medium or rarely, coarse sandstone. The sandstone ranges from feldspar-bearing sublitharenite to quartz arenite. Yellow to pale apple-green glauconite is a
common accessory mineral observed in outcrop near the top of the member (eg at LV901634 and LV977155). Iron oxide pseudomorphs possibly after glauconite and/or pyrite locally occur in the lower part.

Detrital white mica up to 3 mm in length is abundant along bedding planes. Current lineations and tool marks are common features while internal structures include quasi-planar and hummocky cross-stratification. This is well developed near the base at LV632894 and in the upper intervals at LV642880 (Figure 14).

There is some variation in thickness of the Grayling Member throughout HELEN SPRINGS. However, its lithofacies and composition remain relatively uniform throughout. The Grayling Member is interpreted to have been deposited below fair-weather wave base and above storm wave base in a marine shelf environment.

Powell Formation (Prp)

The Powell Formation (new name, see Appendix) is named after Powell Creek in HELEN. The formation forms an extensive, almost continuous, upstanding strike ridge in the northern part of the Ashburton province, north of Morphett Creek in western HELEN SPRINGS. In northern HELEN SPRINGS, outcrop is more extensive and continuous, and continues northward into BEETALOO and NEWCASTLE WATERS where it is the dominant outcropping Proterozoic unit.

The formation dominantly consists of cream to white, variably silicified, thinly to thickly bedded sandstone, minor amounts of granule and pebble conglomerate and rare cream to greenish-grey mudstone. Most sandstone is of quartz arenite, and to a lesser degree, of sublitharenite composition.

Three informal subdivisions, namely the lower, middle and upper lithofacies, are based on facies associations, bedding and grainsize characteristics (Figure 15). Each unit displays distinct geomorphological features that are often identifiable on aerial photographs. Both the lower and upper lithofacies display lighter phototones and typically form more upstanding, benched strike ridges, in comparison with the middle lithofacies. Outcrops are often heavily jointed and have some rounded tor-like features, particularly in the recessive middle lithofacies. The total thickness of the Powell Formation ranges from 300-850 m in HELEN SPRINGS and is about 750 m thick in the type section, which is located on the western side of the Ashburton Range, just north of Gleeson Creek in HELEN (Figure 15).

Exposures of laminated to thinly bedded silicified mudstone in the lower lithofacies are rare (eg in a road cutting at LV649898), but mudstone is common as intraformational, tabular rip-up clasts in the ripple marked and desiccated sandstone intervals of the lower and upper lithofacies. Tabular mudstone lithoclasts are also common in medium to thickly bedded sandstone near the base of the upper lithofacies. However, they are rare or absent in the middle lithofacies.

The lower lithofacies displays considerable variations in grainsize, sorting, bed thickness, and textural and compositional maturity. This unit ranges in thickness between 50 m and 350 m and overall, it coarsens and then gradually fines upward. It is a succession of numerous, cyclic, large-scale channel deposits. Each of these contains medium to thick, trough or tabular cross-bedded, granular to fine pebble conglomerate or coarse sandstone at the base, which fines and thins upward over a 1-5 m interval to a fine or medium sandstone and locally to mudstone at the top. Medium to very thick beds are typical and often they pinch out laterally (Figure 16a). Pinch-and-swell bedding structures are common and some of the thicker bedded sandstone shows overturned cross-beds and fluid escape structures that are indicative of rapid sedimentation. Individual channels have sharp, irregular erosional contacts with underlying units (eg Figure 16b). In places, especially in the middle to upper parts of the lithofacies, abundant desiccation features, halite pseudomorphs and low energy, shallow water ripple marks occur at the top of each cycle (eg at LA635055). This stacked array of channels weathers in outcrop to form benched units, the thicker of which can be seen as strike ridges in aerial photographs.
Figure 16 Powell Formation; (a) medium to very thickly bedded, medium to very coarse sandstone of lower lithofacies at LV644908; (b) medium to thickly bedded sandstone overlying laminated to thinly bedded mudstone, lower lithofacies in road cutting near LV649898 (note irregular scoured contact between sandstone and mudstone in middle of photograph near scale); and (c) typical ridge top exposures of middle lithofacies near LV789635.
The middle lithofacies is typically medium to coarse, moderately to very well sorted and medium to thickly bedded throughout. Planar bedding, and low to high angle simple, and less commonly tabular cross-strata are typical. Reactivation surfaces are common in some intervals. These sedimentary features and the recessive weathering characteristics of this unit clearly distinguish it from the lower and upper lithofacies (Figure 16c). However it is noted that some intervals of the Jangirulu Formation and Short Range Sandstone are lithologically very similar to the middle lithofacies. Hence as noted previously, the possibility exists that rocks to the northeast of Ladabah Bore are not part of the Powell Formation as mapped, but are rather Short Range Sandstone.

The upper lithofacies is similar to the lower lithofacies and represents one major fining- and shallowing-upward cycle with less pronounced channels. In HELEN, the lowermost interval usually contains angular to subangular, tabular green-grey to cream, laminated to massive mudstone clasts up to 8 cm across. The uppermost sandstone of this lithofacies is often proliﬁcally rippled. Halite pseudomorphs are locally abundant and are commonly associated with desiccated ﬁner sandstone and mudstone intervals near the top of the formation.

The contact with the underlying Grayling Member of the Baralandji Formation is placed at the base of the ﬁrst white, thinly to medium bedded quartz arenite. This relationship is well exposed at numerous localities (eg at LV645880) in a 1-3 m transition from laminated red-brown or maroon micaceous sublitharenite. The white, basal quartz arenite beds in this vicinity often pinch out laterally and probably represent broad, higher energy channels. Similar relationships are observed in the type section. The contact with the overlying Wiernty formation is conformable and transitional to a thinly bedded ﬁne sandstone and mudstone (Figure 17).

The Powell Formation was deposited in a marginal, shallow marine setting. Channelling is evident on all scales in the lower lithofacies and individual beds are locally erosional (eg LV649898). There is also evidence for localised hiatuses, episodic subaerial exposure and hypersaline environments near the top of the lower and upper lithofacies. Ripple marks indicate a tidal inﬂuence, but palaeocurrents are clearly polymodal, particularly in the lower lithofacies, and suggest other inﬂuences such as longshore drift or river dominance. Ripple marks also vary from long wavelength, high amplitude, straight and sinuous crested current varieties (high energy tidally? inﬂuenced) to lower energy, shallow water varieties.

The lower lithofacies was deposited in a shallowing-upward marine environment. It probably represents initial sedimentation in an open, higher energy, subtidal environment that passed abruptly upward into a tidally inﬂuenced, prograding marine delta setting with localised supratidal environments in the upper parts. The middle lithofacies represents a return to intertidal and possibly subtidal settings. The maturity of this lithofacies suggests signiﬁcant winnowing and a setting that is probably mostly distal or longshore to the delta systems expressed in the lower lithofacies. The upper lithofacies reﬂects sedimentation shallowing towards supratidal settings and probably continued progradation.

**Wiernty Formation (Erw)**

The Wiernty Formation (new name, see Appendix) is a recessive unit consisting of mostly ﬁne siliciclastic and rare carbonate rocks. Typically, exposures are poor and form a wide valley between the more upstanding ridges of the underlying Powell Formation and the overlying Jangirulu Formation. Throughout most of southeastern HELEN, northeastern MUCKATY and western BRUNCHILLY, the Wiernty Formation is unconformably overlain by the Helen Springs Volcanics and undifferentiated Lower? Cretaceous units.

This formation outcrops throughout the Ashburton Ranges between the vicinity of Muckaty homestead and Elliott, and probable outcrops occur north and northwest of Banka Banka homestead. The most complete section of the Wiernty Formation (~500 m thick) is exposed on the ﬂanks of dissected hills of low relief which are partly capped by more resistant Lower? Cretaceous rocks in northernmost HELEN and southernmost ELLIOTT. In the vicinity of Wiernty Well, from which the unit name is derived, in central western HELEN SPRINGS, the formation is 400 m thick. It is interpreted to be substantially thinner (~100-200 m) in the south, near Banka Banka homestead, where it is inferred to underlie the Helen Springs Volcanics.

![Figure 17 Contact between upstanding Powell Formation (left) and recessive Wiernty Formation (right) at LV533845. Actual contact is located near backpack.](image)
The Wiernty Formation is subdivided into lower and upper lithofacies on the basis of variation in bedding characteristics and lithological associations. The lower lithofacies is composed mainly of planar to low angle cross-laminated, predominantly thinly bedded, fine to medium sandstone and mudstone that is in places prolifically rippled. There is a minor interval of thinly bedded dolomitic mudstone, calcareous siltstone and shale in the upper part of the lower lithofacies that is best exposed in southern ELLIOTT at LA615115.

The upper lithofacies provides the best exposures of the formation and forms rounded low relief benches that are well represented near LA590388. This unit has a distinctly greater proportion of intercalated, often coarser sandstone than the lower lithofacies. Desiccation cracks and halite pseudomorphs are often present in the finer intervals. These rocks form shallowing- and maturing-upward parasequences that are typically 1-10 m thick.

Sandstones of the Wiernty Formation are less texturally and compositionally mature, and are typically more micaeous than those of the preceding Powell Formation. Most are of sublitharenite or quartz arenite composition. Most labile grains are degraded and leached. However, feldspars and biotite, the latter mostly altered to chlorite, have been identified. Intraformational mudstone clasts are common in southeastern HELEN. Red and green mudstone is thinly interbedded with thinly and rarely medium bedded sandstone that in places contains graded bedding, current ripples, water escape structures and desiccation features. Contorted laminae and bedding with rollover structures are features of the lower ~10-15 m of the formation near LV533845. Asymmetric and symmetric ripple marks and parallel and ripple cross-laminations are common sedimentary features throughout most of the Wiernty Formation whereas trough cross-beds are confined to the upper lithofacies.

The contact between the Wiernty Formation and the underlying Powell Formation is exposed at LV533845 (Figure 17). It is placed at the base of the lowest thinly bedded, tan coloured, very fine sandstone and mudstone in a transition from white quartz arenite. Despite showing sharp and locally erosive contacts, sandstones of the upper lithofacies of the Wiernty Formation are transitional with those of the Jangirulu Formation. The mapped contact is placed at the base of a continuous quartz arenite succession that overlies the cyclic sandstone to mudstone parasequences of the Wiernty Formation. This is best exposed near LA592043 and LV 865466 in HELEN SPRINGS, and at LA576239 in ELLIOTT. Near LV880545 in HELEN SPRINGS, the cyclic parasequence arrangement is less obvious, although the relationship is still clearly transitional to the Jangirulu Formation.

Sediments of the Wiernty Formation were deposited in low energy, very shallow marine to supratidal marginal marine and possibly lacustrine environments. A shift towards episodic, higher energy environments is evident in the uppermost parts.

**Jangirulu Formation (Erj)**

The Jangirulu Formation (new name, see Appendix) is named after Jangirulu outstation in northwestern HELEN. It occurs in the northern Ashburton province in three separate regions in HELEN SPRINGS; the most extensive exposures occur in western HELEN and continue north into ELLIOTT. The formation is a distinct ridge-forming unit but good exposure is often confined to creeks or the edges of strike ridges. Complete stratigraphic sections are not exposed in HELEN SPRINGS. The most complete is the type section, 4 km east of Ferguson Bore in ELLIOTT (from LA576239 to LA566242, Figure 18). There, the formation is 845 m thick, whereas in HELEN it is only 350-400 m thick in a section along Bull Creek. Outcrops near LA529081 in HELEN SPRINGS represent the top of the formation.

The Jangirulu Formation mainly consists of quartz arenite, which is white to cream, grain-size-laminated, relatively uniform and moderately to very well sorted. Typically, the sandstone is medium to coarse, but finer rocks...
occur in the lower and uppermost parts of the formation. Bedding throughout the majority of the unit is thin to medium, and in places medium to very thick. However, very thin to thin beds occur in the lower and uppermost parts, where ripple marks are abundant. Halite pseudomorphs and desiccation cracks are usually restricted to the uppermost interval. Planar and tabular cross-bedding is common and minor pinch and swell bedding occurs in places.

Medium to thick, and rarely very thick, tabular or trough cross-laminated beds of coarse to granular quartz arenite locally occur about 50-150 m up-section in southern HELEN SPRINGS (eg at LV881543). These feature overturned cross-beds and fluid escape structures.

Most of this formation was deposited in a shallow intertidal to subtidal open marine environment, apart from the uppermost part where intertidal to supratidal environments dominated. The Jangirulu Formation is a lithostratigraphic correlative of the Bessie Creek Sandstone (Roper Group) in the McArthur Basin. It has similar rock types and sedimentary structures to the Powell Formation, although it is generally slightly finer, more thinly bedded and better sorted. Jangirulu Formation sandstone is very similar to that found in the middle lithofacies of the Powell Formation, the Short Range Sandstone and the Meerie Member of the Hayward Creek Formation.

Lake Woods beds (Prl)

Several low relief outcrops of sandstone, mudstone or chert on the western side of the Ashburton Ranges in HELEN SPRINGS and BEETALOO are mapped as Lake Woods beds (new name, see Appendix). This unit conformably overlies the Jangirulu Formation and the lower parts are intruded by dolerite. Outcrops of the Lake Woods Beds were previously mapped as Middle Cambrian Gum Ridge Formation (Randal et al 1966, Randal and Brown 1969) and were then reassigned to the Montejinni Limestone by Kennewell and Huleatt (1980). However, the Montejinni Limestone, which occurs west of the ranges in southern HELEN SPRINGS and in drillcore in southeastern NEWCASTLE WATERS (Kruse 1998), is distinct from outcrops mapped as Lake Woods beds.

The lowermost Lake Woods beds are recessive and comprise fine to medium, thinly bedded, ripple marked sandstone, siltstone and shale. Quartz arenite occurs in an overlying strike ridge and is fine to coarse, ferruginous, thinly to medium bedded and poorly to moderately sorted. In places, this interval features graded beds, bidirectional cross-beds and grain-size laminations. Sparse outcrops of sandstone, mudstone and chert in slightly higher stratigraphic intervals occur in northwestern HELEN, southwestern ELLIOTT and in excavations on the gas pipeline. The cherty rocks are probably stromatolitic dolostones. Nodular chert, probably after anhydrite, together with barite or gypsum or both, is also present.

The Lake Woods beds are probably at least 250 m thick in HELEN and ELLIOTT and were probably deposited in a predominantly shallow marine to supratidal setting. This unit is correlated with similar rocks in the basal part of the Velkerri Formation (Roper Group) of the McArthur Basin.

PALAEOZOIC STRATIGRAPHY

CAMBRIAN

Cambrian strata are widespread in HELEN SPRINGS and are subdivided into four formations: Helen Springs Volcanics, Gum Ridge Formation, Montejinni Limestone and Anthony Lagoon beds. Figure 2 shows the distribution of Cambrian strata in HELEN SPRINGS.

Helen Springs Volcanics (Clh)

The Helen Springs Volcanics (Noakes and Traves 1954) are widespread in HELEN SPRINGS and TENNANT CREEK, generally as localised valley fills in the Tennant Inlier, where they rest unconformably on an irregular surface developed on folded Proterozoic rock units. The unit is disconformably overlain by the Gum Ridge Formation and Montejinni Limestone (Middle Cambrian), which are also typically flat-lying. The Helen Springs Volcanics are thought to be Early Cambrian in age (Shergold et al 1985, Hanley and Wingate 2000). They comprise intensely weathered and lateritised tholeiitic basalt and minor microdolerite above a basal sandstone unit here formally named and defined as the Muckaty Sandstone Member (see Appendix). Basalt outcrops as mesas in the vicinity of Helen Springs homestead, but elsewhere is generally exposed as low hills, in creek beds or as pebble and cobble rubble.

The freshest basalt is dark grey to green-grey to dark purple, and weathers to dark maroon and red-brown and, in extreme cases, yellow and white. Amygdales of quartz (including milky, smoky, amethyst and chalcedonic varieties), chlorite, dolomite and/or zeolite are locally distinctive. The volcanics have an intergranular to subophitic texture of variably altered plagioclase laths and clinopyroxene (augite?). Where preserved, primary plagioclase is labradorite-andesine and has some normal and oscillatory zoning, but more commonly it is altered to secondary orthoclase, quartz, dolomite and/or albite. Clinopyroxene is partially replaced by chlorite, haematite and amphibole. This alteration probably relates to metasomatism by potassium-rich basinal brines. More severe alteration and weathering produce limonite, haematite, chlorite, sericite and quartz.

Randal (1973) reported a minimum 36 m of basalt in a bore at Muckaty homestead. As exposures of the contact with overlying Middle Cambrian units are rare, the undifferentiated portion of the Helen Springs Volcanics is here defined on the basis of a 7.3 m intersection in the cored drillhole NTGS96/1 at MV214640 (see Appendix). Similar thickness variations of Helen Springs Volcanics occur in TENNANT CREEK. Lanigan et al (1994) reported up to 440 m of probably equivalent basalt (Nutwood Downs Volcanics) from drilling in northern BEETALOO and TANUMBRINI.

Muckaty Sandstone Member (Clhm)

Basalt sandstone included in the Helen Springs Volcanics by Randal and Brown (1969) is here formally named and defined as the Muckaty Sandstone Member (see Appendix). This unit is known in the Georgina Basin but its extension westward into the Wisola Basin is uncertain. It mostly consists of well laminated, medium to thickly bedded, brown-grey
quartz arenite to sublitharenite, but can become increasingly conglomeratic towards the base. Of particular note is the occurrence of metre-scale cross-bed sets with dips surpassing 20°. Randal et al (1666) reported instances where this cross-bedding is up to 7 m thick.

Thickness variations of the Muckaty Sandstone Member can be dramatic. At LV859567, it is at least 16 m thick, but 2.4 km away at LV880582 it is a few millimetres to a maximum of 5 cm thick.

Sandstone typically has well sorted thin laminations to very thin beds defined by variations in grainsize, mostly of component quartz, which ranges from coarse silt to coarse sand or locally, granules. Quartz is typically well to very well rounded to occasionally subangular. It occurs generally as single monocrystalline grains, although a minority is of chert, microquartz, composite quartz or composite quartz+muscovite. Depositional grain shapes are outlined by vacuoles and bear thin syntaxial cement rims; a later generation of iron oxide or rarely, chalcedony cement may be present. Well rounded grains of alkali feldspar, plagioclase feldspar and tourmaline are also present in minor quantities. Iron oxide, muscovite and interstitial chlorite are minor constituents.

Conglomerate at the base of the Muckaty Sandstone Member typically incorporates subangular, pale pink quartz arenite pebbles and cobbles or mudstone flakes locally derived from the underlying units. These outsized clasts are lithologically identical to the Proterozoic units they overlie and are typically randomly dispersed in a well sorted, well rounded, medium to coarse quartz arenite matrix. Basal, trough cross-bedded, conglomeratic sandstone also occurs in a broad channel below the well laminated, well sorted sandstones north of Muckaty homestead. The sandstone matrix in this unit is a slightly different colour and less well sorted than is typical of the Muckaty Sandstone Member.

The uppermost surface of the Muckaty Sandstone Member typically displays a swirled pattern that is interpreted as having been caused by viscous flow and loading of the mantling basaltic lava (Figure 19). These patterns are suggestive of the ropy surface of pahoehoe lava and are here termed ropy impression marks. Some curved rill-like structures with 2-10 cm relief are also evident on this surface and are themselves covered by ropy impression marks. This is suggestive of lobe-like flow structures pushing quantities of sand aside as the lava progressed, or possibly of some differential loading of lava flow lobes. In places, relict straight crested to

Figure 19 Typical example of ropy impression marks preserved on uppermost surface of Muckaty Sandstone Member beneath chilled basalt of Helen Springs Volcanics at LV799853. Pencil is resting on basalt at base of photograph.

Figure 20 Example of peperitic texture in Muckaty Sandstone Member near LV825675, showing darker coloured blocky amygdaoidal basalt and massive red-brown medium sandstone.
bifurcating rippled surfaces are also overprinted by these ropy impression marks. Such features are widespread throughout HELEN SPRINGS, and even occur in the highest parts of a palaeovalley near LV889590.

Where this member is thin and conglomeratic throughout (eg in cliffs adjacent to the Stuart Highway at Maryville), quartz arenite pebbles on the uppermost surface typically protrude slightly above the level of the surrounding sandstone matrix and do not exhibit any ropy impression marks, even though the surrounding sandstone matrix does.

These ropy impression marks provide an interesting, although unusual method of demonstrating the nature of the overlying basalt and its contact relationships with the Muckaty Sandstone Member. Randal (1973) reported intergrowths of quartz and sillimanite or mullite in the sandstone at its contact with the basalt, thus indicating high temperature contact metamorphic effects. Inclusions of sillimanite? clusters have also been found in the basalt (Randal et al 1966). In almost all cases, the underlying sandstone remains well parallel-laminated despite the presence of an up to 5 cm thick indurated (silicified) contact and ropy impression marks on the upper surface of the sandstone. Furthermore, the preservation of ripples, rill-like structures and lamination immediately beneath the basalt all suggest that the sandstone was mostly tightly packed and dry, and that the ropy impression marks and rill-like features were formed on sandstone that was not lithified prior to basalt emplacement. Thus, these relationships indicate a sharp but conformable contact with no apparent time break between the sandstone and the basalt.

Rare peperites occur in the thicker parts of the Muckaty Sandstone Member, stratigraphically below the ropy impression-marked surface (eg near LV825675). They indicate that lava tunneled into less competent sandstone and has interacted with wetter un lithified sandstone. Laminations are disrupted and are not preserved in the sandstone immediately adjacent to the blocky basalt clasts (Figure 20).

These observations, together with the rapid thickness variations and typical occurrence of thick, high angle cross-bed sets in the unit, favour an aeolian dune interpretation for the depositional environment of the Muckaty Sandstone Member (Randal and Brown 1969). A relict 2-5 m high east-west trending dune occurs in a valley near Jeromiah Creek. Dip slopes of 30-35° are preserved beneath a mantle of basalt in this example, resulting in a domelike appearance. Domelike structures are also evident in the vicinity of Helen Springs and Muckaty homesteads, all representing original topographic relief in the dune fields. Some localised fluvial channels are present at the base of the succession.

Gum Ridge Formation (Cmg)

Opik (in Ivanac 1954) introduced the Gum Ridge Formation based on observations at Gum Ridge in TENNANT CREEK. The formation is also extensive in BONNEY WELL and FREW RIVER (Wyche and Simons 1987, Walley 1987, Donnellan et al 1999) and is presumed to underlie all or most of the Barkly Sub-basin in the western Georgina Basin.

At the surface, it consists of low rises of pervasively chertified and lateritised rubble, among which original centimetre-scale bedded impure lime mudstone (now red-brown to yellow-grey tabular chert) and massive limestone (now grey quartzite and chert) are commonly discernible. Both lithotopes are richly fossiliferous and yield trilobites, bradoriids, brachiopods, hyoliths, molluscs, chancelloriids and other problematic organisms (Kruse 1998). Among the trilobites, Redlichia and Aysistrura indicate an early Middle Cambrian (Ordian-early Templetonian) age (Opik, in Ivanac 1954, 1970, 1975). The hyolith Gaduguwalan hardmani is locally abundant as silicified coquinas. Scattered smooth, spheroidal pebbles represent original carbonate nodules, and rough-surfaced, nodular cherts indicate original evaporites. A recurring peritidal influence is indicated within a restricted marine depositional environment.

In HELEN SPRINGS, the freshest outcrop is in a roadcutting on the Stuart Highway south of Banka Banka at LV999183, where interbedded, silicified grey calcimudstone and hyolith rudstone are exposed. The contact with the disconformably underlying Helen Springs Volcanics is barely visible. At the northern rim of an eroded dome near 5 Mile Yard at LV818676, typical chertified Gum Ridge Formation is underlain successively by about 1.5 m of flaky, chocolate micaceous mudstone, 0.15 m of quartz pebble conglomerate with quartz sandstone matrix, and at least 0.8 m of brown, laminated, medium-coarse quartz sandstone; the mudstone, at least, can be confidently assigned to the Gum Ridge Formation. An equivalent interval outcrops 11 km southeast of Gum Ridge in TENNANT CREEK, where dark maroon-purple, rippled or cross-laminated, fine-medium quartz sandstone, beneath thinly bedded maroon mudstone, infills troughs in an irregular contact with the Helen Springs Volcanics.

In the low hills south of No 19 Bore on Brunchilly, the Gum Ridge Formation rests directly on probable Short Range Sandstone. There, the poorly exposed contact interval is marked by scattered cobble to boulder sized blocks of a dark brown medium quartz sandstone, which may represent the basal beds of the Gum Ridge Formation. No exposed contact with the overlying Anthony Lagoon beds has been recognised. Hence, the Gum Ridge Formation is here formally defined on the basis of a 150.5 m thick intersection in cored drillhole NTGS96/1 at MV214640 (see Appendix). The stratotype section spans the interval 84.4-234.9 m depth (Figure 21).

In the type section, the formation comprises two successive marine limestone units, each underlain by thin (8-10 m thick) peritidal intervals (Kruse 1998). Thus, the basal beds are of brown-maroon, mottled, finely brecciated siltstone, the texture of which is reflective of an evaporite solution origin. There is an upward transition through grey, similarly mottled, brecciated, strongly dolomitised limestone into the fossiliferous lower marine unit. Component limestones of this unit include grey massive, ribbon, bioclastic, lithoclast and minor ooid varieties that are all partially to strongly dolomitised to a yellow-brown colour.

The massive limestone is vaguely laminated and has stylolites, solution seams and millimetre-scale to centimetre-scale interbeds of darker grey, more siliciclastic carbonate mudstone. Distinctive centimetre-scale spheroidal concretions in this limestone are occasionally silicified and rarely enclose bioclasts (including hyoliths and trilobites). The micorspar matrix is locally strongly dolomitised.
Figure 21 Lithological and downhole geophysical logs of cored drillhole NTGS96/1, stratotype for Helen Springs Volcanics and Gum Ridge Formation and reference section for Muckaty Sandstone Member.
Massive limestone is intergradational into mottled lithoclast-bioclast wackestone containing carbonate debris and a mix of hyoliths (mainly *Guduguwan hardmani*), echinoderms, brachiopods, molluscs (mainly *Latouchella accordionata*), chancellorids, sponge spicules, fragmentary trilobites and rare bradoriides in lime mud, now microspar (Figure 22a). Bioclasts are likewise now microspar to coarser equant spar and at least some have undergone leaching and subsequent cement infilling. Coated grains are locally present, and may be selectively dolomitised.

Ribbon limestone is among the most fossiliferous of the limestone varieties (Figure 22b). It comprises centimetre-scale, interbedded dark grey, partially siliciclastic dolosparstone (Wright 1992) and light grey calcimudstone to bioclast wackestone. Textures range from well bedded to bioturbated nodular. Bioclasts are generally confined to the lighter, wackestone beds and some are microbially coated. These rocks were earlier described as ‘two-tone’ limestone by Kruse et al. (1990), but are here termed ribbon limestone based on the definition of Coniglio and James (1990). Although Coniglio and James dealt with ribbon limestones that differ in lithological detail and inferred depositional environment from that in the Gum Ridge Formation, their partly depositional-partly diagenetic model for the generation of such limestones may well be applicable. In this model, the original depositional heterogeneity of lithofacies is enhanced by the purging of dispersed carbonate from siliciclastic beds into nearby carbonate beds during shallow burial.

Oncoid (dolo)rudstone contains concentrically textured oncoids up to 2-3 cm in diameter (Figure 22c). The matrix may include bioclasts or peloids and some bioclasts bear micrite envelopes or microbial encrustations.

The interval 143-153 m in the stratotype is marked by grey, mottled, siliciclastic mudstone, and associated stromatolites and microbial dololaminite. These are indicative of the recurrence of peritidal conditions. Immediately above this interval, ribbon limestone reappears in the upper marine limestone unit. However, the bulk of the upper unit is a light grey to yellow-grey, more or less nodular, massive limestone, now strongly dolomitised to dolosparstone. This limestone has much visible porosity and little preserved original texture other than thin siliciclastic interbeds.

Comparison of the Gum Ridge Formation with the coeval Tindall Limestone of the Daly Basin to the north is apt. The ribbon, bioclast and some of the massive limestones are alike in the two formations. In addition, both units commence with maroon siliciclastic siltstone, and include very similar, brief peritidal intervals recognisable by their association of siliciclastic mudstone and microbial dololaminite. However, despite the similar thicknesses of the two formations (maximum of 182.8 m for Tindall Limestone), these peritidal episodes demark up to four marine intervals in the Tindall Limestone, as opposed to the two observed in the Gum Ridge Formation. This discrepancy is due to the southeasterly lensing out of some individual peritidal intervals across the

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**Figure 22** Gum Ridge Formation lithotopes, all from drillhole NTGS96/1 at Nilly Waterhole (MV214640); (a) bioclast-coated grain wackestone (photomicrograph NTGS 5113 from 196.6 m depth); (b) bioturbated ribbon limestone (photomicrograph NTGS 5119 from 139.1 m depth); (c) oncid dolorudstone with bioclast- and peloid-rich matrix (photomicrograph NTGS 5111 from 225.0 m depth). Width of each field is 13 mm.
Daly Basin (Kruse et al 1994) and this is reflected by an overall southeasterly increase in the proportion of carbonate as opposed to siliciclastic sediment comprising the Tindall Limestone. The Gum Ridge Formation, further to the south, shows an even greater proportion of carbonate sediment (94% in NTGS96/1). The mid-formation peritidal intervals of these two units can be confidently correlated. Thus, the Gum Ridge Formation can be viewed as a more offshore shelf equivalent of the Tindall Limestone that was unaffected by two of the four relative sea-level lowstands experienced by the latter.

Montejinni Limestone (Cmm)

Wiso Basin strata attributed to the Gum Ridge Formation in HELEN SPRINGS by Randal and Brown (1969) are here reassigned to the Montejinni Limestone (Traves 1955) consistent with Kennewell and Huleatt (1980). However, outcrops designated as Montejinni Limestone in northwestern HELEN by Kennewell and Huleatt are units of the Mesoproterozoic Renner Group, so that in HELEN SPRINGS, the Montejinni Limestone is exposed only in an area southwest of Ladabah Bore.

The Montejinni Limestone is a unit of limestone, dolostone, mudstone and minor dolomitic quartz sandstone that is apparently continuous across the entire Wiso Basin. It attains a maximum known thickness of 151 m in BMR drillhole Green Swamp Well 6 (Kennewell and Huleatt 1980). Best outcrops are along the northwestern margin of the Wiso Basin (DELAMERE, VICTORIA RIVER DOWNS, WAVE HILL), although these are principally of the basal, microbially laminated lithofacies. The formation thickens and becomes more dolomitic southward, and extends at least as far as TENNANT CREEK (Donnellan et al 1999).

The Middle Cambrian (Ordian-early Templetonian) age of the formation is established from its fossil fauna, which includes the trilobite Redlichia, brachiopods, hyoliths, echinoderm plates, sponge spicules and chancelloriids (Traves 1955; Milligan et al 1986), together with molluscs and rare bradoriids (Kruse 1998). Close faunal similarities at the specific level with the Tindall Limestone (Daly Basin) and Gum Ridge Formation (Georgina Basin) confirm correlations with those units (Kruse 1998).

Like the Gum Ridge Formation, the Montejinni Limestone outcrops in HELEN SPRINGS as low rises of pervasively chertified and lateritised rubble, and yields the same range of rock types. However, despite similarities of fauna and outcrop style, a comparison between the Gum Ridge Formation in cored drillhole NTGS96/1 and the Montejinni Limestone, as described by Donnellan et al (1999) from drillholes in TENNANT CREEK and adjoining map sheet areas, indicates that they are sufficiently dissimilar in lithological detail to justify separate formation names.

Anthony Lagoon beds (Cmy)

Georgina Basin strata assigned to the Anthony Lagoon beds (Plumb and Rhodes 1963, 1964) are extensive in eastern HELEN SPRINGS and underlie black soil plains of the Barkly Tableland. The Anthony Lagoon beds have been mapped across wide tracts of the Tableland; at least 395 m of carbonate and minor sandstone and shale in Brunette Downs 1 drillhole (BRUNETTE DOWNS) has been attributed to the unit (Mines Administration 1965, Randal 1966).

In HELEN SPRINGS, outcrop generally consists of residual rubble on very low rises, in association with scattered ironstone pebbles (iron-enriched and iron-coated fine quartz sandstone to siltstone). The rubble includes red-brown, yellow-brown, chocolate-brown and grey pebbles and cobbles that are pervasively silicified and chertified. These represent original limestones, quartz sandstones and probable siliciclastic and calcimudstones (Donnellan et al 1999). Rare nodular chert implies original evaporites. Local boulder fields of quartz sandstone may represent genuine outcrop.

Fossils are rare and fragmental, and include indeterminate trilobites, echinoderms, brachiopods and stromatolites. On regional stratigraphic grounds, the Anthony Lagoon beds were correlated by Shergold et al (1985) with the Wonarah beds and Burton beds, of late Templetonian-Floran (early Middle Cambrian) age (Southgate and Shergold 1991). The unit is presumed to overlie the Gum Ridge Formation with minor disconformity.

Meagre outcrop data are greatly enhanced by the cored drillhole NTGS96/1 at MV214640, which intersected the basal 50 m of strata assigned to the Anthony Lagoon beds in HELEN SPRINGS (Figure 21). The similarity of these strata to the Jinduckin Formation of the Daly Basin is striking, and they are described here using the lithotope categories of Kruse et al (1990, 1994).

Maroon dolomitic-siliciclastic siltstone

This is the most abundant lithotope, accounting for 68% of the intersected interval (Figure 23a). It consists of approximately equal proportions of fine dolomite spar and interstitial iron oxides+clays, the latter imparting the maroon-brown colour to the rock, together with up to 15% angular to subangular, medium silt-sized to very fine sand-sized quartz. Interstitial calcite and scattered acicular anhydrite are accessories. Original nodular to quasi-bedded evaporite is commonly preserved as a coarse dolomite mosaic; some of this has a poikilitic texture that encloses acicular anhydrite and quartz silt. On this basis, the pervasive, finely brecciated texture of the rock can be attributed to evaporite solution, as can occasional, coarser, flat-pebble breccia of brown mudstone clasts. Grey and yellow-grey dolomitic mudstone toward the base of the formation is included in the lithotope.

Dolomitic sandstone-siltstone interbeds

These are insignificant in the intersected interval (Figure 23b). Darker interbeds in the one thin (20 cm) interval are of olive-green dolomitic-siliciclastic mudstone, which has lamination highlighted by size variations of the component dolomicrospar. They include up to 40% admixed, angular-subrounded, fine silt-sized to very fine sand-sized quartz, together with scattered iron oxides and accessory muscovite. Lighter interbeds are commonly a poikilitic texture of coarse calcite spar, which encloses densely packed dolomite rhombs.

Ooid dolograinstone

Only thin (millimetre-scale) beds of ooid dolograinstone are present in the intersected interval in drillhole NTGS96/1 (Figure 23b), but the lithotope is also known at the surface.
Figure 23 Anthony Lagoon beds lithotopes, all except (c) from drillhole NTGS96/1 at Nilly Waterhole (MV214640); (a) maroon dolomitic-siliciclastic siltstone, with nodular evaporite at top and greater abundance of quartz silt elsewhere (photomicrograph NTGS 5128 from 59.4 m depth); (b) dolomitic siltstone-dolosparsstone interbeds, including ooid-rich interbed (photomicrograph NTGS 5125 from 75.9 m depth); (c) chertified ooid dolostmagesite (photomicrograph NTGS 5144, outcrop sample from Eaglehawk Dam at MV667474); (d) undifferentiated dolostone showing lithoclast wackestone with nodular evaporite at bottom (photomicrograph NTGS 5123 from 82.7 m depth); (e) cryptomicrobial dolostone showing portion of silicified domical stromatolite (photomicrograph NTGS 5126 from 71.9 m depth); (f) cryptomicrobial dolostone showing cryptomicrobial dololaminite (photomicrograph NTGS 5124 from 81.7 m depth). Width of each field is 13 mm.
(Figure 23c). Ooids are preserved either as a mosaic dolomite (showing both concentric and radial structures) or as very coarse equant calcite.

Undifferentiated dolostone
This lithotope includes lithoclast wackestone (Figure 23d) that bears carbonate (now pseudospar) and minor siltstone lithoclasts in a lime mud matrix, as well as minor angular quartz and detrital iron oxide silt. Nodular evaporite (now coarse equant calcite spar) is distinctive. These and other carbonate rocks may be almost totally recrystallised to dolosparstone.

Cryptomicrobial dolostone
Cryptomicrobial dololaminites are present only as rare, thin beds (Figure 23f). Component laminations are defined by variations in dolomicrospar crystal size. As in other lithotopes, dolomitisation is not always complete and remnant interstitial calcite may persist. Centimetre-scale domical stromatolites (Figure 23e), which are rare in most lithotopes, may show patchy siliconification.

Dolomitic quartz sandstone
This lithotope is not intersected in drillhole NTGS 96/1, but brown to purple, fine to medium quartz sandstone, presumably leached of an original dolomite component, is known at the surface. The stratigraphic distribution of this sandstone appears to mirror that in the lithologically similar Jinduckin Formation of the Daly Basin: rare to absent in the lower part of the formation, but common in the upper part (Kruse et al. 1990).

Given the close similarities with the Jinduckin Formation, strata assigned here to the Anthony Lagoon beds can likewise be viewed as a record of peritidal deposition on a mixed carbonate-siliciclastic tidal flat that was subjected to recurring supratidal exposure (Kruse et al. 1990).

This same lithological similarity invites correlation of the two units. However, on accepted lithostratigraphy this would create a paradox whereby the present strata are correlated both with Middle Cambrian units (Wonarah beds, Burton beds) in the Georgina Basin and with the Upper Cambrian-Lower Ordovician Jinduckin Formation. This raises the possibility that the Jinduckin Formation may in fact be Middle Cambrian in age. Thus, the one known age-diagnostic fossil locality attributed to this formation (see Kruse et al. 1990) may represent an overlying, much younger, Early Ordovician unit. Alternatively (or concomitantly), the HELEN SPRINGS strata may represent a unit distinct from the Anthony Lagoon beds as originally described in the northern Georgina Basin and can be directly assigned to the Jinduckin Formation or an equivalent. More data on the Anthony Lagoon beds are required before this correlation problem can be resolved.

MESOZOIC UNITS

CRETACEOUS (K1)

Undifferentiated, flat-lying Early Cretaceous sedimentary rocks in HELEN SPRINGS represent southern outliers of the Dunmarra Basin (Eupene 1990). Outcrop ranges from prominent plateaux and mesas to low boulder rubble. It occurs in palaeovalleys locally on the Tennant Inlier throughout HELEN SPRINGS and is widespread on the Georgina Basin in northern HELEN SPRINGS.

Rock types include intercalated, thinly to thickly bedded, fine to coarse sandstone (including micaceous varieties), siltstone, claststone and conglomerate. These are white to yellow-brown where fresh, but may also display variegated white/yellow/brown/purple colours; weathered surfaces are commonly ferruginised to orange-brown, red-brown or black. Among sedimentary structures are millimetre-scale to metre-scale cross-beds, ripple marks, desiccation cracks and horizons of tabular mudstone pebble moulds.

These rocks are dated by reference to the more complete
Cretaceous succession in the northern portion of the Northern Territory. This was dated as Neocomian to Albian by Skwarko (1966), but has since been reinterpreted by Krassay (1994) as Aptian to Cenomanian. The maximum extent of Australian Cretaceous seas was in the Aptian, during which the HELEN SPRINGS region was inundated (Frakes et al. 1987). Fossil localities in HELEN SPRINGS yield plants (at LV877092 and LV748493, as well as at MA815101 in BEETALOO), trace fossils (at LV730643, LV831734, LV835714, LV843603, LV878092 and MV939938), rare pelecypods (at LV730643) and belemnites (with pelecypods/brachiopods? in coquina at LV861573). Plant remains include stems and leaves, among which Hausmannia sp. has been identified (White 1966). Among the trace fossils are vertical dwelling burrows or root moulds, horizontal bilobed burrows and backfilled burrows.

These undifferentiated Early Cretaceous rocks were deposited on irregular surfaces with preexisting palaeochannels and topographic relief, as is evident in the Tennant Inlier. For the most part, these units appear to have been deposited in a fluvial to lacustrine environment locally dominated by plant fossils in quiescent settings, although the local presence of shelly coquina in the lowermost levels (eg near LV861573) suggests some marine influence.

CENOZOIC UNITS

MIocene

Brunette Limestone (Czb)

The Brunette Limestone (Noakes and Traves 1954) is a thin unit of white to grey limestone that is widespread on the central and western Barkly Tableland. The limestone may be nodular to brecciated, (quasi)laminated, chaledonic, tufaceous or a calcimudstone. It is locally silicified to white and/or purple-brown tones. Exposures are generally poor, and range from scattered cobbles to boulder fields. Pale, chocolate-brown soils, commonly with a network of deep cracks provide evidence that the unit occurs in the shallow subsurface. Apparently genuine outcrop caps a low mesa on Anthony Lagoon beds along Brunchilly Creek at MV750090.

In HELEN SPRINGS, the formation has a maximum known thickness of 4.6 m (Randal and Brown 1969), whereas in neighbouring BRUNETTE DWNS, about 18 m was reported by Randal (1966).

Noakes and Traves (1954) proposed an internally drained lacustrine origin for the Brunette Limestone. Lloyd (1963, 1968) listed gastropods, pelecypods, an ostracode and the foraminifer Ammonia beccarii, indicative of a Miocene or younger age, and suggested a shallow marine, lagoonal or brackish depositional environment. However, at least some of the nodular/brecciated limestone is unquestionably pedogenic, and has rhizoliths, petrified plant roots, soil glaebules (displaying circumgranular and intragranular cracks) and minor clay cutans, alveolar texture and Microcodium (see Esteban and Klappa 1983). This indicates a subaerial calcrete origin (Figure 24). Both alpha fabrics (with dense, micritic to microsparitic groundmasses) and beta fabrics (dominated by biogenic features) are present (Figure 25; see Wright and Tucker 1991).

QUATERNARY

Ferricrete, ferruginised rock or iron-rich pisolites (Czf) are relatively common throughout HELEN SPRINGS, but are indicated on the accompanying map only where sufficiently widespread. Extensive, dissected laterite profiles are sometimes evident in the ranges (eg near LV910470) and have been included in this unit. Silcrete or intensely silicified rock (Czi) is also commonly developed on units in the Tennant Inlier. Most outcrops of Cambrian limestone are intensely silicified. Calcrete (Czk) is typically rare in the Tennant Inlier although it does occur locally (eg on the Morphett Creek, Attack Creek, Carruthers and Shillinglaw Formations). However, it is commonly associated with the Brunette Limestone. Calcrete is also found but is not mapped in northwestern HELEN SPRINGS and may be associated with the former extent of Lake Woods (cf Bowler et al 1998).

Dissected Cenozoic talus slope and colluvial deposits (Cze) flank palaeovalleys and locally spread across palaeovalley floors (Figure 26). They include massive, normally and reversely graded, poorly sorted, subangular to angular conglomerate, sandstone and siltstone. These

![Figure 26 Example of dissected Cainozoic talus slope deposit flanking ridge of Short Range Sandstone at LV911134.](image-url)
deposits are dated by reference to the Cretaceous valley fill. They occur at a higher topographic position and typically lack the intense silicification and deeply leached weathering profile, common to rocks above and below the Cretaceous land surface, respectively, in HELEN SPRINGS. Their highly dissected appearance suggests they are probably older Cenozoic deposits. Examples occur throughout the ranges in HELEN SPRINGS.

Western HELEN SPRINGS is mostly red sandy soils and sand plains (Qs). This map unit represents colluvial and aeolian deposits, including rare, stabilised, northwest trending longitudinal dunes in the southwest and minor alluvium. Grey-black, clay-rich soil plains (Qb) dominate eastern HELEN SPRINGS, but in many places, are not indicated on the accompanying map in order to highlight subcrop. Extensive gilgai development is often expressed in this unit and is especially evident in large palaeodepressions (Qap) that occur in northern HELEN SPRINGS. These depressions may be relics of terminal ephemeral lakes containing extensive lacustrine as well as both alluvial and colluvial deposits.

Active colluvial (sheetwash) and talus slope deposits (Qc) commonly flank the ranges. Active alluvial channels (Qa) drain these higher relief regions and these also occur as internally draining features in eastern HELEN SPRINGS. Clay pans or clay-filled depressions (Qp) are common in active alluvial channels and floodouts, but are also evident in relict systems in southwestern HELEN SPRINGS. At least one clay-filled depression (near LV550154) appears to have been influenced by relatively recent faulting. This is inferred by the presence in the sand plains of a prominent lineament that forms the western margin of the clay plain. In this respect the clay pan may be analogous to Lake Surprise, which is further indicated by the presence of relict alluvial channels in TENNANT CREEK. It is interesting to note that these clay pans and depressions lack extensive evaporite development. Localised, relict, sand-covered alluvial channels (Qas) are common in the western half of HELEN SPRINGS.

The relationship between colluvial and aeolian sand and lacustrine mud in the vicinity of Lake Woods suggests a complex Cenozoic geological history that had several stages of development (eg Bowler et al 1998). Although this complex history is not differentiated on HELEN SPRINGS, some implications are discussed here.

As pointed out by Randal et al (1966) and Randall and Brown (1969), sand plains are actively prograding over the black soils. However, by analogy with observations in southeastern ELLIOTT where isolated residual sand plains overlie black soils developed on Cretaceous rocks, both are actively being eroded. Thus, the sand plains that flank the ranges may also be, in part, older than the black soils. Similarly, older sand plains may have been stripped from eastern HELEN SPRINGS. The existence of older sand plains is further indicated by the presence of relict alluvial channels and clay pan floodouts that are now covered by younger sand deposits in the sand plains. Longitudinal dunes and a thin veneer of sand plain deposits also overlie black soils in the western and southern parts of a much larger palaeo-Lake Woods. However, these sand dunes are not present in the youngest parts of Lake Woods (Bowler et al 1998), as would be expected if the sand plains were migrating across the black soils in general.

Currently, Lake Woods, a terminal ephemeral lake located mainly in southeastern NEWCASTLE WATERS and southwestern BEETALOO, fluctuates between a dry lakebed and a water body with a maximum area of about 600 km². Lake Woods is well known for its ancient shorelines that surround its western margin in NEWCASTLE WATERS and SOUTH LAKE WOODS and these indicate a palaeo-megalake many times the current size (Hills 1955, Randal 1969, Bowler 1981, Hutton et al 1984, Chappell 1991, Bowler et al 1998). Based on longitudinal sand dunes to the west and its shoreline stratigraphy, this megalake is inferred to have existed for extended periods as a secular feature and was not merely related to random flood events (Bowler 1981, Hutton et al 1984, Bowler et al 1998). Recent application of luminescence dating techniques (Hutton et al 1984, Bowler et al 1998) provides timing constraints on the development of Lake Woods. These dates show a basinward aggradation of shorelines and cyclic lacustral (basin flooding) events. Indirectly, they also provide clues to the development of Quaternary units in HELEN SPRINGS, as discussed below.

Based on elevation and levelling data of ostracode-bearing sands in these ancient shorelines, lacustral environments that defined the shorelines occurred at about 180 ka, 96 ka and 60-30 ka. In these megalake stages, palaeo-Lake Woods filled to ~213 m ASL and enlarged to about 5400 km². This is about 10 times the current maximum size. The megalake partly filled recessive valleys in the Ashburton Ranges and linked with Lake Arbunka on the eastern side of the Ashburton Ranges in BEETALOO (Bowler 1981, Bowler et al 1998). The final major lacustral event in the Holocene resulted in a lake level of ~205 m ASL (Bowler et al 1998) and shorelines related to this event appear to be evident in northwestern HELEN. Further west and southwest in SOUTH LAKE WOODS, lacustrine mudstones (black soils) found above this elevation are now covered by aeolian longitudinal dunes that are related to drying near 30 ka. Since that time, hydrologic events controlling the conditions of today have prevailed, although at least one flooding period of semi-permanent duration (at least 20 years) is recorded by Unio shells dated to 600 years BP (Bowler et al 1998).

A large depression in northern HELEN, northern MONMOONA and southern ELLIOTT also has shorelines of similar elevation (~213 m) on its western side in northwestern HELEN. A definitive link between this depression and Lake Arbunka is yet to be established because elevation data are sparse and there may have been a slight topographic barrier given quoted elevations. However, a link may have existed given that an older more diffuse shoreline is a further 25 km west of the abovementioned shorelines around Lake Woods (eg Hutton et al 1984). This suggests that there may have been an earlier megalake stage which expanded to much higher elevations, ~220-225 m, and extends support to the view that large regions of the black soil plains were probably linked as part of a megalake system. Thus, black soils in these regions are lacustrine in origin. However, based on elevation data, not all black soils in HELEN SPRINGS are related to this lacustral event. The Miocene Brunette Limestone, for example, overlies depressions in the black soil plains that are at higher elevations and this suggests that some black soils may have developed much earlier.
In many cases throughout HELEN SPRINGS, the black soils now appear as a residual soil or colluvium of intensely weathered and degraded rock present on gently undulating topography, although some does occur in drainage systems and depressions and is clearly fluvial or lacustrine. In most cases, deeply weathered rock, be it Helen Springs Volcanics, Gum Ridge Formation, Anthony Lagoon beds or undifferentiated Lower Cretaceous units are evident in the mapped black soil unit or are actually mapped instead of the latter. Heavy grey clayey soil encountered in the uppermost 2 m of NTGS96/1 is similar to that described by Randal et al (1966) and Randal and Brown (1969), and is reportedly common in this region.

The above discussion indicates a complex geological history that may in large part be broadly classified as Cenozoic. However, the sand plain and black soil units are specifically mapped as Quaternary rather than Holocene, based on the dates of Bowler et al (1998) from Lake Woods and the fact that the region is undergoing active erosion and reworking.

STRUCTURE

The structure of the Ashburton province in HELEN SPRINGS is dominated by north-northwesterly, north-northeasterly and northeasterly trending faults, and by less significant northwesterly trending faults. These tend to form elongate fault block geometries. Most of the faults appear to be subvertical and both normal and reverse senses of movement are documented, although some faults are rotational. Moderate to low angle faults have been identified, but these are rare. Randal et al (1969) used these faults to divide the outcropping Proterozoic rocks into four main fault blocks. This rather simplistic view has proven useful, as stratigraphic continuity is often evident within individual blocks. However, the overall structural picture is more complex than originally portrayed.

Both their Tomkinson-Powell and Bootu Blocks are cut by numerous faults, some showing vertical displacements equivalent to that which they used to define the structural boundaries, and structures in northern HELEN SPRINGS often propagate southward into their Whittington Block, suggesting a more complicated structural arrangement. In addition, the eastern margin of their Whittington Block does not coincide with a known structure and a tilted horst of Namerini Group is present in their Tomkinson-Powell Block; this suggests the presence of distinct fault blocks within the latter.

The Proterozoic rocks of the Ashburton province typically show low to moderate bedding attitudes, particularly in northern HELEN SPRINGS, although beds can range from subhorizontal to subvertical and rarely may even be locally overturned adjacent to faults. In general, most folds display open to moderate interlimb angles and lack pervasive axial planar cleavages, although associated conjugate fracture cleavages are sometimes evident. Tight to isoclinal folds are present but these tend to be developed in or adjacent to major fault zones.

The earliest major period of folding produced regional northwest trending map-scale anticlines and synclines that are restricted to the Tomkinson Creek Group. These folds are particularly evident in MUCKATY and also in FLYNN, and regional aeromagnetic data suggest that they continue beneath the Georgina Basin in eastern HELEN SPRINGS. Although structurally complicated by later north-northwesterly faulting, a map-scale syncline that is related to this event is also evident in northwestern BRUNCHILLY. It is proposed that this earliest folding event generally produced more open fold styles and that the tight, northwesterly trending folds in MUCKATY have been enhanced by northwesterly faults. The open fold geometry is evident in the general distribution of Short Range Sandstone outcrop as well as in the synclines of central FLYNN and northwestern BRUNCHILLY. The absence of a well developed axial planar cleavage also suggests that this folding event was not intense and occurred at a relatively high crustal level. These major northwest trending folds clearly predate the prominent faults in HELEN SPRINGS.

North-northwesterly trending faulted synclines and anticlines are superimposed on earlier folds in the Tomkinson Creek Group, whereas anticlines, synclines, homoclines and asymmetric folds are present in the Namerini and Renner Groups. These latter folds have notably shorter wavelengths, are often more intensely developed locally, and are clearly related to faulting rather than regional folding. There is often a dramatic steepening in bedding attitudes towards the northerly trending faults. Fold geometries and localised cleavage development (typically on the western side of major north-northwesterly trending faults) generally suggest reverse movement on steeply easterly dipping faults. Quartz dissolution and white mica growth are common in these high strain zones within a dominantly brittle regime. Quartz veins are not a common feature in HELEN SPRINGS, but do occur in these zones.

Open folds are present in the Renner Group. These may likewise be related to fault block movements. Outcrops of Renner Group show conjugate sets of fracture orientations that suggest horizontal east-west compression orthogonal to the major faults.

The Muckaty-Renner Block is a fault bounded, broadly synclinal structure. It is the southern extension of the Beetaloo Sub-basin, a major gravity low to the north of HELEN SPRINGS. Relationships in HELEN SPRINGS suggest that this gravity low is principally the result of structural effects and it can probably be explained by relative downfaulting and tilting of the Renner Group. The Muckaty-Renner Block is also cut by faults but poor outcrop prevents extrapolation. The current juxtaposition of units indicates that some faults were active both prior to and following deposition of the Renner Group.

Significant structuring of the Ashburton province is evident prior to the deposition of the Renner Group. Minor tilting also appears to have occurred before deposition of the Namerini Group but the limited exposure of this contact precludes an adequate understanding. Apparent shifts in palaeocurrent directions and variations in unit thicknesses suggest that there has been variable subsidence and extension throughout the Ashburton province during this interval.

The Ashburton province is unconformably overlain by units of the Georgina and Wiso Basins and these are in turn overlain by Cretaceous units of the Dunmarra Basin. Minor fault reactivation is evident in these younger units although most deformation occurred before deposition of the Georgina and Wiso Basins. Aeromagnetic data clearly indicate that the Helen Springs Volcanics were subjected to later faulting.
GEOPHYSICS

HELEN SPRINGS is covered by regional airborne magnetic and radiometric data acquired in November 1993. These data were obtained using GPS navigation at an average terrain clearance of 100 m along 500 m spaced east-west flight lines. North-south tie lines were flown at 5000 m intervals. The data are available from NTGS, Department of Mines and Energy, Darwin. Regional aeromagnetic data are also available over BEETALOO, NEWCASTLE WATERS, SOUTH LAKE WOODS and TENNANT CREEK and have been considered in the interpretation of HELEN SPRINGS.

An earlier aeromagnetic survey over part of western HELEN SPRINGS was acquired by Aerodata in 1985 on behalf of Clifford Minerals at 200 m line spacing (Ward 1988c). Additional, closely spaced aeromagnetic surveys over small areas were also acquired by Stockdale Prospecting Ltd (Hwang 1994a, b, c) to investigate several prospective dipole anomalies in eastern HELEN SPRINGS.

Regional gravity data are available over HELEN SPRINGS at an average station spacing of about 11 km. These data are available from AGSO as part of the Australian national gravity database. More detailed gravity surveys were acquired by Scintrex PL for Clifford Minerals over parts of HELEN and MUCKATY (Ward 1988c). A further 350 gravity stations were acquired by Search Exploration PL for MIM Exploration over the southern parts of this area (Bruce 1993). No additional gravity data were collected during the present mapping. The widely spaced nature of the available gravity data prohibits any detailed interpretations and suggests that anomalies can typically only be attributed to regional features and/or relatively deep sources.

The solid geology interpretation of HELEN SPRINGS portrayed on the accompanying map is largely based on integration of geological observations and geophysical interpretations extrapolated from outcropping units. This synthesis builds on that of Donnellan et al (1995, 1999).

Gravity Data

Low amplitude Bouguer anomalies within HELEN SPRINGS have a total range of about 200 μm s^-2. On a regional scale, HELEN SPRINGS is part of an extensive, inclined gravity platform in the central and northern parts of the Northern Territory, the gravity values of which gradually increase to the north. In the vicinity of HELEN SPRINGS, low amplitude gravity features form a series of mostly northwesterly trending curvilinear highs and lows which are truncated by northerly, north-northwesterly and northeasterly trending structures (eg Farrar 1994, Donnellan et al 1995).

A regional gravity low occurs south of HELEN SPRINGS and almost encroaches on its southern margin. This gravity low coincides with outcrop of the Flynn Group in northern TENNANT CREEK. In general terms, it corresponds to the central Tennant Inlier and broadly outlines the extent of the younger Ashburton province beneath the Georgina and Wiso Basins.

Plumb and Wellman (1987) outlined the Beetaloo Sub-basin within the Dunmarra Regional Gravity Low (Fraser et al 1977). This gravity low mostly occurs in BEETALOO and TANUMBIRINI but also extends southward into HELEN SPRINGS where it corresponds with downfaulted Renner Group in the Muckaty-Renner Block. Thus, based on Ashburton province geology, the Beetaloo Sub-basin is interpreted to be the result of later structural complications and is not a rift basin as proposed by Plumb and Wellman (1987). Lanigan et al (1994) reached similar conclusions based on seismic studies across the Beetaloo Sub-basin. Similarly, the entire Dunmarra Regional Gravity Low is probably the result of later structures.

Magnetic data

Long wavelength magnetic anomalies of the order of 300 nT in southern HELEN SPRINGS extend into northern TENNANT CREEK and southern SOUTH LAKE WOODS and correspond to the lowermost Tomkinson Creek Group. These can typically be resolved into two or three distinct magnetic units throughout MUCKATY and BRUNCHILLY and are specifically attributed to basalt in the Whittington Range Member and associated dolerite sills in the Hayward Creek Formation. In addition, this stratigraphic interval also typically registers the highest Bouguer anomaly values in the Ashburton province. Hence, this approximately 3.5 km thick stratigraphic interval at the base of the Tomkinson Creek Group is denser and more magnetic than most rocks in this region.

Apart from magnetic dolerite sills in northern HELEN, there are no other highly magnetic units within the Ashburton province. Thus, it is possible to trace the lowermost Tomkinson Creek Group by geophysical means. This assists regional interpretation of the structural framework in areas lacking outcrop and also suggests a method for obtaining wider lithostratigraphic correlations.

Interpretations indicate that most units beneath the Georgina and Wiso Basins in HELEN SPRINGS are geophysical equivalents of those outcropping in the Ashburton province. The geophysical features can be interpreted as a series of regional anticlines and synclines that correspond to variations in the position of the Whittington Range Member and dolerite sills in the Hayward Creek Formation. These geophysical features can be traced extensively and indicate that this interval is widespread. Fault offsets consistent with those in the outcropping Ashburton province are evident. The areally large magnetic high that dominates eastern HELEN SPRINGS is suggestive of a broad anticline, within which the lower Tomkinson Creek Group is relatively close to the surface beneath the Georgina Basin. A major north-northwesterly structure in eastern MONMOWA transects this anticline, and appears to be analogous to the Pybus Fault Zone with a downthrown western side.

Prominent faults evident in the HELEN SPRINGS magnetic data are consistent with structures observed in western HELEN SPRINGS. A large-scale, deep-seated, east-northeasterly trending feature is present in southern HELEN SPRINGS and may reflect an underlying or reactivated structure in the basement to the Ashburton province.

Apart from being relatively non-magnetic, the youngest stratigraphic units of the Ashburton province also typically coincide with the lowest Bouguer anomaly values. This implies an upward accumulation of relatively light (sedimentary) rocks and that gravitational and magnetic changes are due to differences in the overall thickness of the sedimentary succession.
Two folded and faulted dolerite sills occur in the Renner Group in northern Helen. These feature as prominent magnetic units in northwestern HELEN SPRINGS and have dip attitudes ranging from horizontal to vertical. A narrow north-northwesterly trending, segmented, linear magnetic feature also occurs in Helen and Muckaty. Ward (1988c) reported that a mafic unit was intersected during exploration drilling and referred to this feature as the ‘Magnetic Fault’. This feature probably relates to dolerite dykes that intruded a fault zone in the Renner Group.

Distinct low amplitude magnetic anomalies occur at different levels in the Tomkinson Creek and Renner Groups and correspond to contrasts between quartz arenite and less mature sandstone or mudstone. For example, the Grayling Member-Powell Formation contact is conspicuous. Other prominent examples include the base of the Gleeson Formation and its individual cycles, the top of the Powell Formation, and the base of the Short Range Sandstone. Magnetic anomalies are also clearly evident at transitions from carbonate to clastic dominated lithofacies such as the Attack Creek-Bootoo Formation contact. The Kuerschner Member of the Morphett Creek Formation also shows some magnetic character. This may correspond to detrital magnetite in its sandstones that were possibly derived from the underlying Whittington Range Member. The Mucketty manganese occurrence is a prominent magnetic feature, but other Mn occurrences are less apparent.

Units of the Namerinni Group appear to be relatively uniform and non-magnetic in character, in contrast to the Tomkinson Creek and Renner Groups. This suggests the Namerinni Group is a relatively uniform package of sediments with no dramatic compositional changes.

The Helen Springs Volcanics displays a distinct, high frequency magnetic character and commonly has sharp boundaries with relatively non-magnetic Proterozoic sandstones (eg Powell Formation in Helen). The Helen Springs Volcanics are interpreted to be present throughout most of the Georgina Basin in HELEN SPRINGS and this constitutes about two-thirds of the map area.

The high frequency magnetic character of the Helen Springs Volcanics masks the magnetic response of the dolerite sills in central Helen and the Whittington Range Volcanics and associated sills. The dolerite sill that intrudes the Renner Group in Helen has a similar high frequency signature to the Helen Springs Volcanics and, in places where this sill is relatively flat lying in northwestern Helen, it is difficult to differentiate from the Volcanics.

Diamond drilling (NTGS96/1) has confirmed the presence of 7 m of basaltic lava belonging to the Helen Springs Volcanics at a depth of about 250 m in the Georgina Basin. This supports the magnetic interpretation that the Helen Springs Volcanics becomes more deeply buried to the north and east of the Ashburton Ranges. It also confirms that there is significant variation in elevation of the base of the Helen Springs Volcanics across HELEN SPRINGS. Together with sudden changes in the magnetic character of the Helen Springs Volcanics, it is evidence for post-Middle Cambrian block faulting throughout this region. This faulting appears to involve reactivation of existing structures.

Radiometric data

Marked variations in K-U-Th ternary radiometric signatures in HELEN SPRINGS broadly relate to different regolith types. There is a significant contrast between black soil plains in the east and transported sands and sandy soils in the west. Black soil plains have a high K signature and have areas of elevated U and Th corresponding to ferricrete and calcrete. The influence of K-rich clay minerals associated with active drainage systems and floodouts can be seen as a more potassic signature dissecting sand plains east of the Ashburton Ranges. This signature is not as obvious in southwestern HELEN SPRINGS, which is an area that appears to lack large active drainage systems.

Radiometric signatures over outcropping Proterozoic rocks are distinct from the surrounding sand plains. The variably leached outcrops of the Morphett Creek Formation, Namerinni Group and undifferentiated lower Cretaceous units typically all have moderate to high K and relatively low Th and U signatures. This probably reflects the high clay content of the weathered rocks and contrasts with high Th and U signatures in the ferricrete and thin ferruginous sandy soils that cover many of the more upstanding Proterozoic units. Where dissected, some of the Proterozoic sandstone units show distinct spectral patterns consistent with observed lithological changes (eg Gleeson Formation in central Helen). Extensive quartz arenite units which dominate the Ashburton province typically have attenuated signatures due to low contents of K, Th and U. The Th/K ratio is a useful discriminant between outcrops of the Namerinni and Renner Groups in HELEN SPRINGS.

NTGS96/1 downhole data

Resistivity, self-potential and gamma logs were obtained for cored drillhole NTGS96/1 (Kruse 1996), which intersected probable lower Renner Group, Helen Springs Volcanics (including the Muckaty Sandstone Member), Gum Ridge Formation and lower Anthony Lagoon beds (Figure 21).

Deviations in the resistivity log of the probable lower Renner Group stratigraphy can be related to permeability variations in the component sandstones, but the response remains generally low through the Renner Group, Helen Springs Volcanics and the basal siliciclastic siltstone of the Gum Ridge Formation. This is mirrored to a lesser degree in the self-potential log. A distinctive resistivity peak (and self-potential trough) marks the transition from siliciclastic to carbonate rock in the basal Gum Ridge Formation. Log variations through the remainder of the formation are presumed to be primarily due to permeability variations, although there is no consistent relation to visible porosity. The mid-formation peritidal interval is represented by a resistivity peak at the transition from grey mudstone to cryptomicrobial dolostone. For the lower Anthony Lagoon beds, both logs show the expected siliciclastic versus carbonate responses.

The gamma log provides a more consistent indication of lithology. A uniformly low response characterises the Renner Group. Distinctive twin peaks in the Helen Springs Volcanics can be attributed to the amygdaloidal base and top of the single flow present in this drillhole, with a typical
low basalt response between them. A trough at the base of the Gum Ridge Formation carbonate interval coincides with a dolostone subjected to evaporite dissolution, collapse and brecciation; evaporite removal may have induced leaching of radionuclides from this interval. Throughout the Gum Ridge Formation and lower Anthony Lagoon beds generally, strong gamma peaks delineate siliciclastic intervals. Those within the depicted carbonate intervals represent thin siliciclastic interbeds. In particular, the mid-formation peritidal interval and the Gum Ridge Formation-Anthony Lagoon beds contact are clearly defined.

ECONOMIC GEOLOGY

HELEN SPRINGS has attracted considerable exploration activity, particularly since First Edition mapping, but this has resulted in few notable economic discoveries. However, the area contains significant manganese deposits and is prospective for base metals, diamonds, copper and hydrocarbons. Important groundwater resources have also been identified.

Manganese

Numerous manganese occurrences are present in HELEN SPRINGS including the abandoned Mucketty mine. Most of the known manganese mineralisation has a distinct stratigraphic control and is concentrated in two areas, Bootu Creek and Renner Springs. The following is derived from a more comprehensive review by Ferenczi (2001).

Bootu Creek area

The Bootu Creek area contains six named manganese occurrences including the Mucketty deposit. This deposit was first pegged in 1954 and small-scale mining from five shallow open cuts commenced in 1955 to supply manganese oxide for the Rum Jungle uranium treatment plant (Jones 1955). Between 1955 and 1969 some 13 280 t of ore grading about 66% MnO₂ (~42% Mn) was mined (Gamble 1962, Balfour 1989).

Early exploration work by the BMR included geological mapping and sampling by Jones (1955) and the drilling of five shallow diamond drillholes adjacent to the two northern open cuts (MacKay 1956). Post-mining exploration included two percussion holes (MP-1 and MP-2) drilled by Esso Australia Ltd (Ward 1983), rock chip sampling by Eupene Exploration NL (Hickey 1990) and airborne GEOTEM, ground TEM, rock chip sampling and drilling by BHP Minerals in 1995-96 (Nunn 1997).

The Bootu Creek manganiferous occurrences are hosted by the lower lithofacies of the Bootu Formation. The manganiferous horizon can be discontinuously traced for about 24 km around the Bootu Syncline as a series of black ridges and knolls.

Manganese oxides, predominantly amorphous and massive cryptomelane, have replaced a dolomitic siltstone bed, located stratigraphically below a ridge-forming sandstone bed that is also mineralised. Desiccated and rippled, fine to medium sandstone and rare stromatolitic dolostone beds above the hangingwall sandstone have also been pervasively replaced by manganese oxide. Carbonaceous siltstone and dolostone have been intersected below the Mn horizon (Nunn 1997).

At Mucketty (also known as Rossi prospect), shallow open cut mining took place over a 760 m strike length (Crohn 1960). The manganese ore horizon exposed in the open cuts is up to 8.6 m in thickness and averages 6 m. Metallurgical grade (>38% Mn) manganese ore is up to 2.7 m thick and averages about 1.2 m (Jones 1955). This material is grey to black, massive or reniform in texture and found toward the base of the ore zone where the Mn completely replaces siltstone. Pyrolusite is present as veinlets through the massive psilomelane ore.

Five shallow diamond drillholes by the BMR (MacKay 1956) and two percussion holes by Esso Australia Ltd (Ward 1983) failed to intersect metallurgical or medium grade manganese ore. A deeper (225 m depth) percussion/diamond drillhole (HSD002) by BHP Minerals intersected 15 m grading 14.75% Mn from 54 m (Nunn 1997). A bedding plane shear appears to have removed most of the favourable siltstone bed and brought a lower black pyritic shale into contact with the Mn horizon.

Along the eastern limb of the Bootu Syncline, there are four Mn occurrences (Bootu 1, 2, 3 and 4) that contain metal grade (>36% Mn) material. Outcrop in this vicinity is poor relative to the western limb. Rock chip sampling has been conducted by a few companies and drilling at Bootu 4 was undertaken by BHP Minerals Ltd (Nunn 1997). There are at least two manganese horizons present in the conductive zone outlined by an airborne GEOTEM survey (Nunn 1997).

At Bootu 4 (also known as Deposit E and Redwing), drilling by BHP Minerals Ltd over a strike length of 500 m intersected massive manganese mineralisation, 43-75 m below the surface. There is no surface expression of the manganese mineralisation in the vicinity of the drillholes. Only two holes (HSD001 and HSP003) penetrated the entire thickness of the Mn horizon. Results from these two holes suggest the presence of a 9-12 m thick manganese horizon that contains moderate grade (22.8-36.4% Mn) manganese with low (<0.05%) phosphorous. There are indications of secondary supergene enrichment in HSP003 (2 m @ 47.6% Mn from 54 m).

Geochemical sampling and drilling results for the eastern Bootu manganese occurrences indicate significant economic potential. If further drilling is able to substantiate the continuity in ore thickness and grade along the conductive GEOTEM zone (13 km strike length), then potential exists for >20 Mt of manganese material to 60 m depth. The lower 2 m of the horizon appears to contain the low silica, high grade manganese ore. Further potential exists for additional or stacked ore lenses (Nunn 1997). This area is situated 50 km to the east of the proposed Alice Springs-Darwin railway and 45 km to the east of an existing gas pipeline.

Renner Springs area

This area is situated about 15 km to the west of Renner Springs and contains six named manganese occurrences. The Renner Springs Nos 1, 2, 3 and 4 occurrences are hosted by lithologies at the base of the Shillinglaw Formation. Some mining from several small pits was carried out at Renner Springs No 1, where the Mn horizon can be traced over a strike length of 350 m (Ward 1983). Manganese oxides
replace a brecciated siltstone bed at the surface (Wygralak 1993). Jones (1955) described massive manganese ore (44-50% Mn) containing fragments of unreplaced siltstone and estimated a pre-mining resource of 4000 t of ore averaging 31% Mn per vertical foot to a depth of 3 m.

A percussion drillhole located 12 km south-southwest of Renner Springs (W3RDH, drilled by Key Resources NL) intersected 9 m grading 36.7% Mn including 3 m @ 42.4% Mn from 63 m depth (Ward 1987). This hole was collared in poorly exposed Cretaceous rocks but appears to have intersected the Mn horizon in brown siltstone near the base of the Shillinglaw Formation.

The only other significant occurrence in this area is at Renner Springs No 5 (LV617713), where manganese mineralisation is present in lithologies mapped as Cretaceous. Jones (1955) described the occurrence as being characterised by Mn partially replacing siltstone and chert. It essentially contains low grade ore (<22% Mn) and pockets of medium grade ore (22-38% Mn).

**Manganese ore genesis**

A clear stratigraphic control is evident in the manganese deposits in the Bootu Creek and Renner Springs areas, although faults are also present in the vicinity of the manganese occurrences. The basal sections of both host units (Bootu and Shillinglaw Formations) contain interbedded shallow marine sandstone with dolomitic siltstone and dolostone. Surface and subsurface observations indicate that the manganese mineralisation is very fine grained and was formed by replacement of existing rocks. Siltstone and sandstone lithologies are both mineralised; pervasive replacement of the former is common, and has led to the development of massive manganese ore lenses. The occurrence of manganese lenses at the base of the Bootu Formation, 9 km southwest of Banka Banka and also near Attack Creek in Flynn, suggests a regional distribution of the mineralisation.

A lack of oolitic, pisolithic and banded textures, as are common in sedimentary manganese deposits, and the presence of elevated base metal geochemistry in the Bootu Creek mineralisation suggest the involvement of epigenetic, low temperature hydrothermal fluids. The generation of low temperature Mn fluids could have been related to basin dewatering or minor hydrothermal activity. Shallow marine-lagoonal carbonates below the host sequence may have been the source of the Mn metal.

**Base metals**

Because the succession in HELEN SPRINGS is similar to that of the McArthur Basin, considerable effort has been spent looking for McArthur River HYC-style, or Mississippi-style deposits in the western HELEN SPRINGS region. Despite favourable rock units, detailed geological mapping, numerous geophysical and geochemical surveys and numerous drillholes (Ward 1983, 1984, 1985a-b, 1986, 1987, 1988a-c, Howland-Rose 1984, 1985, Ward and Howland-Rose 1986), only uneconomic sulfide stringers and trace galena, sphalerite, chalcopyrite and pyrite mineralisation have been discovered. Preliminary Pb isotope comparison studies indicated that the HELEN SPRINGS samples were highly radiogenic and not comparable to the stratiform and vein style deposits of the McArthur Basin. It was concluded that the HELEN SPRINGS region was not prospective for this style of mineralisation (Ward 1985b, 1986). Ward (1983) also indicated that although elevated base metal values including Co are associated with Mn occurrences, only Ba appears to mirror Mn.

In the early 1990s, Mount Isa Mines Exploration resumed the search for HYC-style deposits, encouraged by the apparently correlatable successions. They showed a large conductor parallel to and west of the Willieray Fault, known from Clifford Minerals efforts to be a clayey shear zone probably of Cretaceous age (Bruce 1993), and surrendered the ground shortly thereafter.

Most recently, BHP Minerals explored the Proterozoic rocks for manganese and base metal mineralisation in 1995. They had little success in their exploration for sediment-hosted base metals, but unlike MacKay (1956) and Ward (1983), they found the manganese deposits to be more extensive in the Bootu Creek area (Nunn 1997).

**Diamonds**

Ashton Mining was active in HELEN SPRINGS during the mid to late 1980s. A number of microdiamonds were found in gravel throughout most of the eastern and central parts of the sheet area (Ashton Mining Ltd 1984a-b, 1986a-f, 1987a-d). Stockdale Prospecting acquired some detailed aeromagnetic surveys to follow up on some prospective anomalies in the NTGS regional aeromagnetic data. Modelling of the new data showed that none had the dipolar characteristics of target kimberlitic diatremes (Hwang 1994a-c).

**Groundwater**

Verma and Jolly (1992) gave details of the hydrogeology of HELEN SPRINGS. The Anthony Lagoon beds have a large number of water bores, but stratigraphic drilling by NTGS indicates that underlying limestone of the Gum Ridge Formation is more porous and may be a much better aquifer. Most of the Anthony Lagoon beds, as intersected in drill core, should have low porosity and permeability and the presence of evaporite minerals suggests that its groundwater would be saline. Thin dolostone units within the Anthony Lagoon beds are therefore probably the main aquifers in this unit. The recharge of these aquifers appears to be related to either the depression in Monmoona or possibly the Helen Springs Volcanics/Muckaty Sandstone Member in northern Helen. Surface springs were also pointed out by traditional owners near the base of Cretaceous sediments in southeastern Muckaty. This suggests that this unit may be an important, but limited source of fresh water in favourable settings.

**Other commodities**

Dillingham Mining Company (1971) conducted reconnaissance investigations aimed at base metal and uranium discovery, but other than some metal scavenging by the manganese deposits, found no anomalous localities. Metals Investment Holdings NL (1971) also explored...
briefly for the same minerals without any success, but noted possibilities for phosphate from Georgina Basin sediments.

Several small copper occurrences were identified southwest of Banka Banka. These secondary supergene occurrences are principally malachite and are hosted by basalt of the Whittington Range Member and siltstone of the Morphett Creek Formation. Although samples are high in copper, analyses of two surface samples failed to indicate any other anomalous base metals or gold. All occurrences are in close proximity to late faults and are probably related to fluids migrating along them. The copper may have been stripped from basalts in the Whittington Range Member. This region has not been extensively explored for copper mineralisation and larger occurrences related to late-stage faulting may exist.

The presence of Velkerri Formation equivalents (ie Lake Woods beds in HELEN SPRINGS) suggests that northernmost HELEN SPRINGS, and also parts of BEETALOO, are prospective for hydrocarbons. This formation is also prospective for base metals (particularly Zn), based on observations of drill core in the Beetaloo Sub-Basin.

GEOLOGICAL HISTORY


1. ca 1805-1710 Ma: Deposition of the Tomkinson Creek Group, a 10.5 km thick succession of fluvial to shallow marine sedimentary rock units. Volcanic activity at about 1780 Ma includes an interval of continental flood basalt and associated high level sills in the lower part of the succession.

2. ca 1710-1660 Ma: Regional deformation, map-scale northwest trending folds related to the Davenport Orogeny and erosion.

3. ca 1660-1610 Ma: Deposition of the Namerinni Group, a 2800 m thick succession of fluvial to shallow marine sedimentary rock units.

4. ca 1610-1500 Ma: Significant hiatus. Regional faulting, tilting and erosion.

5. ca 1500-1430 Ma: Deposition of the Renner Group, a >3500 m thick succession of fluvial to shallow marine sedimentary rock units.

6. ca 1324 Ma: Emplacement of dolerite sills.


8. Early?-Middle? Cambrian: Deposition of Georgina and Wiso Basin strata. This includes up to about 500 m of aeolian sandstone, continental tholeiitic flood basalt and shallow marine sedimentary rock units.

9. Minor faulting, tilting and erosion.

10. Early? Cretaceous: Deposition of up to about 50 m of shallow marine to fluvial and lacustrine sedimentary rock units.

11. Erosion, peneplanation and formation of extensive laterite. Development of the Tennant Creek Surface.


ACKNOWLEDGEMENTS

We thank pastoralists and traditional owners of the HELEN SPRINGS region for their friendly cooperation. A special thanks goes to Max Heggan of the DME and staff of the Tennant Creek Central Land Council for organising access to Aboriginal lands. Phil Ferenczi (NTGS) is acknowledged for the section on manganese deposits. Tim Munson and David Young edited the manuscript and Barry Pietsch provided constructive comments on a draft. Philip Carter, Richard Jong, Jann Lambton-Young and Gary Andrews prepared the figures and Kirsi Rahikainen formatted the manuscript.

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**APPENDIX**

**NEW AND REVISED STRATIGRAPHIC NAMES AND DEFINITIONS**

The definitions below have been approved by the Geological Society of Australia Committee for Stratigraphic Names and have been filed with the Central Register of Stratigraphic Names. Requirements and procedures for new definitions are set out in Staines (1985). Note: All locations refer to AGD84 datum coordinates.

**Tomkinson Creek Group** (redefinition, upgraded status)

**Proposers:** KJ Hussey and N Donnellan.

**Derivation of name:** Tomkinson Creek in western HELEN SPRINGS.

**Constituent units:** In ascending order, Hayward Creek Formation, Morphett Creek Formation, Short Range Sandstone, Attack Creek Formation, Bootu Formation and Carmilly Formation. Currently named members include the Manga Mauda, Meerie, Coodna, Whittington Range, Kuerschner, Mitty and Deagan Members.

**Synonymy:** Previously part of undifferentiated Tomkinson Creek beds in HELEN SPRINGS (Randal et al 1966, Randal and Brown 1969). Donnellan et al (1995) defined the Tomkinson Creek Subgroup based on formations and members in TENNANT CREEK. Now upgraded and expanded to include additional, younger stratigraphic units that crop out in HELEN SPRINGS.

**Distribution:** Outcrops in southern HELEN SPRINGS, northern TENNANT CREEK, southeastern LAKE WOODS SOUTH and northeastern GREEN SWAMP WELL.

**Relationships and boundary criteria:** Overlies the Flynn Group (Donnellan et al 2001) in TENNANT CREEK with a suspected angular unconformity. Unconformably overlain by both the Namerimni and Renner Groups in HELEN SPRINGS.

**Age and evidence:** Statherian. Based on correlation, deposition of Tomkinson Creek Group probably commenced at about 1805 Ma and continued to about 1710 Ma. The oldest rocks are younger than the Flynn Group (maximum age of 1821 Ma, Compston 1995) and are older than 1784 ± 9 Ma (Compston 1995), which is the maximum depositional age for the Meerie Member. They may be as old as 1805 Ma, the inferred age of the Murchison event (Hussey et al 1999, Donnellan et al 2001). The Tomkinson Creek Group was deformed during the Davenport Orogeny (Donnellan et al 2001) at about 1720-1700 Ma. This is coincident with the timing of the unconformity between the Tawallah and McArthur Groups of the McArthur Basin.

**Correlations:** The Tomkinson Creek Group is restricted in outcrop to the Ashburton province of the Tennant Inlier. Probable correlatives include the upper Wauchope Subgroup and entire Hanlon Subgroup in the Davenport province of the Tennant Inlier, the Tawallah Group of the McArthur Basin, and the Birrindudu Group in the Tanami region.

**Kuerschner Member** (new name) of Morphett Creek Formation.

**Proposers:** KJ Hussey and N Donnellan.

**Derivation of name:** Kuerschner Creek in BRUNCHILLY at 18º47'23" S 134º06'29" E (MV060222).

**Synonymy:** Defines units a and b of the Morphett Creek Formation as described by Donnellan et al (1995) from outcrops in FLYNN. Formerly undifferentiated Tomkinson Creek beds in HELEN SPRINGS (Randal et al 1966, Randal and Brown 1969).

**Distribution:** In HELEN SPRINGS, outcrops occur in southwestern BRUNCHILLY and central and southern MUCKATY. Undifferentiated in TENNANT CREEK, but recognised in both FLYNN and SHORT RANGE. Probably outcrops in SOUTH LAKE WOODS.

**Type section:** In BRUNCHILLY, from base at 18º58'26" S 134º05'10" E (MV038018) to top at 18º58'06" S 134º03'55" E (MV016024). The boundary between lower and upper lithofacies is placed at 18º58'16" S 134º04'43" E (MV030021) in this section.

**Reference sections/localities:** In FLYNN, from base near 19º05'17" S 134º07'25" E (MU078892) to top near 19º03'19" S 134º06'13" E (MU057928). In MUCKATY, from base near 18º52'49" S 133º50'03" E (LV772120) to top at 18º53'18" S 133º49'32" E (LV763111). Basal conglomerate is thickest, about 150-200 m, in FLYNN near 19º12'26" S 134º06’21” E (MU060760).

**Lithology:** Lower lithofacies comprises mostly red-brown to cream, medium to very thickly cross-bedded, mostly sorted sandstone and pebble to cobble conglomerate. Upper lithofacies comprises mostly cream to orange-tan, thinly to medium bedded, well sorted, fine to medium sandstone. Minor interbedded siltstone and some mudstone intervals near the top.

**Thickness:** About 1500 m in HELEN SPRINGS, about 1600 m in FLYNN.

**Geomorphic expression:** Ridge-forming unit, variably dissected and rounded hills.

**Relationships and boundary criteria:** Disconformably overlies basalt of the Whittington Range Member of the Hayward Creek Formation. Appears to be concordant with sedimentary units of the underlying Hayward Creek Formation.

**Age:** Statherian.

**Mitty Member** (new name) of Morphett Creek Formation.

**Proposers:** KJ Hussey and N Donnellan.

**Derivation of name:** Mitty Bore in BRUNCHILLY at 18º52'34" S 134º02’21” E (LV988126).

**Synonymy:** Defines units c and d of the Morphett Creek Formation as described by Donnellan et al (1995) in FLYNN. Formerly undifferentiated Tomkinson Creek beds in HELEN SPRINGS (Randal et al 1966, Randal and Brown 1969).
Distribution: Western Brunchilly and central and eastern Muckaty in Helen Springs. Recognised in Flynn and Short Range in Tennant Creek, but is undifferentiated.

Type section: Base in Brunchilly at 18°58′06″ S 134°03′55″ E (MV016024), top in Muckaty at 18°55′22″ S 133°58′45″ E (LV925073). Type section is a composite of the lower lithofacies, best exposed from base at 18°56′54″ S 134°00′58″ E (LV964046) up-section to unconformity with Gleeson Formation at 18°55′29″ S 134°01′02″ E (LV965072), and the upper lithofacies, base at 18°54′17″ S 133°58′04″ E (LV948094) and top at 18°55′22″ S 133°58′45″ E (LV925073). Reference section: in Flynn, from base near 19°03′19″ S 134°06′14″ E (MU057928) to top at 19°04′01″ S 134°04′14″ E (MU022915).

Lithology: Lower lithofacies is a mixed carbonate/siliciclastic unit principally containing interbedded, well sorted fine sandstone, mudstone, chert and stromatolitic dolostone units. Upper lithofacies is predominantly a cream to orange-tan or red-brown, very thinly to medium interbedded sandstone and mudstone unit with rare intervals of conglomerate or carbonate rocks. Evaporite pseudomorphs are common to both units and are locally proli fic. Some chert units may be tuffaceous.

Thickness: About 1500-2200 m in Helen Springs.

Geomorphic expression: Largely recessive with low relief, rounded strike ridges. Some intensely silicified, upstanding, flat topped hills.

Relationships and boundary criteria: Conformably overlies the Kuerschner Member with a transitional relationship. Disconformably to conformably overlie the Deagan Member of the Short Range Sandstone. Unconformably overlain by the Gleeson Formation of the Renner Group.

Age: Statherian.

Deagan Member (new name) of Short Range Sandstone.

Proposers: N Donnellan, KJ Hussey and AJ Crispe.

Derivation of name: Deagan Waterhole in Brunchilly at 18°53′28″ S 134°10′13″ E (MV126110).


Distribution: Western Brunchilly and central and eastern Muckaty in Helen Springs. Northern Flynn and northwestern Short Range in Tennant Creek.

Type section: Base at 18°43′31″ S 134°04′55″ E (MV032293) to top at 18°43′12″ S 134°04′51″ E (MV031299); actual base is best observed along strike near 18°41′31″ S 134°03′16″ E (MV003330).

Reference sections: in Flynn near 19°02′30″ S 134°03′43″ E (MU013943); in Muckaty, base at 18°49′47″ S 133°59′11″ E (LV932177) and top at 18°49′44″ S 133°59′07″ E (LV931178); also in Muckaty, base at 18°55′25″ S 133°58′45″ E (LV925073) and top at 18°54′17″ S 133°58′32″ E (LV921094).

Lithology: Sandstone, predominantly thin to thickly bedded quartz arenite, minor conglomerate and mudstone. Fining-upward succession. Some localised halite pseudomorph-bearing intervals near top.

Thickness: About 30-150 m in Helen Springs.

Geomorphic expression: Low relief hills north of Deagan Waterhole. Elsewhere, the basal units typically form an upstanding strike ridge and the upper units, a recessive valley.

Relationships and boundary criteria: Conformably overlies the Mitty Member of the Morphett Creek Formation. Disconformably to conformably overlie the Short Range Sandstone middle lithofacies.

Age: Statherian.

Bootu Formation (redefinition).


Derivation of name: Bootu Creek in Brunchilly at 18°40′08″ S 134°25′52″ E (MV00357).


Distribution: In Helen Springs, outcrops mostly in northwestern Brunchilly, southeastern Helen and southwestern Monoonaa between Bootu Creek and McKinlay Creek. Small isolated outcrops occur in Muckaty and northwestern Flynn.

Type section: Due to faulting and poor exposure, a composite of three sections is nominated in Brunchilly. Section 1 starts from the actual base at 18°39′50″ S 134°03′03″ E (LV999361) and continues up-section to 18°39′14″ S 134°03′58″ E (MV015372). This spans the lower and middle parts and includes the transitional contact between the lower and middle lithofacies at 18°39′50″ S 134°03′27″ E (MV006361). Section 2 spans the middle lithofacies about 17 km along strike from section 1 and partly overlaps it, starting from near the base of the middle lithofacies northwest of Deagan Waterhole at 18°36′42″ S 134°06′18″ E (MV056419) and continues up-section to the unconformity with the Gleeson Formation at 18°37′01″ S 134°04′53″ E (MV031413). Section 3, about 4 km to the northwest, starts at 18°36′12″ S 134°02′34″ E (LV996428) and continues up-section to 18°35′46″ S 134°02′54″ E (LV996436). Section 3 spans the upper lithofacies, but continuity between sections 2 and 3 is approximated because of fault complications. The actual top is defined about 5 km along strike from the top of section 3 at 18°33′42″ S 134°01′26″ E (LV970474).
Reference section: Stratigraphic equivalents of type section 1 occur in Flynn up-section of 19º03’44” S 134º02’45” E (LU996920). These rocks were first referred to as the transitional and sandstone lithofacies of the Attack Creek Formation (Donnellan et al. 1995) but were subsequently reassigned to the Bootu Formation by Donnellan et al. (1999).

Lithology: predominantly medium to very thickly bedded sandstone, minor pebbly sandstone and mudstone. Intervals of dolostone and stromatolitic dolostone occur in the lower lithofacies.

Thickness: About 1800- 2200 m in Helen Springs.

Geomorphic expression: Mostly expressed as extensive low relief plateaux except for the lower lithofacies which tends to form a series of strike ridges.

Relationships and boundary criteria: Disconformably to conformably overlies the Attack Creek Formation. Conformably overlain by the Carmilly Formation. Unconformably overlain by the Gleeson Formation of the Renner Group and by undifferentiated lower Cretaceous units.

Age: Statherian.

Carmilly Formation (new name)


Derivation of name: Carmilly Creek in Brunchilly at 18º35’23” S 134º03’18” E (MV003443).

Synonymy: Formerly undifferentiated Tomkinson Creek beds in Helen Springs (Randal et al. 1966, Randal and Brown 1969).

Distribution: Mostly outcrops in northwestern Brunchilly, probable middle facies outcrops in central Helen.

Type section: In Brunchilly, the type section commences at 18º33’32” S 134º00’45” E (LV958477) and continues up-section to the contact between lower and middle lithofacies at 18º32’52” S 134º00’11” E (LV948489), then continues up-section to the contact between middle and upper lithofacies at 18º00’00” S 134º00’08” E (LV947489), then continues up-section to the contact with the unconformably overlying Jeromah Formation of the Namerinni Group at 18º32’59” S 133º59’58” E (LV944487). Note: due to faulting the actual contact with the underlying Bootu Formation is not expressed in this continuous section. The lowermost stratigraphic units are repeated about 500 m east of this section and the actual base is defined at 18º33’42” S 134º01’26” E (LV970474).

Lithologies: Laminated to medium bedded sandstone, mudstone, dolostone, stromatolitic dolostone, chert and evaporite pseudomorphs, minor conglomerate. Mixed carbonate/siliciclastic units occur in the lower and upper lithofacies whereas the middle lithofacies only contains siliciclastic units.

Thickness: At least 750 m in Helen Springs.

Geomorphic expression: Lower and upper lithofacies are recessive whereas the middle lithofacies is an upstanding, ridge-forming unit.

Relationships and boundary criteria: Conformably overlies the Bootu Formation with a transitional relationship. Unconformably overlain by the Jeromah Formation of the Namerinni Group.

Age: Statherian.

Comment: All sections through this unit are faulted.

Namerinni Group (new name)


Derivation of name: Namerinni Waterhole in Helen Springs at 18º34’14” S 134º43’38” E (LV657462).

Constituent units: In ascending order, Jeromah, Carruthers, Shillinglaw and Willieray Formations.

Synonymy: All formations were previously mapped as undifferentiated Tomkinson Creek beds in Helen Springs (Randal et al. 1966, Randal and Brown 1969).

Distribution: Outcrops mainly restricted to two fault bounded regions in Helen Springs. The largest region occurs in central and southern Helen and central northern Muckaty and is referred to as the western succession. Outcrops in northwestern Brunchilly, northeastern Muckaty and southeastern Helen are referred to as the eastern succession. The Namerinni Group also outcrops in southern Elliott.

Relationships and boundary criteria: Overlies Tomkinson Creek Group with a subtle angular unconformity; unconformably overlain by the Jeromah Formation of the Namerinni Group.

Age: Statherian.

Comment: All sections through this unit are faulted.

Correlations: The McArthur and McNamara Groups in the McArthur Basin and Lawn Hill Platform, respectively, are probably chronostratigraphic equivalents.
Jeromah Formation (new name)

Derivation of name: Jeromah Creek in northwest Brunchilly at 18°33′41″ S 134°00′11″ E (LV948474).
Distribution: Only known in HELEN SPRINGS; the largest outcrop occurs in the eastern succession in northwestern Brunchilly, northeastern Muckaty and southeastern Helen. Smaller outcropping regions occur in the western succession in central Helen.
Type section: In northeastern Muckaty, from base at 18°31′08″ S 133°59′45″ E (LV940521) north about 500 m along strike to 18°31′52″ S 133°59′45″ E (LV940526), then up-section to 18°31′52″ S 133°59′24″ E (LV934526), then about 2.5 km south along strike to top on western side of small strike ridge at 18°32′10″ S 133°59′17″ E (LV932502). The contact between the lower and upper fining-upward successions in this section occurs at 18°31′11″ S 133°59′35″ E (LV937520).
Reference section/localities: Basal conglomerate is exposed over a 3 km interval south of 18°30′00″ S 133°59′38″ E (LV938542); sandstone or pebbly sandstone occurs at the actual base at 18°32′23″ S 134°00′08″ E (LV947498) and at localities further south in this region; a reference section in Helen has a base at 18°23′56″ S 133°43′02″ E (LV645652) and a top at 18°24′28″ S 133°42′58″ E (LV644642).
Lithology: Medium to very thickly cross-bedded sandstone and pebbly sandstone, some pebble to cobble conglomerate, very thinly to thinly bedded, red-brown to cream fine sandstone and mudstone. Pseudomorphs after halite are common in some finer intervals. Comprises two prominent fining- and thinning-upward successions.
Thickness: About 350-700 m in HELEN SPRINGS.
Geomorphic expression: Variably upstanding, ridge-forming unit, some recessive intervals.
Relationships and boundary criteria: Unconformably overlies the Carmilly Formation of the Tomkinson Creek Group and is the basal unit of the Namerinni Group in HELEN SPRINGS. Conformably overlain by the Carruthers Formation.
Age: Statherian.
Comments: All sections through this unit are faulted.

Carruthers Formation (new name)

Derivation of name: Carruthers Creek in Helen at 18°25′17″ S 133°41′36″ E (LV620627).
Synonymy: Previously mapped as undifferentiated Tomkinson Creek beds in HELEN SPRINGS (Randal et al 1966, Randal and Brown 1969).
Distribution: In HELEN SPRINGS, the largest area of outcrop occurs in the western succession in central Helen and northern Muckaty. Smaller areas of outcrop occur in the eastern succession in northwestern Brunchilly, northeastern Muckaty and southeastern Helen.
Type section: In Helen, from base at 18°24′28″ S 133°42′58″ E (LV444642) to top at 18°20′20″ S 133°39′09″ E (LV576718).
Reference section/localities: In western succession, from actual base on the western side of a small strike ridge at 18°32′10″ S 133°59′17″ E (LV932502) to top in a creek at 18°33′47″ S 133°58′22″ E (LV916472).
Lithology: Laminated to medium bedded sandstone, mudstone, chert and dolostone; stromatolites and evaporite pseudomorphs are abundant in some intervals.
Thickness: About 800-1100 m in HELEN SPRINGS.
Geomorphic expression: The lower and middle lithofacies are mostly recessive whereas the upper lithofacies is predominantly an upstanding ridge-forming unit.
Relationships and boundary criteria: Conformably overlies the Jeromah Formation and is conformably overlain by the Shillinglaw Formation.
Age: Statherian.

Shillinglaw Formation (new name)

Derivation of name: Mount Shillinglaw in Helen at 18°21′28″ S 133°39′56″ E (LV590697).
Synonymy: Previously mapped as undifferentiated Tomkinson Creek beds in HELEN SPRINGS (Randal et al 1966, Randal and Brown 1969).
Distribution: Mostly outcrops in Helen and Muckaty, some outcrop in Brunchilly.
Type section: In Helen, from base at 18°20′20″ S 133°39′09″ E (LV576718) up-section to boundary between lower and upper lithofacies at 18°19′15″ S 133°39′40″ E (LV585738), then up-section to top at 18°17′31″ S 133°40′45″ E (LV604770).
Reference section: In northwestern Muckaty, from base at 18°33′47″ S 133°58′22″ E (LV916472) up-section to transitional contact between lower and upper lithofacies at 18°33′34″ S 133°58′12″ E (LV913476), then up-section to top at 18°33′02″ S 133°57′45″ E (LV905486).
Reference localities: Lower lithofacies in the vicinity of 18°18′36″ S 133°41′29″ E (LV617750); granule- and pebble-bearing dolostone at 18°17′41″ S 133°40′11″ E (LV594767).
Lithology: Mostly laminated to medium bedded sandstone, mudstone, dolostone and quartzic dolostone; some chert and minor conglomerate; evaporite pseudomorphs.

Thickness: About 500-650 m in HELEN SPRINGS.

Geomorphic expression: Variously exposed, largely as benched, recessive outcrops. The lower lithofacies forms an upstanding silicified ridge in the type locality.

Relationships and boundary criteria: Conformably overlies the Carruthers Formation; conformably overlain by the Willieray Formation.

Age: Statherian (see comments under Age of Namerinni Group, above).

Willieray Formation (new name)


Derivation of name: Mount Willieray in HELEN at 18°25'48" S 133°46'05" E (LV699618).

Synonymy: Previously mapped as undifferentiated Tomkinson Creek beds in HELEN SPRINGS (Randal et al 1966, Randal and Brown 1969).

Distribution: Outcrops in HELEN, MUCKATY and BRUNCHILLY.

Type section: In HELEN from base at 18°16'01" S 133°37'37" E (LV547797) up-section to unconformity with Gleeson Formation at 18°15'53" S 133°37'42" E (LV550798).

Reference section: In eastern succession from base 18°30'48" S 133°56'34" E (LV884527), then up-section to 18°30'15" S 133°56'48" E (LV888537).

Lithology: Red-brown to cream sandstone and siltstone; minor conglomerate and mudstone; rare dolomitic mudstone and stromatolites; predominantly thinly bedded; evaporite pseudomorphs.

Thickness: From 70 m to 400 m or greater in HELEN SPRINGS.

Geomorphic expression: Benched strike ridges with recessive intervals.

Relationships and boundary criteria: Conformably overlies the Shillinglaw Formation. Unconformably overlain by the Gleeson Formation of the Renner Group.

Age: Statherian.

Renner Group (new name)


Derivation of name: Renner Springs in HELEN at 18°19'18" S 133°48'11" E (LV735738).

Constituent units: In ascending order, Gleeson Formation, Baralandji Formation (comprising Sweetwater and Grayling Members), Powell Formation, Wiertyna Formation, Jangirulu Formation and Lake Woods beds.

Synonymy: Previously mapped as undifferentiated Tomkinson Creek beds in HELEN SPRINGS (Randal et al 1966, Randal and Brown 1969).

Distribution: Outcrops in the Ashburton Ranges in HELEN SPRINGS, BEETALOO and NEWCASTLE WATERS. Two small isolated inliers also outcrop in the Georgina Basin about 25 km northeast of Renner Springs. Possibly occurs in northern TENNANT CREEK.

Relationships and boundary criteria: Unconformably overlies the Namerinni and Tomkinson Creek Groups. Intruded by dolerite sills. Unconformably overlain by the Early? Cambrian Muckaty Sandstone Member of the Helen Springs Volcanics.

Age: Mesoproterozoic, Calymmian. The oldest units in the Renner Group are inferred to be slightly older than 1492 ± 4 Ma by correlation with Roper Group stratigraphy of the McArthur Basin (cf Mainoru Formation, Jackson et al 1999) whereas the youngest unit in the Renner Group is inferred to be older than 1429 ± 31 Ma (cf Kyalla Member, Krailik 1982).

Correlations: Seismic continuity and numerous lithological similarities support correlation between the Renner and Roper Groups, although younger units do occur in the latter. Other correlatives include the South Nicholson Group of the south Nicholson Basin and possibly the Auvergne Group in the Victoria River Region.

Gleeson Formation (new name)


Derivation of name: Gleeson Creek at 18°13'02" S 133°34'15" E (LV486847) in western HELEN.

Synonymy: Previously mapped as undifferentiated Tomkinson Creek beds in HELEN SPRINGS (Randal et al 1966, Randal and Brown 1969).

Distribution: Largest area of outcrop occurs in HELEN, also outcrops in MUCKATY, BRUNCHILLY MONMOONA and ELLIOTT.

Type section: In central HELEN, from base at 18°15'46" S 133°37'39" E (LV549802) to top at 18°15'04" S 133°38'30" E (LV564815).

Reference section: Mostly in southwestern MONMOONA, from base in northwestern BRUNCHILLY at 18°30'19" S 134°01'41" E (LV974536) along strike to 18°29'18" S 134°01'28" E (LV970555) then up-section to top at 18°29'22" S 134°02'12" E (LV983554).

Lithology: Variably sorted and micaceous, thinly to very thickly cross-bedded sandstone and pebbly sandstone; some laminated micaceous mudstone; minor conglomerate. Informally divided into three laterally extensive lithofacies. The lower and middle lithofacies form an coarsening- and thickening-upward succession whereas cyclic, fining- and thinning-upward successions
constitute the upper lithofacies.

**Thickness:** Between 50-650 m in HELEN SPRINGS

**Geomorphic expression:** Variably upstanding strike ridges; lowermost interval recessive.

**Relationships and boundary criteria:** Overlies both the Tomkinson Creek and Namerinini Groups with angular unconformity. Conformably overlie by the Baralandji Formation.

**Correlations:** The Phelps Sandstone of the Roper Group is the most likely lithostratigraphic correlative in the McArthur Basin. Possibly correlates with outcrops mapped as Rising Sun Conglomerate in northern TENNANT CREEK.

### Baralandji Formation (new name)

**Proposers:** KJ Hussey, PR Beier, AJ Crispe and N Donnellan.

**Derivation of name:** Traditional aboriginal name for a distinct mesa also known as Mount Castle or Lubras Lookout in HELEN SPRINGS at 18°21'09" S 133°49'01" E (LV750704).

**Synonymy:** Previously mapped as undifferentiated Tomkinson Creek beds in HELEN SPRINGS (Randal et al 1966, Randal and Brown 1969).

**Distribution:** In HELEN SPRINGS, mostly outcrops in the Ashburton Ranges in HELEN but also occurs in BRUNCHILLY, MUCKATY and MONMOONA; also outcrops in the Ashburton Ranges in BEETALOO and NEWCASTLE WATERS.

**Type section:** In HELEN, from base at 18°09'01" S 133°41'10" E (LV610927) up-section to 18°09'00" S 133°40'56" E (LV606936) then up-section to 18°08'12" S 133°41'07" E (LV609942) then along strike to 18°10'32" S 133°42'17" E (LV630899), which is the boundary between the Sweetwater and Grayling Members, then up-section to top at 18°11'34" S 133°43'08" E (LV645880).

**Reference sections:** In HELEN, from base at 18°15'04" S 133°38'30" E (LV564815) to top at 18°13'20" S 133°38'17" E (LV560847); in central eastern MUCKATY, from base at 18°46'25" S 133°58'17" E (LV916239) to top at 18°45'53" S 133°58'38" E (LV922249); and in southern ELLIOTT, from base at 17°55'53" S 133°41'40" E (LA617206) to top at 17°54'06" S 133°41'06" E (LA607202).

**Lithology:** Micaceous, predominantly fine to medium sandstone and mudstone, minor pebbly sandstone and conglomerate; laminated to thickly bedded; halite pseudomorphs in lower parts; glauconitic in upper part.

**Thickness:** About 100-700 m in HELEN SPRINGS.

**Geomorphic expression:** Predominantly recessive, variably upstanding strike ridges in the middle and upper parts.

**Relationships:** Baralandji Formation is divided into lower, Sweetwater, and upper, Grayling Members. Conformably overlies Gleeson Formation and conformably overlie by Powell Formation.

### Sweetwater Member (new name) of Baralandji Formation.

**Proposers:** KJ Hussey and AJ Crispe.

**Derivation of name:** Sweetwater Bore in ELLIOTT at 17°50'00" S 133°44'21" E (LA664278).

**Synonymy:** Previously mapped as undifferentiated Tomkinson Creek beds in HELEN SPRINGS (Randal et al 1966, Randal and Brown 1969).

**Distribution:** In HELEN SPRINGS, mostly outcrops in HELEN and MUCKATY; also occurs in the Ashburton Ranges in BEETALOO and NEWCASTLE WATERS.

**Type section:** In HELEN, from base at 18°09'01" S 133°41'10" E (LV610927) up-section to 18°09'00" S 133°40'56" E (LV606936) then up-section to 18°08'12" S 133°41'07" E (LV609942) then along strike and up-section to top at 18°10'32" S 133°42'17" E (LV630899).

**Reference sections:** In southeastern ELLIOTT, from base at 17°53'53" S 133°41'40" E (LA617206) to top at 17°54'06" S 133°41'06" E (LA607202).

**Lithology:** Upward-coarsening, cream to tan, very thinly to thickly bedded, predominantly sandstone succession containing halite pseudomorphs and desiccated, interbedded mudstone intervals in the lower parts, and pebbly sandstone and conglomerate in uppermost part.

**Thickness:** Up to about 200 m in HELEN SPRINGS, 225 m in type section in southern ELLIOTT.

**Geomorphic expression:** Lowermost interval is recessive; upper parts form an upstanding strike ridge.

**Relationships and boundary criteria:** Conformably overlies the Gleeson Formation and conformably overlie by the Grayling Member.

**Correlations:** Appears to be lithostratigraphic correlative of the Mantungula Formation and Limmen Sandstone of the Roper Group in the McArthur Basin.

### Grayling Member (new name) of Baralandji Formation.

**Proposers:** KJ Hussey and AJ Crispe.

**Derivation of name:** Mount Grayling in HELEN at 18°16'28" S 133°45'11" E (LV682790).

**Synonymy:** Previously mapped as undifferentiated Tomkinson Creek beds in HELEN SPRINGS (Randal et al 1966, Randal and Brown 1969).

**Distribution:** In HELEN SPRINGS, mostly outcrops in HELEN; also outcrops in BRUNCHILLY, MUCKATY and MONMOONA, and in the Ashburton Ranges in ELLIOTT and NEWCASTLE WATERS.
Type section: In HELEN, from base at 18°10′32″ S 133°42′17″ E (LV630899) to top at 18°11′34″ S 133°43′08″ E (LV645880).
Lithology: Micaceous sandstone and mudstone; thinly to thickly bedded, hummocky cross-stratified and quasi-planar laminated; glauconitic.
Thickness: About 100-500 m in HELEN SPRINGS.
Geomorphic expression: Predominantly recessive; variably upstanding strike ridges in upper parts.
Relationships and boundary criteria: Conformably overlies the Sweetwater Member and conformably overlain by the Powell Formation.
Correlatives: Appears to be a lithostratigraphic correlative of the Crawford Formation, and possibly also the Mainoru Formation, of the Roper Group in the McArthur Basin.

Powell Formation (new name)

Derivation of name: After Powell Creek in HELEN at 18°04′53″ S 133°40′37″ E (LA360003).
Synonymy: Previously mapped as undifferentiated Tomkinson Creek beds in HELEN SPRINGS (Randal et al 1966, Randal and Brown 1969).
Distribution: In HELEN SPRINGS, mostly outcrops in HELEN and MUCKATY, also found in BRUNCHILLY.
Type section: From base at 18°14′01″ S 133°37′16″ E (LV542834) to top at 18°13′25″ S 133°36′45″ E (LV533845).
Lithology: Fine to very coarse sandstone, predominantly quartz arenite; minor conglomerate and mudstone; thinly to thickly bedded.
Thickness: Between 300-820 m in HELEN SPRINGS.
Geomorphic expression: Upstanding ridges.
Relationships and boundary criteria: Conformably overlies the Grayling Member of the Baralandji Formation and is conformably overlain by the Wiernty Formation.
Correlations: The Powell Formation appears to be the lithostratigraphic equivalent of the Arnold Sandstone, Jalboi Formation and Hodgson Sandstone of the Roper Group of the McArthur Basin.

Wiernty Formation (new name)

Derivation of name: After Wiernty Bore in MUCKATY at 18°32′03″ S 133°49′13″ E (LV755503).
Synonymy: Previously mapped as undifferentiated Tomkinson Creek beds in HELEN SPRINGS (Randal et al 1966, Randal and Brown 1969).
Distribution: Outcrops in HELEN and MUCKATY in HELEN SPRINGS, also occurs in ELLIOTT.
Type section: In southern ELLIOTT, from base at 17°59′15″ S 133°42′12″ E (LA627107) to top at 17°58′49″ S 133°41′24″ E (LA613115).
Reference section: In HELEN, from base at 18°27′23″ S 133°57′02″ E (LV892590) to top at 18°29′49″ S 133°56′21″ E (LV880545).
Lithology: Laminated to thinly bedded sandstone and mudstone; minor dolomitic mudstone; evaporite pseudomorphs.
Thickness: About 400-500 m in HELEN SPRINGS.
Geomorphic expression: Largely recessive with bench ed upper part.
Relationships and boundary criteria: Conformably overlies the Powell Formation with a transitional relationship. The contact with the overlying Jangirulu Formation is transitional conformable to disconformable.

Jangirulu Formation (new name)

Derivation of name: After an Aboriginal outstation in northern HELEN near 18°07′44″ S 133°36′38″ E (LV530950).
Synonymy: Previously mapped as undifferentiated Tomkinson Creek beds in HELEN SPRINGS (Randal et al 1966, Randal and Brown 1969).
Distribution: Mostly in the western parts of the Ashburton Ranges in HELEN and in ELLIOTT; also in MUCKATY.
Type section: In ELLIOTT, base at 17°52′05″ S 133°36′21″ E (LA576239) to top at 17°51′55″ S 133°38′48″ E (LA566242); well exposed section, but intruded by dolerite sill.
Reference section: In HELEN, from base at 18°10′39″ S 133°36′09″ E (LV522896) to top at 18°08′58″ S 133°34′55″ E (LV500927); middle parts and actual top and bottom not seen in this section, which is largely covered by scree.
Lithology: Sandstone, predominantly quartz arenite; minor conglomerate and rare mudstone.
Thickness: Up to about 700 m in HELEN SPRINGS.
Geomorphic expression: Prominent, upstanding strike ridge.
Relationships and boundary criteria: Conformably to disconformably overlies the Wiernty Formation. Conformably overlain by the Lake Woods beds. Intruded by dolerite sills.
Correlations: Appears to be a lithological correlative of the Bessie Creek Sandstone of the Roper Group of the McArthur Basin.
Lake Woods beds (new name)

**Proposer:** KJ Hussey.  
**Derivation of name:** Lake Woods in NEWCASTLE WATERS and SOUTH LAKE WOODS.  
**Synonymy:** Previously mapped as Middle Cambrian Gum Ridge Formation in HELEN SPRINGS (Randal et al 1966, Randal and Brown 1969) and BEETALOO (Brown and Randal 1969), and subsequently reassigned to Montejjinni Limestone by Kennewell and Huleatt (1980).  
**Distribution:** Sparse outcrop in northwestern HELEN and southwestern ELLIOTT.  
**Reference section/localities:** No type section, base occurs at 18°00'41" S 133°36'31" E (LA527080) in northern HELEN, top unknown.  
**Lithology:** Sandstone, mudstone, dolostone and chert; evaporite pseudomorphs; probable stromatolites.  
**Thickness:** At least 200 m in HELEN SPRINGS.  
**Geomorphology:** Largely recessive except for some low relief, rubbly strike ridges.  
**Relationships and boundary criteria:** Transitionally overlies Jangirulu Formation; intruded by dolerite sills. Aeromagnetic data suggests the unit underlies Lake Woods where it is gently folded into an open syncline. Interpreted to be unconformably overlain by Montejjinni Limestone, which outcrops in southeast NEWCASTLE WATERS (Kruse 1998).  
**Age:** Mesoproterozoic  
**Correlatives:** Probably correlates with the Velkerri Formation of the Roper Group of the McArthur Basin.

Helen Springs Volcanics

**Proposer:** PD Kruse, after Noakes and Traves 1954.  
**Derivation of name:** Helen Springs property in HELEN SPRINGS.  
**Distribution:** Localised outcrop on the Tennant Creek Inlier in TENNANT CREEK and HELEN SPRINGS; subsurface continuation probable in some adjoining sheet areas.  
**Geomorphology:** Bold mesa outcrops, low hills, creek bed exposures and as pebble and cobble rubble.  
**Type section:** Cored drillhole NTGS96/1 at 234.9-242.2 m depth at 18°24'55"S 134°14'40"E (MV214640); see also Muckaty Sandstone Member (below).  
**Lithology:** Intensely weathered and lateritised tholeiitic basalt and minor microdolerite; includes basal sandstone and conglomerate of the Muckaty Sandstone Member (below).  
**Thickness:** At least 36 m (exclusive of Muckaty Sandstone Member) in bore at Muckaty homestead (Randal 1973).  
**Structural attitude:** Typically flat-lying.  
**Relationships and boundary criteria:** Undifferentiated volcanic portion rests conformably on the basal Muckaty Sandstone Member, which in turn overlies, with angular unconformity, a variety of folded Palaeo-Mesoproterozoic units of the Tennant Inlier. Volcanics are disconformably overlain by the Gum Ridge Formation and Montejjinni Limestone.  
**Correlations:** Correlates with the Antrim Plateau Volcanics [Traves 1955; a modification of the Antrim Plateau Basalts of David (1932)] beneath the Ord, Daly and western Wiso Basins, the Nutwood Downs Volcanics (Dunn 1963) beneath the northern Georgina Basin; possibly the Peaker Piker Volcanics (Smith and Roberts 1963) and Colless Volcanics (Carter et al 1961; Carter and Öpik 1961) beneath the northeastern Georgina Basin.  
**Age and evidence:** Early Cambrian or possibly slightly older, based on the overlying early Middle Cambrian Gum Ridge Formation and Montejjinni Limestone. Hanley and Wingate (2000) suggested that the Antrim Plateau Volcanics correlate with the 513 ± 12 Ma Milliwindi Dolerite, based on similar geochemical signatures.

Muckaty Sandstone Member of Helen Springs Volcanics (new name)

**Proposer:** PD Kruse.  
**Derivation of name:** Muckaty property in HELEN SPRINGS.  
**Synonymy:** Undifferentiated ‘basal sandstone and breccia’ of the Helen Springs Volcanics (Randal and Brown 1969).  
**Distribution:** Localised outcrop on Tennant Creek Inlier in TENNANT CREEK and HELEN SPRINGS; subsurface continuation probable in some adjoining sheet areas.  
**Geomorphology:** Prominent low ridges.  
**Type area:** 7-9 km southeast of Helen Springs homestead. The lower boundary stratotype is a prominent hill at 18°29’05”S 133°56’20”E (LV876564), where conglomerate of the Muckaty Sandstone Member unconformably overlies variegated mudstone of the Mesoproterozoic Wiertyn Formation; the upper boundary stratotype is the top of a prominent scarp along the northeastern margin of an eroded dome near 18°28’50”S 133°55’50”E (LV861573), where the member is conformably overlain by undifferentiated basalt of the Helen Springs Volcanics. The type area includes a 16 m thick reference section (thickest known section) on the southwestern margin of the same dome at 18°28’37”S 133°55’09”E (LV859567). The member is intersected at 242.2-243.8 m depth (reference section) in cored drillhole NTGS96/1 at 18°24’55”S 134°14’40”E (MV214640).  
**Lithology:** Medium to thickly bedded, brown-grey quartz arenite to sublitharenite; conglomerate towards base incorporates quartz arenite and mudstone clasts up to cobble size from underlying Mesoproterozoic units.  
**Thickness:** Ranges from a few millimetres to a maximum known 16+ m in the reference section at LV859567.
Structural attitude: Outcrops generally subcircular in plan view, representing either original dunes or subsequent eroded domes.

Relationships and boundary criteria: Overlies, with angular unconformity, a variety of folded Palaeo-Mesoproterozoic units of the Tennant Creek Inlier. Conformably overlain by undifferentiated (volcanic) portion of Helen Springs Volcanics.

Correlations: Possibly the Jindare Formation beneath the Antrim Plateau Volcanics along the northern margin of the Daly Basin in PINE CREEK, FERGUSSON RIVER and KATHERINE.

Age and evidence: Early Cambrian or possibly slightly older, based on the lower Middle Cambrian Gum Ridge Formation and Montejinni Limestone that overlie the Helen Springs Volcanics.

Gum Ridge Formation

Proposer: PD Kruse, after Öpik in Ivanac 1954.

Derivation of name: Gum Ridge at 19°35'04"S 134°26'05"E (MU407344) in TENNANT CREEK.

Distribution: Presumed to underlie all or most of the Barkly Sub-basin in the western Georgina Basin; outcrop extensive in HELEN SPRINGS, TENNANT CREEK, BONNEY WELL and FREW RIVER.

Geomorphic expression: Low, rubble-covered plateaux and rises.

Type section: Cored drillhole NTGS96/1, 84.4-234.9 m depth, at 18°24'55"S 134°14'40"E (MV214640) in HELEN SPRINGS.

Lithology: In subsurface, grey, often partially dolomitised, massive, ribbon, bioclast, lithoclast and minor oncoid limestone, minor cryptomicrobial dololaminite and grey siliciclastic mudstone; brown-maroon siltstone at base. At surface, these are pervasively chertified and lateritised.

Thickness: 150.5 m in type section.

Structural attitude: Flat-lying to very gently dipping.

Relationships and boundary criteria: Rests disconformably on the Helen Springs Volcanics. Disconformably overlain by strata assigned to the Anthony Lagoon beds; the boundary is placed at a sharp change between the uppermost thick carbonate interval (thickness about 60 m) and overlying, thin, yellow-brown dolomitic-siliciclastic mudstone.
