Geology of the southern McArthur Basin, Northern Territory

BMR Bulletin

220

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ERRATUM

The caption for the figure on page 103 is missing. It should read:

Fig. 106 Type section the Reward Dolomite (upper part of Brown's section 8) 16 km northeast of new McArthur River homestead. For explanation of symbols, see Fig. 90.

DEPARTMENT OF RESOURCES AND ENERGY
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

BULLETIN 220

Geology of the southern McArthur Basin, Northern Territory

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Cover: Fine-grained sandstone crowded with hopper halite casts and moulds (natural scale) in the Mallapunyah Formation near Kilgour (photo by Dick Brown)

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ABSTRACT

The McArthur Basin contains mainly mid-Proterozoic sedimentary rocks that form a platform cover sequence near the eastern edge of the North Australian Craton. The rocks are gently folded and faulted, unmetamorphosed, and appear to have been deposited in mostly shallow environments in an intracratonic basin, which at times was dominated by a prominent north-trending half-graben—the Batten Trough. The sequence in the southern half of the basin, the subject of this Bulletin, is divided by regional unconformities into four stratigraphic groups.

The oldest, the Tawallah Group (about 4500 m thick), unconformably overlies crystalline basement that is about 1800 Ma old. Most of the group consists of thick formations of resistant quartz sandstone alternating with much thinner formations of deeply weathered basic volcanics and fine-grained clastics. The oldest rocks are arkosic and conglomeratic, and mainly of continental origin. They are succeeded by monotonous, probably marine and aeolian orthoquartzites. The basic volcanics are poorly known, but include subaerial flows, intrusions, and volcaniclastics accompanied by iron formations and other redbeds. Rare units of stromatolitic dolostone similar to those higher in the basin succession are also present. The uppermost units are potassium-rich felsic igneous rocks which host the copper-bearing breccia pipes at Redbank, in the southeast.

The unconformably overlying McArthur and Nathan Groups (combined thickness about 5500 m), which are separated by an unconformity, are dominated by formations consisting of evaporitic and stromatolitic cherty dolostones interbedded with dolomitic fine-grained clastics. The formations, which are of shallow-water origin and contain evidence of exposure and desiccation, were deposited mainly in peritidal, lagoonal, lacustrine, and possibly fluvial environments. A wide variety of evaporite pseudomorphs, solution-collapse breccias, and desiccation features, suggest dominantly arid climates. Tuffs in about the middle of the McArthur Group have yielded a U-Pb age of 1690^{+29}_{-25} Ma.

The Roper Group (up to 2000 m thick), unconformably overlying the Nathan Group, consists of alternating resistant quartz sandstone and recessive micaceous siltstone and shale at least 1400 Ma old. Previous studies have identified three coarsening-up megacycles, which may represent major prograding episodes.

Thin Cambrian and Cretaceous rocks (parts of other basin sequences) form discontinuous outliers in the west and south.

The structure of the southern McArthur Basin is dominated by the Batten Fault Zone (the site of the earlier Batten Trough), an eastward-deepening half-graben—now expressed as a horst—containing up to perhaps 12 km of sedimentary rock; the shelves either side of it contain only about 4 km of rock. During part of its history the basin sediments were deposited in pull-apart style sub-basins related to major northwest-trending right-lateral wrench-faulting.

Although no mines are presently operating, the McArthur Basin shows promising base-metal potential. The large shale-hosted McArthur River Pb-Zn deposits are well known. Other prospects include 1) both discordant-vein and disseminated deposits of Pb-Zn, Pb-Ba, and Cu associated with karstically weathered rocks beneath unconformities, 2) Cu-bearing breccia pipes, 3) stratabound disseminated Cu, 4) pisolitic Fe, and 5) U. More recently a promising hydrocarbon potential has been identified: organic-rich shales occur at several levels; gaseous and solid hydrocarbons have been encountered during drilling; appropriate maturation levels have been indicated; and suitable reservoirs may occur within vuggy carbonates or among the extensive quartz arenites.

INTRODUCTION

Scope of McArthur Basin research, 1977–82

The McArthur Basin contains an unmetamorphosed, relatively undeformed, largely sedimentary sequence up to about 12 km thick. It is exposed over an area of about 200 000 km^2 along the western and southern margins of the Gulf of Carpentaria in northern Australia. The sediments are intracratonic in character: they are dominated by shallow-water sandstones and evaporitic, stromatolitic carbonates.

In 1976, K. A. Plumb proposed that a long-term (about 15 years) program of multidisciplinary studies be carried out over the whole basin (Plumb, 1977). The main aims of this program were to elucidate the basin history and to apply the results to the study of ore deposits, especially the shale-hosted stratiform base-metal deposits of the McArthur River type. The major thrust of the program was to comprise specialised studies—such as sedimentology, magnetostratigraphy, palaeontology, and isotope geochemistry—to illuminate particular aspects of the geology or to solve specific problems; in addition, regional and more detailed geophysical surveys were planned in order to assist in tectonic and structural interpretations. In the process, 1:100 000 geological maps of selected areas were to be produced, and the 1:250 000 maps published in the late 1960s were to be revised and reissued where appropriate.

Such a program commenced in 1977. However, following a change in the roles and objectives of BMR in 1979 the McArthur Basin program as originally planned was significantly modified; in particular, the long-term remapping objective was discontinued. This Bulletin, which has a stratigraphic and sedimentological bias, synthesises the results of the geological work from 1977 to 1982. The studies were started in the better-exposed southern part of the basin, so this Bulletin covers only that area between the Roper River in the north and the Queensland/Northern Territory border in the southeast (locality map on accompanying map sheet, Plate 1).

Most stratigraphic names of units in the basin have been in common use for over 20 years, but have never been formally defined. These are now defined, and, where appropriate, some names have been reassessed, dropped, or changed. In addition to the remapping of the south-central part of the basin, detailed sedimentological studies of several units over a wider area were also carried out. The results of some of these studies have been published separately, but their main results are included here; hence the treatment of individual stratigraphic units is variable: some are extensively described and analysed, others are sketchily treated. A short review of the structure and types of mineral occurrences in the southern part of the basin is also provided.

In addition to the sedimentological studies undertaken between 1977 and 1982, BMR also conducted a number of geophysical surveys, including seismic, gravity, magneto-telluric, and aeromagnetics; these will be reported on separately.

Settlement, access, and communications

The largest settlement within the area is the small town of Borroloola, situated on a rocky crossing of the McArthur River 50 km southwest of the shore of the Gulf of Carpentaria. Although originally a port and supply centre for a large part of the area inland, it is now mainly a supply post for nearby Aboriginal settlements, for the several large pastoral leases that cover the area, and for tourists. It contains a few stores, a post office, a small hospital and school, a police station, and other government offices. It is connected by good-quality sealed highways with Katherine (ca 580 km to the west) and Mount Isa (ca 900 km to the southeast by road); these two towns provided the supply centres for our fieldwork.

Within the area, regularly maintained unsealed roads provide good access to most places during the dry season. Access from these roads is by four-wheel-drive vehicles on station tracks or across country. Parts of the Bukalara Plateau and Tawallah Ranges (see locality map, Plate 1) are inaccessible to vehicles, and were traversed on foot and by helicopter. Effective ground movement within the area during the wet season (commonly December–February) is often impossible.

There are sealed airstrips at Borroloola and the McArthur mine, and dirt strips at most of the stations. Borroloola, the mine, and some of the stations have radio-telephone links with the outside, otherwise communication is via the Royal Flying Doctor Service two-way radio network.

Physiography

The part of the McArthur Basin examined during the program of research between 1977 and 1982 falls mainly within the physiographic region that Stewart (1954) called the Gulf Fall. This comprises the dissected hilly country surrounding the Gulf of Carpentaria in which the natural drainage is towards the coast. To the southwest the Gulf Fall is flanked by the flat and generally featureless Barkly–Birdum Tablelands, with their intermittent internal drainage, whereas to the northeast the Gulf Fall grades into a 50-km-wide, low, sandy coastal plain (Fig. 1).

The Gulf Fall slopes gradually from elevations of around 700 m in the southwest to around 20 m at the coastal plain. It is developed on dissected Proterozoic rocks, and much of it has an undulating topography of low hills, cuestas, or ridges with intervening areas of colluvial and alluvial plains. Two other physiographic subdivisions of the Gulf Fall have a much higher relief: the Bukalara Plateau and the ranges and ridges (Fig. 1), which are commonly elevated more than 100 m above the general level of the surrounding Gulf Fall country.

The Bukalara Plateau is an extensive 'karstic' sandstone plateau standing at elevations around 200 m above MSL in the central part of the area. It is sparsely vegetated, deeply dissected by the rivers that cross it, and virtually impenetrable by vehicles. It is developed on the flat-lying to gently dipping Cambrian Bukalara Sandstone, which unconformably overlies the Proterozoic rocks.

Most of the ranges and ridges are located in a north-trending zone in the west, and consist of areas of Tawallah Group rocks. These comprise alternating steep-sided ridges and valleys formed by differential erosion of the interbedded softer sediments and volcanics within the more resistant sandstones.

Regional setting

A brief account of the regional setting and structure of the McArthur Basin is provided here, so that the results from the southern half of the basin can be considered in a regional context. This summary has been abstracted from Plumb & others (1980, 1981). The information on the McArthur Basin in these two review papers is based largely on the results from the 1957–62 BMR reconnaissance mapping. A more detailed and updated description of aspects of the structure and basin evolution is provided below (p. 153).

The McArthur Basin contains a thick platform-cover sequence overlying the eastern edge of the North Australian

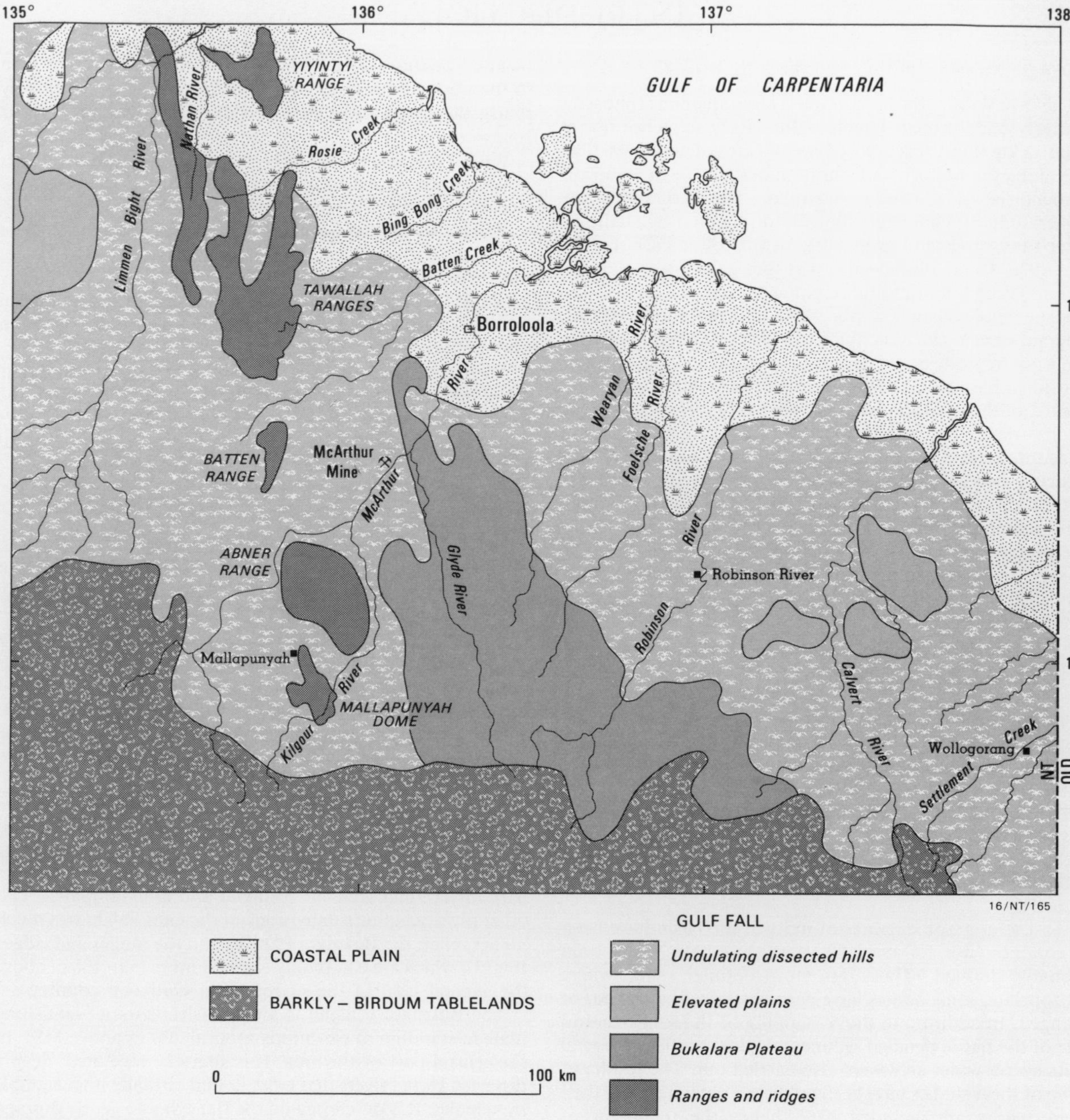

Fig. 1. Physiographic subdivisions of the southern McArthur Basin.

Craton (Fig. 2), which consists of Lower Proterozoic basement rocks. The McArthur Basin has a stratigraphic succession similar to those in the Lawn Hill Platform and Mount Isa Orogen (Fig. 3).

Previously, the McArthur Basin sequence had been divided into three groups (Plumb & others 1980). However, the recent studies have shown the need for removing several formations from the upper part of the McArthur Group and placing them in a new group, which has been named the Nathan Group; and also moving the boundary between the Tawallah and McArthur Groups to below the base of the sandstone unit (to be redefined as the Masterton Sandstone) of the Masterton Formation (to be discontinued). Better correlations have made several published stratigraphic names redundant. The stratigraphic nomenclature and relationships of the southern McArthur Basin are illustrated diagrammatically in Figure 4.

The Tawallah Group consists mainly of quartz sandstone with subordinate volcanics, carbonate, and shale which have a composite maximum thickness of about 4500 m. The overlying McArthur Group now comprises the sequence from the Masterton Sandstone up to and including the Looking Glass and Amos Formations; it consists of about 4000 m of interbedded evaporitic carbonate and shale with subordinate sandstone, chert, and tuff beds. Unconformably overlying this is the Nathan Group, which consists of about 1500 m of dolostone, sandstone, chert, and shale. The youngest sequence in the basin is the Roper Group, which comprises up to 2000 m of alternating sandstone and shale in the southern McArthur Basin, but thickens to over 5000 m to the west.

The major tectonic divisions of the McArthur Basin and adjacent parts of northern Australia are shown in Figure 5. According to Plumb & others (1980) the palaeogeography of the basin was dominated by the northerly trending Batten Fault Zone or Trough—a palaeotectonic feature controlled by syndepositional faults—in which up to 12 km of shallow-water sediments accumulated. In contrast, only a few

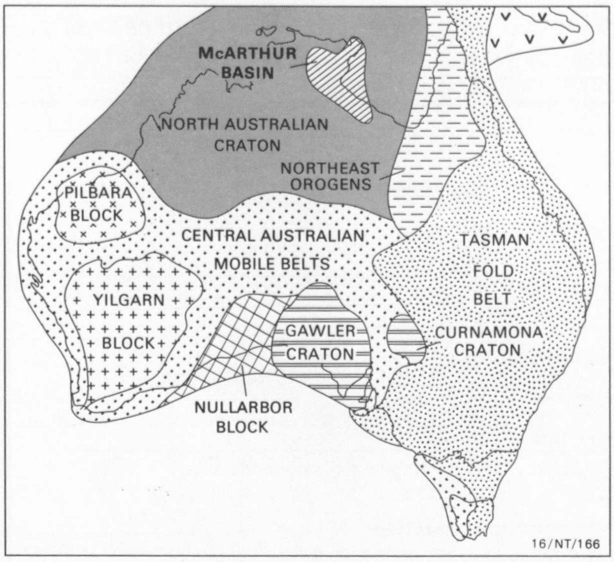

Fig. 2. General location and regional setting of the McArthur Basin (after Plumb & others, 1981).

kilometres of sedimentary rocks are preserved on the adjacent shelves, on either side of the trough. The more recent work suggests a more complicated picture which is discussed on p. 153.

Terminology and classifications used

Locality information

Throughout the Bulletin the use of the unqualified term 'the area' refers to the portion of the basin that was studied between 1977 and 1982—i.e., more than 80 000 km^2 constituting the southern half of the McArthur Basin (locality map, Plate 1). Owing to a lack of place names, references within the text to specific parts of the area generally are referred to the appropriate 1:250 000 or 1:100 000 Sheet areas. To avoid confusion, the names of the 1:250 000 Sheet areas are capitalised throughout the text (e.g., BAUHINIA DOWNS), whilst the names of 1:100 000 Sheet areas are italicised (e.g., *Mallapunyah*, 6064); an index to these Sheet areas is shown in Plate 1.

More specific locations either have been related to a nearby well defined locality (e.g., 1.5 km south or Borroloola) or

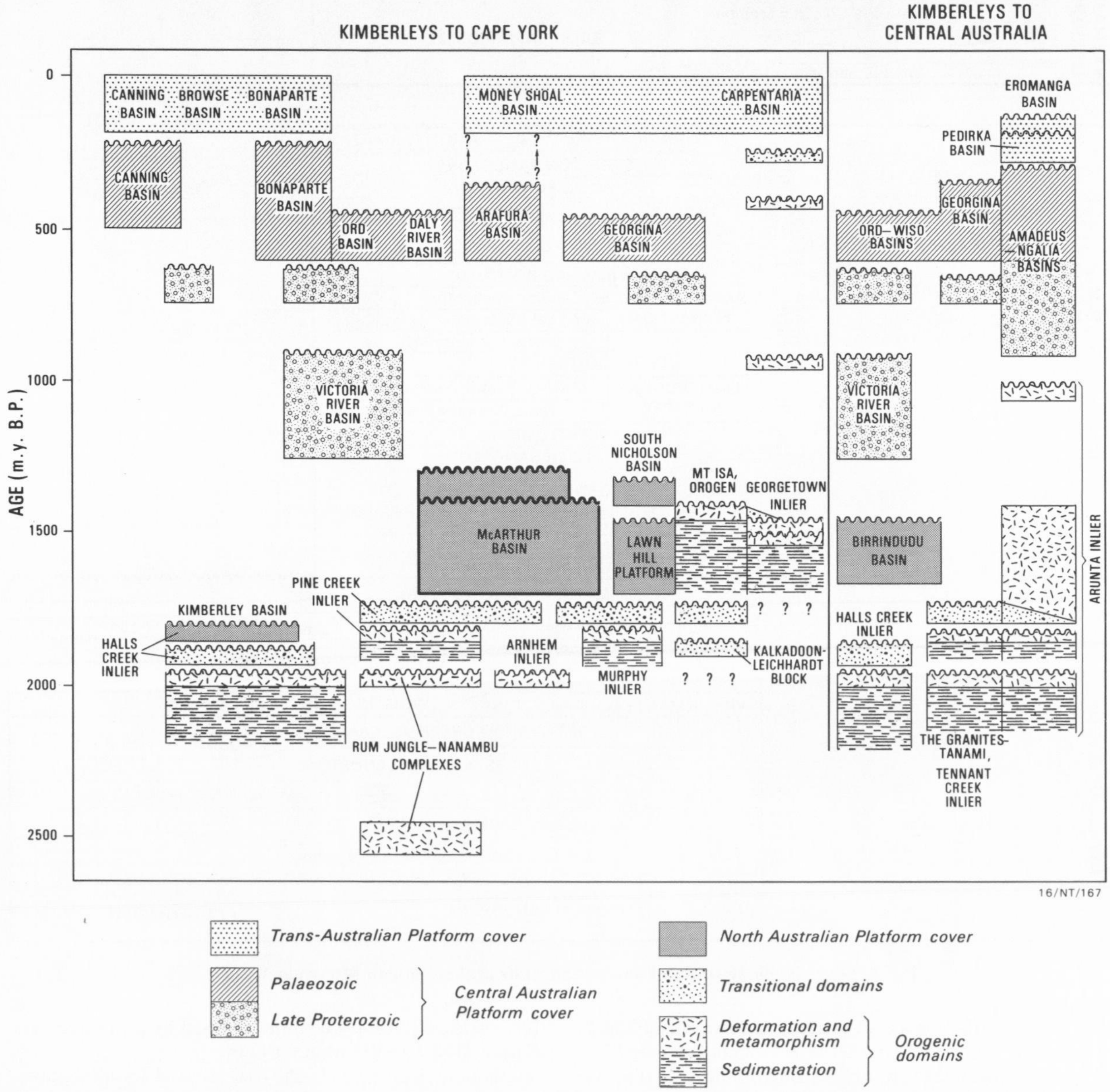

Fig. 3. Diagrammatic representation of the relationships between regional tectonostratigraphic units in northern Australia (after Plumb & others, 1981).

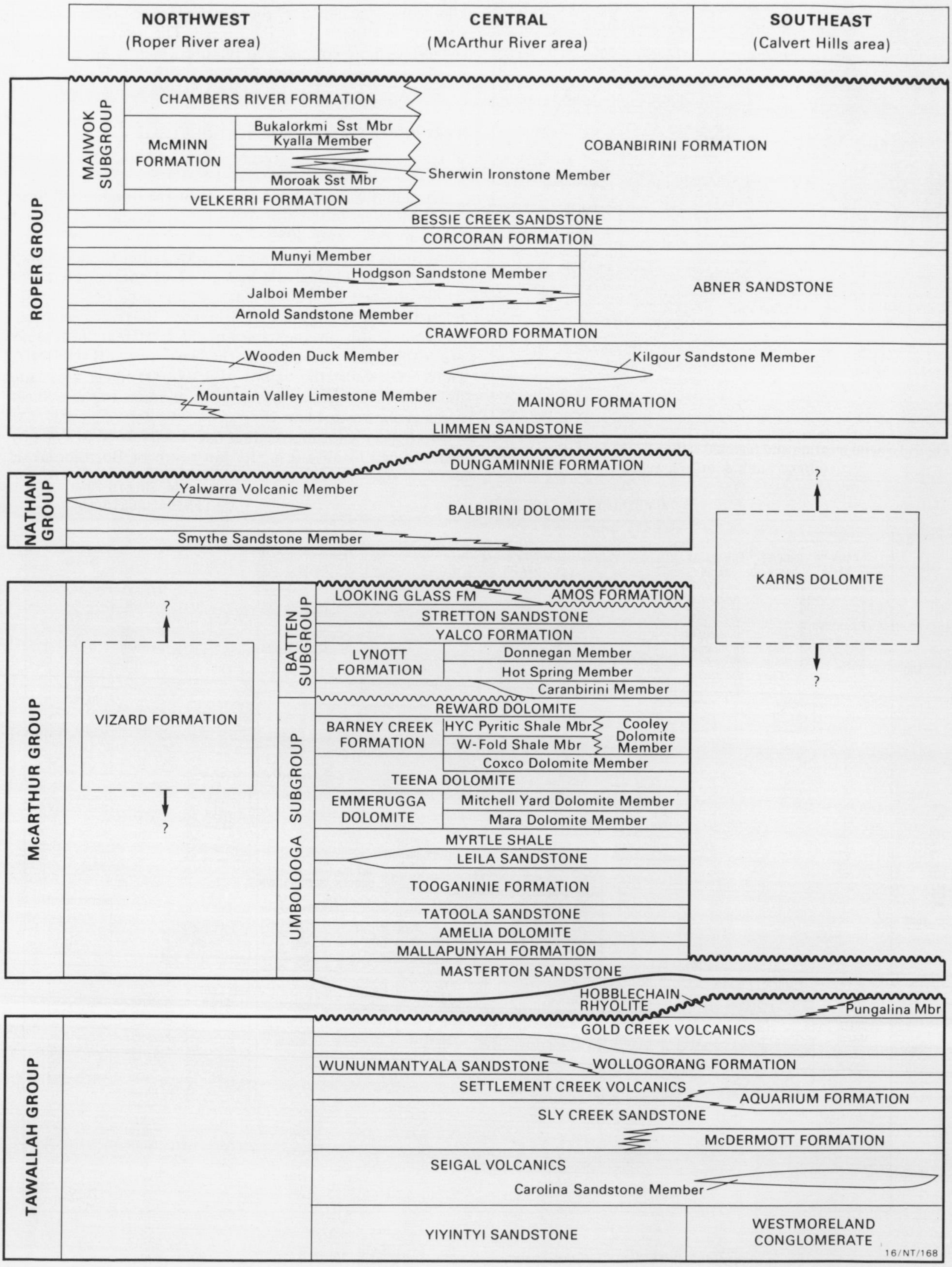

Fig. 4. Stratigraphic relations of Proterozoic units in the southern McArthur Basin.

have been identified by a grid reference from either Plate 1 or from the appropriate 1:100 000-scale topographic map (e.g, 'the type section is at GR 143776 *Borroloola* (6165)'; this location is at easting 143, northing 776, on the Borroloola 1:100 000 Sheet, 6165). Localities defined by grid references are accurate to within about 100 m.

During the field research, the basic control for topography and geology was a set of 1:25 000 colour airphotos taken in

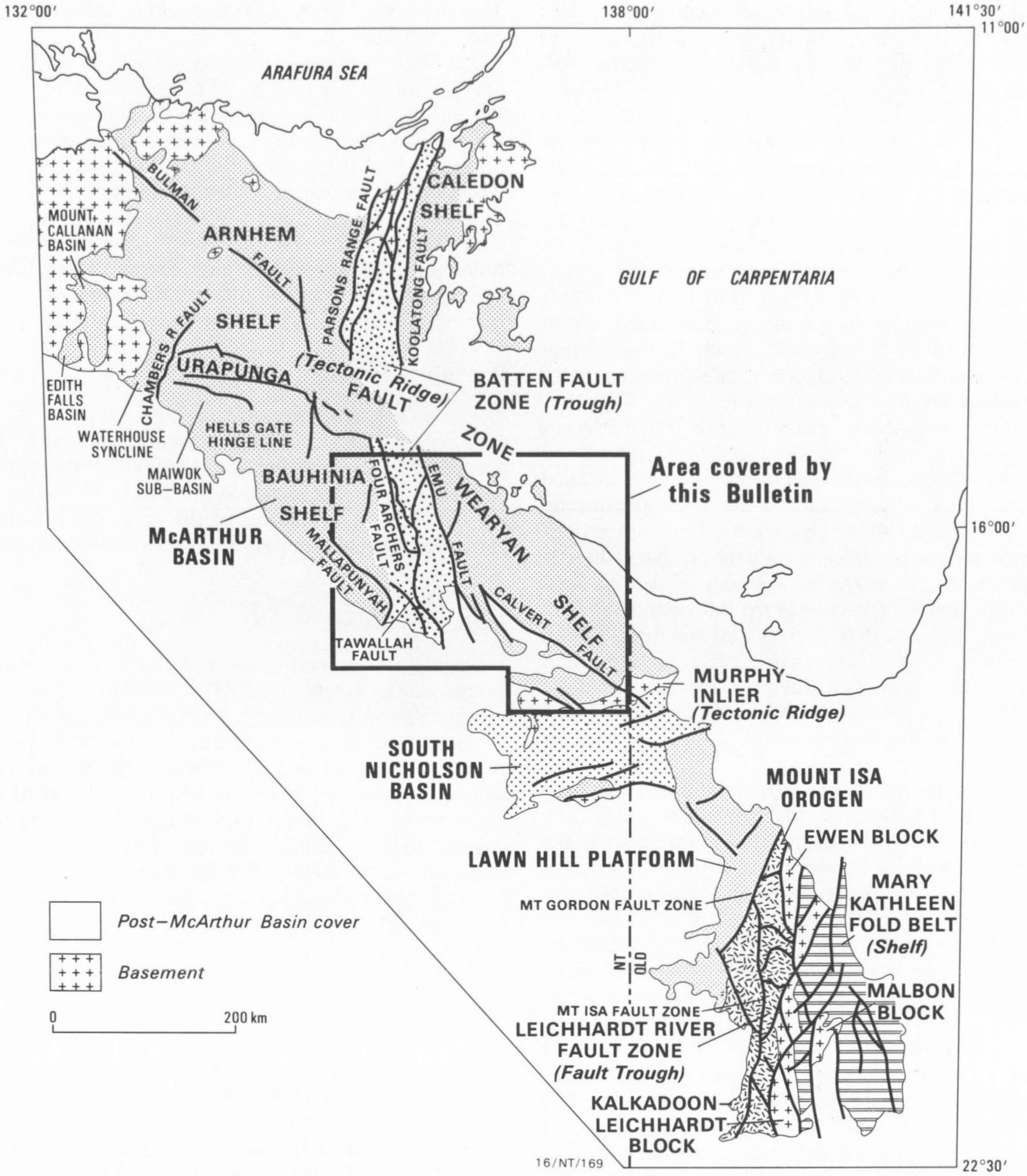

Fig. 5. Regional tectonic setting of the southern McArthur Basin (from Plumb & others, 1981).

1977 for the Commonwealth of Australia. These provide excellent location control and, where used in conjunction with the 1:80 000-scale Adastraphoto 1968 black and white airphotos, they allow very accurate photo-interpretation. For production of the Abner Range Region map, the geological information was taken from transparent photo-overlays, and plotted at photoscale on to topographic base-maps supplied by the Division of National Mapping, Canberra. These were then reduced to 1:100 000 scale, generalised slightly, and redrawn to produce the accompanying map (Plate 1).

During the fieldwork, each locality at which scientific observations were recorded was given a unique identifying number which relates to a card index system stored at BMR. The number is identified by year, project, and officer key numbers (e.g., 79100023 is the 23rd registered locality recorded by Jackson in 1979). The localities were initially plotted on to airphotos in the field (pin-prick and numbering on reverse side), and were later transferred, during compilation, to the topographic maps. Some information recorded in this Bulletin (e.g., measured sections, samples, photographs) is identified by these numbers. Samples are identified by a letter suffix added to the locality number; for example, 79100023C is the third specimen collected at locality 79100023.

Sections measured between 1977 and 1982 are identified by the 1:100 000 Sheet area within which they are located, by the year in which they were measured, and serially in the order in which they were measured; for example, section Tawallah Range 79/02 is the second section measured during 1979 in *Tawallah Range* (6066). Other measured sections reproduced in this Bulletin and originating from prior surveys are identified as unambiguously as possible; thus our notation of *Brown's Section 12* is measured section 12 from Brown & others (1969, plate 10). All measured sections reproduced herein have been located wherever possible by grid references on the 1:100 000 series maps; those falling within the Abner Range Region are plotted in Plate 1.

The detailed sections were measured mainly with a 1.5-m Jacobs staff and Abney level. In much of the area, dips are around 10°, so accurate thickness measurements are possible using this method. All sections were measured by two people: one person (usually a field assistant) marking off 1.5-m intervals by spraying a spot of paint and number on the rocks, and the geologist following up behind compiling the geological information on specially designed charts. A novel method of recording the measured section observations was adopted, wherein two columns of symbols side-by-side were used. One column, on the left, shows the dominant lithology and weathering profile of the unit; the adjacent column, on the right, shows sedimentary structures and textures. Additional features (e.g., evaporites, mineral occurrences) are shown along the edges of the columns. This method has the distinct advantage, over normal one-column schemes, of clearly differentiating these two important aspects of a section and providing a visually striking record of it. The symbols used on the measured sections resulting from our research between 1977 and 1982 are shown in Figure 6. The scheme used by Brown was a slightly different one-column system, but our symbols are mostly compatible.

In the field a standard-scale reduction factor of 1:200 was employed—i.e., 1 m of section is reduced to 0.5 cm on the charts. In areas of very complex sedimentology, more detailed sections were occasionally measured at enlarged scales directly by tape. In stratigraphic units characterised by thick monotonous lithologies, interval thicknesses were calculated directly from the airphotos. To assess the accuracy of various field methods, stratigraphic thicknesses in the Batten and Tawallah Ranges were measured both by Jacobs staff and directly from the photographs; errors of less than 5 per cent were found in sections several hundreds of metres thick. Less accurate estimates of thickness using visual estimation and pacing were sometimes used in areas of very poor and discontinuous outcrop.

Some place names referred to frequently in the text have somewhat unclear definitions; they are more specifically defined here. The new McArthur River homestead is the homestead 1 km north of Bessie Spring at the northern end of the Abner Range (*Mallapunyah* 6064). The old McArthur River homestead refers to the abandoned ruins on the east bank of the McArthur River 2 km southeast of McArthur mine (southwest corner of *Borroloola*, 6165). McArthur mine, HYC mine, HYC prospect, HYC deposit, McArthur River deposit—these are more-or-less synonymous terms given to the large lead-zinc-silver stratiform deposit situated underneath the McArthur River east of Barney Hill in the southwest corner of *Borroloola* (6165); we prefer the terms 'McArthur mine' for reference to the mine workings, and 'HYC deposit' for reference to the orebody. Clyde and Glyde Rivers are the names used for the same river southeast of the Abner Range on a variety of published maps; we use Glyde throughout this Bulletin.

In MOUNT YOUNG and BAUHINIA DOWNS, two widely separated ranges of hills are shown as the Tawallah Range. One is on the western side of *Tawallah Range* (6066), the other is in the north central part of *Batten* (6065). We have used the name Tawallah Ranges to refer to all the mainly quartzite ridges forming rugged topography in the northern half of *Batten* and over most of the western half of *Tawallah Range* (locality map, Plate 1).

Rock type, bedding, structures, colour

Sandstone classification is that recommended by Pettijohn & others (1972, pp. 155–160), bedding terminology is taken from Reineck & Singh (1975, pp. 82–84), and cross-stratification terminology is that of McKee & Weir (1953) or Allen (1963) if it is well enough exposed. Colours quoted are non-specific unless followed by an appropriate Munsell number and letter code (Geological Society of America, 1963). Terms used in stromatolite descriptions are those recommended by Preiss (*in* Walter, 1976). Reineck & Singh (1975), Conybeare & Crook (1968), Bathurst (1975), and Gary & others (1973) were the basic references for most other sedimentary textures and structures.

The classification of carbonates was essentially a field classification suggested by M.C. Brown. A basic grainsize terminology is adopted, in which dololutite is composed of silt and clay-size dolomite, dolarenite of sand-size dolomite grains, and dolorudite of carbonate grains larger than 2 mm. These names are then modified by adding suitable adjectives or prefixes, usually referring to compositional or textural characteristics; for example, poorly sorted intraclast sandy dolarenite. 'Dolostone' is the general term for a rock composed mainly of the mineral dolomite.

Previous investigations

The area has a long and varied history of geological, geophysical, and mineral exploration activity. Detailed accounts of these investigations throughout the whole of the McArthur Basin are provided by Plumb (1977) and Jackson (1979a). The main features of the more significant investigations in the southern part of the basin are summarised here.

Early exploration

Geological observations were made by some of the early explorers (e.g., Leichhardt, 1847; Gregory, 1861) and Government geologists (e.g., Brown, 1908; Woolnough, 1912; Jensen, 1914) who visited or passed through the area. In 1939–40 the Aerial, Geological and Geophysical Survey of Northern Australia undertook mapping in the southeast of the area (AGGSNA, 1939, 1940a, b), and reported on the Redbank copper deposit. Among the most important observations made during these early investigations were the presence of a thick sequence of old ('Cambrian') sedimentary rocks and the recognition of high-grade copper ore in these little-disturbed rocks.

Government systematic mapping (1957–1962)

BMR undertook systematic geological mapping of the whole basin, at 1:250 000 scale, between 1957 and 1962. This mapping was a continuation of similar reconnaissance mapping projects in the adjacent Pine Creek and Mount Isa areas. The impetus for moving into the McArthur Basin was largely provided by the discovery, in the late 1950s, of a large base-metal deposit near McArthur River (Buchanan, 1984). A BMR team of between five and seven geologists carried out ground and helicopter mapping of a large area fringing the Gulf of Carpentaria and stretching from the Queensland border in the southeast to east of Darwin in the northwest. Twenty 1:250 000 geological maps and Explanatory Notes were published. The definition of stratigraphic sequences and the delineation of major structural features were the main results, which provided the basic information for anyone planning mineral exploration programs in the basin. However a major misinterpretation of the stratigraphy was made: the McArthur Group was interpreted as a reef complex with a reef in the Top Crossing area, and various formations were grouped into reef and fore-reef facies (Smith, 1964); in fact, there is no reef—the formations form a fairly simple layer-cake stratigraphy (Fig 4).

After the publication of the Explanatory Notes and maps (by 1965) two BMR Bulletin manuscripts were commenced but never completed. One of these, on the southern part of the basin, deals largely with the area covered by this Bulletin; the other would have covered Arnhem Land. The incomplete draft manuscript on the southern McArthur Basin (Roberts, unpublished) contains much useful basic geological infor-

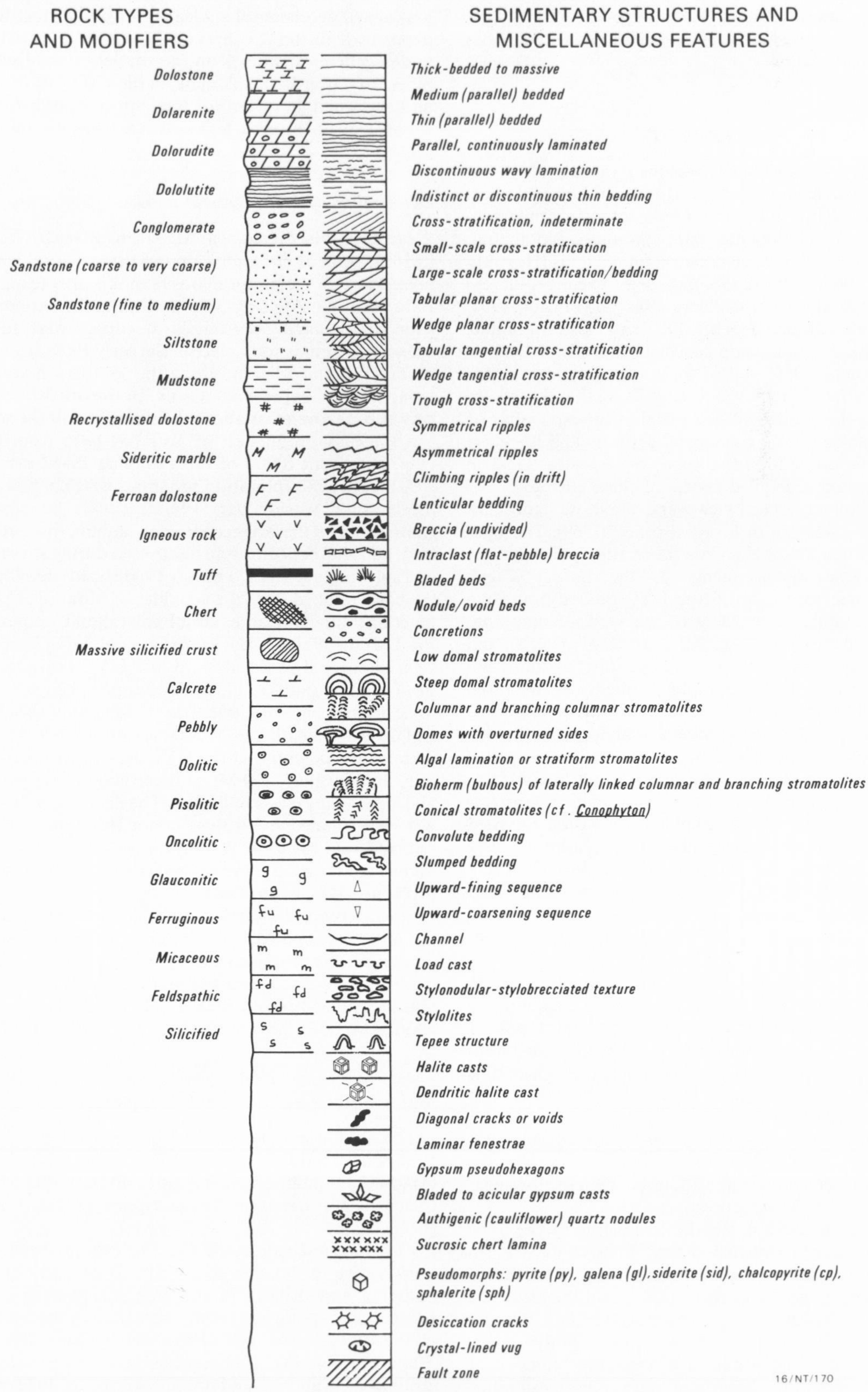

Fig. 6. Symbols used on measured sections and drillhole logs.

mation, and it was of considerable interest and value in the early stages of this present study. It has formed a basic source for some of the units discussed herein that we have not examined in detail. The source of this information is acknowledged as Roberts (unpublished). It should be emphasised, however, that our more detailed work on most of the units has significantly modified or invalidated many of these earlier interpretations.

In addition to the reconnaissance geological mapping, BMR also undertook regional gravity (Neumann, 1964) and aeromagnetic surveys (Young, 1964), the results of which are of interest on a continental scale but of little value on a more detailed basinal scale.

Government ad-hoc investigations (1958–1980)

Between 1958 and 1980 the Government (mainly BMR, but also CSIRO) carried out seven short-term ad-hoc geological and geophysical investigations. These comprise three geophysical surveys including magnetic, spontaneous potential, electromagnetic, and induced polarisation methods (Horvath, 1959; BMR, 1964; Sedmik, 1967); three geochemical surveys using soil, rock-chip, and drillcore material (Fricker, 1962; Haldane, 1965; Lambert & Scott, 1973); and a stratigraphic, sedimentological, and outcrop geochemical study in 1967–69 (Brown & others, 1969). All of these surveys were concentrated around the McArthur mine (Fig. 7), so that they might better define the geological and geophysical expression of mineralised shale-hosted base-metal deposits and therefore assist in exploration for these types of deposits. Jackson (1979a) presented a detailed review of these surveys.

From a sedimentological viewpoint, the most significant of these surveys was that of Brown & others (1969). The main aim of their study was to elucidate the stratigraphic relations and depositional environments of the Barney Creek Formation (host formation to the HYC orebody) and the enclosing dolomitic units. Most of the work—remapping, detailed section measuring, logging of drillcore material, and geochemical analyses of a 'representative suite' of about 360 rock samples from the stratigraphic sequence between the Emmerugga Dolomite and the Reward Dolomite—was done in the area near the McArthur mine and at Top Crossing (50 km to the southwest), but other sections elsewhere were also examined. Probably the most important result to come out of this work was the revision of the stratigraphic interpretations reported in the various Explanatory Notes. Detailed mapping by geologists of Carpentaria Exploration Co. Pty Ltd in the early 1960s had questioned the validity of the reef interpretation, and the study by Brown & others confirmed their reservations. A summary of the revised correlations and stratigraphic nomenclature for the McArthur Group was issued by Plumb & others (1973).

In addition to basic stratigraphy, Brown & others made detailed environmental interpretations, and suggested a depositional history for the evolution of the central part of the basin. Unfortunately, these results were not issued until almost a decade after the study was completed, by which time rapid advances in comparative sedimentology had invalidated some of the interpretations suggested.

The geochemical component of the study by Brown & others provided some interesting results, especially the comparison of elemental compositions between sections near and away from the McArthur mine.

We have incorporated in this Bulletin some of the basic observations made by Brown & others. Thus we have reproduced without significant amendments Brown's measured sections as text figures or in Appendix 1, and the results of Claxton's geochemical investigations in Appendix 2. Because of the availability of their detailed (if slightly dated) sedimentological observations and the large number of stratigraphic units in the basin that had not been examined at all, we avoided systematic studies on most of the units which they studied; rather, we complemented and supplemented their observations with our own, and revised their interpretations.

Two additional geochemical/ore-genesis studies were done. Lambert & Scott (1973, 1975) compared the geochemistry of rocks from drillholes into the HYC deposit with that of rocks from outlying sections, and suggested a number of mineralogical and geochemical guidelines for prospecting for similar deposits. Knutson & others (1979) carried out petrographic and geochemical studies on the copper-mineralised breccia pipes from near Redbank mine, in the southeast of the basin, and suggested an origin for the copper from hydrothermal brines associated with high-level carbonatitic intrusions.

Delineation of main mineral deposits

Lead was discovered near McArthur River by Tom Lynott in 1887, soon after he took up the first pastoral lease in the area. Most of the minor deposits in this area (e.g., Barneys, Bald Hills, Cooks, Coxs, Turnbulls, Squib) were discovered soon after. Small occurrences of copper were found and spasmodic mining took place in the early 1900s from deposits at Yah Yah and Kilgour, along the southern margin of the area, and at Copper Mine Creek, in the northwest. Copper was also discovered at about the same time in the southeast, but the only production of note has been from Redbank (Fig. 7)—about 1000 t of ore averaging 25–52 per cent Cu.

A number of exploration programs were carried out after the Second World War; Plumb (1977) has listed and commented on these. Uneconomic uranium, iron ore, copper, lead, and zinc deposits were discovered during surveys in this and surrounding areas. The most significant development in the basin resulted from the activities of Mount Isa Mines Ltd (later operating as Carpentaria Exploration Company (CEC) Pty Ltd). In 1955, siliceous gossans containing lead and zinc were discovered at the Reward and HYC prospects. Initial work was concentrated at the Reward prospect, which proved to be a supergene enrichment containing only about 100 000 t of 13 per cent Pb ore. It was not until 1959 that drilling revealed the potential of the HYC deposit. A trial shaft was dug, and, by 1965, 190 Mt of ore averaging 9.5 per cent Zn and 4 per cent Pb was indicated. The nearby Cooley deposits were investigated by drilling about this time, and further reserves were found at W-Fold during 1973–74. Large-scale mining at McArthur mine has been prevented by metallurgical problems (Buchanan, 1984).

Several companies carried out exploration programs during the late 1960s and early 1970s, but most were unsuccessful and only a few produced any significant new data. Uranium deposits were discovered and outlined at Westmoreland by Queensland Mines and BHP Co. Ltd. Ore reserves totalling about 4 Mt of 2.5 per cent Cu have been outlined at Redbank.

Major mineral exploration by companies

This section summarises most of the significant geological studies undertaken by non-government agencies, especially exploration and mining companies, in the southern part of the basin. It is based on the description provided by Plumb (1977).

Carpentaria Exploration Co. Pty Ltd has been continuously active in the area since 1955. It carried out detailed mapping and drilling in the area surrounding the HYC prospect. Its geological results were used in the compilation of the northeastern part of the Abner Range Region map (Plate 1). The HYC orebody has been sampled by underground excavations, and mining trials to 1979 provided material for a pilot plant to test the economics of ore treatment. The HYC and related deposits have been the subjects of numerous mineralogical, petrological, and geochemical studies (e.g., Croxford, 1968; Croxford & Jephcott, 1972; Murray, 1975; Smith & Croxford, 1975; Williams, 1974, 1978a, b; Walker, 1980; Walker & others, 1983) and a sedimentological study (Logan, 1980). CEC Pty Ltd possesses a wealth of unpublished data, in addition to its published and open-file reports. It has many thousands of metres of drillcore through the Barney Creek Formation and related units; in 1985 this material was still stored at the Mimets camp at McArthur River mine. During 1975 the company outlined new copper occurrences in the Mallapunyah area in the Tooganinie and Mallapunyah Formations and in the Amelia Dolomite. Recent exploration has proved the presence of banded and brecciated copper-rich mineralised rock at the northern end of the HYC deposit (Logan & Dennis, 1981).

Triako Minerals-Amdex Mining (and a succession of other companies preceding them) have carried out extensive detailed mapping, section-measuring, drilling, and geophysical surveys in the area near Redbank. They have accumulated thousands of metres of drillcore, mainly from the Gold Creek Volcanics; in 1983 this core was still stored at Redbank. Except for a paper by Rod (1978), the data remain unpublished. Unpublished reports by Rod (1977) and Wyatt (1977) on the geology of the Settlement Creek-Redbank area were used during this study to streamline our research on the sedimentology of the upper formations of the Tawallah Group.

BHP Co. Ltd carried out exploration for lead-zinc in eastern Arnhem Land, north of the area (see Plumb 1977), and for uranium near Westmoreland. It also commenced a base-metal search in the Batten-Tawallah Ranges in 1980. This program includes detailed remapping, stratigraphic studies, and drilling; results were unavailable when this Bulletin was written.

Australian Geophysical Pty Ltd undertook major field surveys in 1966, 1967, and 1969 in the Calvert Hills-Robinson River-Mallapunyah area. It defined stream-sediment geochemical anomalies, which were geologically mapped and gridded with IP and magnetic surveys; soil and rock samples were also analysed. The program culminated with the drilling of seven drillholes. Stratabound copper was found in the Karns Dolomite, Settlement Creek Volcanics, Wollogorang Formation, Amelia Dolomite, and McDermott Formation. Comprehensive reports are available on open file at NTGS in Darwin (Australian Geophysical Pty Ltd, 1967, 1968, 1970). The first two reports contain detailed maps of Tawallah Group inliers between Mallapunyah and Calvert Hills; they were used extensively to facilitate our sedimentological research and remapping. The 1970 report covers the stratigraphic drilling. The core material from this drilling is stored at the Department of Mines and Energy, Darwin.

Australian Cities Services undertook similar surveys to those of Australian Geophysical Pty Ltd in about the same area (Australian Cities Services, 1975). They investigated the Karns Dolomite as well as the upper Tawallah Group units. They drilled three holes in the Robinson River area, but the location of the resulting core material is not known.

CRA Exploration Pty Ltd mapped areas between Bauhinia Downs homestead and Eastern Creek, and around Urapunga, during 1973 (Johnston, 1974a,b). As part of a more recent program, drilling in a joint venture with Amoco Minerals Australia north of HYC (near Caranbirini) in 1982 intersected mineralised Barney Creek Formation.

Australian Aquitaine Pty Ltd investigated the oil potential of the McArthur Group during the early 1960s and measured several sections. BMR holds a copy of its report (Rueff & Haskins, 1965).

AGIP Nucleare Australia Pty Ltd carried out airborne radiometric and magnetometer surveys of the Tawallah Ranges area, and ground-checked and assayed anomalies, during the early 1970s. Anomalies were due to lithological variations and superficial effects, and to a small placer of Th-U minerals in the Yiyintyi Sandstone. High backgrounds were recorded over the Scrutton and Seigal Volcanics (AGIP, 1973, 1974a,b).

Kratos Uranium NL carried out a large airborne radiometric and magnetometer survey and ground follow-up program over the Roper Group between OT Downs and Roper Bar. Its magnetic surveys successfully delineated several major structures and basic intrusives. It drilled, cored, and logged a number of holes down to 400 m through the Corcoran Formation (Kratos, 1971, 1972).

AO Australia Pty Ltd (now Ashton Mining Pty Ltd) mapped and drilled the Barney Creek Formation and the Lynott Formation in the area northwest of CEC Pty Ltd's HYC leases between 1976 and 1980 as part of a base-metal exploration program. Several small copper occurrences were also mapped and drilled.

Shell (Minerals) Australia drilled and analysed bedrock samples north of AO's leases on the northern extension of the Batten Trough in the late 1970s.

Amoco Minerals Australia undertook base-metal exploration east of the Emu Fault Zone during the late 1970s, largely by drilling for McArthur-style mineral deposits hidden beneath the extensive cover of Cambrian Bukalara Sandstone. It defined a number of shale-hosted sulphide bodies. One of its drillholes encountered a pocket of gas which caused a blow-out for several months in 1979. With Kennecott Exporations, it drilled a hole through the Lynott Formation, Reward Dolomite, and upper Barney Creek Formation 3 km southwest of Caranbirini Waterhole.

Amoco International commenced in 1981 a major petroleum exploration program of stratigraphic studies, geophysical surveys, and drilling (Amoco, 1981).

All the known reports originating from these varied projects are included in the References. Most of them are unpublished, but are available as open-file company reports from the Department of Mines and Energy, Darwin.

Other studies

Micropalaeontology. The first microfossils were described from samples of the HYC Pyritic Shale Member of the Barney Creek Formation by Hamilton & Muir (1974). Although published earlier, the next description of microfossils in the area was from black chert of the Amelia Dolomite (Croxford & others, 1973). Since that time numerous microfossil assemblages have been discovered in the McArthur Basin sequence: from the Amelia Dolomite (Muir, 1974, 1976), Mara Dolomite Member of the Emmerugga Dolomite (Muir, 1982b), HYC Pyritic Shale Member of the Barney Creek Formation (Oehler, 1977; Oehler & Logan, 1977), Cooley Dolomite Member of the Barney Creek Formation (Muir, 1978), Balbirini Dolomite (Oehler, 1978), and Barney Creek Formation (Muir, 1981). One assemblage has been described from the Wollogorang Formation (Muir, 1982a), and one from the Roper Group (Peat & others, 1978).

The microfossil assemblages appear to be stratigraphically and environmentally useful.

Stromatolites. The stromatolites in the McArthur Basin also appear to be stratigraphically useful, and have been commented on briefly by Cloud & Semikhatov (1969), Walter (1972), and Jackson (1982d). A study of selected stromatolites (Walter & others, in press) suggests a lower Riphean age.

Evaporites. Evaporitic sequences of the area were the subjects of sedimentological and environmental studies (Williams, 1976; Walker & others, 1977) before BMR embarked on its multidisciplinary program in the McArthur Basin in 1977.

BMR INVESTIGATIONS 1977-82

Major geological field research was done in 1977, 1978, and 1979, and additional follow-up surveys were undertaken in 1981 and 1982. A number of geophysical parties operated throughout the southern part of the basin between 1978 and 1980.

Geological investigations

The southern part of the McArthur Basin was remapped using 1:25 000-scale colour airphotos. The results were compiled into a 1:100 000 geological map—Geology of the Abner Range Region (Plate 1). In addition, a 1:250 000-scale geological map of BAUHINIA DOWNS, showing revised stratigraphy in areas where the new mapping had shown it to be drastically incorrect, was included in the 1977 fieldwork Record (Jackson & others, 1978). Although some mapping north of the Abner Range Region was done, this was not completed, and plans to compile a second 1:100 000 sheet covering the Batten and Tawallah Ranges have been abandoned. During this later mapping, a significant mistake in the portrayal of the geology of the Tawallah Group in these ranges in the BAUHINA DOWNS (Smith, 1964) and MOUNT YOUNG geological sheets (Plumb & Paine, 1963) was discovered (see p. 30).

Concurrent with the remapping, more specialised studies, focusing on comparative sedimentology, were commenced, and as the program evolved these became the main aspect of the work. In addition, a number of other studies was carried out by non-BMR personnel attached to the various field parties. These ancillary studies included such topics as isotopic dating of carbonate phases in sedimentary rocks (M. Kralik, Australian National University); identification of stromatolites (I. Krylov, Geological Institute, Academy of Sciences of USSR); isotopic studies of mineral deposits (T. Donnelly, Baas Becking Geobiological Laboratory); geochemistry of Precambrian organic matter (M. Fowler, University of Newcastle, England); and geochemistry of tuffaceous units (D. E. Large, Technical University of Brunschweig, Federal Republic of Germany).

The results of these specialised studies are mentioned in this Bulletin where pertinent, but except for one they are not reported in any detail. This exception is the lithogeochemical study carried out by D. E. Large during 1977. The analyses provide useful 'background' geochemistry. The results of this study are reproduced in Appendix 3.

The geologists who made significant contributions to the field research synthesised in this Bulletin are listed here: in *1977* — M. C. Brown (Canberra College of Advanced Education), M. J. Jackson, D. E. Large, M. D. Muir, and K. A. Plumb; in *1978* — M. J. Jackson, I. Krylov, M. D. Muir, W. J. Perry, K. A. Plumb, and C. J. Simpson; in *1979* — M. J. Jackson and M. D. Muir; in *1981* — M. J. Jackson; and in *1982* — K. A. Plumb. K. J. Armstrong co-ordinated technical and non-professional services for the duration of the program. Individual responsibilities for the various scientific results originating from these field surveys are contained in the progress Records (issued quarterly or half-yearly). Most of the detailed sedimentological research was undertaken by Jackson, who concentrated on the lower half of the McArthur sequence (Tawallah Group and lower McArthur Group), and Muir, who concentrated on the upper part of the basin sequence (upper McArthur Group and Nathan Group). Plumb has made detailed studies of the Lynott Formation and related units in the Batten Subgroup, of which some of the early results are included here. Systematic observations of the Roper Group were not made during the program.

Some aspects of the program have been published already, either in full research papers or as abstracts of talks presented at conferences. Where there are obvious conflicts in interpretation between these already published papers and this Bulletin, the latter should be considered the more authoritative.

Geophysical investigations

The geophysical investigations done by BMR between 1978 and 1980 were designed to test the geological model of the Batten Trough based largely on geological information gathered during the reconnaissance mapping of the late 1960s. Specifically they were designed to determine the deep structure across the Emu Fault Zone, and to compare basin structure and physical characteristics of the trough with those of the flanking shelves. Like the geological results, the initial interpretations of these investigations have been presented in the various progress Records. A full synthesis of the geophysical results is not presented in this Bulletin. Some of the major results, however, have been incorporated where appropriate into the geological interpretations presented here, especially in the section on structure, but a fuller discussion of the results of the geophysics will be published elsewhere.

A short review of the work is presented here.

Aeromagnetics. The whole of the basin was surveyed between 1977 and 1978. Most of the recording was done at elevations of 150 m above the ground surface along east-west lines spaced usually 3 km apart. Processing of the results was completed in 1980, and maps of magnetic intensity contours, radiometric contours, and stacked profiles are available from the Government Printer Copy Service.

Reconnaissance gravity. The whole of the basin had been covered as part of BMR's regional gravity coverage of Australia, which was completed in 1976. The reconnaissance nature of this type of survey, and comparisons with more detailed land surveys (see below), suggest that the density of measurements is not close enough to enable precise intra-basinal structural interpretations to be made.

Detailed gravity, magnetotellurics, and seismic. These geophysical methods are reviewed together because they were applied along the same east-west traverse line, from near Daly Waters across the centre of the Batten Trough to Westmoreland on the Queensland/Northern Territory border (i.e., normal to the major structural trend). The seismic survey also included deep crustal refraction and reflection profiles as part of a separate study of the character of the crust and upper mantle in Australia. The seismic and magnetotelluric results indicate a major discontinuity at the Emu Fault Zone, and a thick McArthur Group sequence to the west of it; this is what would be expected from a cursory examination of the regional geology. The detailed land gravity measurements, however, show no aggregate mass difference across the fault. Detailed descriptions and interpretations of these surveys are documented by Cull & others (1981a, b), Cull (1982), and Collins (1981, 1983).

Magnetostratigraphy. Over 2500 oriented small cores were collected in 1979 at intervals of 1 m from the measured geological sections. These were collected to a) determine the magnetostratigraphic column of polar reversals through the McArthur Basin, as an aid to chronostratigraphic correlation, and b) determine the polar-wander curve for the Middle Proterozoic.

Remote sensing. During August 1979, ground and helicopter spectral radiometric measurements were made on rock, soil, and vegetation targets in order to facilitate calibration of Landsat data. The objective of this work was to develop computer-assisted techniques that would aid (a) the search for mineralised rock and (b) the discrimination of rock types.

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We have been shown a number of interesting geological features by, and have held stimulating discussions with, a number of company geologists—including Don Ward, Joe Janacek, Neil Williams, Neil Runnalls, Bob Walker, Bob Dennis, and Ross Logan (all of CEC Pty Ltd); Henry Shannon and Russell Saint-George (formerly with AO Australia); Neil Wilkins (Amoco Minerals Australia); and Mike Raetz (BHP Co. Ltd). The hospitality shown by CEC and MIM staff at the Mimets camp at McArthur mine is also acknowledged. We have also benefited from interaction with a number of geologists who have visited our field camps, especially Chris von der Borch (Flinders University), Bob Burne, Malcolm Walter, John Bauld, Ralph Jensen, Bruce Radke, John Truswell, Alan Wells, Gerry Wilford (BMR), Don Sangster (Geological Survey of Canada), and Igor Krylov (Academy of Science, USSR).

The contributions of unpublished data from previous BMR surveys by Max Brown and Bert Roberts are also gratefully acknowledged.

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STRATIGRAPHY AND SEDIMENTOLOGY

PROTEROZOIC ROCKS

TAWALLAH GROUP

The Tawallah Group is the oldest group in the McArthur Basin. It consists largely of quartz sandstone and subordinate volcanics, lutites, and carbonates with a maximum composite thickness of about 4500 m in the area. It comprises the following stratigraphic units: Westmoreland Conglomerate, Yiyintyi Sandstone, Seigal Volcanics, McDermott Formation, Sly Creek Sandstone, Aquarium Formation, Settlement Creek Volcanics, Wununmantyala Sandstone, Wollogorang Formation, Gold Creek Volcanics (including the Pungalina Member), Hobblechain Rhyolite, and Packsaddle Microgranite.

The Tawallah Group unconformably overlies the Scrutton Volcanics in the Tawallah Ranges, and the Cliffdale Volcanics, Nicholson Granite Complex, and Murphy Metamorphics in the Murphy Inlier (Fig. 7). It is unconformably overlain by the Masterton Sandstone, which is now redefined as the base of the overlying McArthur Group (cf. Plumb & Brown, 1973; Plumb & Sweet, 1974; Plumb & others, 1980, 1981).

Age

The age of the Tawallah Group can be constrained between about 1700 and 1800 Ma. The Tawallah Group must be older than 1690^{+29}_{-25} Ma, the age of the middle McArthur Group. Reassessment of field and geochronological data in Gardner (1978) suggests that the Cliffdale Volcanics were intruded by granite at least 1820–1830 Ma old (the significance of widespread 1730 Ma Rb–Sr isochrons in the Cliffdale Volcanics and Nicholson Granite Complex is uncertain in terms of the basement unconformity).

Several workers (e.g., Plumb & Sweet, 1974; Plumb & others, 1980; Hutton & Sweet, 1982) have favoured a general correlation between the Tawallah Group and the Haslingden Group at Mount Isa, although Plumb & others (1981, p. 263) and Sweet (1985) have suggested that the Haslingden Group is mostly older than the Tawallah Group. The age of the Haslingden Group (Page, 1983) is well constrained by U–Pb zircon ages between 1678 $\pm$ 3 Ma (Carters Bore Rhyolite) and 1790^{+10}_{-8} Ma (Bottletree Formation).

WESTMORELAND CONGLOMERATE

The Westmoreland Conglomerate is the basal formation of the Tawallah Group. It occurs only along the southeastern margin of the basin in southeastern CALVERT HILLS and adjacent parts of WESTMORELAND, where it unconformably overlies basement rocks of the Murphy Inlier. It was originally defined by Carter & others (1961), and has been mapped and described in detail by Sweet & Slater (1975), Sweet & others (1981), and Ahmad & others (1984). We did not study it in our program of research; this short review is based solely on the previous references.

The Westmoreland Conglomerate consists of a thick sequence of conglomeratic sandstone, quartz sandstone, and conglomerate. It is usually thickly to very thickly bedded, commonly trough-cross-stratified, and characterised by an absence of interbedded finer-grained sandstone and siltstone. The sandstones commonly contain clay, either in the form of grains or as a matrix; this clay is probably largely weathered feldspar.

The formation varies markedly in thickness from north to south across the northwestern edge of the Murphy Inlier, which coincides with a hinge line—the Tin Hole Hinge Line (Sweet & others, 1981)—that controlled sedimentation. South of this line the Westmoreland Conglomerate is between 20 and 100 m thick; in contrast, north of the line (only 3 to 4 km away) it is more than 1000 m thick. Along strike the formation also varies in thickness from about 1900 m in about the middle of the outcrop belt to around 1000 m at its western and eastern ends. The formation is divisible into five major units, each of which shows a distinct upward-fining character (Ahmad & others, 1984).

The presence of channels, trough-cross-beds, upward-fining cycles, poorly sorted constituents, and abundant sand-supported gravels is interpreted by Ahmad & others (1984) to indicate a fluvial environment. Their palaeocurrent studies show a very consistent southwesterly direction of transport for all the individual members of the formation (cf. Plumb & others, 1980, 1981). Because of the consistent palaeocurrents and absence of fine-grained deposits they favour an alluvial-fan model. The sandstones and conglomerates were deposited by braided rivers and debris flows as an alluvial fan which originated in basement source areas to the northeast; the several upward-fining cycles reflect repeated periods of uplift in the source area. The Westmoreland Conglomerate is considered to be the lateral equivalent of the Yiyintyi Sandstone, a thick arenitic unit which crops out in the north of the area in the Batten, Tawallah, and Yiyintyi Ranges.

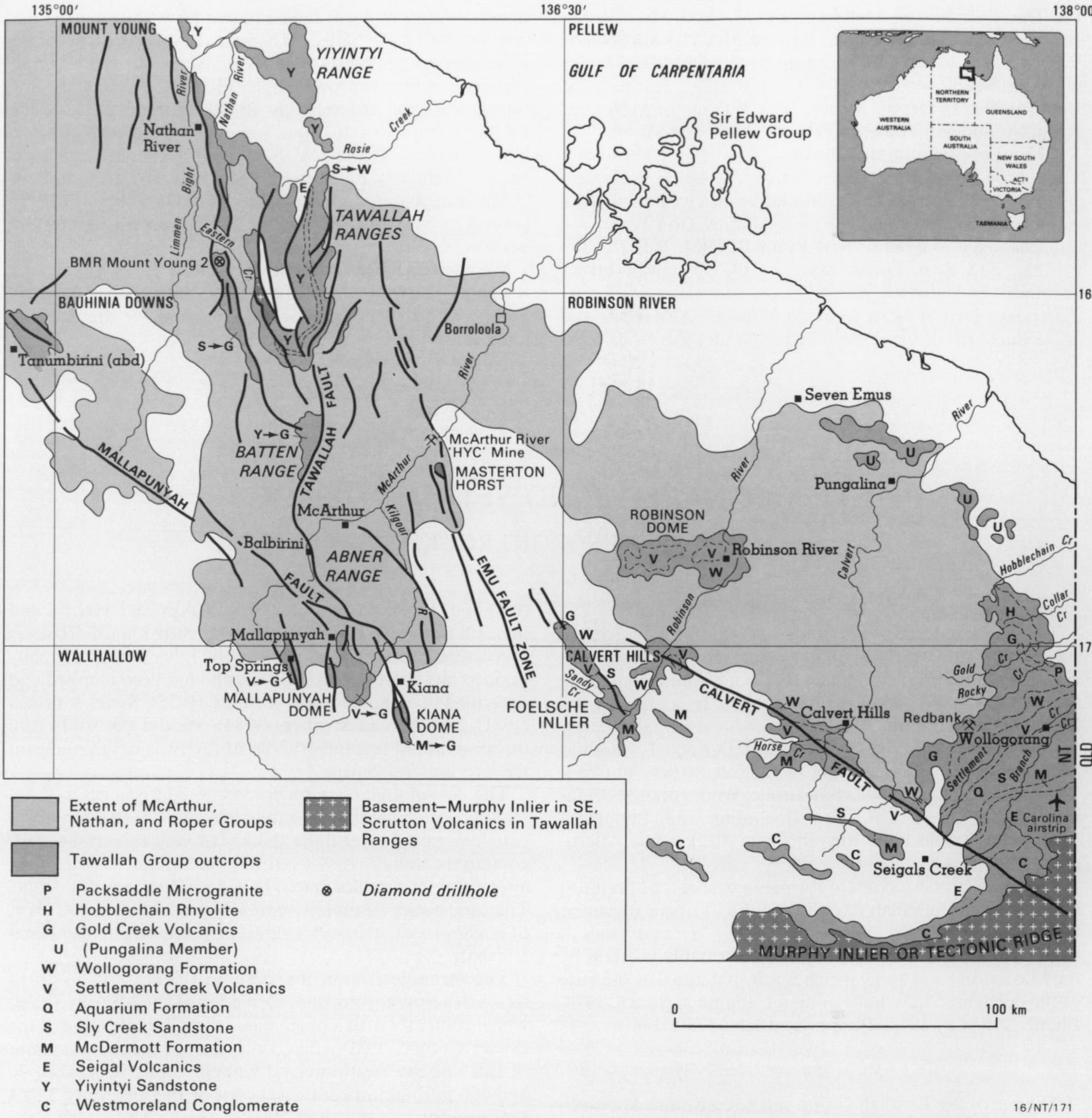

Fig. 7. Distribution of Tawallah Group outcrops in the southern McArthur Basin.

Yiyintyi Sandstone

The name Yiyintyi Sandstone has been published by a number of authors—including Smith (1964), Plumb & Paine (1964), Plumb & Derrick (1975), and Plumb & others (1980)—without an adequate formal definition. Although we have not studied the unit in any detail (because it crops out mainly north of the area where most of our research was done), a formal definition based largely on Roberts (unpublished) is presented here. The name is derived from the range of hills in northern MOUNT YOUNG, where the formation is extensively exposed.

Distribution and thickness

The Yiyintyi Sandstone crops out over about 270 km^2 in the southeast-plunging anticlinorium that forms the Yiyintyi Range in northern MOUNT YOUNG, and in faulted strike ridges farther south along the western and eastern sides of the Tawallah Ranges. The most southerly outcrop is a faulted slice containing only the uppermost part of the unit along the eastern side of the Batten Range (Fig. 7).

Plumb & Paine (1964) estimated a maximum thickness of about 2500 m for the unit in the Yiyintyi Range. In most areas though, the upper and lower contacts are not exposed and parts of the formation are faulted out. Owing to this lack of contact relationships and the structural complications, it is almost impossible to establish whether there are any significant thickness variations.

Reference area and type section

Roberts (unpublished) nominated the southeast end of the Tawallah Ranges (latitude 16°05′S, longitude 135°45′E) as the reference area. He noted that a complete section through the formation occurs here—along a southeasterly trending line running from outcrops of Scrutton Volcanics at latitute 16°04'S, longitude 135°43'30"E, through to the overlying Seigal Volcanics at latitude 16°06'S, longitude 135°45'E. This section is here nominated as the type section.

Stratigraphic relations

The Yiyintyi Sandstone unconformably overlies the Scrutton Volcanics (considered to be part of the basement), and is conformably overlain by the Seigal Volcanics. In view of their similar stratigraphic relations and lithologies, the Yiyintyi Sandstone and Westmoreland Conglomerate are considered to be stratigraphic equivalents.

Lithology

According to Roberts (unpublished) the Yiyintyi Sandstone is a thick unit of medium to thick-bedded mature quartz sandstone. The main rock type is a medium-grained, well rounded, well sorted quartz arenite, but finer and coarser-grained sandstones are also present. Outcrop samples of the arenite contain little or no matrix, and comprise strongly silica-cemented grains.

Thin sections from samples collected during the earlier mapping have been examined. Although quartz sandstones predominate they commonly contain lithic material, especially fragments of weathered igneous rocks (Fig. 8), implying that perhaps the sandstones are not as mature as Roberts suggested.

Cross-stratification (size and type not defined) and current ripples are very common. The foresets appear to dip randomly, except in the Yiyintyi Range, where an easterly source is suggested. The basal 100 m of the formation is usually coarser-grained, more arkosic, and commonly conglomeratic with pebbles, cobbles, and rare boulders of quartz, quartz sandstone, and porphyritic acid volcanic rocks.

Discussion

Roberts (unpublished) noted that the sediments deposited near the base of the Yiyintyi Sandstone show significant lateral variations. From northeast to southwest these beds contain less feldspar, are fine-grained, and contain fewer pebbles and proportionately more quartz pebbles in relation to the total pebble content. He interpreted these observations as indicating a northeasterly provenance, which is supported by the presence of exposed basement rocks in eastern Arnhem Land. It may be significant that Sweet & others (1981) and Ahmad & others (1984) also reported mainly southwesterly flowing palaeocurrents for the equivalent Westmoreland Conglomerate.

Apart from this initial deposition of varying facies, Roberts (unpublished) attributed the bulk of the Yiyintyi Sandstone to deposition, by traction currents, in shallow water over a long period during which the various factors influencing sedimentation remained constant. He suggested that the sediments were probably derived from stable, relatively low-lying lands undergoing slow epeirogenic uplift complementary to the slow but continual subsidence of the McArthur Basin. This, however, contrasts with the clear episodic uplift of the basin margin to the south, as recently documented by Ahmad & others (1984) for the equivalent Westmoreland Conglomerate.

Roberts's (unpublished) general description of the Yiyintyi Sandstone precludes us from deducing specific depositional environments for the unit. Its apparent immense thickness of ?mature quartz sandstone lacking any obvious cycles, internal trends, or key structures is difficult to accommodate into the standard facies models currently available (e.g., Reineck & Singh, 1975; Reading, 1978; Walker, 1979) for the

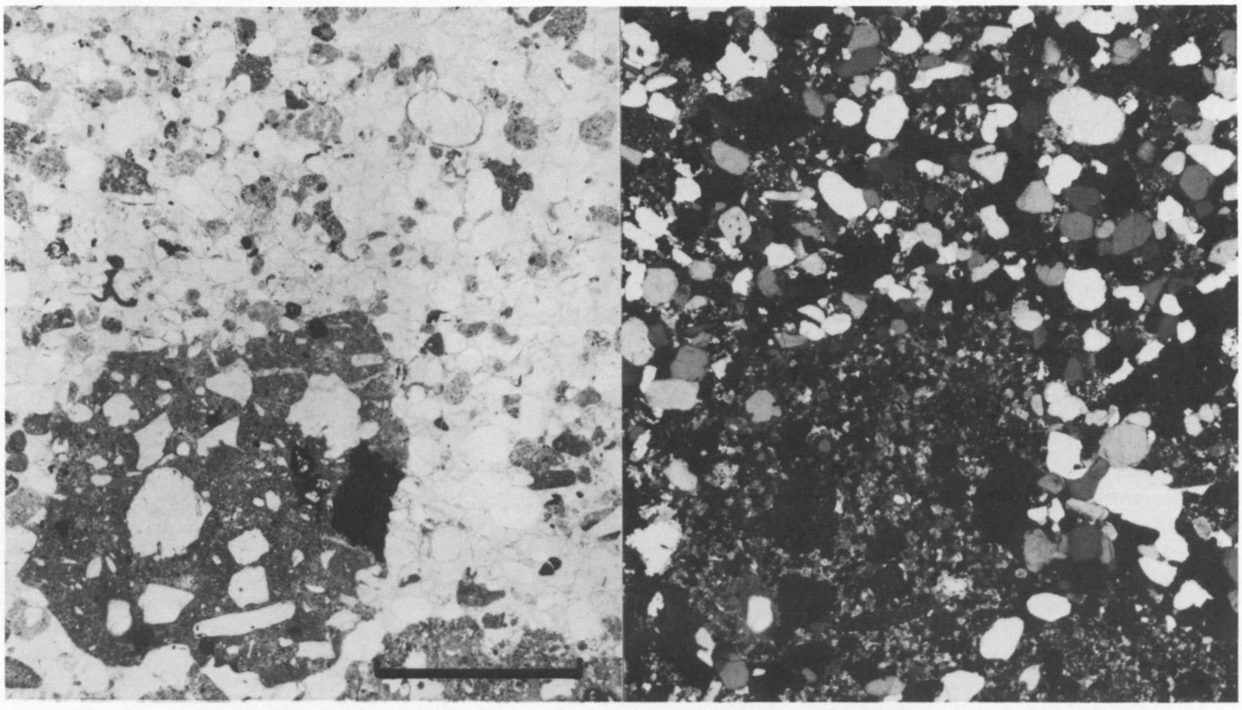

Fig. 8. Thin section of lithic quartz sandstone (specimen R9891) of the Yiyintyi Sandstone in the Yiyintyi Ranges (left ppl, right X-nicols). Note the large clasts of devitrifed volcanic rock with angular and embayed quartz crystals and iron-rich opaque minerals in a grey finer matrix; small (medium grey) lithic clasts scattered through the slide; embayed (volcanic) quartz grains (e.g., top right); and quartz overgrowths in optical continuity on both angular and rounded grains. The heavy black line represents 4 mm.

shallow-sea sedimentation that Roberts (unpublished) inferred.

The apparently uniform monotonous character of the Yiyintyi Sandstone also contrasts markedly with the alternating vertical lithological changes evident in the overlying part of the Tawallah Group, and in the McArthur Group, suggesting that it accumulated in a contrasting tectonic setting from that of the younger rocks.

Seigal Volcanics

The Seigal Volcanics overlie the Westmoreland Conglomerate in the southeast, and the Yiyintyi Sandstone in the Batten, Tawallah, and Yiyintyi Ranges. They crop out well in the southeast in CALVERT HILLS and ROBINSON RIVER, and have been mapped in detail and described by Sweet (1981) and Sweet & others (1981). On the earlier published maps—BAUHINIA DOWNS (Smith, 1964), CALVERT HILLS (Roberts & others, 1964) and MOUNT YOUNG (Plumb & Paine, 1964)—they are incorrectly correlated with, and mapped as, the Peters Creek Volcanics. North of about latitude 17°30′S, they are usually represented by a vale of no outcrop between resistant quartzite ridges. Consequently, we were unable to deduce much from the few poor outcrops examined, and the description that follows is summarised from Sweet & others (1981) and Roberts (unpublished).

In the southeast the Seigal Volcanics consist of basic lava flows, commonly less than 20 m thick, and numerous interbeds of siltstone and sandstone with a cumulative thickness of between 1000 and 1600 m. The clastic interbeds are commonly less than a metre thick, except for the *Carolina Sandstone Member*, which is a flaggy to massive fine-grained feldspathic sandstone and interbedded siltstone unit—up to about 12 m thick—with cross-stratification, ripples, and desiccation cracks. The lavas are extensively altered, but massive, amygdaloidal, vesicular, and brecciated varieties have been recognised. Dolerite dykes intruding the basement and volcanics in eastern CALVERT HILLS may be possible feeder systems for the lavas.

Little is known of the unit in the north. Intercalated sedimentary rocks have not been seen there, where the only outcrops at this stratigraphic level are extremely altered hematitic basic igneous rocks with rare amygdaloidal textures. Estimates of formation thickness from airphotos suggest that the Seigal Volcanics gradually thicken southwards. They are about 100 m thick along the western side of the Yiyintyi Range, 200–300 m thick in the Tawallah Ranges, and at least 300 m thick in the Batten Range. They do not crop out between here and the southeast margin of the basin, a distance of about 250 km, where they are up to 1600 m thick.

The Seigal Volcanics are believed to be equivalent to the lowermost of the six members constituting the Peters Creek Volcanics, which are a thick volcanic sequence forming part of the Lawn Hill Platform sequence south of the Murphy Inlier (Sweet & others, 1981).

In the north the Seigal Volcanics represent a period of widespread eruption of basic magmas. The vesicular textures and apparent lack of sedimentary rocks presumably indicates subaerial extrusion. In contrast, in the southeast, the much thicker sequence of lava flows, pyroclastics, and associated sedimentary rocks indicates a more varied evolution. Sweet & others (1981) suggested that some of the lavas in the south were extruded adjacent to and perhaps into a shallow sea. They interpreted the Carolina Sandstone Member as a shallow-marine deposit. The dolerite dykes are evidence of eruptive fissures along the southern margin of the basin; a southerly provenance for the magmas is also suggested by the northwards thinning of the lava flows.

McDermott Formation

The name McDermott Formation has been published by several authors—including Roberts & others (1963), Yates (1963), Grimes & Sweet (1979), Plumb & others (1980), and Sweet & others (1981). Sweet & Slater (1975) provided a systematic stratigraphic description of the formation in the Westmoreland region (20 km east of Wollogorang homestead). We studied the McDermott Formation in detail, so a formal definition and a detailed discussion of its sedimentological evolution are presented here. The name is derived from McDermotts Creek, a small ephemeral tributary of Branch Creek in east central CALVERT HILLS. Branch Creek has cut through the Proterozoic rocks in this area, providing good sections of the McDermott Formation and overlying Sly Creek Sandstone.

Distribution and thickness

The McDermott Formation is restricted to the southern part of the area (south of 17°S) described in this Bulletin (Fig. 7). It crops out most extensively in CALVERT HILLS and adjacent parts of Queensland. Its main areas of outcrop—all in CALVERT HILLS—are in Branch Creek (east), Horse Creek (centre), and Sandy Creek (northwest). It also crops out south of Kiana homestead, in northern WALLHALLOW. Its thickest preserved section is in the Horse Creek area, where it is at least 400 m thick and the base is not exposed. In the southeast of CALVERT HILLS, it varies from around 150 m near Carolina airstrip to zero at the southeast end of this belt of outcrop, where the Sly Creek Sandstone directly overlies the Seigal Volcanics.

Modification to previous use

Rocks now mapped as the McDermott Formation were included in the Wollogorang Formation by Carter (1959) and Firman (1959b). Roberts & others (1963), however, recognised two separate carbonate units in the CALVERT HILLS area, and therefore defined two units—an older McDermott Formation and a younger Wollogorang Formation.

Type and reference sections

A measured section in the Horse Creek area of central CALVERT HILLS is here nominated as the stratotype (Fig. 9). Unfortunately, the base of the formation is not exposed here, so the section in Branch Creek (eastern CALVERT HILLS), where the lower part of the formation is well exposed, is nominated as a reference section (Fig. 10).

Stratigraphic relations

The McDermott Formation lies conformably on the Seigal Volcanics in east central CALVERT HILLS, but is absent from the southeastern part of the Sheet area, where the Sly Creek Sandstone directly overlies the Seigal Volcanics. Roberts & others (1963) and Roberts (unpublished) suggested that the McDermott Formation lenses out southwards, but Sweet & others (1981) considered that the formation had been uplifted and eroded in the southeast, so that the Sly Creek Sandstone overlies the McDermott Formation and Seigal Volcanics with slight angular unconformity. On a regional scale, our detailed sedimentological studies suggest that the McDermott Formation of the southeastern part of the basin is a time-equivalent of the lower part of the Sly Creek Sandstone of the northern part of the basin (see p. 19).

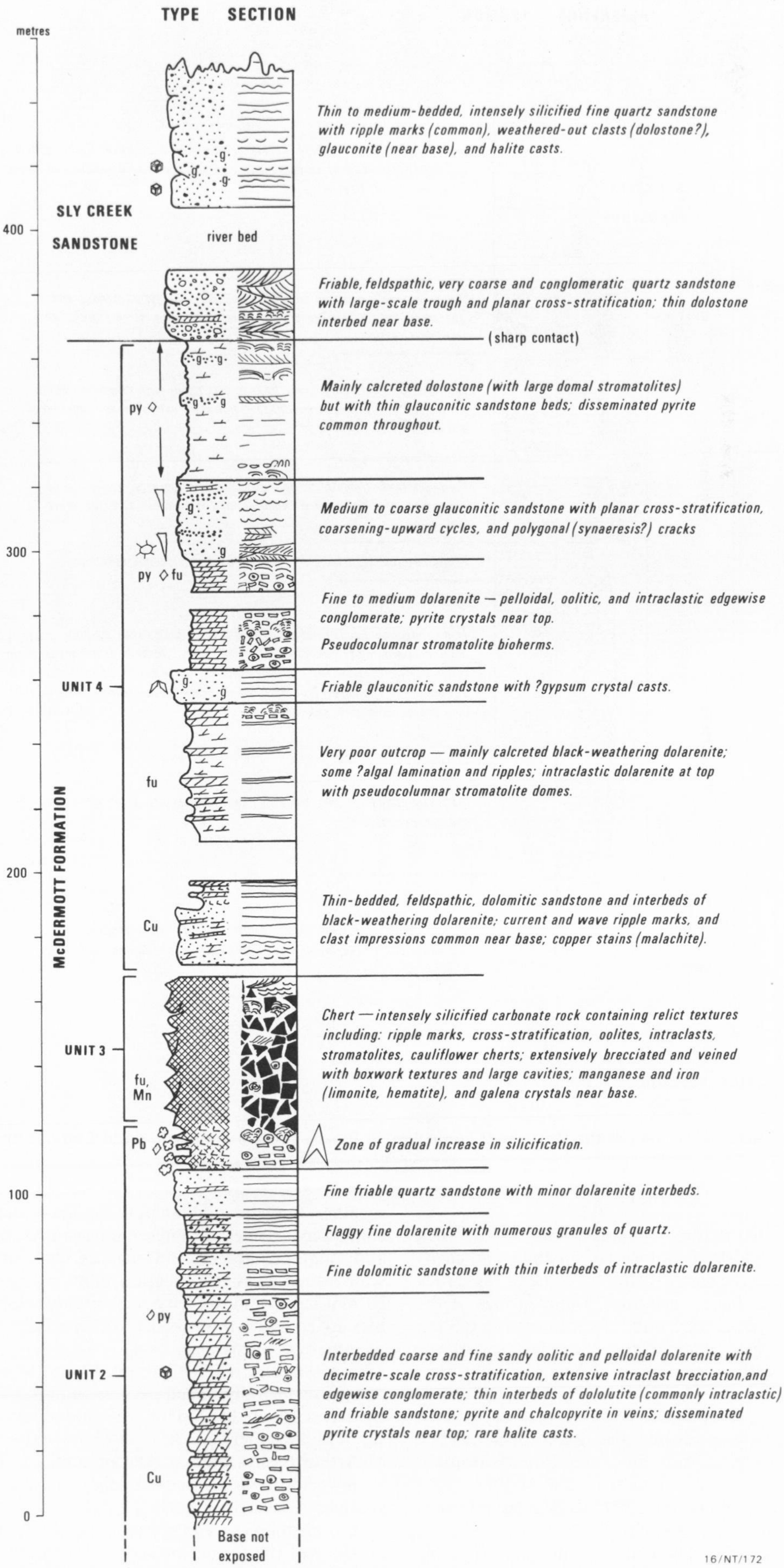

Fig. 9. Type section of the McDermott Formation, in Horse Creek 12 km southwest of Calvert Hills homestead.

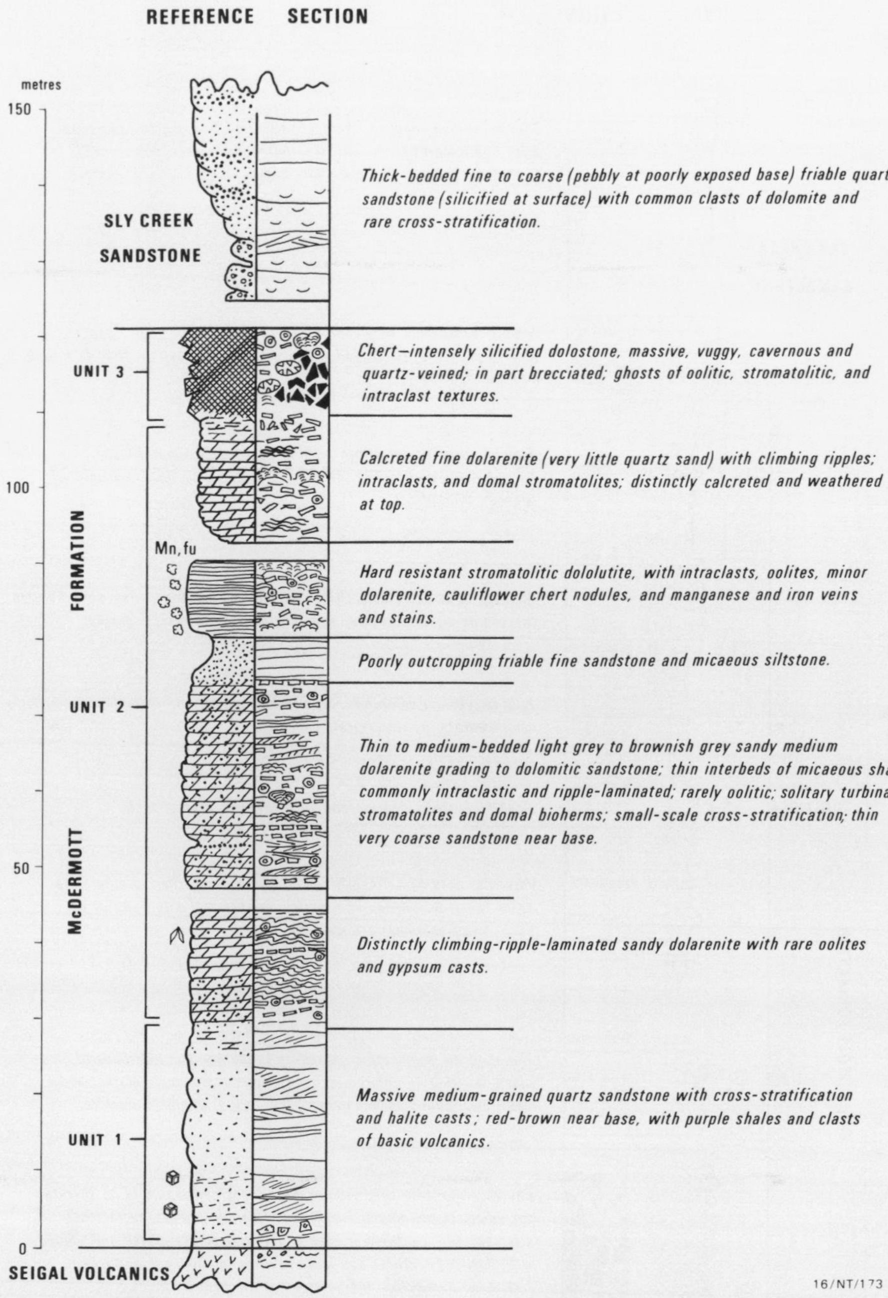

Fig. 10. Reference section of the McDermott Formation, in Branch Creek 8 km northwest of Carolina airstrip.

Lithology

The McDermott Formation contains a wide range of rock types—including sandstone, dolostone, siltstone, and chert. It is characterised by the repetitive interbedding of these rock types and by lateral facies variations. Detailed logs of the formation at the type section and reference section (65 km to the east-southeast) illustrate the main features of the formation (Figs. 9, 10), including the differentiation of four units.

Unit 1, at the base, comprises red or white medium-grained cross-stratified quartz sandstone and dolomitic sandstone with poorly outcropping shaly interbeds. Roberts (unpublished) reported halite casts in these beds, but we did not find any in our study. The unit is about 30 m thick at the reference section, and is poorly exposed elsewhere.

Unit 2 consists of sandy dolarenite and fine-grained friable sandstone. It contains a host of sedimentary structures which together indicate high-energy shallow-water to emergent conditions—oolites, pisolites, intraclast and edgewise breccias and conglomerates, erosion surfaces, tepee structures, small-scale trough-cross-stratification, climbing-ripple lamination, current scour, and starved coarse-grained ripples. Stromatolites are common towards the top especially in the reference section; two forms occur: one is a solitary turbinate form with a synoptic relief of about 20 cm, whereas the other comprises laterally linked pseudocolumnar forms up to 10 cm across which develop into low domal bioherms (Figs. 11, 12). Although these are the oldest known stromatolites in the McArthur Basin sequence, they are similar to forms common in intraclastic dolostones in the stratigraphically much younger Amelia Dolomite.

In both the type and reference sections, unit 2 contains evidence of the former presence of a variety of evaporites. Authigenic quartz nodules up to 2 cm diameter ('cauliflower

Fig. 11. Small domal bioherm of laterally linked stromatolites within intraclastic dolarenite breccias of the McDermott Formation in Branch Creek (see Fig. 12 for view of upper surface). These are the oldest known stromatolites in the McArthur Basin. (BMR negative GB 3023)

Fig. 12. Bedding-plane surface of stromatolite bioherm shown in Fig. 11. The columns are mostly circular in plan. (BMR negative GB 3022)

cherts'), probably replacing former anhydrite nodules (see discussion, p. 59), are present in finer-grained stromatolitic dolostones near the top of the unit, and poorly preserved casts of small gypsum crystals and well preserved small hopper halite casts are present lower down.

Well rounded grains and granules of quartz form a common component of the dolarenites, but appear to be absent in the finer-grained sandstone parts of this unit. These sandstone beds are thin to medium-bedded and consist largely of weakly carbonate-cemented fine quartz grains. In contrast to the dolarenites, these clastic rocks lack evidence of strong current activity and erosion.

Unit 3 is a brecciated vuggy cherty interval, 10 m thick and incomplete owing to erosion in the reference section but 45 m thick and probably complete in the type section. Remnants of sedimentary structures and textures identical with those in unit 2 are just visible, and their identification indicates that this chert was formed by the chertification of pre-existing lithified carbonates. Although none of the previously published descriptions of the McDermott Formation appear to mention this chert it is strikingly unusual in appearance and texture, and, we believe, extremely significant for regional correlations (see below).

In the type section, ferruginous and manganiferous boxwork textures, botryoidal structures, quartz-veining, and cavities containing large dogtooth crystals of quartz indicate extensive late-stage precipitation of iron, manganese, and silica in open cavities. At the reference section, unit 3 lacks the extensive sesquioxide veining and precipitation, but veins and pods of botryoidal manganese and iron occur in the stromatolitic dolostones 20 m below this chert interval (Fig. 10).

At the type section the base of unit 3 is clearly gradational over a stratigraphic interval of about 10 m. The base is not so clearly exposed at the reference section, where a zone of calcrete (soft, crumbly, dedolomitised rocks) 5 m thick underlies the chert. The upper contact of unit 3 is sharp and, owing to the resistant nature of the chert, this unit forms a prominent topographic bench at both localities.

Unit 4 comprises about 200 m of interbedded glauconitic sandstone and dolarenite. It is discontinuously exposed at the type section, but has been removed by erosion in the southeast (reference section). It consists of intervals, 5 to 15 m thick, mainly of dolarenite or friable glauconitic sandstone, but neither rock type is exclusive to any interval. Closely related interfingering facies are indicated. The dolarenite is similar to that in unit 2. The sandstone is commonly thinly to medium-bedded and flaggy, and shows rare coarsening-upward cycles 4–5 m thick. Gypsum pseudomorphs, syneresis cracks, symmetrical ripples, and carbonate clast impressions are the main sedimentary structures. Disseminated pyrite crystals are common in the upper 30 m.

A sharp planar contact marks the base of the overlying conglomeratic quartz sandstone. Although a thin impersistent stromatolitic dolostone bed occurs within this sandstone, the succeeding beds lack significant carbonates and they form a prominent steep escarpment which has been mapped as the Sly Creek Sandstone.

Interpretation and comments

The McDermott Formation is the oldest formation containing stromatolitic carbonates in the McArthur Basin. It was therefore examined in detail to establish whether these stromatolitic rocks were significantly different from those higher up in the McArthur sequence. Although no differences were found between these older and the younger dolostones, some interesting interpretations of tectonics and sedimentation were prompted by the detailed studies carried out.

Environments of deposition

The colour, composition, stratification, oolitic and intraclastic textures, and types of stromatolites in the McDermott Formation are similar to those of the Amelia Dolomite, Tooganinie Formation, and Reward Dolomite, and are similarly interpreted as being of peritidal orgin. The features of the carbonates in the McDermott Formation are typical of a shallow-water marginal-marine carbonate-bank to shoreline facies. Individual dolostone layers were deposited in a variety of shallow subtidal through intertidal to supratidal subfacies. The algal-laminated structures and quartz (after sulphate) nodules in the carbonates, together with other evaporite relics in the sequence, imply an arid shoreline environment or 'sabkha overprint' similar to those seen along the modern-day Trucial Coast (Kinsman, 1969; Till, 1978; Kendall, 1979). The arid evaporitic environments so typical of the McArthur Group (Walker & others, 1977) therefore appear to have been established very early on in the evolution of the basin sequence.

In one respect, however, the McDermott Formation differs significantly from most of the stromatolitic carbonate sequences in the McArthur Group, and that is in the character of the associated clastic facies. In the McArthur Group these interbedded clastics are mainly siltstone, dolomitic siltstone, and shale, but in the McDermott Formation feldspathic and glauconitic sandstones dominate. Although the sandstones themselves do not contain such clear environmentally diagnostic textures as the dolostones, the presence of glauconite in abundance suggests a shelf type of environment. In a recent review, Odin & Matter (1981) commented that the glauconite facies is widespread on present-day continental shelves at water depths between 50 and 500 m, and is particularly abundant between 200 and 300 m. The finer grainsize, better sorting, lack of rip-up textures, and more regular and even stratification in the sandstone facies of the McDermott Formation is consistent with a deeper-water, quieter environment than that evident for the carbonates. The formation also contains coarser-grained cross-stratified intervals with ripple and dune bedforms, and coarsening-upwards cycles which probably indicate a range of sub-environments grading upwards towards the shallow carbonate-dominated shoreline. The presence of carbonate clasts in several sandstone intervals in the type section implies penecontemporaneous rip-up and offshore transport, by strong waves or currents, of earlier lithified parts of the adjacent carbonate facies.

The common presence of very coarse-grained quartz in the dolarenites, and its paucity in many of the laterally equivalent finer sandstone intervals, provide good evidence for a facies arrangement in which the carbonates formed a shoreline fringe that trapped most of this coarser detritus.

The intimate association of sandstone and dolostone lithofacies in the McDermott Formation is unusual for the McArthur Basin sequence. It is ascribed to two factors: a more unstable tectonic setting and a more quartz-rich provenance than for most other units in the McArthur Group. The likelihood that the tectonic setting was more unstable is suggested by two factors: firstly, the depositional area of the McDermott Formation was close to the Tin Hole Hinge Line, which was a major zone of movement during deposition of the slightly older Westmoreland Conglomerate; and secondly, removal of an increasing thickness of the McDermott Formation southwards across CALVERT HILLS before the Sly Creek Sandstone was deposited indicates contemporaneous tectonic warping and uplift.

A quartz-rich source area containing a large supply of fine and coarse quartz grains is indicated by the presence of both the finer-grained sandstone facies and the coarse grains in the carbonate facies. Uplift and erosion of the older Westmoreland Conglomerate—a thick and extensive formation containing a large volume of quartz sandstone—is considered the most likely source for this supply of sand. Uplift and erosion of basic igneous and metamorphic rocks of the Murphy Inlier, underlying the Westmoreland Conglomerate, may have supplied the iron and potassium for the precipitation of authigenic glauconite.

Chert and regional correlations

Unit 3 in both measured sections is a thick chert interval. It consists of completely silicified carbonates containing 'ghost' structures and textures identical with those preserved in the underlying unsilicified dolostones—e.g., oolites, intraclasts, cross-stratification, and stromatolites. The unit has a sharp planar top, but a gradational lower contact, and the immediately underlying rocks are weathered and dedolomitised. The unit is vuggy and brecciated, and in addition to the pervasive silica replacement is also enriched in iron and manganese. This chert represents a significant stratigraphic break within the McDermott Formation, during which time lithified dolostones were uplifted, eroded, deeply weathered, and silcreted to a considerable depth. In many respects it closely resembles the silcrete duricrusts and their associated deeply weathered profiles that are well developed on the Mesozoic and Cainozoic rocks of Australia (Langford-Smith, 1978; Senior & Mabbutt, 1979; Jackson & van de Graaff, 1981), and it is here interpreted as such.

As Tertiary silcretes of this size (here related directly to thickness) are laterally extensive in Australia, one of the most obvious implications of this interpretation is that it could imply a widespread distribution of silcrete at this stratigraphic level in the Proterozoic of northern Australia. An intensely silicified oligomictic sandstone breccia, several metres thick,

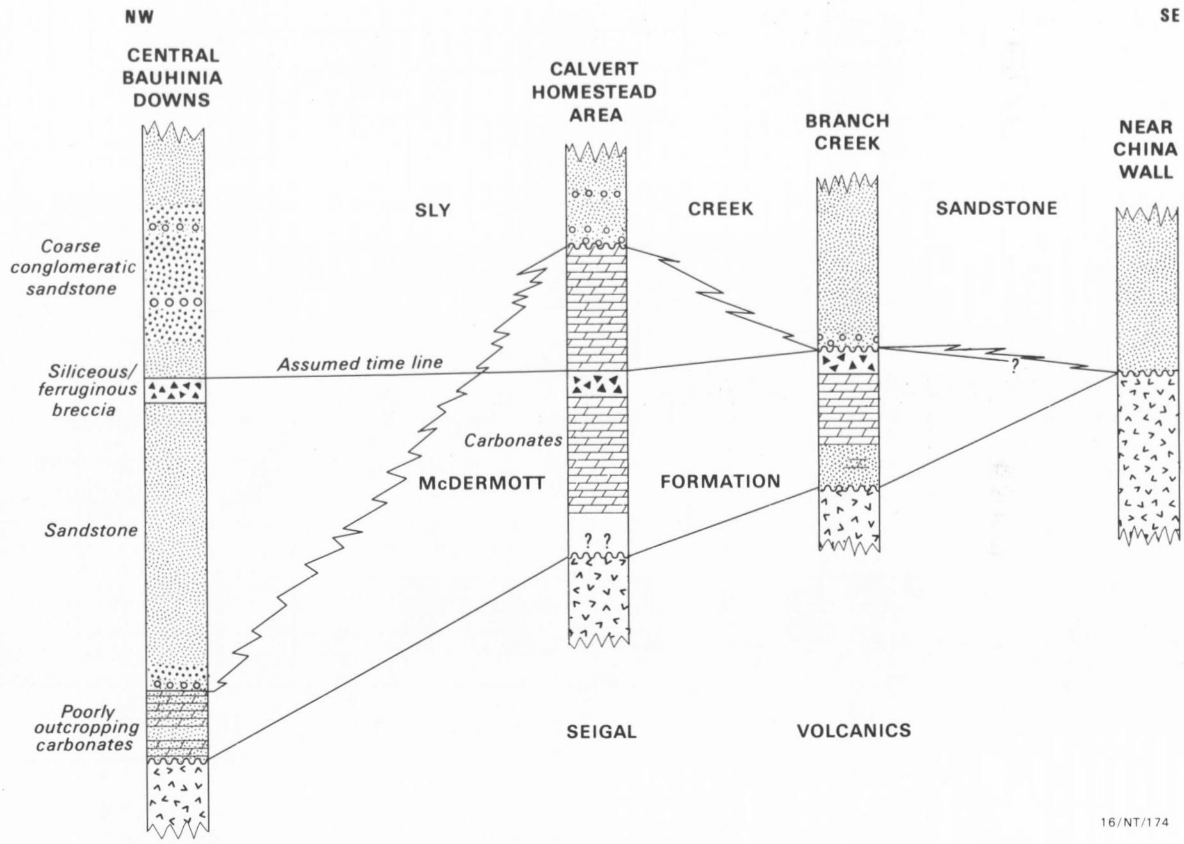

Fig. 13. Lateral facies variations in the McDermott Formation and Sly Creek Sandstone assuming that the siliceous interval is roughly isochronous.

had in fact been identified in the Batten and Tawallah Ranges during earlier section measuring of the Sly Creek Sandstone. Jackson (1979b) interpreted this chert breccia as a silicified regolith, and suggested that it indicates a previously unrecognised widespread break in sedimentation. It now seems logical to correlate this chert breccia in northern outcrops of the Sly Creek Sandstone with unit 3 of the McDermott Formation in the southeast (Fig. 13). As a consequence, the Sly Creek and McDermott lithologies must be diachronous. The McDermott Formation dolostone and sandstone in the southeast of the basin must be a facies equivalent of mostly quartz arenite forming the lower part of the Sly Creek Sandstone in the central and northern parts of the basin (Fig. 13).

Sly Creek Sandstone

The name Sly Creek Sandstone is here proposed for a prominently outcropping sandstone and minor conglomerate unit situated between the poorly exposed Seigal and Settlement Creek Volcanics. It is derived from Sly Creek, a small tributary of Eastern Creek in the Tawallah Ranges of south central MOUNT YOUNG (latitude 15°52′30″S, longitude 135°30′E).

Modification to previous use

In the past, throughout most of the area, the part of the McArthur Basin sequence between the Seigal Volcanics and Settlement Creek Volcanics had been divided into the Sly Creek Sandstone below and the Rosie Creek Sandstone/Aquarium Formation above (Yates, 1963; Roberts & others, 1963; Plumb & Paine, 1964; Smith, 1964; Roberts, unpublished). The Sly Creek Sandstone is described as a lithologically uniform white quartz sandstone. The main distinguishing features of the Rosie Creek Sandstone are said to be the presence of glauconite and interbedded ferruginous sandstone, a more variable sandstone lithology, and a lack of continuity of outcrop (Roberts, unpublished). Based on a number of detailed measured sections through this clastic part of the basin sequence, we can see no systematic stratigraphic or sedimentological differences (except in the far southeast) that would justify dividing it into two separate mappable sandstone formations. The use of the term Rosie Creek Sandstone is therefore discontinued.

In the extreme southeast of the basin, however, where outcrop continuity is good and there are no structural complications, Roberts & others (1963) and Sweet & others (1981) described a unit of glauconitic sandstone and siltstone—which they called the Aquarium Formation—between the Sly Creek Sandstone and overlying Settlement Creek Volcanics. Because the stratigraphic relations are clear and the mapping is facilitated by good exposures in this part of the basin, the name Aquarium Formation is retained and defined herein (q.v.).

Distribution and thickness

The Sly Creek Sandstone is present throughout the area. It is most completely exposed in steep-sided faulted ridges in the Tawallah and Batten Ranges, but is also exposed in most parts of the Tawallah Group outcrop—e.g., Tanumbirini, Mallapunyah, Kiana, and Robinson River (Fig. 7). The thickest section known is in the Batten Range, in the centre of the area, where 900 m is exposed. Farther north the

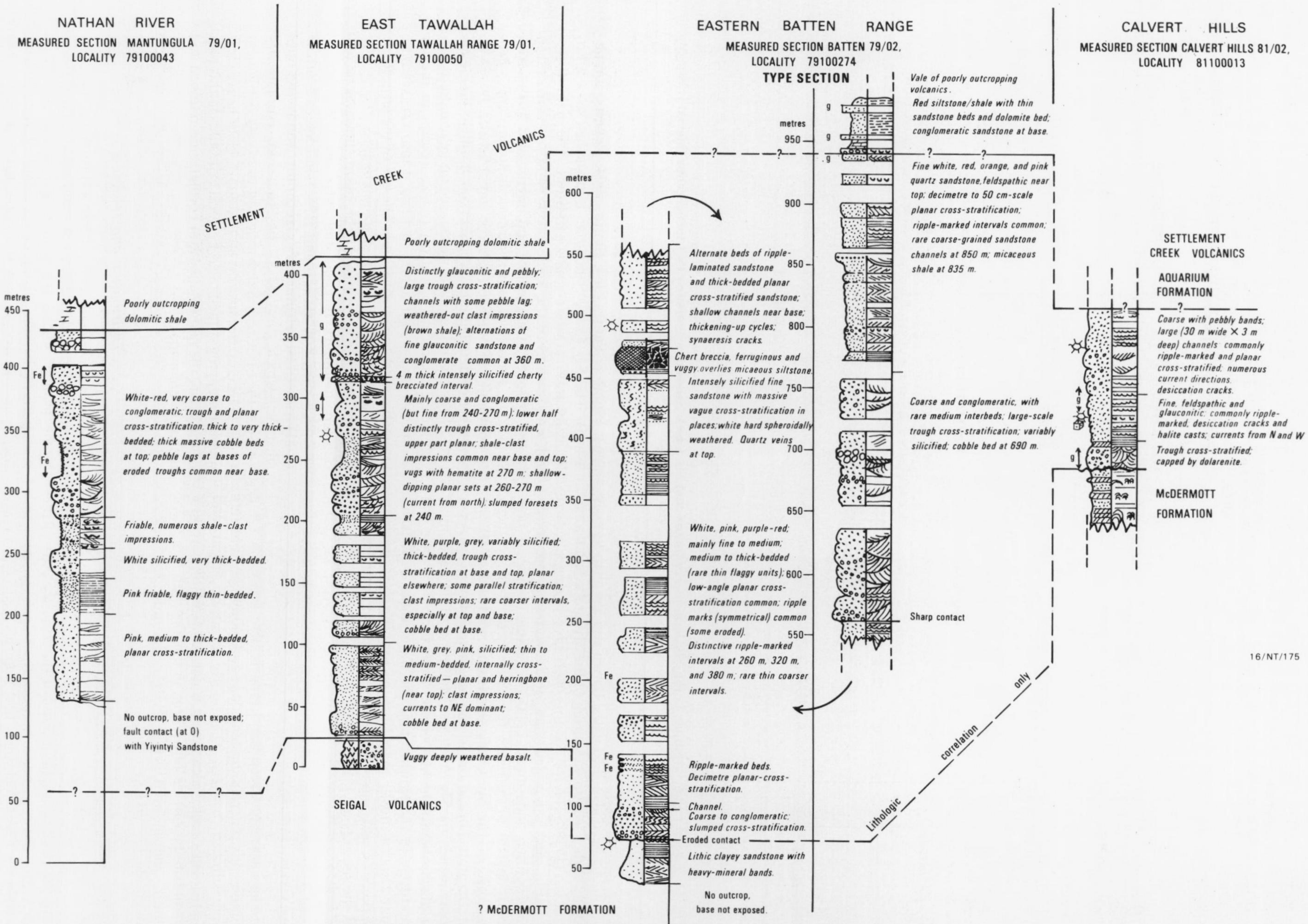

Fig. 14. Measured sections, including the type section, of the Sly Creek Sandstone.

formation is around 300–400 m thick; to the west it is at least 100 m thick (base not exposed); and to the south (WALLHALLOW) and southeast (CALVERT) it is only around 100 m thick.

Type and reference sections

A measured section (Batten 79/02; Fig. 14) through the eastern side of the Batten Range from GR 796810 to GR 784811 *Batten* (6065) is here nominated as the type section. This is the thickest, best exposed, and most complete section through the formation, and it is readily accessible from the old Borroloola Highway. Measured section Tawallah Range 79/01 (Fig. 14) along the eastern side of the Tawallah Ranges between GR 789533 and GR 803519 *Tawallah Range* (6066) is here nominated as a reference section. Although this locality is not as accessible as the type section, it does have the advantage of reasonably well exposed contacts, and it is situated in the area originally nominated by Roberts (unpublished) as the reference area.

Stratigraphic relations

The Sly Creek Sandstone is underlain by either the Seigal Volcanics or McDermott Formation. Both of these underlying units are less resistant to weathering than the overlying quartzites, which usually form a prominent escarpment, and a clearly mappable contact is evident on the airphotos. In most areas the Sly Creek Sandstone is overlain by the Settlement Creek Volcanics, but in the southeast the Aquarium Formation is sandwiched between them. The upper contact of the Sly Creek Sandstone is gradational and, owing to poor outcrop, is often difficult to define; for mapping purposes it is located at the upward limit of more-or-less continuously outcropping sandstone. The overlying poorly outcropping volcanics— with glauconitic sandstone, siltstone, shale, and rare dolostone beds near the base—are assigned to the Settlement Creek Volcanics.

Lithology

Figure 14 summarises the rock types and sedimentary structures present in the Sly Creek Sandstone at four widely separated localities. In general, the Sly Creek Sandstone consists mainly of white, grey, pink, purple, or red mature quartz arenite. Medium-grained varieties predominate, but very fine, coarse, and very coarse-grained units are also present. Intervals of pebbly granular sandstone and conglomerate are common at some exposures. Minor lithologies include micaceous siltstone and shale, chert breccia, and dolarenite. Unexposed intervals in most of the sections examined indicate that friable finer-grained rock types (e.g., fine sandstone, siltstone) probably form a higher proportion of the unit than is evident in outcrop. For ease of description, we have documented the lithologies by geographic location in the area—north, south, and central.

North

Here a fairly distinctive two-fold division of the formation is evident. Apart from cobble beds at the basal contact and at about 120 m in the east Tawallah section (Fig. 14) the lower 200 m of the formation is characterised by white, pale grey, and pale pink, fine to medium-grained, well rounded, well sorted, strongly cemented mature quartz arenites. These fine-grained clastics are distinctly and regularly, thinly to thickly parallel-bedded, and form continuous blocky outcrops. Internal low-angle (5–15°) planar cross-stratification is common, but apart from the lowermost 30 m, where north-easterly palaeocurrents are dominant, the low foreset dip-angles and apparently variable dip-azimuths make it difficult to ascertain reliable palaeocurrent directions. Evidence of mutually opposed currents is provided by thin intervals of decimetre-scale herringbone cross-stratification between 70 and 100 m in the east Tawallah section. Weathered-out shale clasts, forming circular impressions up to several centimetres in diameter, are also a common feature.

The upper 200 m of the formation, by contrast, is less well sorted and is dominated by coarse-grained to conglomeratic quartz arenite with large-scale trough-cross-bedding. Bimodal grain populations are evident in most thin sections from this interval (Fig. 15). Darker ferruginous intervals are common, and in places these are distinctly glauconitic (Fig. 16). Intervals of finer-grained blocky quartz arenite with planar cross-stratification, identical with those in the lower half of the formation, are present but subordinate to the coarser lithologies. Intervals, tens of metres thick, of trough-cross-stratified sandstone with large gently curved foresets indicate an origin as large linguoidal dune forms. Azimuth readings on foresets cover a wide range, but a northerly source is dominant. Some periods of rapid deposition are indicated by the presence of oversteepened and slumped foresets. Erosional troughs with pebble lags defining shallow channels, and intervals comprising alternations of fine-grained glauconitic sandstone and conglomerate, are common in the upper part of the east Tawallah section. A complex intertonguing of facies is indicated by the interbedding of the various lithologies.

An intensely silicified brecciated interval, 4 m thick, with large quartz crystal-lined cavities forms an unusual marker bed at 320 m in the east Tawallah section.

At both measured sections in the north, the Sly Creek Sandstone is succeeded by poorly outcropping dolomitic shale. In both areas this is incorrectly shown as Wollogorang Formation and Rosie Creek Sandstone on the MOUNT YOUNG geological map (Plumb & Paine, 1964), but it is now known to be part of the Settlement Creek Volcanics. At the Nathan River section, two massive quartz sandstone cobble beds, each several metres thick and comprising rounded clasts of ferruginous sandstone in a white pebbly sandstone matrix, are present near the top of the Sly Creek Sandstone (Fig. 17).

South

Outcrops of the formation around Mallapunyah, Kiana, and Calvert Hills are dominated by white to pink, fine to medium-grained, flaggy to blocky quartz arenites (Fig. 18) like those in the lower part of the formation in the north. However, the basal 25 m near Calvert Hills is coarser-grained to conglomeratic (Fig. 14); it contains glauconite, pebble bands, and shallow channels (Fig. 19).

Rippled parting planes are more evident in these southerly outcrops. The ripples are usually straight to slightly sinuous, symmetrical, and commonly bifurcate. Wavelengths are around 5–10 cm and amplitudes 1–3 cm. Rare planed-off ripples, commonly accompanied by desiccation cracks and halite casts, are also present. In addition, rare linguoid and rhombohedral ripples are evident in the Kiana inlier.

Southeasterly trending palaeocurrent directions are dominant in the lower 50 m of the section at Calvert Hills, but in the rest of the Sly Creek Sandstone here, and at most other southerly outcrops, ripple orientations and foreset azimuth measurements indicate a wide range of palaeocurrent directions; no dominant orientation is evident .

Evaporite pseudomorphs are present in the northern part of the Kiana Dome, where only the uppermost 30 m of the

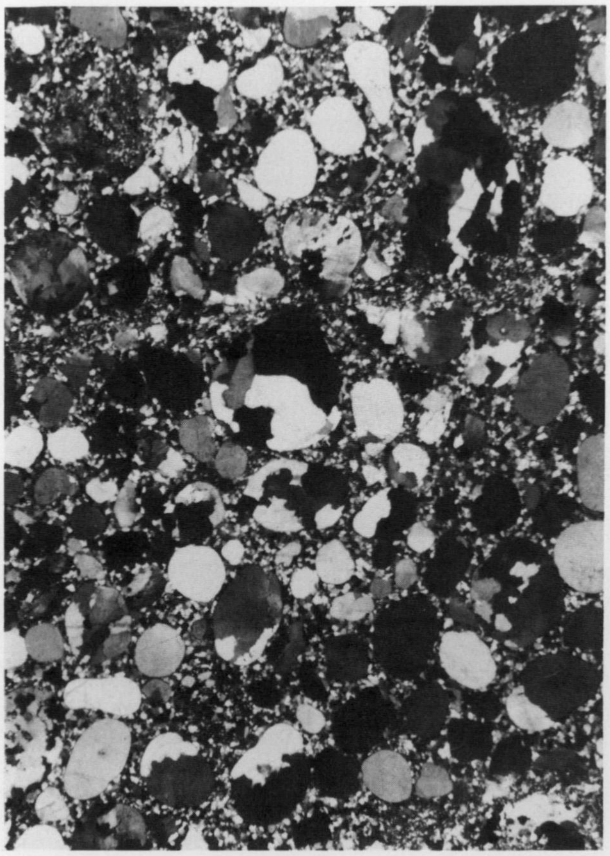

Fig. 15. Thin section viewed through crossed nicols of bimodally sorted quartz arenite (TS 79100043D) of the Sly Creek Sandstone in measured section Mantungula 79/01, near Nathan River homestead. Note the exceptionally well rounded larger grains of polycrystalline quartz with polygonised internal contacts; the dissolution of some of these larger grains; and the finer-grained less well rounded matrix. The large grain in the centre of the photo is 3 mm in diameter.

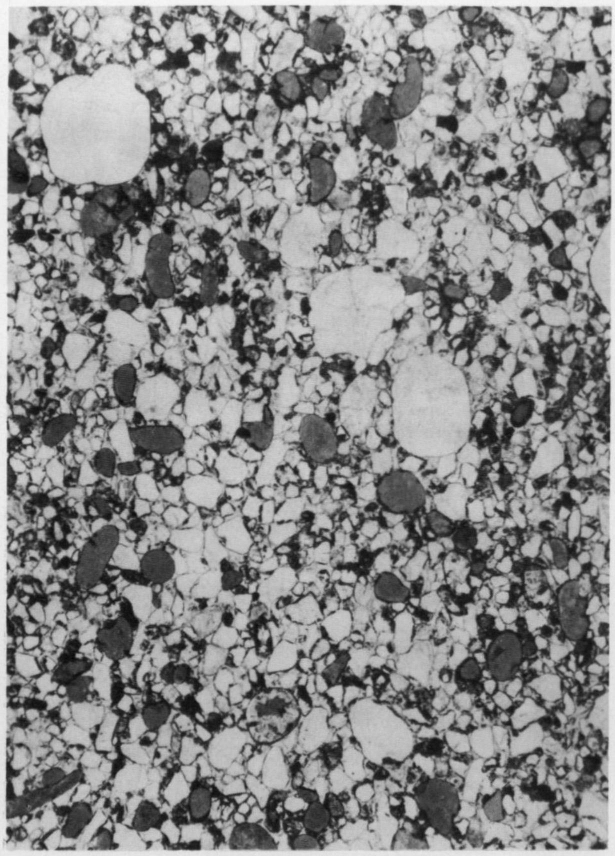

Fig. 16. Thin section viewed through plane-polarised light of bimodally sorted glauconitic quartz arenite (TS 79100050G) of the upper part of the Sly Creek Sandstone in measured section Tawallah Range 79/01. Note the abundance of well rounded (medium grey) grains of glauconite around 0.3 mm in size. The large quartz grain at top left is 1 mm in diameter.

Sly Creek Sandstone is exposed. Several large bedding slabs of white fine-grained quartz arenite are crowded with V-twinned lozenge-shaped crystal casts, almost certainly after swallow-tail gypsum crystals. Irregular small mound-like structures resembling sand volcanoes are also present on adjacent bedding planes. The presence of these sulphate evaporite relics at Kiana—together with the dewatering features, desiccation cracks, and halite casts at Calvert Hills—indicates periods of desiccation and the presence of penecontemporaneous or early diagenetic saline formation fluids in the southern part of the area at this time.

Centre

The type section (Fig. 14) comprises 900 m of mostly mature quartz arenite with rare interbedded micaceous shale and a prominent ferruginous chert level. A broad fivefold division of the arenites is evident (Fig. 14): a lower 30 m of clayey sandstone with heavy-mineral bands; 30 m of conglomeratic coarse-grained sandstone with channels and other eroded bed contacts (70–100 m); 460 m of mainly fine-grained planar cross-stratified and rippled arenite dominated by easterly and southeasterly palaeocurrents (100–560 m); 210 m of coarse-grained and conglomeratic trough-cross-stratified arenite (560–770 m); and an upper 170 m of fine-grained sandstone which is feldspathic and glauconitic towards the top. However, as in the other sections, the rock types in each of these divisions are not mutually exclusive: there are beds

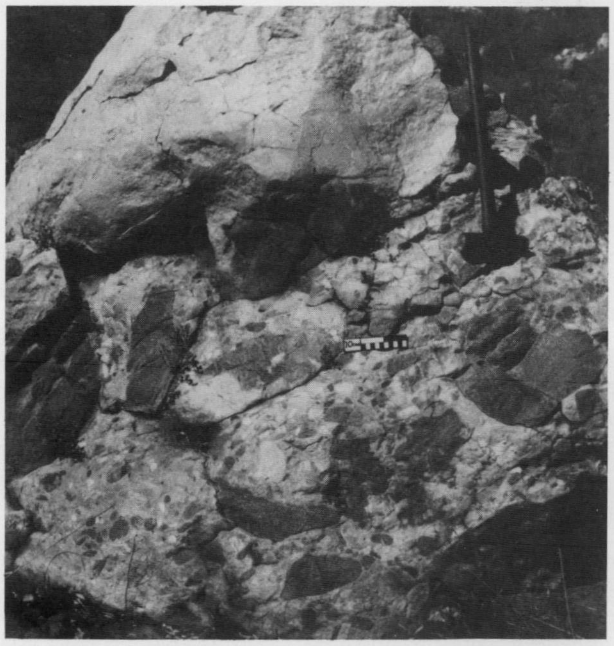

Fig. 17. Intensely silicified and cemented cobble conglomerate near the top of the Sly Creek Sandstone east of Nathan River homestead. Note the fine-grained sandstone matrix; the subangularity of darker (ferruginous) sandstone cobbles; and the lack of stratification. Regional bedding is roughly horizontal. Measured section Mantungula 79/01 at 380 m. (BMR negative GB 3057)

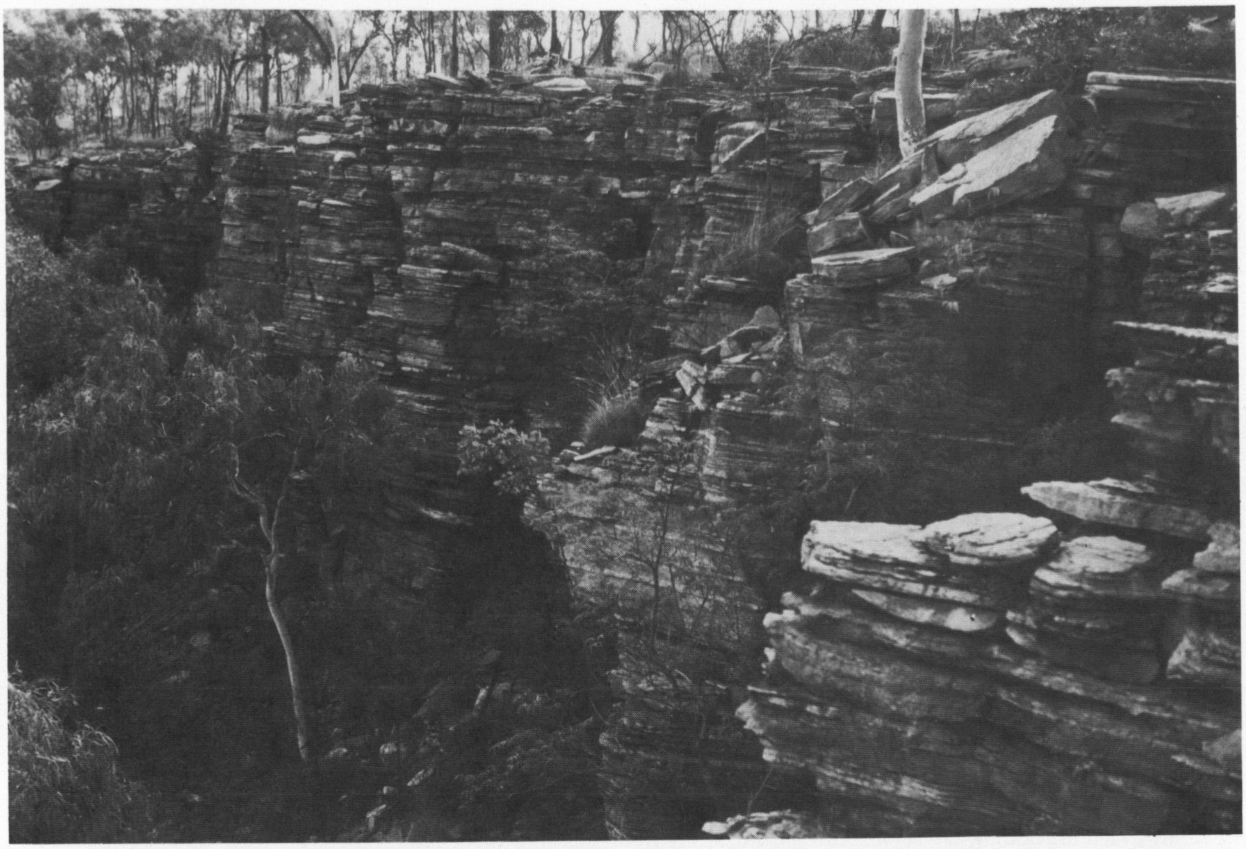

Fig. 18. Distinctly parallel thin to medium-bedded Sly Creek Sandstone in a steep cliff face in measured section Calvert Hills 81/02, 9 km southwest of Calvert Hills homestead. The cliff is about 25 m high. (BMR negative GB 3056)

Fig. 19. The basal part of the Sly Creek Sandstone in a cliff face in measured section Calvert Hills 81/02, 9 km southwest of Calvert Hills homestead. This part of the section underlies the distinctly parallel-bedded section shown in Fig.18. Note the shallow channel about 10 m wide × 1 m thick in the centre of the photograph. (BMR negative GB 3055)

of finer-grained arenite in the thick coarser-grained units and, conversely, beds of pebbly coarse sandstone in thick dominantly fine-grained arenite.

In general the coarse and fine-grained end-member facies are similar to those in the north and south. However, the coarser-grained facies in the centre is less well sorted; in addition, although curved foresets indicate that trough cross-stratification is common, much of the stratification in this facies in the centre is indistinct, and thick planar sets may be present as well. Scattered subrounded pebbles of quartz and tabular shale clasts are present along some of the large gently curved foresets. In places, pebbles form up to about 5-10 per cent of the total rock. An oligomictic cobble conglomerate 1 m thick containing purple sandstone pebbles and cobbles in a white silicified arenite matrix, very similar to the cobble beds near the top of the formation in the Nathan River section (Fig. 17), occurs at 690 m in the type section.

The finer-grained facies, although generally better sorted, shows a wider range of sedimentary structures and more rapid vertical variations in stratification. Continuous and regular medium to thick parallel bedding is dominant. These beds display mostly planar-tabular cross-stratification (alpha, beta, and gamma types of Allen, 1963), in which the cross-laminae dip up to 20° and have a discordant angular relationship with the lower bounding surfaces of the sets (Fig. 20). Intervals with very low-dipping cross-laminae (1 to 5°) are present (e.g., at 160 m in the type section), but they are generally rare. Beds with distinctive internal horizontal even lamination, picked out by thin bands of quartz granules, are present between 177 and 186 m. Thinner-bedded flaggy intervals which are commonly rippled are present at many levels—105, 141, 250-260, 300-320, 450-460, 480-500, and 860 m. A variety of ripples is present, but small (0.5 to 2 cm amplitude) symmetrical and asymmetrical straight to slightly sinuous forms with wavelengths between 5 and 15 cm are most common; the largest ripples evident are asymmetrical ripples with an amplitude of 5 cm and a ripple index near a value of 2. Eroded or planed-off ripples, indicating temporary emergence, are present. A systematic detailed analysis of the ripple orientations has not been done, and the lack of three-dimensional outcrops hinders analysis of the cross-stratification, but, as previously noted, easterly and southeasterly-flowing palaeocurrents dominate in the lower half of the unit in the central area.

A common lithological association within the finer-grained facies is the rhythmic interbedding of rippled sandstone beds 10-60 cm thick and more massive sets of planar-cross-stratified sandstone commonly up to 60 cm thick (Figs. 20, 21). These are well exposed between 250 and 260 m, 300 and 320 m, 440 and 460 m, and 500 and 540 m. The rippled units are fine-grained, somewhat friable, and often pale brown, indicating a higher iron content than the adjacent more massive beds of white to pale grey cleaner quartz arenite. The contacts between these two sandstone types are sharp, and the slight variation in composition usually leads to differential erosion, which emphasises the couplets. Some contacts, especially at the bases of rippled sets, are clearly erosional. In places, channels of rippled beds 15 to 20 m wide are incised by 1 m into the underlying cosets.

A similar pattern of alternating lithologies is present near the top of the formation, but here the rippled beds are replaced by laminated siltstone or shale. These couplets therefore are composed of resistant planar-cross-bedded

Fig. 20. Interbedded ripple-laminated sandstone and planar- cross-bedded sandstone in the Sly Creek Sandstone at 320 m in measured section Batten 79/02, in the southeast Batten Range. Note the eroded base of the rippled interval 10 cm above the scale, and the eroded base of the cross-bedded set about 35 cm below the scale. (BMR negative GB 3053)

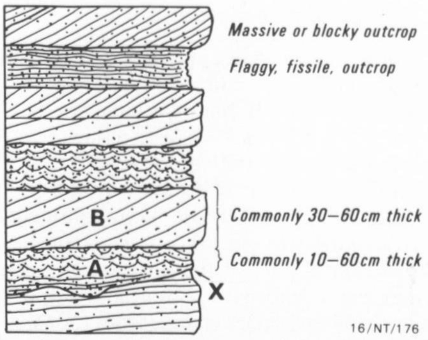

Fig. 21. Diagrammatic sketch of rhythmically interbedded rippled or flat-laminated sandstone (A) and planar-cross-stratified sandstone (B) which form units 5–15 m thick in the Sly Creek Sandstone in the eastern Batten Range. Set contacts are sharp, and in places are clearly eroded into the underlying strata (e.g., X); compare with Fig. 20.

quartz arenite in sets up to 40 cm thick, alternating with interbeds of fissile purple micaceous shales 5 to 10 cm thick. At this stratigraphic level the sequence also contains indistinct channels between 30 and 50 m wide and up to 5 m deep.

A lithologically distinctive but poorly outcropping chert breccia is present between 460 and 472 m in the type section (Fig. 14). It consists of intensely silicified angular blocks and fragments of red, purple, and white sandstone strongly cemented in a sandy or cherty hematitic matrix (Fig. 22). The presence of cross-cutting quartz veins within the clasts, and the angular nature of the clasts, indicate that it formed by the brecciation of a consolidated and lithified quartz sandstone, and therefore reflects a marked stratigraphic break. Quartz-veining of the whole breccia interval, and the presence of large cavities filled with quartz crystals, indicate a later period of silica precipitation in voids in the brecciated beds. Although the exposure of the brecciated interval is not good, it is traceable along strike for several hundred metres either side of measured section Batten 79/02, where it appears to vary in thickness from around 5 to 12 m. The immediately underlying beds do not crop out, but a float of laminated micaceous siltstone and fine sandstone suggests that the breccia caps a distinctly finer-grained interval about 5 m thick. Although surface silicification of the Sly Creek Sandstone is variable on a regional scale, the 60 m of sandstone below this chert breccia marker are more intensely and continuously silicified than elsewhere, contain numerous quartz veins, and have lost much of their internal structure and texture. This silicified arenite weathers spheroidally and forms prominent resistant ridges. The effects of the pervasive silicification are also clearly evident in thin sections from the interval.

Interpretation and discussion

Roberts (unpublished) considered that the sediments of the lower Sly Creek Sandstone underwent long transport and intense winnowing before they were deposited on a broad continental shelf. He noted that '. . . deposition of the Sly Creek Sandstone marked a reversion to the general tectonics and environmental circumstances pertaining during the deposition of the Yiyintyi Sandstone and Westmoreland Conglomerate.' He ascribed the less mature and more variable upper Sly Creek Sandstone ('Rosie Creek Sandstone') to a markedly different tectonic setting with '. . . adjacent uplifted land areas, greater rates of basin subsidence and considerable fluctuations in water depth.' From the coarse grainsize, more labile content and poorer sorting of the 'Rosie Creek Sandstone'—in contrast to the characteristics of the Aquarium Formation—he interpreted a westerly provenance for the detritus.

Fig. 22. Intensely silicified sandstone–breccia in the Sly Creek Sandstone in the Batten Range. Note the quartz veins in the breccia clasts (predating brecciation) and the later quartz and ferruginous breccia veins. (BMR negative M2572/21)

Based on our work, we suggest a somewhat different interpretation, which involves much less emphasis on tectonic variability. Rather, we consider that the vertical and horizontal lithological changes within this clastic unit are mainly facies variations within a dominantly marine environment; the main features of the unit (i.e., glauconite, good sorting and rounding, little matrix, medium-scale planar cross-bedding, and shallow wide channels) suggest that a shallow-marine environment prevailed. According to Reading (1978, p.229), 'The most reliable criteria for recognising ancient shallow marine deposits are features controlled by the salinity and depth of sea water. Thus marine body fossils, trace fossils, certain minerals and geochemical parameters may be characteristic. Sedimentological data such as texture, sedimentary structures, lithofacies association, sand body geometry and palaeocurrent patterns, are usually not in themselves diagnostic'. Of the sedimentary characteristics listed above, perhaps the presence of glauconite should therefore be considered the most reliable indicator of the shallow-marine setting of the facies of the Sly Creek Sandstone that contain this mineral.

On a more detailed scale, the specific environments in which small parts of the formation accumulated may be hard to identify. Their identification is further complicated by two significant factors. Firstly, quartz arenites like those of the Sly Creek Sandstone do not appear to be forming today. Pettijohn (1957) estimated that about one third of all sandstones are the quartz arenite (orthoquartzite) variety, yet they are known to be forming today only by aeolian process in parts of the Libyan Desert. This direct analogy is patently not applicable for much of the Sly Creek Sandstone. We therefore appear to lack modern analogues with which to make direct comparisons. Secondly, analysis of rhythmic cycles is a powerful tool in the genetic interpretation of clastic sequences. Evidence of rhythmic cycles in the Sly Creek Sandstone is scant, except for the example described above. Hence, as well as the lack of modern analogues, we also appear to lack one of the major tools developed recently for environmental interpretations. Despite the limitations expressed in these qualifying remarks, we have attempted to summarise and analyse (below) the features that we feel are pertinent in environmental and genetic interpretations.

Rock type

Almost all of the Sly Creek Sandstone comprises compositionally and texturally supermature silica-cemented quartz arenite (more than 95 per cent quartz). The only variations to this that were identified during the mapping are: 1) near the top of the formation, where it has a gradational contact with immature sedimentary rocks of the overlying Settlement Creek Volcanics, and 2) immediately underneath the chert marker bed, where micaceous siltstone is present. Excluding these two exceptions, the arenites are composed of well rounded grains which are either unimodally or bimodally sorted. They are typical quartz arenites or orthoquartzites as described by Pettijohn & others (1972).

The quartz arenites of the Sly Creek Sandstone probably represent multicycle sands derived from the weathering and erosion of pre-existing sandstones. If so, the only known potential source in the area would be the Yiyintyi Sandstone, which would have had to have been extensively winnowed in order to remove all the clay material before the residue was deposited as the Sly Creek Sandstone. This lack of clay, either in the matrix or as interbedded shale, is very puzzling. Dott & Byers (1980), in a recent discussion of the orthoquartzite–carbonate suite (of which the Sly Creek Sandstone is an example), commented on this anomaly; they speculated that the lack of clay may reflect more extensive wind erosion in the Proterozoic, and that most of the clay was blown away from source areas rather than being transported by streams and later deposited in alluvial and nearshore environments.

Quartz arenites have a world-wide distribution. They are well known as basal blanket sands in the Cambro-Ordovician of North America but thick sequences are only strikingly prominent in the Precambrian (see for example—Rothrock, 1944; Brett, 1955; Fahrig, 1961; Donaldson, 1967; Brunn & Hobday, 1976; Button & others, 1981; Goode, 1981; Plumb & others, 1981; Rutland & others, 1981). Pettijohn & others (1972) suggested that quartz arenites are characteristic of stable cratonic areas, and are mainly multicyclic. They also stated that '. . . it seems improbable that a quartz arenite sand of the kind found in the geological record could ever be produced by river transport no matter how prolonged'. However, in contradiction to this, Dott & Byers (1980) noted that in recent research on the orthoquartzite–carbonate suite many operating processes and environments (including aeolian, fluvial, surf, intertidal, and outer shelf) have been documented with varying degrees of certainty.

Geometry and lateral relationships

The Sly Creek Sandstone is presently preserved over an area of at least 80 000 km^2, and varies in thickness between about 100 and 1000 m. It has a tabular to blanket-like geometry (Krumbein & Sloss, 1963) with a thickness-to-width ratio of more than 1:400. Individual genetic units (<1 m thick) are laterally persistent over distances of at least hundreds of metres. Although of limited use in environmental interpretation, the geometry of the lithosome—with the thickest sections in the central part of the area—does suggest that the central area was a depocentre. Additional support for this is provided by the lateral facies change from the thick central arenites in the Batten Range to the thinner arenites and sabkha carbonates (McDermott Formation in the southeast) near the Murphy Inlier. According to Sweet & others (1981), the Murphy Inlier may have been an uplifted area forming the southern basin margin.

Vertical characteristics

The vertical homogeneity of the Sly Creek Sandstone in the Batten Range is remarkable, especially when compared with the heterogeneity of the formations in the overlying McArthur and Roper Groups. Following a thin basal transgressive conglomeratic unit, the formation shows little variation in rock type and only minor variations in sedimentary structures. It lacks clear evidence of progradational sequences or the rhythmic cycles which characterise modern shallow-marine environments (e.g., Walker, 1979; Reading, 1978). In the northern part of the area, the unit comprises two distinct parts: a lower, fine-grained, mainly planar-cross-bedded arenite (around 150 m thick) deposited largely as sandwaves; and an upper, coarse-grained pebbly arenite with large-scale trough-cross-stratification (around 200 m thick) representing fossilised dune or megaripple fields. The rare cobble conglomerates in the coarser facies are sharply defined discrete beds which are characterised by lateral regularity in thickness and texture (over distances of at least hundreds of metres), a lack of channelling, and a lack of obvious imbrication—features more suggestive of wave-worked rather than alluvial gravel (Clifton, 1973).

Mineralogy and sedimentary structures

Although not confirmed by X-ray diffraction or chemical analyses, the Sly Creek Sandstone contains thick sections rich in well rounded green grains which are here assumed to be glauconite. Glauconite is considered to be an index mineral of marine deposits (e.g., Reading, 1978, Reineck & Singh, 1975); Odin & Matter (1981) noted that it is widespread on present-day continental shelves, and particularly abundant on the upper slope and outer shelf between 200 and 300 m. In the Sly Creek Sandstone it is intriguing that glauconite is common in both the coarse and fine-grained facies, indicating that both are of marine origin. It also occurs in bimodally sorted sands, indicating that in the Sly Creek Sandstone bimodality is unlikely to be of aeolian origin. It is present throughout the upper 120 m of the east Tawallah section (Fig. 14) in large-scale trough-cross-stratified sands with channels. It is rare in the east Batten Range section (type section), except at the very top, but common in both the fine and coarse facies at Calvert Hills near what would have been the southern basin margin during deposition. These observations suggest that the inferred depocentre of the Sly Creek Sandstone (the centre of the area) is poorer in glauconite than the basin margins.

As mentioned above (under subheading *Vertical characteristics*), the types of cross-bedding present indicate deposition mainly as sandwaves, dunes, or megaripples, implying that tidal or other persistent directional bottom currents were active. Large-scale planar cross-bedding is dominant in the fine-grained facies, and in places it alternates with beds a few metres thick containing symmetrical ripples, some of which bifurcate. The presence of symmetrical straight ripples with bifurcating crest lines provides reasonably good evidence of wave activity (Reineck & Singh, 1975; Harms, 1975) in the Sly Creek Sandstone, in addition to the activity of the tidal or other persistent bottom currents. The alternations of the planar cross-bedded sets and the rippled sets with erosional breaks is similar to that described by Reading (1978) for the Jura Quartzite of Scotland—a late Precambrian shallow-marine blanket sand. The vertical alternation of bedding types and the erosion surfaces record marked fluctuations in bottom current strengths. He interpreted this type of sequence as being due to alternating fair-weather and storm conditions; parts of the Sly Creek Sandstone may have been deposited under similar conditions.

In summary, the Sly Creek Sandstone is interpreted as a largely shallow-marine unit in which subtle internal variations in lithology and structures reflect slightly different sub-environments—ranging from offshore deeper marine through to shoreline beach and associated littoral deposits.

The chert marker bed in the east Batten Range and east Tawallah sections is tentatively equated with the silcreted regolith in the McDermott Formation (see p. 19); this implies a significant break in sedimentation. Although there is evidence of facies changes consistent with such an interpretation in the type section, this is not the case in the east Tawallah section. More detailed studies are required to solve this enigma.

Aquarium Formation

The name Aquarium Formation has been published without adequate definition by several authors, including Roberts & others (1963), Yates (1963), Plumb & Derrick (1975), Grimes & Sweet (1979), Plumb & others (1980), and Sweet & others (1981). We did not study the unit in detail during our research, and most of the data in the definition presented below have been derived from Roberts (unpublished). The name is derived from Aquarium Spring, in the headwaters of Settlement Creek in east central CALVERT HILLS. The main exposures of the formation occur along the Settlement Creek valley.

Distribution and thickness

The Aquarium Formation occurs only in the southeast of the area, where it is exposed (1) along the Settlement Creek valley, (2) around Horse Creek, and (3) in the headwaters of the Robinson River (all in CALVERT HILLS), and (4) around Hopplestrap Creek (in ROBINSON RIVER). It is everywhere estimated to be about 150 m thick.

Reference area

No section has been measured in detail, but a reference area in the headwaters of Settlement Creek at about latitude 17°29′S, longitude 137°37′30″E is nominated.

Stratigraphic relations

The Aquarium Formation conformably overlies, with transitional contact, the Sly Creek Sandstone, and is conformably overlain by the Settlement Creek Volcanics. It was previously correlated with the 'Rosie Creek Sandstone' (e.g., Plumb & Derrick, 1975), and thus would now be equivalent to the upper Sly Creek Sandstone in the Batten–Tawallah Ranges area. The Settlement Creek Volcanics in this same area include a considerable dolomite and siltstone component, and so they might be in part equivalent to the Aquarium Formation also.

Lithology

The Aquarium Formation is a characteristically glauconitic thin-bedded unit grading from glauconitic sandstone at the base into glauconitic shale and dolomite at the top. The sandstone contains both symmetrical and asymmetrical ripple marks; and halite casts are present in the glauconitic shale unit near the top. Roberts (unpublished) has compiled a composite section from the reference area (Table 1).

TABLE 1. COMPOSITE STRATIGRAPHIC SEQUENCE, AQUARIUM FORMATION

Settlement Creek Volcanics

Thickness (m)	
6	*Glauconitic silty dolomite*: flaggy, micaceous
40	*Glauconitic shale*: purple-brown to grey-green, micaceous, with fine-grained sandstone interbeds. Both comprise quartz, mica, glauconite, and feldspar in chloritic matrix. Dolomitic towards top, where halite casts are locally abundant
45	*Glauconitic quartz sandstone*: fine-grained, flaggy, ripple marks, lithic grains, and sericite flakes. Silty interbeds. Fines upwards
60	*Glauconitic quartz sandstone*: medium-grained, ferruginous, flaggy, ripple marks. Minor feldspar, volcanic fragments. Fines upwards.
150	

Sly Creek Sandstone

Interpretation

Although we have not done a detailed sedimentological analysis of the unit, the Aquarium Formation is clearly transitional from the marine Sly Creek Sandstone below, to the continental Settlement Creek Volcanics and lacustrine lower Wollogorang Formation above. Such a marginal-marine setting is totally consistent with the abundance of glauconite, with the littoral to paralic transition reflected in the fining-upwards section, and with dolomite and halite at the top.

Settlement Creek Volcanics

The name Settlement Creek Volcanics is here proposed for a unit of basic to intermediate igneous and associated sedimentary rocks which is present throughout most of the area. Firman (1959b) originally included the volcanic outcrops in Settlement Creek in the Peters Creek Volcanics, but subsequent mapping (Roberts & others, 1963) showed that these outcrops constitute a separate stratigraphic unit higher up in the Tawallah Group, and they were therefore renamed the Settlement Creek Volcanics. The name is derived from Settlement Creek, a wide alluvium-filled valley which is underlain by the volcanics and which runs northeasterly from near Seigals Creek homestead, past Wollogorang homestead, and into the Gulf of Carpentaria (Fig. 7).

Distribution and thickness

The Settlement Creek Volcanics are present in all areas of Tawallah Group outcrop, with the possible exception of the Masterton Horst (locality map, Plate 1). They are reasonably well exposed along the Settlement Creek valley and in the Mallapunyah Dome, but in general both the volcanics and the accompanying sedimentary rocks weather deeply and crop out poorly, so that this stratigraphic level is usually represented by a valley between more resistant quartzite ridges. In fact, during the 1:250 000 reconnaissance mapping in the 1960s, the Settlement Creek Volcanics were not identified in the Batten, Tawallah, and other northern ranges, and Roberts (unpublished) concluded that they were missing from the Tawallah Group succession to the north of the Abner Range. This, we now know, is not the case. Volcanics which were incorrectly assigned to the 'Festing Creek Formation' in MOUNT YOUNG are in fact the Settlement Creek Volcanics. The formation is also present in valleys previously mapped as Wollogorang Formation in the Batten and Tawallah Ranges where they appear to contain more sedimentary than igneous rocks; the portrayal of the Tawallah Group geology on the BAUHINIA DOWNS (Smith, 1964) and MOUNT YOUNG (Plumb & Paine, 1964) maps is therefore incorrect (see also comments on p. 30).

The Masterton Horst is a small upfaulted inlier of uppermost Tawallah Group rocks situated within the Emu Fault Zone a few kilometres southeast of the McArthur mine (Fig. 7). Walker & others (1978) and Walker (1980) described the stratigraphy of this complexly block-faulted area, and suggested that the Settlement Creek Volcanics are not present in this area. They showed a thin Sly Creek Sandstone section (about 20 m thick) directly overlain by the Wollogorang Formation. Although the Emu Fault Zone is a long-lived active fault zone that can clearly be seen to have markedly affected sedimentation during deposition of parts of the McArthur Group, and could conceivably also have affected deposition of the earlier Tawallah Group sequence, the poor outcrop in the Masterton Horst offers scope for an alternative interpretation: the lowest beds exposed in the horst might be the Wollogorang Formation and uppermost part of the recently recognised underlying Wununmantyala Sandstone; if so, then the present erosion surface has not yet reached the level of the Settlement Creek Volcanics, whose character in the horst is therefore unknown.

Poor outcrop has precluded the accurate measurement of thickness variations in the Settlement Creek Volcanics. However, in most places where the overlying and underlying resistant quartzites crop out, and where there are no obvious structural complications, calculations of equivalent stratigraphic thicknesses for this valley of poor outcrop indicate values commonly between 100 and 150 m.

Type area

Although Roberts (unpublished) suggested the headwaters of the Settlement Creek as an appropriate reference area for the formation, we have nominated the Mallapunyah Dome (lat. 17°05′S, long. 135°50′E) as the type area, for three reasons: (1) the unit is more continuously exposed in this area; (2) it contains a mixture of extrusive and intrusive varieties in this area, where it is probably more representative of the formation as a whole, and (3) this area is much more accessible than the headwaters of Settlement Creek. A sealed road passes near Mallapunyah homestead, and a good graded track from Mallapunyah to Kiana homestead traverses the middle of the outcrop belt. To complement this type area with one where sediments are dominant, a section at the northeastern end of the Batten Range (lat. 16°21′S, long. 135°46′30″E) is nominated as a reference section (Fig. 23); igneous rocks are not apparent in this section.

Stratigraphic relations

The Settlement Creek Volcanics conformably overlie the Aquarium Formation in the southeast, and the Sly Creek Sandstone elsewhere. The unit is overlain with structural conformity by the Wollogorang Formation in the south and southeast, and by the Wununmantyala Sandstone in the Batten and Tawallah Ranges.

Lithology

In the southern half of their outcrop area the Settlement Creek Volcanics contain a range of intermediate to basic igneous rocks—including lavas, pyroclastics, and intrusives—with minor intercalated sedimentary rocks. The most commonly outcropping igneous rock is a red-brown-weathering dark grey-green massive basalt or andesite. However, there is a wide range in grainsize and texture from very coarse-grained and porphyritic varieties to fine-grained subophitic varieties. The components of these rocks are commonly altered and weathered, largely to chlorite, sericite, clay minerals, and iron oxides. Although not common, agglomerates and vesicular basic lavas with amygdales of chlorite, celadonite, quartz, dolomite, pyrite, and various copper minerals do occur. Tuff, tuffaceous siltstone, and ferruginous shale are the most common volcaniclastic rocks in most of this southern belt, but in the Calvert Hills area pink, well banded dolomitic tuff and purer dolostones form lenses up to 4 m thick in the upper parts of the unit. Intrusive phases of the Settlement Creek Volcanics include alkali dolerite, quartz dolerite, microsyenite, and dacite; like the extrusives, all are extensively altered: the plagioclase is commonly altered to K-feldspar and sericite, and the pyroxene and amphibole have been replaced by chlorite and actinolite.

Both the upper and lower contacts of the Settlement Creek Volcanics in the southern part of the area are marked by brown siltstone and shale units which are transitional between the volcanics and the enclosing clastics. The siltstone at the top of the unit in the southeast has been included with and described in the section on the Wollogorang Formation (see p. 33).

The character of the Settlement Creek Volcanics changes north of about latitude 16°40′S, where sedimentary rocks become the main component. The formation is poorly exposed in most of its northern outcrops, where red and brown hematitic shale and siltstone with thin beds of granular hematitic ironstone, dark grey crystalline dolostone, and very fine-grained dolomitic or micaceous sandstone and siltstone are the main rock types, together with deeply weathered basic igneous rocks.

The shale in the reference section (Fig. 23) does not contain any distinctive sedimentary structures, but the dolostone is commonly ripple-laminated or planar-cross-stratified; additional evidence of currents is indicated by claystone pellets and intraclast breccias. The two dominant end-member rock types have clearly defined bed contacts. In the lower half of the section the proportion of dolostone interbeds increases from the base upwards, and so does the thickness of these interbeds (from 20 cm up to about 3 m). The overlying poorly outcropping part of the formation lacks dolostone and appears to be mainly red shale, and contains rare feldspathic and glauconitic sandstone beds 1–2 m thick.

One of the most distinctive features of the sedimentary rocks in the Settlement Creek Volcanics is the high proportion of iron, mainly in the form of hematite, especially as a matrix

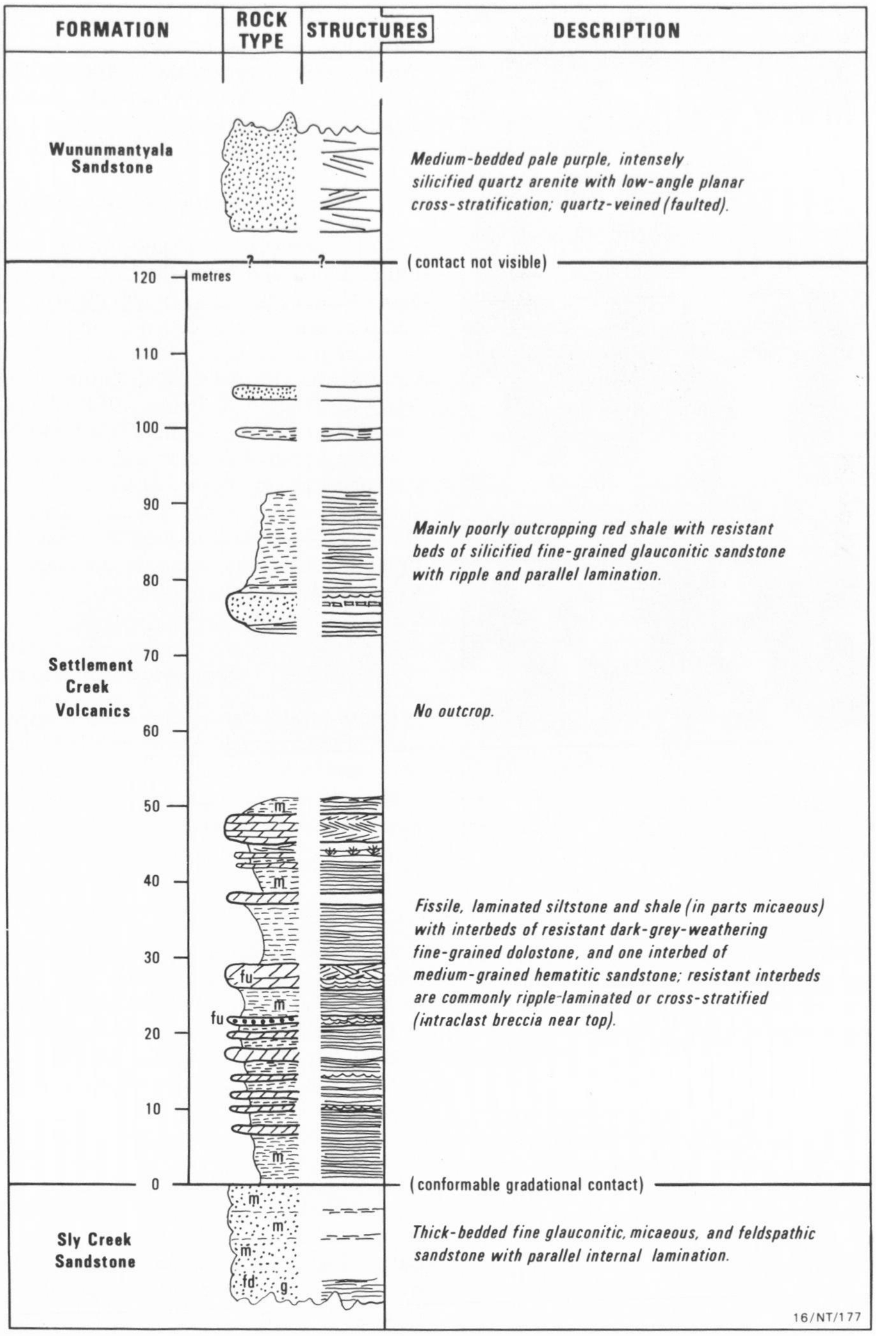

Fig. 23. Reference section of the Settlement Creek Volcanics (measured section Batten 79/04) in the northeastern part of the Batten Range.

in the sandstone and siltstone. Some samples consist mainly of iron (hematite) with clastic grains (Fig. 24).

Interpretation

The extent and generally uniform thickness of the formation imply a fairly uniform and widespread episode of intermediate to basic volcanism, related high-level intrusive activity, and concomitant sedimentation. Systematic studies of the igneous rocks—for example, of the internal structures of individual flows, extrusive-intrusive relationships, petrology, and geochemistry—have not been carried out, so details of their evolution are not available. In fact, the generally poor exposure precludes an accurate assessment of the ratio of extrusive to intrusive phases present. Amygdaloidal and vesicular ropy flow tops suggest that some of the flows are of the pahoehoe type—i.e., rapidly extruded fluid magmas. In contrast, the presence of breccias and agglomerates indicate periods characterised by more explosive igneous activity.

The thin intercalated sedimentary rocks in the south are fine-grained and commonly tuffaceous, and of limited lateral extent except at the very top and bottom of the unit. They lack evidence of extensive reworking by water, and current activity appears to have been minimal, so relatively quiet deposition in small ponds, lakes, or lagoons in a landscape dominanted by volcanic landforms is inferred.

In the north, however, the thicker and more variable sedimentary component indicates more widespread sub-

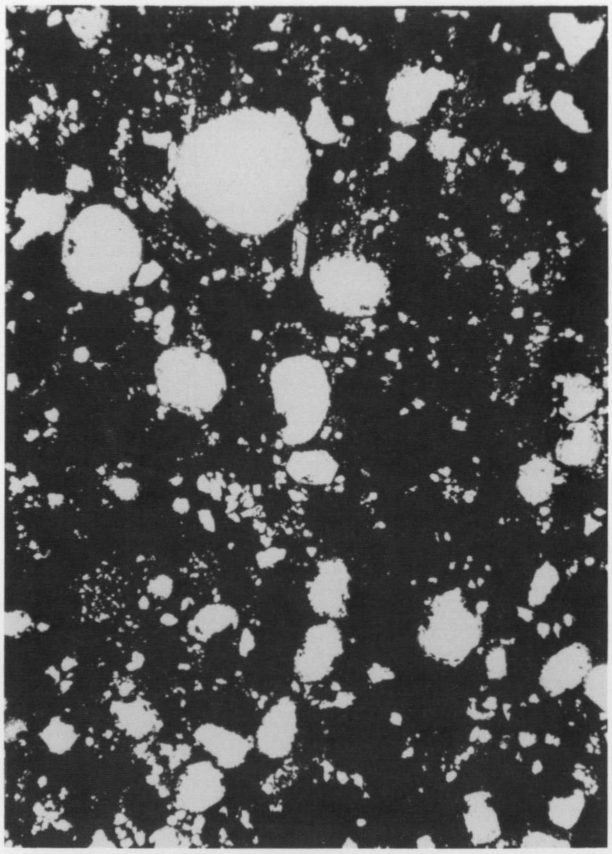

Fig. 24. Thin section of sandy ironstone of the Settlement Creek Volcanics (TS 81100050F) in the southeastern Tawallah Ranges. The bulk of the rock is composed of rounded 'ghost' grains of hematite in a hematitic matrix (all black). The larger quartz grains are commonly overgrown with quartz and then etched by hematite. Note the crystal faces indicating extensive secondary silicification. The largest quartz grain is 1 mm in diameter.

aqueous deposition in a landscape largely free of volcanic landforms. This implies a palaeogeography comprising a southern, mostly volcanic, landmass and a northern seaway. Measurements of a few current directions on ripple marks and cross-bedding indicate mainly easterly flowing currents. The character of the northern seaway is uncertain: the thin beds of rippled glauconitic sandstone and granular hematitic ironstone suggest shallow-marine conditions, but the fine-grained massive dolostone and laminated shale may indicate lagoonal or deeper marine environments.

The extensive alteration of the volcanics appears to be due to a late period of potassium metasomatism, rather than just surface alteration, because the volcanics—even in drillholes—are altered. The younger Gold Creek Volcanics, which crop out over much the same area as the Settlement Creek Volcanics, show similar but more intense potassium metasomatism.

WUNUNMANTYALA SANDSTONE

The name Wununmantyala Sandstone is here proposed for a newly identified sandstone unit that occurs in about the middle of the Tawallah Group north of latitude 16°30′S. In BAUHINIA DOWNS (Smith, 1964) and MOUNT YOUNG (Plumb & Paine, 1964) these rocks were originally mapped as part of a thick sandstone and volcanic unit called the Masterton Formation. Our studies disclosed the presence of an unconformity within this unit. Accordingly we have adopted the modified name Masterton Sandstone for the sandstones above the unconformity, and introduced the name Wununmantyala Sandstone for those below it. The formation is named after Wununmantyala Spring, GR 657632 in *Tawallah Range* (6066).

Distribution and thickness

The Wununmantyala Sandstone has been examined in the Batten Range and along the eastern and western sides of the Tawallah Ranges, but as systematic remapping of these areas has not been done its distribution is not accurately known. However, most areas of 'Masterton Formation' in the northern half of BAUHINIA DOWNS (Smith, 1964) and in MOUNT YOUNG (Plumb & Paine, 1964) should probably be re-assigned to the Wununmantyala Sandstone.

In the Batten Range, in measured section Batten 79/03, the formation is about 520 m thick. It appears to be of a similar thickness in the Tawallah Ranges, but no accurate sections have been measured there; as this area is cross-cut by numerous faults, accurate thickness values are difficult to establish from the airphotos.

Stratigraphic relations

Photo-interpretation and ground inspection suggest that the Wununmantyala Sandstone concordantly overlies the Settlement Creek Volcanics, and appears to be conformably overlain by the Wollogorang Formation in the Batten Range, but probably unconformably by younger units in other areas.

Type section

The lower part of measured section Batten 79/03 is here nominated as the type section. It is the only place where detailed observations of the unit have been made. It is situated at the southwestern end of the Batten Range between GR 778800 and 770800 in *Batten* (6065), just north of the top of Plate 1. A generalised log of the section is shown in Figure 25.

Lithology

Only about 60 per cent of the formation crops out in the Batten Range. The measured section (Fig. 25) comprises steep-sided sandstone ridges separated by valleys of no outcrop. Unfortunately, there is no direct evidence as to the lithology of the non-outcropping part of the formation. However, small reddish brown shale clasts are common in the sandstones, and may reflect the lithology of the remaining 40 per cent of the formation. The sandstones are mainly red fine to medium-grained, moderately well sorted quartz arenites composed largely (>90 per cent) of well rounded quartz grains, minor chert grains, and accessory heavy minerals. Thin sections commonly contain remnants of a red limonitic–hematitic matrix and rare hematite grains. Even in the purer quartz arenites, where the grains have been enlarged by silica precipitation in optical continuity with the original grains, thin surface coatings of iron oxides are visible on most of these grains indicating that they were originally well rounded and that most of the sandstones were originally hematitic.

Coarser-grained sandstone is present only in the lowest 50 m and between 340 and 343 m (Fig. 25). In the lower interval the coarser grains are commonly concentrated along low-angle foreset laminations, whereas at 340 m they are concentrated into a medium-bedded interval of subrounded

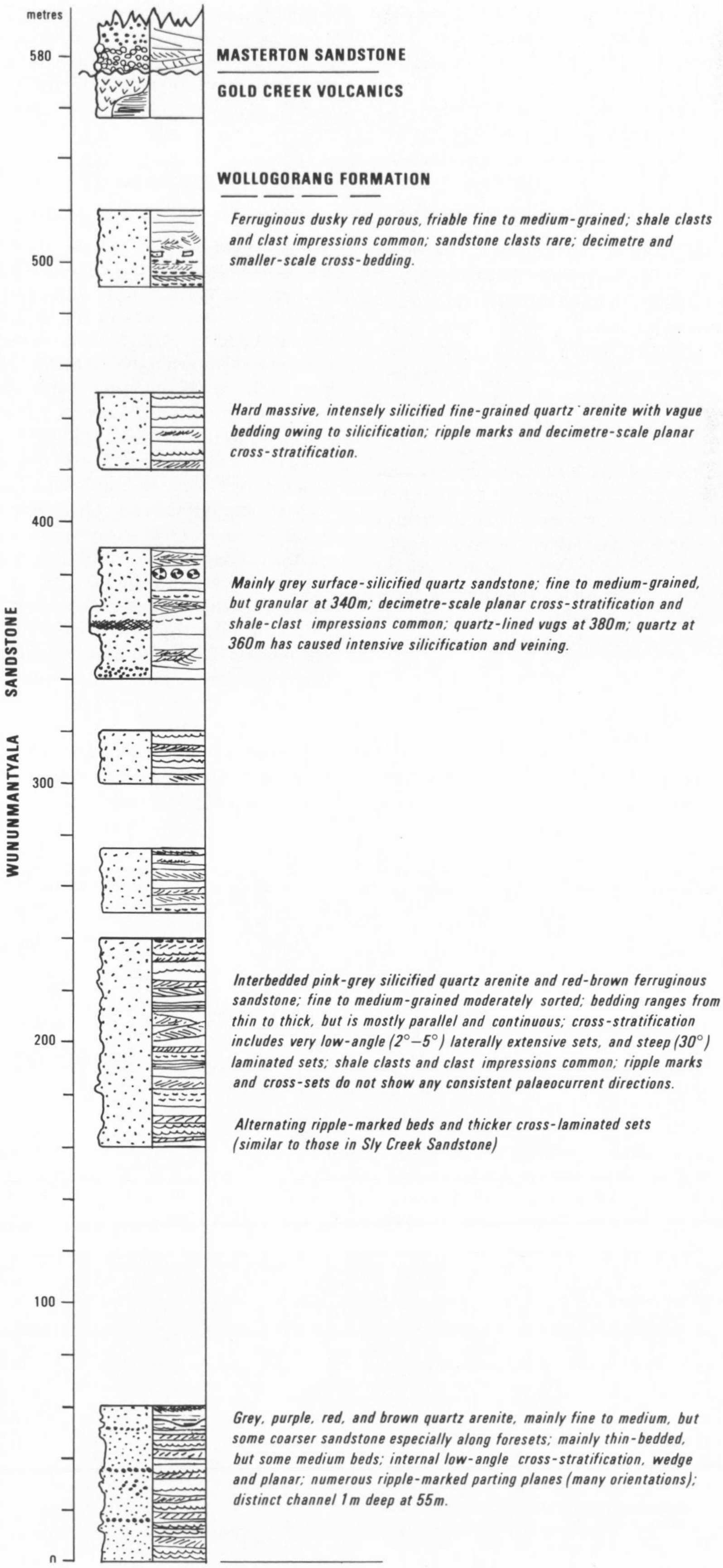

Fig. 25. Type section of the Wununmantyala Sandstone (measured section Batten 79/03), in the southwestern Batten Range.

to subangular, poorly sorted quartz sandstone which overlies 20 m of no outcrop; this somewhat atypical lithology may indicate that a stratigraphic break is present in the underlying interval of no outcrop.

Bedding in the formation ranges from thin to thick (but is mostly thin to medium); it is regular and parallel (Fig. 26). Rippled parting planes are very common in some intervals of measured section Batten 79/03 (e.g., lowermost 60 m, around 180 m, around 240 m). Most of the ripples are symmetrical, straight to slightly sinuous, and commonly 1 to 2 cm high, and have wavelengths of 5–20 cm. They have a wide range of orientations, and apparently no single palaeocurrent direction predominates. Marked differences in orientation on adjacent parting planes only centimetres apart indicate a wide range of original ?wave orientations. Cross-stratification is also common and occurs mainly in sets less than 30 cm thick. Both very low-angle foresets (2–5°) and steeper foresets (30°) are evident. Planar and wedge sets are apparent, but owing to the effects of both ferruginisation and surface silicification, and the lack of three-dimensional outcrops, the cross-stratification can be characterised only with difficulty. As with the ripples, palaeocurrent directions are variable, but foresets dipping east appear to predominate.

Reddish brown shale clasts and impressions of these on bedding surfaces throughout the formation are the most common sedimentary structures. Angular clasts of sandstone a few centimetres long and of intraformational origin are evident at 500 m (Fig. 25).

Interpretation

From our limited observations of this unit, we tentatively conclude that the thick uniform quartz arenites with their regular and laterally persistent stratification accumulated in a mostly sublittoral marine environment. The unit is similar to the underlying Sly Creek Sandstone and the overlying Masterton Sandstone, both of which can be interpreted more confidently as mainly of sublittoral origin.

Wollogorang Formation

The name 'Wollogorang Series' was coined by Jensen (1940) for limestones and associated rocks in the Redbank–Wollogorang homestead area (Fig. 7). The term was changed to Wollogorang Formation by Firman (1959b), who restricted it mainly to carbonates in the area. Firman unfortunately applied the term Wollogorang Formation to the carbonates that are now known to be in the McDermott Formation lower down in the Tawallah Group. Carter (1959) published the term following Firman's use. Roberts & others (1963) corrected the definition so that it refers only to the mainly carbonate unit between the Settlement Creek Volcanics and Gold Creek Volcanics or Masterton Sandstone. The name originates from Wollogorang homestead, which is situated at 17°13′S close to the Queensland/Northern Territory border.

The Wollogorang Formation is a distinctive sedimentary unit, usually around 100 m thick, comprising a lower dark-weathering fine-grained carbonate part and an upper sandy part. It usually crops out discontinuously in gently dipping escarpments, but it contains diagnostic cherty stromatolites, laminated shales, and bituminous nodules which usually make it readily identifiable throughout the southern half of the McArthur Basin.

A detailed sedimentological investigation of this unit was made (Jackson, 1982a) because previous reports (Australian Geophysical Pty Ltd, 1967, 1970) had indicated a potential

Fig. 26. Regular, parallel, medium to thick-bedded ferruginous sandstone dipping at about 45° in the middle part of the Wununmantyala Sandstone exposed in the southern Batten Range. About 50 m of continuous outcrop is visible. (BMR negative M2572/3)

for stratabound mineral deposits similar to that present near McArthur River. This section is largely a summary of Jackson's (1982a) dissertation.

Distribution and thickness

The Wollogorang Formation is present throughout the whole area. It crops out extensively in the Settlement Creek valley (in the far southeast of the area) and also around domal inliers of Tawallah Group rocks between Mallapunyah and Robinson River homesteads (in the south central parts of the area). Elsewhere, it usually forms poorly exposed belts of shale and dark brown carbonates between sandstone ridges in areas of strike-faulted Tawallah Group rocks. The discontinuous outcrop and faulting probably contributed to misidentification of the formation in much of northern BAUHINIA DOWNS (Smith, 1964) and MOUNT YOUNG (Plumb & Paine, 1964). Outcrops shown as the Wollogorang Formation on these maps are now known to belong largely to the Settlement Creek Volcanics; rocks belonging to the Wollogorang Formation crop out in a narrow strike valley within areas shown as Masterton Formation (now mostly Wununmantyala Sandstone) and Mulholland Sandstone (now mostly Masterton Sandstone).

The unit has a maximum thickness of 150 m in the far southeast. At several localities in the south and at Eastern Creek in the north, it is around 100 m thick. Elsewhere, it appears to be around 50–100 m thick, but poor exposure hinders accurate thickness measurements. It is therefore a widespread thin sheet-like body sandwiched between subaerially extruded volcanic rocks.

Type and reference sections

The type section is here nominated as the mesa (at lat. 17°14′S, long. 137°50′E) located about 12 km west of Wollogorang homestead and on the northern side of the road that runs from the homestead to Redbank mine. A reasonably well exposed and accessible complete section of the formation is here available for examination; Figure 27 summarises the main features of it. Additional outcrops of the formation are common in the escarpment flanking the northwestern side of Settlement Creek.

Jackson (1982a, p.47) nominated BMR drillhole Mount Young No. 2 as a reference section for the formation. This drillhole, situated in the north of the area (Fig. 7), provides a continuous core through the formation which Jackson (1982a) has studied in detail. The core is stored at BMR's Core and Cuttings Laboratory, Canberra, and is freely available for inspection.

The detailed sedimentological study (Jackson, 1982a) has shown that the lateral character of the formation varies little, so that these nominated sections are good representations of the formation as a whole.

Stratigraphic relations

In the south and southeast, the Wollogorang Formation overlies the subaerially extruded lavas and associated intrusions of the Settlement Creek Volcanics with structural conformity. Where the contact is gradational, red and purple crumbly amygdaloidal volcanics grade upwards over a few metres into friable red-brown tuffaceous shale containing volcanic debris. At localities where this type of contact zone is reasonably well exposed, tuffaceous beds in the basal 10 m of the Wollogorang Formation and continuous shaly lenses in the uppermost 20 m of the Settlement Creek Volcanics indicate a wide overlap between volcanism and sedimentation. In the north the Wollogorang Formation appears to conformably overlie the Wununmantyala Sandstone, but outcrops are few and far between and contact relations are consequently difficult to define.

The Wollogorang Formation is overlain by either extrusive phases of the Gold Creek Volcanics or, where these are absent, the Masterton Sandstone. In the southern Batten Range, shales in the formation have been baked by intrusive phases of the Gold Creek Volcanics. At the type section, a coarsening-upwards (regressive) unit of clastics at the top of the Wollogorang Formation is baked and silicified by the overlying fine-grained lava flow of the Gold Creek Volcanics.

Rod (1978) has described Jura-type folds in the Wollogorang Formation and in the overlying Gold Creek Volcanics. He ascribed them to detachment of rocks at the base of the Wollogorang Formation along a shear zone at the contact with the Settlement Creek Volcanics. Because he had not seen any evaporites or other similar potential lubricants at this postulated zone of detachment, the mechanism that he invoked to trigger the decollement was infiltration of carbonated potassium-rich hydrothermal fluids under pressure at the same time as the Redbank breccia pipes were emplaced. Evaporites are now known to be widespread throughout the Wollogorang Formation (Jackson, 1982a), and probably facilitated decollement folding in the formation. Similar types of decollement folding are also apparent in evaporite-rich units in the overlying McArthur Group.

Lithology

The generalised log of the type section of the formation (Fig. 27) is here used as a standard for description; significant variations from this are described thereafter. The generalised section is divided into four distinct units.

Unit 1, at the base, comprises generally poorly exposed grey, red, or brown-weathering shaly mudstone–siltstone which is commonly difficult to distinguish from fine-grained tuffaceous beds in the underlying Settlement Creek Volcanics. At some places there appears to be a gradational contact from rubbly volcanic rock to deeply weathered shales; at others a sharp planar contact is present (e.g., BMR Mount Young No. 2). In general, this basal unit is several metres thick, but Wyatt (1977) reported a thickness of up to 15 m in the type area, and Rod (1977) recorded a surprisingly thick 65 m in a section only 10 km northeast of Redbank.

Parallel continuous and discontinuous laminae and breccias characterise the 10 m of this unit in BMR Mount Young No. 2. Elsewhere, sedimentary structures are usually not very evident, but indistinct wavy lamination and poorly developed ripple lamination—indicating some current activity during deposition—are apparent in some sections. Moulds and casts after hopper halite crystals are common at several localities. In BMR Mount Young No.2, a 7-m interval of this basal unit contains fibrous dolomitic bands and cherty stringers replacing bedded evaporites (Fig. 28). The interbedded breccias in this part of the drillhole are matrix-poor and clast-supported. The clasts are intraformational (i.e., they consist of red-brown siltstone with evaporite pseudomorphs), are angular and unsorted (Fig. 29), and obviously indicate minimum transport.

Unit 2 is a thin pale grey-weathering coarsely crystalline dolostone with a number of distinctive sedimentary structures. The lower four metres are usually parallel-laminated or small-scale ripple-laminated, medium-grained, oolitic and pelloidal dolarenites. Several types of ripple are present, including symmetrical wave ripples, asymmetrical ripples (in-phase and in-drift), and interference ripples. These current and possibly wave-deposited dolostones also contain thin (up to 5 cm thick) laterally persistent biostromes of small

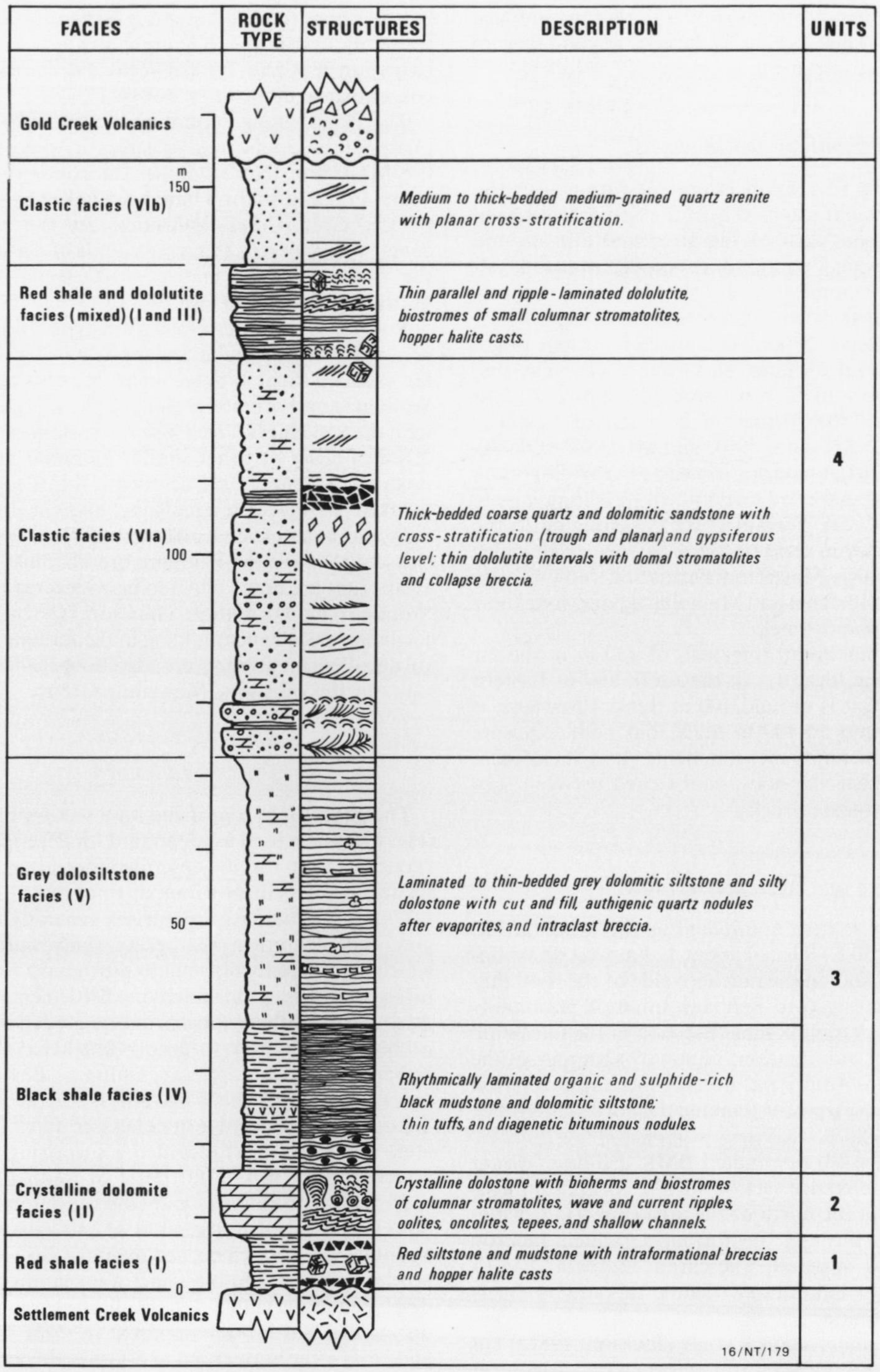

Fig. 27. Stratigraphic section of the Wollogorang Formation in the type area, near Redbank mine (after Jackson, 1982a).

digitate columnar stromatolites. Columnar stromatolites in the upper 2–3 m of the unit have developed laterally into large cherty bulbous bioherms (Fig. 30); they are a diagnostic feature of this formation, and have not been found in any other unit. Some of these bioherms may have developed into wave-resistant features, as they have steeply overhung margins and are flanked by intraclastic debris. Other bioherms are situated on the flanks of small channels (2–5 m wide by 1–2 m deep) which contain poorly sorted intraclastic and oncolitic carbonates. In addition to the structures already mentioned, chertified tepees and chertified polygonal cracks occur near the base of some of the domal bioherms at the type section.

At many localities in the north and some in the south, these carbonates have undergone extensive recrystallisation, which appears to have destroyed much of the original texture and structure producing stylonodular and stylobrecciated rocks (see Logan & Semeniuk, 1976).

Despite the effects of this overprinting, subtle lateral facies changes can still be recognised. For example, at the type section and near Calvert Hills (40 km due west) the unit is 4–5 m thick and contains the distinctive ripples and stromatolites described above. In contrast, in a measured section in Settlement Creek halfway between these two localities, the unit is 11 m thick and comprises only wave-

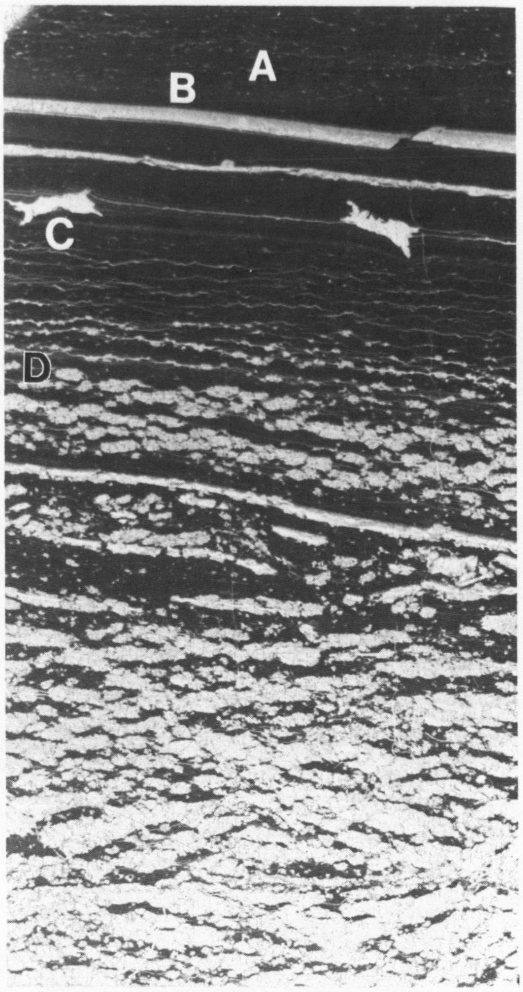

Fig. 28. Thin section (80100076A—photographed in white light on a light box) of greyish red interlaminated mudstone–siltstone (black) with crystalline dolomite and chert (after evaporites) in unit 1 of the Wollogorang Formation at 127 m in BMR Mount Young No. 2: A—discontinuous wavy laminae or fenestrae of very fine-grained dolomite and minute hexagonal chert and dolomite pseudomorphs (up to 0.1 mm across) after ?gypsum; B—a chert layer about 1 mm thick containing hexagonal pseudomorphs (up to 0.1 mm across) after ?gypsum; C—mould of halite crystal, now coarsely crystalline mosaic of euhedral dolomite; the mould was squashed owing to compaction during lithification; D—bands of pale grey-brown dolomite, which has a distinctive fibrous habit and extinction, developed along the lamination or wavy fenestrae. Note the small square or diamond-shaped pseudomorphs (after ?halite) in dark siltstone between these dolomite bands.

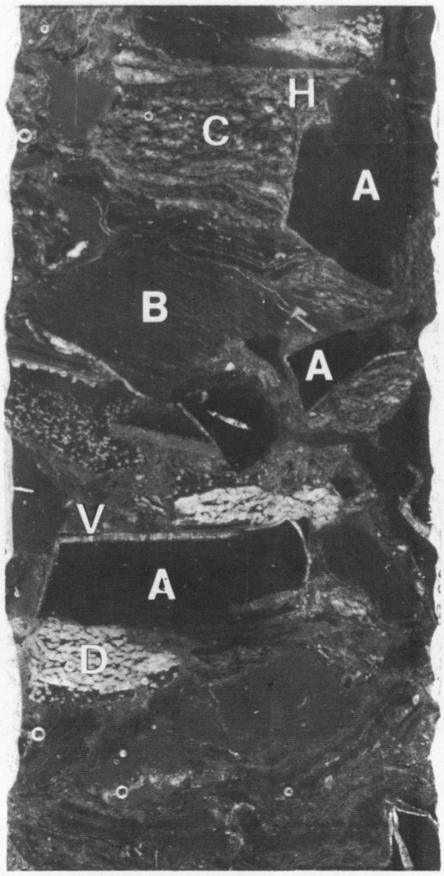

Fig. 29. Slabbed, polished, and lacquered core of intraformational matrix-poor clast-supported breccia in unit 1 of the Wollogorang Formation from BMR Mount Young No. 2 (130.20–130.33 m): A—dark reddish brown mudstone; B—greyish red wavy-laminated mudstone; C—greenish grey mudstone with dolomite bands (after evaporites); D—greyish olive-green mudstone with dolomite bands and square pseudomorphs (after evaporites); H—right-angle shape, perhaps reflecting the corner of a halite mould; V—veinlets of fibrous dolomite. Numerous clasts have been formed by breakage along these pre-existing veinlets. This feature, together with the very angular nature of the clasts, indicates minimal transport. The lithology of clasts C and D is similar to the rock shown in Fig. 28.

rippled dolostone. In BMR Mount Young No. 2, this equivalent stratigraphic interval is considerably thicker (almost 40 m), and comprises two levels of hard crystalline stylolitic dolomite (each 3-4 m thick) with interbedded dolomitic siltstone (Appendix Fig. A2).

Unit 3, which overlies the resistant dolostone of unit 2, consists of light brown to dark grey-weathering thin-bedded to laminated dolomitic siltstone and shale up to about 70 m thick. Although generally poorly exposed, this unit contains hard bituminous dolomite nodules which are resistant to erosion. These nodules commonly weather out to form conspicuous float in areas of shaly bedrock (Fig. 31), and permit unambiguous identification of the concealed stratigraphic unit. Owing to poor exposure, little can be deduced about this unit from surface outcrops alone, except that it is thin-bedded to laminated and ranges in composition from grey dolomitic siltstone and black shale through to silty fine-grained dolostone, and that it contains the nodules. The nodules are usually oblate spheroids, commonly 3 to 10 cm long, but sausage, dumb-bell, and more complex shapes do occur. In the type area and near Mallapunyah, they are concentrated in the lower few metres of the unit; they gradually decrease in size and concentration upwards; and they change in composition from bituminous-rich crystalline dolostone to chert.

Although appearing somewhat monotonous in surface outcrop, unit 3 in the core from BMR Mount Young No. 2 contains a range of lithologies and sedimentary structures. Rock types present include black organic-rich sulphide-bearing mudstone, grey dolomitic siltstone, silty fine-grained dolostone, varved mudstone and dolostone, and thin green illitic clay bands which are probably completely altered tuffs. Stratification includes rhythmically laminated varves on a millimetre to centimetre scale, graded laminites up to about 3 cm thick, and ungraded 'massive' beds of dolomitic siltstone up to about 20 cm thick. As well as the diagenetic nodules visible at the surface, thin intraclast or flat-pebble breccias,

Fig. 30. Large bulbous bioherm of chertified stromatolites in unit 2 of the Wollogorang Formation at its type section (from Jackson 1982a). The scale is 10 cm long.

Fig. 31. Float of ovoid beds in unit 3 of the Wollogorang Formation in the Mallapunyah Dome: pale nodules of crystalline dolostone in laminated dolomitic siltstone.

minor cut-and-fill, and dewatering structures are visible in the core. Minute authigenic quartz nodules with radial and concentric textures, present near the top of this interval in BMR Mount Young No. 2, probably indicate the former presence of anhydrite or similar evaporite nodules.

Unit 4, which overlies unit 3 with a sharp contact, comprises mainly coarse-grained quartz sandstone of variable thickness and character. It is thickest in the southeast, where up to 80 m of it is preserved between unit 3 and the overlying Gold Creek Volcanics. Elsewhere, however, unit 4 is seldom more than 10 m thick, which may reflect either original depositional variations in thickness or differential erosion before the overlying Gold Creek Volcanics and Masterton Sandstone were deposited.

In the southeast, unit 4 contains three distinct subunits. The lowest is mainly a thick-bedded coarse-grained dolomitic quartz sandstone with common trough and planar cross-stratification. Originally gypsiferous beds with an overlying collapse breccia are preserved at about the middle of this subunit in the type section (Figs. 32, 33).The middle subunit, comprises mainly fine-grained dololutite, 10 m thick, with structures similar to those near the base of the formation—i.e., stromatolites, evaporites, and ripples (Fig. 27). The uppermost subunit, 15-30 m thick, consists of medium to thick-bedded well sorted quartz arenite with low-angle planar cross-stratification; it coarsens upwards in the top 2 m to a poorly sorted cross-bedded conglomerate, indicating a regressive phase before the overlying vuggy, amygdaloidal Gold Creek Volcanics accumulated.

In contrast to unit 4 in the southeast, the upper clastic part of the Wollogorang Formation at most other localities comprises a few metres of mainly non-dolomitic medium to coarse-grained well sorted quartz arenite with sedimentary features that include small-scale cross-stratification, ripples, and rare desiccation cracks. Hence it is most similar to, and

Fig. 32. Large chert pseudomorphs after gypsum crystals in coarse-grained dolomitic sandstone of unit 4 in the Wollogorang Formation at the type section. Note the swallow-tail and interpenetrating twin habit typical of gypsum.

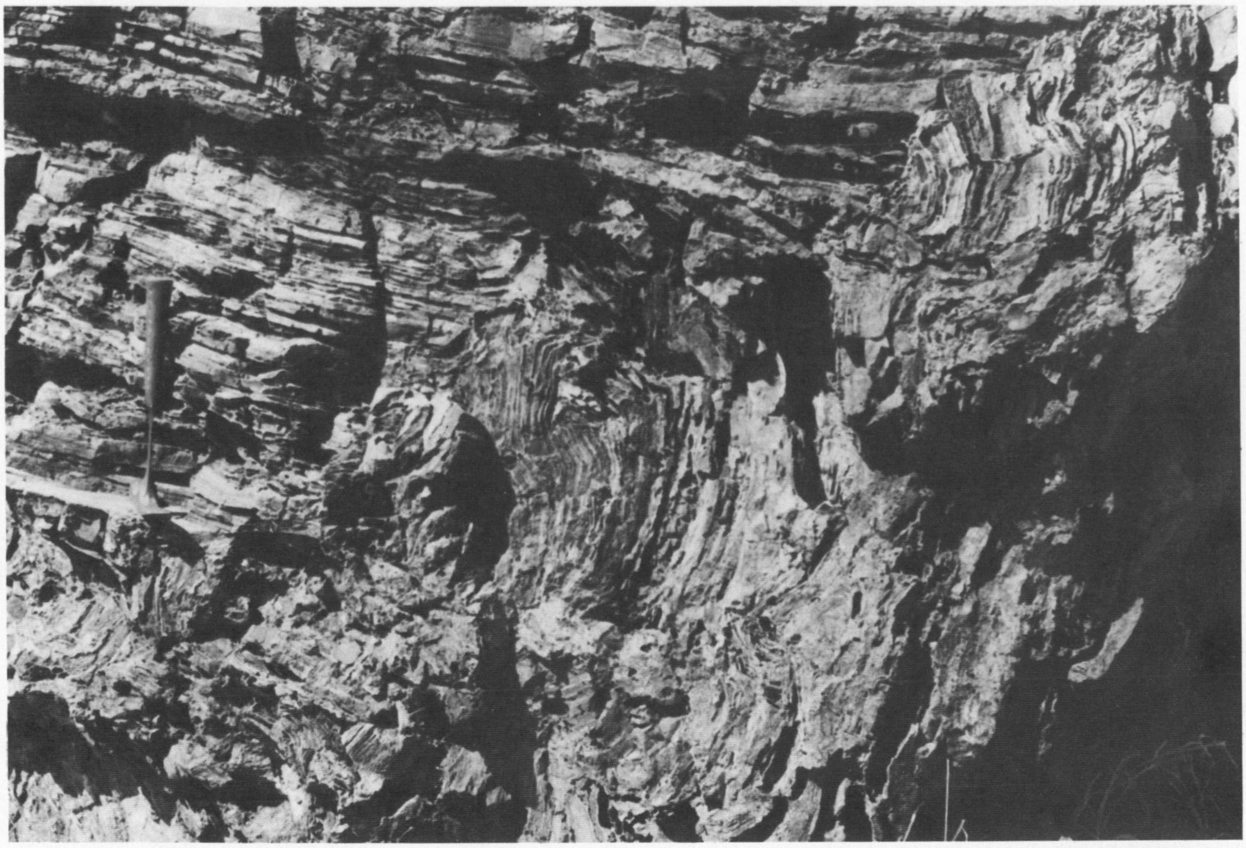

Fig. 33. Thin-bedded dolomitic sandstone and siltstone grading laterally into collapse breccia in unit 4 of the Wollogorang Formation at the type section. The dolomitic sandstone with evaporite pseudomorphs shown in Fig. 32 is located 15 m from this part of the type section, and about 2 m stratigraphically below the level of the geological pick.

is correlated with, the uppermost subunit of unit 4 in the type area, suggesting that the dolomitic sandstone and dololutite in the southeast are of local significance only.

Environments of deposition

Most of the Wollogorang Formation was probably deposited in a continental setting. The rock types and structures described above have been differentiated into six distinct lithofacies, whose main characteristics are listed in Table 2.Details of lateral variations in these facies are shown in Appendix Fig. A2.

A *red shale facies* (I) is characterised by marked lateral thickness variations (from 0 to 60 m), indistinct bedding, intraformational breccias, desiccation features, and evaporites. It was formed in a quiet oxic environment (see Berner, 1981). The almost complete lack of sand-size or larger grains, and the absence of much evidence of current or wave activity, indicate mainly quiet deposition from suspension in a saline mudflat or lagoonal environment. However, some periods of more active sedimentation are indicated by the breccia beds, which are interpreted as local debris flows. The bedded evaporites were probably formed penecontemporaneously with sedimentation, whereas the large hopper halites grew displacively in unlithified muds during diagenesis. Near the top of the formation, where it is sandwiched between coarse clastics of braided fluvial origin, it is probably of alluvial-plain origin.

Facies I is succeeded by a *crystalline dolomite facies* (II), which contains a range of shallow-water to emergent features with evidence of current and wave activity—e.g., intraclast-draped stromatolite bioherms, cross-stratified oolitic dolarenite, channels filled with intraclast breccia, oncolites, and rippled dolostone (Fig. 34). The facies is characterised by sharp contacts between adjacent rock types, and rapid fluctuations in depositional processes are indicated. In isolation, these features strongly suggest deposition in a shallow-water marginal-marine carbonate-shelf environment (e.g., Bathurst, 1975; Sellwood, 1978; James 1979a, b), but when considered in their stratigraphic setting a marginal lacustrine environment is more likely (see discussion in Jackson, 1982a, pp. 82–87). Similar sequences which have likewise been interpreted as marginal lacustrine deposits include part of the Pliocene Ridge Basin of California (Link & Osborne, 1978), part of the Eocene Green River Formation of Wyoming (Williamson & Picard, 1974), and parts of the Triassic of South Wales (Tucker, 1978). The preferred interpretation of marginal lacustrine rather than marginal marine is based mainly on the lacustrine character of the overlying facies—IV.

Detailed examination of core from BMR Mount Young No. 2 has helped to identify two intergradational facies in the dolomitic siltstone and shale (unit 3): a *black shale facies* (IV) and a *grey dolosiltstone facies* (V).

The black shale facies consists of distinctly interlaminated (varved) black organic-rich mudstone and very fine-grained dolostone. Jackson (1985) has described the varves from this facies in detail, and suggested that they are similar to the varved banded iron formations of the Hamersley Basin, in Western Australia (Trendall, 1972, 1973). From measurements of varve thicknesses he has recognised 7, 11, and ~ 300 y periods in this facies. The facies represents anoxic quiet-water distal-lacustrine deposition.

The grey dolosiltstone facies is less distinctly and thicker-bedded than facies IV. It contains less organic matter and

TABLE 2. SUMMARY OF THE CHARACTERISTICS OF THE LITHOFACIES OF THE WOLLOGORANG FORMATION

Lithofacies	*Subfacies*	*Thickness variations m*	*Rock types*	*Sedimentary structures and other features*				
				Stratification	*Penecontemporaneous structures*	*Diagenetic structures*	*Other comments*	*Processes/Environment/Interpretation*
I Red shale facies		0–15 (60 in one area)	Red, brown, purple siltstone–mudstone; dolomite after evaporites	Generally indistinct (massive) to very poorly laminated (shaly). Wavy discontinuous laminae of carbonate in BMR Mount Young No. 2. Rare ripple-drift lamination	Poorly preserved ripples, intraformational breccia, desiccation cracks, halite casts, bedded evaporites	Halite casts, veins of evaporites	Gradational lower contact with volcanics. Commonly basal unit of formation; also present near top	Oxidising and evaporitic environment. Deposited on irregular volcanic land surface. Little evidence of currents. Early post-lithification brecciation and slumping. Probably saline mudflat–lagoon–lake
II Crystalline dolomite facies	a. Oolitic dolostone subfacies	0.5–3	Pale grey, well sorted, fine to coarse-grained oolitic and pelloidal dolarenite	Medium-bedded, horizontal	Rhombohedral ripples, wave ripples	Recrystallisation, stylolites. Grades into subfacies IIc. Irregular nodular chert pods	Upper contact sharp with megaripples	Agitated water; ooid shoal or bank
	b. Rippled stromatolitic subfacies	2–3	Ranges from fine-grained algal-laminated dololutites to pebbly intraclastic dolarenite; commonly chertified	Variable. Both thin laterally persistent wave and algal lamination and thicker discontinuous bedding and cross-bedding	Laterally persistent thin biostromes and isolated bulbous bioherms of columnar stromatolites. Ripples (symmetrical, asymmetrical, climbing, interference). Intraclasts, oncolites, channels, desiccation cut-and-fill	Selective chertification of stromatolites and irregular chertification. Tepee structures, small 'cauliflower' chert nodules	Only well developed in Wollogorang area. Commonly copper-enriched	Variable; shallow-water to emergent strandline deposits. Channels 3–4 m deep. Currents in several directions. Rapid current deposition alternating with slower, quieter conditions
	c. White dolostone subfacies	5–10	Pale grey to white coarsely crystalline dolostone; commonly weathers dark grey	Generally absent, 'massive'	Generally absent or vague, but indistinct ripples, oolites, intraclast breccias, and stromatolites	Extensively recrystallised stylolitic, stylonodular, and stylobrecciated textures. Pseudomorphs of sulphate evaporites in Mount Young No. 2	Recrystallised variety of subfacies IIa and b. Commonly copper-enriched	A diagenetic facies, presumably originally deposited as IIa and IIb
III Dololutite facies		Usually thin (1–2)	Very fine-grained dololutite (micritic). Hard and resistant, commonly with 'rillenkarren' surface. Colour ranges from pink, red, brown to purple	Massive or structureless, parallel-laminated, algal-laminated (low domes), and ripple-laminated	Ripples-in-drift, desiccation cracks, large skeletal and hopper halites, sucrosic chert laminae, sulphate evaporites	Pseudomorphs of sulphate evaporites	?Dolomitic equivalent of largely clastic facies I	Shallow subaqueous (stromatolite-supporting) playa lake or supratidal or fluvial interchannel deposits
IV Black shale facies		10–20	Dark grey to black organic and pyritic mudstone interlaminated with pale grey very fine-grained dolostone	Distinctly parallel, continuous, and thin-laminated. Dominated by cyclical laminates (varves), also thin graded beds	Rare microconvolution	Bituminous dolomite nodules (dewatering)	Grades into facies V; rarely crops out	Quiet anoxic deposition dominated by seasonal variations. Deposition mainly from suspension; rare density flows. Distal lacustrine

TABLE 2. SUMMARY OF THE CHARACTERISTICS OF THE LITHOFACIES OF THE WOLLOGORANG FORMATION (Cont.)

Lithofacies	*Subfacies*	*Thickness variations m*	*Rock types*	*Sedimentary structures and other features*				
				Stratification	*Penecontemporaneous structures*	*Diagenetic structures*	*Other comments*	*Processes/Environment/Interpretation*
V Grey dolosiltstone facies	a. Bedded subfacies	10–40	Mainly pale grey dolomitic siltstone grading to silty dolostone, rare black mudstone interbeds	Distinctly parallel and thin-bedded and laminated. Some 'massive' beds, graded beds, rare cyclic laminates. Some less distinct beds with discontinuous lamination (algal?)	Thin intraclast breccias, rare desiccation cracks, microscopic cut-and-fill, load casts	Dolomitic and cherty nodules, bladed beds, small quartz nodules (after evaporites)	Grades into facies IV; generally poorly exposed	Deposited by suspension and traction currents. Similar to IV but less regular, less continuous sedimentation. Occasionally emergent. Probably more proximal lacustrine facies
	b. Brecciated subfacies	Few tens of centimetres up to about 2 m	Intraformational clast-supported, very angular breccia of dolomitic siltstone	Non-stratified, no grading, no sorting	Includes slightly displaced broken beds	Quartz nodules (after evaporites) in breccia	Rarely exposed; well developed in BMR Mount Young No. 2	Collapse and slump brecciation—related in part to solution of interbedded evaporites
VI Clastic facies	a. Coarse dolomitic sandstone subfacies	15–24	Coarse-grained strongly cemented dolomitic sandstone, granule conglomerate; thin gypsiferous sandstone interbeds	Medium to thick, parallel continuous, also non-parallel discontinuous	Cross-stratification, channels, ripples, graded beds, eroded bed contacts, convolute lamination, rip-up and intraclast beds, rare desiccation cracks	Halite casts; collapse breccias associated with solution of sulphate evaporites	Restricted to southern part of basin	Current-deposited; marked variations in current velocities; lag gravels in channels. Low-sinuosity braided fluvial environment
	b. Blocky quartz sandstone subfacies	5–44	Pale grey fine to coarse, well sorted quartz arenites, rare conglomerates; commonly silicified	Medium to very thick, parallel and continuous	Cross-stratification, ripples		Widespread; forms uppermost beds of formation	Shallow marine with intermittent shoaling

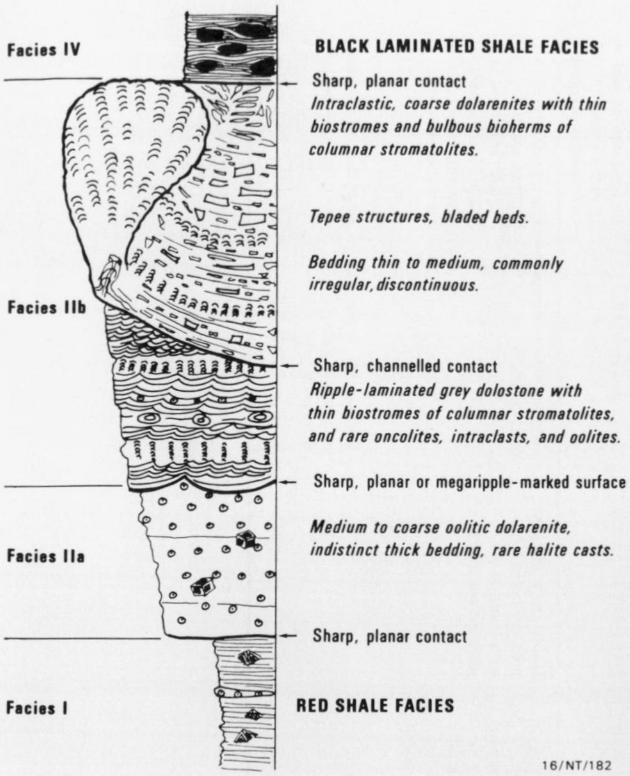

Fig. 34. Schematic section of facies II in the Wollogorang Formation, showing details of sedimentary structures and bedding characteristics (after Jackson, 1982a).

fewer sulphides, and more evidence for bedding disturbance and current activity—e.g., cut-and-fill and thin intraclast breccias. It also contains numerous small quartzine spherulites, probably after former nodules of anhydrite. It is a more proximal facies than facies IV, and reflects deposition in a shallower higher-energy lacustrine environment with an evaporitic (sabkha-like) overprint.

The upper part of the formation is dominated by a *clastic facies* (VI), which is thickest and best preserved in the southeast. The trough-cross-stratification, channel contacts, poor sorting, and pebble lags indicate that the dolomitic sandstone subfacies (VIa) is probably of fluvial origin. The absence of fining-upward cycles indicates braided rather than meandering systems. The presence of mixed trough and planar cross-stratification with variable foreset dip directions bears strong resemblance to sequences of in-channel and cross-channel bars from braided systems (e.g., Walker, 1979; Reading, 1978). The presence of parallel lamination indicates periods of high flow regime, whilst the numerous erosion surfaces indicate frequent channel migration and/or sporadic sheet floods of coarse sandy material of wide lateral extent across an alluvial plain. The uppermost blocky quartz sandstone subfacies (VIb) is better sorted, more uniform, and more widespread than the dolomitic sandstone. Cross-stratification is generally planar, and ripples are more common. Although lacking diagnostic features, the subfacies may have accumulated in an open shallow-marine environment.

A *dololutite facies* (III) is present in some places near the top of the formation.It is very fine-grained, and contains well-preserved evaporite pseudomorphs, algal laminations, and ripples. It was deposited in a playa-lake or supratidal environment, and is thought to represent a dolomitic equivalent of facies I.

In summary, the Wollogorang Formation records deposition in mainly lacustrine and fluvial environments, but shows evidence of possible marine inundation at the top. The earliest event recorded is the filling-in and smoothing-off, by the deposition of the red shale facies, of the irregular surface of the Settlement Creek Volcanics. A widespread lacustrine complex then developed over all the area. Several subenvironments can be recognised, including proximal and distal examples. Tuffaceous material, possibly originating from volcanic eruptions to the south of the area, was blown northwards across the area.

At about mid-Wollogorang time, uplift and erosion in the south of the area—now represented by the Murphy Inlier (see locality map in Plate 1)—are suggested by the subsequent development of a northward-building alluvial plain of coarse-grained clastics over the lacustrine sediments. Quiet lacustrine and associated terrestrial deposition probably continued in the far north.

Towards the end of Wollogorang time the whole area was probably inundated by a shallow sea in which clastic sediments accumulated. At the close of Wollogorang time the sea must have retreated, depositing a coarser regressive clastic phase, and the area was only slightly eroded before the Gold Creek Volcanics were extruded.

Microfossils

Muir (1982) described a varied but generally poorly preserved microfossil assemblage obtained from the black shale facies in drillcore at Redbank. Among the group Cryptarcha (Diver & Peat, 1979), Muir identified *Eoastrion simplex* Barghoorn, 1965; *Biocatenoids pertenuis* J.H. Oehler, 1977; *Coleobacter primus* J.H. Oehler, 1977; *Cyanonema inflatum* J.H. Oehler, 1977; *Gunflintia minuta* Barghoorn 1965; and several different species of *Oscillatoriopsis* Schopf, 1968. In addition, she mentioned members of the subgroups Sphaeromorphitae (emend. Diver & Peat, 1979) and Synaplomorphitae (Diver & Peat, 1979).

A striking feature of the assemblage is a number of larger organic structures which may be 'mini-stromatolites' or very large filamentous microfossils. They comprise large (30–65 μm diameter) twisted and knotted filaments with spherical cross-sections, and stacked dome-like discs of organic matter up to about 1 mm high.

The microfossils show considerable morphological diversity, and great abundance of individuals of particular species. In this, they contrast with other microfossil-bearing units from the McArthur Basin sequence—e.g., the Amelia Dolomite and Balbirini Dolomite—which tend to have fewer species and usually have one dominant species. The most similar assemblage to that in the Wollogorang Formation is the one that Oehler (1977) described from the HYC Pyritic Shale Member of the Barney Creek Formation: the assemblages have a great deal in common in terms of both the number of species present, and the individual numbers within species groupings. The Wollogorang assemblage is typical of others of its age world-wide.

Mineralisation

The Wollogorang Formation contains anomalous copper associated either with stromatolitic dolostone near the base of the formation, or with coarse-grained sandstone near the top; and fine-grained stratiform disseminated Pb–Zn in black dolomitic shale, also near the base (Table 3). The Pb–Zn occurrence is similar in style to the McArthur River deposit in the Barney Creek Formation (Jackson, 1981a, b). However, as the black shale facies of the Wollogorang Formation lacks

TABLE 3. GEOCHEMICAL VALUES FOR BASE-METALS FROM DRILLHOLES INTERSECTING THE WOLLOGORANG FORMATION

Drillhole and location	*Copper ppm*		*Lead ppm*		*Zinc ppm*	
	Background	*Anomalous*	*Background*	*Anomalous*	*Background*	*Anomalous*
BMR Mt Young No. 2 (northwest)	20-50	500-1500	10-20	60-100	10	50
Aust. Geoph. MN1) (south;) Mallapunyah	20-50	600-2000	20	200-400	20-50	600-800
Aust. Geoph. MN2) Dome)	10-50	200-2000	30-40	—	20-40	—
Redbank AD5) (southeast;) Redbank mine	20-50	100	20-30	—	20-30	50
BSF4) area)	20-100	1000	40-50	150	20-30	—

interstratified breccias and evidence of penecontemporaneous faulting—features highly significant in the formation of the McArthur deposit—its mineral potential in this area is assessed as small.

GOLD CREEK VOLCANICS

In previous publications (e.g., Smith, 1964; Roberts & others, 1963; Plumb & Sweet, 1974; Knutson & others, 1979) the Gold Creek Volcanics and some related rocks in the Wollogorang area (i.e., Hobblechain Rhyolite and Pungalina Member) had been included with a thick, overlying quartz sandstone in a unit called the Masterton Formation. Our studies in the central and northern parts of the area have identified a significant unconformity between the volcanics and the overlying quartz sandstone, so the stratigraphic terminology is here revised. The quartz sandstone is here redefined as the Masterton Sandstone and moved up, out of the Tawallah Group, to form the basal unit of the McArthur Group. The underlying mainly igneous rocks are defined as a new formation—the Gold Creek Volcanics. A poorly defined sedimentary unit previously referred to as the Pungalina Member (Yates, 1963) and Pungalina beds (Rod, 1978) is here assigned the status of a member of the Gold Creek Volcanics. Although we have not studied them, the comagmatic Hobblechain Rhyolite and Packsaddle Microgranite appear to be valid mappable units, so we have retained the terms and have accorded them formation status. Figure 35 shows the stratigraphic relations of these various units.

The Gold Creek Volcanics are widespread and form a distinctly mappable stratigraphic unit, with readily definable contacts, between the Wollogorang Formation below and the Masterton Sandstone above. The term 'Golden Creek Formation' had earlier been used by Newton & McGrath (1958) for these volcanics, but is now considered invalid. The name 'Gold Creek' is derived from a small creek which flows northwards from near Redbank across these volcanics towards the Gulf of Carpentaria (Fig. 7).

We have not studied the Gold Creek Volcanics in any detail, so much of the information presented below is a compilation of previously published and unpublished results—especially Roberts (unpublished), Australian Geophysical Pty Ltd (1967, 1968), Rod (1978), and Knutson & others (1979).

Distribution and thickness

The Gold Creek Volcanics crop out over roughly the same area as the Wollogorang Formation, but they are thickest and best exposed in the southeast along the Settlement Creek valley and in the south around the Mallapunyah Dome. The unit is characterised by abrupt lateral lithological and thickness variations. Roberts (unpublished) suggested that the Gold Creek Volcanics are restricted to the southern part of the basin, but poorly exposed igneous rocks at this stratigraphic level were identified during our recent mapping in both the Batten Range (centre) and Tawallah Ranges (northwest), indicating that they are laterally extensive throughout the area studied.

The thickest section—around 225 m—is near Redbank. Orridge & Mason (1975) reported that the unit thins locally to the north and east of here owing to a reduction in thickness of individual lavas flows, implying a source near Redbank. Around the Mallapunyah Dome the Gold Creek Volcanics are a complex unit of extrusives and intrusives up to about 200 m thick, but marked thickness variations are evident; for example, near the Kilgour River Gorge (GR 850030) a 50-m section of cliff-forming agglomerate thins to only 5 m over a distance of about 500 m. Near Robinson River homestead the unit is 8-10 m thick, and in the Masterton Horst and Batten Range it is about 30 m thick.

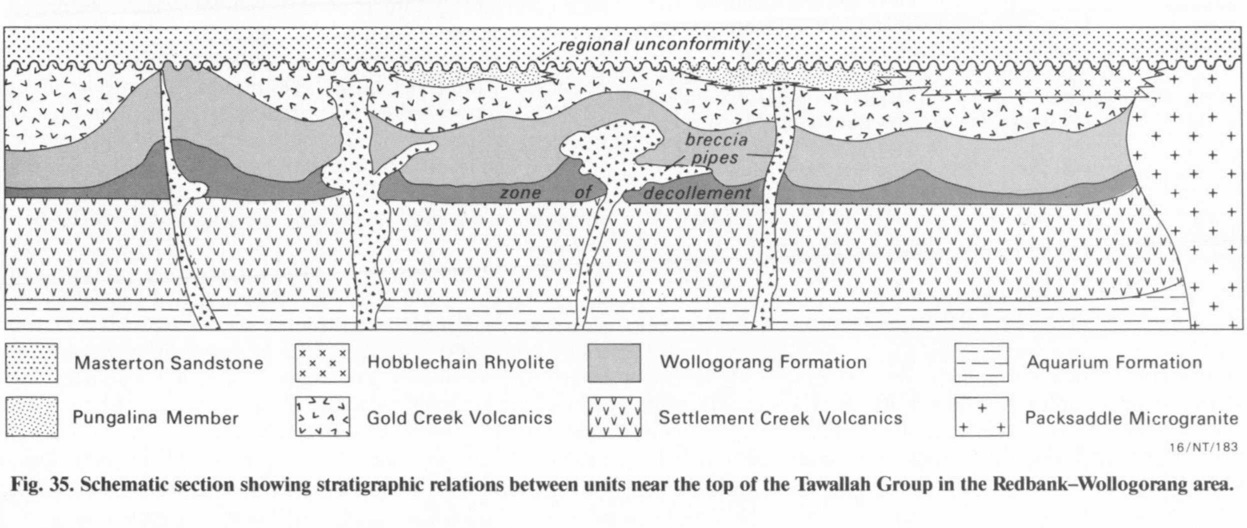

Fig. 35. Schematic section showing stratigraphic relations between units near the top of the Tawallah Group in the Redbank–Wollogorang area.

Reference sections

Roberts (unpublished) nominated the area 16–20 km southwest of Redbank mine as the reference area. A section measured by J.M. Rhodes (*in* Roberts, unpublished) from this area, and a summary of the subdivision of the unit based on the drilling from Redbank (Orridge & Mason, 1975), are nominated as reference sections (Tables 4 and 5).

TABLE 4. REFERENCE SECTION OF THE GOLD CREEK VOLCANICS
(18.5 km southwest of Redbank mine)
measured by J. M. Rhodes (*in* Roberts, unpublished)

Masterton Sandstone

1.2 m	Siltstone, red-brown, hard, vesicular appearance
18 m	Sandstone, red-brown, fine-grained; tuffaceous siltstone, agglomerate
13 m	rubble
11 m	Aphanitic volcanics, yellow-brown, weathered, pale green amygdales and fine-grained sandstone xenoliths
1 m	Tuffaceous siltstone, red-brown
6 m	Amygdaloidal volcanic flow, red-brown, aphanitic
0.6 m	Tuffaceous sandstone, red-brown, fine-grained
6 m	Aphanitic volcanic flow, yellow-brown, part amygdaloidal
74 m	Poor outcrop, agglomerate near base passing upward into volcanic and tuffaceous siltstone rubble

Wollogorang Formation

TABLE 5. REFERENCE SECTION OF THE GOLD CREEK VOLCANICS
(Redbank mine area; after Orridge & Mason, 1975)

Masterton Sandstone

Pungalina Member (60 m thick)	Transition sandstone	Medium to coarse-grained thinly bedded feldspathic or kaolinitic quartz sandstone
	Lithic sandstone	Poorly sorted ripple-marked flagstone with abundant volcanic fragments
	Quartz-rich lithic sandstone	Massive, locally conglomeratic quartz sandstone with abundant volcanic fragments
	Breccia-conglomerate	Subangular to rounded cobbles of trachyte and rhyolite in lithic sandstone matrix
Middle and lower parts of Gold Creek Volcanics (about 165 m thick)	Middle and lower units locally recognised with intervening lithic sandstone and dolomitic tuff horizon	Trachyte and trachyandesite lavas and lava-mud breccia flows interbedded with thin lithic sandstone and dolomitic tuff layers. Lavas are fine-grained and commonly porphyritic. Magnetite and hematite present in some trachyandesites. Flow tops are commonly intensely vesicular, and locally brecciated, pillowed, and silicified

Wollogorang Formation

The Gold Creek Volcanics have been extensively drilled during copper exploration in the Redbank mine area over the past 20 years. The core material from this drilling is stored at Redbank, and was still available for examination in 1982 at the Redbank mine.

Stratigraphic relations

The Gold Creek Volcanics conformably overlie the Wollogorang Formation, and we consider that they are unconformably overlain by the Masterton Sandstone. However, based on more recent (1983) detailed mapping in CALVERT HILLS, M. Ahmad (Northern Territory Geological Survey, personal communication 1.7.84) interprets a conformable contact between the two formations in the southeast of the basin. The Gold Creek Volcanics are intruded by mineralised breccia pipes that contain subeconomic copper at Redbank, and by the Packsaddle Microgranite near Wollogorang homestead.

Lithology

The Gold Creek Volcanics are characterised by a wide variety of basic to intermediate igneous rocks and interbedded volcaniclastics, including trachyte or trachyandesite lava, agglomerate, tuff, dolerite, microsyenite, and tuffaceous and lithic sandstone and siltstone. Leached and reddened vesicular and amygdaloidal varieties of lavas are common, but porphyritic and aphanitic flows are also present. Knutson & others (1979) described the trachytes as consisting of mainly feldspar laths set in a groundmass of cryptocrystalline K-feldspar, chlorite, and chert. Some specimens have undergone various degrees of chloritisation, and others show extreme hematite staining. Amygdales contain one or more of the following: dolomite, hematite, chlorite, celadonite, quartz, pyrobitumen, chalcopyrite, pyrite, marcasite, and, more rarely, covellite and sphalerite. The Gold Creek Volcanics show marked differences in composition resulting from extreme alteration of the original rocks, especially by fluids enriched in Fe, Mg, K, and possibly Al (Knutson & others, 1979).

The copper-bearing volcanic breccia pipes of the Redbank area intrude the Gold Creek Volcanics and underlying formations. They are not known to intrude the overlying Masterton Sandstone, so are here interpreted as a late magmatic phase of the Gold Creek Volcanics. There are over fifty pipes, whose locations are apparently controlled by a series of easterly and northeasterly trending lineaments (Orridge & Mason, 1975; Rod 1978). Copper approaching economic grade has been identified in two of the pipes. Knutson & others (1979) have presented detailed information on the petrology, mineralogy, and elemental and stable isotope geochemistry of the pipes (and some adjacent units) which is not repeated here.

In the Calvert Hills area (50 km west of Redbank) the Gold Creek Volcanics comprise over 100 m of saussuritised and uralitised basic to intermediate lavas with thin interbeds of acid flows and agglomerates; a rhyolite breccia is interpreted as the location of a possible volcanic vent (Australian Geophysical Pty Ltd, 1967). According to Australian Geophysical Pty Ltd (1967, p.14) these igneous rocks overlie about 70–80 m of cross-bedded and ripple-marked ferruginous and quartzitic sandstone, which they have assigned to the Gold Creek Volcanics (not to the underlying Wollogorang Formation); so, according to this interpretation, a period of clastic sedimentation is indicated for the lower part of the formation in this area.

In the Mallapunyah Dome, detailed mapping by Australian Geophysical Pty Ltd (1968) has shown that the Gold Creek Volcanics consist of at least four lenticular extrusive bodies, each about 1000 m long and up to about 50 m thick, and three intrusive bodies. The extrusives, mainly trachytes, are similar in composition and texture to those at Redbank—agglomerate, tuff, and trachyte lava predominating. Fragments of the underlying stratigraphic units (e.g., Settlement Creek Volcanics and Wollogorang Formation), ranging in size from clasts only centimetres across up to blocks several metres across, have been ejected with the trachytes.

The intrusives in the Mallapunyah Dome are of highly altered microsyenite containing a high proportion of carbonate. They are lithologically similar to the breccia pipes near Redbank, have equivalent intrusive relationships, and presumably a similar genesis. Our recent mapping also identified similar intrusive rocks in the southern part of the Batten Range, where grey to black deeply weathered and altered highly potassic intrusive rocks have brecciated and hornfelsed laminated shales of the Wollogorang Formation. Large pods and veins of barite and hematite are present within the intrusion. As in the Redbank area the intrusion does not penetrate the overlying Masterton Sandstone, which here has a thick cobble bed overlying the unconformity cut into the Wollogorang Formation.

Origin

The Gold Creek Volcanics represent a widespread phase of intermediate igneous activity with concomitant sedimentation. A complex igneous history is indicated. Extrusive igneous activity ranged from repeated quiet eruption of lava flows through to explosive eruption of agglomerates and tuffs. Forceful emplacement accompanied by stoping of country rocks is evident in several intrusions, which include the copper-bearing breccia pipes near Redbank. Knutson & others (1979) concluded that the breccia pipes formed by explosive release of fluids following the build-up of pressure in a carbonated, potassium-rich trachytic magma at depths of roughly 2 to 3 km beneath the surface. This was accompanied by intense metasomatism, and precipitation of carbonate and sulphide minerals, which partly infilled the open spaces. They also suggested that the thermal gradients and fracturing caused extensive circulation of connate brine (and possibly descending sea water) which remobilised sedimentary and magmatic hydrothermal components in and around the pipes; copper in the Redbank area precipitated mainly from the brine.

The associated sediments are varied in lithology, but commonly show a volcanic imprint. Most of them were probably laid down in shallow-water terrestrial environments, but the thicker sections of more mature sediments—for example, those noted at Calvert Hills by Australian Geophysical Pty Ltd (1967), if not part of the Wollogorang Formation—could be marine deposits.

PUNGALINA MEMBER (of the Gold Creek Volcanics)

Yates (1963) and Roberts (unpublished) used the term Pungalina Member (of the Masterton Formation) for a distinctive arenaceous unit overlying the Gold Creek Volcanics in ROBINSON RIVER. Rod (1978) used the name 'Pungalina beds' for this unit, which he noted was also widespread in southeast CALVERT HILLS. Unfortunately, he provided no further details, and, in the light of recent developments in the stratigraphic code as to the use of the term 'beds', we prefer to define the unit as the Pungalina Member of the Gold Creek Volcanics.

Distribution and thickness

The Pungalina Member crops out between Seven Emus homestead (central ROBINSON RIVER) and the northeastern part of CALVERT HILLS. It is probably up to about 40 m thick in the reference area (see below), but owing to poor outcrop little information is available on thickness variations. In the Redbank area, Orridge & Mason (1975) showed the Gold Creek Volcanics as comprising a section 60 m thick of conglomerate and sandstone overlying mainly volcanic rocks (Table 5); the upper, sedimentary rocks are here interpreted as the Pungalina Member.

Stratigraphic relations

Because the Pungalina Member is poorly exposed and has not been studied in detail, its stratigraphic relations are not well known, but it interfingers with volcanic rocks of the Gold Creek Volcanics and is overlain by the Masterton Sandstone. According to Roberts (unpublished), the Pungalina Member in the Hobblechain Creek area (Fig. 7) appears to occupy the same stratigraphic interval as the Hobblechain Rhyolite. Rod (1977), who carried out detailed mapping in the Settlement Creek area, considered the rocks of the Pungalina Member to be erosional derivatives of the Gold Creek Volcanics and Hobblechain Rhyolite, which confirms Roberts's stratigraphic interpretations.

Reference area

As we have not studied this unit in detail, nor measured a type section, we follow Roberts (unpublished) and nominate the upper reaches of the Hobblechain Creek (southeast ROBINSON RIVER) as the reference area.

Lithology

In outcrops in southeastern ROBINSON RIVER, the Pungalina Member consists of thin-bedded flaggy pale reddish brown (10R 5/4) fine-grained sandstone and siltstone. Some parts are slightly micaceous, and other parts are coarser-grained and conglomeratic. In this area, sedimentary structures are common and visually striking; they include flute casts, load casts, wrinkled surfaces, desiccation cracks, and halite casts and moulds. In contrast, in the Redbank mine area (Table 5), poorly sorted conglomerate and quartz and lithic sandstone containing abundant volcanic material predominate. At Redbank mine, well exposed slabs of poorly sorted sandstone with planed-off current ripples show evidence of having been showered with volcanic debris: current crescents and streaming lineation originating from where these volcanic bombs settled on the sediment indicate ejection of the material on to soft unconsolidated sands (Fig. 36).

Environment of deposition

Detailed sedimentological studies on this unit have not been carried out, but the rock types and structures noted above, and the close relationship between this unit and the subaerially extruded volcanics, indicate that a fairly complex and variable terrestrial depositional setting is most likely. The desiccation cracks, planed-off ripples, volcanic bombs, etc., indicate episodes of very shallow to emergent conditions.

HOBBLECHAIN RHYOLITE

The name Hobblechain Rhyolite has been previously published by several authors—including Yates (1963), Roberts & others (1963), and Knutson & others (1979)—without adequate definition. Although we have not studied the unit, a formal definition based on Roberts (unpublished) is presented here. Roberts (unpublished) originally proposed that the Hobblechain Rhyolite be regarded as a member of

Fig. 36. Exhumed rippled bedding plane of fine-grained quartz sandstone in the Pungalina Member of the Gold Creek Volcanics at Redbank mine. The surface contains small bombs of volcanic ejecta which have produced current crescents. The current flowed from the top right. Note the bombs eroded off the higher parts of the stoss side of the ripples. (BMR negative GB 3001)

the 'Masterton Formation', but owing to our modifications to the latter term the Hobblechain Rhyolite is here accorded formation status. The name is derived from Hobblechain Creek, a small ephemeral creek draining towards the Gulf of Carpentaria across the southeastern corner of ROBINSON RIVER (Fig. 7).

Distribution and thickness

The Hobblechain Rhyolite is exposed over a total area of about 200 km^2 in the extreme southeastern part of ROBINSON RIVER, and north of Wollogorang homestead in CALVERT HILLS. The formation is thickest (around 60–70 m) in its southernmost outcrops, and it appears to thin northward and westward from here and gradually wedge out.

Reference area

Roberts (unpublished) nominated the headwaters of Collar Creek (lat. 16°55′S, long. 137°51′E) in southeastern ROBINSON RIVER as the reference area.

Stratigraphic relations

The Hobblechain Rhyolite appears to overlie the Gold Creek Volcanics conformably, and is unconformably overlain by the Masterton Sandstone. Roberts (unpublished) suggested that the Hobblechain Rhyolite and Pungalina Member of the Gold Creek Volcanics occupy the same stratigraphic position. The Hobblechain Rhyolite and Packsaddle Microgranite are thought to be comagmatic.

Lithology

The Hobblechain Rhyolite consists mainly of reddish brown or pink-weathering fine-grained porphyritic rhyolite with phenocrysts of quartz and K-feldspar, and cobble conglomerates of reworked porphyry. The rock is partly altered to clay minerals and hydrated iron oxide. Roberts & others (1963) noted that flow banding occurs locally. Knutson & others (1979) commented that prominent spherulitic textures of radiating feldspar prisms in the Hobblechain Rhyolite distinguish it from the Packsaddle Microgranite.

Interpretation and regional correlation

The Hobblechain Rhyolite appears to be mainly a series of extrusive acid lava flows, originating from a feeder system represented by the Packsaddle Microgranite, that was emplaced later than the bulk of the more basic Gold Creek Volcanics. Grimes & Sweet (1979) noted similarities between this rhyolite and acid members of the much thicker Peters Creek Volcanics, which were extruded on to the Lawn Hill Platform—south of the Murphy Tectonic Ridge. Samples from the Hobblechain Rhyolite and Packsaddle Microgranite have yielded a minimum Rb–Sr age of 1575 $\pm$ 120 Ma. In the light of the more recent U–Pb zircon age of 1690^{+29}_{-25} Ma for tuffs from the Barney Creek Formation (3000–4000 m higher up in the McArthur Basin sequence), this Rb–Sr age seems to be too young.

PACKSADDLE MICROGRANITE

The Packsaddle Microgranite has been described by several authors as the intrusive equivalent of the Hobblechain Rhyolite (Roberts & others, 1963; Rod, 1977; Knutson & others, 1979). Although there does not appear to be much petrological, textural, or chemical difference between the two units, the Packsaddle Microgranite is coarser-grained and has a very distinctive surface joint pattern which allows it to be readily identified on airphotos and in the field, so it can be considered a mappable unit. Although we have not studied the unit in any detail, we present here a formal definition based on information from previously published and unpublished reports. The name is derived from Packsaddle Waterhole, which is 15 km north-northeast of Wollogorang homestead—within the main area of outcrop of the Packsaddle Microgranite.

Distribution

The Packsaddle Microgranite is exposed in a northwesterly trending belt of rugged outcrops over a total area of about 70 km^2 in the northeast corner of CALVERT HILLS (Roberts & others, 1963). Its subsurface extent and the attitude of its contacts with the surrounding country rocks are not well known.

Reference area

The headwaters of Rocky Creek (lat. 17°03′S, long. 137°54′30″E), in the northeast corner of CALVERT HILLS, are here nominated as the reference area. At this locality, a steep gorge that Rocky Creek has eroded through the Packsaddle Microgranite provides good outcrops of the intrusion and its contact relations with the Wollogorang Formation and Gold Creek Volcanics.

Stratigraphic relations

As noted above, the Packsaddle Microgranite and Hobblechain Rhyolite grade laterally into one another and are considered comagmatic (Roberts & others, 1963; Sweet

& Slater, 1975; Rod, 1977). In Rocky Creek the microgranite intrudes both the Wollogorang Formation, where it has produced a thin (1-2 m wide) contact aureole of baked siltstone, and the Gold Creek Volcanics, which likewise are altered at the contact. Roberts & others (1963) observed that the Packsaddle Microgranite has domed the Gold Creek Volcanics, which dip radially from the contact at angles of up to 20°.

Lithology

The Packsaddle Microgranite is an intensely hematitised porphyritic microgranite with graphic texture and minor spherulites. Phenocrysts of K-feldspar and quartz total about 15 per cent. As with other igneous rocks in the Redbank-Wollogorang area, Knutson & others (1979) have noted that the Packsaddle and Hobblechain rocks are depleted in Na_2O and CaO, and enriched in K_2O and iron, relative to values for average granite.

McARTHUR GROUP

The McArthur Group overlies the Tawallah Group unconformably throughout most if not all the area, but possibly conformably in the southeast (M. Ahmad, personal communication, 1983). It comprises a sequence of interbedded carbonates and lutites with subordinate sandstones up to about 4000 m thick. It is divided into two subgroups—the Umbolooga Subgroup and the overlying Batten Subgroup (Fig. 4).

Other formations in Arnhem Land—The Bath Range Formation, Baiguridgi Formation, Yarrawirrie Formation, Zamia Creek Siltstone, Conway Formation, Vaughton Siltstone, Strawbridge Breccia, Koolatong Siltstone, Fleming Sandstone, Blue Mud Bay beds, and Vizard Formation—are defined constituents of the McArthur Group, but are not described in this Bulletin.

Units which were previously included in the upper part of the McArthur Group by Plumb & Brown (1973)—the Balbirini Dolomite, Dungaminnie Formation, Smythe Sandstone, Stott Formation, Mount Birch Sandstone, and Kookaburra Creek Formation—are now separated from the McArthur Group, and herein redefined as a new group—the Nathan Group.

Age

The McArthur Group is between about 1600 and 1700 Ma old. The best direct estimate is a U-Pb zircon age of 1690^{+29}_{-25} Ma (Page, 1981) for tuff beds within the HYC Pyritic Shale Member (Barney Creek Formation), which is roughly in the middle of the group. This compares with minimum diagenetic ages of 1537 ± 52 Ma (illite) and 1589 ± 14 Ma (feldspar) from Rb-Sr isochrons of samples from the same formation (Kralik, 1982). The U-Pb age range is the preferable estimate, because tuffs from the equivalent Mount Isa Group (to the southeast, in the Mount Isa Inlier) yield an indistinguishable U-Pb zircon age of 1670^{+20}_{-17} (Page, 1981). These tuffs unconformably overlie the 1678 ± 1 Ma Carters Bore Rhyolite (Page, 1983). The only direct younger limit to the age of the group is Kralik's (1982) 1430 Ma age for the top of the overlying Roper Group, and this is a minimum age. A more reasonable constraint may be derived from regional correlation with the long-lived 1620-1490 Ma period of superimposed metamorphism and folding which postdates the equivalent Mount Isa Group (Page, 1978; Plumb & others, 1980). Perhaps Kralik's 1537 Ma and 1589 Ma isochrons of samples from the Barney Creek Formation reflect this metamorphic event and provide a valid upper age limit for the group.

UMBOLOOGA SUBGROUP

Plumb & Brown (1973) demonstrated that the early interpretation of stratigraphic relations in the McArthur Group (Plumb & Paine, 1964; Plumb & Rhodes, 1964; Smith, 1964) was wrong. Their interpretation involved discarding the old 'Bauhinia Downs Subgroup' and replacing it with a new and larger Umbolooga Subgroup, to encompass all the conformable units in the McArthur Group below the Batten Subgroup. Plumb & Brown's usage is retained here, but we have incorporated into the Umbolooga Subgroup the Masterton Sandstone.

The name Umbolooga Subgroup is derived from Umbolooga Creek, which joins Tooganinie Creek at latitute 16°48'S and longitude 135°29'E adjacent to some of the best exposures through the subgroup in BAUHINIA DOWNS.

The Umbolooga Subgroup is between about 2000 and 3300 m thick, and is well exposed throughout northern WALLHALLOW, BAUHINIA DOWNS, and southern MOUNT YOUNG. It is overlain by the Batten Subgroup with apparent conformity within the central Batten Trough, but an unconformity is widespread beneath the Batten Subgroup adjacent to, and across, the marginal faults of the trough. In WALLHALLOW and western MOUNT YOUNG, and locally in the Tooganinie Creek area of southwestern BAUHINIA DOWNS, the Umbolooga Subgroup is overlain unconformably by the Nathan Group. In the Lansen Creek and Emmerugga Creek areas of western and southwestern BAUHINIA DOWNS respectively, the Roper Group rests with regional unconformity on the Umbolooga Subgroup. The stratigraphic relationship between Umbolooga Subgroup rocks in the Foelsche Inlier of southeastern BAUHINIA DOWNS and younger units of the McArthur or Nathan Groups is concealed by the cover of Cambrian Bukalara Sandstone.

MASTERTON SANDSTONE

The upper sandy part of the former 'Masterton Formation' is here redefined as the Masterton Sandstone (see p.00), and the term 'Masterton Formation' is abandoned. The Masterton Sandstone is a widespread resistant sandstone unit with intercalated volcanics in the west (Tanumbirini Volcanic Member). It unconformably overlies various formations of the Tawallah Group, and now forms the basal unit of the McArthur Group. The detailed studies that were undertaken to clarify the stratigraphic setting of the Masterton Sandstone have also provided useful data for more detailed sedimentological interpretations (Jackson, 1981c) which are summarised here.

The name is derived from Masterton Cave, at the Redbank mine, where the unit forms a prominent escarpment.

In previous reports (e.g., Smith, 1964; Plumb & Paine, 1964) the term 'Mulholland Sandstone' was introduced, but never formally defined, for a unit of flaggy sandstone near the top of the 'Masterton Formation' in the southern and western parts of the Tawallah Ranges and in the Batten Range. The 'Mulholland Sandstone' as mapped in BAUHINIA DOWNS and MOUNT YOUNG is in fact the complete section of the Masterton Sandstone, so the term 'Mulholland Sandstone' is abandoned.

The Masterton Sandstone contains a number of distinctive facies in different parts of the basin, but none of these, except for the Tanumbirini Volcanic Member, warrant consideration as separate stratigraphic units.

Distribution and thickness

The Masterton Sandstone is widespread throughout the area mapped and, as it is resistant to erosion, it forms prominent outcrops in many areas. It crops out in the extreme southeast of the area (along the Settlement Creek valley), in the far northeast (in the Sir Edward Pellew Islands), in the extreme west (Tanumbirini district), in the far northwest (Roper River area), and extensively in the more central Batten Trough and Wearyan Shelf areas (inset, Plate 1).

The unit shows more obvious thickness variations, on both a local and regional scale, than the overlying parts of the Umbolooga Subgroup between the Mallapunyah Formation and Emmerugga Dolomite. Facies differences commonly accompany the thickness variations. In the south around the Mallapunyah Dome the formation ranges from about 50 to 150 m thick. Farther north, in the Batten Range, it is 340 m thick, but 40 km due east of there (in the Masterton Horst) it is only about 40 m thick. In the faulted inlier of the Sawtooth Range (northeast *Batten*) it is 650 m thick, but only 20 km southwest of there (in the Tawallah Ranges), it is only about one-sixth of this thickness. In the far west of the area (Tanumbirini) locally derived volcanics cause abrupt thickness variations, but the formation is probably up to 500 m thick.

Type section

It is difficult to assign a stratotype to a unit showing such marked lateral variation, but an easily accessible section in Archies Creek in the Mallapunyah Dome is typical of the fine-grained thinner sections preserved in the south, and is here nominated as the type section. It is measured section Kilgour 78/01 (Fig. 37) measured from GR 954103 to 957102 (Plate 1), immediately underlying the type section of the Mallapunyah Formation.

Stratigraphic relations

The unconformable contact between the Masterton Sandstone and underlying units is clearly exposed in the Batten Range, Redbank area, and Masterton Horst. At the southwest end of the Batten Range the Masterton Sandstone oversteps progressively the Gold Creek Volcanics, Wollogorang Formation, and Wununmantyala Sandstone. In Camp Creek (20 km southwest of Redbank), the basal unconformity truncates gently folded Wollogorang Formation, and, in the Masterton Horst, Walker & others (1977) have described the Gold Creek Volcanics as having been iregularly eroded before the Masterton Sandstone accumulated. In most other areas, such clear evidence of angular discordance is not apparent, so that the relationship appears to be structurally conformable.

At most localities where the upper part of the Masterton Sandstone has not been removed by later erosion it has a gradational conformable contact with the Mallapunyah Formation. As described later a distinctive chertified stromatolite bed forms a good marker that defines the contact. East and southeast of the Bukalara Plateau, in the Foelsche River–Robinson River–Calvert River area, the Masterton Sandstone is unconformably overlain by the Karns Dolomite.

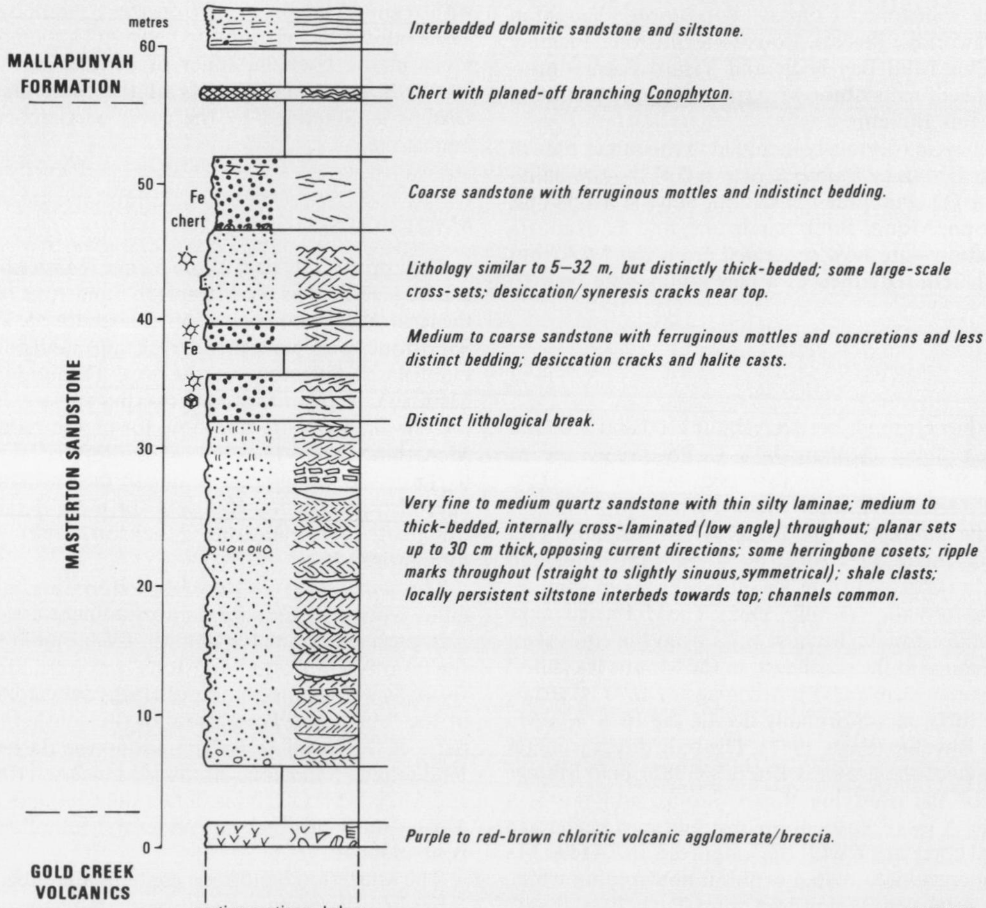

Fig. 37. Type section of the Masterton Sandstone (measured section Kilgour 78/01), in Archies Creek.

Lithology

Mallapunyah Dome (type section)

At the type section (Fig. 37) the Masterton Sandstone comprises 55 m of quartz sandstone with minor siltstone. The section coarsens upward from very fine-grained quartz wackes to coarse-grained siliceous, ferruginous, and dolomitic sandstone at the top. The basal contact is not exposed at the type section, but at a locality several hundred metres to the southwest a thin pebbly sandstone marks the unconformity.

The lower half of the formation consists of very fine to medium-grained red-brown quartz sandstone which is commonly surface-silicified. Thin-section studies indicate that the sandstone has a lithology ranging from quartz arenite through lithic arenite to lithic wacke (Fig. 38). The sandstone is less mature and not as well sorted as the arenites in the Tawallah Group, nor does it contain such well rounded quartz grains. The presence of a silty matrix indicates much less winnowing than most of the older arenites.

Although the surface silicification commonly imparts a massive texture to the sandstone, careful examination shows that most of this lower 30–40 m is internally cross-laminated or rippled. Planar cross-stratification dominates in sets up to about 30 cm thick, but decimetre-scale herringbone cross-bedding is present between 25 and 28 m. Isolated trough sets 10–40 cm thick containing purple siltstone clasts as lags along lower bounding surfaces are also present. Gently curved bedding surfaces at a number of levels are interpreted as possible shallow channels.

Rippled bedding surfaces are very common. Symmetrical, straight to slightly sinuous ripples commonly 0.5–1 cm high and 1–5 cm apart are dominant, but bedding slabs with planed-off ripples, linguoid ripples, and rhombohedral (boxwork) ripples are also present. Ripple orientation varies considerably. Measurement of over 50 ripple orientations gave three principal orientations (around 020°, 100°, and 150°). Purple siltstone–shale drapes are present in the troughs on several rippled slabs, and in two of these the presence of mud-cracks indicates intermittent emergence. Towards the top of the lower half of the formation (i.e., near 30 m) discontinuous wedges of desiccated purple siltstone 10–20 cm thick and 0.5–1.50 m wide are present amongst Nu-cross-stratified cosets, which are separated by thin (4–8 cm) rippled intervals.

The upper part of the formation contains coarse-grained sandstone, which in places is distinctly ferruginous and siliceous. Cross-bedding and ripples are generally larger, desiccation features are more common, and halite casts (cubes and skeletal hoppers) are present. The sandstone is commonly vuggy, pitted, spotted, or irregularly mottled (Figs. 39 and 40), and shows other evidence of secondary movement of siliceous and ferruginous solutions, such as crystal-lined cavities and veins and small pods of chert. Large-scale subtle thickness variations (Fig. 41) suggest the presence of large-scale channel features or an environment with significant variation in the relief of the depositional surface.

From about 50 m upwards, exposure deteriorates, but the coarse sandstone passes up into dolomitic sandstone and siltstone with chertified stromatolites. Desiccation cracks, discontinuous granular sand wedges, eroded ripples, and very irregular and intense ferruginous mottling are characteristic of this Masterton Sandstone–Mallapunyah Formation transition zone; they indicate very shallow conditions with emergence during deposition, and that the contact zone has been one of post-lithification fluid movement.

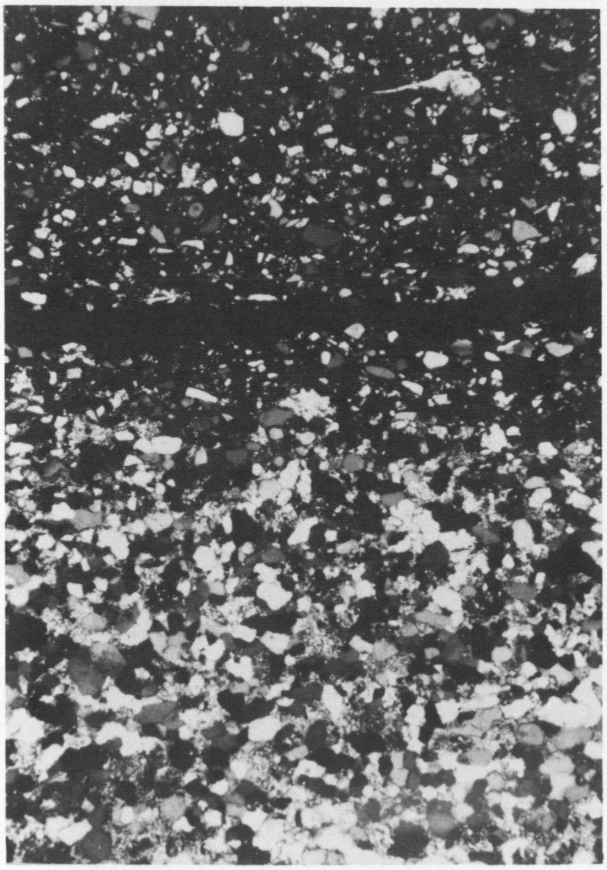

Fig. 38. Thin section viewed through crossed nicols of poorly sorted quartz sandstone in the Masterton Sandstone (TS 81100027C) in the type section at Archies Creek. The lower half of the thin section shows quartz wacke with subangular to rounded grains of quartz in a silt matrix (fine, speckled grey patches). The top half of the thin section is a ferruginous micaceous silty sandstone. The black band is a gap in the slide. Quartz overgrowths are present, and show that the original shapes of quartz grains varied from rounded to subangular. The large elongated shard in the top right is mica. The width of the field of view is 4.5 mm.

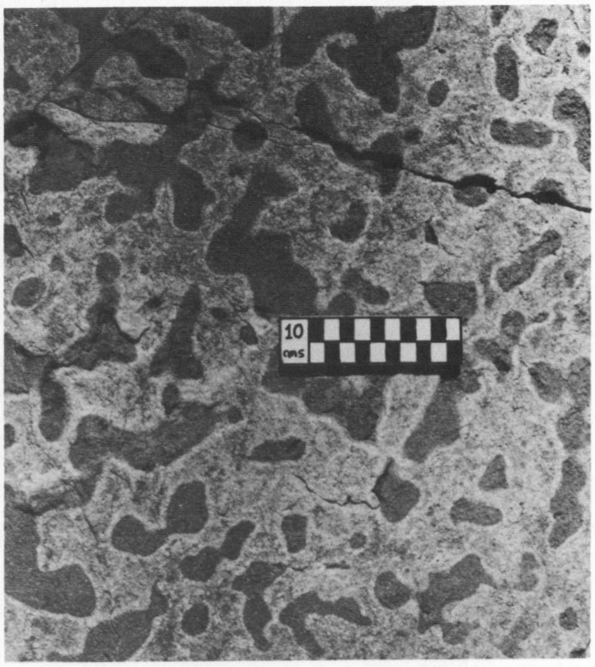

Fig. 39. Bedding-plane surface of the Masterton Sandstone with irregular ferruginous mottles, each rimmed by a bleached margin, at 39 m in the type section. (BMR negative M2572/6)

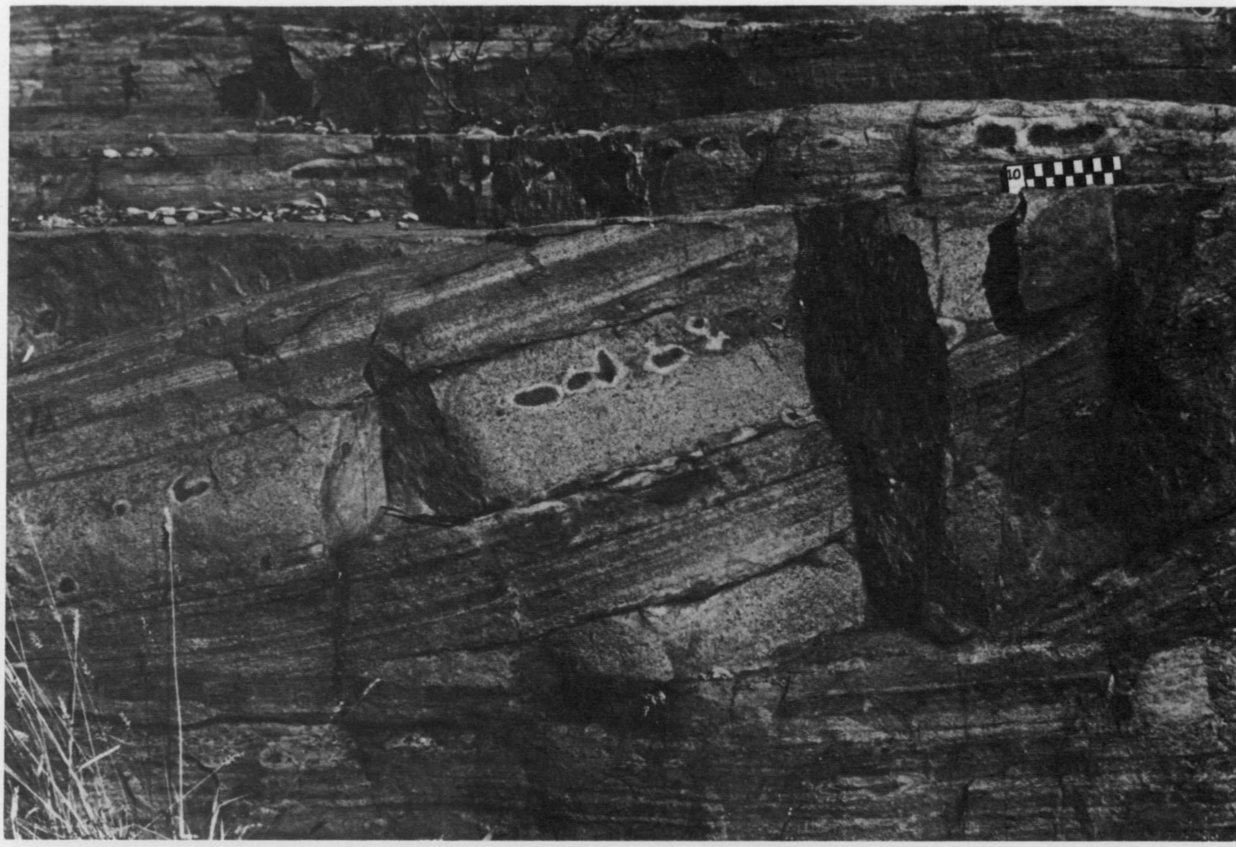

Fig. 40. Large-scale (45 cm+) solitary set of cross-bedded sandstone with planar upper and lower contacts in the Masterton Sandstone at 48 m in the type section. Note the asymptotic relationship of foresets to the lower bounding surface; and the ferruginous mottles along the bedding, both in the large set and in the overlying flat-laminated set, indicating post-lithification groundwater movement through the formation. (BMR negative No. 2572/9)

Fig. 41. Cliff face of most of the 50 m of the Masterton Sandstone exposed at the type section, showing large-scale thickening of cosets in the upper part of the formation. Depite the perspective effect, the unit at AA is about 3 m thicker than it is at BB. (BMR negative M2572/13)

Kiana

A similar section 75 m thick is present at the northern end of the Kiana Dome (9 km east of the type section), but it has some subtle differences. Trough-cross-sets up to 30 cm thick with siltstone clasts on foresets are much more common, and indicate the presence of large linguoid dune forms which are not apparent in the type section. Palaeocurrent measurements are again variable, and indicate currents to the west, northwest, and east.

Halite moulds and casts are much more obvious in this section, and were found on the undersides of many beds, especially in the lower half of the formation. In addition to hopper cubes, skeletal and pagoda forms, interpreted by Southgate (1982) to indicate precipitation in brine pools, are also present. The presence of streaming lineation behind one halite cast suggests that at least some of the salt was deposited in moving water (on the floor of a supersaturated brine pool?), though some may have grown diagenetically from saline brines in uncompacted sediment. Thin desiccated laminae of purple siltstone (i.e., the material that forms the intraclasts on foresets) are present on some of the parting planes crowded with halite casts, suggesting that these silty beds were formed from suspension sedimentation in the brine pools. In the middle of the section these thinner-bedded halite-rich units alternate with thick trough-cross-stratified sets (10–40 cm thick) with erosional lower bounding surfaces. Deposition of large bedforms (sandwaves up to a metre high) alternating with deposition in ?supratidal brine pools is therefore indicated.

As at the type section the upper part of the formation is distinctly coarser-grained (Fig. 42). It is also friable and contains numerous weathered-out shale clasts. A bedding plane about 10 m below the top of the formation also contains irregularly dispersed enigmatic conical structures, probably produced by dewatering, which occur over an area of several hundred square metres (Figs. 43 and 44).

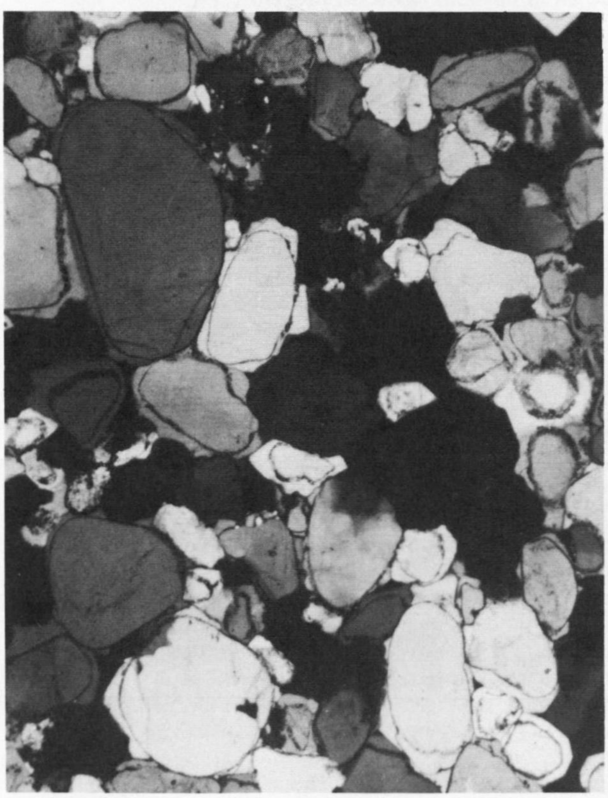

Fig. 42. Thin section seen through crossed nicols of coarse-grained well rounded quartz arenite near the top of the Masterton Sandstone (TS 81100026D) at Kiana Dome. Well developed quartz overgrowths in optical continuity with the original grains are clearly defined by dust rims of hematite. The largest grain in the top left is 1 mm long.

Calvert Hills area

The Masterton Sandstone is well exposed near Calvert Hills homestead and farther north along the Calvert River, both 150 km east of the type section. Unfortunately, complete sections are not available as the unit is folded and faulted near Calvert Hills homestead and almost flat-lying north of here.

Near Calvert Hills homestead the formation resembles that described in the type section, although Australian Geophysical Pty Ltd (1967) noted in addition the presence of small lenses of conglomerate composed of pebbles and cobbles of white quartzite and quartz. It also described glauconitic quartzite 'developed locally' but we did not see it.

The outcrops along the Calvert River comprise friable, well sorted, well rounded quartz arenite containing very large-scale cross-sets unlike any seen elsewhere (Figs. 45, 46). Near where the Borroloola–Burketown road crosses the Calvert River the large-scale cross-bedding is of Allen's gamma type (i.e., solitary sets bounded underneath by an erosion surface); dominant palaeocurrent directions are to the north. At the Bluey Creek locality, 23 km to the southwest (Fig. 46), the large-scale cross-bedding contains numerous second-order bounding surfaces (see, Brookfield, 1977). In plan the cross-bedding is gently curved, indicating very large-scale trough sets. Palaeocurrents were mainly to the north and northeast with a secondary mode to the southeast. Low-amplitude long-wavelength ripples with reverse grading are preserved in some of the megasets.

Central localities

In the Batten Range and Masterton Horst, the Masterton Sandstone consists of rock types and structures similar to

Fig. 43. Side view of conical structures (probably a dewatering feature) in coarse-grained cross-stratified sandstone in the upper part of the Masterton Sandstone at Kiana Dome. The two cones in the centre of the photograph are well defined and intact; note the outline of another cone structure (3 cm from left-hand edge of photograph) which cuts through the cross-lamination enhanced by weathering. (BMR negative GB 2752)

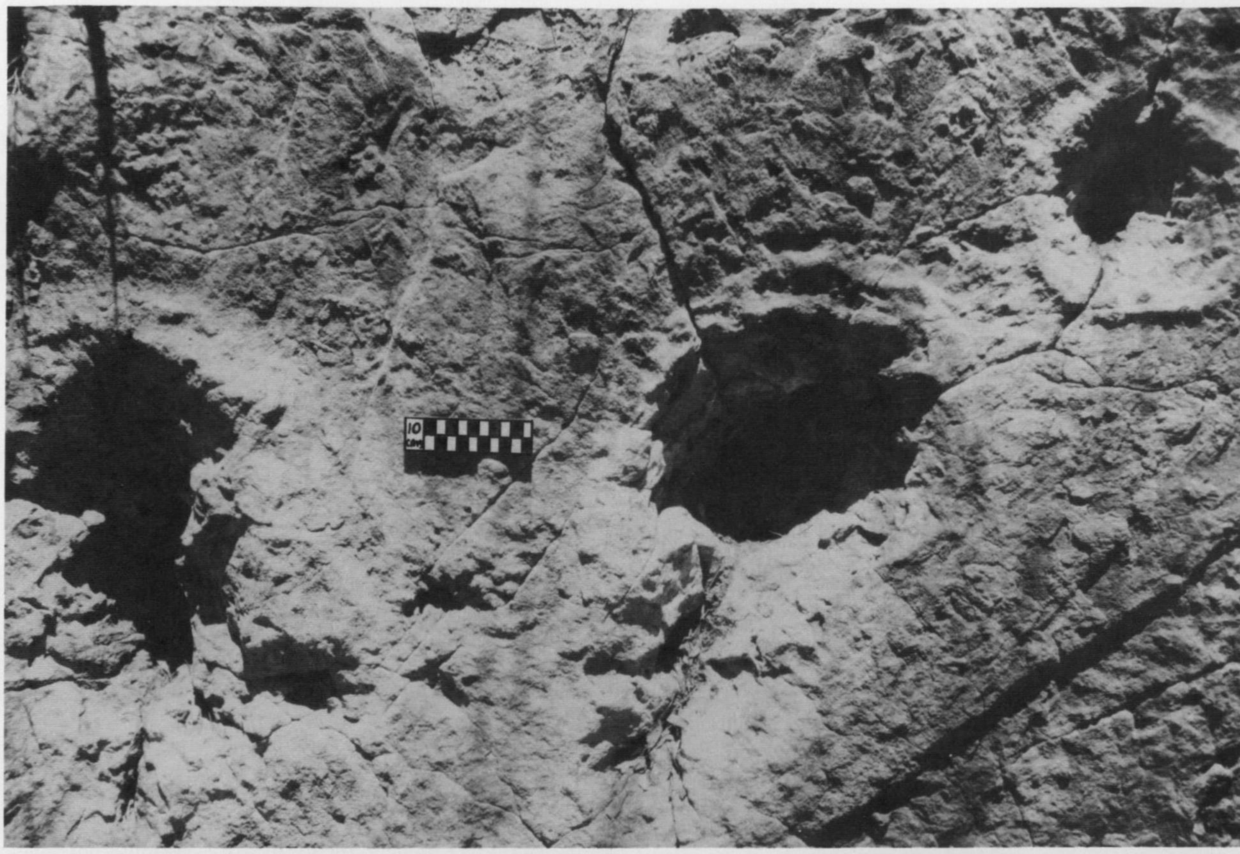

Fig. 44. Top view of weathered-out cone structures on an exhumed horizontal bedding plane in the Masterton Sandstone at Kiana Dome. Note the slightly raised 'rim' of the cone in the top right; the irregular shallow protuberance (bleached white) from the cone to the right of the scale; and the polygonal double cone to the left of the scale. (BMR negative GB 2749)

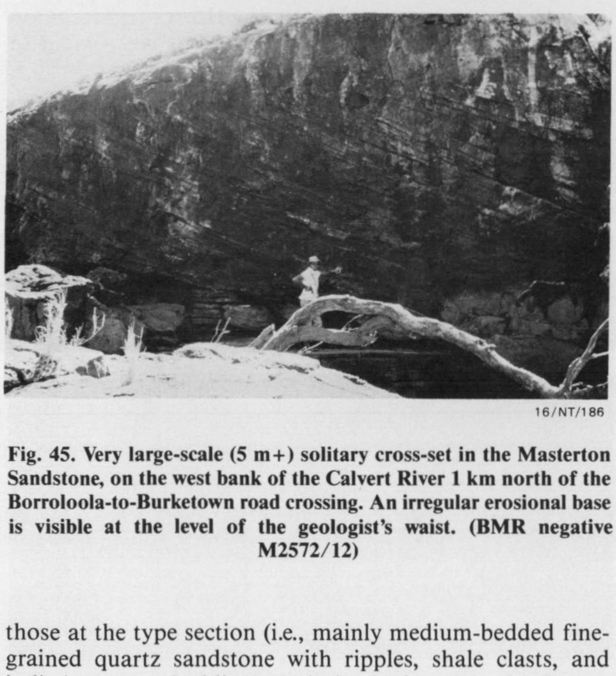

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Fig. 45. Very large-scale (5 m+) solitary cross-set in the Masterton Sandstone, on the west bank of the Calvert River 1 km north of the Borroloola-to-Burketown road crossing. An irregular erosional base is visible at the level of the geologist's waist. (BMR negative M2572/12)

those at the type section (i.e., mainly medium-bedded fine-grained quartz sandstone with ripples, shale clasts, and indistinct cross-bedding). It is intriguing that the Batten Range section is nine times thicker than that in the Masterton Horst (340 m cf. 40 m), yet the lithologies are almost identical. At both localities, the Masterton Sandstone unconformably overlies the Gold Creek Volcanics, but at the southwest end of the Batten Range the basal 4 m comprises a clast-supported quartzite-cobble conglomerate. This conglomerate lacks any signs of imbrication or grading, and is laterally uniform in thickness and character over a distance of about 3 km along which it was traced. At the northern end of the Batten Range (12 km farther north), this basal cobble conglomerate is still present, but a second cobble conglomerate is present about 40 m above the base. This second conglomerate is similar to the basal conglomerate in that it lacks grading and imbrication, but it is about 8 m thick. It has sharp planar contacts with the fine-grained sandstones above and below. Conglomerates are not present in the Masterton Horst.

In parts of the northern Batten Range, distinctly flaggy and thin-bedded intervals of a similar facies to that in the Tatoola Sandstone (p. 73) are present in the upper part of the unit. The recognition of thick intervals of this flaggy facies is probably what prompted the field mapping geologists to separate it (as the 'Mulholland Sandstone') from the 'Masterton Formation' in the 1960s. These flaggy beds contain herringbone cross-stratification, wide shallow channels, ball-and-pillow and load structures, syneresis cracks, and ripple-drift laminae. Also common in the upper part of the unit in the Batten Range are beds of resistant sandstone with internal planar cross-laminations alternating with softer rippled intervals (similar to those described in the Sly Creek Sandstone; see Fig. 21). The sandstone in the uppermost 20 m in the Batten Range contains friable weathered ferruginous 'spots', which are pseudomorphs after lozenge-shaped gypsum crystals (Fig. 47) identical with those preserved in evaporitic facies of other formations in the basin (e.g., Wollogorang Formation, Fig. 32, and Amelia Dolomite, Fig. 75). As in the type section, these uppermost beds of the formation are coarser-grained and less well sorted, and also contain halite casts and moulds and desiccation cracks,

Fig. 46. Large-scale cross-bedding in the Masterton Sandstone near Bluey Creek (15 km northwest of Calvert Hills homestead.) Relief on the major truncation surfaces A-A' and B-B' is at least 10 m. Foresets indicate palaeocurrents mainly to the northeast (left). The figure in the centre foreground is about 1.7 m high. The regional stratigraphic dip is roughly horizontal. (BMR negative 2572/10)

indicating a distinct shallowing of the depositional environment.

Northern localities

Towards the end of the fieldwork, we paced several traverses through the Masterton Sandstone in northern *Batten* and *Tawallah Range*, but we did not measure any detailed sections. In this part of the McArthur Basin, considerable lateral variations occur in both thickness and facies. Indeed, lateral variations are apparent between sections only a few kilometres apart in the Sawtooth Range.

The southern part of the Sawtooth Range comprises 600 m of mainly coarse-grained and conglomeratic sandstone with large-scale trough-cross-stratification in sets commonly up to 2–3 m thick. Only in the upper 100 m is the fine-grained rippled quartz sandstone facies, so typical of the formation elsewhere, developed. The lowest 60 m is dominated by thick matrix-supported ungraded cobble conglomerate 10–20 m thick separated by very coarse-grained pebbly sandstone. Above this basal unit, very coarse-grained sandstone becomes dominant, but pebble and cobble beds 50 cm to 1 m thick are common, generally forming the lower parts of trough-cross-sets. Most of the pebbles and cobbles are composed

Fig. 47. Large block of friable porous coarse-grained quartz sandstone crowded with ferruginous lozenge-shaped pseudomorphs after gypsum crystals in the Masterton Sandstone 20 m below the contact with the Mallapunyah Formation in the northeastern Batten Range. (BMR negative 2572/22)

of well rounded quartzite, but rare dark grey and green porphyritic igneous rocks are also present. Fine-grained friable red-brown ferruginous sandstone, commonly with shale-clast impressions, forms thin layers in the coarse sandstone. Intervals of no outcrop about 10 m thick are also assumed to be composed of mainly friable ferruginous sandstone. In addition to the trough-cross-stratification, decimetre-scale planar-cross-stratified intervals are present, especially in the upper 240 m of the formation.

Five kilometres to the north, in the central Sawtooth Range, the lower 50 m of the formation consists of fining-up sandstone units 50 cm to 1 m thick (Fig. 48). These units comprise a thin pebble layer at the base, overlain by trough-cross-stratified very coarse-grained sandstone, which is capped by horizontal parallel-laminated medium sandstone (Fig. 49). Dominantly south-flowing palaeocurrents are suggested by the facing of the foresets of these large cross-beds. This is somewhat puzzling because the massive cobble conglomerate 5 km to the south must be a more proximal facies, and north-flowing palaeocurrents would therefore have been expected. This lower 50 m is overlain by about 80 m of interbedded conglomeratic sandstone and medium-grained sandstone in units 8–12 m thick; the medium-grained sandstone is rippled and has thin sets of very low-angle (1–5°) planar cross-bedding (Fig. 50). These units are succeeded by a uniform sequence of about 400 m of coarse-grained friable sandstone with rare cobble and pebble beds. Its internal structures are vague, but large-scale (50 cm to 2 m) trough-cross-stratification is visible. In places, however, current lineations, straight-crested symmetrical ripples, and slightly sinuous asymmetrical ripples are exposed on bedding-plane slabs. In this middle and upper part of the section palaeocurrents are mainly from the south.

In the Tawallah Ranges (20 km to the southwest) the lowermost 80 m of the Masterton Sandstone consists of similar fining-up sandstone units with trough-cross-bedding, but the overlying 400 m is markedly different. Here it comprises two main facies alternating on a tens-of-metres scale—a medium-grained well sorted decimetre-to-metre-scale cross-stratified sandstone facies and a flaggy to fissile thin-bedded micaceous very fine-grained sandstone-to-siltstone facies. The coarser facies contains numerous symmetrical ripples and shale-clast impressions, while the finer facies, which is poorly exposed, contains load structures, pinch-and-swell, and small current ripples.

Western margin

The Masterton Sandstone in the Tanumbirini district comprises well sorted quartz sandstone similar to that in the type section, but in addition it contains felsic quartz porphyry and associated volcaniclastic rocks ranging from fine-grained lithic sandstone to boulder conglomerates composed largely of volcanic debris. Paine (1963) named the volcanic facies the *Tanumbirini Volcanic Member*. Stratigraphic relationships between the Masterton Sandstone and the underlying shales and carbonates of the Wollogorang Formation in this part of the basin are not clear, but a sharp eroded contact was observed at one locality. The exact position of the Tanumbirini Volcanic Member within the formation is also not clear, but it is overlain and underlain by medium to fine-grained quartz sandstone; at least 200 m of sandstone overlies the volcanic member, but only about 50 m has been measured below it. The Tanumbirini Volcanic Member has a maximum thickness of about 100 m and contains a variety of litho-

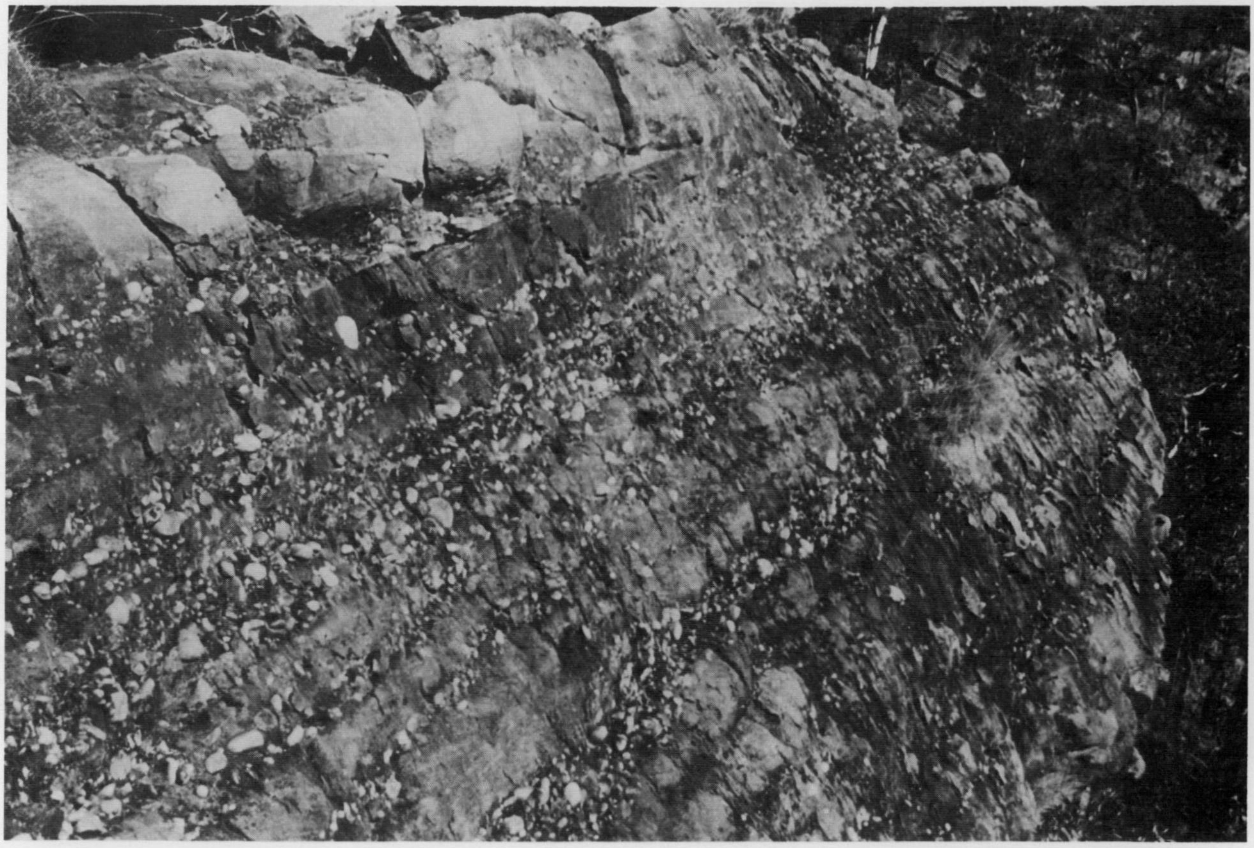

Fig. 48. Cliff section composed of the basal 10 m of the Masterton Sandstone in the central Sawtooth Range. It comprises repeated units of cobble beds overlain by large-scale cross-stratified sandstone. Note the irregular thickness and the interfingering nature of some of the cobble beds. (BMR negative M2572/14)

Fig. 49. Fining-upward sandstone units in the Masterton Sandstone in the Sawtooth Range. Two cycles are shown; the scale (10 cm long) is in the middle of the upper cycle. A cobble bed at the base is overlain by cross-stratified coarse sandstone about 50 cm thick, which is capped by parallel-bedded medium to fine sandstone. Currents flowed to the right (south) in these two units. (BMR negative 2572/18)

Fig. 50. Well sorted sandstone with low-angle planar cross-stratification and ripple-marked surfaces (30 cm above the handle of the hammer) near the base of the Masterton Sandstone in the central Sawtooth Range. (BMR negative M2572/23)

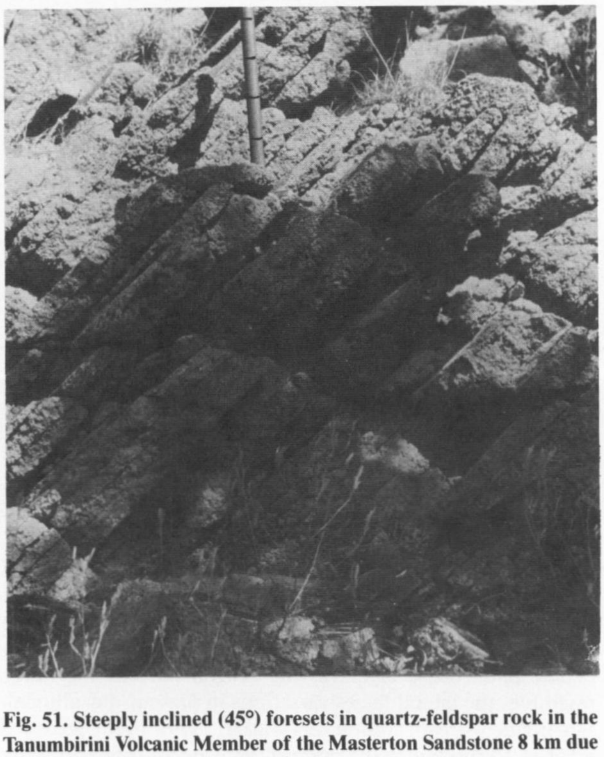

Fig. 51. Steeply inclined (45°) foresets in quartz-feldspar rock in the Tanumbirini Volcanic Member of the Masterton Sandstone 8 km due east of Tanumbirini homestead. Such steeply inclined foresets indicate that the material was highly cohesive during deposition. The marks on the handle of the hammer are 10 cm apart. (BMR negative M2572/4)

logies—including quartz and feldspar rocks (Fig. 51), tuff, volcanic breccia, polymictic pebble, cobble, and boulder beds (Fig. 52), and quartz sandstone.

Fig. 52. Volcaniclastic rocks in the Tanumbirini Volcanic Member of the Masterton Sandstone 16 km northeast of old Tanumbirini homestead. The hammer head rests on a dislodged boulder of coarse conglomeratic sandstone, which is draped by lithic pebbly sandstone (supporting the handle of the hammer) capped by pebble conglomerate (darker grey) of largely volcanic material. Overlying cobble conglomerate is visible in the background. The hammer is about 1 m long. (BMR negative M2572/15)

Interpretation

The Masterton Sandstone shows marked lateral variations in both lithology and thickness, suggesting that it was deposited in a variety of environments. We present below our interpretations of some of the facies; the lack of a systematic regional analysis precludes us from deciphering the evolutionary history of the unit.

A well defined volcanic–alluvial system was obviously developed in the west during deposition of the Tanumbirini Volcanic Member. The general character of the volcaniclastic sediments—poorly sorted and angular—and the presence of large angular boulders up to several metres across, indicate minimal transport as debris flows around the volcanic centres. The interbedded sandstones are immature, commonly contain volcanic debris, are largely channel-confined, and were deposited in alluvial fans flanking the volcanoes. The finer-grained sandstones above and below the Tanumbirini Volcanic Member are similar to those interpreted as shallow-marine elsewhere in the formation.

In the Sawtooth Range area, to the northeast, the formation contains evidence of lateral variations in depositional environments of the coarse-grained facies. The change from massive cobble conglomerates tens of metres thick at the southern end of the range to coarse sandstone units with pebble and cobble layers in the central part of the range resembles the lateral facies variations in present-day alluvial-fan–braided-stream complexes (Walker, 1979). In the proximal reaches, to the south, the predominant facies is horizontally stratified clast-supported coarse gravel. Distally, to the north, there is an increase in cross-stratified sets, and transitions from clast-supported gravel, through matrix-supported gravel, to sand. The overlying beds include, in the south of the range, very low-angle dipping foresets and symmetrical ripples in a well sorted medium sandstone—a combination of features diagnostic of beach and very shallow littoral deposits; in the centre, however, thick intervals of pebbly trough-cross-bedded coarse sandstones are probably of braided fluvial origin.

Similar facies diagnostic of alluvial-fan–braided fluvial environments also characterise the lower part of the formation in the northern and central parts of the area (Tawallah Ranges, Batten Range), but they are succeeded by a thick accumulation of more regular, laterally uniform facies, probably of marine origin (littoral to offshore wave-dominated environments).

The very large-scale cross-stratification, steeply dipping foresets, and presence of reverse-graded wind ripples (see Kocurek & Dott, 1981) indicates that some of the Masterton Sandstone in the southeast is of aeolian origin, formed under winds blowing mainly to the north and east.

The south-central (type) area contains a thin, coarsening-up (gradually shallowing) section which lacks pebbles. Much of it was deposited as megaripples about 10–30 cm thick from strong currents, but the numerous symmetrically rippled parting planes also indicate persistent wave activity. Palaeocurrent measurements indicate three principal orientations; such a variety is typical of neritic marine environments. The gradual shallowing to an intertidal and shallower environment is indicated by the upward change through thin layers containing herringbone cross-stratification, to coarser beds with desiccation cracks and planed-off ripples signifying periods of emergence. This section grades up into the supratidal to alluvial-plain sediments of the Mallapunyah Formation.

Mallapunyah Formation

The Mallapunyah Formation is a poorly exposed but distinctive redbed unit containing visibly striking evaporite relics that occurs near the base of the McArthur Group. In previous reports (e.g., Smith, 1964; Plumb & Brown, 1973) it was defined as the basal unit of the McArthur Group. However, this no longer holds: we now define the base of the McArthur Group at the base of the underlying Masterton Sandstone. The name is derived from Mallapunyah homestead (GR 865230). A partial description of the formation, and an interpretation of some aspects of its sedimentology, are provided by Muir (1979e). The following account extends and expands this paper.

Distribution and thickness

The Mallapunyah Formation crops out in northern WALLHALLOW, in several parts of BAUHINIA DOWNS, and in southern MOUNT YOUNG (Plate 1). Although the formation weathers readily it is well exposed around cores of Tawallah Group rocks in the Mallapunyah Dome, in the Masterton Horst, and along the western side of the Batten Range. In poorly exposed areas, such as around the eastern and southern margins of the Tawallah Ranges, the presence of the formation is usually indicated by float of the large cauliflower chert nodules that are diagnostic of the unit. East of the Tawallah Ranges, the formation now comprises the lower silty part of the 'Festing Creek Formation', which Smith (1964) and Plumb & Paine (1964) mapped in BAUHINIA DOWNS and MOUNT YOUNG. Plumb & Brown (1973) recommended that the name 'Festing Creek Formation' be dropped (and that other parts of the formation be incorporated in the Amelia Dolomite and Tatoola Sandstone).

Thickness variations in the Mallapunyah Formation are difficult to assess owing to poor outcrop. However, the formation appears to be thicker in the south: in measured sections around the Mallapunyah Dome it is between 200 and 220 m thick, whereas in the Masterton Horst (70 km to the north) it is only half this thickness. Owing to poor outcrop, low dips, and structural complications, we have been unable to confirm a thickness estimate of about 750 m for the formation along the west wide of the Batten Range as suggested by Smith (1964) and Plumb & Brown (1973); we believe that a thickness in the range 100–200 m is more likely. Estimates from airphotos and pacing in the Tawallah Ranges indicate a thickness of around 100 m.

Type, reference, and other measured sections

A well exposed section on the eastern edge of the Mallapunyah Dome (Kilgour 77/11) is here nominated as the type section. It is situated along the lower reaches of Archies Creek and in adjacent parts of the Kilgour River. It is easily accessible because the road from Mallapunyah to Kiana crosses the section. It runs from GRs 957102 to 968104 and 967102 to 968095, and is summarised in Figure 53. Because the formation is well exposed around the Mallapunyah and Kiana Domes, several other partial sections and one complete section were measured to help assess lateral characteristics in this southern area. Two of these, Kilgour 77/10 (3.5 km northeast of the type section) and Kilgour 78/07 (5 km north of the type section), are here nominated as reference sections (Appendix Figs. A4, A3). The other partial sections, and the log of Amoco drillhole No. 6 in the Foelsche Inlier, are also reproduced (Appendix Figs. A5, A6, A7, A8, A11).

A measured section in the Masterton Horst area near the Emu Fault Zone (Appendix Fig. A9) and the log of part of CEC drillhole Tawallah Pocket No. 1 (Appendix Fig.A10) are here nominated as partial reference sections for the eastern and northern parts of the area respectively.

Stratigraphic relations

The Mallapunyah Formation conformably overlies the Masterton Sandstone, and is conformably overlain by the Amelia Dolomite. Both contacts are gradational over a few metres. At the basal contact the underlying Masterton Sandstone changes upwards from a clean quartz arenite, through feldspathic and clayey sandstone, and then through ferruginous hematitic and dolomitic sandstone, into the red-brown dolomitic siltstone typical of the Mallapunyah Formation. At the top of the formation, red-brown dolomitic siltstone and sandstone are interbedded with, and gradually replaced by, cherty stromatolitic dolostone of the Amelia Dolomite. The actual contact is somewhat arbitrarily placed at a resistant green chert marker bed (1-3 m thick) which usually can be identified even in areas of poor exposure.

Lithology

The Mallapunyah Formation is characterised by reddish brown dolomitic siltstone, shale, and sandstone containing a suite of distinctive evaporite pseudomorphs. It is softer and more easily weathered than most other formations in the McArthur Group, and hence does not form prominent outcrops. Much of the formation is thin-bedded or laminated, and it weathers to form valleys of no outcrop or low round hills covered with shaly or flaggy float (Fig. 54). The presence of the weathered-out cauliflower chert nodules or halite casts in this float are unambiguous signs of the identity of the concealed stratigraphic unit.

Mallapunyah Dome (including the type section)

The Mallapunyah Formation at the type section has been divided into seven distinctive units A to G (Fig. 53).

Unit A comprises thin, poorly exposed deeply weathered hematitic rocks with rippled granular sandstone lenses, distinctly laminated dololutite, and planed-off stromatolites (Fig. 55)—indicating exposure and erosion. Although Muir (1979e) described the stromatolites as *Conophyton*-like, they do have a distinctly branched conical form and are therefore more like *Jacutophyton**. Chertified algal material⁺ is present at all localities visited at this stratigraphic level; it forms a good mappable marker horizon, and allows ready definition of the contact between the Masterton Sandstone and Mallapunyah Formation.

Unit B consists of purple interbedded dolarenite, silty dololutite, dolomitic sandstone, and quartz sandstone 10–12 m thick; bedding is thin to medium, irregular and discontinuous. The irregular bedding is largely a primary feature, resulting from scouring and channelling, but some of it is probably due to recent weathering which has caused extensive dedolomitisation of the carbonate-rich beds in this part of Archies Creek. Symmetrical and asymmetrical ripples, intraclasts, discontinuous dololutite lenses (a few centimetres thick), desiccation cracks, and hopper halite casts and moulds

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*Similar but better preserved stromatolite forms have been seen elsewhere in the McArthur Basin sequence where Walter & others (in press) compared them with *Thyssagetaceae* (Vlosov).

⁺The type of algal material varies from place to place: *Jacutophyton*-like forms occur in the Batten Range; wavy to stratiform stromatolites are present in Leila Creek and at the southern end of the Tawallah Ranges; and pseudocolumnar forms predominate at Kiana and Top Crossing.

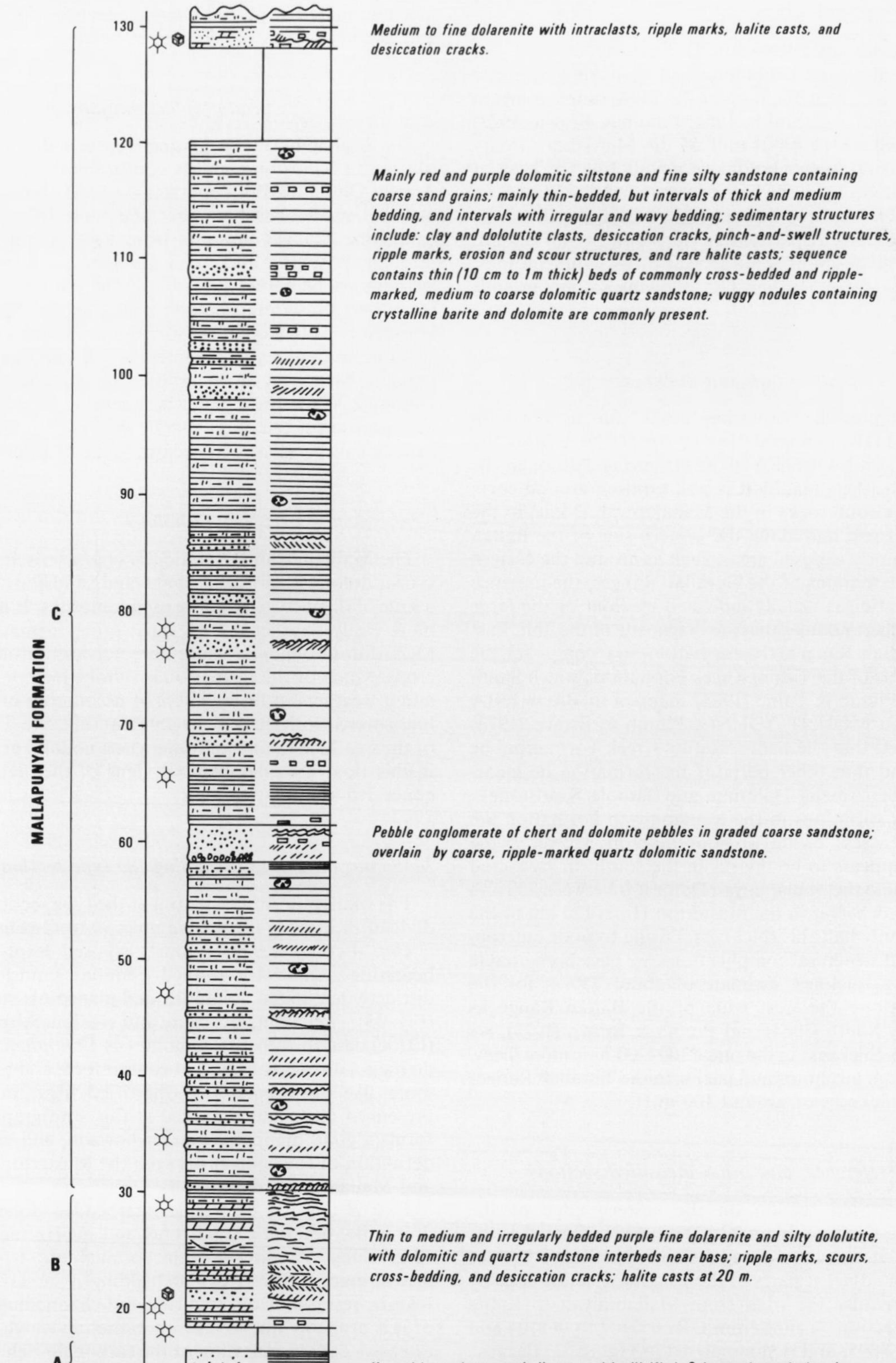

Fig. 53. Type section of the Mallapunyah Formation (measured section Kilgour 77/11), in Archies Creek (from Jackson & others 1978).

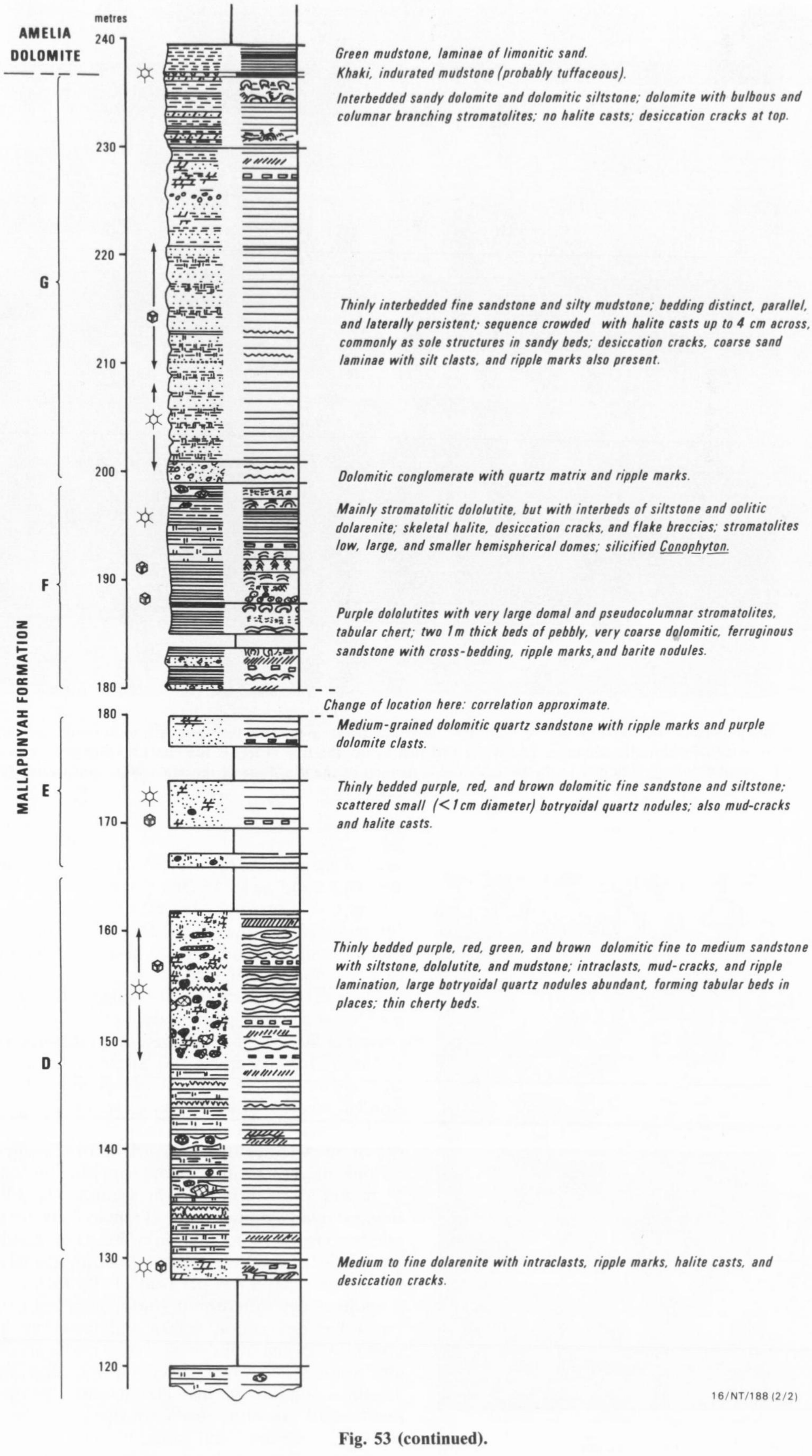

Fig. 53 (continued).

Fig. 54. Typical outcrop pattern of the Mallapunyah Formation in the Kiana Dome area. Thin resistant beds of dolomitic sandstone forming steps are separated by scree of dolomitic siltstone. The white bed just below the tree at left is the chert marker bed shown in detail in Fig. 60. The trees are about 6 m high. The rise in the background is formed by the dip slope of the Masterton Sandstone. (BMR negative M2568/12A)

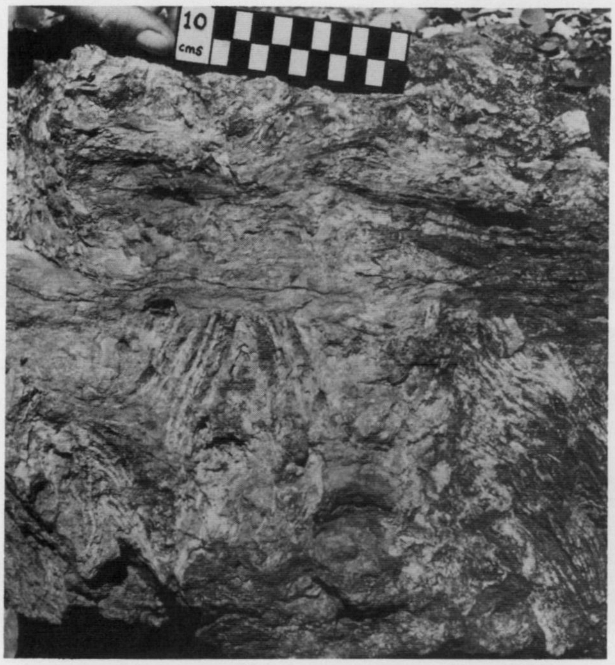

Fig. 55. Chertified branching conical stromatolites in irregularly ferruginised and silicified beds at the contact between the Mallapunyah Formation and the Masterton Sandstone. Note the truncation of the conical stromatolite by erosion (?wave-cut platform) 12 cm directly below the scale. (BMR negative 2568/14A)

are the main features visible. The sandstones are intensely hematitic, and occur in cross-stratified and rippled lenses.

Unit C—100 m thick—is a rather monotonous part of the formation comprising mainly dark reddish brown and purple dolomitic siltstone (grading to mudstone) with thin (10 cm to 1 m) interbeds of medium to coarse-grained dolomitic sandstone; a conglomerate of rounded chert and dolostone pebbles in a coarse-grained dolomitic sandstone matrix is present at the base of the thickest of these sandstone interbeds (between 58 and 61 m, Fig. 53). Stratification in the dolomitic siltstone is variable: some sections are indistinctly thin-bedded, whereas others are massive. Pinching-out of some of the massive sections is so indistinct that it is difficult to determine whether this is of original sedimentary or later tectonic origin. Distinct laminae are rare, but are present at 57 m and 63-65 m in the type section (Fig. 53). Very well rounded quartz grains up to 2-3 mm in diameter with frosted outer surfaces are a common constituent of the siltstone; they are usually present as scattered 'floating' grains and seldom form more than a few per cent of the rock.

Sedimentary structures in the siltstone are generally rare, but a few desiccation cracks and intraclast breccias are present; vugs and nodules filled with barite and/or dolomite are, however, common. Irregular mottling and pseudo-columnar jointing are also characteristic of this unit. The interbedded sandstone beds are sharply defined from the enclosing siltstone, and contain the following features: erosionally scoured bases, rippled mud-cracked upper surfaces, low-angle cross-bedding, siltstone intraclasts, and halite casts. Palaeocurrents from the northwest are evident from asymmetrical ripple orientations at 129 m.

Unit C in reference section Kilgour 78/07 (0 to 110 m, Appendix Fig. A3) is similar, but there are some differences in detail. The 3 m-thick sandstone at 60 m in the type section is almost certainly equivalent to the sandstone bed between 32 and 34 m in the reference section. Using this as a marker, we have been able to detect subtle variations in the texture and structure, indicating minor differences in both sedimentation and early diagenetic histories: for example, the prominent fining-upward sandstone with numerous shale clasts between 56 and 58 m in the reference section is not obvious in the type section; and pseudomorphs after gypsum in the reference section appear to take the place of the halite casts in the type section.

Palaeocurrent measurements on ripples and cross-stratification in reference section Kilgour 78/07 indicate currents from the east and northeast (cf. from the northwest in the type section). Barite nodules in the reference section contain malachite and hematite.

Unit D—30 m thick—is characterised by abundant botryoidal quartz nodules (cauliflower cherts; Fig. 56) and thin green or pink chert bands. In some respects, the rocks in this unit are similar to those in unit C (i.e., comprising interbedded dolomitic siltstone and sandstone), but, in addition, they also include beds of pale purple and pale green dololutite, green fissile mudstone, and chert. The stratification within unit D is also more distinctive and variable than that of unit C.

The cauliflower cherts are flattened parallel to bedding (Fig. 57), but in places they are almost spherical (Fig. 58). They range in thickness from 5 mm to about 90 cm, and in length from 5 mm to about 1.5 m. The nodules are obviously diagenetic in origin as they push the bedding apart. In places they coalesce to form irregular pod-like and tabular beds. Individual cauliflower cherts have a fine-grained cherty outer rind, whose weathered surface comprises an interlocking meshwork of elongated crystal laths after lutecite (Walker &

Fig. 57. Cauliflower cherts elongated parallel to bedding within interbedded dololutites and dolomitic shales of the Mallapunyah Formation (unit D at the type section), same locality as Fig. 56. The scale is 10 cm long. (BMR negative M2568/34A)

Fig. 56. A cliff face of the Mallapunyah Formation (unit D at the type section) at the confluence between Archies Creek and the Kilgour River. The thin-bedded section, about 12 m thick, is crowded with botryoidal chert nodules (cauliflower cherts), which are shown in detail in Figs. 57 and 58. (BMR negative M2568/29A)

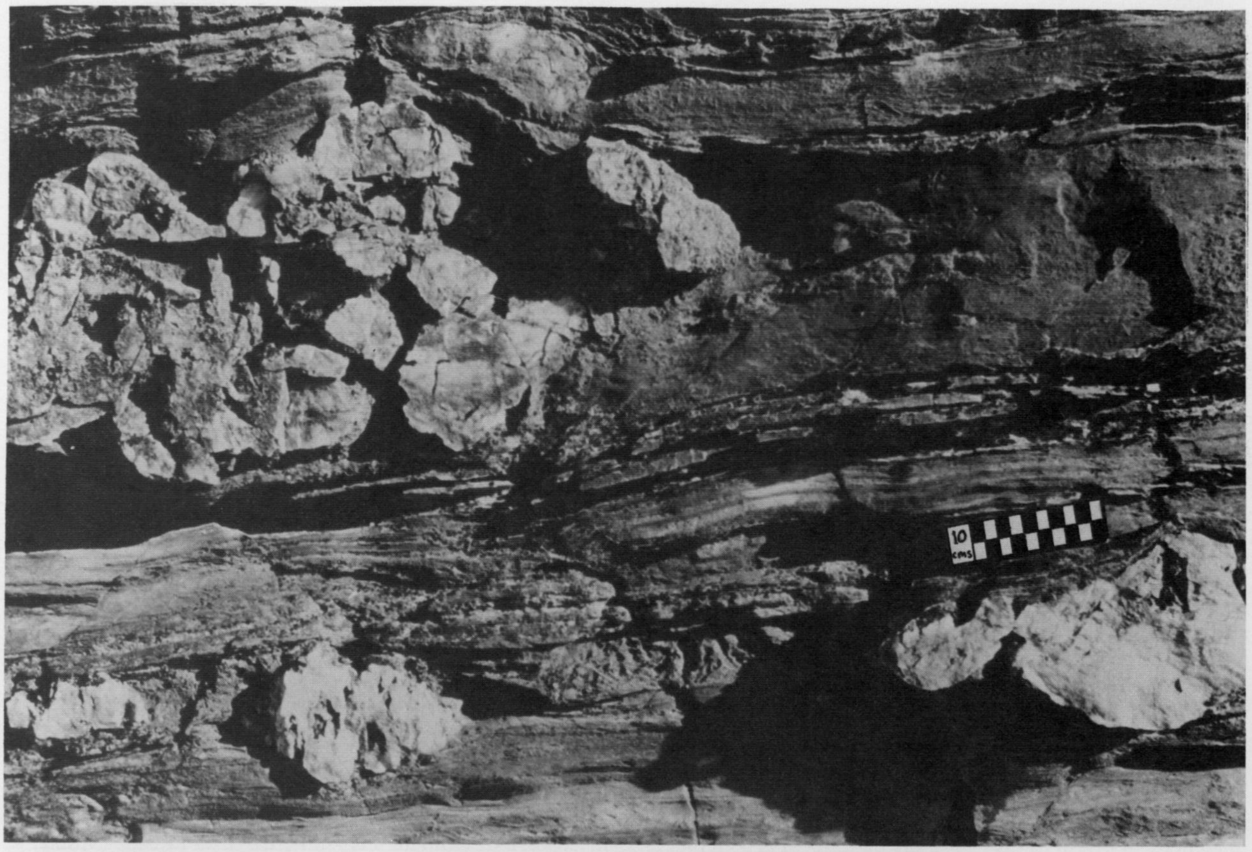

Fig. 58. Large, almost spherical, cauliflower chert nodules (top left) and smaller nodules flattened parallel to bedding in the Mallapunyah Formation (unit D at the type section), at the same locality as Fig. 56. (BMR negative M2568/31A)

others, 1977). Their centres, which are commonly hollow, are lined with anhedral to euhedral crystals of quartz, dolomite, and fluorite (and sulphides such as chalcopyrite and pyrite in some), which grade outwards into enterolithic chert forming the bulk of the nodule. Muir (1979e) discovered trace amounts of precious metals in the centres of some nodules, and inclusions of anhydrite in the outer rind of others.

Besides the disruption to bedding caused by the diagenetic growth of these former anhydrite nodules, the original bedding of this unit is also markedly discontinuous and irregular: desiccation cracks and intraclasts are common features; and rip-up and scouring has occurred at the tops of both the fine-grained dololutite interbeds and the sandy dolostones containing the cauliflower cherts (Fig. 59).

Unit D contains at least two different types of chert beds. One is green, and forms internally structureless beds 1-2 cm thick. Six of these are clearly visible in both the type section and reference section Kilgour 77/10. During the original section measuring, they were identified as possible tuffs, and were shown as such on the measured sections. The other chert is white, cream, pink, or red, and it forms much thicker resistant beds up to about 20 cm thick with complex internal structures. Several of these beds are well exposed in reference section Kilgour 78/07. These thicker chert beds are obviously postdepositional features because they are slightly discordant to the bedding; however, they may be diagenetic in origin as they preserve original sedimentary structures—including cut-and-fill, evaporite pseudomorphs, dewatering cracks, and ripple marks (Fig.60)—very clearly.

Unit E is not well exposed in the measured sections, but it is a thin interval dominated by dolomitic sandstone. It ranges in thickness from 5 m in reference section Kilgour 77/10 (Appendix Fig. A4) to about 15 m in the type section (Fig. 53). Therefore in this small area round the northeast of the Mallapunyah Dome it shows a marked thickening towards the south. The unit contains sedimentary textures and structures similar to those in unit D—for example, cauliflower cherts, desiccation cracks, and intraclast breccias—but it also contains numerous halite casts. In reference section Kilgour 77/10 it contains thin stromatolitic dololutite layers.

Unit F consists mainly of purple dololutite, but it also contains thin interbeds of siltstone, oolitic dolarenite, and sandy dolarenite. The dololutite contains a variety of stromatolites and evaporitic relics. The stromatolitic dololutite is commonly irregularly chertified, so that stromatolite morphology at some localities is difficult to establish (see, for example, Fig. 61). Large round domes (1-2 m diameter), smaller domes (decimetre-size individuals or laterally linked biostromes), and pseudocolumnar forms are present. As in many of the formations in the McArthur Basin, stromatolites in unit F are arranged into bioherm series (Fig. 61), in which a marked upward change in stromatolite morphology occurs. In addition to the forms already mentioned, chertified conical algal laminations are commonly picked out by the irregular patches of chert. These are somewhat irregular in shape and size; they appear to be 'branched', and they do not have the axial zones characteristic of *Conophyton*; they are probably similar to the *Jacutophyton*-like forms present in the basal unit of this formation and in the overlying Amelia Dolomite.

In addition to the stromatolites, unit F contains a range of sedimentary structures similar to those in units D and E. These include: flake breccias, erosional scour channels, desiccation cracks, halite casts, skeletal and pagoda hopper halite pseudomorphs, cross-bedding, and ripples. Polygonal cracks outlining polygons 3-4 m across are visible in low-dipping bedding planes etched by the Kilgour River at the Mallapunyah-to-Kiana road crossing. These large-scale

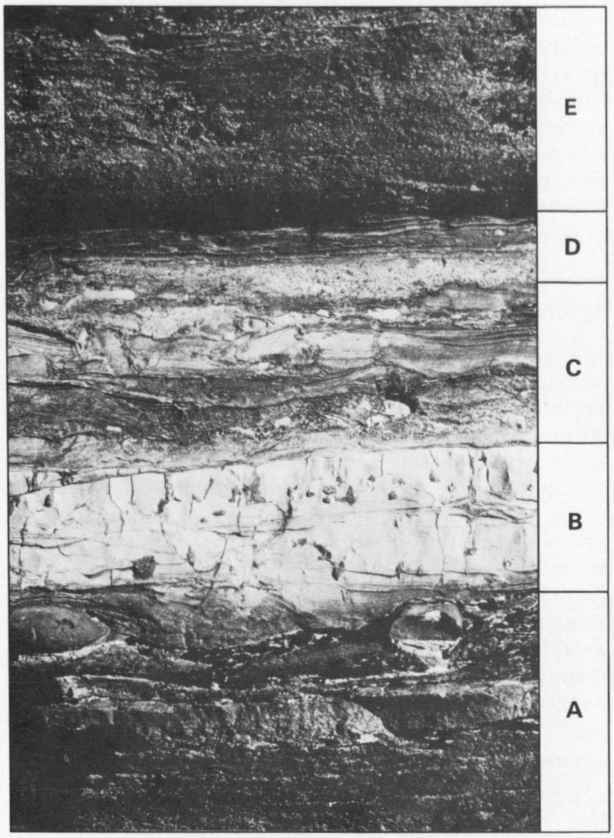

Fig. 59. Heterogeneous rock types and structures in a small part of unit D of the Mallapunyah Formation at the type section (same locality as Fig. 56). A—dark grey fine dolomitic sandstone with indistinct ripples, and ovoid chert nodules near the top; B—purple dololutite 4 to 5 cm thick with a load cast at the base, sharp eroded and desiccated top with cracks infilled from above, and probable gypsum pseudomorphs; C—ripped-up dololutite clasts in sandy dolarenite 5 cm thick; D—conglomerate grading up into laminated dolarenite; E—dark-weathering fine dolomitic sandstone similar to A. Interval A–B is similar to the chert marker bed shown in detail in Fig. 60. (BMR negative M2568/36A)

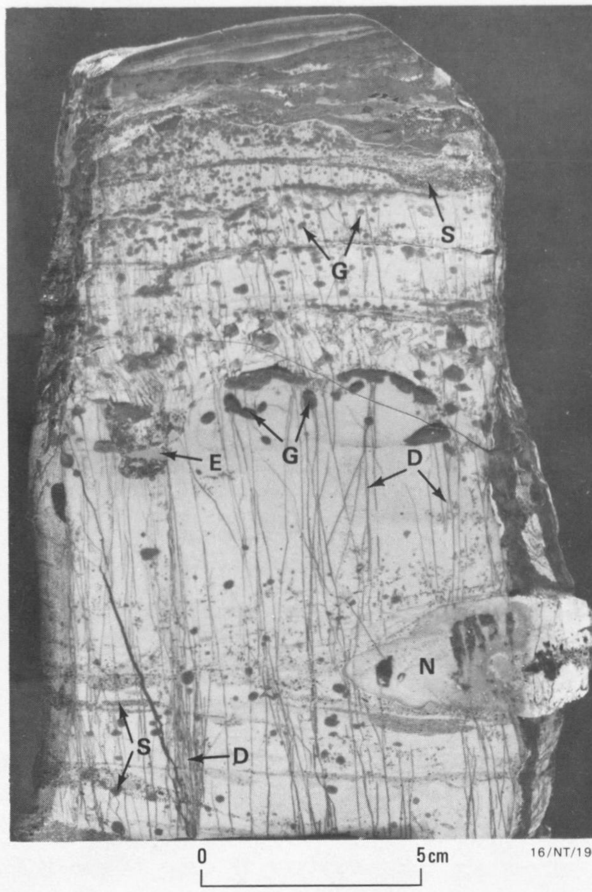

Fig. 60. Polished slab of chert marker bed in unit D of the Mallapunyah Formation (specimen 78100099B) in reference section Kilgour 77/10. The original sedimentary and diagenetic structures enhanced are: discontinous sandy wedges and laminae (S); distinct erosion surface (E) infilled with sand and intraclast debris; earlier chert nodule (N); possible former gypsum crystals (G) of various shapes and sizes (now ferroan chert); and ?dewatering cracks (D) containing the same ferroan chert as that which forms the gypsum pseudomorphs. (BMR negative GB3105)

features are often difficult to identify in outcrops where large expanses of bedding planes are not exposed.

Unit G—the uppermost unit of the formation—consists mainly of thinly interbedded fine sandstone and silty dolomitic mudstone overlying a conglomeratic base. In contrast to the disrupted stratification of units D, E, and F, the bedding in this unit is regular, parallel, and laterally persistent. Hopper halite casts and moulds are extremely abundant, and many bedding planes are crowded with them (Fig. 62). Desiccation cracks, ripple marks, and sole structures are also present. Because of the abundant halite casts this unit forms a readily identifiable marker unit at the top of the Mallapunyah Formation throughout the southern part of the area.

An upward increase in the matrix content of fine-grained dolomite, and the appearance of thin stromatolitic dololutite beds, indicate a gradational contact with the overlying Amelia Dolomite. For convenience, a prominent khaki-green hackly fracturing cherty rock (thought to be a tuff bed) is used to define the contact between the two formations. This khaki chert is resistant to erosion, and can usually be identified, even in poorly exposed sections; it forms a satisfactory marker bed to define a gradational stratigraphic contact.

Foelsche Inlier

The Mallapunyah Formation is poorly exposed in this area (60 km east of the type area), but some lateral facies changes can be inferred from the section intersected in Amoco drillhole No. 6 (Appendix Fig. A8). A green cherty rock at 142 m overlain by stromatolitic dolostone correlates well with the Amelia/Mallapunyah contact zone at the type section. Below this is a 52 m section of mainly red, purple, and green siltstone, claystone, and sandstone which in part are dolomitic. It contains some features that can be related to parts of the type section.

The interval 142 to 162 m in Amoco drillhole No. 6 probably correlates with unit G of the type section. It is a richly evaporitic part of the section containing enterolithic dolostone (formerly anhydrite beds) and pseudomorphs after gypsum. Thus, a sulphate suite of evaporites dominates this stratigraphic level in the Foelsche Inlier, in contrast to the type section, where halite dominates. The bases of these correlative units are marked by basal conglomerates on erosional surfaces, implying a sedimentary break of probably regional significance—in contrast to the many diastems and intraclastic layers which are purely of local significance.

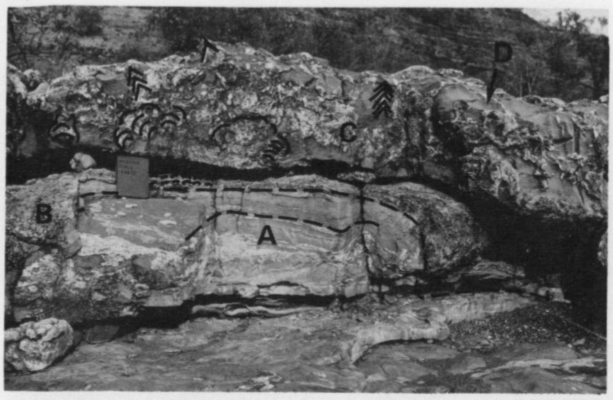

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Fig. 61. Purple stromatolitic dololutite with irregular chertification in unit F of the Mallapunyah Formation at the type section (Kilgour River near Mallapunyah-to-Kiana road crossing). The structures are hard to decipher owing to irregular chertification, but some have been highlighted by annotation: large stromatolite dome with overhung sides (A) capped by smaller columnar stromatolites clearly visible in chert at B, overlain by biostrome containing domal to pseudocolumnar forms and irregularly branching conical forms (C); dololutite at D contains large skeletal halite casts infilled by crystalline dolomite. Compare with the similar bioherm series in the Balbirini Dolomite (Fig. 158). The notebook is 17 cm long (BMR negative M2568/13A)

Most of the rest of the drillhole (164-194 m) consists of red and green mottled siltstone and shale with coarse spherical quartz grains and interbeds of silty sandstone—a facies similar to unit C of the type section. If this correlation is correct then the 70 m of evaporitic and stromatolitic cherts and carbonates of units D, E, and F at the type section are here represented by the 2 m of ferruginous brecciated stromatolitic carbonates between 162 and 164 m, reflecting a local erosional episode.

Masterton Horst

A complete though discontinuous section through the Mallapunyah Formation near the Masterton Horst (70 km north of the type section) is shown in Appendix Fig. A9. Although only about half as thick as the southern sections it comprises broadly similar lithologies and sedimentary structures. However, the vertical distribution of the various facies is different, and the Masterton Horst section has, in addition, a distinctive facies not seen in the type area. In this section, large cauliflower cherts are most common in the lower half of the formation, and barite-filled geodes are more common in the upper half—a reversal of the order in the type area. In this northeastern part of the area the formation is mainly dolomitic siltstone, and there are few of the interbedded sandy layers so common in the type area. A massive

Fig. 62. Dolomitic sandstone from unit G of the Mallapunyah Formation (type section) consisting almost entirely of hopper halite casts and moulds. Natural scale.

sideritic dolostone crowded with large gypsum crystal pseudomorphs occurs near the middle of the section. This rock type is identical with beds in the overlying Amelia Dolomite near Leila Creek. It illustrates a problem common in the Umbolooga Subgroup: the difficulty of distinguishing between stratigraphic units which are packages of subtly varying lithofacies in Proterozoic sequences that lack precise age control.

Batten Range

Gently dipping Mallapunyah Formation flanks the western and northern margins of the Batten Range. As noted above, the outcrops are so discontinuous that an accurate thickness could not be measured. However, there are important differences between these outcrops and those already described, so we have drawn up a summary column of the formation in the western Batten Range (Fig. 63). The most obvious difference between this and the other areas is the dominance of quartz sandstone. Although the lack of outcrop continuity may well give a somewhat false impression of the amount of shale or siltstone present, there is no doubt that sandstone is much more prevalent in the Batten Range. The sandstone ranges from fine-grained clean quartz arenite to coarse-grained silty sandstone. Rippled bedding planes are common, and the size, type, and orientation of ripple marks vary considerably. Most ripple marks have wavelengths between 3 and 10 cm and amplitudes of 0.25 to 2 cm, but rare larger forms are present. Planar cross-stratification is on a decimetre-scale, but troughs are up to at least 8 m wide. Halite casts are apparent on rippled bedding surfaces, especially those associated with mud-cracked clay drapes in ripple troughs. The few measured palaeocurrent directions show a gradual swing from a westerly source near the base to an easterly and northeasterly source higher up.

Although the bulk of the Batten Range section shows marked facies differences from the type section, it is intriguing that the base of the formation in the Batten Range is marked by a stromatolitic chert with *Jacutophyton*-like and columnar forms, and the upper few metres of the formation comprises float of large cauliflower cherts.

Northern parts of the area

The Mallapunyah Formation is even more poorly exposed north of about latitude 16°20′S. In places where we saw it in outcrop (e.g., eastern Tawallah Ranges) it usually comprises either red dolomitic siltstone/shale or red silty sandstone with well rounded quartz grains. Float of cauliflower chert is again a conspicuous feature of the unit, and in many places is commonly the only clue to the identity of the concealed unit.

A summary log of the lower part of CEC drillhole Tawallah Pocket No. 1 (Appendix Fig. A10), which intersected the uppermost 50 m of the formation, shows some similarities to the upper beds of the type area, but dark grey organic-rich shales are present near the top of the formation. Most of the formation in Tawallah Pocket No. 1 consists of red shale and dolomitic siltstone with rare evaporites (cauliflower cherts and gypsum pseudomorphs). This shows that the northward increase in the amount of coarse clastic detritus suggested by the lithological change between the type area and the Batten Range is not continued farther north.

The Mallapunyah Formation has apparently been intersected by recent BHP drilling along the coastal plain east of the Yiyintyi Range (Plate 1), but we have not seen the core.

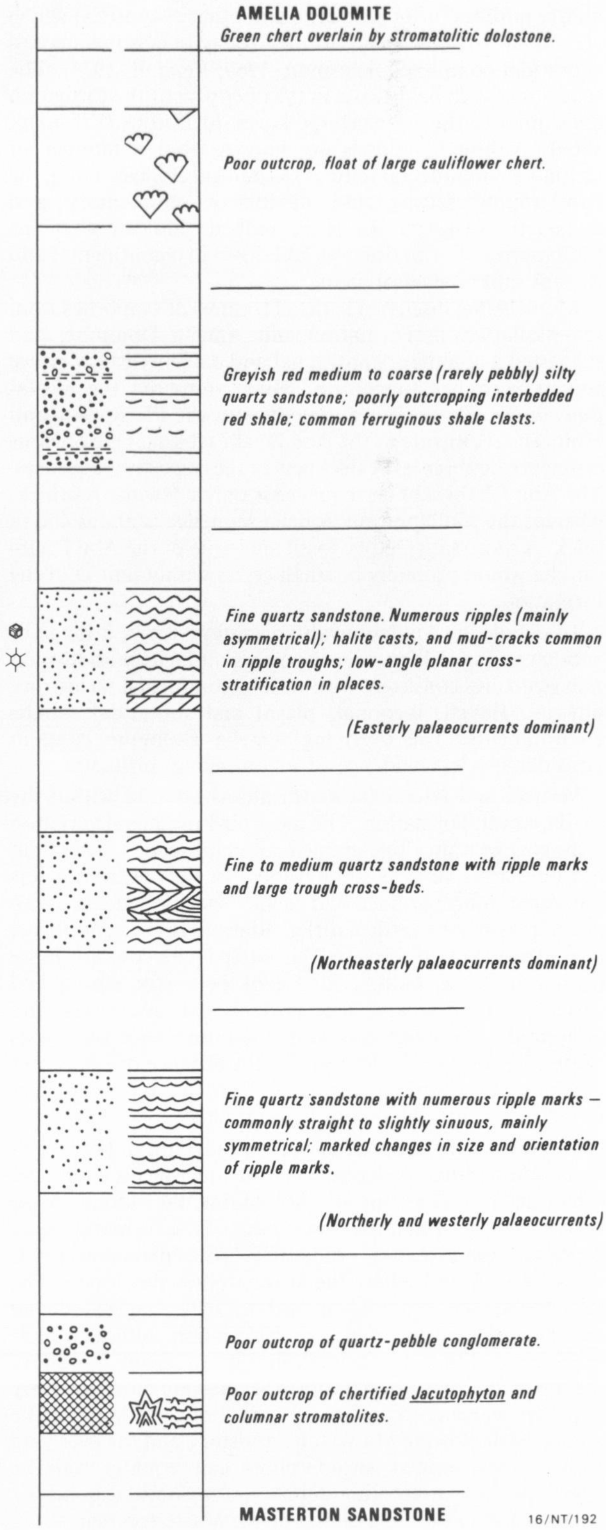

Fig. 63. Section through the Mallapunyah Formation on the western side of the Batten Range.

Interpretation

The Mallapunyah Formation is mainly a redbed facies. In the south and north-central parts of the area it overlies a regressive sequence of shallowing littoral sands (Masterton Sandstone). It contains numerous sedimentary structures indicative of very shallow-water deposition with frequent emergence—for example, numerous diastems, desiccation cracks, polygons, and intraclast breccias. It also contains large quartz nodules (after anhydrite and other evaporites) which are similar to those being formed today in continental and supratidal complexes (Kinsman, 1969; Kendall, 1979). The sandstones with halite casts in the uper part of the formation are similar to the 'haselgebirge facies' of Europe (Kinsman, 1969). Although redbeds are known from a number of tectono-environmental settings (Krumbein & Sloss, 1963), the stratigraphic setting and distinctive sedimentary and diagenetic structures of these redbeds indicate that the Mallapunyah Formation was laid down in a continental and coastal sabkha environment.

Muir (1979e) discussed in detail textures of evaporites from the Mallapunyah Formation and Amelia Dolomite, and suggested a complex depositional and diagenetic history; we concur with her suggestion. Muir compared the Mallapunyah–Amelia sequence directly with the Pleistocene and Holocene sediments of the Abu Dhabi sabkha. One obvious difference however is the thickness of the respective sequences. The Abu Dhabi sabkha sequence is only a few metres thick, whereas the Mallapunyah–Amelia sequence is about 400 m thick. A more satisfactory fossil analogue of the Abu Dhabi sabkha would probably be small cycles within unit D of the formation.

In detail, the Mallapunyah Formation shows a range of subtly varying shallow-water to emergent facies with textures and structures consistent with various continental (lacustrine, alluvial, fluvial, lagoonal, playa) and supratidal sabkha environments. The overlying Amelia Dolomite contains considerably less evidence of a continental influence.

Vertical and lateral facies variations abound within the Mallapunyah Formation. The most obvious lateral variation is the change from a fine-grained dolomitic redbed facies (that has numerous vertical subdivisions) in the south to a less dolomitic, coarse-grained and cleaner sandstone facies (with much less obvious vertical differentiation) in the central part of the area (Batten Range). This latter facies contains more regular bedding, more evidence of persistent strong and variable currents, and less evidence of evaporites and desiccation. Although a fluvial environment for this facies cannot be completely discounted, the absence of evaporites and lack of signs of emergence indicate that a deeper-water lacustrine or littoral setting is more likely.

The vertical differentiation of the Mallapunyah Formation in the south indicates deposition of distinct facies within the broad geological setting of the continental margin. Muir (1979e) envisaged that the lowest beds of the formation were deposited on extremely wide flats with perennial pools (lagoons or lakes) where the stromatolites developed. The stromatolites are commonly planed off, indicating widespread exposures and erosion after their lithification. Although Muir (1979e) stated that the stromatolites occur about 3 m above the top of the Masterton Sandstone, they are more correctly described as being located at the transition zone between the gradually shallowing Masterton Sandstone and the overlying redbeds; the eroded stromatolites can equally well be interpreted as representing deposition in subtidal ponds or lagoons during the final phases of the Masterton regression.

Muir (1979e) did not specify a depositional environment for units B and C (Fig. 53), although she did discuss the origin of the small barite and dolomite nodules that occur in unit C. She compared these nodules with those described by Hirst & Smith (1974) from the Permian Lower Magnesian Limestone of northern England. She concluded that the Proterozoic nodules are similarly early diagenetic and concretionary in origin, and speculated that the barium may have originated from the underlying Wollogorang Formation or Gold Creek Volcanics.

The rocks of units B and C indicate fluctuating energy levels in the depositional environment: conditions of quiet sedimentation with occasional emergence (the dolomitic siltstone with desiccation cracks and intraclasts) alternating with more active erosion and sedimentation (cross-stratified sandstone). The scoured bases, fining-upward character, and lateral thickness variations in these sandstone interbeds are more consistent with a low-gradient fluvial rather than a marine origin. If this is so, much of the silt-size material is likely to be of overbank flood or aeolian (loess) origin. The spherical quartz grains in the dolomitic siltstone of unit C are possibly also of aeolian origin; unless they were blown in, their 'floating' habit is difficult to explain by normal sand-grain transport mechanisms.

Some of the sandstone in unit C may be the product of aeolian dunes migrating across the alluvial plain. The well sorted, well rounded nature of the grains and the lack of matrix do suggest aeolian activity, but with such thin beds it is difficult to determine whether they are the product of (1) direct aeolian deposition, (2) aqueous reworking of aeolian sands, or (3) aqueous deposition of non-aeolian sand. The mottling and pseudocolumnar jointing are tentatively interpreted as features produced by weathering or pedogenesis.

The most likely depositional setting for most of units B and C is a fine-clastic alluvial system (Reading, 1978). A closer analogy may well be the anastomosing fluvial system of the present Cooper Creek in central Australia. A depositional model for such arid-zone anastomosing fluvial systems comprises a mud-dominated succession with minor channel sands, and deep desiccation cracks, minor carbonaceous horizons and duricrusts, and evaporites (Rust, 1981)—most of which are present in this part of the Mallapunyah Formation.

As the overlying cauliflower cherts in units D and E are remarkably similar to the anhydritic nodule beds in the Abu Dhabi sabkhas, Muir (1979e) suggested a direct analogy between them. These nodule beds form high in the supratidal zone, in an area which is almost never flooded by sea water. Concentrated brines derived from marine and continental groundwater precipitate sulphates and carbonates which grow interstitially in the uncompacted sediments (Kendall, 1979; Kinsman, 1969; Shearman, 1966).

At a detailed level, however, such a direct comparison is not so evident. Unit D comprises many thin cycles (each around 1 m thick) which contain the large displacive cauliflower cherts in their upper halves (B and C, Fig. 64). These are similar to those at Abu Dhabi (A, Fig. 64), but the lower halves of the Proterozoic cycles show significant variations from the features in the modern-day cycles, the most notable being in the character of the subtidal or lagoonal sediments low in the cycles and the more common erosion within the Proterozoic examples.

Much of unit F consists of a similar facies to that in the lower parts of these cycles and is thus interpreted to be of more marine character. Desiccation cracks and intraclast breccias, however, indicate periods of emergence, suggesting a shallow environment (?intertidal), but *Conophyton*-like stromatolites and large domal stromatolites with synoptic relief of several decimetres indicate water at least this deep during some of the time. The continued activity of highly saline brines is indicated by the presence of skeletal halite pseudomorphs.

The uppermost beds at the type section were laid down on an erosion surface following a regression of the underlying sabkha shoreline. The interbedded sandstone and mudstone facies of unit G is crowded with hopper halite casts and moulds and, as noted above, is similar to the European 'haselgebirge facies'. It contains evidence of emergence (desiccation cracks) and traction currents (sole structures and ripple marks), and appears to be broadly similar to but coarser-grained than the continental deposits lower down in

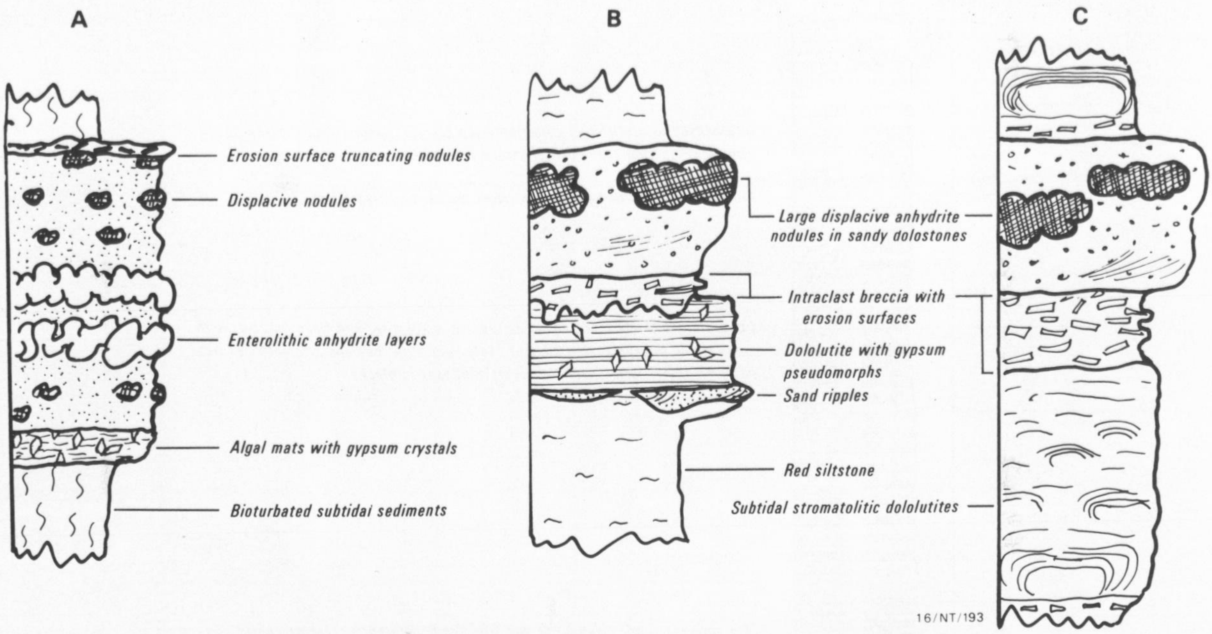

Fig. 64. Characteristic features of the modern coastal sabkha at Abu Dhabi (A), after Shearman (1966) and Kinsman (1979), compared with two typical cycles (B and C) from unit D in the Mallapunyah Formation at the type section.

the formation. However, the rocks are dominantly sandstone, and the stratification is more laterally persistent and more regular than that in units A, B, and C. Handford (1981) described and illustrated very similar 'haselgebirge facies' from the Permian of Texas, and compared them with coastal sabkha salt-pan environments.

The uppermost beds of the formation show a gradual change to a stromatolitic dolostone facies, which reflects a gradual increase in marine influence.

In summary, the Mallapunyah Formation contains a range of continental and peritidal facies. The relative stratigraphic positions of these facies in the various measured sections, and the subtle lateral variations that are evident, indicate a complex history of deposition with frequent migrations of the shoreline. As described below, the overlying Amelia Dolomite contains critical elements of this scenario.

AMELIA DOLOMITE

The Amelia Dolomite is the oldest conspicuously stromatolitic unit in the McArthur Group. It consists mainly of prominently outcropping stromatolitic dolostones, and is underlain and overlain by the mainly clastic Mallapunyah Formation and Tatoola Sandstone. In places, it contains massive beds of dark brown sideritic 'marble' which represent unusual and thick beds of former gypsum crystals. The presence of these beds in the Amelia Dolomite, and other evaporites in the associated formations, is of world-wide significance . Walker & others (1977) used them to unequivocally show that large volumes of sulphate evaporites were present in mid-Proterozoic times. This assertion was in contradiction to most existing models of crustal, hydrospheric, and atmospheric evolution, which implied that there were no significant evaporites of this type before about 800 Ma ago.

The name is derived from Amelia Creek, a small ephemeral creek that joins the left bank of the Glyde River about 20 km south-southeast of the McArthur mine (Plate 1). Most of the dolomitic outcrops in the area between the northeast side of the Abner Range and the Emu Fault Zone were originally mapped as Amelia Dolomite (Smith, 1964), but more recent work has shown that these outcrops comprise rocks belonging to not only the Amelia Dolomite but also to several other formations in the Umbolooga Subgroup and to younger formations.

The middle stromatolitic dolostone part of the 'Festing Creek Formation', which crops out along the eastern side of the Tawallah Ranges in BAUHINIA DOWNS (Smith, 1964) and MOUNT YOUNG (Plumb & Paine, 1964), comprises typical Amelia Dolomite although in places it is intensely silicified. As noted above (p. 55), use of the term 'Festing Creek Formation' has been discontinued now. Although Plumb & Paine (1964) described porphyritic basic volcanics and tuffs in the upper part of the 'Festing Creek Formation', Plumb & Brown (1973)—in their revision of the stratigraphy—made no mention of these igneous rocks. Our detailed mapping in 1981 has shown that these volcanics are equivalents of the Settlement Creek Volcanics.

The Amelia Dolomite was the target for early sedimentological and palaeontological studies in the basin. Croxford & others (1973) and Muir (1974, 1976) described microfossils from the formation, and interpreted them as mainly the remains of blue-green algae.

Because of the interesting evaporitic textures and the variety of stromatolites present, we have also examined the Amelia Dolomite in some detail (e.g., Muir, 1979e; Jackson, 1980a). In addition, the formation is the host to a number of unusual uneconomic copper deposits which are discussed below (p. 161).

Distribution and thickness

The Amelia Dolomite crops out over a similar area to the Mallapunyah Formation—that is, the northern part of WALLHALLOW, most parts of BAUHINIA DOWNS, and on the flanks of the Tawallah Ranges in central MOUNT YOUNG (locality map, Plate 1). The stromatolitic dolostones are resistant to erosion, and are well exposed in the Top Springs Inlier and in the Mallapunyah and Kiana Domes, along the southern edge of the area; most of our detailed work was done in this part of the basin. The formation also crops out to the west of the Batten Range from Leila Creek

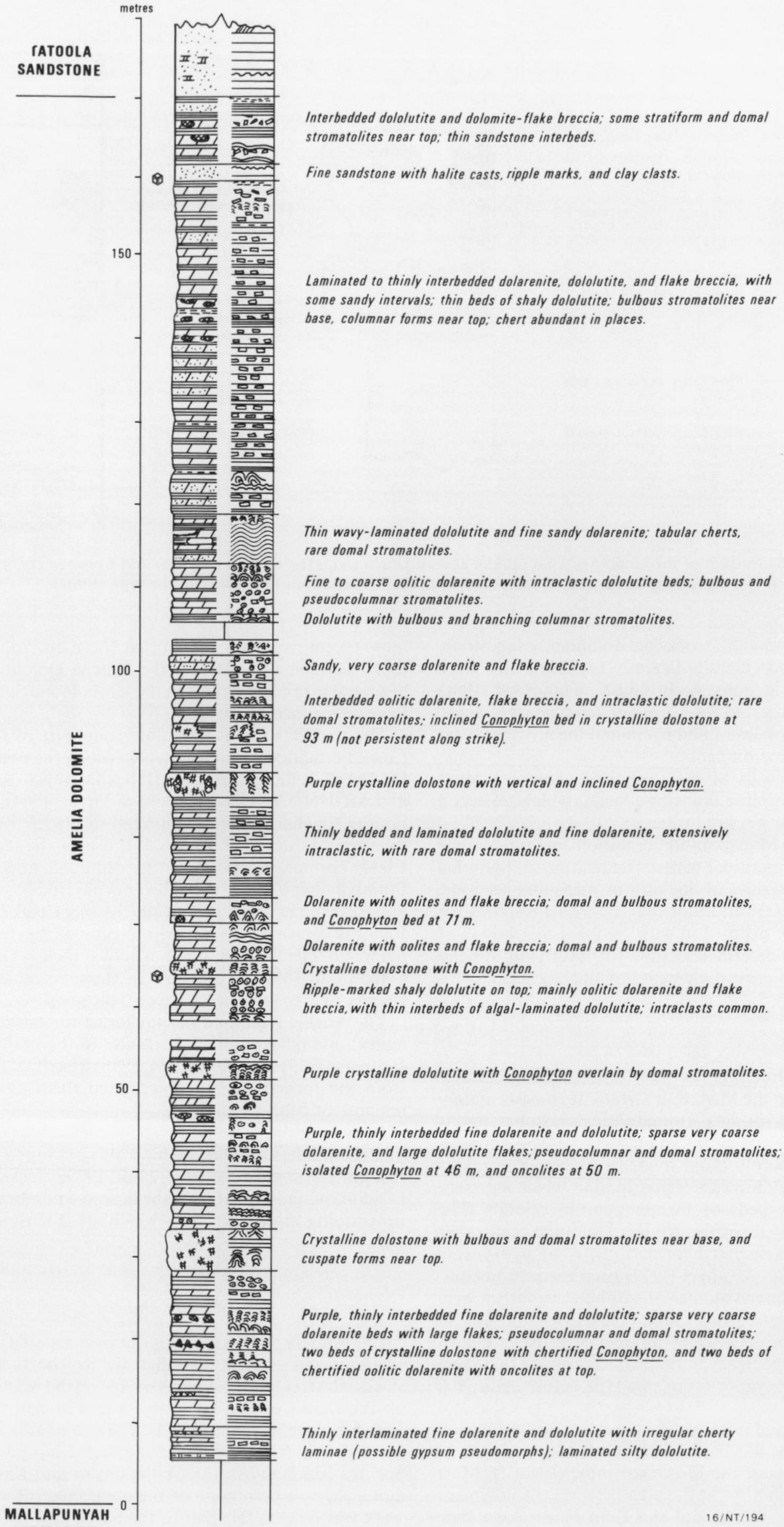

Fig. 65. Type section of the Amelia Dolomite (measured section Kilgour 77/10), in the Kilgour River (from Jackson & others, 1978).

in the south to near Eastern Creek in the north. Early studies of microfossils and evaporitic sedimentary rocks (Muir, 1976; Walker & others, 1977) were concentrated in this outcrop belt near the Leila 1st Crossing (Plate 1).

The Amelia Dolomite is part of a conformable sequence, and in most measured sections it appears to have a uniform thickness of 150 to 180 m. An exception to this is in the Emu Fault Zone, southeast of McArthur mine, where the maximum thickness is about 50 m. In Amoco drillhole No. 6 (Foelsche Inlier) the Amelia Dolomite is about 90 m thick, but it has a brecciated and eroded top, indicating that it was originally thicker.

Type, reference, and other measured sections

Measured section Kilgour 77/10, which forms steep cliffs on the right bank of the Kilgour River east of the Mallapunyah Dome, is here nominated as the type section (Fig. 65). It extends from GR 975125 to GR 990139 (Plate 1). Except for the lower few metres, the formation is continuously exposed, and the upper contact with the Tatoola Sandstone is clearly visible. Although the basal contact is concealed here, it is well exposed at the top of the type section of the Mallapunyah Formation (Fig. 53) only 3 km to the southwest.

Measured section Kilgour 78/06, from the Top Springs area 23 km west of the type section, and measured section Kilgour 78/05, from the Kiana Dome 10 km southeast of the type section, are here nominated as reference sections for the southern belt of outcrops (Appendix Figs. A11, A12 respectively). Measured sections Mallapunyah 77/07, 77/08, 77/09, 77/10, 77/11, and 77/12, all from the Leila Creek area, are reproduced as Appendix Figures A13 to A18, and include examples of evaporite-rich and evaporite-poor sections. Appendix Figure A19 is a summary of the Amelia Dolomite measured by R.N. Walker (Carpentaria Exploration Co. Pty Ltd, written communication, 27 March, 1979) near the McArthur mine. We do not have detailed measured sections from locations farther north, mainly because discontinuous exposures preclude accurate section measuring; however, CEC drillhole Tawallah Pocket No. 1, which intersected about 54 m of the lowermost part of the Amelia Dolomite, provides us with some information on the formation in the north of the area.

Stratigraphic relations

The Amelia Dolomite has conformable gradational contacts with the underlying Mallapunyah Formation and the overlying Tatoola Sandstone, except at Leila Creek, where a local disconformity is recorded at the base of the Tatoola Sandstone (Jackson & others, 1978). The upper contact is represented by a unit of interbedded dolostone and sandstone 5 to 20 m thick.

Lithology

The Amelia Dolomite consists mainly of thinly bedded fine-grained dolarenite and dololutite containing intraclast breccias, flat-pebble conglomerates, oolites, and oncolites; more massive intervals of irregularly chertified stromatolitic dolostone contain a variety of stromatolites. These two basic components have different weathering characteristics: the stromatolitic units are much more resistant to erosion than the intraclastic units, and a stepped outcrop pattern—with cliffs of stromatolitic dolostone 2-3 m high separated by rubble-covered benches—is characteristic of the unit, both in the field and on the airphotos.

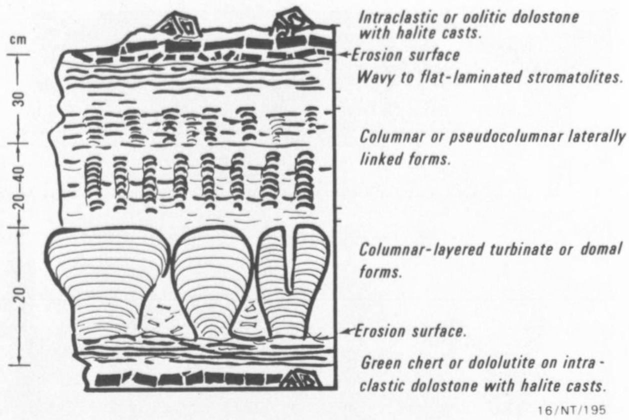

Fig. 66. Basal stromatolite bioherm series in the Amelia Dolomite showing upward shallowing trend. Compare with Fig. 67.

Type section and southern reference sections

At all localities in the south the base of the formation is marked by a distinctive stromatolite bioherm series which is about 1 m thick and comprises turbinate columns or large convex domes (20-30 cm relief) at the base grading up, through pseudocolumnar and columnar non-branching forms, into flat to wavy stratiform stromatolites at the top (Figs. 66, 67). At several localities the base and top of the bioherm are clearly erosional. This bioherm commonly overlies the cherty green ?tuff marker near the top of the Mallapunyah Formation. I. Krylov (Geological Institute, USSR, personal communication, 10 July 1979) compared the columnar turbinate forms with *Omachtenia omachtensis* (lower Riphean of USSR). In some sections a second green cherty ?tuffaceous bed is present above the basal stromatolite bioherm.

The bioherm is succeeded by 60 to 80 m of interbedded stromatolitic and non-stromatolitic (intraclastic and oolitic) dolostones with individual units showing remarkable lateral persistence. Careful examination of the dolostones has revealed eight or nine stromatolite levels. Each of these is between 1 and 4 m thick, having a uniform thickness for hundreds of metres along strike but showing slight thickness variations over tens of kilometres. The intervening intraclastic and oolitic dolostone intervals are between 5 and 14 m thick.

In extremely well exposed sections the stromatolite units can be seen to form distinct bioherm series. A common bioherm series comprises large domes at the base, overlain by large columnar stromatolites, overlain by regular conical forms and finally irregular-branching conical forms at the top. Jackson (1982d) suggested a correlation between the Amelia bioherms and the '*Jacutophyton* cycles' from the lower Riphean of USSR (Serebryakov, 1976), because the two types share a remarkable similarity in stromatolite types, cycle characteristics, and vertical and lateral dimensions. Although originally thought to be *Conophyton*, and still described as such on many of the measured sections, rare three-dimensional outcrops indicate that a variety of shapes and forms is present. Some of the conical stromatolites are branched or laterally interconnected, and have a range of ridges and buttresses on their flanks (Fig. 68). Although some are circular in cross-section (Fig. 69) many are distinctly asymmetrical (Fig. 70) and some are star-shaped (Fig. 71).

In detail, therefore, these '*Conophyton*' bioherms are obvious complexes of many stromatolite forms. The two components of the lower half of the Amelia Dolomite (i.e., the stromatolitic units and the intraclastic units) are intimately interstratified and obviously closely related facies.

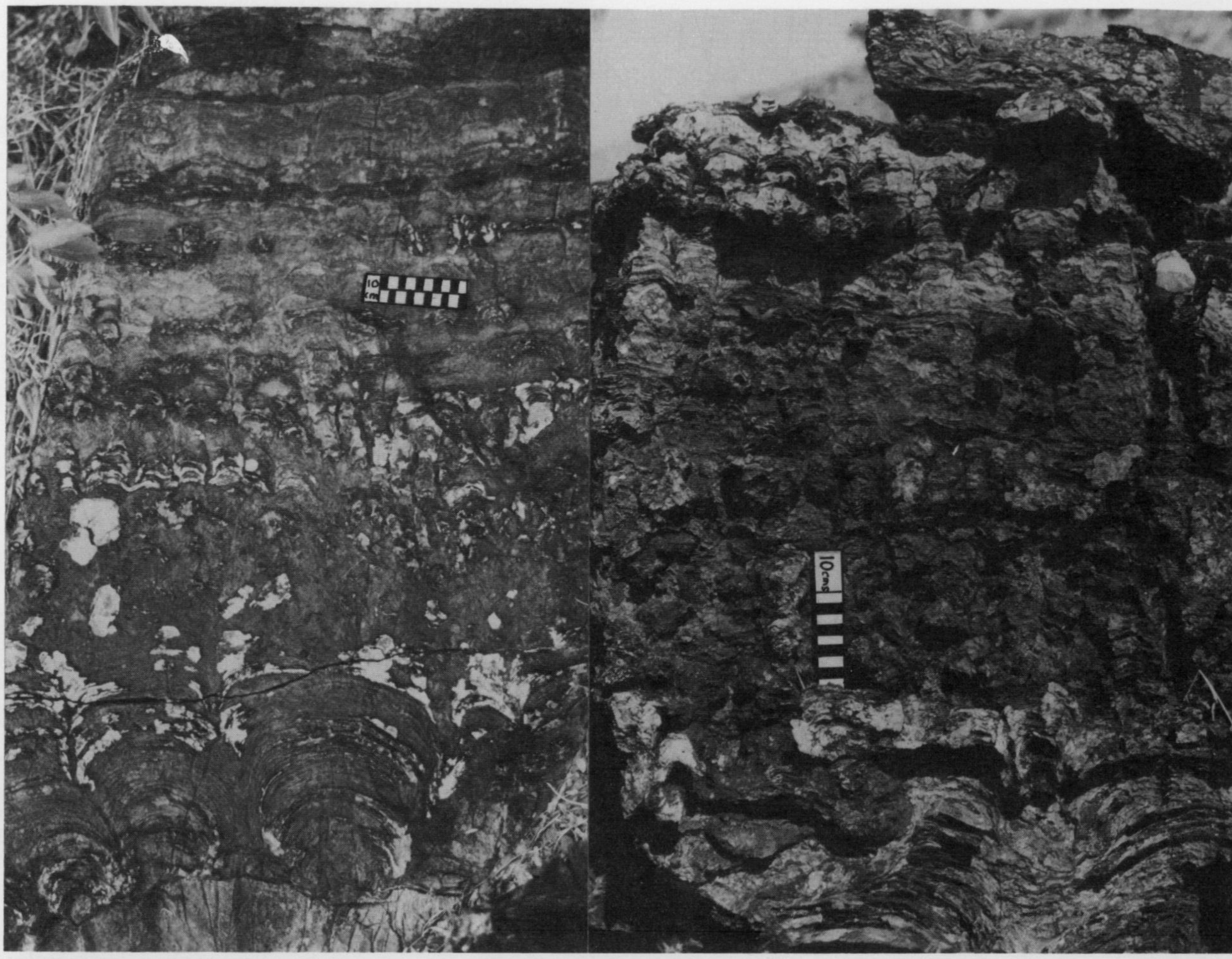

Fig. 67. Basal stromatolite bioherm series in the Amelia Dolomite at the type section (left) and near Mallapunyah homestead (right). Although detailed lateral variations are evident, the basic trend from large domes at the base through smaller columnar forms to stratiform stromatolites at the top is apparent at these two widely separated localities (cf. Fig. 66). At both localities the bioherm is capped by intraclast breccias (top of both photographs). (BMR negatives M2568/16A, left; M2568/30A, right)

The overlying part of the Amelia Dolomite (e.g., 110–170 m in Fig. 65) is everywhere dominated by the intraclastic facies (Fig. 72), but it contains solitary rare stromatolites which have an aspect of being 'drowned out' by the coarser-grained detritus (Fig. 73). In the east (type section and at Kiana) this upper part of the formation is about 60 m thick, but in the west (Top Springs) it is almost twice as thick and contains a significant proportion of quartz sand (100–200 m, Appendix Fig. A11). Except for the thickness difference, the sand content, and a higher content of ooliths in the west there are no other obvious differences between the lithologies of these two areas. A similar depositional environment is thus indicated, but the Top Springs area must have been closer to a source of clean quartz detritus, and may therefore represent a more proximal facies. This is supported by the presence in the Top Springs area of two prominent breaks in sedimentation marked by ferruginised and/or silicified, vuggy and brecciated dolostones (at 78 and 105 m, Appendix Fig. A11). Although the intraclasts and flake breccias indicate shallow water with considerable agitation and penecontemporaneous and early postdepositional breakup of sediments, these more obvious stratigraphic breaks are much more significant features: they indicate longer periods of emergence and erosion, and may represent fossil wave-eroded platforms (cf. Donaldson & Ricketts, 1979).

An additional conspicuous stromatolitic unit, slightly different from those already described, occurs near the middle of the formation at the type section (101–105 m, Fig. 65), about two-thirds of the way up the section at Kiana (134–139 m, Appendix Fig. A12), and at a somewhat higher level in the Top Springs area (175–180 m, Appendix Fig. A11); it forms a useful marker bed for mapping. It is composed of fine-grained yellow to tan dololutite, and contains columnar, domal, turbinate, and wavy stromatolites. Unlike the basal bioherm series it does not show a consistent vertical change in stromatolite form (see measured sections for details) and it appears to have sharp boundaries with the overlying and underlying sandy intraclastic and oolitic rippled dolostones.

All of these sections of the Amelia Dolomite along the southern margin of the basin contain rare halite casts and gypsum crystal pseudomorphs.

Foelsche Inlier

Although not well exposed in this area the Amelia Dolomite is of similar thickness to sections near Mallapunyah and contains a variety of stromatolitic dolostones and intraclastic units.

Leila Creek area

Six sections of the Amelia Dolomite (Mallapunyah 77/7 to 12, Appendices Figs. A13 to A18) were measured by M. D.

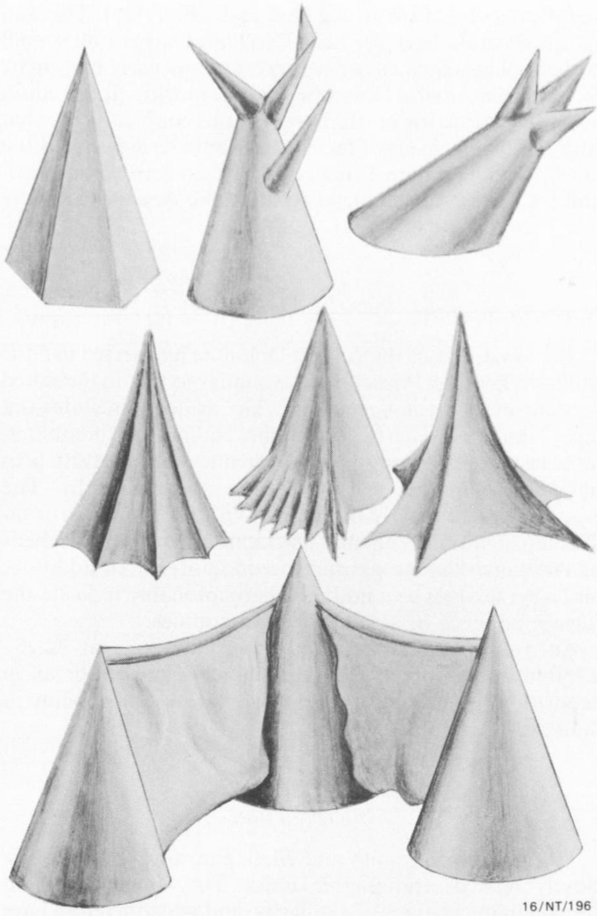

Fig. 68. Sketches showing variety in the external form of *Conophyton* and *Jacutophyton*-like stromatolites in the Amelia Dolomite in the Kilgour River.

Muir west of Leila 1st Crossing in 1975, before BMR's program of specialised studies in the McArthur Basin started. These sections have not been re-examined in detail for bed-to-bed comparison with the type area (60 km to the south), but in general the Amelia Dolomite near Leila Creek appears to be broadly similar to that in the type area. Muir erected an informal five-fold stratigraphic subdivision of the Amelia Dolomite in the Leila Creek area, and suggested a correlation with the type area (*in* Jackson & others, 1978, table 1). Later studies have failed to substantiate a distinct five-fold subdivision of the formation in the type area, so this informal scheme is not suitable for more than very localised correlation, and is not used here.

Broad similarities between these two widely separated localities are apparent, especially in the predominance of stromatolite bioherm series with conical and domal stromatolites in the lower half of the formation and oolitic and intraclast breccias higher up. However, the volume of evaporites is considerably greater in the Leila Creek area, where late-diagenetic replacement of anhydritic and gypsiferous carbonates (Fig. 74) has produced units of sideritic 'marble' (Fig. 75) up to at least 30 m thick (e.g., Appendix Figs. A17, A18). The distribution of these former sulphate evaporites is patchy: it varies from complete replacement of all the early carbonates by sulphate to no replacement at all. Beds of sideritic 'marble' several metres thick lens out laterally over distances of tens to hundreds of metres.

Masterton Horst

The Amelia Dolomite on the northern flank of the Masterton Horst, which is at about the same latitude as Leila Creek (45 km to the west) also contains thick evaporite beds. It comprises mostly massive sideritic 'marble' with gypsum crystal pseudomorphs, but remnants of the original desiccation-cracked dolostones with domal stromatolites and small

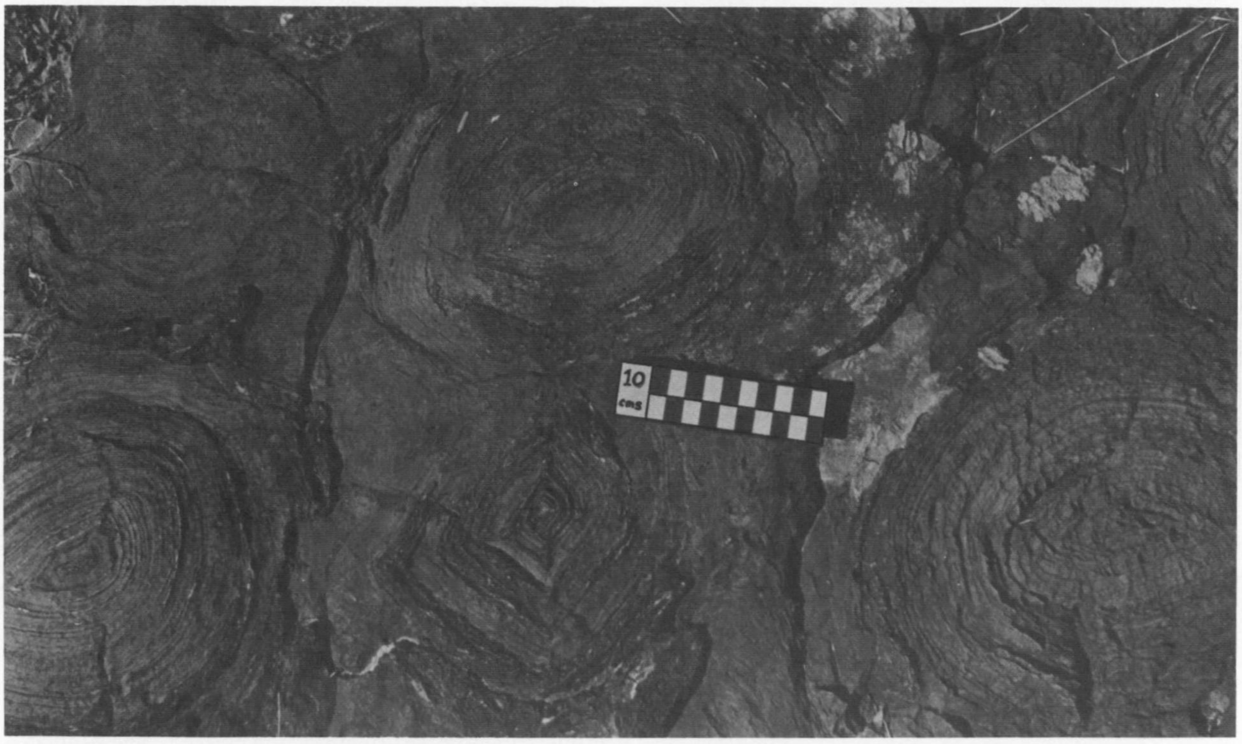

Fig. 69. Horizontal bedding surface showing cross-section of large *Conophyton*-like stromatolites in the Amelia Dolomite at the type section. (BMR negative M2568/23A)

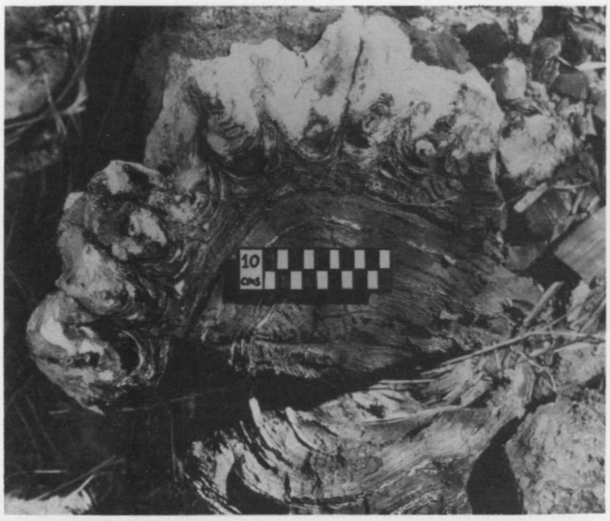

Fig. 70. Bedding-plane section of tear-shaped *Conophyton*-like stromatolite in the Amelia Dolomite at the type section, Kilgour River; the tail points to the right side of the photo, and the axis is normal to the plane of the photo. Note the chert-infilled 'buttresses' along only one side of the stromatolite. (BMR negative M2568/33A)

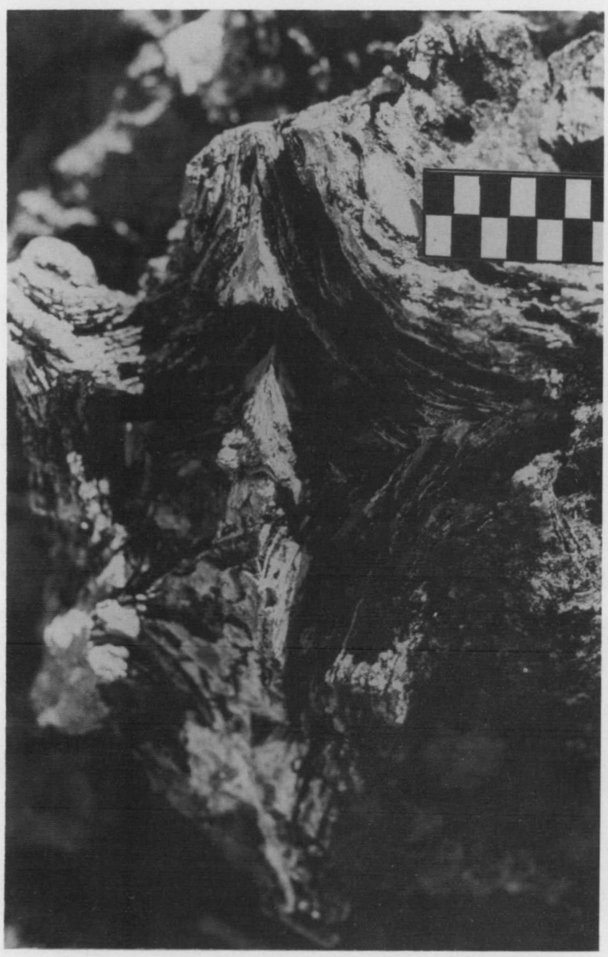

Fig. 71. Star-shaped conical stromatolite in the Amelia Dolomite at the type section, Kilgour River; view looking vertically down the central axis of the cone. The algal laminations are preserved in laminated chert. The scale subdivisions are 1 cm long. (BMR negative M2568/32A)

cauliflower cherts are visible (Appendix Fig. A19). This and the information from the Leila Creek area suggest an overall latitudinal arrangement of sedimentary and early diagenetic facies in the Amelia Dolomite: non-evaporitic in the south and evaporitic in the north. However, this conflicts somewhat with the arrangement of facies that would be expected if the north-trending Batten Trough had been an active palaeogeographic feature during deposition of the Amelia Dolomite (see Plumb & others, 1981, p. 247).

Northern localities

The lower part of the Amelia Dolomite intersected in CEC drillhole Tawallah Pocket No. 1 is similar to that in measured sections in the Leila Creek area. The drillcore includes flat algal-laminated cherty dolostone, domal stromatolites, intraclastic, oolitic, and rippled dolarenites, and extensive beds of sideritic 'marble' with evaporite pseudomorphs. The evaporites were mainly originally gypsum, and range from disseminated small euhedral pseudomorphs to massive beds of large interlocking gypsum pseudomorphs. In addition, bird's-eye textures and nodular cherts probably indicate the former presence of small anhydrite nodules.

An extensively leached and brecciated zone at 22.20–22.50 m in the core, is related to either a marked break in deposition similar to those near Top Springs, or possibly to faulting.

Interpretation

The Amelia Dolomite and Mallapunyah Formation are closely related stratigraphic units. They interfinger and contain many features of similarity, and must therefore have had complementary depositional environments. Thus an interpretation of the setting of the Amelia Dolomite must be compatible with and evolve from the evaporitic continental to sabkha setting envisaged for the Mallapunyah Formation. Muir (1979e) discussed in detail the evolution of the evaporites in both units, and suggested that the diagenetic changes took place within sediments in a marginal marine sabkha setting strikingly similar to the Pleistocene and Holocene Abu Dhabi sabkha. In a later paper (Muir,1983c), however, she noted that these evaporitic rocks could be either marine or continental. We do not propose to repeat at any length her results, but will concentrate mainly on analysing the original depositional environments.

In addition to the evaporites the Amelia Dolomite contains a range of environmentally diagnostic lithologies, sedimentary structures, and textures. Breaks in sedimentation, ranging from minor diastems to more obvious breaks where the exposed surface has undergone karstic weathering, are very common throughout the whole formation, suggesting that at no stage was the Amelia Dolomite deposited far from the water–air interface. With the variety of structures present a plethora of subtly varying subfacies could be defined, but in essence two depositional facies dominate: (1) intraclastic and (2) stromatolitic. The intraclastic and stromatolitic facies indicate deposition under contrasting agitated and quieter conditions.

The *intraclastic facies*—comprising intraclast breccia, flat-pebble conglomerate, and oncolites—provides evidence of extensive erosion. This erosion probably happened during storms, and is most likely to have occurred on supratidal flats or in subtidal channels (Shinn, 1983). Cross-stratified oolitic and sandy dolarenites indicate slightly deeper-water environments with more persistent traction currents. The stromatolites that are present in this facies are usually solitary domal or turbinate forms that persisted only for short periods before

Fig. 72. Intraclastic flat-pebble conglomerate composed of elongate clasts of dololutite in coarse-grained sandy dolarenite matrix, Amelia Dolomite at the type section, Kilgour River. Note the lack of imbrication of the clasts. The eraser is 7 cm long. (BMR negative M2568/28A)

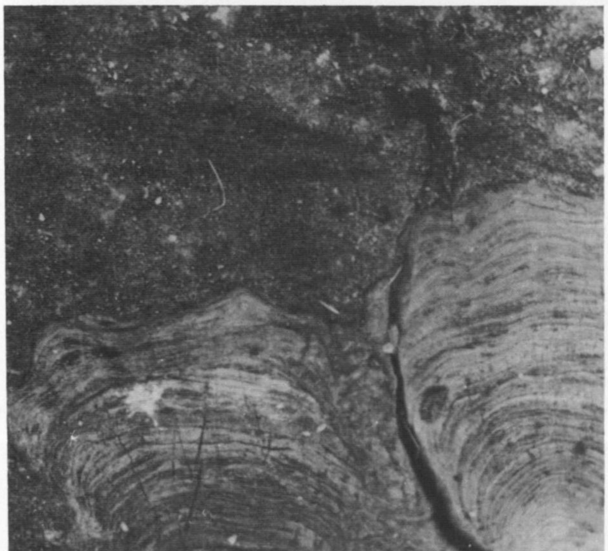

Fig. 73. Columnar stromatolites in the upper part of the Amelia Dolomite 'drowned out' by coarse-grained cross-stratified sandy dolarenite in the Leila Creek area. Width of field of view is 17 cm. (BMR negative M2568/17A)

Fig. 74. Thin section of sideritic 'marble' from the Amelia Dolomite at Leila 1st Crossing (GR 725680): discoidal and interpenetrating crystals of siderite (after gypsum) in fine-grained laminated and stylolitic dololutite. Note the loss of some crystals along stylolites, and the penetration of algal laminations by crystals, indicating a diagenetic origin.

being drowned-out by the coarse debris. Eriksson (1977), James (1979a, b), and Smosna & Warshauer (1981) have described similar features from high intertidal to supratidal

Fig. 75. Sideritic 'marble' in the Amelia Dolomite at Leila 1st Crossing: algal-laminated dololutite shows extensive replacement of a 'mush' of former gypsum crystals by ferroan dolomite.

settings, and a similar environment is envisaged for the intraclastic facies of the Amelia Dolomite. The hypersaline character of the facies suggests a tidal-flat depositional environment similar to that of the arid Persian Gulf (rather than a more humid setting such as the Bahamas).

The *stromatolitic facies*—in which individual units are commonly bounded by diastems above and below but seldom show signs of erosion internally—comprises algal-laminated coarsely crystalline dolostone which lacks quartz and other detritus, and which was probably deposited in low-energy environments as fine-grained algal-bound or algal-precipitated dololutite. Some of the Amelia bioherms show an upward decrease in synoptic height, which in most published examples has usually been interpreted as suggesting gradual shallowing (Walter, 1976; James, 1979b). However, in the Amelia Dolomite, the stromatolitic and intraclastic facies are not arranged into clear and obvious shallowing cycles like those described by Aitken (1966), Hoffman (1976b), Cecile & Campbell (1978), and James (1979b). We feel therefore that the alternating facies in the Amelia Dolomite are unlikely to represent regular regressive events (shoaling cycles), but are more likely to reflect tectonically induced rapid alternations of deposition in two contrasting settings: agitated intertidal and supratidal flats on the one hand, and quiet-water lagoons or lakes on the other. The mechanism causing the stacking is not clear. The lateral persistence of most of the eight to nine major bioherm series over tens of kilometres indicates that these lagoons or lakes must have been extensive bodies of water. Serebryakov (1976) discussed in some detail the problems associated with an environmental interpretation of similar stromatolite cycles and bioherm series in the USSR.

As noted by Muir (1979e), lateral variations in the evaporites can be correlated with the complex facies arrangement in modern marginal-marine sabkhas. In the Trucial Coast sabkhas, for example, Butler (1969) reported a direct correlation between the frequency and extent of flooding, the mineral phases developed, and the chemical composition of interstitial brines. He found that the most extensive deposition of gypsum crystal mushes is essentially restricted to a narrow zone adjacent to the gulf, and that anhydrite gradually replaces gypsum inland. Following this analogy for the Amelia Dolomite, the contrast in evaporites between the southern (Top Springs–Mallapunyah–Kiana) and northern (Leila Creek–Masterton Horst) outcrops suggests a more terrestrial environment in the south. As noted above, and emphasised by James (1979a, b), however, these types of environments today are very complex, and numerous sub-environments exist in close proximity both perpendicular and parallel to the shorelines, so our tentative palaeogeographical reconstructions should be treated with caution.

Discussion

The similarity in the facies of the Mallapunyah Formation and Amelia Dolomite west (Kiana, Mallapunyah) and east (Foelsche Inlier) of the Emu Fault Zone suggests to us that the Batten Trough was not a dominant feature of the palaeogeography at this stage of the evolution of the southern part of the McArthur Basin (cf. Plumb & others, 1981). The reduced thicknesses and stratigraphic breaks in the Foelsche Inlier, however, may reflect localised tectonics (fault movements) as precursors to the main development of the Batten Trough during upper Umbolooga and Batten Subgroup times.

TATOOLA SANDSTONE

The Tatoola Sandstone is a distinctive white-weathering quartz sandstone that separates the Amelia Dolomite from the Tooganinie Formation, both mainly dolomitic formations. It commonly crops out well and is a valuable stratigraphic marker. It has been emphasised with a heavy line screen in Plate 1 to assist in displaying the regional structure of the lower part of the McArthur Group. Because of its distinctive lithology it was mapped accurately during the original reconnaissance mapping, except (1) in the east, where it was previously mapped as part of the 'Eastern Amelia Dolomite' (see Plumb & Brown, 1973), and (2) in northeastern BAUHINIA DOWNS and adjacent MOUNT YOUNG, where a unit of blocky white to pink medium-grained quartz sandstone was mapped as the 'Warramana Sandstone' or 'upper Festing Creek Formation'; these terms have been abandoned now.

The name of the formation is derived from Tatoola Creek a tributary of the McArthur River southwest of Top Crossing (grid square 8044). The formation crops out extensively in the headwaters of the creek.

The Tatoola Sandstone is one of the formations that we have not studied in detail. We have enough information to provide an adequate stratigraphic definition and to suggest a likely environment of deposition, but not enough to provide a systematic analysis of its origin and lateral characteristics.

Distribution and thickness

The Tatoola Sandstone crops out over a similar area to the underlying Mallapunyah Formation and Amelia Dolomite—that is, the northern part of WALLHALLOW, most parts of BAUHINIA DOWNS, and the southern and northwestern parts of MOUNT YOUNG. It crops out extensively in the southwest of the Abner Range region (Plate 1).

Muir (1979c) suggested that a conspicuous white sandstone in the Vizard Formation at Mount Vizard (URAPUNGA) may be the lateral equivalent of the Tatoola Sandstone.

We do not have reliable information on thickness variations in the formation. The only accurately measured thickness is 120 m at the type section in the south. At most other localities it appears to be of a similar thickness, or thinner. However, this impression of slightly thinner sections in some areas may be caused by the lack of continuity of outcrop, and the gradational upper stratigraphic contact of the formation.

Type section

Measured section Kilgour 77/09, located in the Kilgour Gorge east of the Mallapunyah Dome, is here nominated as the type section (Fig. 76). It extends from GR 984145 to GR 986146 in Plate 1.

Stratigraphic relations

In most areas the Tatoola Sandstone appears to have a conformable lower contact and a gradational conformable upper contact, but a local unconformity is noted at the base of the Tatoola Sandstone at Leila Creek (Jackson & others, 1978) and Yah Yah. In most areas the Tatoola Sandstone comprises a lower fine-grained sandstone, and an upper medium to coarse-grained sandstone which commonly contains a few interbeds (2–3 m thick) of poorly exposed dolostone; we define the base of the overlying Tooganinie Formation at the start of more-or-less continuous dolostone deposition.

A more complex stratigraphic relationship between the Tatoola Sandstone and the underlying Amelia Dolomite is apparent in the Yah Yah area (southwest corner of Plate 1), where Umbolooga Subgroup rocks are unconformably overlain by Roper Group rocks in a series of faulted north-plunging anticlines. Although extensively calcreted and poorly exposed, the Amelia Dolomite in this area contains sinuous bedding trends and is considerably brecciated. The overlying Tatoola Sandstone has more open folds and dips more regularly off the flanks of the anticlinal cores of Amelia Dolomite. We interpret this complexity near Yah Yah as being due to local evaporitic tectonics, in which the Amelia–Tatoola contact was a zone of decollement along which detachment occurred and under which the Amelia Dolomite was more tightly folded. Similar types of stratigraphic relationships, in which more tightly folded beds are overlain by gently flexured units, occur at other levels in the McArthur Basin sequence (e.g., in the Wollogorang Formation, see p. 33, and Tooganinie Formation, see p. 80).

Lithology

In almost all areas the Tatoola Sandstone can be divided into a lower fine-grained flaggy facies and an upper medium to coarse-grained thicker-bedded sandstone and dolostone facies. Even in areas where later pervasive silicification is evident (e.g., along the southeastern side of the Tawallah Ranges) this two-fold subdivision is clearly visible. The sandstones are commonly pale grey, pale green, or pale brown.

The lower fine-grained facies consists mostly of very fine to fine-grained quartz sandstone which in places grades to siltstone. At the type section some intervals are slightly micaceous, and, in the Leila Creek area, tuffaceous siltstone is present. The bedding is mostly continuous and commonly flaggy to fissile. Pinch-and-swell is rare at the type section, but common elsewhere.

Small shallow channels (only centimetres deep) filled with medium sand and with erosional basal contacts are evident in the type section in the basal 30 m (Fig. 76). Much more impressive channels, aligned northwest, occur near Leila 1st Crossing (GR 725685, Plate 1), where lenses of fine-grained sandstone 1.5 m thick × 20 m long occur in a facies of flaggy interbedded sandstone and tuffaceous siltstone (Fig. 77). These lenses of sandstone are loaded into the underlying beds, and the sediment in them is complexly contorted. This facies also contains intervals of plane-laminated sandstone and possible hummocky cross-stratification.

In addition to pinch-and-swell and load-casts the lower Tatoola Sandstone is characterised by the presence of numerous bedding-plane markings which we have variously termed parting lineation and swish, prod, groove, scrape, swirl, and feather-like markings (Fig. 78). Clay and dololutite clasts, and impressions of these, are common in the type section, and so too are the bedding-plane markings noted above; the clasts are probably the source of the groove-and-scrape marks, but the origin of the faint and delicate swirl and feather-like surface markings is not clear.

A variety of ripple marks is present in the type section, including both symmetrical and asymmetrical ripples, interference ripples, and microripples (millimetre-scale wavelength and amplitude). Larger bedforms are common at Leila 1st Crossing, where climbing ripples (Fig. 79) and hummocky cross-bedding are visible.

In the type section, desiccation or syneresis cracks are present between 40 and 50 m, and halite casts and moulds are present at several levels (Fig. 76). Towards the top of the lower subdivision, the sandstone becomes coarser, the bedding becomes thicker, and the ripples are larger and commonly planed-off. Poorly outcropping dololutite between 67 and 72 m contains irregularly chertified domal (30 cm × 20 cm) and *Conophyton*-like stromatolites. The top of the lower subdivision is somewhat arbitrarily placed at 81 m, where coarse sandstone becomes dominant.

In the coarser-grained thicker-bedded upper part of the Tatoola Sandstone the rocks grade from ferroan dolomitic sandstone into sandy dolostone, which in place is intraclastic or conglomeratic. Pitted weathering surfaces are common. At Leila 1st Crossing, rhombic vugs resembling swallow-tail twinned gypsum pseudomorphs are present in these beds. Larger ripples and decimetre-scale wedge and trough-cross-stratification replace the surface markings characteristic of the lower subdivision.

Laterally linked domal and pseudocolumnar stromatolites and small isolated turbinate stromatolites (10 cm diameter), similar to those present in the underlying Amelia Dolomite, are well exposed in the type section. Repeated bioherm series similar to those in the Amelia Dolomite are generally not present. However, there are two possible examples: one at 93 m (Fig.76), where domal stromatolites (30 cm diameter × 6 cm relief) are capped by small pseudocolumnar forms (2 cm × 1 cm); and the other at 100 m, where domal stromatolites (75 × 10 cm) are capped by larger domal stromatolites (up to 1.5 m × 20 cm).

The presence of oncolites and large laminated dololutite clasts within the coarse dolomitic sandstone is evidence for the penecontemporaneous erosion of algal-bound sediments. The pebbly dolomitic sandstone between 105 and 108 m contains clasts of red–brown coarse-grained quartz sandstone, a rock type not indigenous to the Tatoola Sandstone. This indicates erosion of a nearby source area containing that rock type, which is most likely to have been derived from the Mallapunyah Formation or Masterton Sandstone.

The Tatoola Sandstone in a well exposed section near Amos Creek (GR 755500), about half-way between the type section

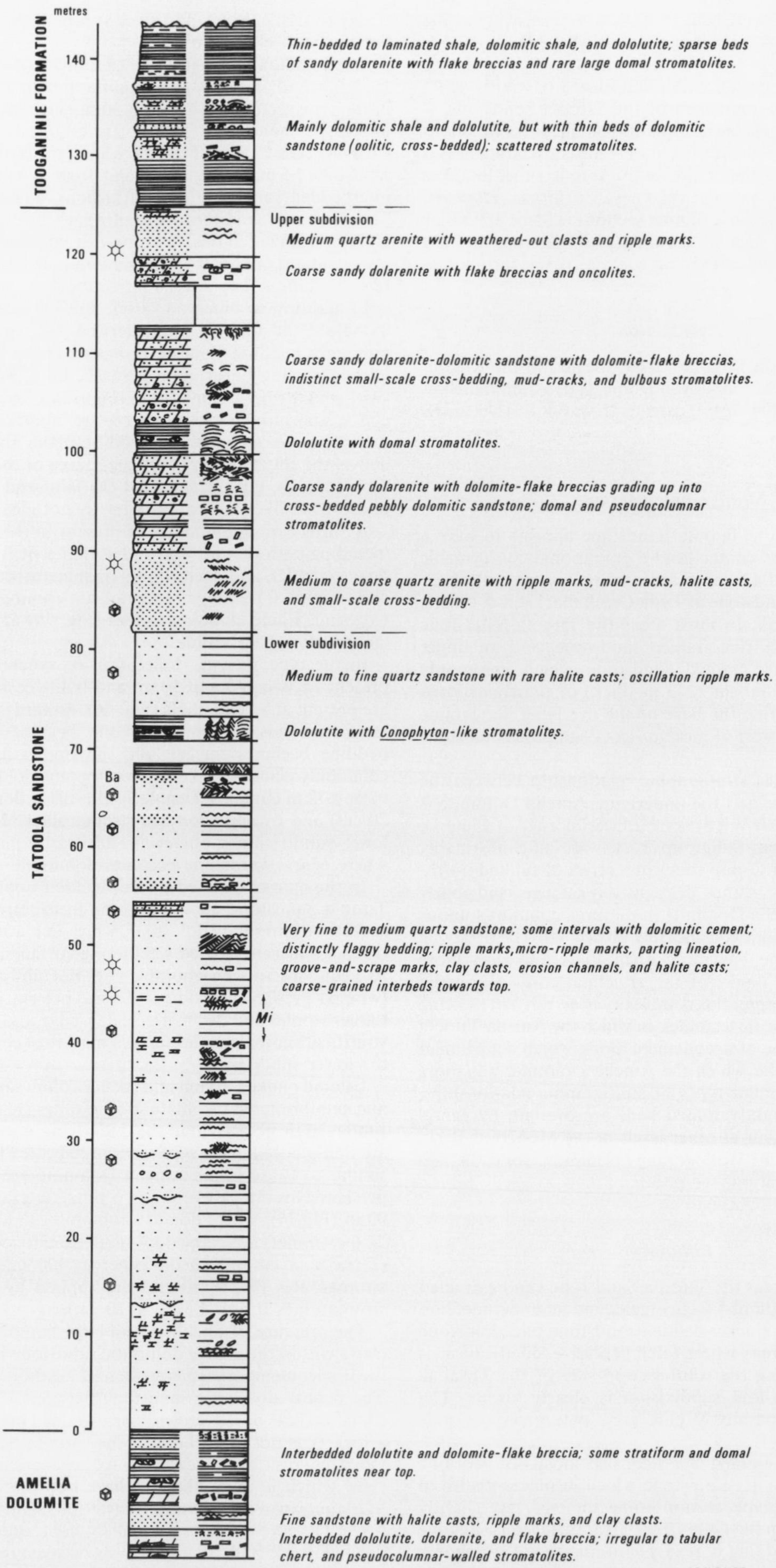

Fig. 76. Type section of the Tatoola Sandstone (measured section Kilgour 77/09), in the Kilgour River (modified after Jackson & others, 1978).

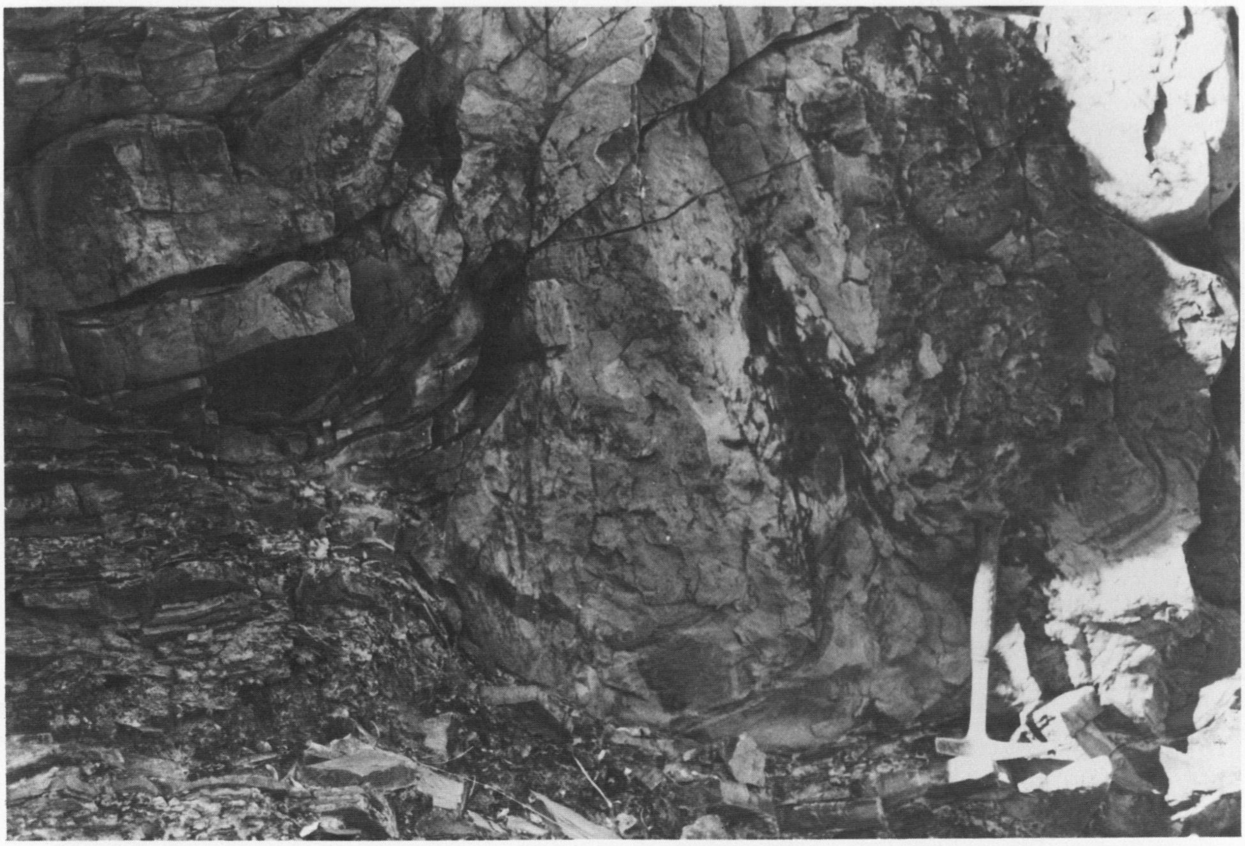

Fig. 77. Load-casted and slumped channel sandstone (on right) in thin-bedded sandstone and siltstone of the Tatoola Sandstone near Leila 1st Crossing.

Fig. 78. Bedding-plane surface of the Tatoola Sandstone showing irregular prod, scrape, and swirl-like surface markings. Float at the type section, in the Kilgour River. (BMR negative M2568/26A)

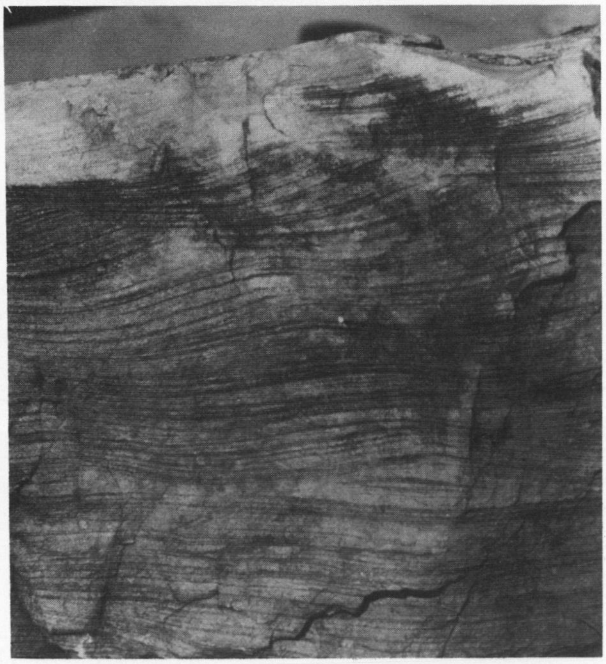

Fig. 79. Climbing-ripple lamination in a sample of the Tatoola Sandstone from Leila 1st Crossing. The width of the field of view is 25 cm. (BMR negative M2552/11A)

and the Leila Creek outcrops, is more like the formation in the type section, but some subtle differences are evident. At the Amos Creek locality, the flaggy beds of the lower subdivision contain either parallel laminations or low-angle trough-cross-laminations with gently curved hummocky partings similar to those present at Leila 1st Crossing. Also, many of the vugs in the upper coarse sandstone subdivision are rhombic in shape and contain limonitic powder (presumably after a ferruginous dolomitic precursor), and may be replacements of evaporites. Climbing ripples-in-drift with palaeocurrents from the southeast are also present at this locality, and so are well preserved large halite casts (up to 2 cm) in the uppermost few metres.

In Amoco drillhole No. 6—located at the northern end of the Foelsche Inlier, about 60 km east of the type section—the Tatoola Sandstone appears to be somewhat thinner than farther west, and—although containing sandstones similar to those elsewhere in the formation—it also contains a much higher proportion of interbedded claystone and siltstone (Fig. 80). The hole was spudded below the top of the Tatoola Sandstone, so the 50 m of sandstone shown in Figure 80 represents only the lower, finer subdivision of the formation as defined farther west. Although the sandstones in the drillhole are similar to those in the type section, they contain more coarse sandstone and are interbedded with a lot of grey-green claystone. Fine-grained clastic partings are only rarely seen in outcrop (for example, the lower part of Fig. 77). Most of the smaller-scale structures in the type section (e.g., ripple marks, cut-and-fill, load casts and halite casts) are also visible in the core.

The sandstone between 20 and 40 m in Amoco drillhole No. 6 is commonly bimodally sorted: a very fine-grained component forms a matrix for the medium and coarse grains*. All of the quartz grains are well rounded, indicating

*This is not evident (if present) in surface sections of the Tatoola Sandstone, where most of the coarser-grained sandstone is weathered and friable.

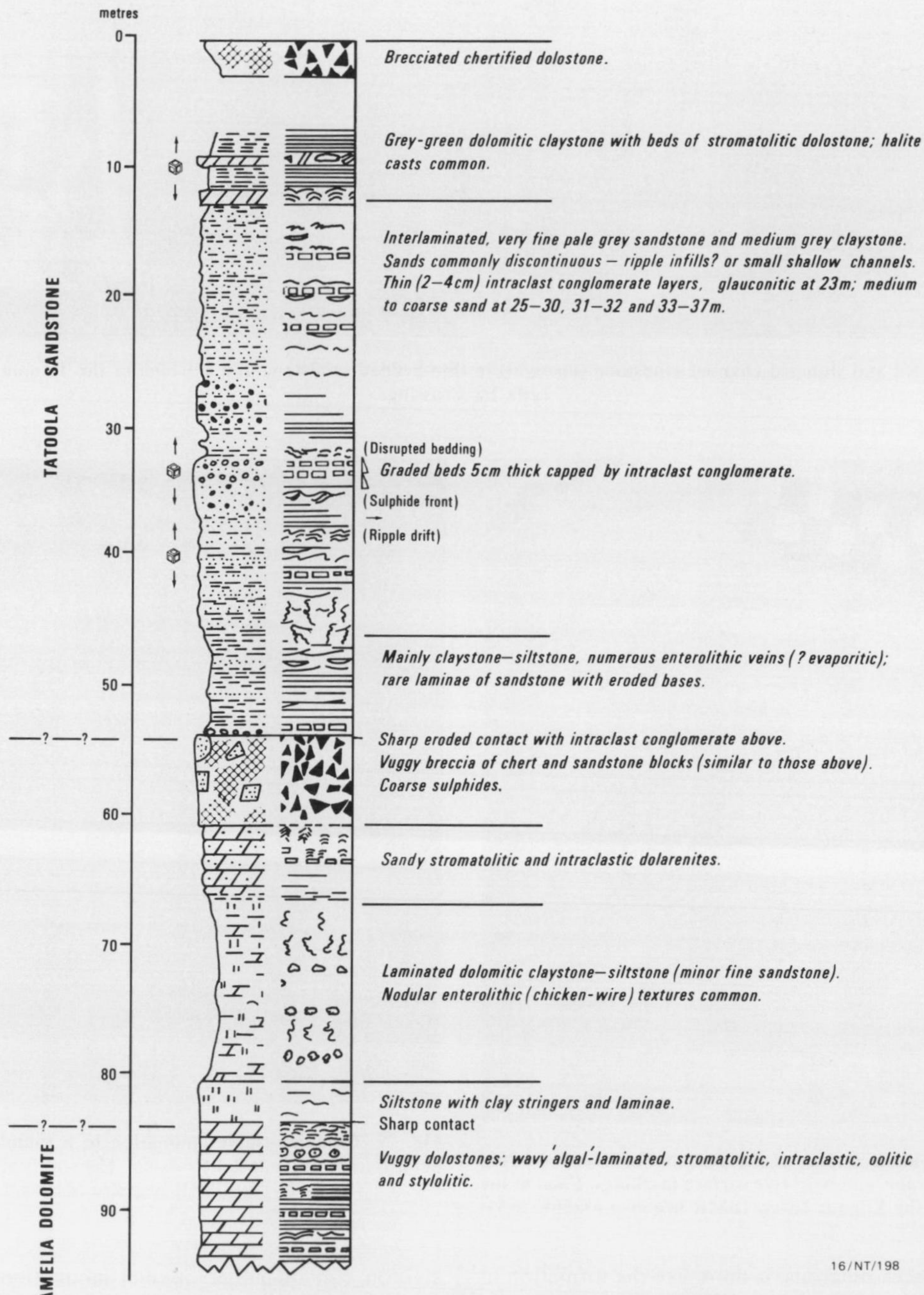

Fig. 80. Lower part of the Tatoola Sandstone in Amoco drillhole No.6, Foelsche Inlier.

a source of mature quartz sand detritus; some intervals are slightly feldspathic, and some contain rare lithic fragments. Large greenish blue clayey grains and matrix (identified by XRD as illite and pyrite) at 28 m are similar to rare dark green grains between 22 and 25 m that we suspect may be glauconite (which is indistinguishable from illite on the XRD equipment used); the illite may have been derived from the suspected glauconite (not enough to analyse) by the loss of iron in the precipitation of pyrite. In addition, disseminated sulphide patches (mainly pyrite, but also chalcopyrite and marcasite) in the sandstone matrix are common. The presence of these sulphide patches in the matrix, and a sharp contact between sulphide-rich coarse sandstone and sulphide-poor dolomitic shale at 38 m suggests that the sulphides are secondary and related to the higher porosity/permeability in the sandstone.

We have shown the base of the Tatoola Sandstone at the top of an unusual brecciated interval at 53 m (Fig. 80). Although typical Amelia Dolomite occurs only below about 82 m, the ex-evaporitic laminated dolomitic claystone and sandy dolarenite (62–82 m) below the breccia are probably better grouped with the Amelia Dolomite than with the Tatoola Sandstone. An evaporitic clayey interval like this could well have provided the lubricating zone to facilitate the type of decollement interpreted at this stratigraphic level in the Yah Yah area. The unusual breccia between 53 and 62 m in Amoco drillhole No. 6 may have been formed as a result of decollement too.

Interpretation

We do not have enough information to attempt a detailed environmental interpretation of the Tatoola Sandstone. However, the formation shows a distinct and widespread coarsening-upwards character, and has a clear interfingering relationship with the peritidal carbonates of the overlying Tooganinie Formation. The depositional setting of the upper coarser part of the Tatoola Sandstone must therefore complement the peritidal evaporitic setting envisaged for the Tooganinie Formation. The interbedded coarse sandy carbonates and dolomitic sandstone that form the upper Tatoola Sandstone contain numerous features (e.g., planed-off ripples, halite casts, intraclast conglomerates, desiccation cracks, and oncolites) that imply an agitated, shallow-water intermittently emergent depositional environment. Deposition mainly in the form of migrating sand shoals and small channels in a peritidal setting seems most likely.

In contrast, the lower finer-grained Tatoola Sandstone contains a significantly different suite of structures that suggest deposition in a quite distinct depositional environment. It also shows evidence of subtle lateral variability, suggesting deposition in a number of subenvironments. At the type section, in the Leila 1st Crossing area, and in the Foelsche Inlier, the basal contact is sharp, and there is a marked lithological contrast between underlying dolostones and overlying clastics. It seems likely therefore that the clastics of the lower Tatoola Sandstone represent deposition of material shed from newly uplifted adjacent blocks comprising largely sandstone (e.g., the Mallapunyah Formation, Masterton Sandstone, or Tawallah Group).

The presence of features such as climbing ripples, load-casts, pinch-and-swell, slumping, and hummocky stratification suggests deposition from fast-moving, heavily laden, partly storm-generated currents within subaqueous environments somewhat deeper than that evident in the associated carbonate formations. Northwesterly directed palaeocurrents, and a comparison of features in the type area with those in the Leila Creek area (to the northwest), indicate that the type area was generally shallower and of a more proximal character. The groove-and-scrape casts, common in the south, indicate currents containing floating and rolling debris. The clay clasts and clast impressions in some sections suggest that these clasts may be the origin of most of the surface markings. These clasts might have been derived from the numerous intraclast breccias and conglomerates that dominate the peritidal facies of the associated upper Amelia Dolomite; the clasts could have been swept out, perhaps in tidal channels, into an adjacent slightly deeper environment. The presence of interference ripples and symmetrical ripples, and the signs of intermittent emergence in the south, are not inconsistent with this environment, but show that Tatoola Sandstone sedimentation never attained a deep-marine setting.

At Leila 1st Crossing some of the lowest sandstone beds are tuffaceous, indicating volcanic activity contemporaneous with the movements that initiated the deposition of this clastic facies.

The basal part of the formation in the Foelsche Inlier is a finer-grained facies with enterolithic veins of dolomite replacing former evaporites (?anhydrite)—a facies which in most other formations we would probably interpret as supratidal.

In summary, our limited studies indicate that the formation is characterised by a rapid initial transgression with the development of subtidal deeper-marine, occasionally storm-affected environments in the north, and shallower, occasionally emergent, more evaporitic and dolomitic environments in the south and southeast. This regional differentiation disappeared near the top of the formation as the whole region gradually shallowed into the peritidal environments characteristic of the Tooganinie Formation.

TOOGANINIE FORMATION

The Tooganinie Formation is a thick unit of mixed dolomitic rocks containing sedimentary structures and textures similar to those in the Amelia Dolomite. Rhythmic alternations of harder stromatolitic dolostone and more easily weathered shale produce a characteristic ribbed pattern on airphotos. We have measured only a few sections through the Tooganinie Formation, and hence cannot supply either a full and adequate systematic description or a detailed interpretation. However, a formal definition is proposed, and comments are provided on several features which are considered significant in environmental interpretations.

Plumb & Brown (1973) separated out two members at the top of the formation—the Myrtle Shale Member and the Leila Sandstone Member. As these two units contain distinctive lithologies that are mappable throughout the region, we here propose to elevate both of them to formation status. Before Plumb & Brown's (1973) stratigraphic revisions, most outcrops of the Tooganinie Formation in the eastern half of BAUHINIA DOWNS had been incorrectly mapped as Amelia Dolomite or 'Hammer Creek Member' (of the Lynott Formation), and the Tooganinie Formation had been interpreted as a back-reef facies restricted to the western half of the Sheet area only (Smith, 1964). Plate 1 shows the revised distribution of the formation in the south-central part of BAUHINIA DOWNS.

The name comes from a creek that flows into the McArthur River 14 km west of Top Crossing. On the *Mallapunyah* (6064) map, this creek is annotated as 'Tooganginie' (not 'Tooganinie' as shown on the older 1:250 000 Geological Sheet). As 'Tooganinie' has been widely published we propose to retain this older name to avoid confusion.

Distribution and thickness

The Tooganinie Formation has a similar distribution to the underlying Mallapunyah Formation–Tatoola Sandstone

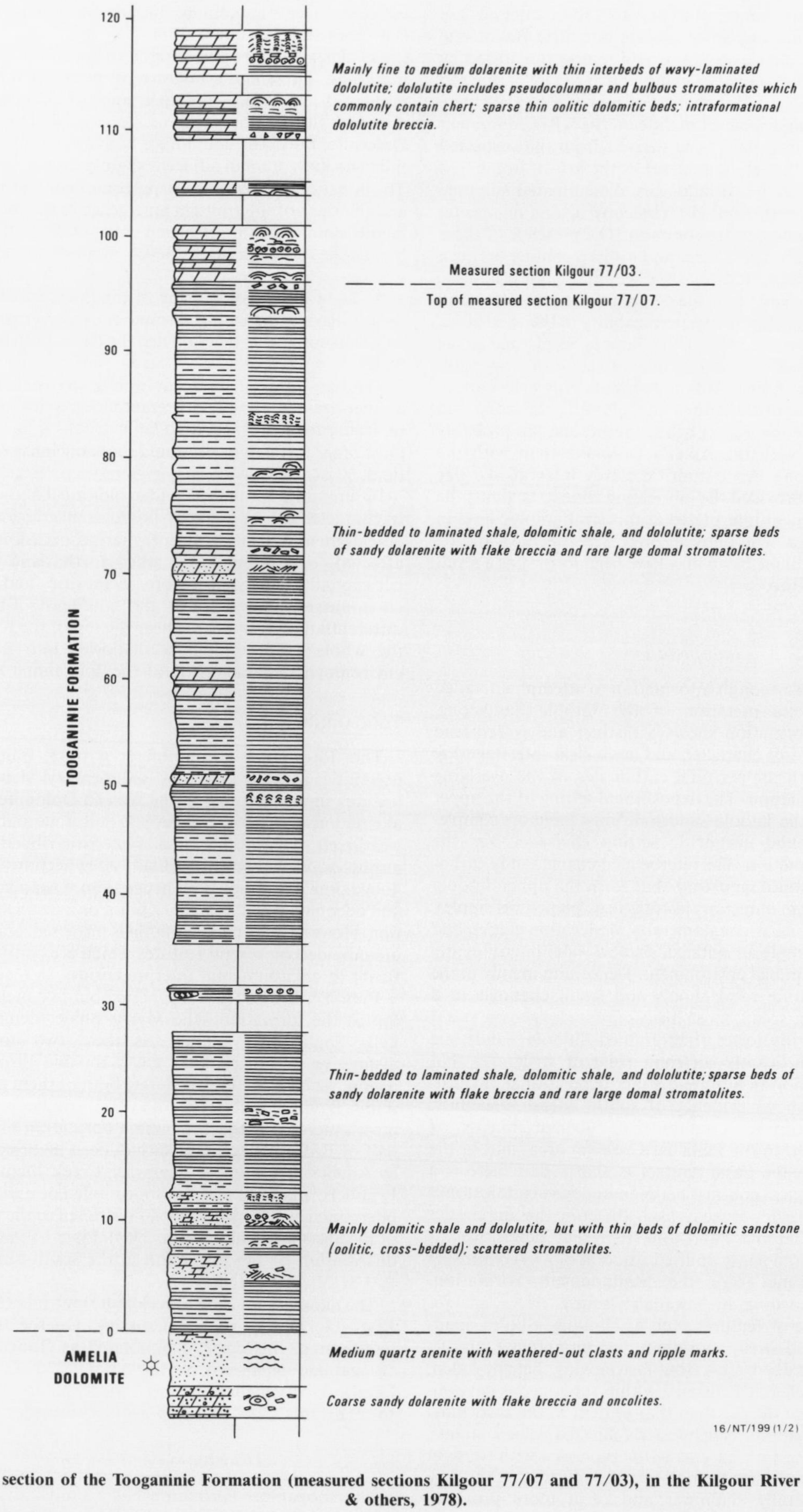

Fig. 81. Type section of the Tooganinie Formation (measured sections Kilgour 77/07 and 77/03), in the Kilgour River (from Jackson & others, 1978).

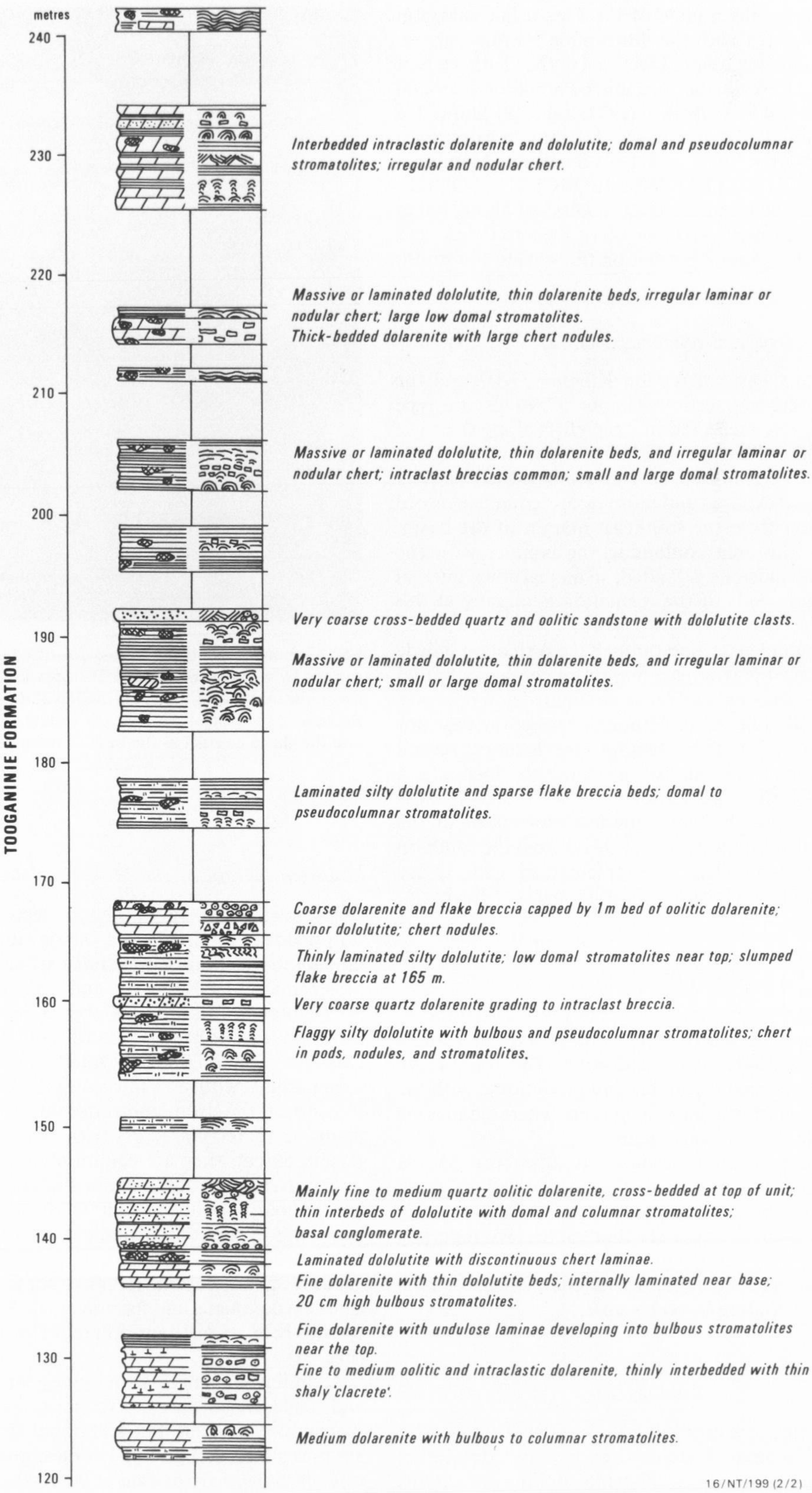

Fig. 81 (continued).

sequence. It is well exposed throughout BAUHINIA DOWNS, in the northern parts of WALLHALLOW, and in the south of MOUNT YOUNG. Poorly exposed silicified outcrops lying between the Tatoola Sandstone and Nathan Group between the Limmen Bight and Cox Rivers—previously mapped as part of the Vizard Formation (Plumb & Paine, 1964)—are a northern continuation of the Tooganinie Formation. Muir (1979c) correlated shale and sandstone in about the middle of the Vizard Formation in the Roper River area with the Tooganinie Formation.

In two incomplete measured sections in the southern part of BAUHINIA DOWNS, the Tooganinie Formation is around 200 m thick. Plumb & Brown (1973, table 2) showed a thickness of about 500 m for the Tooganinie Formation (excluding the 'Myrtle Shale' and 'Leila Sandstone Members') in central BAUHINIA DOWNS. In MOUNT YOUNG, Plumb & Paine (1964) indicated a thickness of about 300 m along the Limmen Bight River, north of Eastern Creek, and noted that the Tooganinie Formation thickens to the south.

Type and reference sections

We nominate measured section Kilgour 77/07 and the immediately overlying section Kilgour 77/03 as the type section. These were measured in steep cliffs along the right bank of the Kilgour River east of Mallapunyah Dome, between GRs 987144 and 997154 (Plate 1). This combined section (Fig. 81) provides a well exposed and more-or-less complete record of the formation from the southeast margin of the basin. Unfortunately, the area containing the contact with the overlying Leila Sandstone is faulted, so an unknown interval of the uppermost beds of the formation is missing at this locality.

A second incomplete section through the formation (Glyde 78/01), also from the southern margin of the basin but 23 km northeast of the type section, is nominated as a reference section (Appendix Fig. A20). Although neither the base nor top of the formation is present at this locality, several prominent stromatolitic dolostone intervals facilitate a comparison with the type section.

As noted earlier, we have only limited information on the Tooganinie Formation, and most of this is from the southern margin of the basin. This is supplemented with sparse information from spot localities in other parts of the basin.

Stratigraphic relations

The Tooganinie Formation conformably and gradationally overlies the Tatoola Sandstone; the contact is located where dolostone predominates over sandstone. The top of the formation likewise is conformable and gradational with the Leila Sandstone, whose base is placed where sandstone predominates over shaly carbonate.

In some areas, bedding trends on airphotos of the Tooganinie Formation are slightly more complex than those within the enclosing stratigraphic units, indicating gentle decollement folding—similar to that in the Wollogorang Formation and Amelia Dolomite. This is evident only on a large-scale on the airphotos (i.e., several kilometres), but even at that scale the folding is very gentle.

Lithology

The Tooganinie Formation contains a variety of dolomitic rocks: parallel-laminated dololutite; massive dololutite; stromatolitic dololutite; sandy dolarenite; oolitic, intraclastic, conglomeratic, and oncolitic dolarenite; and dolomitic siltstone and shale. A characteristic feature of the formation is the regular interbedding of resistant dolostone units (2-5 m thick) and softer shaly or silty units (2-10 m thick). These two components weather differently, and, depending on bedding attitude, produce either outcrop ridges separated by poorly exposed vales (where beds dip at more than 5°) or stepped outcrops with numerous small steps of dolostone and wide benches of shaly float (where beds dip at less than 5°).

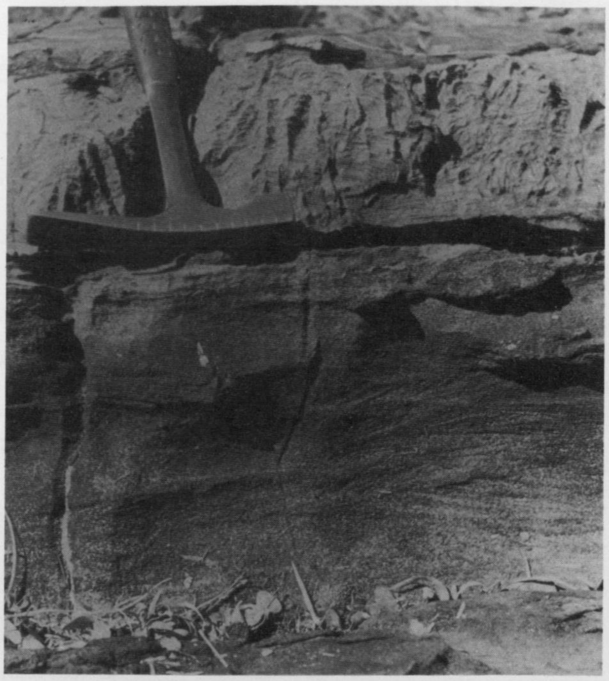

Fig. 82. Small-scale trough-cross-stratified oolitic sandy dolarenite capped by a biostrome of domal to pseudocolumnar stromatolitic dololutite in the Tooganinie Formation at the type section 10 m above the base of the formation. Note the variation in foreset dip directions, and the sharp contact at the base of the biostrome. (BMR negative 2551/31A)

Southern margin of the McArthur Basin

The lower 90–100 m of the type section (Fig. 81) is mainly thin-bedded to laminated shale and dolomitic shale (apparently lacking sedimentary structures) with interbeds of stromatolitic dololutite and coarser sandy dolarenite. Sedimentary structures in the coarser-grained interbeds include intraclast breccias, ooliths, oncolites, and small-scale cross-stratification (Fig. 82); small domal to pseudocolumnar stromatolites with very low synoptic relief are also present. In contrast, the stromatolitic dololutites contain large domal forms up to 100 cm across with synoptic relief of between 10 and 50 cm; they are commonly elongated east–west.

The overlying 50 m contain similar rock types (Fig. 83), but the coarser oolitic and intraclastic dolostones form about two-thirds of the section, and the shaly intervals seldom crop out.

Above about 150 m, recessive shale and dololutite once again predominate, and form intervals 5-15 m thick separated by thin beds of resistant dolarenite or dolomitic sandstone (Fig. 81).

A similar sequence of alternating stromatolitic dolostone and shale constitutes the reference section (Glyde 78/01; Appendix Fig. A20), but additional forms of stromatolites are present. Although large domes predominate, specimens of *Conophyton* are present at 80 m where they form vertical columns up to 2 m high separated by intraclastic debris and small columnar stromatolites; and also at 27 m, where cones up to 40 cm high and inclined to the west are present in a resistant sandy dolostone.

Evidence of emergence in the form of tepee structures and desiccation cracks, and of the former presence of evaporites—represented by halite casts and gypsum crystal pseudomorphs—is present at several levels in the reference section.

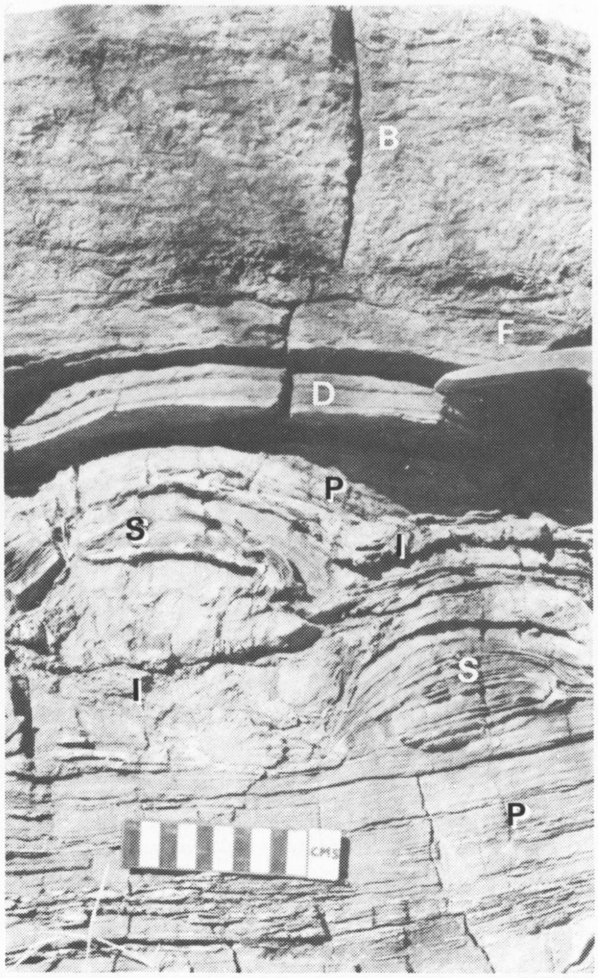

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Fig. 83. Part of the Tooganinie Formation at the type section (140 m). Parallel-laminated dololutite at the base (P) is overlain by low rounded domal stromatolites (S) separated by sandy dolarenite with intraclastic debris (I), which is capped by parallel-laminated dololutite. Above these, fine to medium dolomitic sandstone (D) is overlain by rippled dolomitic sandstone with plates and intraclasts of algal-bound dololutite (F), which is capped by intraclastic breccia/conglomerate with oblong dololutite clasts of a uniform size in a coarse sandy dolarenite matrix (B). About 50 cm of the section is visible. (BMR negative M2551/37A)

Northern Abner Range map area

Sideritic dolostone (sideritic 'marble') composed of masses of interlocking gypsum crystal pseudomorphs, identical with those described previously from the Amelia Dolomite and presumably formed in a sabkha-like environment, were observed at a number of widely separated localities in the northern half of the Abner Range map area (Plate 1). At some localities the former gypsum crystal mushes form the centres of large domal stromatolites, whereas in others they form small discontinuous beds or lenses parallel to the bedding.

In small ridges east of Rocky Waterhole (GR 035665) much more extensive evaporite replacement is evident. Here about 25 m of stromatolitic Tooganinie Formation is extensively replaced by sideritic 'marble' for a distance of several hundred metres along strike. Visibly striking but discontinuous secondary copper deposits occur in a vuggy coarse-grained sandy dolostone 2-3 m thick capping the evaporitic facies. This evaporitic facies of the formation must continue farther north and east from here, because Walker & others (1977) described evaporites in the Tooganinie Formation in the Emu Fault Zone, just south of the Cooley II area (east of the HYC deposit). They commented that '. . . it differs from normal [sic] Tooganinie sequences in the Batten Trough in that certain stromatolite beds, usually *Conophytons*, are almost completely replaced by siderite pseudomorphs after discoid-shaped gypsum crystals'.

In addition to these sulphate occurrences, halite casts and moulds are also common in the formation in this part of the Abner Range, where they are concentrated in the dolomitic silty sections of the formation. In areas of discontinuous outcrop the presence of beds of yellow-tan dololutite with domal stromatolites and sulphate evaporites alternating with silty float containing numerous halite casts is a clear indication of the presence of the Tooganinie Formation.

In an unusual but interesting short section of the Tooganinie Formation exposed at GR 750520, a unit of slumped dololutite with a sharp eroded top is overlain by a fining-upward unit of dolomitic sandstone and ripple-laminated dololutite (Fig. 84).

Though not confirmed by systematic section measuring, information from partial sections northwest of the Abner Range indicates that the Tooganinie Formation gradually becomes more clastic and finer-grained northwards. Although continuity of outcrop across strike is not good, the upper part of the Tooganinie Formation along Leila Creek (along the northern margin of Plate 1) appears to be dominated by sections (tens of metres thick) of laminated to thin-bedded dolomitic shale and siltstone. The shale is purple, red-brown, or green and micaceous; it contains small symmetrical and asymmetrical ripples, desiccation cracks, halite casts, and authigenic barite nodules. In many respects these sections of the Tooganinie Formation are strikingly similar to the continental and evaporitic redbed facies of the Mallapunyah Formation.

North of the Abner Range map area, studies by Amoco International (1981) indicate that the Tooganinie Formation consists mainly of interbedded dolomitic sandstone and siltstone. In addition, the possible correlation of the Tooganinie Formation with a sandstone-shale sequence in about the middle of the Vizard Formation in the Roper River area reinforces the impression that the Tooganinie Formation gradually becomes more clastic northwards.

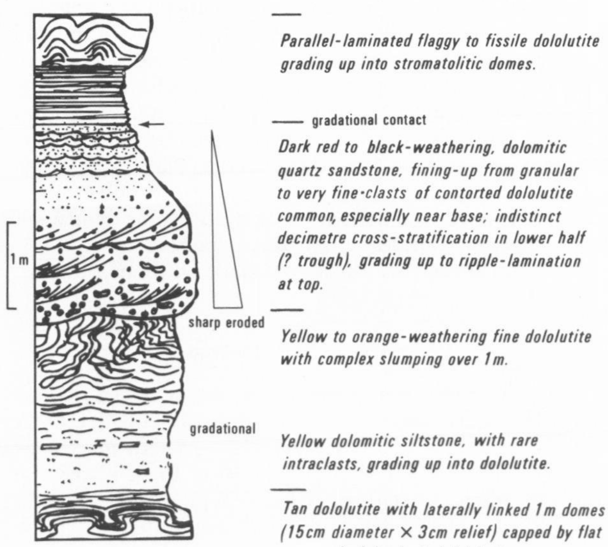

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Fig. 84. Sketch of a section of dolomitic sandstone and slumped dololutite in the Tooganinie Formation in Amos Creek (locality 77100310), northwest of Top Crossing.

Interpretation

In the absence of systematic studies, a convincing palaeogeographic reconstruction is not possible. However, the Tooganinie Formation is remarkably similar to the Amelia Dolomite–Mallapunyah Formation and it must have been deposited within similar environments. The change from a richly stromatolitic facies in the south (Mallapunyah–Kilgour area) through a richly evaporitic sabkha facies north of here (northern half of Plate 1) to a mainly clastic facies in the north may reflect a palaeogeography with a northern land area grading southwards through a marginal sabkha into a southern peritidal marine complex with quiet-water stromatolitic lagoons and more agitated shallower-water bars and shoals. In this tentative interpretation, the palaeogeographic setting of the Tooganinie Formation is the reverse of that interpreted for the Tatoola Sandstone which had deeper marine environments in the north and proximal shallower environments in the south.

Like the older units of the McArthur Group, the Tooganinie Formation appears to lack evidence for the presence of a north-trending Batten Trough at this stage in the evolution of the basin.

On a small vertical scale (centimetres to metres) some outcrops show marked changes in local energy conditions. For example, the section 50 cm thick shown in Figure 83 indicates a contrast between mainly quiet subaqueous deposition (?lagoonal, or perhaps subtidal marine) in the lower part and much more turbulent and agitated conditions for the ripped-up intraclastic bed (?supratidal storm deposit) in the upper part.

Similarly, the section shown in Figure 84 also indicates abrupt variations in energy conditions with time in the depositional environment. The upper half of the outcrop closely resembles the model proposed for meandering fluvial systems (Walker, 1979; Reading 1978; Reineck & Singh, 1975): a sharp eroded basal contact (i.e., channel floor) underlies coarse-grained cross-bedded sand that gradually fines upwards, with a consequent reduction in ripple size (lateral-accretion in-channel deposit), to a fine-grained top (overbank vertical-accretion deposit).

Leila Sandstone

The Leila Sandstone was originally mapped as a member of the Tooganinie Formation. Although this unit is thin, and continuous sections are rare, we were able to consistently map it throughout the Abner Range region in much the same way as the Tatoola Sandstone, so we here elevate it to formation status. It is named after Leila Creek, which flows across the northern part of the Abner Range region (Plate 1) and joins the McArthur River near Leila Lagoon. Smith (1964) originally interpreted it as the back-reef stratigraphic equivalent of the Stretton Sandstone, but this is not so.

We have not carried out a systematic study of the unit.

Distribution and thickness

The Leila Sandstone is present in the northern part of WALLHALLOW and is widespread throughout BAUHINIA DOWNS, but it lenses out along the southern margin of MOUNT YOUNG. It is about 20–30 m thick across the southern margin of the Abner Range region, 10 m thick in outcrops west of Balbirini homestead, and about 10 m thick in the Leila Creek area. It seems to gradually lens out northwards from here, and is not recognisable in the outcrops along the Limmen River in western MOUNT YOUNG. In the Emu Fault Zone near McArthur mine, it occurs as quartz arenite beds (unspecified thickness) below the red–green siltstone of the Myrtle Shale (Walker & others, 1978, p. 369). Plumb & Brown (1973) indicated a thickness of about 140 m for the formation, but we have found no evidence for any thickness in excess of about 30 m.

Type section

The only detailed section we have measured is Glyde 78/02 (Fig. 85)—near William Yard, east of Abner Range— which we here nominate as the type section. The section extends from GR 186287 to 185289 (Plate 1).

Stratigraphic relations

The Leila Sandstone conformably and gradationally overlies the Tooganinie Formation, and is in turn conformably overlain by the Myrtle Shale. Owing to its distinctive lithology and greater resistance to erosion than the uppermost beds of the Tooganinie Formation and most of the Myrtle Shale, it is generally a valuable stratigraphic marker.

Lithology

In the type section (Fig. 85) the Leila Sandstone consists mainly of coarse-grained cross-bedded quartz and dolomitic sandstone with thin intervals of dolomitic shale. Near the middle of the unit, coarse-grained sandstone contains up to about 10 per cent of dark green grains, which are presumably glauconite and indicate a marine origin for at least part of the formation. In addition to the cross-bedding, desiccation cracks are evident near the base and intraclast breccias were recorded at several levels in the type section. Barite, dolomite, and pyrite-filled vugs are also present at two levels in about the middle of the formation.

A similar section of rippled and cross-stratified glauconitic sandstone, which also contains oolitic sandstone and thin beds of sandy dolarenite, is present in Kilgour Gorge, 22 km to the southwest.

In the far west (north of Yah Yah) and west of Top Crossing, the Leila Sandstone and associated formations are complexly faulted by north-trending splays from the Mallapunyah Fault. Although samples from near these faults are extensively silicified to form quartzite, the Leila Sandstone can be differentiated into two distinct parts: a lower pale grey medium to thin-bedded sandstone, and an upper dark brown to black-weathering cross-bedded sandstone.

The lower part comprises medium to coarse-grained, dolomitic quartz sandstone commonly with decimetre-scale tabular or wedge-shaped cross-sets. Green and yellow grains or patches are common on weathered surfaces. In some outcrops these look like well formed grains of glauconite, but in others they resemble decomposed grains or clasts of carbonate. Thin sections show that the rocks from the lower part of the formation include oolitic sandy dolarenite and medium to coarse-grained dolomitic sandstone (Fig. 86); carbonate material is common, both as clastic grains and as a matrix (now recrystallised).

The upper black-weathering part of the formation in the west comprises mainly fine-grained sandy dolarenite; poorly exposed thin dololutite beds are evident at a few outcrops. Bedding is neither as regular nor as continuous as in the underlying sandstone. Small-scale ripple-drift lamination and discontinuous coarser wedges indicate marked variations in current strength. These beds contain a higher proportion of dolomite, especially in the form of ooid grains (Fig. 87), than the underlying sandstone.

In the Leila Creek area and farther north, the Leila Sandstone is thinner and comprises various lithologies,

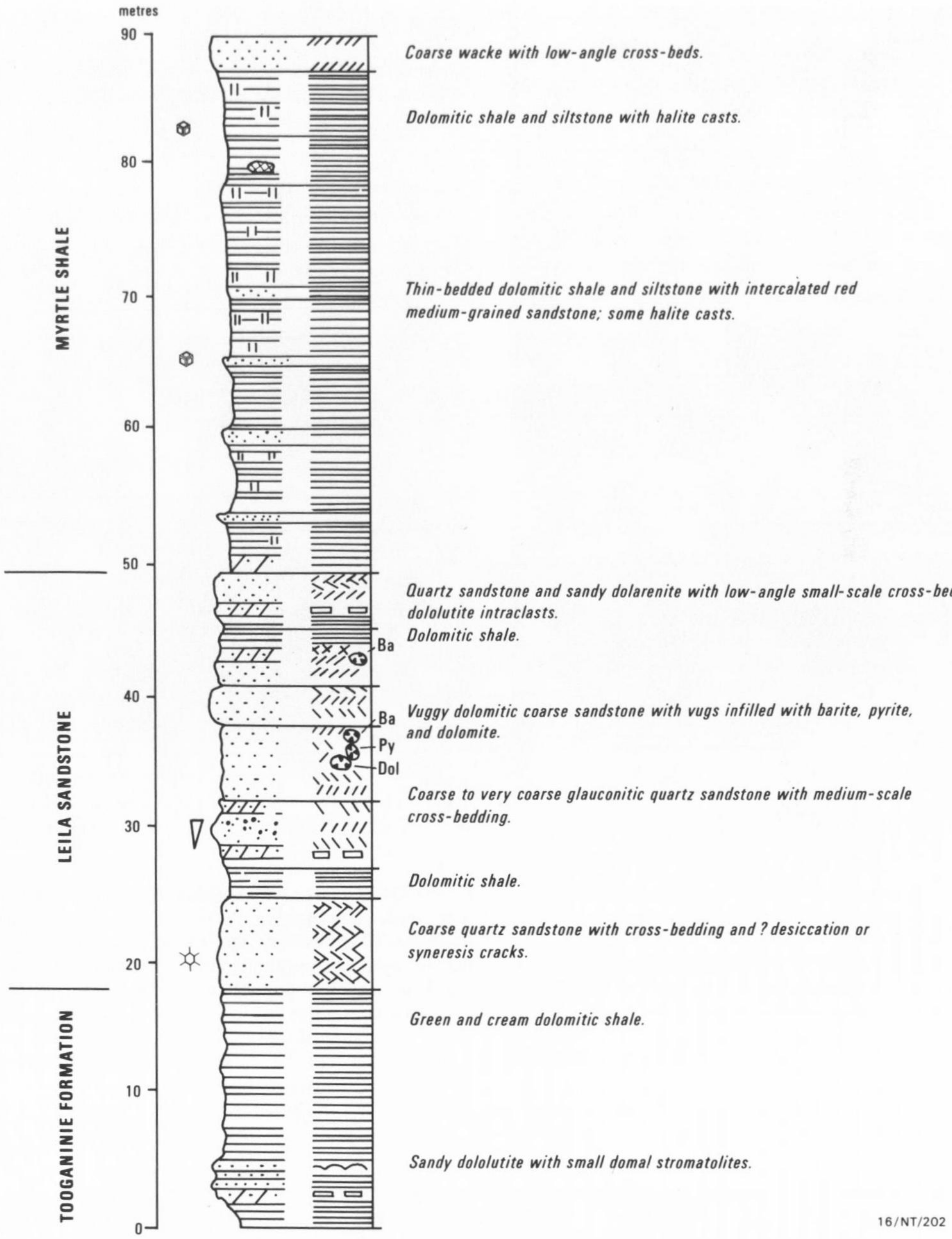


Fig. 85. Type section of the Leila Sandstone (measured section Glyde 78/02), 1.2 km west of William Yard (modified after Jackson & others, 1978).

including oolitic and pisolitic dolarenite, dolomitic sandstone, stromatolitic dolostone, and intraclast breccia.

Interpretation

The presence of glauconite, the dominance of current-deposited oolitic dolarenite and well rounded quartz sandstone, and a general absence of evidence for repeated emergence suggest deposition in a more persistently submerged subaqueous environment than the depositional environments interpreted for some of the underlying formations. However, desiccation cracks are present at some outcrops, indicating occasional emergence. A comparison with submerged ooid shoals similar to those commonly formed in modern carbonate banks (e.g., James, 1979b) is tempting. The northwards thinning and eventual wedging out of the Leila Sandstone is consistent with the south to north, marine to continental facies arrangement of the underlying Tooganinie Formation.

Myrtle Shale

The Myrtle Shale is a thin evaporitic redbed unit. During the original mapping (Smith, 1964; Plumb & Paine, 1964; Plumb & Rhodes, 1964), it was not mapped as a separate unit, but was shown as undifferentiated Tooganinie Formation above the 'Leila Sandstone Member'; Plumb & Brown (1973) introduced the name 'Myrtle Shale Member' (of the Tooganinie Formation) for this unit. Like the Leila Sandstone, it is lithologically distinct and mappable throughout the southern half of the area, so we here elevate it to formation status.

The name is derived from Myrtle Creek, a small tributary which joins the McArthur River about 10 km south-southwest

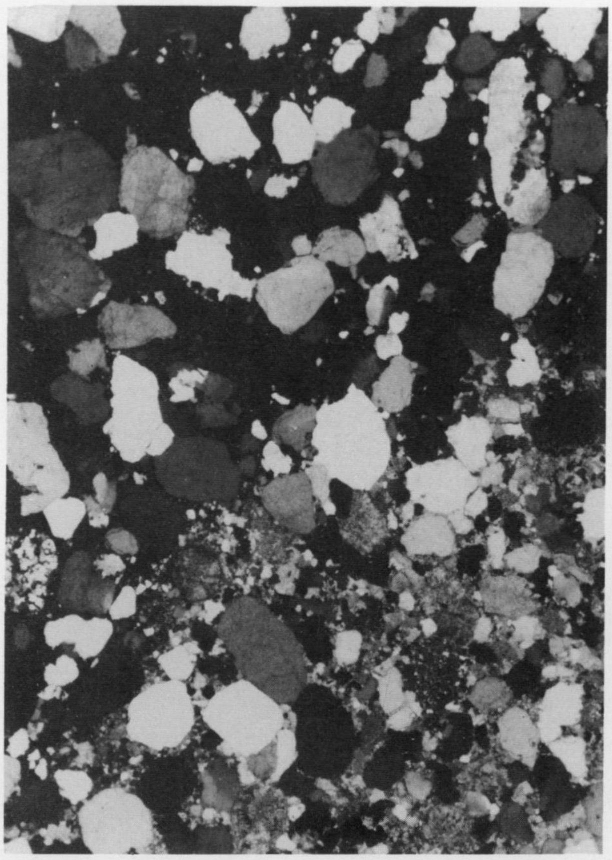


Fig. 86. Thin section viewed through crossed nicols of medium-grained dolomitic sandstone (specimen 77100420A) in the lower part of the Leila Sandstone 10 km west of Top Crossing. A carbonate matrix (pale grey) is preserved in the bottom half of the thin section; elsewhere this matrix has been removed and replaced by ironstained cement (black). Note the angularity of quartz grains produced by silica overgrowths in optical continuity on originally well rounded grains. Carbonate is also present as well rounded grains (medium grey with fine speckles), forming up to about 10 per cent of the rock. The large white quartz grain in the centre is 1 mm across.

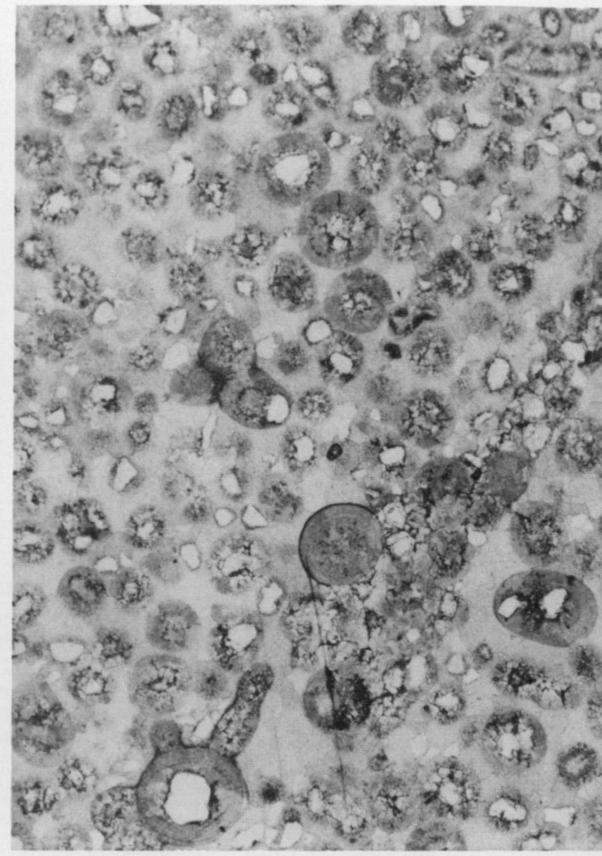


Fig. 87. Thin section viewed through plane-polarised light of sandy oolitic dolarenite (specimen 77100421A) in the upper part of the Leila Sandstone 10 km west of Top Crossing. Careful examination indicates that the rock was originally composed mainly of ooids (many now visible as ghosts) in a carbonate matrix. Most of the quartz grains (clear) are in fact ooid nuclei; some are clearly so, but under higher magnification most can be seen to contain ooid coatings. These quartz grains also have extensive silica overgrowths in optical continuity so now appear angular instead of well rounded which they originally were. The large ooid below centre is 0.8 mm across.

of McArthur mine. The formation is poorly exposed, and we have not carried out a systematic study of it.

Distribution and thickness

The Myrtle Shale is widespread through BAUHINIA DOWNS and the northern part of WALLHALLOW. Owing to its poor exposure its distribution north of Eastern Creek (southern MOUNT YOUNG) is difficult to determine. Like the Leila Sandstone, we suspect that it thins northwards and lenses out north of BAUHINIA DOWNS.

At the type section and at several other sections in the south of the area, the Myrtle Shale is around 60 m thick. Plumb & Brown (1973, table 2) indicated a thickness of 30 to 240 m for it, but they did not provide details on this apparently large variation in thickness. Our measurements suggest that the latter figure is excessive. Nowhere in BAUHINIA DOWNS is the Myrtle Shale thicker than about 100 m.

Type and other measured sections

The only detailed section that we have measured through the Myrtle Shale is Kilgour 77/08, situated in the Kilgour River east of Mallapunyah Dome at GR 002161 (Plate 1), where the unit is 56 m thick. We nominate this as the type section (Fig. 88). In addition, we have measured partial sections near William Yard, 22 km northeast of the type section (Fig. 85; Appendix Fig. A24), and west of Top Crossing. Brown's measured section 9 (Appendix Fig. A29), from near Amelia Spring (GR 250640) in the Emu Fault Zone, also includes a thin section (25 m) of the Myrtle Shale.

Stratigraphic relations

The Myrtle Shale conformably overlies the Leila Sandstone with a gradational contact a few metres thick. The contact zone comprises interbedded dolomitic sandstone, sandy dolarenite, and shale which grade up into mainly dolomitic siltstone and shale.

The upper contact with the overlying Emmerugga Dolomite is difficult to define owing to poor exposure, but it also appears to be conformable. The uppermost beds of the Myrtle Shale are commonly brecciated and deeply weathered; they are succeeded by hard and resistant crystalline dolostones of the basal Mara Dolomite Member. In areas of good exposure the lower part of the Mara Dolomite Member can be seen to contain thin interbeds of red dolomitic siltstone which we consider indicates a transitional upper contact.

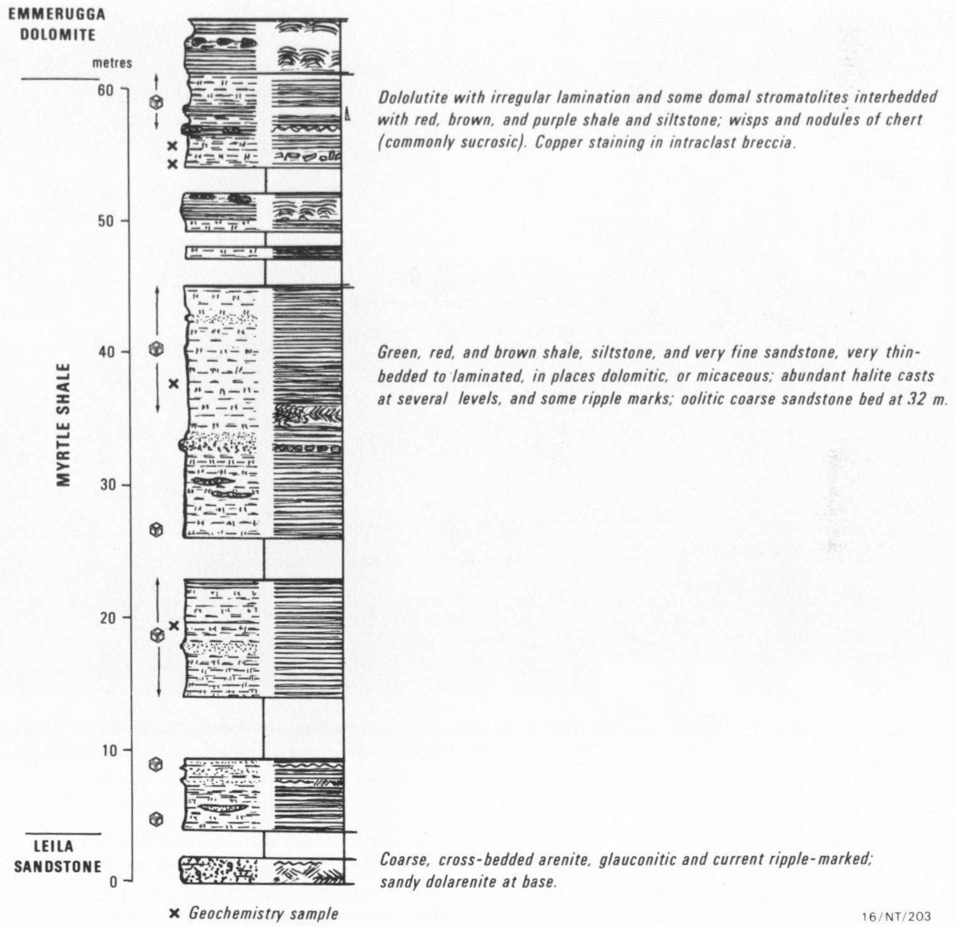


Fig. 88. Type section of the Myrtle Shale (measured section Kilgour 77/08), in Kilgour Gorge (modified after Jackson & others, 1978).

Lithology

The Myrtle Shale consists mainly of red-brown siltstone and very fine-grained sandstone with rare thin interbeds of coarse-grained sandstone, oolitic dolarenite, dololutite, and silty dololutite. Some sections are slightly micaceous. Halite casts ranging in size from a few millimetres to a few centimetres across are ubiquitous.

Most of the type section comprises parallel thin-bedded to laminated dolomitic siltstone and very fine-grained sandstone with halite casts. Near the base of the type section, medium to fine-grained sandstone beds are present either as graded discontinuous wedges only a few centimetres thick and a few metres in lateral extent, or as more laterally persistent beds containing ripple-drift lamination. A distinctive bed of coarse-grained oolitic sandstone similar to those in the underlying Leila Sandstone occurs in about the middle of the formation. This is succeeded by a 30-cm interval of no exposure and then by a 1-m-thick slumped and brecciated dolomitic siltstone. It is not clear whether there is a direct relationship between the slumping and the underlying coarse sandstone.

The upper 10 m of the Myrtle Shale at the type section contains thin interbeds of dololutite, perhaps reflecting a gradation into the overlying Emmerugga Dolomite. The dololutite contains small domal stromatolites and sucrosic chert laminae (after halite)—both features diagnostic of the sedimentary cycles in the basal Emmerugga Dolomite. It also contains malachite-stained intraclast breccias.

Geochemical analyses of three samples from the type section (Appendix 3, Table A7, samples MA 047–049) indicate a dominance of clastic material—SiO_2 around 55 per cent, Al_2O_3 around 8 per cent, and CaO and MgO (combined) around 12 per cent. Values of around 5 per cent for Fe_2O_3 reflect the redbed nature of the rocks. The K_2O content (5%) and the K_2O:Na_2O ratio ($\sim$15) are anomalously high, and are similar to the tuffaceous dolomitic siltstone in the Barney Creek Formation. However, there is no evidence for tuffaceous material in the siltstone of the Myrtle Shale, so we suspect that the anomalous K_2O may be related to diagenetic alteration by saline groundwater that would have been present during deposition and diagenesis—as evidenced by the ubiquitous halite casts.

At a number of localities the upper few metres of the Myrtle Shale and basal part of the overlying Mara Dolomite Member are extensively brecciated; the rocks are broken up into clasts ranging in size from metres down to millimetres. These clasts are very angular and commonly little disturbed. They show no signs of transport, and in many places resemble a slightly pulled-apart jigsaw puzzle (Fig. 89). At Top Crossing the upper few metres of the Myrtle Shale immediately below the breccia is crowded with halite casts, indicating the former presence of large amounts of halite.

Interpretation

Brown & others (1969) interpreted the red dolomitic siltstone of the Myrtle Shale as a subaerial deposit composed largely of wind-transported dust. They also suggested that the incoming dololutite interbeds at the top of the unit indicate the early stages of a transgression during which

Fig. 89. Solution-collapse breccia at the contact zone between the Myrtle Shale and the Mara Dolomite Member of the Emmerugga Dolomite 1.5 km southwest of Top Crossing. Adjacent fragment edges match, indicating that a coherent lithified bed has collapsed owing to solution of evaporites or carbonates. The scale bar is in centimetres (BMR negative M2219/7)

shallow incursions of sea water or salt lakes occasionally flooded the surface and deposited carbonate. The brecciated zone between the Myrtle Shale and Emmerugga Dolomite was explained by solution collapse. They suggested that the sediments at the top of the Myrtle Shale probably built up high concentrations of halite, which then slowly dissolved as incursions of sea water became more frequent during deposition of the lower Emmerugga Dolomite. The reduction in volume caused the more competent carbonates to fracture, and the softer silt and clay (probably in part an insoluble residue of the halite-rich sediments) to be squeezed up between the carbonate blocks.

We agree with most of these suggestions. The Myrtle Shale facies is similar to parts of the Mallapunyah Formation—units B, C, and G—which we interpreted as lacustrine and/or low-gradient alluvial-plain deposits with a possible aeolian origin for the finer material. The presence of small graded channel sand wedges, climbing ripples, slumped dololutites and oolitic dolarenites indicates periods of subaqueous deposition from fairly rapidly flowing currents.

The halite casts in the Myrtle Shale are like those in the Mallapunyah Formation—that is, six-sided hoppers scattered throughout the unit along bedding planes. They probably grew as rafts in standing bodies of water, and then floundered to the sediment surface.

The widespread collapse breccia at the Myrtle–Emmerugga transition may indicate the former presence of much more concentrated evaporites, but—owing to poor exposure, and in the absence of drilling—evidence of such is lacking. Similar evaportic sections in the upper Permian of West Texas (Anderson & others, 1972) contain collapse breccias 3 m thick, which are the result of solution of halite beds up to 43 m thick.

EMMERUGGA DOLOMITE: MARA DOLOMITE MEMBER AND MITCHELL YARD DOLOMITE MEMBER

The term Emmerugga Dolomite is here proposed for a unit of dolostone (with or without stromatolites), minor breccia, siltstone, and sandstone, and rare potassium-rich mudstone. Smith (1964) included in the Emmerugga Dolomite the rocks belonging to a number of other formations: the Balbirini Dolomite in its type area, the former 'Top Crossing Dolomite' at Top Crossing, and the Amelia Dolomite in the area between Balbirini Junction and McArthur mine. Plate 1 shows the updated stratigraphic interpretations as far north as latitude 16°30′S.

Plumb & Brown (1973) redefined the Emmerugga Dolomite, and suggested dividing it into two members: a lower Mara Dolomite Member, and an upper Mitchell Yard Dolomite Member. The formation name is derived from Emmerugga Creek, which rises at GR 514318 in *OT Downs* (5964) and flows into the McArthur River via Tooganinie Creek. The Mara Dolomite Member is named after Mara Hill (GR 187743, *Glyde*, 6164), 8 km south of the HYC deposit; the Mitchell Yard Dolomite Member is named after an old stockyard at GR 138774 in *Borroloola* (6165).

Thickness, outcrop expression, and distribution

The Emmerugga Dolomite reaches a maximum thickness of 620 m (Brown & others 1969). It shows considerable thickness variations, mainly due to postdepositional erosion: the Mitchell Yard Dolomite Member is commonly not present; and erosion has, in many places, removed the upper part of the Mara Dolomite Member. For example, at the Mariner lead–zinc prospect (GR 598221, *Batten*, 6065), the Limmen Sandstone of the Roper Group directly overlies the silicified lowermost few metres of the Mara Dolomite Member; and at Lansen Creek (GR 089942, *Bauhinia Downs*, 5965), the Reward Dolomite overlies the lowermost laminated and stromatolitic dolostone of the Mara Dolomite Member.

The Mara and Mitchell Yard Dolomite Members are usually well exposed. The Mara Dolomite Member forms characteristic benched ridges in which the stromatolitic and more massive dolostones are well exposed. The interbedded laminated and more impure dolostones usually form recessive

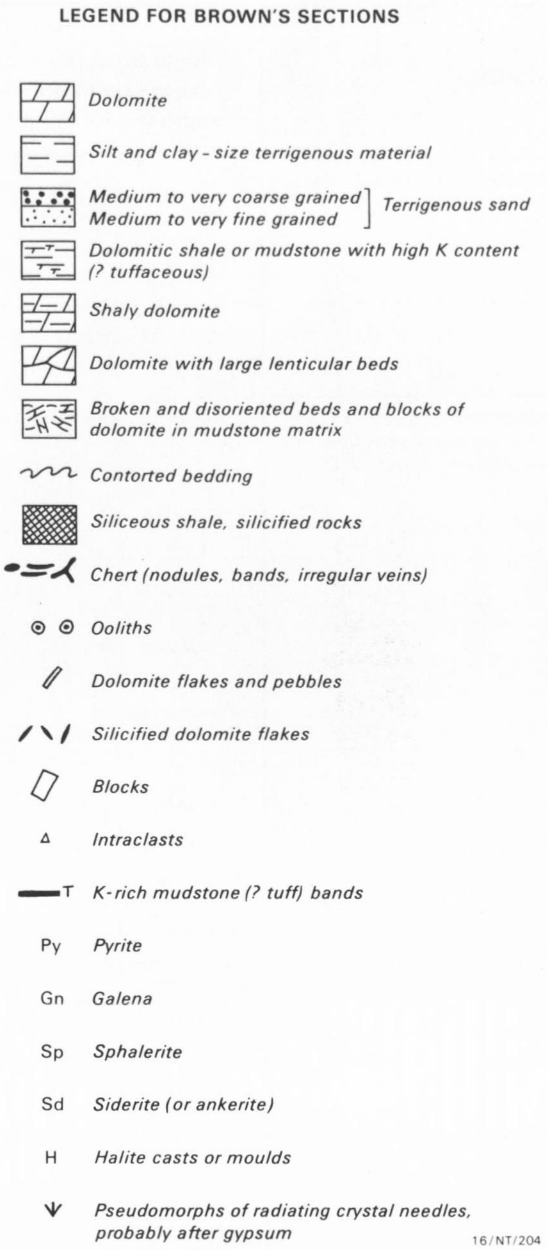


Fig. 90. Explanation of symbols used in Brown's 1969 measured sections (Figs. 91, 92, 97, and 106)

benches, but they are exposed in a few localities where recent erosion has cut down to near the present water-table. Unfortunately, original sedimentary textures and structures are commonly obscure because the Mara Dolomite Member has suffered varying degrees of surface alteration. Some beds, particularly the stromatolitic units, are variably silicified. Silicification took place not only during both deposition and diagenesis but later as well: severe silicification related to Cretaceous and younger weathering episodes is apparent, and most extensively developed near the present topographic highs. In addition to silicification, the Mara Dolomite Member has also suffered vadose recrystallisation—especially of its more massive carbonate beds. Karstic solution features, enlarged joints, and caves are common.

The Mitchell Yard Dolomite Member forms low hills of dark grey dolostone in which extensive karstic alteration and recrystallisation have obliterated many of its original sedimentary structures. Solution features such as karstic fluting are abundant, and solution effects have commonly reduced exposures to piles of blocky rubble. Caves, cave pearls, and flowstones are characteristic of the Mitchell Yard Dolomite Member. Some of the caves were used as Aboriginal burial sites. In contrast to the Mara Dolomite Member, the Mitchell Yard Dolomite Member is not silicified, apart from small traces of opaline silica on joint faces.

The Emmerugga Dolomite crops out well in BAUHINIA DOWNS, northern WALLHALLOW, and parts of MOUNT YOUNG. Whereas the Mara Dolomite Member is present in all of these areas the Mitchell Yard Dolomite Member appears to be preserved mainly in the south. Laminated dark grey dolostone in the Vizard Formation at Mount Birch (northwest corner of locality map, Plate 1) may be a lateral equivalent of the Emmerugga Dolomite.

Type sections

The measured section near Top Crossing mentioned by Plumb & Brown (1973) and figured by Brown & others (1969, plate 4) is here proposed as the type section for the Mara Dolomite Member; it is reproduced as Figure 91. The top of the Mitchell Yard Dolomite Member is poorly exposed in this section, so a section about 15 km northeast of the McArthur River homestead is nominated as the type section for this member; this section was measured by Brown & others (1969, plate 6), and is here reproduced as Figure 92. Several other measured sections, on which a lithologic description of the formation is based, are mentioned under *Lithology*.

Stratigraphic relations

The Mara Dolomite Member overlies the Myrtle Shale, apparently conformably, and in most places is conformably overlain by the Mitchell Yard Dolomite Member. The Mitchell Yard Dolomite Member, where present, is conformably overlain by the Teena Dolomite.

Lithology

This description of the Emmerugga Dolomite is based largely on a summary of a number of measured sections through the formation. Four, all in the headwaters of the Kilgour River southeast of the Abner Range, were measured during the multidisciplinary program between 1977 and 1982 (Appendix Figs. A21, 22, 23, and 24). In addition to the two proposed type sections, Brown measured several other sections in 1968–69, which include the Emmerugga Dolomite at four other localities: one in the Top Crossing area (Appendix Fig. A26), one east of Bauhinia Downs homestead (Appendix Fig. A27), one close to the HYC prospect (Appendix Fig. A28), and two near Amelia Spring, 20 km southeast of the HYC prospect (Appendix Figs. A29, A30).

Mara Dolomite Member

Where it is undisturbed, the base of the Mara Dolomite Member is defined as the base of the lowest massive dolostone bed. In the following description, the member is divided into four units.

Unit 1 is well exposed in the Kilgour River sections, where it constitutes the lowermost 30 m of the member—consisting of eight well preserved sedimentary cycles (Fig. 93). Each cycle is between 2 and 4 m thick and can be divided into five subunits (Fig. 94). Although we have since identified these cycles in the Top Crossing area, they were not recognised by Brown & others (1969), and hence are not shown in Figures

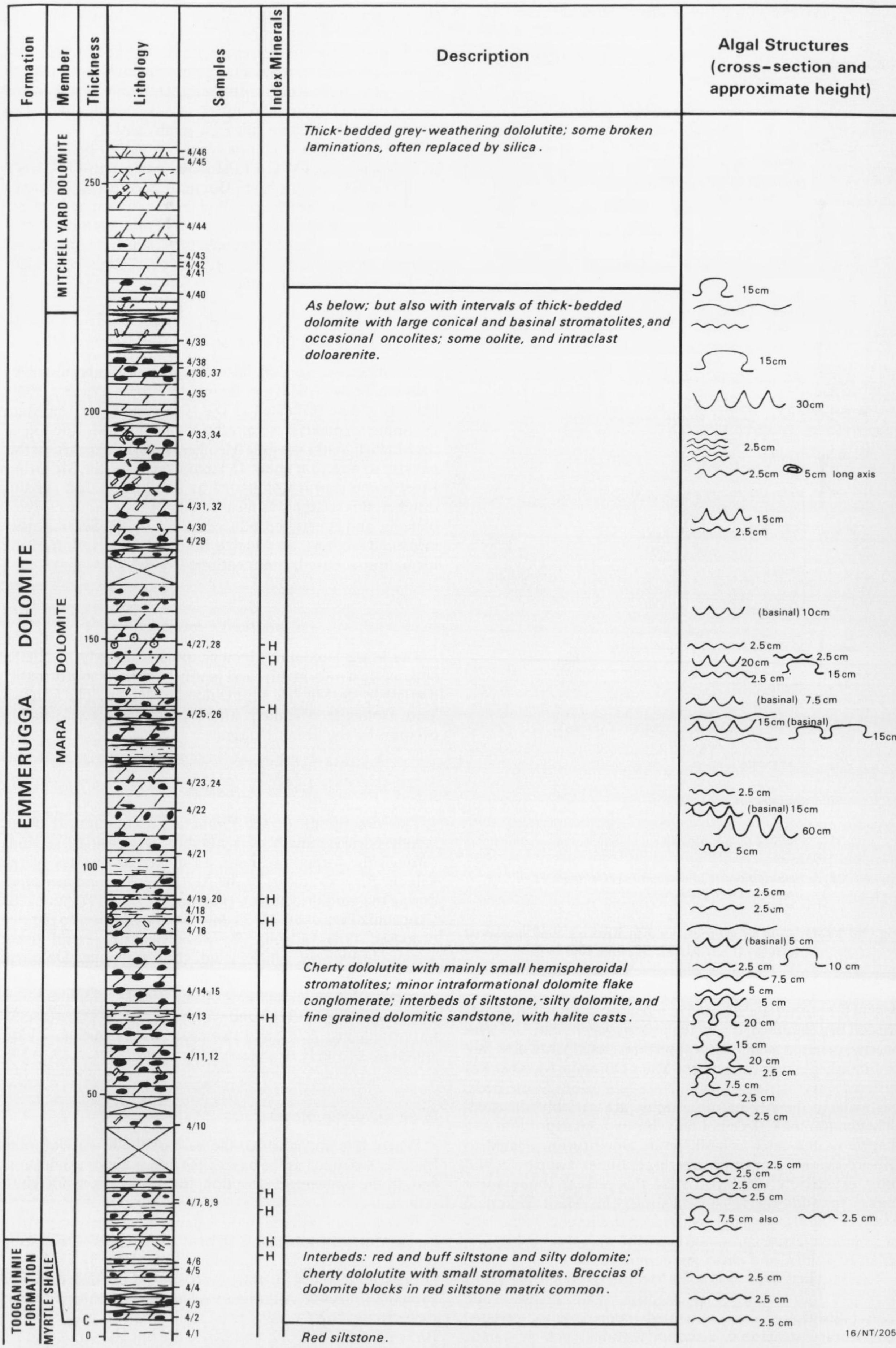


Fig. 91. Type section of the Mara Dolomite Member, Emmerugga Dolomite (Brown's section 4), 1.5 km southwest of Top Crossing. For explanation of symbols, see Fig. 90.

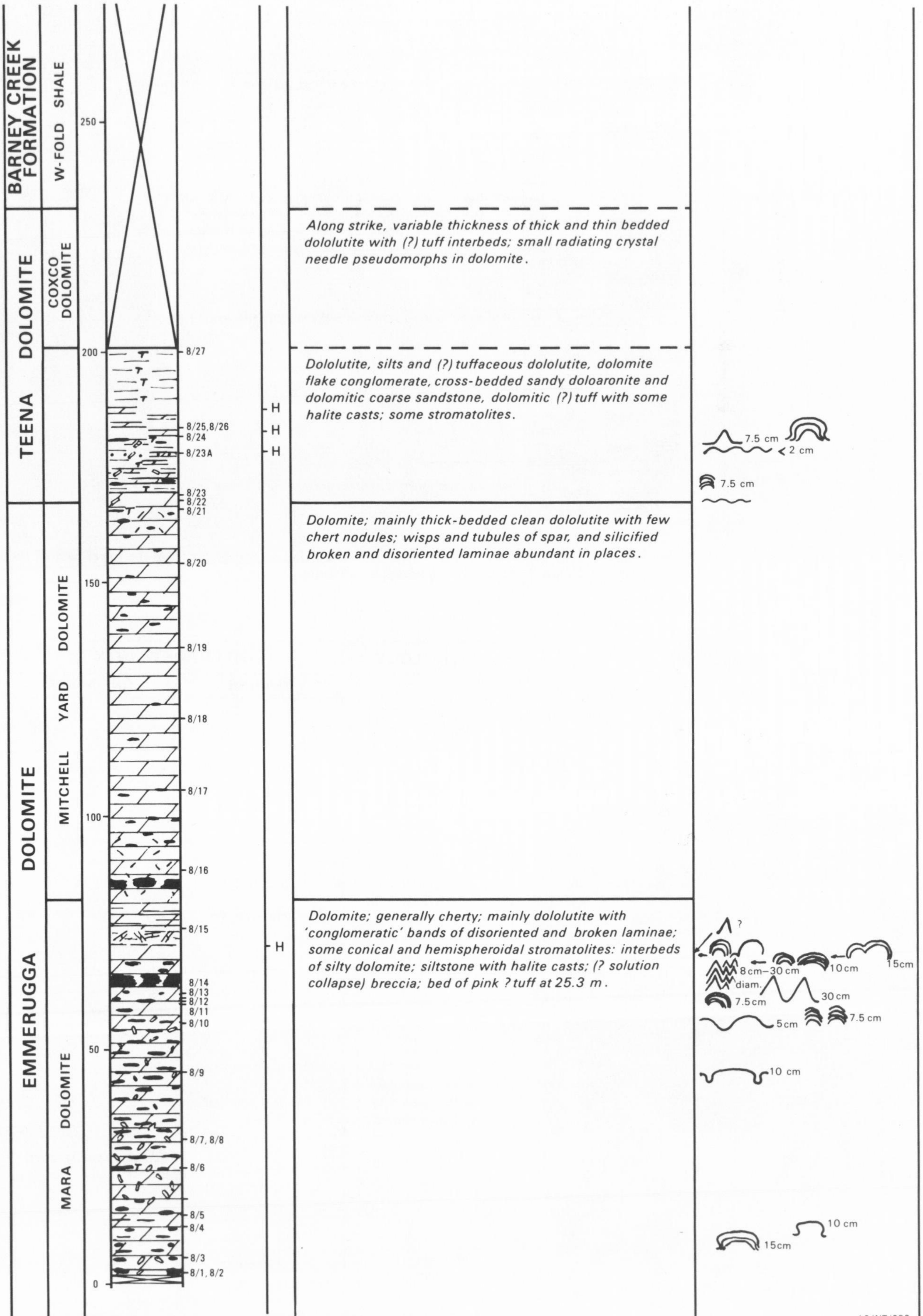


Fig. 92. Type section of the Mitchell Yard Dolomite Member, Emmerugga Dolomite (Brown's section 8), 15 km northeast of McArthur River homestead. For explanation of symbols, see Fig. 90.

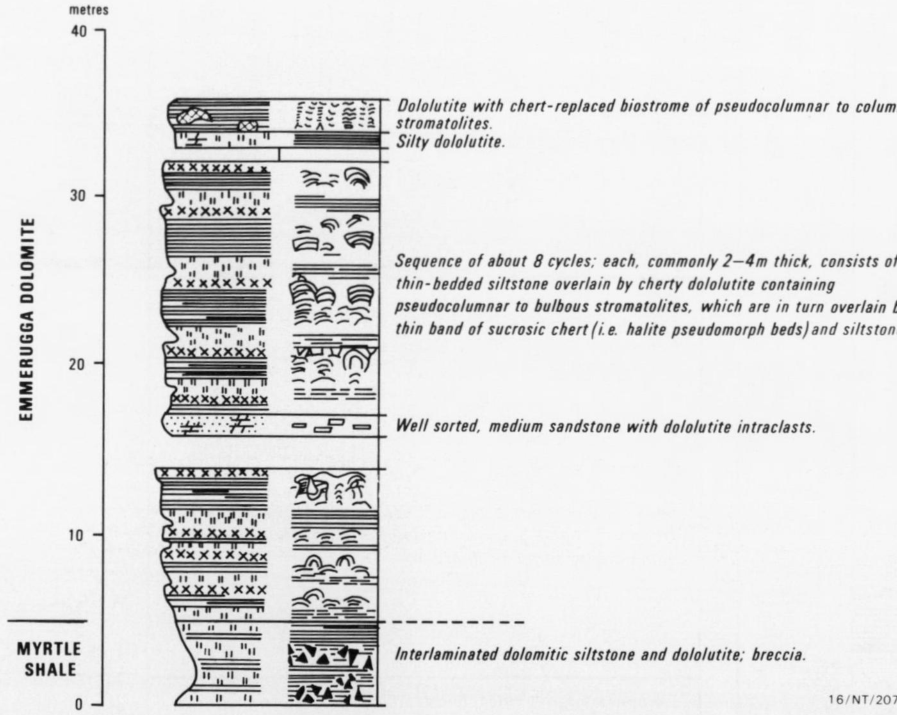


Fig. 93. Basal part of measured section Kilgour 77/01 (after Jackson & others, 1978), showing several cycles from the lower part of the Mara Dolomite Member, Emmerugga Dolomite.

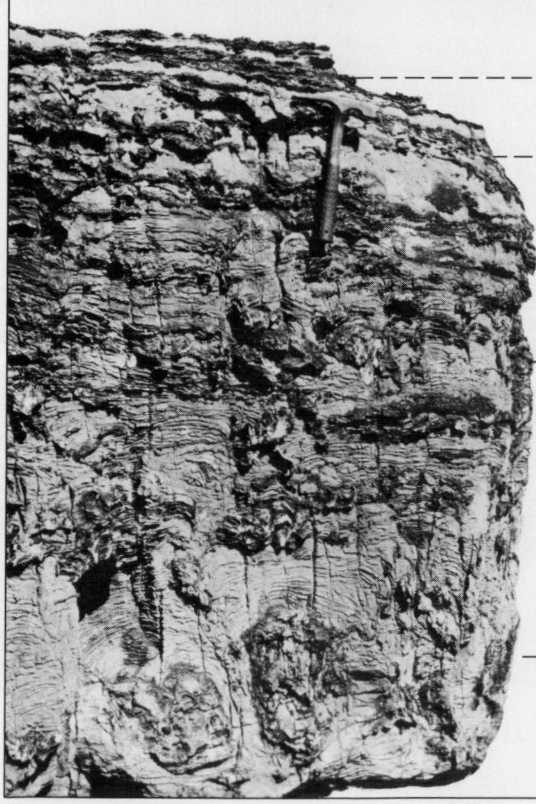
OUTCROP	LITHOLOGY	INTERPRETATION	
		MARINE	CONTINENTAL
	Siltstone with mud-cracks	Supratidal flat	Exposed marginal flats
	Saccharoidal cherts		
	Flattened domes	Intertidal (? stronger currents)	Lagoon (shallower part)
	Fine dolostone with rounded to elongate domes	Shallow subtidal	Lagoon (deeper part)
	Massive fine dolostone	? Deeper	

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Fig. 94. Shallowing-upwards cycle from the lower part of the Emmerugga Dolomite; alternative interpretations of the subdivisions of the cycle are indicated.

91 and 92. Thin beds or discontinuous wedges of medium-grained cross-bedded sandstone occur at intervals throughout this part of the section.

Although the cyclic sequence dominates the lowest unit of the Mara Dolomite Member throughout much of BAUHINIA DOWNS, at some localities it passes laterally into an extension of the solution-collapse breccia at the top of the Myrtle Shale. Whereas the thin sucrosic chert intervals of the cycle contain abundant cubic and hopper halite casts, the solution-collapse breccia is dominated by the chevron variety of halite and gypsum casts. The fragments in the solution-collapse breccia are invariably angular, and are composed of quartz and dolomitic siltstone, white and pink dololutite, and pink potassium-rich mudstone. The breccia matrix is pink to red dolomitic, ferruginous mudstone with abundant unsorted small dololutite fragments. In cliff sections at the southeast end of the Abner Range (grid square 1632), where the solution-collapse breccia laterally replaces the lower part of sedimentary cycles over a distance of about 400 m, the sections containing breccias are about 30 per cent thinner than the sections with undisturbed cycles, which must reflect the solution of evaporites. In these sections the overlying dololutite beds are slightly buckled as a consequence of the collapse.

Unit 2, which overlies unit 1, consists of about 30 m of mainly laminated dololutite with a few stratiform and small domal stromatolites. Specimens of black chert from this unit collected at both the Cooleys lead-zinc prospect and near the McArthur River Bridge at Top Crossing contain abundant microfossils (Muir, 1982b).

Unit 3, overlying unit 2, comprises about 80 m of thin to thick-bedded dololutite and dolarenite containing intraclast conglomerates, oolites, oncolites, and stromatolites of a variety of forms and sizes (Walter & others, in press). The most impressive are the extremely large specimens of *Conophyton** (Fig. 95). Although the laminae of these stromatolites are thin (1-2 mm), the relief on each lamina is up to 2 m. These specimens of *Conophyton* reach a diameter of about 70 cm, and contain minor amounts of chert. At Top Crossing they form part of a bioherm series that shows a gradual reduction in synoptic relief (see Walter & others, in press). Dolarenite beds of unit 3 have been markedly affected by karstic weathering, and, from a distance, can be confused with the Mitchell Yard Dolomite Member. They are, however, distinguished from the latter by remnants of their fine stromatolitic lamination.

Unit 4, at the top of the Mara Dolomite Member, comprises a few metres of grey dolostone and chert with fine-grained pink to buff potassium-rich mudstone (with up to 12 per cent K_2O).

Mitchell Yard Dolomite Member

Because the Mitchell Yard Dolomite Member has undergone extensive weathering it is extremely difficult to ascertain the original nature or composition of the rock. Bedding structures are, at best, difficult to see, and in many localities cannot be distinguished at all.

The dolostone is commonly a dark grey dololutite, which in places is mottled by white to pale cream spar. M. Brown examined many sections of the Mitchell Yard Dolomite Member and described: '. . . various types of breccia or pseudobreccia, consisting of abundant flakes of dololutite (apparently broken laminae), blocks of thin-bedded dololutite, or flake-shaped patches of sparry dolomite, set in a matrix of unlaminated dololutite. The textures are sometimes accentuated in places by the partial or complete silicification of the "clasts".' (Brown & others, 1969).

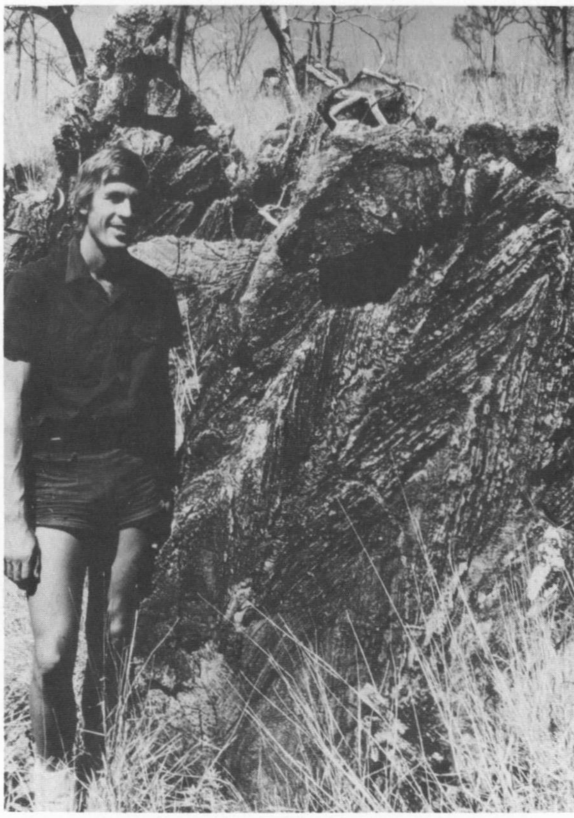

Fig. 95. Large *Conophyton* in unit 3 of the Mara Dolomite Member, Emmerugga Dolomite, 2 km south of Top Crossing. The man in the photo is 180 cm tall. (BMR negative GB 3072)

From this description, we infer that at least some of the fresh Mitchell Yard Dolomite Member was thinly laminated flat-bedded dololutite. It was probably not stromatolitic, since stromatolites, when preserved in massive recrystallised dolostones even after severe karstic weathering (the Mara Dolomite Member and Amelia Dolomite *Conophyton*, for example), tend to retain their fine structure.

The Mitchell Yard Dolomite Member may represent extensively altered lower Teena Dolomite and not a separate stratigraphic unit. The boundary between the two formations is inferred by Brown & others (1969) to be at a level where thick bedding (massive character) of the Mitchell Yard Dolomite Member gives way to thin bedding of the Teena Dolomite. Since blocks of thinly laminated dololutite are known from the Mitchell Yard Dolomite Member, the distinction between these two units is not very clear. The Mitchell Yard Dolomite Member is dark grey-weathering, whereas the Teena Dolomite commonly weathers cream, and the karstic topography of the Mitchell Yard Dolomite Member gives rise to a very characteristic photo-pattern. These features have enabled us to map out the distribution of the two units, but without very detailed studies we cannot solve the enigma about their relationship, so at this stage we retain the Mitchell Yard Dolomite Member as part of the Emmerugga Dolomite.

Geochemistry

Although we have referred to all the carbonates in the Emmerugga Dolomite as dolostone, geochemical studies by Claxton (Appendix 2) have shown that some are high-

* A re-examination of these specimens during field inspection in 1986 suggests that they may instead belong to the *Thyssagetacea* form group (K. Grey, Geological Survey of Western Australia, personal communication July 1986).

magnesium limestone. The average Ca:Mg ratio in Brown's measured sections is 1.8 (Table 6). Near McArthur mine, the Emmerugga Dolomite has a Ca:Mg ratio of 1.67, whereas in areas remote from the mineralisation the ratio is 1.75. Brown & others (1969) calculated that the Ca:Mg molar ratios are between 0.973 and 1.14, and the Ca:Mg+Fe ratios are between 0.933 and 0.970. Samples (14/1, 14/2, 14/4) from Brown's measured section 14 (Appendix Fig. A28) cannot be defined as dolostones, but rather as very high-magnesium limestones. Similar results were also obtained from measured section 12 (Appendix Fig. A30).

In areas remote from McArthur mine, the Emmerugga Dolomite consists of dolostone relatively depleted in iron and manganese. In contrast, near the mine, it consists of ferruginous high-magnesium calcite (Brown & others, 1969).

TABLE 6. AVERAGE CALCIUM: MAGNESIUM RATIOS OF CARBONATES IN THE EMMERUGGA DOLOMITE IN SECTIONS MEASURED BY M. C. BROWN 1968-69.

Section No.	*Ca:Mg*
3	*1.8*
4	*1.8*
5	1.85
6	2.0
7	*1.8*
8	*1.8*
9	1.85
10	2.0
11	2.1
12	*1.55*
13	*1.6*
14	*1.75*
Average (all samples)	1.8

Note: Italicised data are from sections which include the Mara Dolomite and Mitchell Yard Dolomite Members. The numbers and locations of samples analysed are plotted against the measured sections in Appendix 1.

Interpretation and discussion

Brown & others (1969) based their interpretation of the depositional setting of the Emmerugga Dolomite largely on a comparison with the only recent stromatolitic environment that was well understood at that time (1967-69)—Shark Bay, in Western Australia—where the stromatolites occur in a marginal-marine hypersaline lagoon (Logan & others, 1964). Since that time, however, stromatolites have been described from a number of Pleistocene and Holocene environments: marine lagoons; continental groundwater lakes near sea level; inland lakes fed by continental groundwaters; and silica-bearing waters of hot springs (Walter, 1976). It is evident that stromatolites and carbonate can occur in a wide variety of environments, and the earlier interpretations of Brown & others (1969) require revision as a result of both more-recently published information and our investigations in the area.

Mara Dolomite Member

Brown & others (1969) equated the sedimentary environment of the domal and stratiform stromatolites in the Mara Dolomite Member with that of the Shark Bay stromatolites described by Logan & others (1964)—that is, hypersaline intertidal zones sheltered from wave action, or ephemeral salt lakes not connected to the sea. If a marine environment is accepted, the cycles in unit 1 of the Mara Dolomite Member (not recognised by Brown & others, 1969) could be interpreted as regressive or shoaling cycles (Jackson, 1980b), and would imply a tidal range of a few metres in amplitude.

Jackson & others (1978), however, had earlier compared these cycles in unit 1 of the Mara Dolomite Member with Holocene sediments in the ephemeral Coorong lakes in South Australia. In these continental lakes, fine-grained aragonite and hydromagnesite precipitate as 'yoghurt' mud and support stratiform and small domal stromatolites. During the dry months of the year, evaporation of surface brines causes halite to concentrate in brine pools and to precipitate within the crusts on the tops of the stromatolites. The sequence through the lake sediments—'yoghurt' mud, stromatolites, and halite crust corresponds closely to the cycle (dolostone, stromatolite, and sucrosic chert) in unit 1 of the Mara Dolomite Member (Fig. 94).

The two interpretations are illustrated in Figure 94.

The Coorong lake systems occupy long, northwesterly aligned 'corridors' separated from one another by carbonate and quartz sand dunes, of which the most recent—the Younghusband Peninsula—is a barrier dune on the edge of the Southern Ocean. When the vegetation dies, uncemented dune sands are blown over lakes and interlake areas, and are reworked by water during wet seasons. The arenites associated with unit 1 of the Mara Dolomite Member may have been formed by such a process. The dunes are unlikely to have been preserved in the geological record as a dune facies, because their topographic setting suggests that they would have been exposed to erosion and reworking rather than burial and fossilisation.

Like unit 1, units 2 and 3—the laminated and more massive carbonates—can be interpreted in more than one way. Brown & others (1969, p.21) stated that: 'The upper part of the Mara Dolomite Member, as well as containing some intervals of sediments deposited in sheltered tidal flats, lagoons, or salt lakes, also contains sediments probably deposited from water with more open access to the open sea, and mainly below low-tide level. The oolitic dolarenites are the main indicators of shallow marine conditions, and beds of *Conophyton* and clean massive to thickly laminated dololutite, are also thought to have been deposited below wave and low tide base'. We consider that neither oolites nor *Conophyton* necessarily implies marine conditions.

According to work by Davies & others (1978), ooids can form under quiet-water conditions where organic membranes and a suitable pore-water chemistry are present; the ooids cannot form where organic matter is not available. In the fossil example preserved in the Mara Dolomite Member, there is plenty of evidence for the presence of organic matter; the oolitic dolarenites, therefore, are not necessarily indicators of marine or agitated waters.

The environmental setting of *Conophyton* likewise is equivocal: both shallow-water (Walter, 1976) and deep-water (Donaldson, 1976) examples are known. We therefore question the need to interpret a marine setting for such a quiet subaqueous environment of deposition—all that is required is for the microorganisms not to be exposed to the air, an absence of waves and currents, and a suitable water chemistry. The specimens of *Conophyton* in the Mara Dolomite Member are not associated with desiccation, wave, or current-generated structures, and, since the maximum synoptic height of these stromatolites is about 2 m, then all that is needed is a quiet standing body of water a few metres deep.

The analogies of the interpreted depositional environments that we have suggested for the Mara Dolomite Member—between unit 1 and the ephemeral lakes of the Coorong on the one hand, and between units 2 and 3 and more-persistent quiet-water lagoons or ponds on the other—could have a bearing on the interpretation of the geochemical results.

We assume that the rocks reflect the chemistry of the groundwater of Proterozoic times. The differences between the chemistry of the Mara Dolomite Member near to and distant from McArthur mine may be significant. Near McArthur mine, the Mara Dolomite Member is calcitic, ferruginous, and manganiferous; farther from the mine it contains much more magnesium and less iron and manganese. Thus, the area of the McArthur mine may have been a chemical depocentre for the groundwaters of the Emmerugga Dolomite in much the same way that groundwaters precipitate carbonate sequentially in the Coorong lakes area: the most magnesium-rich carbonates are precipitated at the continental end of the lake chain, and the dolomites and calcites (and halite) are precipitated farther down the groundwater gradient (von der Borch, 1976a).

Mitchell Yard Dolomite Member

According to Brown & others (1969) the '. . . uniform nature of the Mitchell Yard Dolomite Member and lack of chert suggests a subtidal environment of deposition, either shallow marine . . . or subtidal lagoons'. However, virtually none of the structures seen in the member are primary, so it is difficult to substantiate any interpretation. The only primary structures reported (laminated dololutite) are non-diagnostic. The huge amount of vadose alteration which appears to predate at least some of the overlying Teena Dolomite implies prolonged emergence and exposure of the rocks during Proterozoic times; hence the caution to which we alluded above on the stratigraphic validity of the member status for the Mitchell Yard Dolomite Member.

In summary, Brown & others (1969) suggested that the Emmerugga Dolomite was deposited in a variety of marginal-marine environments: the Mitchell Yard Dolomite Member was interpreted by them as wholly subtidal; the Mara Dolomite Member was stated to contain subtidal, sheltered intertidal, lagoonal, and ephemeral salt-lake deposits. We feel, however, that there is no compelling evidence for deeper marine (subtidal) facies within the unit, and that much of it could have been deposited in shallow lagoonal and saline lacustrine environments.

TEENA DOLOMITE

The term Teena Dolomite is here proposed for a unit mainly of laminated and thin-bedded dololutite (some stromatolitic) between the Emmerugga Dolomite and the Barney Creek Formation. In addition the unit also contains thin interbeds of intraclast conglomerate, dolarenite, dolomitic siltstone, sandstone, and potassium-rich mudstone. Outcrops belonging to this formation were mapped by Smith (1964) as part of the Emmerugga Dolomite and Amelia Dolomite. The formation as herein defined corresponds to the 'laminated dolomite' of Cotton (1965) and to the Teena Dolomite of Murray (1975).

The Teena Dolomite was incompletely defined by Plumb & Brown (1973), who separated out and named the Coxco Dolomite Member encompassing the upper part of the formation. This member is characterised by distinctive acicular radiating crystal casts. Neither unit (lower Teena Dolomite or Coxco Dolomite Member) has been formally and validly defined, but—because the names have been commonly used since 1973, and both units are readily mappable—the names are retained and herein defined.

The formation is named after the Teena prospect (GR 063823, *Batten*, 6065). The Coxco Dolomite Member is named after the Coxco Valley—a narrow steep-sided valley which extends for about 20 km parallel to and along the Emu Fault Zone—south-southeast of McArthur mine.

Distribution, thickness, and type of outcrop

The main outcrop area of the Teena Dolomite is in BAUHINIA DOWNS and WALLHALLOW (Plate 1). In addition, it has been recognised in a section west of Nathan River homestead in MOUNT YOUNG. A correlation with part of the Mount Vizard Formation farther north, near the Roper River, is not evident.

The Coxco Dolomite Member varies in thickness from about 15 to 70 m, and the lower Teena Dolomite (i.e., the formation excluding the Coxco Dolomite Member) is up to about 60 m thick; thickness variations are mainly due to later erosion. In places—for example, near Amelia Springs—the Teena Dolomite is represented only by the Coxco Dolomite Member (e.g., Brown's measured section 9, Appendix Fig. A29); elsewhere—for example, near Bauhinia Downs homestead—the lower Teena Dolomite is thin and difficult to recognise (e.g., Brown's measured section 7, Appendix Fig. A27).

The formation as a whole rarely crops out well, and most lithological information comes from a study of creek sections or drillcore. Informative sections of the Coxco Dolomite Member are seasonally exposed in Barney Creek at GR 163812 (*Borroloola*, 6165) and in a nearby tributary of Barney Creek at GR 159823. Although the Teena Dolomite contains some early diagenetic chert, it is rarely silicified like the Amelia and Emmerugga Dolomites.

Vadose alteration effects are also less pervasive than in many of the other McArthur Group formations, and in the Teena Dolomite they are more or less restricted to recrystallisation. However, a peculiar and visibly striking texture—here informally termed 'paisleyite' (Fig. 96), after a design that is popular for cotton and silk prints—is present in the Coxco Dolomite Member. It is an intricately patterned open-space vadose filling consisting of brown banded and spotted ferruginous dolostone. Other solution features such as karstic fluting and the formation of small caverns occur, but they are nowhere near as extensive as those in the underlying Emmerugga Dolomite.

Stratigraphic relations

At some places the Teena Dolomite overlies the Mitchell Yard Dolomite Member with an apparently conformable and gradational contact (Fig. 97). At other localities the Mitchell Yard Dolomite Member appears to be absent, and the Teena Dolomite therefore directly overlies the underlying Mara Dolomite Member.

The Barney Creek Formation conformably overlies the Coxco Dolomite Member of the Teena Dolomite. The contact

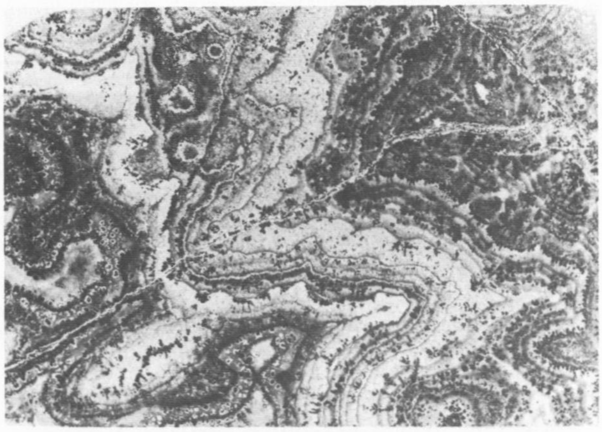

Fig. 96. Thin section viewed through plane-polarised light of 'paisleyite' in the Teena Dolomite at Barney Creek about 4 km north of McArthur mine. The control of the major features by cracks, and the colloform textures, are clearly shown. The small black speckles are manganese dendrites. The width of the thin section is about 3 cm.

between the carbonate-rich Coxco Dolomite Member and the terrigenous Barney Creek Formation is commonly gradational over several metres. The Coxco Dolomite Member is locally brecciated and fairly tightly folded. The folds appear to be penecontemporaneous, and most of the brecciation is of solution-collapse type. The implications of this folding are discussed below.

Type section

The type section of the formation (Brown's measured section 13, Fig. 97) is located at GR 143776 (*Borroloola*, 6165), 5 km southwest of McArthur mine. Several other measured sections, on which the lithological description of the formation is based, are mentioned under *Lithology*.

Lithology

This description of the lithology is based largely on the measured sections of Brown & others (1969; Fig. 97; Appendix Figs. A26–A34 and A36), supplemented by our more recent observations.

Lower Teena Dolomite

Most of the lower Teena Dolomite is thick to thin-bedded or laminated dololutite. Brown & others (1969) described it as 'cherty dololutite', implying dololutite with some proportion of chert. However, the chert occurs as nodules, irregular patches, and thin discrete lenses. Drillcore contains a much lower proportion of chert, and some of the chert in outcrop may well be related to weathering and silicification of either the present surface or the Cretaceous or Cambrian regoliths. Chert nodules from two thin sections of the lower Teena Dolomite are clear and show no traces of organic matter or primary bedding structures. They appear either to be primary or to have developed early in diagenesis before compaction had any great effect.

The lower Teena Dolomite is rarely stromatolitic, but thin beds of small *Conophyton*-like stromatolites, columnar forms (up to 7.5 cm high and 2 cm in diameter), and domal and stratiform stromatolites were recorded by Brown & others (1969). The stromatolites are more-or-less confined to the top or the bottom of the unit, and the middle part typically consists of parallel-laminated dololutite with chert nodules and lenses.

Less common rock types include dolomitic shale (in places with halite casts), intraclast breccia and conglomerate, coarse and fine-grained dolarenite and dolomitic sandstone, and rare potassium-rich mudstone. The arenites are in places ripple-marked (oscillation ripples), and have parting lineations on the bedding planes. The content of sand, silt, and clay increases towards McArthur mine.

Coxco Dolomite Member

The overlying Coxco Dolomite Member is basically thick-bedded dololutite, but it also contains thin-bedded dololutite with abundant interbeds of pink, buff, or orange-weathering potassium-rich mudstones (?tuffs) in the Bulburra Depression near McArthur mine (Fig. 98). Rare stromatolites occur in the lowest few metres of the unit; these are columnar *Conophyton* with columns about 2.5 cm in diameter.

The most striking feature of the Coxco Dolomite Member is the abundance of crystal casts. The commonest are radiating bundles of acicular crystal casts rarely more than 2 mm in diameter but up to 6 cm long (Fig. 99). The number of needles in each cluster ranges from tens to hundreds, and the crystal casts have a six-sided cross-section and appear to be zoned. They are subtly enhanced by weathering, but—where they have not been silicified—they can be easily overlooked in the field because they differ little in colour from the matrix dolomite. Plumb & Brown (1973) interpreted the casts as aragonite pseudomorphs, but later crystallographic studies (Walker & others, 1977) demonstrated that they are pseudohexagonal gypsum pseudomorphs.

Rarer crystal casts, well exposed in the bed of Barney Creek near McArthur mine include small (up to 5 mm) discoidal casts similar to those described from the Amelia Dolomite. In addition, radiating bundles of acicular unzoned crystals occur in a 2-m interval of the member; they have an irregular three, four, or five-sided cross-section, though most are four-sided, and are up to 5 mm in cross-section and 10 cm long. The tops of many of these unzoned crystals were snapped off before lithification. This broken habit has not been observed in the more regular six-sided gypsum crystal casts.

Other distinctive crystal casts occur in the small creek which is crossed by the road linking McArthur mine with the McArthur River Camp, and rarely elsewhere in the Coxco Dolomite Member. They comprise six-sided thin plates (5 mm wide and up to 2 mm thick) consisting of microcline, in contrast to the other crystal cast types already described which are mainly preserved as dolomite. This feldspar replacement is therefore somewhat noteworthy, though microcline replacement of gypsum and other evaporite minerals has been previously reported by Rowlands & others (1980) from the Middle Proterozoic Callanna Group of South Australia.

One particular rock texture which is confined to the Coxco Dolomite Member, and which is particularly well developed in Barney Creek, is 'paisleyite'. It is a yellowish brown, intricately patterned, somewhat leached clay-rich dololutite with spots and bands of iron (or manganese) oxides scattered through and defining the texture. The texture is related to solution channels in the rock, which are quite distinct owing to their darker brown, more siliceous margins. The lateral migration from these channels of various sesquioxides as Liesegang fronts gives rise to the intricate texture, which is controlled by the orientation and intersection of the solution channels (Fig. 96). The rock originally may have been brecciated, resulting in a secondary permeability through which the solutions travelled.

The Coxco Dolomite Member is commonly mineralised. Galena crystals up to 5 mm in diameter are associated with both the 'paisleyite' and the discoidal and monoclinic crystal casts. Galena crystals and irregular patches of yellow secondary sphalerite are associated with the six-sided microcline plates.

Geochemical studies (Appendix 2) indicate that the Teena Dolomite is composed largely of dolomite. Like the Emmerugga Dolomite, it also shows increased iron and manganese contents and a similar calcium deficiency near McArthur mine.

Interpretation

Lower Teena Dolomite

Brown & others (1969) diagnosed the depositional environment of the lower part of the Teena Dolomite as '. . . probably of shallow subtidal and intertidal origin (indicated by the presence of oolitic carbonate, dolomite flake breccias, and flat-laminated sandstone with primary current lineation). The dolomite with *Conophyton*, at the base and top of the unit, is interpreted as a shallow subtidal facies.' However, for

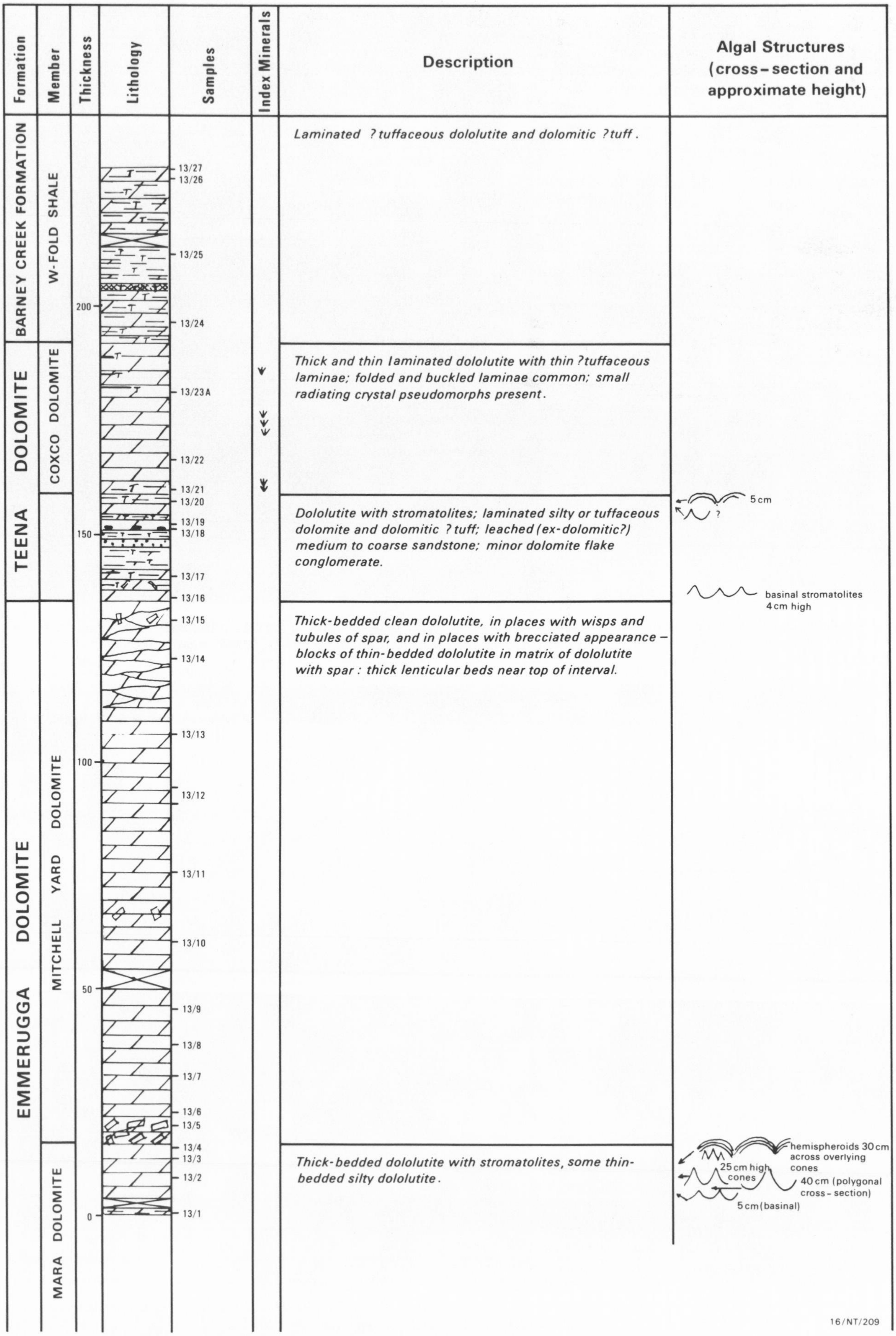

Fig. 97. Type section of the Teena Dolomite (Brown's section 13), 5 km southwest of McArthur mine. For explanation of symbols, see Fig. 90.

Fig. 98. Thin parallel-bedded dololutite with resistant potassium-rich ?tuff bands (pale grey)in the Coxco Dolomite Member of the Teena Dolomite near BMR McArthur River No.2 diamond drillhole (GR 002675; Plate 1). (BMR negative GB 3068)

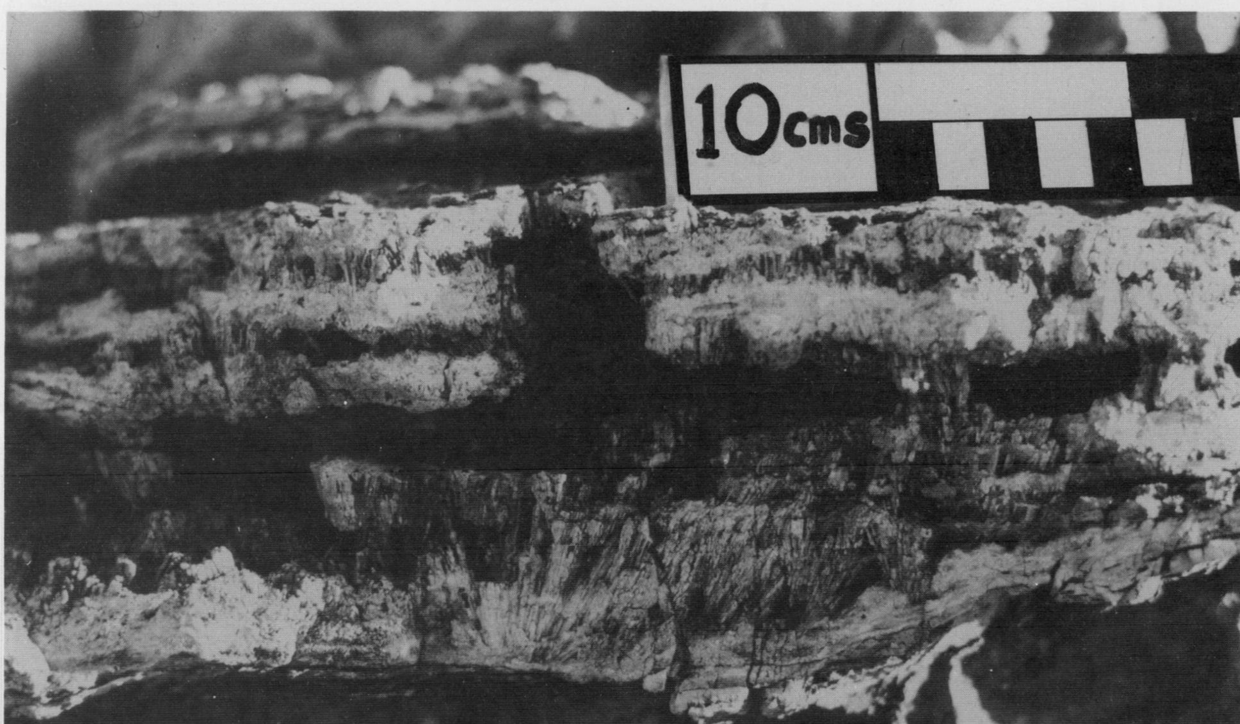

Fig. 99. Close up of chert-replaced radiating acicular gypsum crystals in the Coxco Dolomite Member of the Teena Dolomite in outcrop about 3 km north of Leila Lagoon (BMR negative GB 3070)

reasons referred to in an interpretation and discussion of the Mara Dolomite Member of the Emmerugga Dolomite (p. 92), such features as oolites and *Conophyton* are not diagnostic exclusively of a marine environment.

The intraclast breccias, which are more common in the Teena Dolomite than in the Emmerugga Dolomite, warrant further discussion. In most of these flake breccias, evidence of current action is lacking. The flakes have not travelled far. They are relatively uniform in size, and the outlines of the flakes are roughly polygonal. Most are completely angular and lie at an angle of no more than 5° to the bedding. Broken edges can be matched on adjacent flakes. Although some of the flakes overlap slightly, imbrication is not evident. Petrologically, the flakes are indistinguishable from one another and from the matrix, but the top surfaces of the flakes are zoned in places, and are more sharply defined from the matrix than are the lower edges.

Flake breccias of this type have been compared with the remnants of surface crusts on hypersaline lakes which have been broken up by dehydration and gently rearranged by later shallow flooding (Williams & Logan, 1981). These authors described crusts of this type in the HYC Pyritic Shale Member, and similar crusts have also been described by Muir & others (1980b) in the Yalco Formation. The Yalco Formation crusts were compared with crusts in the ephemeral lakes of the Coorong region, South Australia, and there is good reason for interpreting the Teena Dolomite intraclast breccias in much the same way (see p. 125 for a description of the process leading to the formation of such intraclast conglomerates). It should perhaps be emphasised here that—although comparisons are being made with the Coorong region—similar structures have been described from other hypersaline lacustrine environments, but the sedimentary structures of the Coorong region are more familiar to us.

The clear chert nodules that are associated with the laminated dololutite appear to be primary or earliest diagenetic. Holocene carbonate sediments in the ephemeral Coorong lake systems contain up to 15 per cent disseminated silica (von der Borch & Jones, 1976), and the clear cherts in the Teena Dolomite may represent some form of accumulation of silica of this kind.

Thus the available evidence from the lower part of the Teena Dolomite suggests to us deposition mainly in a hypersaline lacustrine environment, in which very shallow-water and emergent conditions alternated, rather than subtidal and intertidal environments as originally proposed by Brown & others (1969).

Coxco Dolomite Member

In the Coxco Dolomite Member, the abundant crystal casts can be interpreted as indicating the former widespread presence of a specific suite of evaporite minerals. Extrapolation from these evaporite minerals enables us to roughly determine the water/sediment chemistry during deposition and/or early diagenesis.

The six-sided acicular zoned crystals were originally interpreted as having been primarily aragonite (Brown & others, 1969), but later work by Walker & others (1977) demonstrated clearly that the crystal angles could have been produced only by gypsum. Similar crystal clusters are known from brine pools in the Arabian Gulf in marginal-marine areas, and also in early Holocene deposits at Marion Lake, South Australia (von der Borch & others, 1977). In Marion Lake, radiating bundles of six-sided gypsum crystals are replaced by aragonite in a two-stage process: initially a thin film of calcium carbonate is deposited around the gypsum crystals forming a thin skin of calcite; groundwaters subsequently dissolve out the remaining gypsum, without dissolving the calcite, to leave a hollow mould of the crystal which is later infilled with carbonate. This type of mechanism is a likely means of producing the type of zoning in the casts in the Coxco Dolomite Member. At Marion Lake the replacement of the gypsum with carbonate is caused by the passage of groundwaters of different chemistries through the primary sediments in the phreatic and vadose zones. It occurs before compaction has taken place, and the crystals—because they are eventually replaced by a material that is almost identical with their matrix—do not break upon compaction.

In contrast, the broken acicular crystals must have retained their original chemical composition until compaction was well advanced and, because the matrix was fine-grained and more readily compacted, tended towards brittle fracture. These crystals are not zoned, and contain inclusions of the matrix, and therefore must have grown displacively. Morphologically, they are similar to trona crystals from the Eocene Green River Formation (Fahey, 1962), and are tentatively interpreted to be relics of this mineral. Crystallographic examination of the casts unfortunately has proved inconclusive, but if they are pseudomorphs after trona we have an unambiguous criterion for identifying their depositional environment as lacustrine: trona ($NaHCO_3.Na_2CO_3.2H_2O$) cannot be precipitated by the evaporation of sea water, in which the supply of carbonate ions is exhausted by the time sodium ions precipitate; the sodium in sea water invariably crystallises as the chloride.

The other crystal casts—the discoids, monoclinic forms, and six-sided platy microcline crystals—all appear to be pseudomorphs after gypsum, which can be precipitated from either marine or continental waters. While it is possible to argue that the two evaporite types—gypsum and ?trona—could indicate that the depositional environment oscillated between marine and continental, we consider that this is unlikely—mainly because the host sediments do not appear to vary at all, and also because there is an absence of documentable trangressive or regressive features. If the tentative identification of trona is correct then the Coxco Dolomite Member must be of continental origin.

Turning from the evaporites to other textures—the 'paisleyite', which is interbedded with these evaporitic rocks, shows the effects of alteration caused by the passage of solutions of variable composition through the rock. The Liesegang fronts indicate differential passage and arrest of solutions, and are most likely to have been formed in the phreatic or vadose zone.

Barney Creek Formation

The term Barney Creek Formation is here proposed for a poorly exposed unit of mainly dolomitic, carbonaceous, and pyritic siltstone and shale. Tuff beds, breccias, and graded units are locally abundant. The unit is of considerable economic importance because it is the host to the large stratiform HYC lead-zinc-silver deposit, and, as a result of this, has been the subject of intensive study by a number of company geologists over a long period. For this reason we have made only limited observations on the unit, and the following description is largely a review of previously published information (Cotton, 1965; Murray, 1975; Williams, 1978a, b, 1979; Rye & Williams, 1981; Oehler, 1977; Oehler & Logan, 1977; Williams & Logan, 1981, Hamilton & Muir, 1974; Muir, 1983b; Lambert, 1976; Walker & others, 1978).

The Barney Creek Formation is divided into three members around McArthur mine. The *Cooley Dolomite Member* is a poorly exposed massive chaotic breccia best known from drilling. The *HYC* ('Here's Your Chance') *Pyritic Shale Member*, which hosts the HYC deposit of fine-grained lead-zinc-silver at McArthur mine, is a thick pyritic, carbonaceous, dolomitic siltstone-shale unit with interbedded breccia. The lowermost *W-Fold Shale Member* is a unit of siltstone and shale with vitric tuff; its base is marked by the 'grit marker bed' (local usage), the first graded lithoclastic dolarenite above the Coxco Dolomite Member of the Teena Dolomite.

Smith (1964) and Cotton (1965) referred to the rocks of this formation as the Barney Creek Member of the Amelia Limestone. Plumb & Brown (1973) used the term Barney Creek Formation, which they divided into the three members, and supplied summary descriptions. The names have been in general usage since then, and because of their relevance to the HYC orebody they have been extensively published. However, they have never been formally and validly defined; this is corrected here.

Much of the stratigraphic information on the formation is based on subsurface data (drillholes and underground excavation), compiled and published by Carpentaria Exploration Co. Pty Ltd, from within a small area near McArthur mine. BMR McArthur River No. 2 (GR 955676) intersected about 200 m of the Barney Creek Formation, and provides information away from the mine area. This localised and detailed information has been supplemented with observations from outcrops in other areas, but—as noted above—the Barney Creek Formation seldom crops out, so there is no precise understanding of its regional character and variability.

The stratigraphic divisions of the formation, which were erected in the McArthur mine area, are more in the nature of lateral facies equivalents rather than basinwide lithostratigraphic units. This is especially applicable to the relationship between the Cooley Dolomite and HYC Pyritic Shale Members.

The formation is named after Barney Creek, a tributary of McArthur River (junction at GR 177828, *Borroloola*, 6165); the W-Fold Shale Member after W-Fold Hill (GR 080822, *Borroloola*, 6165); the HYC Pyritic Shale Member after the HYC deposit (GR 170831, *Borroloola*, 6165); and the Cooley Dolomite Member after Cooleys lead-zinc prospect (GR 198821, *Borroloola*, 6165).

Distribution and thickness

The Barney Creek Formation is poorly exposed in BAUHINIA DOWNS, WALLHALLOW, and MOUNT YOUNG. A thin unit of green glassy pyritic tuff in the Vizard Formation south of Mount Birch (locality map, Plate 1) may be a lateral equivalent of the Barney Creek Formation.

The formation is at its thickest (about 700 m) near McArthur mine (BAUHINIA DOWNS), where the lithologies characteristic of the three members are best developed adjacent to the Emu Fault Zone. West of the Tawallah Fault the Barney Creek Formation consists of flat-laminated grey and brown tuffaceous and silty dololutites, which are about 80 m thick and directly overlain by the Reward Dolomite near Bauhinia Downs homestead (Appendix Fig. A27). Brown & others (1969) interpreted the Barney Creek Formation here as being composed mainly of the W-Fold Shale Member; although we have retained this interpretation in Appendix Figure A27, the similarities between the lithologies in this section and those in the type area are slight. Indeed this section of the formation might, for other reasons, be referred to the HYC Pyritic Shale Member; for example, the same beds are mineralised in outcrops about 5 km east-northeast of Bauhinia Downs homestead, where cubes of malachite up to 5 mm are present and geochemical anomalies of more than 1000 ppm Pb and Zn (Johnston, 1974a, b) have been recorded.

Elsewhere in BAUHINIA DOWNS, the Barney Creek Formation crops out at Top Crossing (160 m thick) and south of the Abner Range (about 10 m thick), where it comprises thin-bedded to laminated flaggy dolomitic pyritic shale and siltstone. Although Brown & others (1969) divided it into two of its constituent members near Top Crossing (Brown's measured section 2, Appendix Fig. A33), Jackson & others (1978) commented that these members could not be reliably mapped there.

The members of the formation are best developed and attain their maximum thicknesses a few kilometres west of the Emu Fault Zone in an area known as the Bulburra Depression (Murray, 1975): the W-Fold Shale Member may be as much as 150 m thick 20 km west of McArthur mine; and the HYC Pyritic Shale and Cooley Dolomite Members are both about 600 m thick. The thickest development of the Cooley Dolomite Member, near the McArthur mine, coincides with the maximum thickness of the formation.

East of the Emu Fault Zone, the Barney Creek Formation crops out in several small inliers in the Cambrian Bukalara Sandstone, and AMOCO Minerals Pty Ltd identified the HYC Pyritic Shale Member with minor base-metal mineral deposits in drillholes in this area.

Within the Emu Fault Zone, sections measured by Brown & others (1969) indicate that the Barney Creek Formation is either thin or absent (Appendix Figs. A29, A34), and identification of the members is not possible.

Farther north, the Barney Creek Formation crops out as about 20 m of locally pyritic flaggy dolomitic siltstone west of the Nathan River homestead (Fig 7; MOUNT YOUNG).

Unlike the underlying formations, the thickness variations in the Barney Creek Formation do not appear to be due mainly to erosion; rather they appear to reflect variable original depositional thicknesses.

In summary, although it is widespread the Barney Creek Formation is never well exposed. Even the type section, in Barney Creek (see below), is variably exposed, depending on the amount of silt deposited each year at the end of the wet season. In many places, identification of the Barney Creek Formation relies mainly upon its stratigraphic position and distinctive shaly character. Where the dolomitic siltstone and shale are oxidised, the formation is commonly bleached to pale grey shaly float; original sulphide minerals are altered to carbonate (cerussite, smithsonite), silicate (hemimorphite), and oxide/hydroxide (goethite, limonite).

Type and other measured sections

The type section for the formation is located in Barney Creek, and extends from Barney Hill to the junction of Barney Creek and the McArthur River (GRs 162829 to 177828, *Borroloola*, 6165). The type section for the W-Fold Shale Member is at the W-Fold prospect (GR 080822, *Borroloola*, 6165), about 8 km west-northwest of McArthur mine; that for the HYC Pyritic Shale Member is in Barney Creek (at GR 175833, *Borroloola*, 6165) about 300 m upstream from the junction with the McArthur River; and that for the Cooley Dolomite Member is in CEC drillhole DDH Ie 115, between 46 and 610 m. Representative samples of core from this drillhole (sample numbers 72/10/0201 to 72/10/0255) and a copy of the detailed drill log are held in the Core and Cuttings Laboratory of the Bureau of Mineral Resurces, Canberra; a simplified log of this type section is reproduced in Appendix Figure A31.

In addition to the type sections, Brown (*in* Brown & others, 1969) measured several other sections through parts of the Barney Creek Formation. We have included his logs of these sections as Appendix Figures A27–A30 and A32–A36.

Stratigraphic relations

The Barney Creek Formation overlies the Teena Dolomite with apparent conformity. The contact between the Barney Creek Formation and the overlying Reward Dolomite is gradational in places where continuous sedimentation occurred, but elsewhere the Barney Creek Formation is unconformably overlain by the Reward Dolomite, or by younger formations (of the Batten Subgroup).

Lithology

The lithology of the Barney Creek Formation is more variable than that of many other formations in the McArthur Group. The description of the lithologies of the individual members below is based mainly on data from near McArthur mine. It is followed by a generalised lithological description of the undivided formation in areas away from the HYC deposit.

W-Fold Shale Member

The basal unit of the Barney Creek Formation consists mainly of green and red dolomitic potassium-rich siltstone and shale, and green vitric tuff containing pyroclastic fragments and scattered feldspar crystals; the proportion of vitric tuff increases towards the top of the member (Brown & others, 1969). Walker & others (1978) considered that the member is '. . . restricted to the deeper sub-basins* of the Bulburra Depression where it represents the transition from evaporitic carbonate sedimentation of the Coxco Dolomite Member to euxinic shale sedimentation of the H.Y.C Pyritic Shale Member.'

There is little published information on the sedimentology of the W-Fold Shale Member. Although the rocks contain a small amount (about 10%) of fragmental tuffaceous material, most of the beds show some evidence of having been water-laid (e.g., graded beds, scour structures, flame structures, and small ripple marks), but none show any evidence of evaporites.

HYC Pyritic Shale Member

The HYC Pyritic Shale Member is the host to stratiform mineral deposits in the area. Despite its name, the member is a carbonaceous, dolomitic, pyritic siltstone (not shale), especially at the mineralised levels. The unmineralised higher parts of the Barney Creek Formation are generally very fine-grained. When fresh, the pyrite is usually a dingy green rather than the more typical brassy yellow.

Like the W-Fold Shale Member the HYC Pyritic Shale Member also contains potassium-rich mudstone, some of which contains shards and crystals and is undoubtedly a tuff—similar to the tuff marker beds at Mount Isa mine (Croxford & Jephcott, 1972).

Most of the rocks in this member are finely laminated, but graded beds, scour structures (Fig. 102), ripple marks, flame structures, and soft-sediment slumping are evident in places.

Walker & others (1978) distinguished three types of sedimentary breccia (Fig. 103)—based on clast lithologies, direction of flow, and source area—in the HYC Pyritic Shale Member, and differentiated them from the Cooley Dolomite

*The sub-basins referred to above are the HYC sub-basin, host to the HYC deposit; the W-Fold sub-basin, host to the W-Fold deposit (and west of the HYC deposit); and the Emu Plains sub-basin, host to the Emu Plains deposit, 3 km north-northwest of the HYC deposit (Fig. 100). The W-Fold Shale Member occurs in all three sub-basins (Fig. 101).

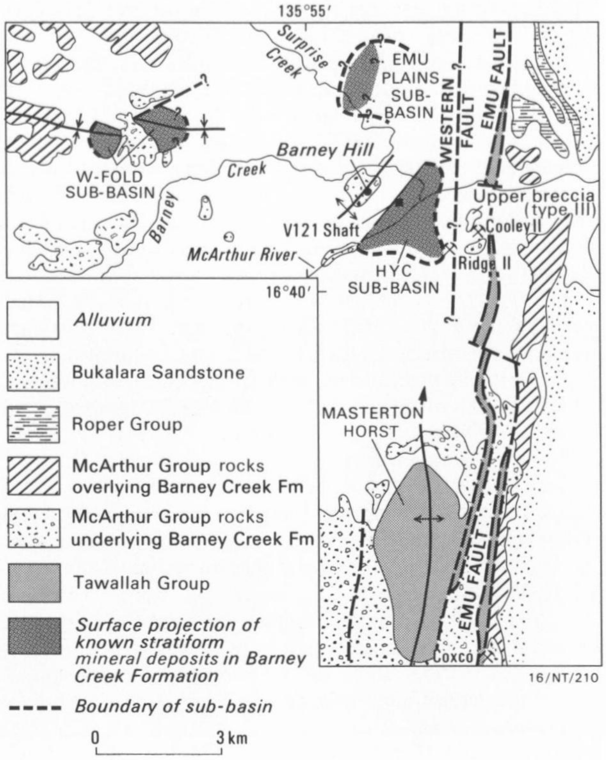

Fig. 100. Simplified geology of the area around McArthur mine (after Walker & others, 1978).

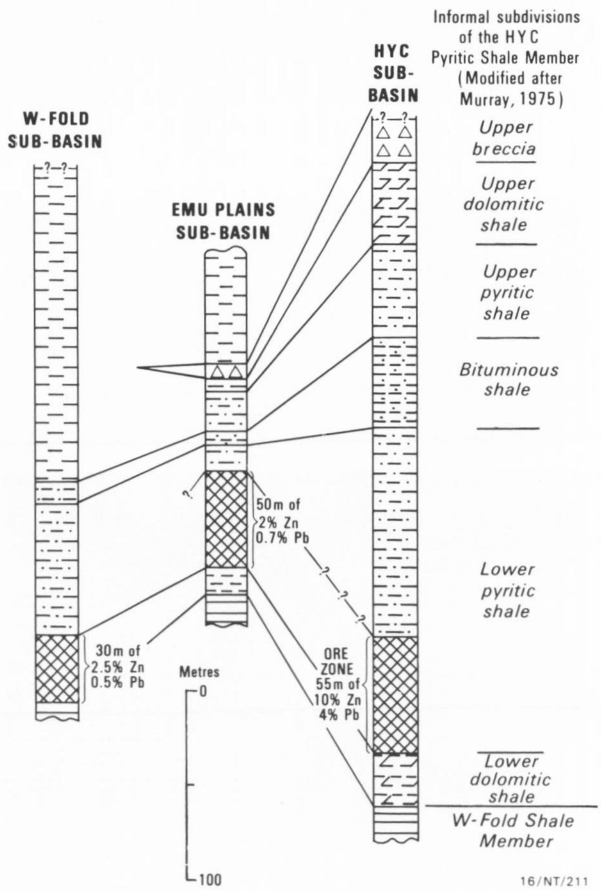

Fig. 101. Correlations between the HYC, Emu Plains, and W-Fold sub-basins (after Walker & others, 1978).

Member, which consists mainly of chaotic breccias. They referred to these as types I, II, and III breccias.

In the northern part of the HYC sub-basin, the *type I* breccia beds are chaotic, unsorted, and ungraded—comprising clasts up to 10 m—surrounded by contorted rock. In the southern part of the HYC sub-basin, the clasts are smaller, and the beds are thinner, better sorted, well graded with scours in places at the base, commonly laminated and ripple-marked, and do not distort the underlying shales. The clasts are derived from all the McArthur Group formations underlying the Barney Creek Formation.

The *type II* breccia beds are more common in the higher parts of the HYC Pyritic Shale Member. Their clasts are derived from the Emmerugga and Teena Dolomites.

The *type III* breccia beds are confined to the uppermost parts of the member, and are chaotic, ungraded, and unsorted. Their clasts, which range in size from a few millimetres up to several tens of metres, are derived from the underlying parts of the McArthur Group and from the Gold Creek Volcanics. Murray (1975) referred to the type III breccia as the 'upper breccia', which is the only breccia recognised in the Emu Plains sub-basin. There are no major breccias in the W-Fold sub-basin.

The HYC Pyritic Shale Member has been the subject of several independent studies that both complement the lithological observations and have implications for an interpretation of the depositional environment. These studies are briefly mentioned below.

Microfossils. Hamilton & Muir (1974) extracted small spherical microfossils from fine-grained carbonaceous pyritic shale. The microfossils are extremely abundant, and constitute a large proportion of the 5 per cent organic carbon recorded from the member.

Oehler (1977) and Oehler & Logan (1977) examined thin sections of chert, which forms rare wisps and lenses in the member. This chert contains abundant well preserved microfossils, amorphous organic matter, and pyrite. The microfossils in the chert are mainly filamentous, and include several spheroidal varieties. An interesting organism (often pyritised)

Fig. 102. Load and scour structures in graded laminated siltstone of the HYC Pyritic Shale Member, Barney Creek Formation, in the adit at McArthur mine. The diameter of the lens cap is 6 cm. (BMR negative M2552/16A)

Fig. 103. Inter-ore breccia in outcrop of the HYC Pyritic Shale Member of the Barney Creek Formation in Barney Creek. Note the variety in the type and size of the fragments, and the circular patterns of *Conophyton* stromatolites above the hammer head. (BMR negative GB 3192B)

is the manganese and/or iron-fixing bacterial fossil *Eoastrion*. Many of the filamentous forms are also pyritised.

Stable isotopes. A number of stable-isotope studies (Croxford & others, 1975; Williams & Rye, 1974; Rye & Williams, 1981) have yielded information pertinent to the chemical environment in which the member accumulated.

Sedimentary structures. Williams & Logan (1981) and Logan & Williams (1984) have described shallow and deeper-water facies in the member. The former includes desiccation structures, thin intraclast conglomerates and crusts, pedogenic pisoids, and nodular carbonate which contains pseudomorphs of acicular anhydrite needles.

Mineralisation-related studies. In studies of the mineral parageneses of the stratiform and stratabound deposits in the area, Williams (1978a, b, 1979) described various sedimentary structures (graded beds, scour structures, flame structures, etc.) that have been preserved in the extremely fine-grained ore.

In addition, Williams, (1978c) described the envelope of carbonate nodules which surrounds the orebody at McArthur mine. These nodules range up to 5 × 15 cm, and comparison of compaction ratios for layers inside and outside the nodules indicate that they formed at depths of between 10 and 100 m below the sediment-water interface. We observed similar nodules in outcrops of the Barney Creek Formation in the Mallapunyah Fault Zone, west of Top Crossing (Plate 1).

Cooley Dolomite Member

We have not studied the Cooley Dolomite Member at all. The observations that we present below are summarised from previously published information (Walker & others, 1978; Murray, 1975).

The Cooley Dolomite Member occurs to the west of the Western Fault (Fig. 104), where it has an interfingering relationship with the other members of the Barney Creek

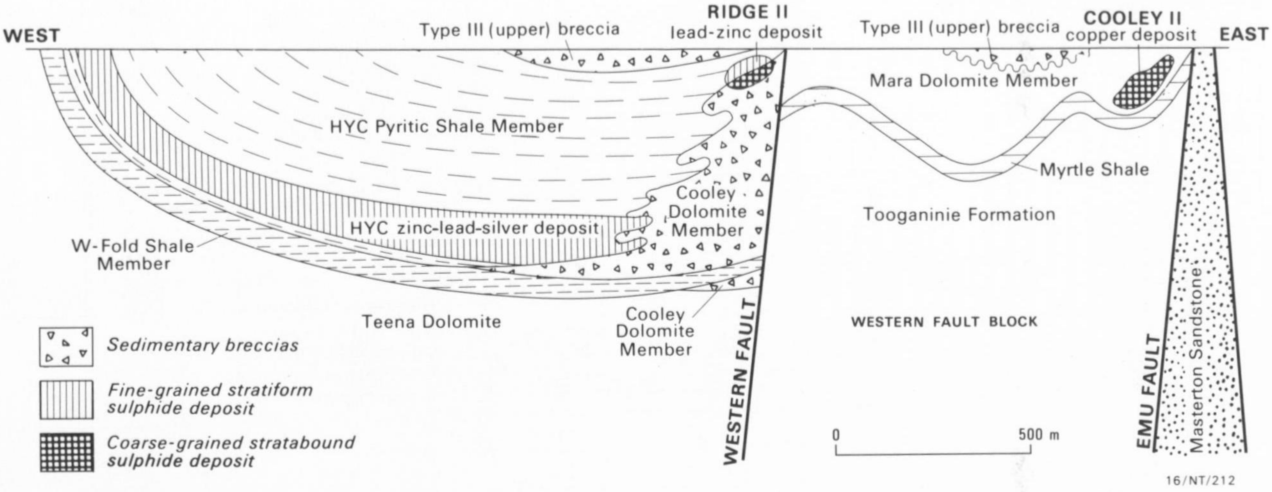

Fig. 104. Generalised section through the HYC sub-basin of the Bulburra Depression in the area of McArthur mine, showing the relationship between mineralisation, stratigraphy, and faults (after Walker & others, 1978).

Formation. It is a chaotic breccia with clasts ranging from millimetres to several tens of metres derived mainly from the Emmerugga and Teena Dolomites. Most of the breccia overlies the W-Fold Shale Member, but—locally, along the Western Fault—lenses of breccia lie between the Coxco Dolomite Member (of the Teena Dolomite) and W-Fold Shale Member.

Muir (1978) commented on poorly preserved microfossils from the type section of the Cooley Dolomite. An assemblage of filaments, spheroids, and *Eoastrion*—all enveloped in coatings of manganese dioxide—occurs in a chert lens at 156 m.

Undivided Barney Creek Formation

Jackson & others (1978) described the Barney Creek Formation in the Top Crossing area (Plate 1). Interbedded fine dolarenite and red-weathering ferruginous silty dololutite in the lower part is overlain by finely laminated dolomitic siltstone and silty dolostone*. Potassium-rich mudstone beds, 2-10 cm thick, are common.

The boundary between the Barney Creek Formation and the overlying Reward Dolomite is difficult to discern, but in the southern part of the Top Crossing area it is characterised by a thin and distinctive paper shale. Elsewhere, the base of the Reward Dolomite is defined by the first occurrence of wavy-laminated and stromatolitic dolostones.

Breccias in the Coxco Dolomite Member (of the Teena Dolomite) and Barney Creek Formation in the Top Crossing area (Fig. 105) appear to be related to syn-sedimentary faults similar to those at McArthur mine. The breccia clasts are commonly pyritic but otherwise unmineralised except for traces of galena.

Radiating acicular crystals (after anhydrite or gypsum) found in the Barney Creek Formation during the mapping in the upper reaches of Tooganinie Creek are similar to those in the Coxco Dolomite Member.

Interpretation

Initial interpretations of the depositional environment of the Barney Creek Formation generally favoured deep-water environments (e.g., Brown & others, 1969). This was based on (a) the fine-grained carbonaceous and pyritic (euxinic) nature of the rocks, and (b) the presence of turbidite-like graded beds and breccias.

The environment in which euxinic sediments accumulate is generally considered to indicate an anoxic water column at the site of sedimentation; in a marine environment, an anoxic water column can occur only below wave-base, and hence in moderately deep water. However, black organic and sulphide-rich sediments are commonly found today beneath fully oxygenated waters, and are the products of postdepositional (diagenetic) reduction of sediments below the surface (Curtis, 1978, 1980). Accordingly, we conclude that the interpreted euxinic environment in which the Barney Creek Formation accumulated places no constraints on water depth.

The presence of turbidites also does not necessarily impose a deep-water marine model on the Barney Creek Formation: although it is true that turbidites do form in deep oceanic environments, turbidites were first described from Lake Geneva, and also occur in many other shallow environments (e.g., Sturm & Matter, 1978; Fenton & Wilson, 1985).

Recent detailed studies of sedimentary structures in cores from the McArthur mine area (Williams & Logan 1981; Logan & Williams, 1984) have identified a shallow-water and a deeper-water facies in the HYC Pyritic Shale Member. The shallow-water facies is characterised by desiccation structures and carbonate cycles, and includes such features as: lithified dololutite crusts, tepees, intraclast conglomerates, carbonate nodules after anhydrite, and vadose (soil) carbonate pisoliths. These features closely resemble and are interpreted by Williams & Logan (1981) to be Proterozoic examples of the nodular carbonate-anydrite-bearing sediments that form today in shallow to emergent sabkhas and saline lakes.

The deeper-water facies contains abundant graded turbidites, slump breccias, and laminated siltstones. Although water depths are indeterminate they must have been sufficient to allow the formation of turbidite beds that are graded over thicknesses up to several metres.

Logan & Williams (1984) envisaged that the depositional environment was either a saline lake or nearshore lagoon complex that developed on the eastern edge of the Batten Trough, during a period of instability along the bounding Emu Fault Zone, so that water depths fluctated widely. Using isopach and isolith maps of the HYC Pyritic Shale Member, they have delineated subtle palaeogeographic changes during deposition. While the sediments above and below the HYC

*This is a more accurate lithological description of the undivided Barney Creek Formation than that annotated in the map legend.

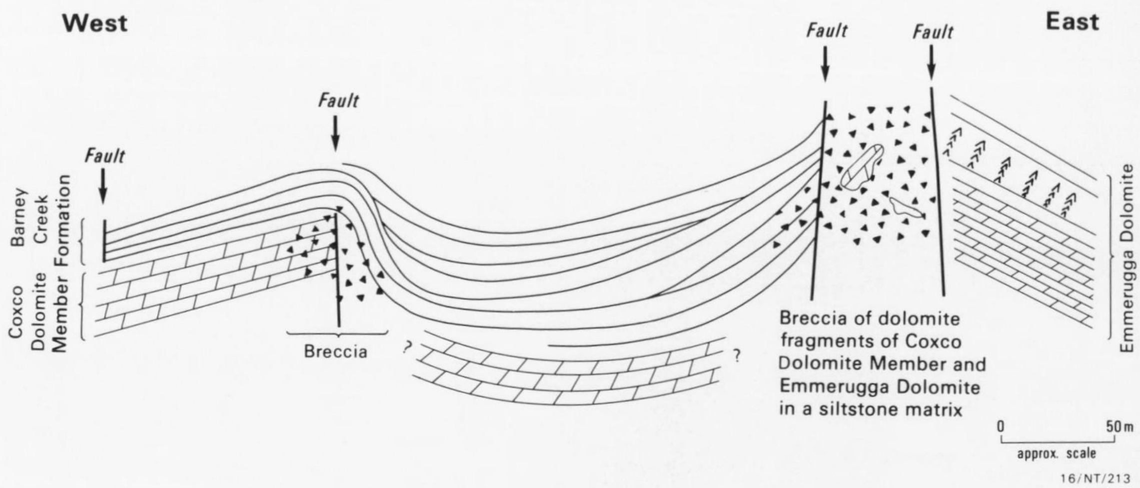

Fig. 105. Schematic section showing structural interpretation of units in the upper part of the Umbolooga Subgroup in the southwest part of the Top Crossing area (from Jackson & others, 1978).

deposit were forming, the area lay on the eastern margin of a large lake or lagoon that extended well to the west of the present western edge of the HYC deposit; the environment was relatively open, and a shallow to emergent zone adjacent to the Cooley Dolomite graded westwards to deeper water. While the sediments of the HYC deposit were forming, however, the area was occupied by much smaller lakes or lagoons of similar size to the HYC mineralised area.

The one aspect of the Barney Creek Formation which so far has not been discussed in this section is the Cooley Dolomite Member, and the related graded breccias which are interbedded with the ore horizons. Walker & others (1978) have shown how the Cooley Dolomite Member breccias are talus-slope deposits derived from the Western Fault scarp (Fig. 104). The type I breccias of the HYC Pyritic Shale Member were derived from the Western Fault scarp at the northern end of the basin, and spread out as turbidites over the southern area. Compared with the type I breccias, the type II breccias have a more restricted pebble assemblage, which is considered to reflect more local derivation—from the southeastern part of the basin margin. The chaotic breccias of type III, which include blocks of Gold Creek Volcanics and Masterton Sandstone, are probably sourced from horsts in the Emu Fault Zone, but the exact source area and the direction of movement are not known.

The HYC sub-basin is not the only mineralised section in the Barney Creek Formation. Two other sub-basins each host small deposits—the W-Fold and Emu Plains deposits (Murray, 1975; Walker & others, 1978)—which are similar to though lower in grade than the HYC deposit. Their depositional environments are similar to that of the HYC deposit, but—in contrast to the HYC sub-basin—there are no breccias in the W-Fold sub-basin and only the type III breccias in the Emu Plains sub-basin. This distribution of the breccias probably reflects the distances of the sub-basins from the Western Fault.

The limited surface studies in the Top Crossing area indicate that some elements of the geological setting in the McArthur mine area are present here also (Fig. 105)—synsedimentary faulting, breccias, slumping, a nearby major fault system (Abner Fault)—but not enough is known to make a closer palaeogeographic comparison.

In most other areas the presence of fairly thin sections of Barney Creek Formation and absence of breccias possibly indicates deposition in quiet water in distal environments of the lakes and lagoons proposed by Logan & Williams (1984).

Reward Dolomite

The term Reward Dolomite is here proposed for a unit of dolostone—stromatolitic in places—dolomitic breccia, siltstone, sandstone, and rare potassium-rich mudstone that occurs between the shaly Barney Creek Formation and the cherty and sandy Batten Subgroup. Smith (1964) included outcrops now assigned to the Reward Dolomite in a number of units, including the Amelia Dolomite, Lynott Formation, 'Billengarrah Formation', and Emmerugga Dolomite. The unit as herein defined corresponds to the Reward Dolomite and 'Deep Creek Dolomite' of Cotton (1965).

The Reward Dolomite shows striking variations in both lithology and thickness, but it has not been subdivided into members. We have not studied the formation in detail, and most of the following observations are based on the results of Brown & others (1969). The name of the formation is derived from the Reward prospect, 12 km west of McArthur mine.

Distribution and thickness

In BAUHINIA DOWNS and WALLHALLOW the Reward Dolomite has a distribution similar to that of the Barney Creek Formation. To the north, in MOUNT YOUNG, the Reward Dolomite occurs east of the Emu Fault Zone and just west of the Nathan River (Fig. 7). A lateral equivalent of the Reward Dolomite has not been recognised in the Vizard Formation in southeast URAPUNGA, but it may be represented by sandstone and dolostone with tuffaceous shale at Mount Vizard (locality map, Plate 1).

The Reward Dolomite ranges from a few tens of metres up to about 350 m thick. The thicker sections, in which the rocks are mainly shale, coincide with the thick developments of the Barney Creek Formation; conversely, where the Barney Creek Formation is thin, so too is the Reward Dolomite.

Type section

Brown's section 8—located, about 15 km northeast of the new McArthur River homestead—is nominated as the type section (Fig. 106). Good outcrops of the lower part are present immediately east and northeast of the Reward prospect (GR 026835, *Batten*, 6065), and good examples of the upper part and the karstic alteration (see p. 105) are present along the

Formation	Member	Thickness	Lithology	Samples	Index Minerals	Description	Algal Structures (cross-section and approximate height)
LYNOTT FORMATION						*White to pink weathered shale.*	
REWARD DOLOMITE		500 450 400 350		8/54 8/53? 8/52 8/51 8/50 8/49 8/48 8/47 8/46 8/45 8/44 8/43 8/42 8/41 8/40 8/39 8/37 8/36 8/35 8/34 8/33 8/32 A	xPy? xPy?	*Dolomite; mainly yellowish-weathering (?) tuffaceous, thin bedded dololutite, in places with ripple-bedded laminae of fine sandy doloarenite, and in places with tabular bands or small nodules of chert; small siliceous spheroids around 5 mm diameter common. Interbeds of coarse to very coarse sandy doloarenite a few cms to 1.5 m thick, often with blocks and contorted. inclusions of dololutite; coarse breccia with blocks of dololutite and dolomitic (?) tuff about 25 cm maximum size; intervals of tuff or tuffaceous siltstone; and some clean grey crystalline dolomite mottled 'thrombolitic' dolomite, and dololutite with ? algal balls (oncolites) 1 cm to 2 cm diameter.*	mottled 'thrombolitic' dolomite O 2 cm diameter spherical ? oncolites
BARNEY CREEK FORMATION	HYC PYR SHALE ?			8/31, 32		*Along strike, variable thickness of interbedded grey silty dololutite and grey (pink-weathering) dolomitic shale.*	
	W-FOLD SHALE	300		8/30 8/29 8/28		*Along strike, variable thickness of buff to dark grey thin laminated dolomitic ? tuffaceous siltstone and ? tuffaceous silty dolomite.*	

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Kilgour River in the southeast of the Abner Range area. Brown's section 11 from the south of the area is included as Appendix Fig. A36.

Stratigraphic relations

The Reward Dolomite overlies the Barney Creek Formation conformably, except (1) where the lower part is missing, and the upper part disconformably overlies the Barney Creek Formation, and (2) in places in fault zones where the Reward Dolomite oversteps the Barney Creek Formation to lie unconformably on the Mara Dolomite Member of the Emmerugga Dolomite (Walker & others, 1983).

A local unconformity occurs at the top of the Reward Dolomite. The unconformable relationship between the formation and younger units is especially clear in areas away from the Bulburra Depression and near fault zones, where formations of the Batten Subgroup, Nathan Group, and Roper Group and the Bukalara Sandstone overlie the Reward Dolomite with a profound unconformity. The unconformity is most strikingly displayed in or near fault zones—for example, close to the Coxco lead-zinc deposit, where evidence of prolonged weathering of the Reward Dolomite (as well as other formations) has been described (Walker & others, 1983). At the southeast end of the Abner Range, near-vertical Reward Dolomite is overlain by almost horizontal Lynott Formation as a result of post-Reward Dolomite faulting on a splay of the Mallapunyah Fault.

Lithology

The Reward Dolomite comprises mainly dolostone with subordinate dolomitic shale, dolomitic coarse sandstone and breccia, and potassium-rich mudstone. The dolostone is mainly dololutite, pelletal dolarenite (Fig. 107), or intraclastic dolarenite, The unit commonly contains abundant chert nodules, and a characteristic feature is the presence of small silica-rich spheroids (Fig. 108), generally a few millimetres to a few centimetres in diameter, which occur in beds of impure dololutite. These spheroids are a valuable stratigraphic marker because they are not known from any other unit in the basin.

Marked lateral facies and thickness changes generally reflect similar changes in the underlying Barney Creek Formation: the thinner sections generally consist mainly of dolostone and overlie thin sections of dolomitic Barney Creek Formation; thick shaly sections overlie thick shaly Barney Creek Formation.

Some of the thinner sections (e.g., 8 km west-northwest of Mallapunyah homestead; 4 km north-northwest of Balbirini homestead; and in the Emu Fault Zone around Cooks and Coxs lead prospects) consist mainly of chert-free dolostone and generally contain abundant domal, columnar, and some *Conophyton* stromatolites; clusters of radiating acicular gypsum pseudomorphs commonly cross-cut the *Conophyton* laminations (Fig. 109). Locally these stromatolitic dolostones are interbedded with, or overlain by, very coarse sandy intraclastic dolarenite and rippled dolomitic sandstone containing pebbles of stromatolitic dolostone or chert, and slump breccias (Fig. 110). The coarse dolomitic sandstone and dolarenite generally show only vague traces of flat bedding, but in places show sets of large-scale cross-beds and scouring.

Thicker sections (near McArthur mine) contain a variety of rock types and sedimentary structures: laminated and thin-bedded grey and brown dololutites—with abundant small nodules and thin bands of chert, and with variable potash content—grading into potassium-rich mudstone are most

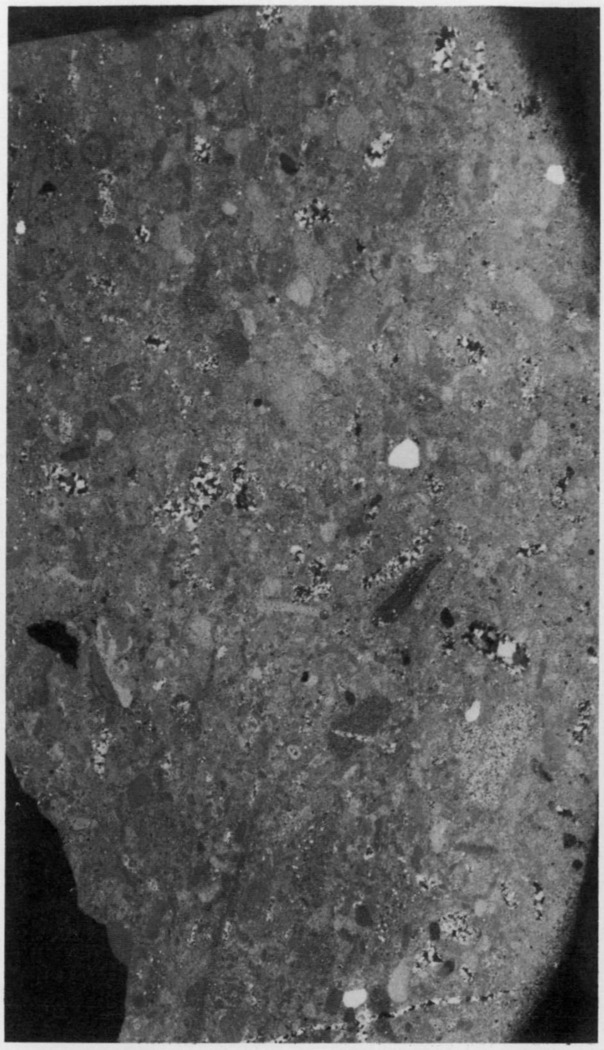

Fig. 107. Thin section (×3) of pelletal dolarenite in the Reward Dolomite from the type section. Most grains are coated, and the patches of chert may be space fillings, or replacements of spar. (BMR negative GB 3101/1)

characteristic; and fine sandy and pelletal dolarenites, in isolated rippled lenses and thin beds with current-ripple laminations and load casts, are common (Fig. 111), particularly in the type section (Fig. 106). The laminae frequently show small recumbent folds and low-angle overthrusts resembling those produced experimentally by the shearing of laminated mud by differential movement of more competent strata above and below; within individual localities the direction of shearing is fairly constant.

Arenites and rudites, generally with abundant coarse to very coarse quartz sand, are interbedded with these fine-grained sediments in places, especially within the area of the Bulburra Depression. In the type section the interbeds vary from small lenses of sandy dolarenite and dolomitic sandstone, generally with erosional bases, to 3-m-thick beds of coarse and very coarse sandy dolarenite containing scattered pebbles and blocks of the interbedded intensely contorted fine-grained dololutite and potassium-rich mudstone. In places these interbeds grade into coarse poorly sorted intraformational breccias. In outcrops west of Amelia Spring (GR 257643), thin lenticular beds of very coarse sandy dolarenite and sandstone occur within dololutite and potassium-rich mudstone. A channel fill of very coarse dolomitic pebbly sandstone and conglomerate about 10 m thick and 45 m wide

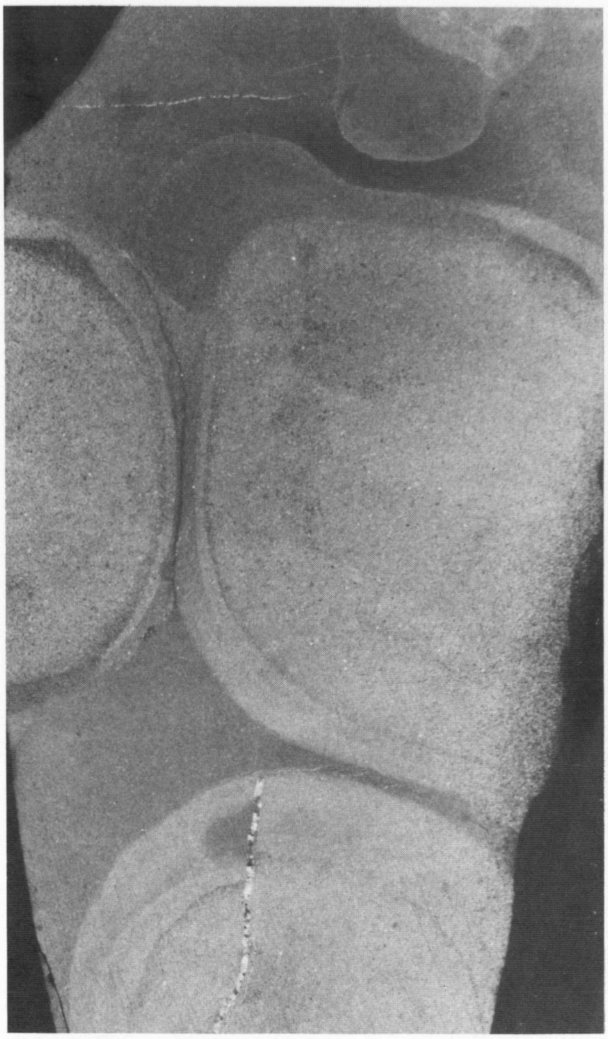

Fig. 108 Chert-coated spheroids (20 mm diameter) in the Reward Dolomite from the Reward prospect. (BMR negative GB 3101/3)

is also present in this area. Brown & others (1969) also reported intervals of the pale grey dololutite containing oncolite-like spheres (2 cm in diameter, which they referred to as 'oncolites') and mottled zones (which they interpreted as 'thrombolites') in several sections near the type section.

Sections through the formation in the northwest of the Abner Range area are intermediate in character between the sections described above: they commonly grade upward from interbedded laminated dololutite and potassium-rich mudstone (often contorted and with thin interbeds and lenses of coarse dolarenite and breccia), through clean dolostone with chert nodules (locally 'thrombolitic'), to interbeds of well sorted coarse sandy dolarenite and dolostone with columnar stromatolites.

The abrupt lateral facies changes characteristic of the formation are evident in the Top Crossing area. Here, in a distance of less than 5 km, the lower part of the formation in the north comprises wavy-laminated and stromatolitic dololutites—in which radiating gypsum pseudomorphs crosscut *Conophyton* laminations—which grade southwards into thin-bedded to laminated dololutite with discontinuous chert bands and nodules.

The top of the Reward Dolomite is commonly marked by a thin interval (around 5 m) of intraclastic sandy dolarenite or dolomitic sandstone, which at Top Crossing contains a 1-3-m pink tuff bed.

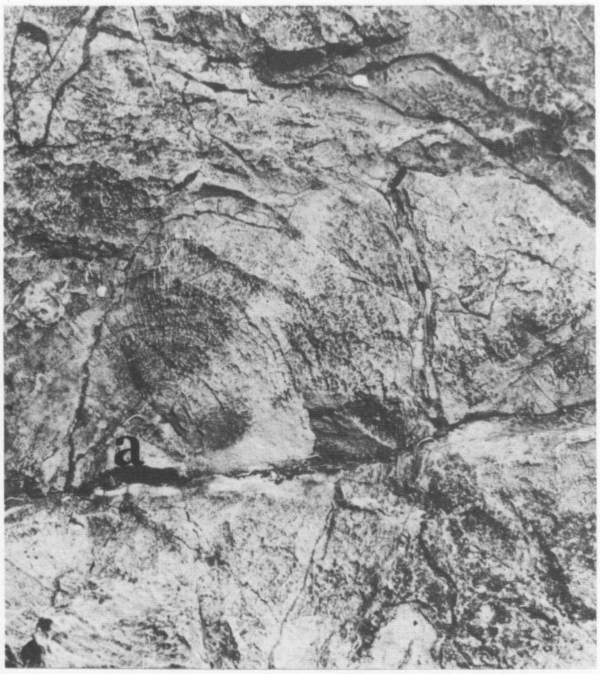

Fig. 109. Horizontal bedding-plane section through dololutite in the Reward Dolomite in the Coxco Valley, showing faint circular traces of *Conophyton* laminations (axis at a) and faint radiating acicular gypsum crystal pseudomorphs. The width of the field of view is 15 cm. (BMR negative M2551/8A).

At localities where the dolostone of the upper Reward Dolomite is unconformably overlain by arenaceous units (particularly the basal clastics of the Balbirini Dolomite or the Limmen Sandstone), its texture is modified in a peculiar way. The dolostone resembles coarse-grained dolomitic quartz sandstone in the top 2 to 3 cm below the unconformity surface. This texture is due to small blebs of whitish chert—resembling quartz grains—which occur in the superfical skin at the top of the Reward Dolomite. The origin of this rock type is discussed below.

Proterozoic karstic alteration

Along the Kilgour River, the Reward Dolomite is intensely recrystallised, and has undergone severe karstic alteration and weathering: extensive cave systems have developed, and solution-collapse features are prominent. In places, blocks of exotic rocks rest on the Reward Dolomite: for example, along the river at the southeast end of the Abner Range, where boulders of Limmen Sandstone hundreds of metres across occupy dolines in the Reward Dolomite. These large dolines are rimmed by coarsely crystalline dolostones with abundant zoned carbonate and chert veins, small and large caves, abundant karstic fluting, and flowstones; few of the primary bedding structures are preserved.

About 2 km south of Possum Point Yard (GR 100247), a spectacular example of fossil tower karst is developed in the Reward Dolomite overlain by the Yalco Formation and Stretton Sandstone. The tower is about 400 m wide at the exposed base tapering to about 10 m at the top; its maximum height is about 35 m. The phenomenon of fossil tower karst was recently described by Maslyn (1974) from Colorado. He was able to map a tower of carbonate which had protruded into overlying beds during their deposition. The Possum Point Yard example is similar. It comprises a tower of much altered Reward Dolomite flanked on its lower slopes by somewhat

Fig. 110. Chaotic breccia, the result of slumping, in the Reward Dolomite in the type section. (BMR negative M2553/20A)

Fig. 111. Alternating beds of massive dololutite (light grey) and ripple-laminated dolarenite (dark grey) in the Reward Dolomite at the type section. Note the sharp bed contacts and the load casts in the dololutite bed at the level of the pick handle. (BMR negative M2551/16A)

silicified but otherwise unaltered Yalco Formation. Where it is in contact with the Yalco Formation, the Reward Dolomite is preserved as recrystallised dolostone. The tower is buried and flanked in its upper parts by the Stretton Sandstone. The upper part of the tower is intensely silicified and altered to a brownish porcellanite at the contact with the Stretton Sandstone.

Although the karstic alteration of the Reward Dolomite superfically resembles that of the Mitchell Yard Dolomite Member lower in the sequence, the older unit breaks up into smaller blocks and forms less rugged topography. Thus the two units are quite distinctive on airphotos, and can also be distinguished by their stratigraphic setting: where the Mitchell Yard Dolomite Member is preserved, it invariably overlies the large *Conophyton* stromatolites of the Mara Dolomite Member; whereas the Reward Dolomite overlies non-stromatolitic carbonates of the Barney Creek Formation.

Interpretation

The only previously published interpretation of the depositional environment of the Reward Dolomite is that of Brown & others (1969). The considerable variation in lithologies influenced these authors to infer a variety of depositional environments, including shallow subtidal (on the evidence of the stromatolites), lagoonal (the acicular gypsum pseudomorphs), and possible tidal channels (cross-bedded arenites). They considered that the 'oncolites' and 'thrombolites' reflect an 'intermediate facies' of a more open sea with a depth of less than 60 m, permitting the penetration of sunlight for algal growth. They interpreted the dololutite and potassium-rich mudstone facies as having been deposited in even deeper water, on appreciable slopes which contributed to the slumping.

Brown & others (1969) also suggested that the lateral variations in the Reward Dolomite reflect the palaeogeography of the underlying Barney Creek Formation, and therefore indicate a topographic setting similar to that established during deposition of the older formation. Their interpretation of the Reward Dolomite, therefore, depends largely on that which they envisaged for the Barney Creek Formation, and, as we have already seen, there are sound reasons for modifying some aspects of their interpretations of that formation. However, we have not systematically studied what is obviously a laterally variable unit, so are unable to provide a tenable, integrated, alternative interpretation. Even so, we discuss a number of features which we feel have a significant bearing on some aspects of environmental interpretations.

Except for a higher carbonate content, the Reward Dolomite rocks contain some similarities to those of the Barney Creek Formation, so that similar environmental interpretations can be logically suggested. The graded beds and breccias indicate spasmodic delivery of detritus, perhaps as a result of periodic seismic activity. Current action is evident in the scouring and ripple marks. Periods of rapid sedimentation can be inferred from the load casts and slumping. The slumping may also imply sediment dumping on to depositional surfaces that were periodically tilted.

The available evidence points to subaqueous deposition alternating from time to time with possible emergent phases in an area in which spasmodic tectonic activity led to tilting, slumping, and concomitant erosion. We feel that there is no convincing evidence anywhere for deep-water deposition.

The 'oncolites' and 'thrombolites' noted by Brown & others (1969) require further discussion. The 'thrombolites' are grey dololutite mottled with white spar. This texture is similar to that observed in the vadose-altered Mitchell Yard Dolomite Member of the Emmerugga Dolomite. It is not clear whether the white spar has replaced an early more-soluble carbonate mineral or an evaporite phase such as anydrite, but the mottling is secondary, since the spar clearly grows upon and out from the crystal boundaries within the grey dololutite.

The 'oncolites' are similar to the pisoids in the Amos Formation (they do not appear to be typical oncolites), and are likewise interpreted as pisoids developed during vadose weathering (see p. 133).

Thus, we suggest that the 'oncolites' and 'thrombolites' are more likely to be alteration textures which indicate post-depositional emergence and vadose weathering, rather than deeper, open-marine conditions as originally interpreted by Brown & others (1969).

The depositional environment of the stromatolitic dolostones and cross-bedded arenites is more difficult to interpret, but a shallow-water origin seems most likely. The small *Conophyton* stromatolites could well have formed in shallow hypersaline lagoons or lakes, since the acicular crystals intergrown with them are morphologically identical with the gypsum pseudomorphs from the Teena Dolomite (Williams, 1976; Walker & others, 1977). The maximum synoptic height of the columnar stromatolites is only about 15 cm implying a minimum water depth of this magnitude. The extensive scouring at the bases of the cross-stratified arenite units, the channel-fill morphology of some of the units of pebbly conglomerates, and the presence of fining-upward cycles (Appendix Fig. A37) are not inconsistent with an origin as fluvial deposits.

In summary, the overall depositional environment for the Reward Dolomite that we favour is similar to that of part of the Barney Creek Formation—that is, very shallow-water to emergent conditions under which sediments accumulated in small bodies of standing water (e.g., lakes, ponds, lagoons) that were at or near the prevailing regional groundwater-table. Although conclusive evidence for a marine influence is lacking, we cannot dismiss such a possibility.

The effects of emergence and vadose activity are more pronounced in the Reward Dolomite than the Barney Creek Formation. An interpretation invoking deposition in an open, deeper-marine environment would have to resolve the interbedded relationship between the probable vadose pisoids ('oncolites' of Brown & others, 1969) and unaltered rock; frequent alternations of deep-marine deposition and vadose weathering are difficult to envisage.

A few comments are presented here on the origin of silica spheroids in the Reward Dolomite, and the unusual chert skins at the top of the Reward Dolomite, but neither has been systematically studied in either the field or laboratory. The silica-shelled spheroids remain enigmatic. We tentatively suggest that they are related to early diagenetic rearrangement of an original silica fraction in the primary carbonate mud. In an SEM study, von der Borch (1976a) and von der Borch & Jones (1976) noted that primary carbonate in the ephemeral Coorong lakes precipitated as spheroids, which later recrystallised to form carbonate rhombs. They also noted that the carbonate muds contain an unexplained amorphous silica, which accounts for as much as 15 per cent of the total sediment. It seems likely that if the silica were to precipitate early in spheroidal form around spherical carbonate grains, then structures similar to those in the Reward Dolomite could be produced.

Although we have no evidence for the mechanism, we speculate that the chert skin at the top of the formation could be deposited from silica-bearing groundwater passing through the weathered surface layer of the Reward Dolomite after it was sealed by deposition of the overlying clastic sediments. Karstic weathering, which commonly enlarges pore spaces (even on a microscopic scale), might have enhanced the porosity of the surface layer of the Reward Dolomite. Under suitable conditions the enhanced porosity could have been preserved during the burial, and the chert later precipitated in it. We suspect that the silica-bearing groundwater was related to the overlying arenite, since the chert skin appears only to be present at localities where the Reward Dolomite is overlain by arenite.

BATTEN SUBGROUP

Plumb & Paine (1964) and Smith (1964) assigned the term Batten Subgroup to a sequence of related formations in the eastern part of the Batten Trough which were interpreted as a 'basinal facies' stratigraphically equivalent to (but now known to be younger than) a now discarded 'Bauhinia Downs Subgroup' in the west. The sequence is particularly extensive in the Batten Creek area of BAUHINIA DOWNS, from whence the name is derived; it forms the upper half of the McArthur Group.

Plumb & Brown (1973) showed that the earlier interpretation of stratigraphic relationships in the McArthur Group was incorrect. In a revision of the stratigraphy of the McArthur Group they discarded the term 'Bauhinia Downs Subgroup' (now Umbolooga Subgroup), but retained the name Batten Subgroup for its original constituent formations, with the exception of the 'Hammer Creek Member, which they showed comprises deeply weathered representatives of the Umbolooga Subgroup and so discarded the name. We have made only two modifications to Plumb & Brown's organisation of the Batten Subgroup: we have added to it the Amos Formation, which is now known to be a lateral equivalent of the Looking Glass Formation; and we have discarded the term 'Billengarrah Formation' for rocks which Plumb & Brown identified as correlatives of the Batten Subgroup and which we have reassigned to other formations in the subgroup.

The Batten Subgroup thus comprises the Lynott Formation (divided into the Caranbirini Member, Hot Spring Member, and Donnegan Member), Yalco Formation, Stretton Sandstone, Looking Glass Formation, and Amos Formation.

The Batten Subgroup overlies the Umbolooga Subgroup with local unconformity: adjacent to and within major fault zones of the Batten Trough—such as the Mallapunyah, Tawallah-Abner, Hot Spring, and Emu Faults—the contact is marked locally by erosion, karstic features, silcreted regoliths, or breaks in the sequence. In contrast, within the central depocentre of the Batten Trough the contact appears conformable and is, in places, commonly gradational. The subgroup is unconformably overlain by the Nathan Group and, in the Yalco Creek area to the east of the Tawallah Ranges, by the Roper Group.

The Batten Subgroup ranges in thickness from about 150 m to 1000 m (Fig. 112), and is known only from the Batten Fault Zone or its immediate margins. All units show generally compatible variations in thickness which reflect fault-controlled development of the Batten Trough.

The subgroup is most extensively exposed in fairly continuous sections within eastern BAUHINIA DOWNS and MOUNT YOUNG—between the Tawallah-Abner Fault system and the Emu Fault Zone (inset, Plate 1). Other sections occur in continuous strike ridges along Billengarrah Creek, in western BAUHINIA DOWNS. Possible extensions of the Batten Subgroup to the east of the Emu Fault Zone are almost totally concealed by a blanket of Cambrian Bukalara Sandstone, and the northward continuation of the Subgroup in eastern MOUNT YOUNG is obscured by the coastal plain.

The Batten Subgroup is absent from sections to the southwest of the Mallapunyah Fault, on the Bauhinia Shelf (locality map, Plate 1), and in the Eastern Creek-Limmen Bight area. Although this might be ascribed to postdepositional erosion, the westwards-to-southwestwards regional thinning of the subgroup (apparent in Fig. 112) suggests that it is more likely to reflect non-deposition in these areas.

As a working hypothesis, we envisage the depositional area of the Batten Subgroup as having been largely confined to the Batten Trough, which was constrained at that time to a north-south belt between the Tawallah and Emu Fault Zones. In the northwest, a thin embayment extended to Billengarrah Creek, between the Mallapunyah and Four Archers Faults, while in the east the relatively thick Catfish Hole section (Fig. 112) may reflect a diagonally complementary southeast embayment. A northeastward fault-bounded embayment transgresses the Emu Fault Zone in the Yalco Creek area.

LYNOTT FORMATION

The unit of dolomitic siltstone, dolarenite, stromatolitic dolostone, and chert which comprises the lower half to three-quarters of the Batten Subgroup (Fig. 112) was first identified and mapped as the Lynott Formation by Plumb & Paine (1964) and Smith (1964). The name is derived from Mount Lynott, at GR 934605. These workers identified two members locally: the Donnegan Member at the top (in the area around Batten Creek) and the 'Hammer Creek Member' at the base. Plumb & Brown (1973) demonstrated that the rocks assigned to the 'Hammer Creek Member' are deeply weathered Umbolooga Subgroup units, and recommended that the name be discarded; we follow their recommendation. Despite this modification, and our identification and mapping of the Lynott Formation along Billengarrah Creek (in place of the now discarded 'Billengarrah Formation'), the Lynott Formation as originally mapped is essentially correct, and so we retain the name.

The Donnegan Member can now be identified throughout almost all exposures of the Lynott Formation, and we have added two new members: the Hot Spring Member beneath the Donnegan Member, and the Caranbirini Member at the base of the formation.

The *Caranbirini Member* is a poorly exposed unit of dolomitic siltstone, shale, and silty dololutite at the base of the Lynott Formation; it is characteristically pyritic and bituminous in fresh drillcore. Slump structures and slump breccias are locally abundant. The diagnostic features of the member in outcrop are the lack of stromatolitic dolostones and the scarcity of arenites. The name is derived from Caranbirini Creek, which cuts thick and typical exposures of the member about 18 km north of McArthur mine.

The *Hot Spring Member* is a generally boldly outcropping unit of dolomitic siltstone, silty dololutite, dolarenite, and stromatolitic dolostone and chert between the Caranbirini and Donnegan Members. A recently identified upper evaporite unit in the member (Fig. 113) contains distinctive bladed gypsum-stromatolite-tepee cherts. In addition, abundant pseudomorphs after various forms of gypsum, and evidence of desiccation, throughout the member testify to very shallow-water deposition. The stromatolites, arenites, evaporite types, and stratigraphic position are diagnostic. The Hot Spring Member is the thickest and most widely distributed member of the Lynott Formation; sections where the constituent members have not been distinguished invariably have the characteristics of the Hot Spring Member. The name is derived from Hot Spring Creek, which rises within extensive exposures of the member around GR 930850 (*Batten*, 6065), west of the Reward mine.

The *Donnegan Member*, at the top of the Lynott Formation, is a readily identifiable unit of purple-brown and green ripple-bedded dolomitic fine-grained sandstone and siltstone, with stromatolitic dolostone at the base. Cauliflower cherts after anhydrite, which are abundant throughout the

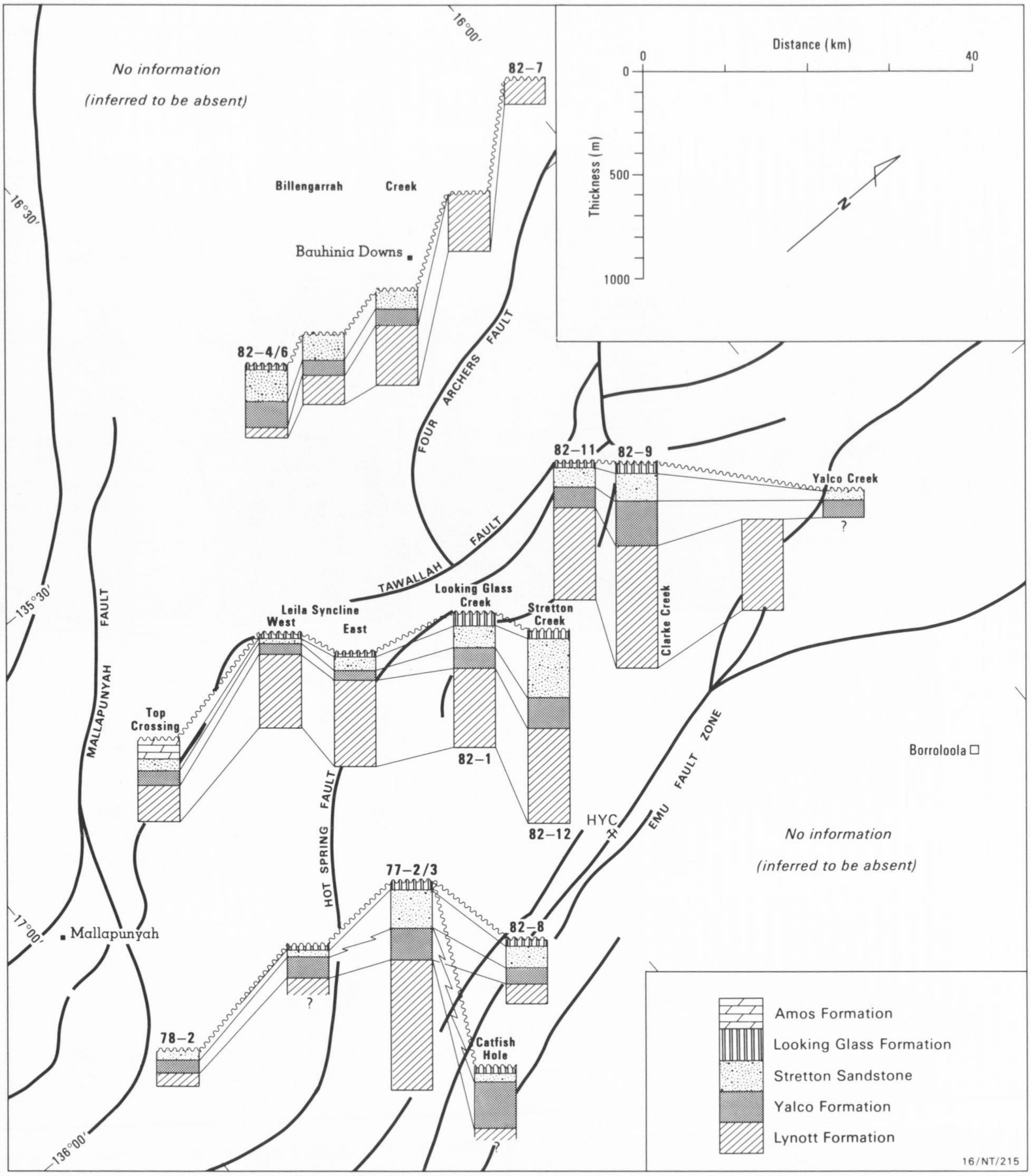

Fig. 112. Summary of variations in the thickness of the Batten Subgroup. Numbered columns refer to detailed measured sections. Other sections are estimated from field observations or airphotos; the tops of these columns indicate the approximate localities of the sections on the map.

member, are diagnostic and distinguish the member from all other units in the McArthur Basin except the Mallapunyah Formation. The member is a facies equivalent in part and locally interfingers with the upper evaporite unit in the Hot Spring Member. The name is derived from Donnegan Creek, a minor tributary of Surprise Creek that cuts outcrops of the member at about GR 064934 (*Batten*, 6065).

Distribution and thickness

The distribution of the Lynott Formation is essentially the same as that of the Batten Subgroup as a whole; that is, it crops out extensively within the Batten Trough between and lapping on to the Tawallah and Abner Faults and the Emu Fault Zone, and along Billengarrah Creek. Its thickness ranges from about 50-600 m, the depocentre lying roughly along the axis of the Batten Trough—subparallel to the Emu Fault Zone (Fig. 113). The thickest section so far measured is the type section, Glyde 77/02 (77-2 in Fig. 113), on the Kilgour River. The individual members show significant differences in distribution and relative thickness.

The *Caranbirini Member* varies in thickness from 0->300 m, and thins regionally southwestwards (Fig. 113). Its thickest

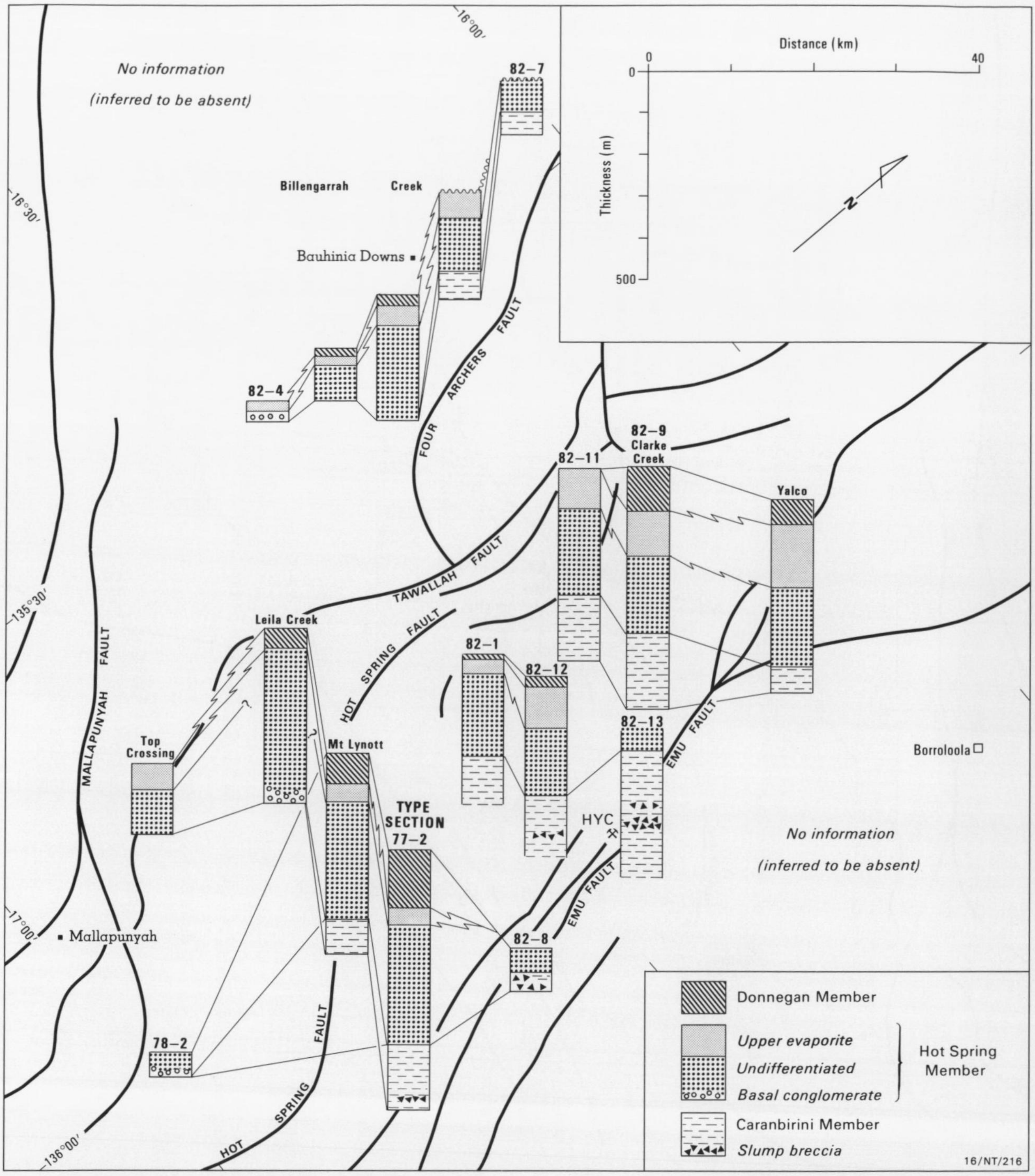

Fig. 113. Summary of the stratigraphy of the Lynott Formation. Numbered columns refer to detailed measured sections. Other sections are estimated from field observations or airphotos; the tops of these columns indicate the approximate localities of the sections on the map.

measured section (82-13) is exposed around Caranbirini Creek; it lenses out abruptly southwest of the Hot Spring Fault.

The distribution of the *Hot Spring Member* is the same as that for the Lynott Formation as a whole; it is the only member present in all measured sections. Its thickness varies from 50 m at the southern end of Billengarrah Creek to around 350 m in the depocentre of the Batten Trough (Fig. 113).

The *Donnegan Member* has an irregular distribution and thickness. It varies from 0 m southwest of the Hot Spring Fault, where it lenses out, to 134 m in the type section; elsewhere, it is locally absent or difficult to distinguish from the upper evaporite unit of the Hot Spring Member.

Type sections

Measured section Glyde 77/02—where recent dissection has exposed relatively fresh rock—is nominated as the type section of the Lynott Formation (Fig. 114, Appendix Fig. A38). It extends from GR 075590 to 073567, and includes the type sections for all three constituent members, whose intervals and grid references in the section are as follows:

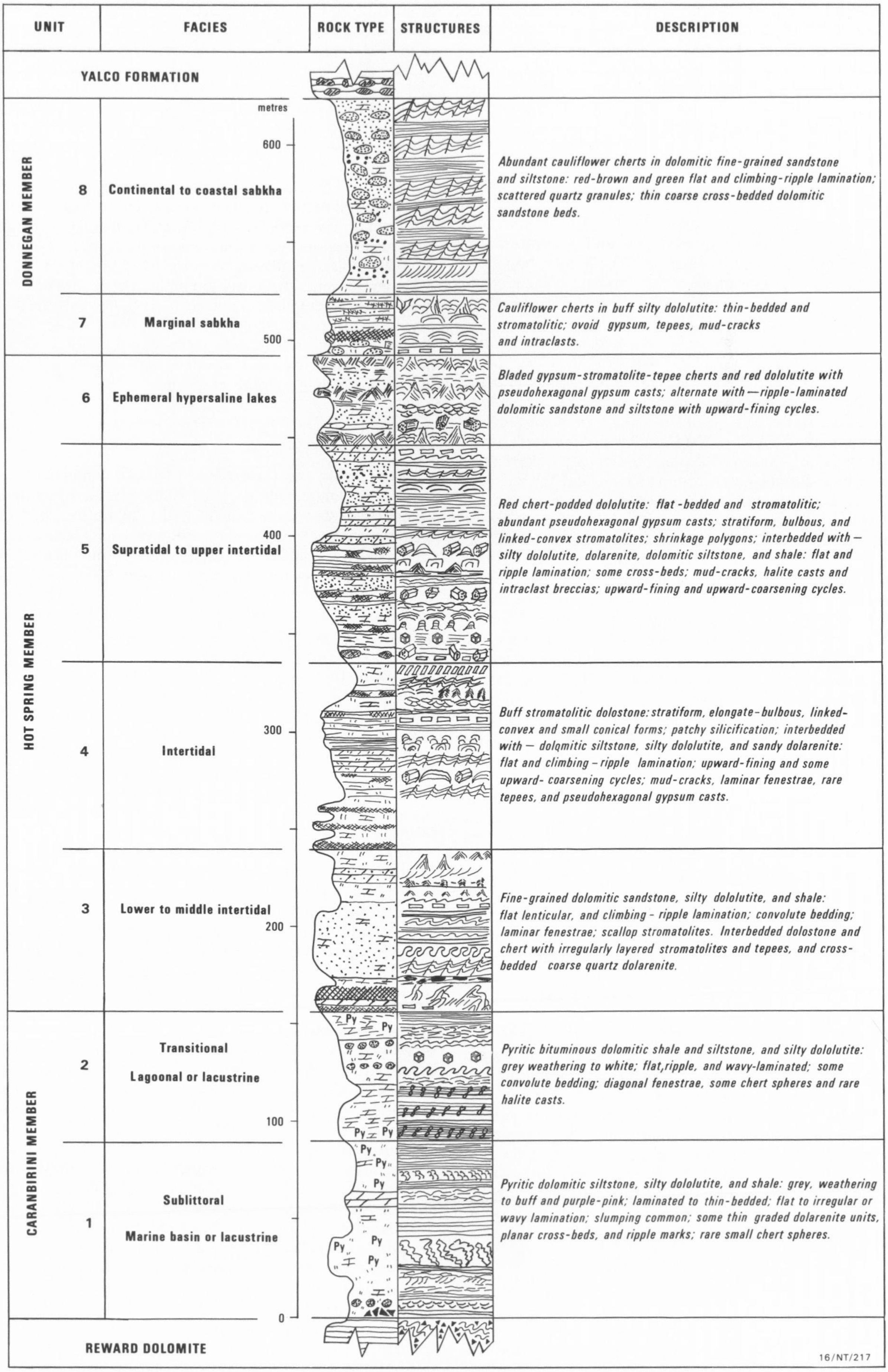

Fig. 114. Simplified diagrammatic log of the type section of the Lynott Formation (measured section Glyde 77/02), about 7 km southeast of the confluence of the Kilgour and McArthur Rivers.

Caranbirini Member—0-156.5 m (075590 to 073587); Hot Spring Member—156.5-491 m (073587 to 073571); and Donnegan Member—491-625 m (073571 to 073567).

Several more detailed sections have been measured through the Lynott Formation, but only two—Mallapunyah 77/01 and 77/02 (from near the type section)—are reproduced here (Appendix Figs. A39 and A40).

Stratigraphic relations

The Lynott Formation overlies the Reward Dolomite and older units with local unconformity, and is conformably overlain by the Yalco Formation. The upper boundary coincides with the appearance of the abundant nodular cherts which characterise the lower Yalco Formation; the lower boundary is more complex.

In the type section (Glyde 77/02), and extending northwards from the Hot Spring Fault through the depocentre of the Batten Trough, the Reward Dolomite grades into the Caranbirini Member; the boundary is placed where mainly buff dololutite of the Reward Dolomite gives way to mainly carbonaceous siltstone of the Caranbirini Member. Locally to the west of the type section the contact is intricately slumped, and in the north, around Clarke and Yalco Creeks (Fig. 113), the contact is obscured by poor exposure and Mesozoic? silcrete. Elsewhere, within and adjacent to the marginal fault zones of the Batten Trough, the contact is marked by depositional breaks. Walker & others (1983) described karstic features and silicification in the Reward Dolomite in the Coxco Valley, within the Emu Fault Zone, where it is unconformably overlain by Caranbirini Member shale. Southwards from here, along the Emu Fault Zone, the Caranbirini Member progressively rests on units as low as the Teena Dolomite. Adjacent to the Hot Spring Fault, along the upper Kilgour River, tower karst in the Reward Dolomite is onlapped by the Hot Spring Member and younger units of the Batten Subgroup (see p. 105). Farther west, in the Mount Lynott-Leila Creek area (Fig. 113), the Caranbirini Member thins abruptly westwards across the Hot Spring Fault, and wedges out southwestwards from there. The absence of the Caranbirini Member from the sequence coincides with karstification, silicification, and erosion of the underlying Reward Dolomite. The regional southwestwards onlap of younger members of the Lynott Formation on to the Reward Dolomite is marked by a discontinuous basal conglomerate in the Hot Spring Member at Leila Creek and in section 78/02 (Fig. 113).

The nature of the contact along Billengarrah Creek is obscured by poor exposure and extensive Mesozoic? silcrete. A thin Hot Spring Member with a basal conglomerate overlies fresh Reward Dolomite in the south (section 82/04; Fig. 113); siltstone provisionally assigned to the Caranbirini Member occurs in the north.

The foregoing indicates that sedimentation in the Batten Trough depocentre (where the Barney Creek Formation and Reward Dolomite reach their maximum thicknesses) was continuous from the Reward Dolomite into the pyritic-carbonaceous shales of the Caranbirini Member. Around the marginal fault zones of the trough, however, sedimentation ceased briefly—allowing the Reward Dolomite to be weathered, karstified, and eroded—and resumed with the progressive onlap of younger strata and the deposition of local basal conglomerates.

Lithology

Although the Lynott Formation generally forms relatively bold ridges, most outcrops are deeply weathered and leached. Stromatolitic dolostone is altered to massive chert in which original structures are preserved to varying degrees, and dolomitic siltstone and sandstone are leached and silicified to porous quartz-chert-clay residues. However, east of the Kilgour River (northeast corner of Plate 1), recent dissection and stripping of the Cambrian Bukalara Sandstone has exhumed fresh sections of the Lynott Formation, and most of the detailed knowledge of the formation is derived from this part of the area. Scattered fresh sections from elsewhere have demonstrated that in general terms the type section is typical of the unit as a whole, and so the description of the formation given here is based almost entirely on the type section (Fig. 114, Appendix Fig. A38), supplemented by discussions of regional variations where appropriate. Thickness intervals, unless qualified, refer to the type section.

For convenience, the formation in the type section has been divided into eight informal units (Fig. 114), but only the three named members are recognisable throughout the area. The bladed gypsum-stromatolite-tepee cherts of unit 6 are, however, a distinctive marker, so they have been distinguished in Figure 113 as the upper evaporite.

Caranbirini Member

Where fresh, the Caranbirini Member comprises thin-bedded to laminated, grey to black pyritic-bituminous dolomitic siltstone and shale and silty dololutite, but more commonly these are deeply weathered and leached to a yellow-brown or buff, white (exbituminous), and purple-pink (expyritic) porous residue. Superficially these rocks can resemble those of the Barney Creek Formation. The rocks comprise coarse silt to fine sand-size subangular quartz grains and disseminated pyrite in a matrix of microcrystalline quartz and micritic dolomite. Fine laminations, of the order of 1-2 mm, are rhythmically graded from quartz-rich bases to fine carbonate-rich tops.

Unit 1 (0-90 m). Unit 1 is in gradational contact with massive slump breccias of the Reward Dolomite in the type section. It is characterised by planar lamination grading into irregular or wavy lamination; slumping is extensive in some beds. Symmetrical ripples and planar cross-beds, and small silica spheroids similar to those in the Reward Dolomite, occur near the base.

Two kilometres westwards, near the Kilgour River (section Mallapunyah 77/01, Appendix Fig. A39) the Reward-Caranbirini contact is intricately interdigitated and brecciated, apparently by slumping, and several lenses of allochthonous polymict breccia are dispersed through the overlying Caranbirini Member. Similar slump breccia (Fig. 115) and associated slump folds (Fig. 116) characterise unit 1 throughout the Kilgour-Glyde, Caranbirini, and Reward areas—that is, adjacent to the Emu Fault Zone. Most clasts in the breccia appear to be derived from the Caranbirini Member itself; others are from the Reward Dolomite and other unidentified dolostones. Immediately west of the Emu Fault Zone (e.g., Caranbirini Creek area) transport directions are clearly from the east; farther west (e.g., Reward mine area) they are more variable, from both east and west.

Unit 2 (90-156.5 m). The unit 1-unit 2 contact is marked by two thin (1 mm) irregular opaline crusts (visible in thin section) interpreted as possible microregoliths. Unit 2 is characterised by rock types similar to unit 1, commonly with irregular cracks or voids up to a few millimetres long arranged oblique to the bedding. Some are filled with chert or spar. They are poorly preserved in outcrop, and variously resemble diagonal or vertical fenestrae (Kendall, 1969), shrinkage or syneresis cracks, or even gypsum casts. Microscopic laminar-parallel fenestrae are also present.

Other characteristics of unit 2 are a greater abundance of thin shaly lamination and a progressive upward increase in

Fig. 115. Typical lens of massive polymict slump breccia in the Caranbirini Member of the Lynott Formation at about 30 m in section Mallapunyah 77/01. Fragments are mostly intraformational siltstone enclosed in a silty matrix, but exotic fragments of chert and dolomite (of undetermined sources) are also present. (BMR negative GB 3130)

Fig. 116. Slump-folded dolomitic siltstone in the Caranbirini Member of the Lynott Formation about 1 km southwest of the Reward mine. Local transport direction is from right to left, which is towards 060°. (BMR negative GB 3117)

ripple and wavy lamination. A marker bed at 133 m contains hopper halite casts. Small chert spheroids are common. The same interval near Reward mine (measured section 82/12) has mud-cracks and small tepees.

Hot Spring Member

Stromatolitic dolostone or massive chert after stromatolites—interbedded with ripple-laminated dolomitic siltstone, dololutite, and dolarenite—distinguish the Hot Spring Member from other members of the Lynott Formation. Gypsum pseudomorphs and desiccation structures are common. The boundary with the underlying Caranbirini Member is defined as the first prominent stromatolite bed, or where cross-bedded dolomitic sandstone becomes abundant; commonly the two coincide.

Unit 3 (156.5-241 m). In the type section, and continuing westwards to measured section Mallapunyah 77/01, a hill capping of massively silicified rock after stromatolitic dolostone and cross-bedded dolarenite marks the base of unit 3 (which coincides with the base of the Hot Spring Member). The same stratigraphic level in measured section Mallapunyah 77/02 (Appendix Fig. A40), 3 km farther west, is marked by an upward-fining slumped channel-fill of coarse to fine dolomitic sandstone-dololutite.

Two different facies characterise unit 3: a lower one between 156.5 and 215 m, and an upper facies between 215 and 241 m (Glyde 77/02; Appendix Fig. A38). In the type section the lower facies is dominated by fine-grained sandstone and siltstone containing various types of ripple bedding: climbing ripples ranging from in-phase to in-drift; large ripples of up to 60 cm wavelength; truncated ripples; and lenticular bedding. These rippled clastics alternate with highly convoluted upward-fining units of sandstone and purple-brown shale with ball-and-pillow bases.

The equivalent beds in section Mallapunyah 77/02 (Appendix Fig. A40), probably representing the more common facies throughout, are characterised by abundant small irregularly layered stromatolites among which highly

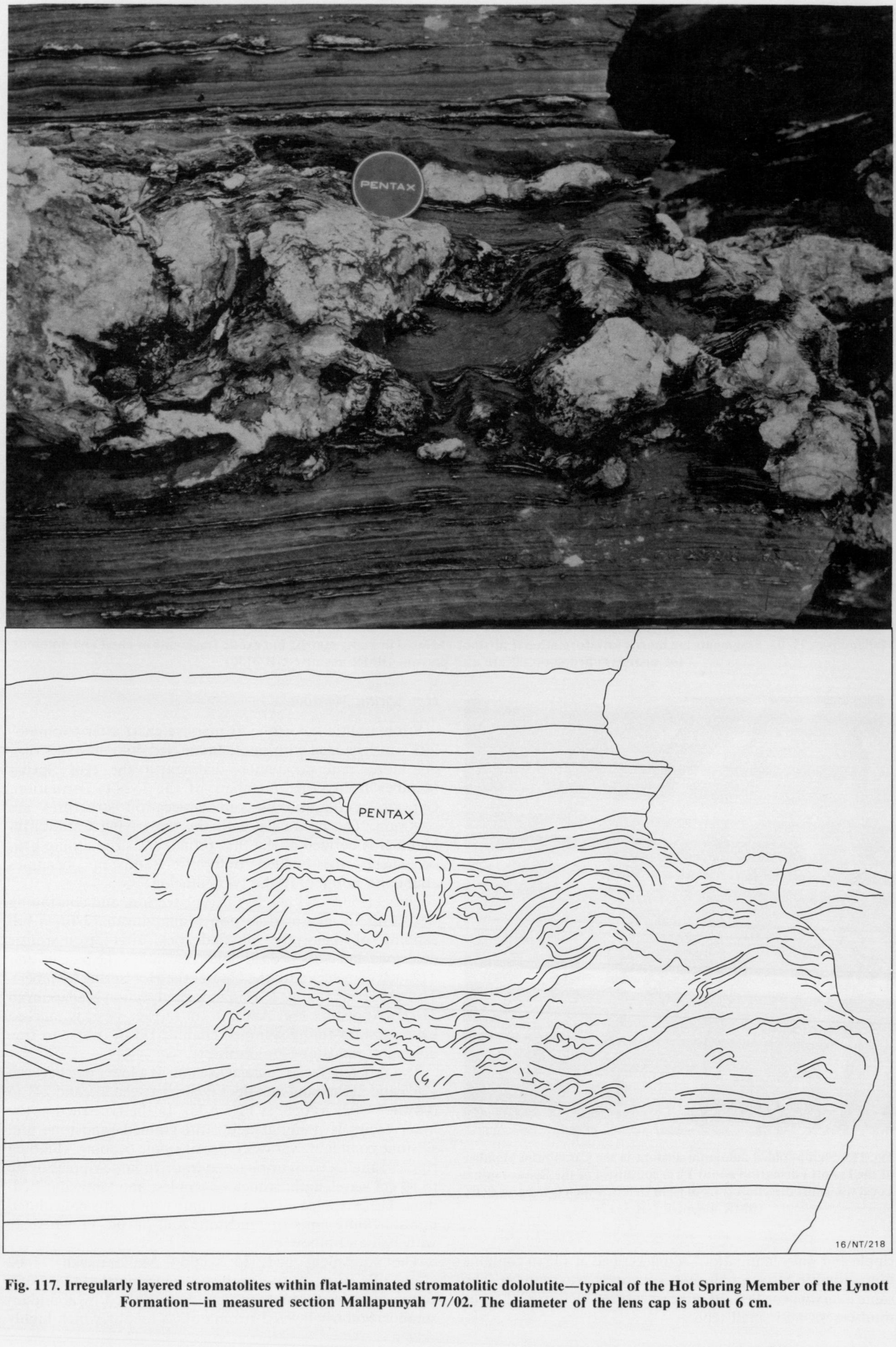

Fig. 117. Irregularly layered stromatolites within flat-laminated stromatolitic dololutite—typical of the Hot Spring Member of the Lynott Formation—in measured section Mallapunyah 77/02. The diameter of the lens cap is about 6 cm.

contorted convex to conicl forms with a synoptic relief of about 5 cm are patchily developed within an otherwise planar algal layering (Fig. 117).

These stromatolites superficially resemble present-day forms within the Gladstone Embayment, Shark Bay, Western Australia (Davies, 1970). They are interbedded with dolomitic siltstone and medium to coarse dolarenite (Fig. 118) with various shallow-water features: in-phase climbing ripples; plane cross-bed sets up to 20 cm; lenticular bedding; ripple-form lenses; intraclasts; mud-cracks; diagonal and laminar fenestrae; and upward-fining and, rarely, upward-coarsening cycles.

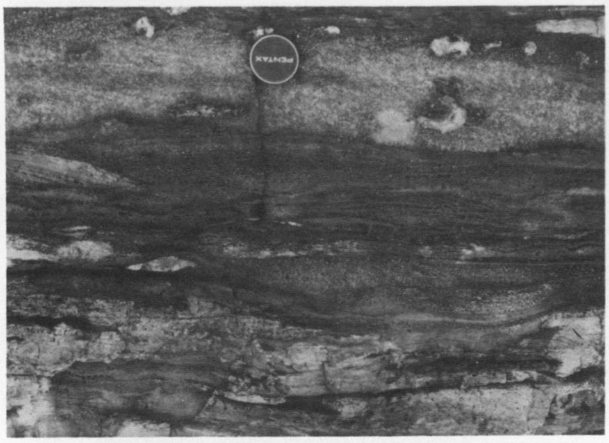

Fig. 118. Ripple cross-bedded coarse-grained quartz dolarenite in the lower part of the Hot Spring Member of the Lynott Formation at about 45 m in section Mallapunyah 77/02. The diameter of the lens cap is about 6 cm. (BMR negative GB 3123)

A second diagnostic stromatolite characterises the other main facies of unit 3—for example, between 215 and 241 m in the type section, where small (1-2 cm) scallop or gently conical stromatolites have developed on ripple crests in dolomitic siltstone (cf. Fig. 119). These have a form similar to tufted mats of the middle to upper intertidal zone at Shark Bay (Hagan & Logan, 1974, fig. 13C; Logan & others, 1974, fig. 8D).

Unit 4 (241-335.5 m). As in unit 3, dolomitic siltstone, silty dololutite, and dolarenite are the most abundant rock types in unit 4, whose most distinctive feature is the abundance and variety of stromatolites in patchily silicified and chert-podded buff-coloured dolostone. Forms include stratiform, continuously layered, pseudocolumnar, gently to steeply convex, domal, bulbous (Fig. 120), and branching-conical (Fig. 121). Synoptic relief is commonly less than 3 cm, but locally it is up to 10 cm. Domes in plan are almost always elongated east-west. Small bioherm series regularly display upward gradation in size from, for example, steeply convex, through small pseudocolumnar, to planar stratiform; the planar stratiform stromatolites are disrupted by intense desiccation into tepee-like features. The siltstone and sandstone contain plane and ripple lamination, mud-cracks, intraclast breccias, and fenestral fabric. Thin upward-fining cycles grade over one metre or less from dolarenite to chert-podded dololutite; rare upward-coarsening cycles are also present. Red-brown stubby pseudohexagonal-prism pseudomorphs after gypsum occur in places in the dololutite.

Unit 5 (335.5-448.5 m). The distinction between units 4 and 5 is based principally on the change in colour of the dololutite beds from buff to red, and so cannot be made in weathered outcrop away from the type section. The dolostone

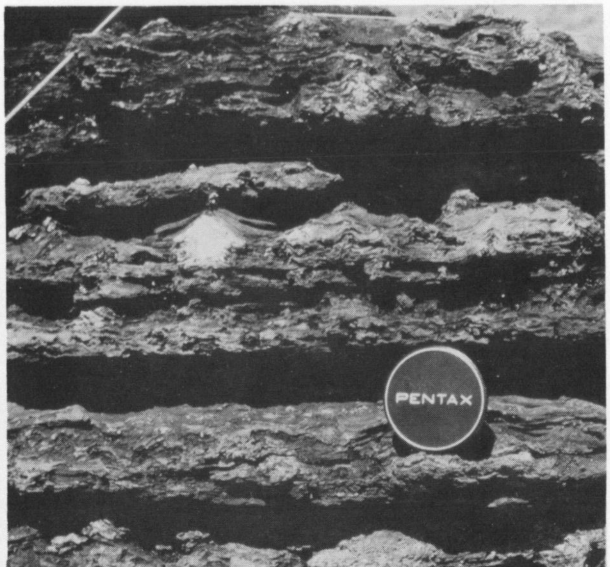

Fig. 119. Distinctive marker bed at 74 m in section Mallapunyah 77/02 near the top of unit 3 in the Hot Spring Member of the Lynott Formation, comprising diagnostic scallop or gently conical stromatolites developed on ripple crests in dolomitic siltstone. The diameter of the lens cap is about 6 cm.

of unit 5 is characteristically red or purple-pink and chert-podded (Fig. 122). It is either stromatolitic or plane-bedded, and contains abundant brown stubby pseudohexagonal-prism pseudomorphs after gypsum (Figs. 123, 124); in other sections, discoidal gypsum is more typical. Stromatolites are similar to those of unit 4 below, but include small columnar forms. Interbedded detrital rocks are carbonate-rich; silty dololutite and dolarenite are dominant over siltstone and sandstone. Bedforms include planar to ripple bedding (Fig. 125), and cross-bedding in arenite. Both upward-fining and upward-coarsening cycles over 1-2.5-m intervals are common. Halite casts occur in green shale. Mud-cracks and fine intraclast breccias are abundant. Stromatolitic shrinkage polygons occur at 388 m (Fig. 126). Siltstone towards the top of the unit contains rare small cauliflower cherts.

Unit 6 (448.5-491 m). Unit 6 is characterised by several beds of chert 1-2 m thick pseudomorphing intergrown

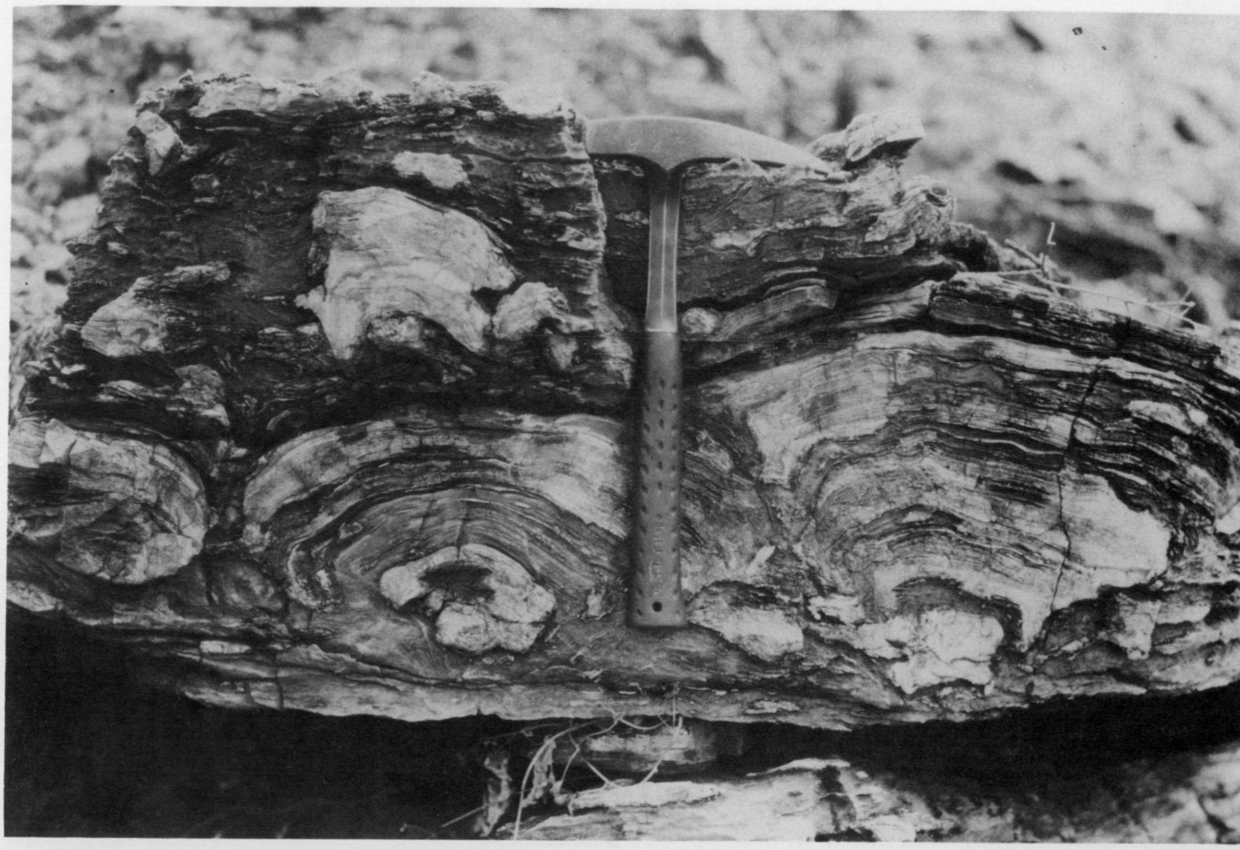

Fig. 120. Vertical section of patchily silicified stromatolites, typical of unit 4, at 287 m in the type section of the Hot Spring Member of the Lynott Formation. (BMR negative GB 3124)

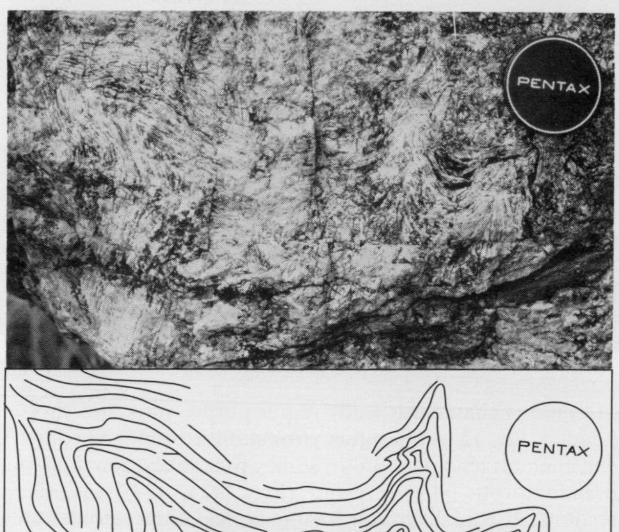

Fig. 121. Highly silicified irregular continuously layered conical stromatolites in unit 4 at 319 m in the type section of the Hot Spring Member of the Lynott Formation. Note the inclined (or branching?) columns on the left side. The diameter of the lens cap is about 6 cm.

stromatolites, gypsum, and tepees. These are informally referred to as the upper evaporites in Figure 113. The stromatolites are characteristically low-relief continuously layered pseudocolumnar forms. The chert pseudomorphs after evaporite display fibrous to bladed masses of crystals intergrown with or beneath but disrupting the stromatolitic layering (Fig. 127). The whole structure is in turn disrupted by steep-sided tepees (Fig. 128). The chert beds are typically overlain by pink dololutite beds, 30 cm thick, with pseudo-hexagonal gypsum casts. In sections away from the type area, discoidal gypsum casts are more common than bladed masses.

Apart from the detailed gypsum morphology, the overall structures in unit 6 are similar to Holocene stromatolites and gypsum at Marion Lake in Spencer Gulf, South Australia (von der Borch & others, 1977).

In places, fibrous evaporite pseudomorphs occur as rosettes interbedded with cauliflower cherts of the Donnegan Member; a complete gradation from rosettes to cauliflower cherts is apparent. A suggestion (Jackson & others, 1980) that these bladed and fibrous pseudomorphs resemble the trona pseudomorphs in the Cambrian Observatory Hill beds of South Australia (White & Youngs, 1980) has not been substantiated by a preliminary crystallographic study: most are gypsum, but another unknown mineral is intimately intergrown with the gypsum (Dr. C. Cluff, James Cook University of North Queensland, personal communication, 1983).

Donnegan Member

The Donnegan Member grades into and locally interfingers with unit 6. By definition, beds with abundant cauliflower

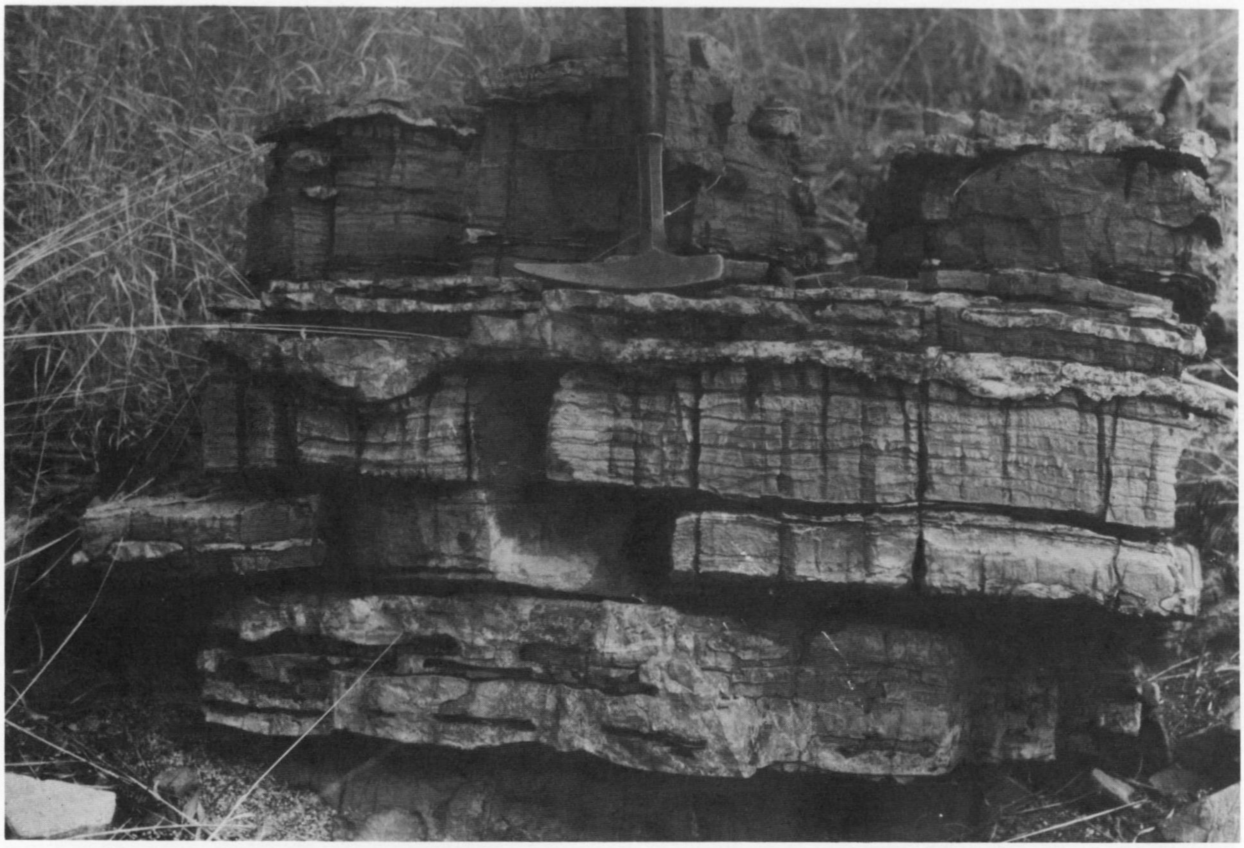

Fig. 122. Purple–pink plane-bedded chert-podded and chert-layered dololutite—characteristic of unit 5, Hot Spring Member, Lynott Formation—at 337 m in the type section. (BMR negative GB 3119)

Fig. 123. Red–brown carbonate pseudomorphs after pseudohexagonal gypsum crystals in purple–pink dololutite of unit 5 at 370 m in the type section of the Hot Spring Member of the Lynott Formation. Concentration of the pseudomorphs along joint planes indicates a late diagenetic origin. (BMR negative GB 3127)

cherts (after nodular anhydrite) are confined to the Donnegan Member, whereas the gypsum–stromatolite–teepee cherts are confined to unit 6.

Unit 7 (491–524 m). Unit 7 in the type section is gradational from the Hot Spring Member. Silty dololutite containing abundant cauliflower cherts are interbedded with stromatolitic dolostone containing tepee structures and discoidal gypsum casts. This facies is common throughout the south—for example, in the type section and the section at Mount Lynott (Fig. 113)—but it dies out northwards, where the Donnegan Member is represented entirely by unit 8.

Unit 8 (524–625 m). Unit 8 comprises the typical facies of the Donnegan Member: red-brown and lesser green dolomitic fine-grained sandstone and siltstone with alternating planar and climbing-ripple lamination. Coarse granules are scattered through the ripples, and predominate in places to form thin beds of cross-bedded coarse sandstone. Scattered throughout (though not everywhere at the very top of the Lynott Formation) are cauliflower cherts (after anhydrite nodules), about 10 cm across, which display typical displacive growth and, commonly, enterolithic structure (Fig. 129); relict gypsum casts are evident in places.

Interpretation

From their observations, mostly of deeply weathered exposures, particularly of the Caranbirini Member, and owing to the generally prevailing lack of appreciation at the time of modern intertidal–supratidal dolomite and chert formation, Plumb & Paine (1964) and Smith (1964) originally interpreted the Lynott and Yalco Formations as deep-water basinal or fore-reef deposits. However, from the criteria provided by more recent studies of modern environments, the characteristics of the Lynott Formation now clearly indicate an overall regressive sequence of paralic facies (Fig. 114), wholly consistent with the ephemeral-lake model of the overlying Yalco Formation (see p. 123).

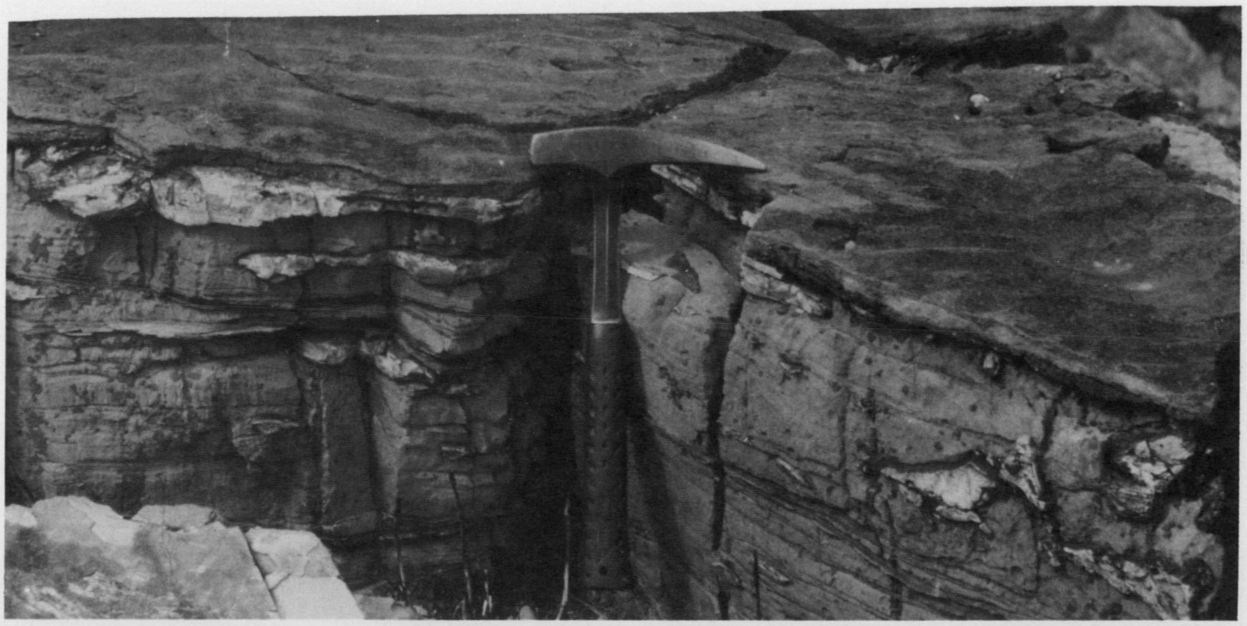

Fig. 124. Thin ripple-bedded sandstone interbedded with chert-podded dololutite of unit 5 at 370 m in the type section of the Hot Spring Member of the Lynott Formation. Note the abundant gypsum casts to the right of the hammer. (BMR negative GB 3118)

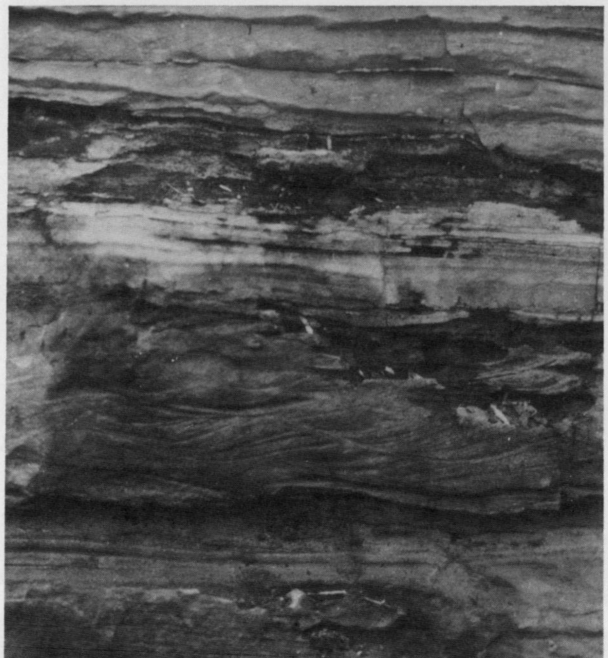

Fig. 125. Climbing-ripple cross-stratification in dolomitic siltstone interbedded with plane-bedded dololutite of unit 5 at 377 m in the type section of the Hot Spring Member of the Lynott Formation. The width of the field of view is about 15 cm. (BMR negative GB 3125)

The Lynott Formation, particularly the Caranbirini Member, has features which may well be interpreted as lacustrine, but it also has features similar to those in modern marginal-marine evaporative environments—such as Shark Bay, the Persian Gulf, and Spencer Gulf. Our interpretations may well be modified by detailed studies which are now in progress.

Unit 1 lacks any evidence of subaerial exposure; distal sublittoral deposition is consistent with the ubiquitous (seasonal?) fine graded silt laminations. A transgressive-regressive cycle is indicated. Subsidence was initiated in the Kilgour-Caranbirini area, adjacent to the Emu Fault, where sections are thickest and continuous from the shallow-water Reward Dolomite. Chert spheroids, wavy bedding, ripples, and cross-beds near the base illustrate this gradation. Maximum subsidence can be correlated with widespread slump breccias in the middle of the unit, although these need not imply great depth. Movement along the Emu Fault, where exotic clasts are common, might have generated subaerial mass flows.

Unit 2 marks a change to shallower conditions. Intermittent exposure (reflected by halite casts, mud-cracks, and tepees) of anoxic pyritic organic-rich muds possibly in restricted lagoons or shallowing lakes is inferred. The thin opaline crusts (microregoliths?) at the base might represent exposure of the lagoonal barrier. Fenestral fabric is widely correlated with intertidal-supratidal facies.

The *Hot Spring Member* has an assemblage of sedimentary structures which are typical of the littoral zone: ubiquitous graded fine lamination and ripple lamination, ripple-marked coarse sandstone lenses in mudstone, mud-cracks, intraclast or flat-pebble conglomerate, tepee structures, desiccation polygons, displacive halite and gypsum, and closely associated upward-fining and upward-coarsening cycles. The variety of ripple types, including in-drift and in-phase climbing ripples, imply considerable current action, more appropriate to a tidal than a lacustrine environment. The low-relief to stratiform stromatolite types which dominate the member are typical of linked hemispheroids, which Logan & others (1964) described as being typical of protected intertidal or lacustrine environments. The almost ubiquitous and uniform east-west elongation of these forms (perpendicular to the shoreline?) invites comparison with the intertidal environment at Shark Bay (Logan & others, 1974; Hoffman, 1976).

Within this context then, the sand-rich part of *unit 3* is interpreted as a littoral sand flat—probably mostly middle

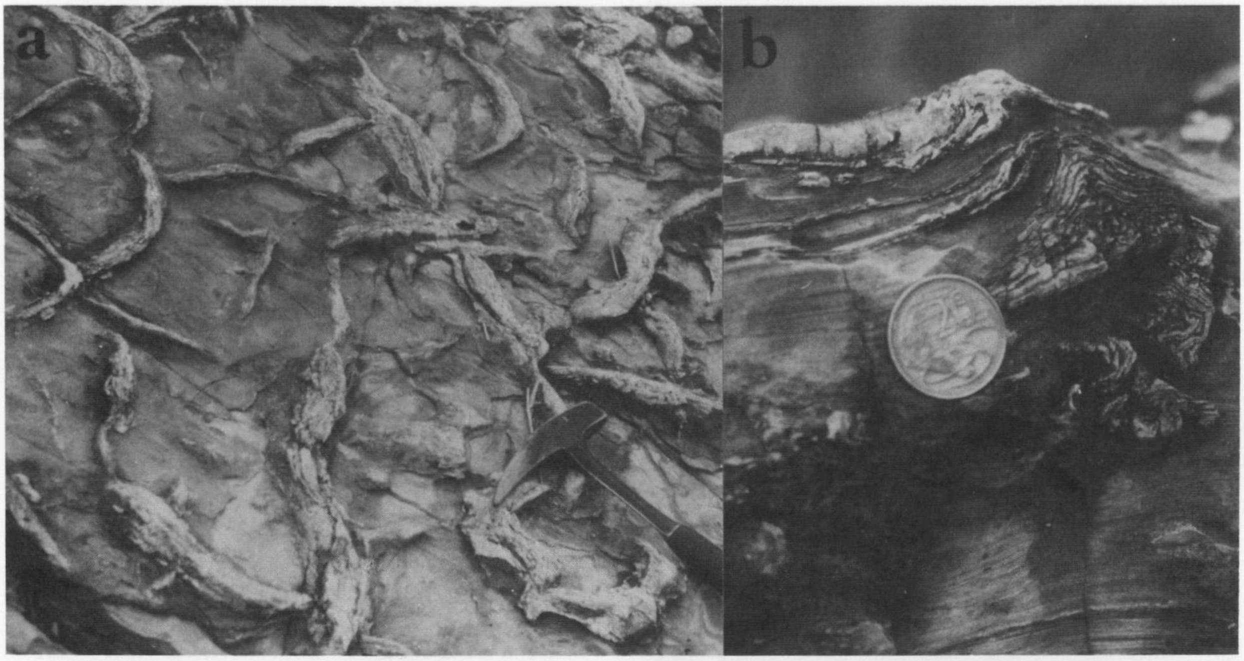

Fig. 126. Stromatolitic shrinkage polygons developed in dololutite of unit 5 at 388 m in the type section of the Hot Spring Member of the Lynott Formation: (a) bedding surface, (b) vertical section. Note the continuity of the algal lamination in the vertical section, and the absence of tepee-like disruption of the bedding. (BMR negatives a, GB 3121; b, GB 3114)

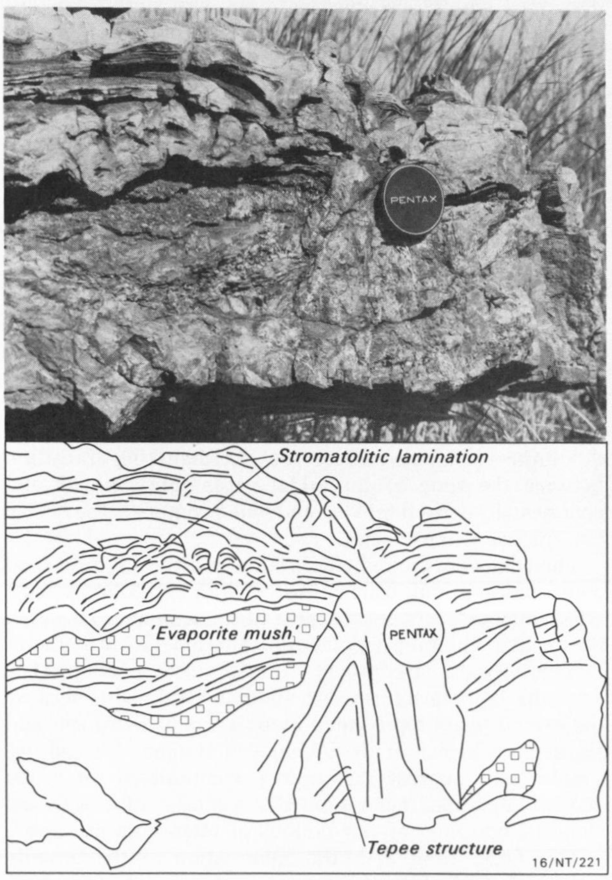

Fig. 127. Bladed gypsum–stromatolite–tepee chert bed, characteristic of unit 6, at 448.5 m in the type section of the Hot Spring Member of the Lynott Formation. The diameter of the lens cap is about 6 cm.

Fig. 128. Bedding-plane surface of steep-sided tepee structures forming a polygonal pattern in unit 6 at 448.5 m in the type section of the Hot Spring Member of the Lynott Formation. Note the layers or pods of bladed gypsum casts interlayered with stromatolites between the tepees. (BMR negative M2273/30)

to lower intertidal, grading locally to subtidal—with abundant sediment supply (convoluted bedding) inhibiting algal growth. The thick sand interval (177–207 m) with upward-fining cycles and current-ripple bedding in the type section, and the slumped upward-fining lower part in Mallapunyah 77/02 are interpreted as channel fills. The irregular continuously layered stromatolites in unit 3 are equated with deformed smooth-mats from areas of high organic productivity in quiet subtidal to lower tidal channels and flats at Shark Bay (Davies, 1970; Hoffman, 1976); associated diagonal fenestrae are compatible with this setting. Similar comparisons with Shark Bay for the scallop mats reflect an overall upward regression to an upper intertidal setting higher in the unit.

Unit 4 is typical of an intertidal complex. The continuously layered pseudocolumnar to bulbous (linked hemispheroid; Logan & others, 1964) stromatolites, and associated wave,

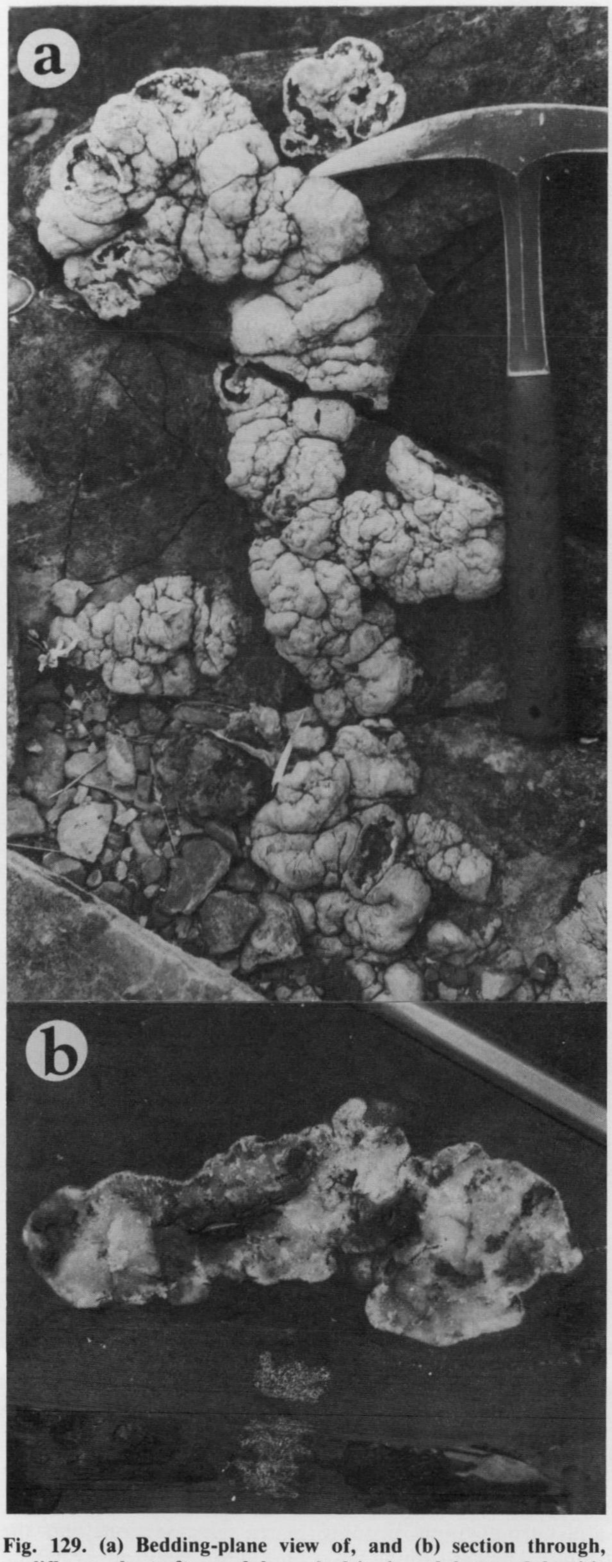

Fig. 129. (a) Bedding-plane view of, and (b) section through, cauliflower chert after nodular anhydrite in red–brown dolomitic siltstone of unit 8 (at about 575 m) in the type section of the Donnegan Member of the Lynott Formation. Note the typical enterolithic structure, particularly at the bottom of (a), and deformed enclosing laminae in (b). (BMR negatives a, GB 3126; b, M614/10)

current, and desiccation structures, are typical of tidal flats. Stratiform mat disrupted by desiccation and evaporite growth typify upper intertidal to supratidal zones. Upward-fining cycles reflect tidal channels. Small columnar bioherm series are ascribed to tidal ponds. Scattered displacive gypsum casts reflect the outer limits of sabkha-type diagenesis, probably by continental groundwaters.

The critical rock of *unit 5* is the red microcrystalline chert-podded and layered dololutite. Overall, unit 5 is more dolomitic than units 3 and 4; intertidal cycles become more carbonate-rich towards the top. The pink to red colour, due to dispersed iron oxide dust in an oxidised environment, suggests a supratidal environment. A recent analogue may be the aphanitic siliceous 'yogurt' dolomite precipitating today from supratidal lakes of the Coorong region in South Australia (von der Borch & Lock, 1979). Identical pink to red dololutites are closely interbedded with the supratidal upper evaporites in unit 6 (see below); indeed, units 5 and 6 are almost certainly in part lateral equivalents. Other indicators of high intertidal to supratidal environments in unit 5 include: hopper halite casts and more abundant desiccation features than in the lower units; couplets of upward-fining and upward-coarsening cycles, which are typical of tidal channels in intertidal–supratidal zones; and small columnar branching stromatolites, which may occur in supratidal ponds. The abundance of displacive gypsum indicates an active sabkha-like environment; post-lithification introduction of the gypsum is amply illustrated by the association between gypsum and joints.

The unusual bladed gypsum–stromatolite–tepee cherts of *unit 6* are so similar to the gypsiferous stromatolites of Marion Lake (von der Borch & others, 1977) that an immediate comparison is drawn. Unit 6 is interpreted as having formed from supratidal ephemeral hypersaline lakes, developed within and interdigitating with supratidal flats below (unit 5) and continental sabkha (Donnegan Member) above.

The diagnostic feature of the *Donnegan Member* is the cauliflower cherts after nodular sulphate evaporites. Their displacive habit, enterolithic structure, and gypsum relicts all confirm their origin by replacement of original diagenetic gypsum. Their similarity to the gypsum and anhydrite nodule beds which grow interstitially in uncompacted sediments in the supratidal zone of the Abu Dhabi sabkhas (Shearman, 1966; Kinsman, 1969; Kendall, 1979) invites a direct comparison between the Donnegan Member and the Abu Dhabi sabkhas. However, the contrasting scales (thicknesses) of the two impose limitations on such a comparison (see discussion on p. 64).

Within this framework, therefore, *unit 7*—comprising alternating tepee stromatolites and cauliflower chert in dololutite—is interpreted as the interdigitating transition between the zone of supratidal stromatolitic ponds and continentally derived sabkha, and *unit 8* comprises the typical continental sabkha facies.

The characteristic red colouration and the silt/fine sand composition of unit 8 are consistent with an aeolian source, which may well account for most of the sediment. However, the regular climbing ripples that alternate with a planar lamination must have formed in a subaqueous medium. They are unlikely to have formed in alluvial flood plains because the overall facies represented by unit 8 is too uniform and shows no evidence of fluvial channel systems. Instead, we provisionally suggest that unit 8 accumulated on broad aeolian–supratidal flats subjected to regular marine or fluvial flooding and intermittent periods of intense desiccation.

This facies (unit 8) is the culmination of the broadly regressive paralic Lynott Formation preceding the transition into the overlying Yalco Formation.

YALCO FORMATION

The term Yalco Formation is here proposed for a unit of intensely chertified dolostone that occurs in about the middle of the Batten Subgroup. It contains a wealth of desiccation features and unusual globular and biscuit-shaped stromatolites that distinguish it from other formations in the subgroup. Owing to the intense silicification that it has undergone it has a distinctive white airphoto pattern that allows ready identification, especially on colour airphotos. Because of this unique photo expression and the unusual sedimentary structures, the distribution of the formation as shown on the early maps (e.g., Smith, 1964) is essentially correct. Despite the intense silicification, the original sedimentary textures and structures are well enough preserved in places to enable us to reconstruct the original depositional setting and sedimentary evolution of the formation. Muir & others (1980b) have described these features in detail; their results are summarised here.

The formation is named after Yalco Creek, which flows into Batten Creek 21.5 km north-northwest of Borroloola (locality map, Plate 1).

Distribution, thickness, and outcrop expression

The Yalco Formation is widespread throughout the area. It crops out in most parts of BAUHINIA DOWNS and in southeastern and southwestern MOUNT YOUNG, but has not been positively identified in the far northwest of the area.

West of the Tawallah Fault, rocks that are now known to be the Yalco Formation were previously included—together with rocks now known to belong to other formations of the Batten Subgroup—in a unit called the 'Billengarrah Formation' (Smith, 1964; Plumb & Brown, 1973). This name has now been discarded.

In sections in central BAUHINIA DOWNS the Yalco Formation reaches a maximum thickness of about 250 m, but generally it is thinner because erosion has removed the upper parts.

The silicification that has overprinted the Yalco Formation is a product of the weathering that followed this erosion . The Yalco Formation may be more susceptible to silicification than some of the other formations because it contains abundant early diagenetic chert in the form of nodules and laminae.

The formation is seldom well exposed: in most areas it comprises only low (30 cm high) benches and rubbly chert float. Nonetheless, even in most silicified sections, primary structures generally can be determined, confirming the identification of the unit.

Type and reference sections

The type section (Fig. 130) is here nominated as the complete and reasonably well exposed section extending south from GR 053554 to 047548. In addition, we nominate as a reference section a well exposed and easily accessible but incomplete section just south of the Boroloola–Bauhinia Downs road at GR 099087 (*Borroloola*, 6165); this is the section from which Muir & others (1980b) obtained most of their well illustrated sedimentary structures and upon which most of the interpretations are based (Fig. 131).

Stratigraphic relations

In most areas the Yalco Formation conformably overlies the Donnegan Member of the Lynott Formation, but in southeast BAUHINIA DOWNS it onlaps older units of the Umbolooga Subgroup. It appears to be conformably overlain by the Stretton Sandstone. In many areas, however, the upper parts of the formation have been removed by erosion, and a number of younger units—including formations of the Nathan Group, Roper Group, Cambrian, and Cretaceous—rest unconformably on various levels of the Yalco Formation.

Lithology

In the type and reference sections (Figs. 130, 131) rocks of the Yalco Formation are generally fine-grained and parallel-bedded aphanitic dololutite and dolarenite with abundant nodules and laminae of early diagenetic chert and minor interbedded lithic sandstone. The rocks have an unusually knobbly appearance, which is the combined result of the interbanding of the components and a large amount of nodular chert.

The dolostones are commonly stromatolitic. Forms include small domal (synoptic height 1 cm, diameter 2.5 cm), globular (diameter 2.5 cm), biscuit-shaped (on the surface of mud-cracked polygons), and in places biohermal masses of columnar stromatolites (synoptic height 0.5 m, column height 30 cm, and column diameter about 1.5 cm). The stromatolites are preferentially silicified (Fig. 132) and white, and are conspicuous against the brown-weathering aphanitic dololutite containing them. Finely laminated spheroidal oncolites or pisolites with cores of dololutite are present in places (e.g., at 83 m in the type section).

The dololutite also contains a host of distinctive and environmentally significant sedimentary features. Among these are intraclast breccias, which are of three types: (1) *non-transported intraclast breccia*, the most common type, containing angular flakes in a fine dolomite matrix (Fig. 133); (2) *deformed mud-flake breccia*, fairly common, some of which shows signs of transportation such as imbrication; and (3) *random-textured breccia*, containing randomly oriented, locally derived, mostly angular flakes in a dololutite matrix (Fig. 134). The clasts in the breccias are commonly chert, but we have not been able to determine whether they were deposited as chert, or as carbonate that was later silicified.

Other sedimentary features in the dololutite include ripple marks, pseudohexagonal gypsum casts (e.g., near the base in the type section, Fig. 130), discoidal casts up to 1 cm long (which may be pseudomorphs after gypsum crystals), tepee structures, and polygonal cracks. The polygonal cracks are of two types: (1) small polygons and desiccation cracks—the polygons of these are commonly four to six-sided, have straight to slightly sinuous sides, and are between 5 and 40 cm wide (Fig. 135); the cracks are filled with unstratified mudstone deposited from above; and (2) large polygons and tepee structures—the polygons of these are between 40 and 300 cm wide; the material filling the cracks has a complex stratified structure (which is generally selectively silicified), is commonly capped by a ridge of small domal stromatolites (Fig. 136), and originated by upward percolation of carbonate-rich groundwater.

Some of the dolostones in the less-silicified sections exhibit a brain-like surface texture (Fig. 137), similar to surface textures of Cambrian phosphorites observed near Lady Annie phosphate mine, Queensland. Chemical analysis of these dolostones has revealed a P_2O_5 content of about 5 per cent.

The minor lithic sandstone interbedded with the dolostone in most of the better-exposed sections is fine to coarse-grained and in places conglomeratic, and occurs in lenticular beds. It is mostly parallel-bedded with parting lineation, but low-angle cross-bedding (Fig. 138) and less common ripple-lamination are evident in places. The conglomeratic sandstone mostly occurs in lenses or channels. One channel (with one vertical and one gently dipping side)—in measured section Glyde 77/04A (Appendix Fig. A41) about 20 km east of McArthur River homestead—is 6 m deep and scoured into horizontally bedded dololutite. In this channel, fragments (up to 20 cm) in the conglomerate consist of chert and

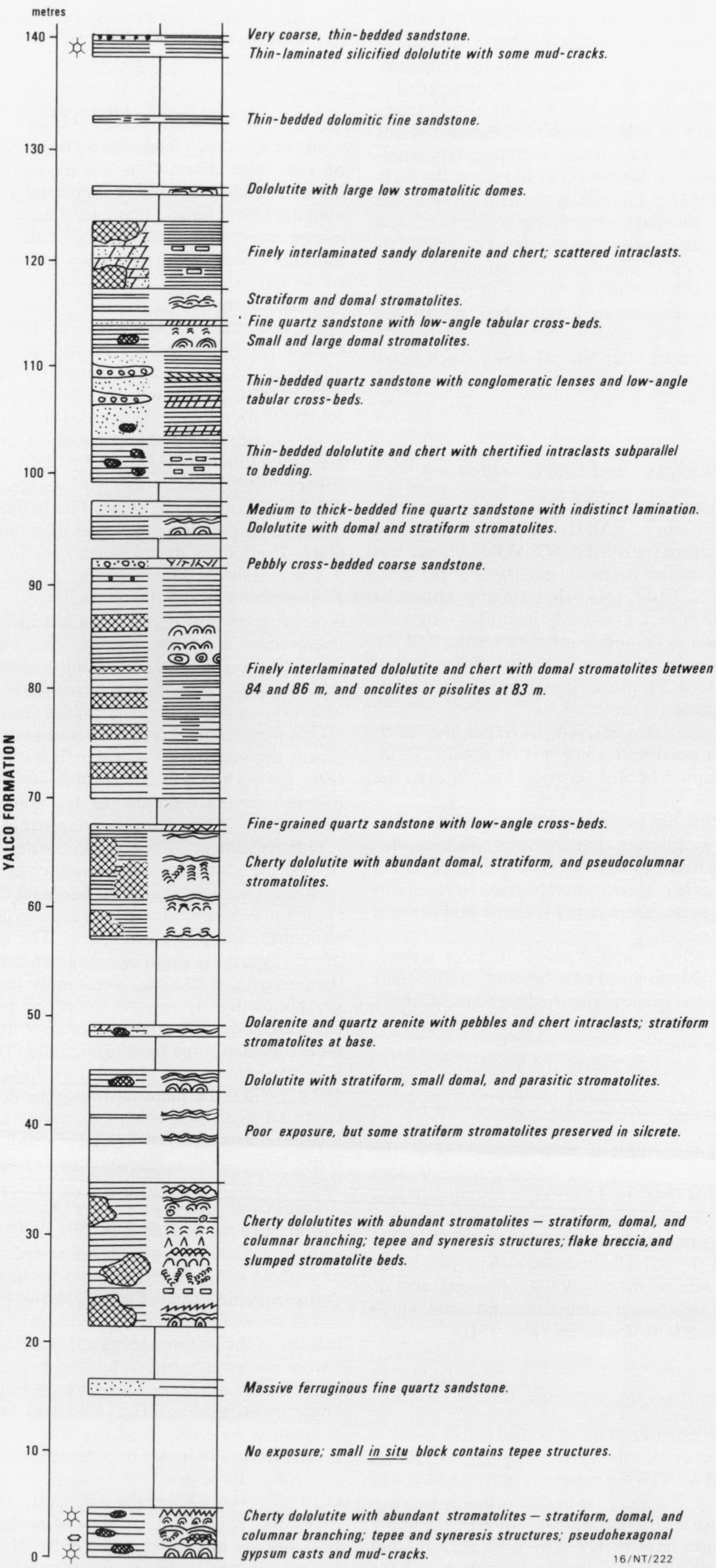

Fig. 130. Type section of the Yalco Formation (measured section Glyde 77/03), in the Kilgour River valley (from Jackson & others, 1978).

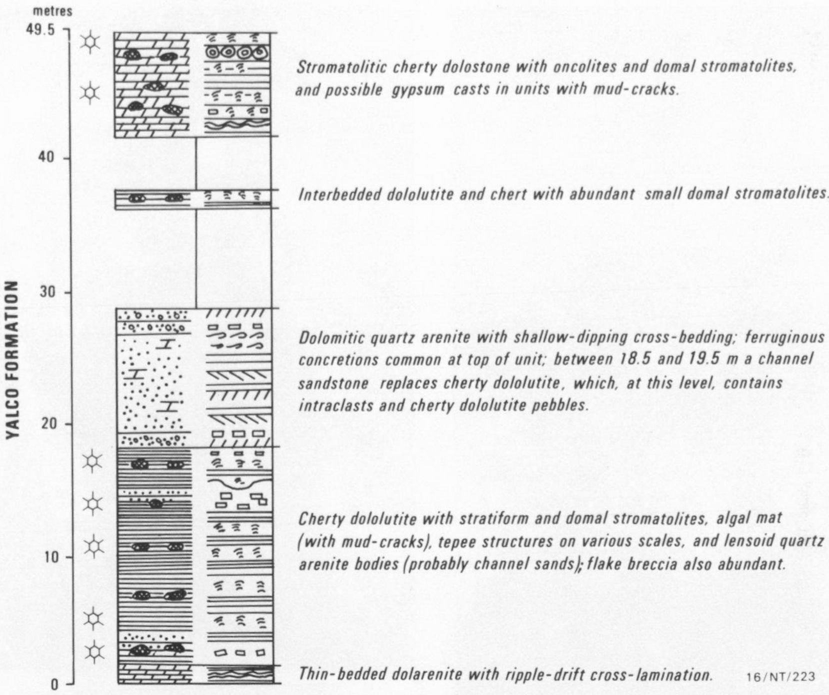

Fig. 131. Reference section of the Yalco Formation (measured section Borroloola 77/01), 4 km southwest of Ryan Bend (from Jackson & others, 1978).

Fig. 132. Small laterally linked, preferentially silicified stromatolites in the Yalco Formation at the reference section, near Ryan Bend. The width of the field of view is 15 cm.

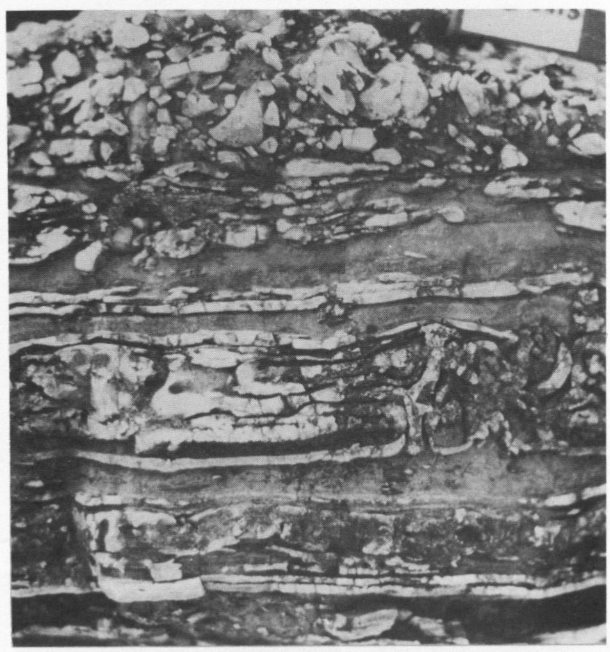

Fig. 133. Mud-flake breccia near the top of the Yalco Formation in the reference section, near Ryan Bend. The width of the field of view is 15 cm. (BMR Negative M2551/29A)

dololutite indistinguishable from those in the host Yalco Formation. Some of the fragments are rounded, others are angular, and yet others are distorted mud flakes. The largest fragments are at the base adjacent to the steepest side of the incised channel; the conglomerate fines upwards to a lithoclastic arenite comprising grains of mainly silicified carbonate and quartz.

Although the sequence of rock types at the type and reference sections appears to be fairly representative of the formation where mapped, the upper part of the formation southeast of the Abner Range comprises mostly thinly interlaminated dolostone with tabular cherts, stromatolitic dolostone, and clean quartz arenite, and lacks desiccation cracks and polygons. In the same area, a 9-m-thick conglomerate consisting of rounded and silicified stromatolitic dolostone clasts is present at the base of the formation, and indicates local relief and erosion before the Yalco Formation was deposited.

Lateral facies variations are therfore evident, but we have not systematically studied their character and distribution.

Interpretation

After comparing sedimentary structures (especially desiccation features and stromatolite types) Muir & others (1980b) suggested that the Yalco Formation is a fossil

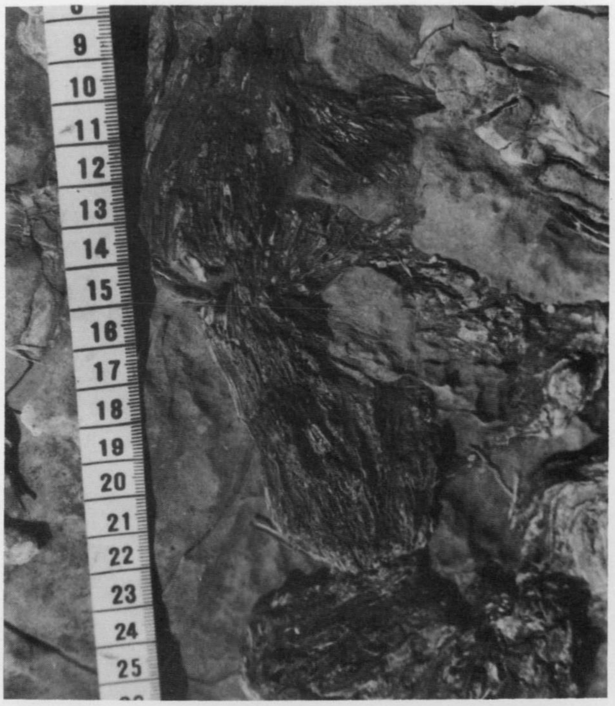

Fig. 134. Edgewise breccia in the Yalco Formation at the reference section, near Ryan Bend.

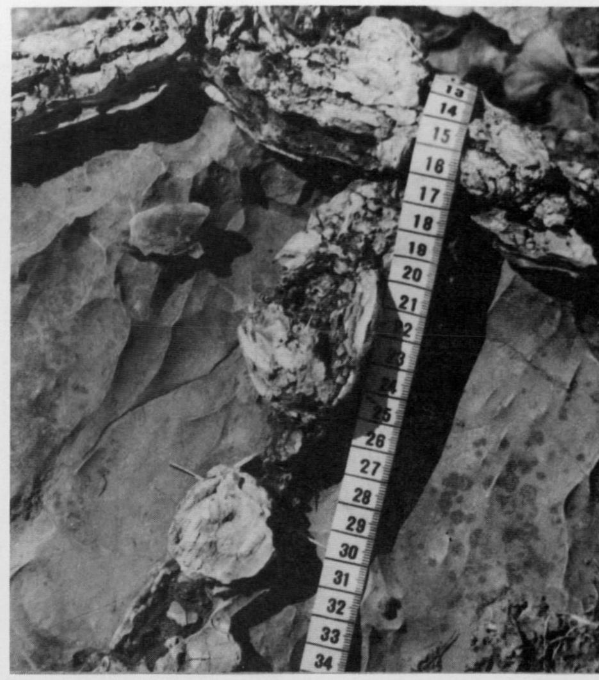

Fig. 136. Plan view of part of a tepee structure in the Yalco Formation in the reference section, near Ryan Bend. Chertified small domal stromatolites have developed along the tepee cracks.

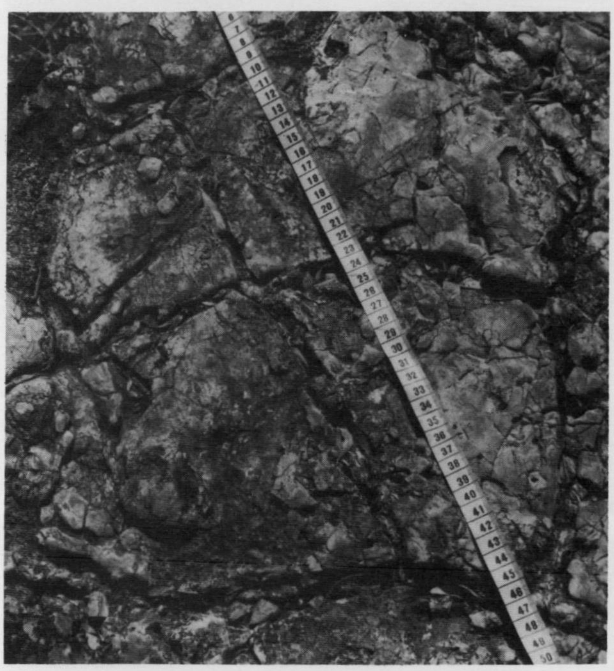

Fig. 135. Desiccation cracks in cherty dololutite in the Yalco Formation in the reference section, near Ryan Bend.

equivalent of the ephemeral-lake sediments in the Coorong Lagoon of South Australia. We present here a brief review of the most significant findings of their study.

Sedimentary structures in the Yalco Formation identical with those described from the Coorong region are abundant, especially in the lower third of the formation, where repeated shoaling cycles a few metres thick contain sequences of structures similar to those found in ephemeral lakes of the present-day lagoon.

Fig. 137. 'Brain' texture in mud-cracked phosphatic dololutite of the Yalco Formation in the reference section, near Ryan Bend. The width of the field of view is 9 cm.

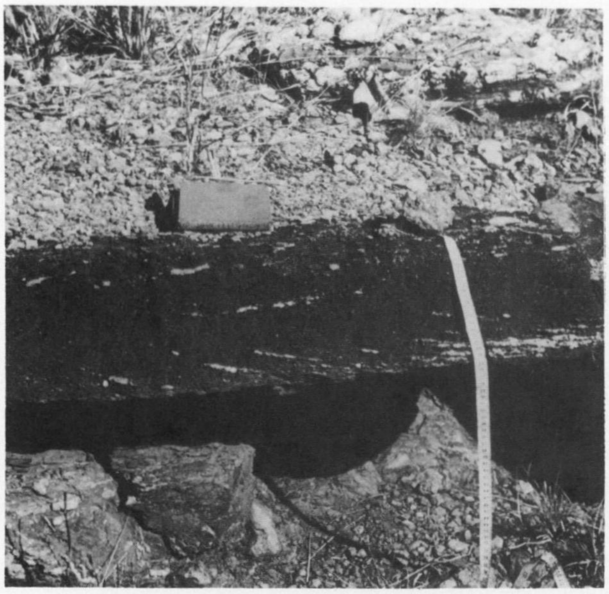

Fig. 138. Cross-bedded quartz and lithoclast arenite in the Yalco Formation at the reference section, near Ryan Bend. (BMR negative M2551/32A)

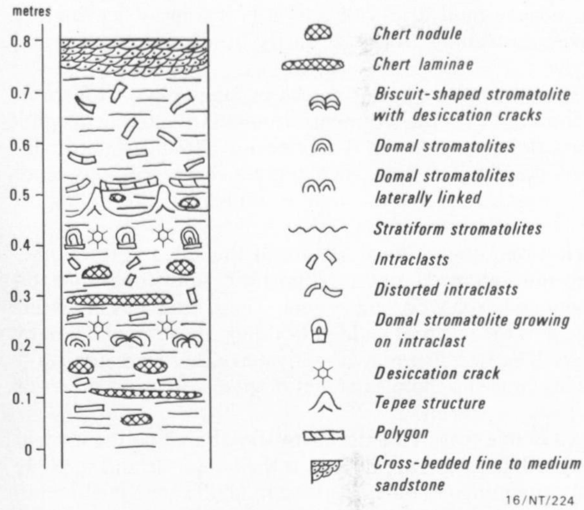

Fig. 139. Vertical section of dolomitic sediments with chert nodules, showing how a small lake system in the lowermost part of the Yalco Formation is sealed (after Muir & others, 1980b). Similar sections occur repeatedly as cycles throughout the Yalco Formation, although none of them is persistent laterally, indicating to some extent the relatively small size of the lakes.

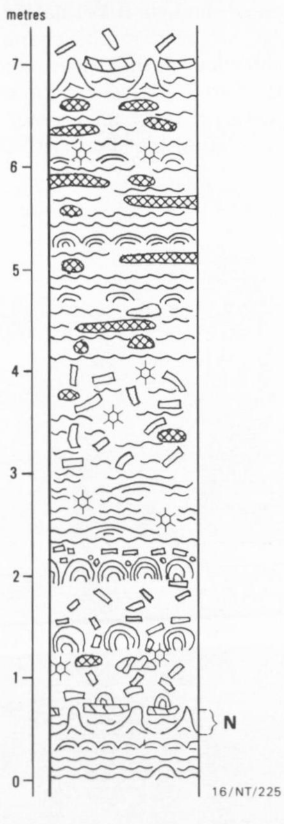

Fig. 140. Vertical section showing how the sealing process in a small lake system in the lowermost part of the Yalco Formation might have been interrupted (after Muir & others, 1980b). A change in water-table level at the top of unit N has caused flooding and re-wetting of the tepees and polygons, and small domal stromatolites have become re-established. Distorted mud flakes are incorporated in an an overlying intraclast breccia. See Fig. 139 for explanation of symbols.

Sedimentary structures indicative of subaerial exposure and desiccating conditions abound in the aphanitic dolostone, in which—as in the Coorong carbonates—evidence of evaporites is rare. A similar seasonally humid climate is therefore inferred for the Yalco Formation—a noticeable contrast to much of the McArthur sequence in which evidence of arid sabkha environments abounds.

Low-angle cross-bedding in several thin dolostone bands, and very fine laminae of well sorted and, in places, cross-bedded dololutite and chert, suggest that some of the sediment was deposited in a subaqueous medium which was subjected to some current reworking. Further, the presence of small domal stromatolites on intraclasts—a common feature in the ephemeral Coorong lakes—suggests that in places there might have been seasonally standing water. The laminae in some of the dolostone generally take the form of stratiform stromatolites, or even small domal stromatolites with little relief. In the modern Coorong analogue, prograding algal mats occur on marginal flats which are alternately flooded and dried. The small domes may indicate slightly more persistent pools, perhaps nearer the centre of a shallow lake.

The tepee-bounded polygons in the Yalco Formation are similar in size, shape, and structure to polygons in various parts of the ephemeral Coorong lakes. In this modern setting, their formation is due to interference between resurgent seasonal groundwater below lake margins and the lithified crusts that seal the lake sediments. Cherty non-transported intraclast breccias immediately overlying the polygons in the Yalco Formation (Fig. 139, 140) are considered to be the erosional remnants of the lithified crust and its tepees, because—unlike the flakes in other beds—they show no sign of soft-sediment deformation. Deformed mud-flake breccia—comprising flakes that have undergone considerable plastic deformation—are apparently due to desiccation, which caused spalling of the soft moist surface sediments; these were later deformed during episodes of flooding.

The random-textured breccia in the Yalco Formation is considered to be analogous to deflation breccia in the Coorong lake system. On the margins of these lakes, broken fragments of lithified crust become embedded at random angles in aphanitic dolomite mud washed on to the marginal flats during seasonal flooding. When the flood waters retreat, the mud partly dehydrates, holding the flakes firmly in place at whatever angles they came to rest. During further exposure, the surface mud dries out and is blown away, leaving the flakes protruding from the partly lithified dolomite mud below.

Thus the Yalco Formation shares many physical features in common with the sediments accumulating today in ephemeral dolomite lakes in the Coorong system, in particular the desiccation features—such as mud-cracks, polygons, tepee structures, and breccias—and a number of morphological varieties of stromatolites.

However, one physical feature of the Yalco Formation—the thin interbeds of conglomeratic sandstone—has no analogue in the Coorong system. These interbeds are interpreted as the result of sudden flooding of the small lakes by rivers. The flooding may be activated either by tectonism—having caused a change in relief or increased water flow—or perhaps by storms.

A notable feature of the chemistry shared by the ancient and present-day accumulations is their chloride and sulphate evaporite mineral contents; these minerals are ephemeral in the Coorong region and very rare in the Yalco Formation. Chemically, the cherty dolostones of the Yalco Formation represent a feasible diagenetic end point to the mineral systems at present prevailing in the Coorong lakes. By analogy, a similar hydrological system is suggested for the Yalco Formation.

Finally, we note that our interpretation of the Yalco Formation contrasts markedly with that of the underlying uppermost part of the Lynott Formation, which has all the sedimentological and stratigraphic characteristics of an arid supratidal sabkha depositional environment. Consequently, we interpret an overall regressive sedimentation model and a major climatic change to explain the stratigraphic differences and relationships between the Yalco and Lynott Formations.

STRETTON SANDSTONE

The term Stretton Sandstone is here proposed for a widespread unit of flaggy very fine to medium-grained sandstone and minor siltstone sandwiched between the cherty dolostones of the Yalco and Looking Glass Formations near the top of the Batten Subgroup. The unit is lithologically distinct, and hence was accurately portrayed during the original reconnaissance mapping (Smith, 1964). Plumb & Brown (1973, table 2) disputed Smith's (1964) identification of the formation in the Top Crossing area, but our recent work has shown that it is present there; it is intensely silicified, and was misidentified by Plumb & Brown (1973) as the 'Smythe Sandstone' (which we have now redefined as the basal member of the Balbirini Dolomite, overlying the McArthur Group).

Although the formation has been partly described and the name published several times, the unit has never been formally defined. The name is derived from Stretton Creek, which flows into Looking Glass Creek at GR 987009 (*Batten*, 6065), 26.5 km northwest of McArthur mine.

We have not studied the formation in detail, nor undertaken systematic sedimentological studies of it. We can only make a general interpretation of its stratigraphic setting and sedimentological evolution.

Distribution and thickness

The formation is well exposed in BAUHINIA DOWNS and in the southern part of MOUNT YOUNG. It has been recognised also in the northeastern corner of WALLHALLOW. Like other units of the Batten Subgroup, its rocks had previously been included in the now abandoned 'Billengarrah Formation', so constitute some of the

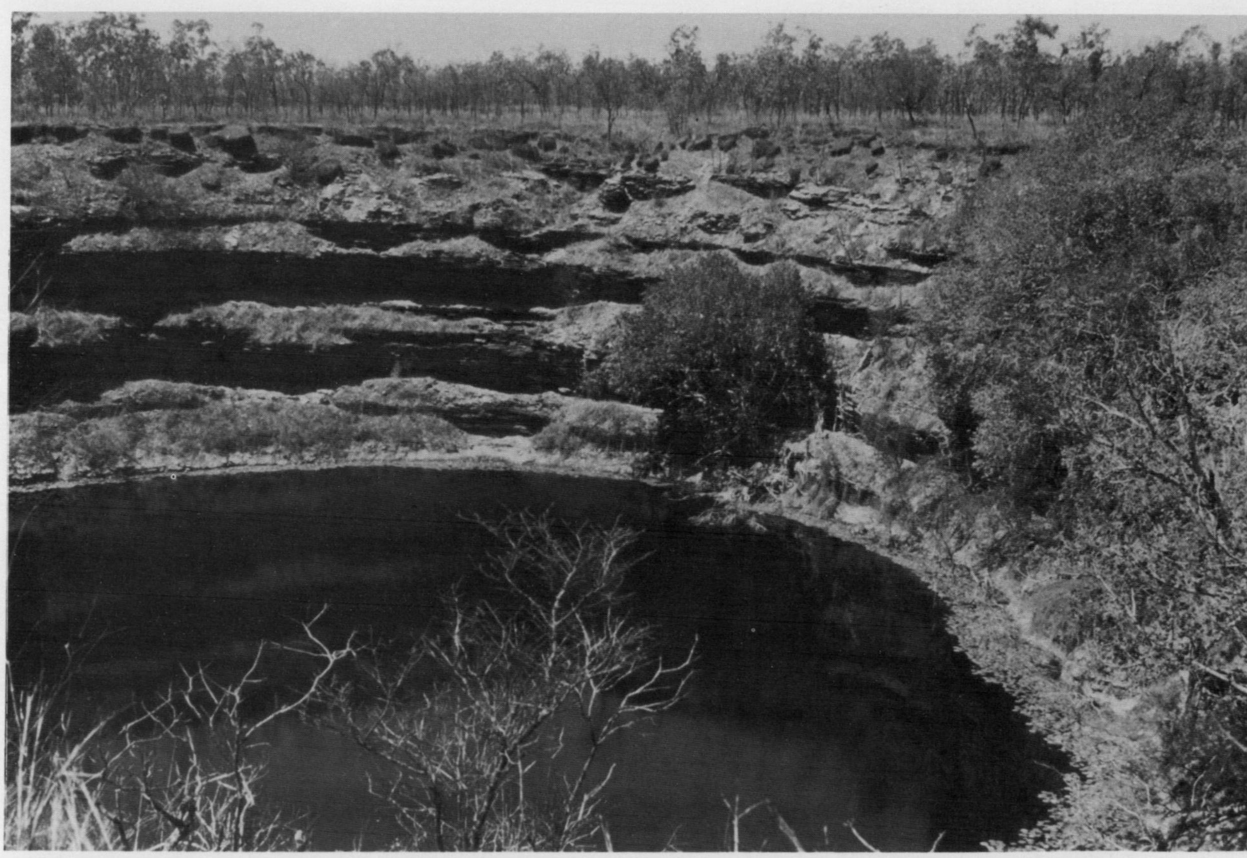

Fig. 141. Nhumby Nhumby sinkhole with 20-m-high cliffs of Stretton Sandstone. (BMR negative M2553/21A)

'Billengarrah Formation' outcrop shown on the BAUHINIA DOWNS map (Smith, 1964).

One striking topographic feature in the Stretton Sandstone is the water-filled deep doline of Nhumby Nhumby (GR 140329, *Bing Bong*, 6166). Although the doline, which has an area of about 0.5 km^2, is undoubtedly caused by solution collapse in the underlying Yalco Formation or older units, the 20-m-high cliffs are entirely in the Stretton Sandstone (Fig. 141). The doline is a striking topographic feature in otherwise flat-lying countryside. A small ephemeral stream that flows over its west side has no visible outlet.

The thickness of the Stretton Sandstone ranges from 30–270 m, depending on the amount of erosion it has undergone.

Type and reference sections

The Stretton Sandstone is well exposed along the lower Kilgour River, where part of measured section Glyde 77/03 (Fig. 142)—extending south from GR 047548 to 046547—is proposed as the type section (where it overlies the type section of the Yalco Formation).

The formation is also well exposed in the ridges north of Clark Creek (east central *Batten*, 6065), and a section at GR 909091 (*Batten*, 6065) is nominated as a reference section.

Stratigraphic relations

Owing to poor exposure of the overlying and underlying cherty dolostone, the contact relations of the Stretton Sandstone are difficult to define, but it appears that the unit conformably overlies the Yalco Formation and is conformably overlain by the Looking Glass Formation. In places the upper part of the unit has been removed by erosion, and the lower part is overlain by a variety of younger rocks—including the Amos Formation, and formations of the Nathan Group, Roper Group, Cambrian, and Cretaceous. In such places the uppermost remaining beds of the Stretton Sandstone are commonly intensely silicified.

Lithology

The Stretton Sandstone consists mainly of very fine to medium-grained, slightly micaeous pale green and grey quartz sandstone which in places is slightly feldspathic and glauconitic; the absence of dolomite is an unusual character for rocks of the McArthur Group. Thin sections indicate that the rocks are strongly cemented by silica in optical continuity with the original grains. Rare dust rims suggest that the original grains were well rounded, but the rocks now consist mainly of interlocking irregularly shaped quartz grains and crystals, indicating a pervasive postdepositional silicification. There is no evidence of an original clay matrix, implying that the original sandstone was mainly a clean quartz arenite.

The rocks in well exposed sections have a flaggy parting and distinctly wavy to parallel thin bedding (Fig. 143). In this respect they differ from most of the arenites in the McArthur Group (except for the Tatoola Sandstone), which are characterised by discontinuous stratification, and more closely resemble arenites in the overlying Roper Group. Small intervals of the type section are more fissile, and indicate the presence of laminated micaceous, very fine-grained sandstone or siltstone interbeds. Some of the flaggy sandstone beds contain low-angle cross-lamination or rarely ripple-lamination (Fig. 143), although in general they are unstructured or parallel-laminated.

The most common sedimentary structures in the type section (Fig. 142) are clay clasts and clay-clast impressions, distorted mud-cracks (?dewatering structures), groove-and-scrape marks, and parting lineation. Two unusual beds occur in the type section: one is a coarse-grained slumped sandstone in a channel 4 m wide and 40 cm deep with ball-and-pillow structures; the other is a medium-grained cross-stratified sandstone containing dolomitic or ferruginous concretions (20 × 5 cm).

The reference section, 58 km north of the type section, contains similar rock types and sedimentary structures: mostly fine flaggy sandstones with fissile interbeds, and bedding-plane features such as shale-clast impressions, streaming lineation, parting lineation, and prod-and-groove casts are common. As inferred for the Tatoola Sandstone, the surface markings were probably caused largely by the shale clasts, which are 1–4 cm long and composed of rectangular to ellipsoidal mudstone and siltstone. The composition of the clasts appears to be similar to that of the beds in the fissile laminated sections. This implies that the fissile beds represent a lateral facies equivalent of the flaggy sandstones, and that they were intermittently exposed and eroded to produce the clast debris for incorporation into the flaggy facies.

In the southeast of the outcrop area at GR 130350—about 26 km south of the type section—a well exposed cliff face in the Stretton Sandstone contains three unusual rock types in addition to the very fine-grained flaggy sandstone facies: (1) a laterally persistent pink ?tuff 20 cm thick with vague internal ripple lamination; (2) beds of very coarse-grained quartz sandstone 5–15 cm thick capped by symmetrical megaripples (wavelength 20 cm, amplitude 5–8 cm, orientation 080°); and (3) a massive very fine-grained sandstone bed about 4 m thick with large load and ball-and-pillow-like structures at its base (this might be equivalent to the thinner, channel-confined, slumped sandstone at the type section).

In the field the pink ?tuff appears to be similar to pink beds in many other McArthur Group units. It is very fine-grained and laterally persistent and generally has a conchoidal fracture. Pink beds elsewhere in the McArthur Group are potassium-rich (Appendix 2), and thin sections show that they contain very angular quartz and feldspar crystals; most of them are suspected as having a tuffaceous origin, but this is usually difficult to establish. However, the pink bed in the Stretton Sandstone contains probable gas bubbles, and devitrified glassy shards (Fig. 144), implying a tuffaceous origin. The presence of indistinct cross-lamination in this bed indicates some current reworking of the ash-fall material. Although a similar pink bed is not evident at the type or reference sections (in the northeast), it is apparent in several sections in the south and northwest, where it occurs in the upper third of the formation.

A coarse conglomerate facies is locally developed in the Stretton Sandstone along the Emu Fault Zone. At GR 133093 (*Borroloola*, 6165), 7 km south of Ryan Bend and west of the highway, up to 100 m of massive conglomerate lies between the Yalco Formation and Looking Glass Formation; in an overall upward-fining sequence, conglomerate with rounded and imbricated chert boulders up to 20 cm across at the base grades up to cross-bedded pebbly sandstone at the top. Three kilometres to the south the conglomerate changes laterally into just a few metres of fine and coarse-grained sandstone. A striking upward-fining sequence, 50 m thick, occurs at Catfish Hole on the Glyde river (GR 315515, *Glyde*, 6164): a basal conglomerate comprising several individually graded beds (1–2 m thick), with rounded chert boulders up to 30 cm across, grades up to fine to medium-grained ripple-marked and cross-bedded sandstone at the top. Palaeocurrent directions near Ryan Bend and at Catfish Hole are from the southeast.

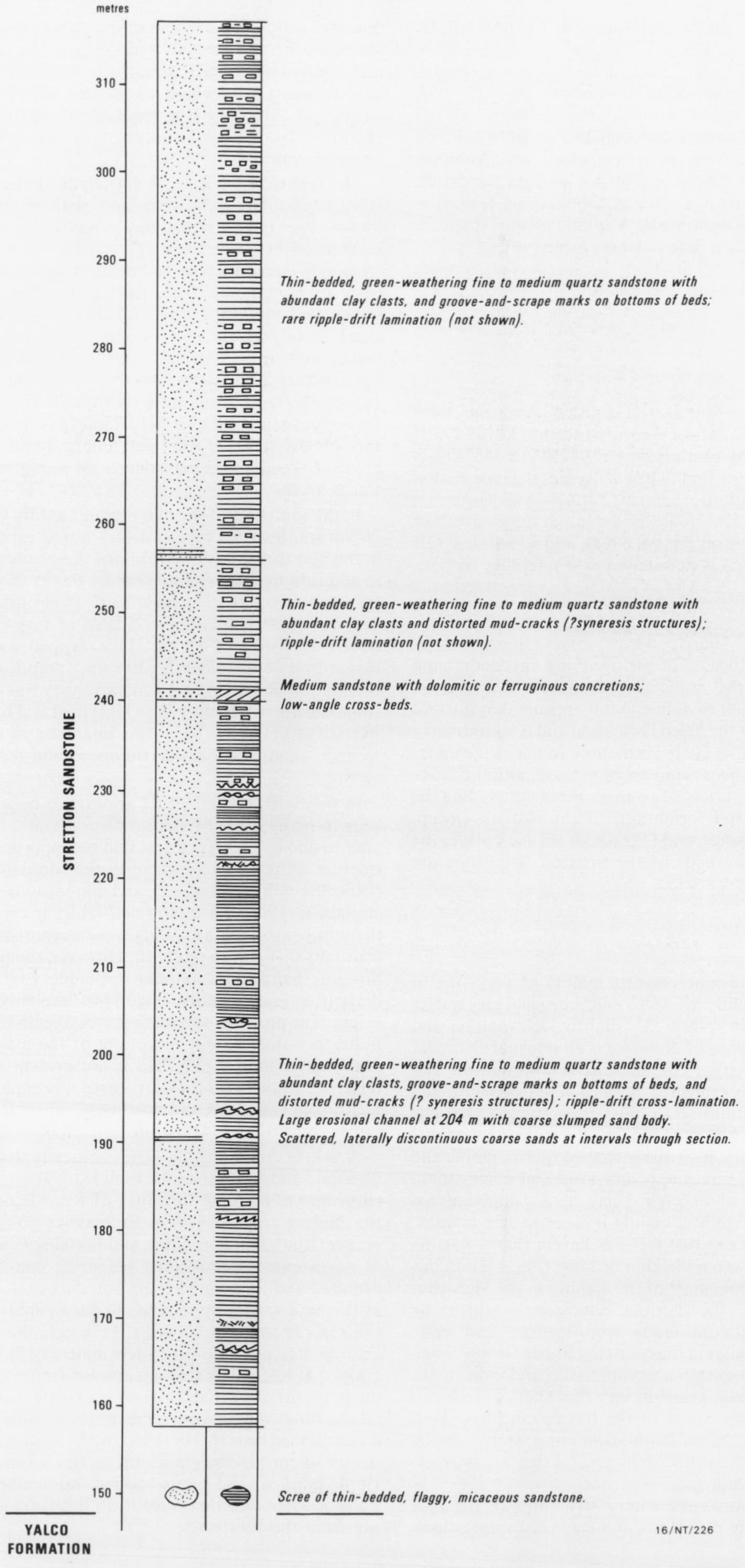

Fig. 142. Type section of the Stretton Sandstone (measured section Glyde 77/03), in the Kilgour River valley (from Jackson & others, 1978).

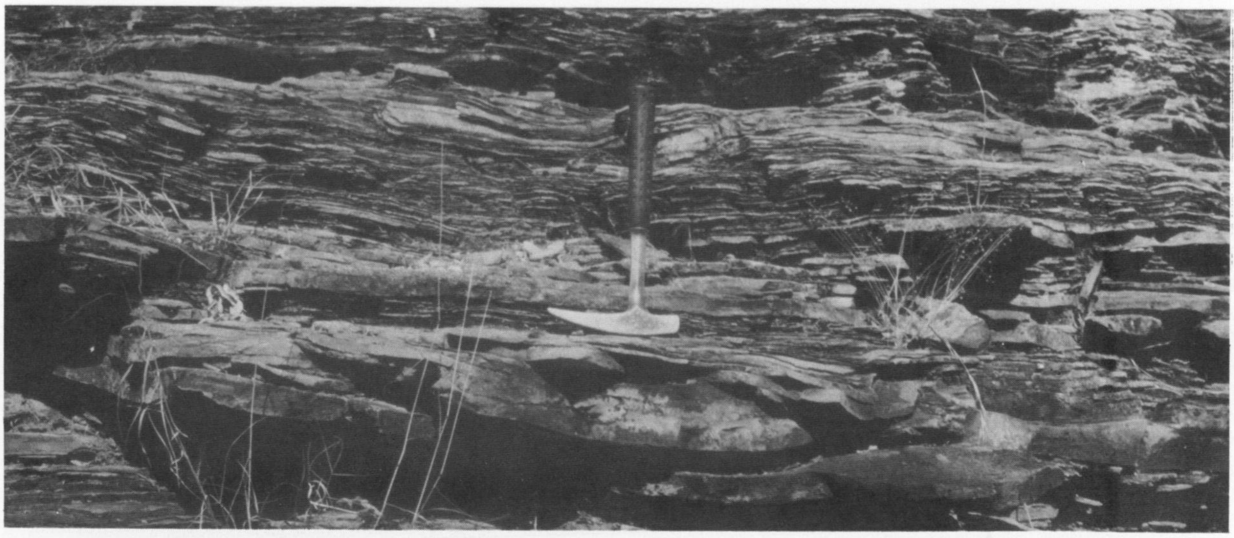

Fig. 143. Thin-bedded fine-grained Stretton Sandstone in the headwaters of Looking Glass Creek. Note the large wave ripples below the hammer head.

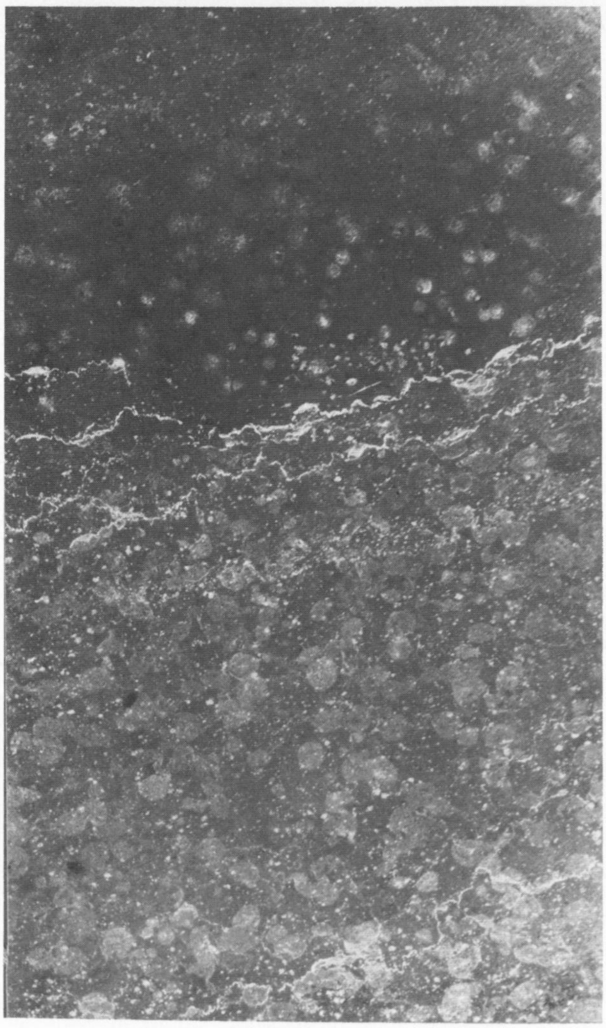

Fig. 144. Thin section of pink ?tuffaceous bed in the Stretton Sandstone on the east bank of the Kilgour River 7 km north of Possum Point Yard, showing probable devitrified glass and gas bubbles about 1 mm in diameter. (BMR negative GB 3101/5)

A relatively coarse sandstone facies is also developed locally in the Top Crossing area along the Abner Fault, but it also grades into fine sandstone to the north.

Interpretation

Probably the most striking features of the flaggy sandstone facies of the Stretton Sandstone are its lateral uniformity and its persistent, regular, thin bedding. These features, together with the lack of carbonates and evaporites, set it apart from most of the other formations in the McArthur Group (except for the Tatoola Sandstone), and indicate a contrasting environment of deposition. The presence of glauconite, although only in small amounts, is considered to indicate a marine environment (Odin & Matter, 1981). The fine-grained, well sorted, well rounded quartz grains indicate distinct maturity, and the absence of a clay or dolomitic matrix suggests effective winnowing. These chracteristics imply a shallow-water marine environment, an interpretation which—if valid—contrasts sharply with the setting of the underlying Yalco Formation—most of which is demonstrably continental in origin.

The other sedimentary features in the Stretton Sandstone are not particularly diagnostic of any specific environment. Ball-and-pillow structures indicate rapid deposition of sand on water-saturated substrates. They are common in deep-water turbidites, which commonly reflect rapid sedimentation (Pettijohn & others, 1972), but they are also known in fluvial and neritic shallow-water environments (Reineck & Singh, 1975; Conybeare & Crook, 1968).

The numerous tool marks, likewise, do not appear to be environmentally diagnostic: they are profuse in flysch, and in shallow-water sediments accumulating in environments subject to changes in water-level—for example, intertidal flats and flood plains. The marks are most likely to be due to the movement of shale clasts, which are well preserved in many sections of the Stretton Sandstone. We envisage a shallow-water environment adjacent to exposed flats from which the shale clasts were derived.

The facies accumulating on these flats could have been the fissile interbeds in the Stretton Sandstone, but we did not see much evidence of intraclasting of them in the field. The underlying Yalco Formation is full of polygonally cracked and desiccated dololutites, and therefore could have been a prime source for the intraclasts; however, none of the intraclasts in the Stretton Sandstone are cherty, and we interpret much of the Yalco Formation chert as having been deposited during very early diagenesis. The source of these intraclasts therefore remains a mystery.

The other sedimentary features present—mud-cracks, rippled coarse-grained sandstone interbeds, ripple-drift lamination, and one example of a channel—are typical of a wide-range of shallow-water environments.

The coarse conglomerate facies, however, can be more confidently interpreted as a typical proximal alluvial fan facies, clearly related by position and palaeocurrents to activity along the Emu Fault Zone. The sedimentary source of this facies was the uplifted Wearyan Shelf, immediately to the east of the fault zone. There is thus good evidence for an alluvial/fluvial environment near to the Emu Fault Zone, but we have been unable to establish whether the finer-grained flaggy facies is largely fluvial with some marine influence (favoured by MDM and KAP) or largely marine (favoured by MJJ).

Looking Glass Formation

The term Looking Glass Formation is here proposed for a unit of intensely silicified, commonly stromatolitic dolostone, intraclast conglomerate, and minor sandy dolarenite. The unit is essentially the same as that mapped by Smith (1964) throughout BAUHINIA DOWNS, but some rocks in the Top Crossing area that he mapped as the Looking Glass Formation are part of the Stretton Sandstone. The most conspicuous feature of the Looking Glass Formation is its intense silicification. In a few sections in the southern part of the Tawallah Ranges, silicified Stretton Sandstone has also been mistakenly mapped as the Looking Glass Formation.

The formation is named after Looking Glass Creek, which flows into Batten Creek at GR 047061 (*Batten*, 6065)—28 km north-northwest of McArthur mine .

Distribution and thickness

Like the other formations of the Batten Subgroup the Looking Glass Formation crops out in BAUHINIA DOWNS, in the southern half of MOUNT YOUNG, and in the extreme northeast of WALLHALLOW. It has a similar distribution to the Yalco Formation and Stretton Sandstone. In the type section, it is 63 m thick, which—as in most sections—represents a minimum for the original depositional thickness because the upper contact is erosional.

Type section

A measured section (Batten 79/01) in east central *Batten* (GR 994029), starting near the top of the Stretton Sandstone and intersecting the Looking Glass Formation and the unconformably overlying basal Nathan Group, is here nominated as the type section (Fig. 145).

Stratigraphic relations

The Looking Glass Formation appears to conformably overlie the Stretton Sandstone, although the contact is not exposed; in most sections containing the contact zone, discontinuous outcrop and float of flaggy sandstone is succeeded by float of chertified carbonate rubble. As noted above, the upper contact is erosional; in the Top Crossing area the Amos Formation overlies the Looking Glass Formation with erosional contact but apparent structural conformity.

Lithology

Everywhere it is exposed, the Looking Glass Formation is almost completely silicified. Even in drillcore (BMR Bauhinia Downs No. 4, GR 058451) it is almost totally silicified, and has a marked secondary porosity; in this drillhole solid and liquid hydrocarbons occur in vugs and pores at the top of the formation (Muir & others, 1980a).

Despite the silicification, careful examination of the formation in several poorly exposed sections and in drillcore has revealed a number of primary sedimentary structures. Most sections of the Looking Glass Formation are stromatolitic.

The original lithologies appear to have consisted of dololutite with chert nodules (in places slightly phosphatic), dolarenite and dolomitic quartz arenite (cross-bedded in places), intraclast conglomerate, and stromatolitic dolostone.

The stromatolites include: stratiform varieties; irregular domes up to 30 cm high and 30 cm in diameter; small columnar forms (synoptic height 0.5 cm, diameter 1–1.5 cm, column height 10 cm); complexes of small columnar forms growing on domal stromatolites and about the same size as the other columnar forms; and erect, inclined, and branching *Conophyton*-like and *Jacutophyton*-like forms.

Interpretation

The primary depositional environment of the Looking Glass Formation is difficult to discern because of the intense pervasive secondary silicification, which masks some structures and obscures details of lithological and textural relationships.

The predominance of stromatolitic carbonate suggests a lacustrine or peritidal shallow-marine environment.

The silicification of the Looking Glass Formation probably occurred during the weathering that affected the Amos Formation and effected the sub-Nathan Group unconformity. It is not a recent superficial phenomenon since the Looking Glass Formation is silicified also in drillcore.

During the course of this silicification and weathering, a coarse secondary porosity developed in the Looking Glass Formation in the Beetle Springs area, on the east side of the Abner Range. These secondary interstices now host solid and liquid hydrocarbons (Muir & others, 1980a). The source of the hydrocarbons is unknown, but is most likely to be organic-rich black shale in the Lynott Formation or in the Barney Creek Formation. This reservoir in the Looking Glass Formation is sealed by a mudstone at the base of the unconformably overlying Nathan Group.

Amos Formation

The term Amos Formation is here proposed for a unit of massive, karstically weathered dolostone with unusual pisolitic and stylolitic textures locally mapped at the top of the Batten Subgroup along the western side of the Abner Range. The low karstic outcrops of the formation on either side of the Tablelands Highway form strikingly unusual scenery (Fig. 146). The heavily jointed massive brownish grey dolostone with clint-and-grike surfaces is quite different from all other carbonate units in the McArthur Basin, with the possible exception of parts of the Mitchell Yard Dolomite Member of the Emmerugga Dolomite. Muir (1983a) has described the petrology of the dolostones and suggested that the Amos Formation is a calcrete.

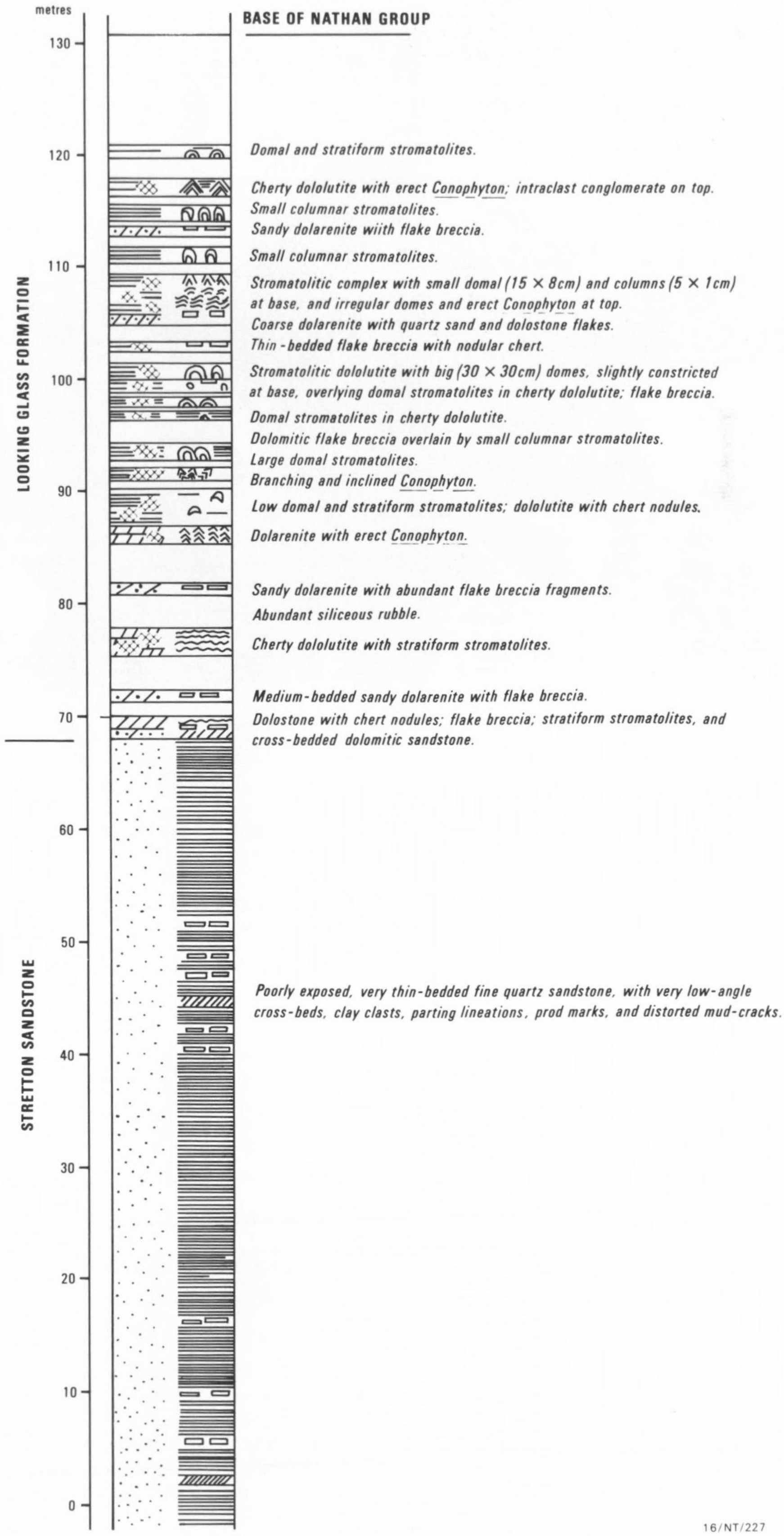

Fig. 145. Type section of the Looking Glass Formation (measured section Batten 79/01), 15 km west of Ryan Bend.

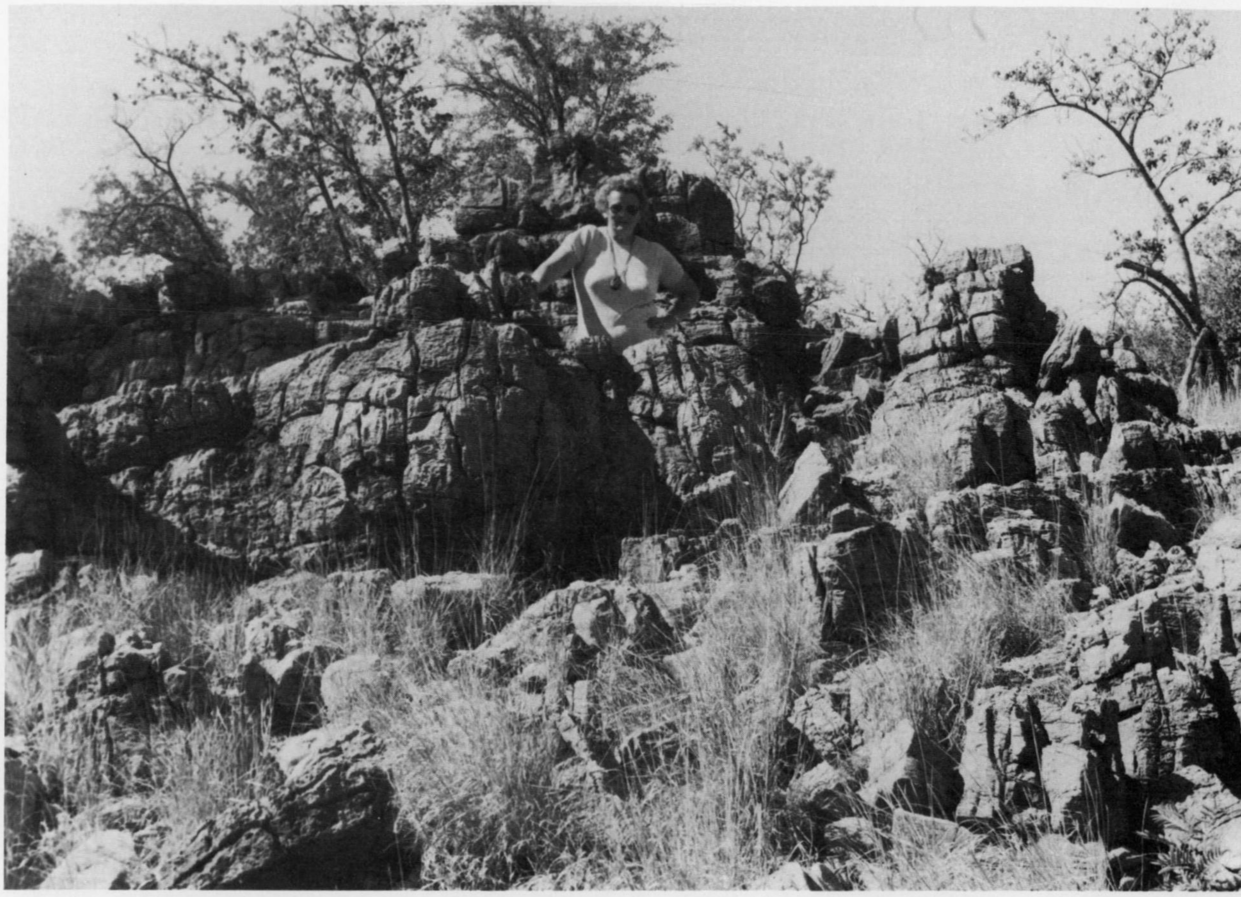

Fig. 146. Karstically weathered blocks of the Amos Formation from near the middle of the type section, near Top Crossing.

The formation is named after Amos Creek (GR 778512), a small tributary of the McArthur River that flows past outcrops of the formation 1 km north of Balbirini homestead.

end of its outcrop near Leila Creek (GR 790710), where these outcrops have been incorrectly labelled with the symbol Ṗmnh in Plate 1 .

Distribution and thickness

The Amos Formation is confined to a narrow north-trending belt of outcrops—30 km long—between the north-west end of the Abner Range and the southern end of the Batten Range (Plate 1). It has the smallest outcrop area of any of the formations in the McArthur Basin sequence. Unlike the other members of the Batten Subgroup, the Amos Formation has not been recognised along the eastern and southern margins of the Abner Range.

On the BAUHINIA DOWNS map (Smith, 1964), most outcrops shown as the Amos Formation are part of the Myrtle Shale; in the accompanying Explanatory Notes the Amos Formation is incorrectly shown as a laterally restricted facies in the lower part of the Emmerugga Dolomite. Plumb & Brown's (1973) revised stratigraphy corrected this, but they incorrectly included in the Amos Formation 63 m of fine-grained micaceous sandstone and siltstone belonging to the overlying Balbirini Dolomite.

The outcrops of the Amos Formation along the Tablelands Highway west of the Abner Range are critical for an understanding of the final events that took place in the evolution of the Batten Subgroup. The record of these events was removed in all other areas during the marked stratigraphic break indicated by a major unconformity at the base of the Balbirini Dolomite (Nathan Group).

The preserved thickness of the Amos Formation is about 90 m at the type section, and about the same at the northern

Type section

Measured section Mallapunyah 77/03—located in the Top Crossing area, 3 km south of Balbirini homestead—is here nominated as the type section (Fig. 147).

Stratigraphic relations

The Amos Formation concordantly overlies the Stretton Sandstone and Looking Glass Formation. It is unconformably overlain by the Balbirini Dolomite of the Nathan Group.

Lithology

At the type section (Fig. 147) the Amos Formation contains a number of rock types. Poorly exposed reddish purple ferruginous, micaceous, dolomitic thinly interbedded fine sandstone grading to siltstone, which is indistinctly cross-stratified and rippled, occurs in cycles near the base; its contact with the underlying Stretton Sandstone is not exposed. The siltstone interbeds commonly show dessication cracks. The tops of these cycles consist of discontinuous vuggy, mottled, and brecciated intervals up to 30 cm thick.

The basal beds are succeeded by interbedded redbeds and grey dolostones; the redbeds gradually diminish between about 30 m and 50 m (Fig. 147). Grey dolarenites and dololutites with quartz and chert granules, and beds of pink and

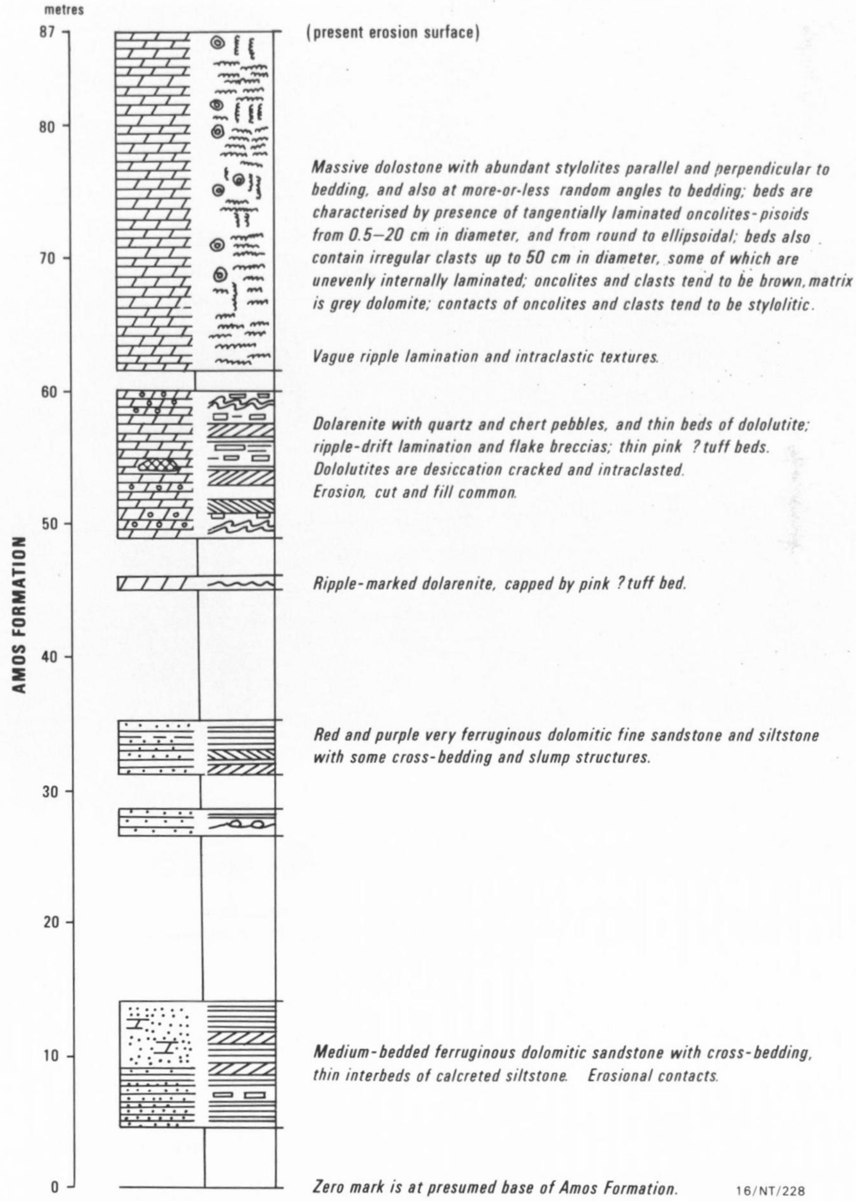

Fig. 147. Type section of the Amos Formation (measured section Mallapunyah 77/03), 3 km north-northwest of Top Crossing (from Jackson & others, 1978).

white chert, dominate between 50 and 60 m. Desiccation cracks and intraclasts in the dololutites are common; the dolarenites are cross-bedded and commonly graded, and contain ripped-up clasts of the dololutites (Fig. 148). Erosion of both chert (Fig. 149) and dolostone beds indicates several episodes of prolonged exposure.

Above about 60 m (Fig. 147) structures and textures gradually become diffuse, and massive recrystallised carbonates with stylolites predominate. Pisoids are apparent at about 68 m (0.5-3 cm in diameter), and increase in abundance and size (up to 20 cm) upwards (Fig. 150). Apart from the pisoids, the most striking feature of the upper part of the unit (70-87 m) is the abundant stylolites—parallel, oblique, and perpendicular to bedding. Many of the stylolites enclose 'clasts' containing vague laminations (original bedding), and pisoids commonly adjoin stylolites.

North of Leila Creek, the Looking Glass Formation is overlain by red dolomitic siltstone and grey dolarenite similar to the lower part of the Amos Formation at the type section. Between Balbirini and Leila Creek, the Amos Formation in some places appears to occupy the same stratigraphic level as the Looking Glass Formation, and the two formations were at first believed to be lateral (facies) equivalents. However, recognition of the disconformity below the Amos Formation at Balbirini suggests that this apparent lateral equivalence is better explained by the Amos Formation filling in hollows from which the Looking Glass Formation had been previously eroded.

The uppermost 20 m of the Amos Formation has been karstically weathered, and contains numerous solution features—such as karstic fluting, enlarged joints, caves, flowstones, and stalactites. The top surface of the formation is marked by a layer of ferricrete 2 cm thick.

Petrography

Samples from the upper 25 m of the Amos Formation at the type section consist of scattered grey-brown dolomitic pisoids in a paler grey dolomitic matrix. Stylolites abound, but appear to bypass or enclose pisoids rather than to cut through them (Fig. 151). The pisoids consist of a finely

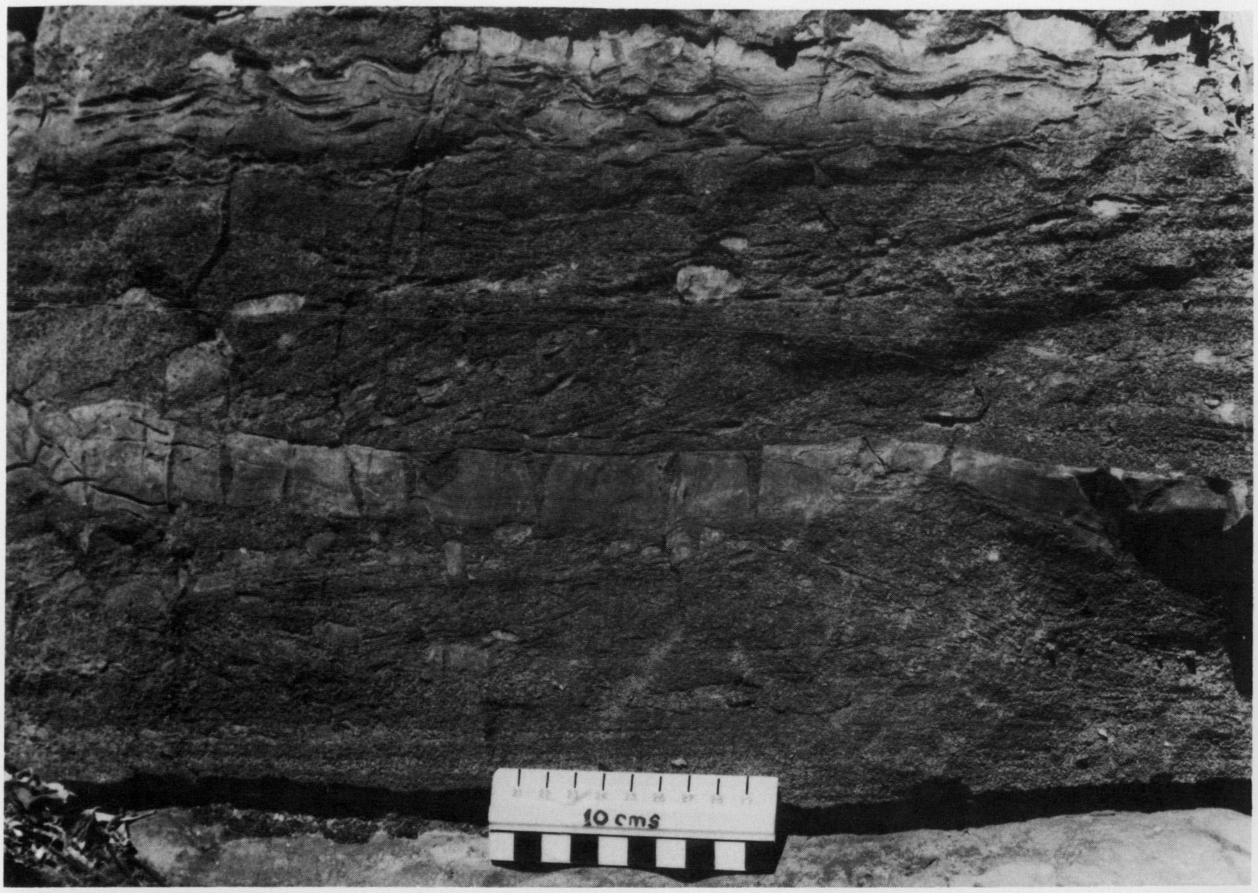

Fig. 148. Interbedded coarse-grained sandy dolarenite and dololutite in the Amos Formation at the type section. The upper layer of the dololutite is algal-laminated; the lower layer contains prominent desiccation cracks. The dolarenite is cross-bedded and contains rounded clasts of dololutite.

laminated outer zone with a micritic fabric surrounding a core which is generally sandy dolarenite. The matrix consists of much smaller pisoids, with thin overgrowths, and etched and embayed sand grains set in a micritic to sparry cement. Some of the grains are quartz, and others are carbonate sand; these, and the pisoids, appear to float in the carbonate matrix (see Watts, 1978).

All the rock samples examined are very ferruginous, and fine-grained hematite is common in all thin sections. Lamination in the Amos Formation is a product of colour-banding due to alternating iron-rich and iron-poor layers. In the stylolites, the cumulate is nearly all hematite. The laminated sediments in the stylolite-bound 'clasts' have some of the overall features of flat-laminated stromatolites, but the fabric of these laminations contains abundant peloids, even in columnar forms.

Interpretation

According to the literature, in particular Read (1976), the massive dolostones in the uppermost 30 m of the Amos Formation appear to fulfil some of the criteria that distinguish calcreted carbonates from stromatolitic and oncolitic sediments. The distinguishing criteria which can be observed in the Amos Formation include the following (after Read, 1976, and Muir, 1983).

(1) Calcretes develop in profiles characterised by vertical sequences of structures and fabrics. They show vadose diagenetic effects and in-situ brecciation. The profiles are formed by weathering processes in the vadose zone. Such weathering is inferred for the Amos Formation, whose sequence from unaltered dolarenite, through fractured and stylolitised recrystallised dolostone, to the brecciated pisoidal and stylolitic top of the formation has a great many features in common with the calcrete profile at Shark Bay (Read, 1976).

(2) Modern calcretes follow topography. This is difficult to demonstrate for the Amos Formation except on a microscopic scale.

(3) Modern calcretes contain micro-unconformities, which are abundant in the Amos Formation.

(4) Lamination in modern calcretes is due to colour-banding (ironstaining), as it is in the Amos Formation.

Thus the uppermost part of the Amos Formation appears to fit reasonably well some of the criteria used to distinguish calcretes from unaltered stromatolitic dolostones.

Below the level of extensive calcretisation (about 63 m at the type section) the original sedimentary structures and textures are more clearly visible, but environmental reconstruction is hindered by the discontinuity of the outcrop. Three main features are evident:

(1) down the section, the proportion of dolostone gradually decreases, and the red clastic material increases proportionately;

(2) deposition was mostly in very shallow high-energy environments that effected rapid fluctuations in current strength and lacked winnowing and sorting agents; and

(3) deposition was broken by several episodes of emergence and erosion.

An early clastic redbed environment with possible periods of soil formation (the vuggy brecciated zones at the tops of

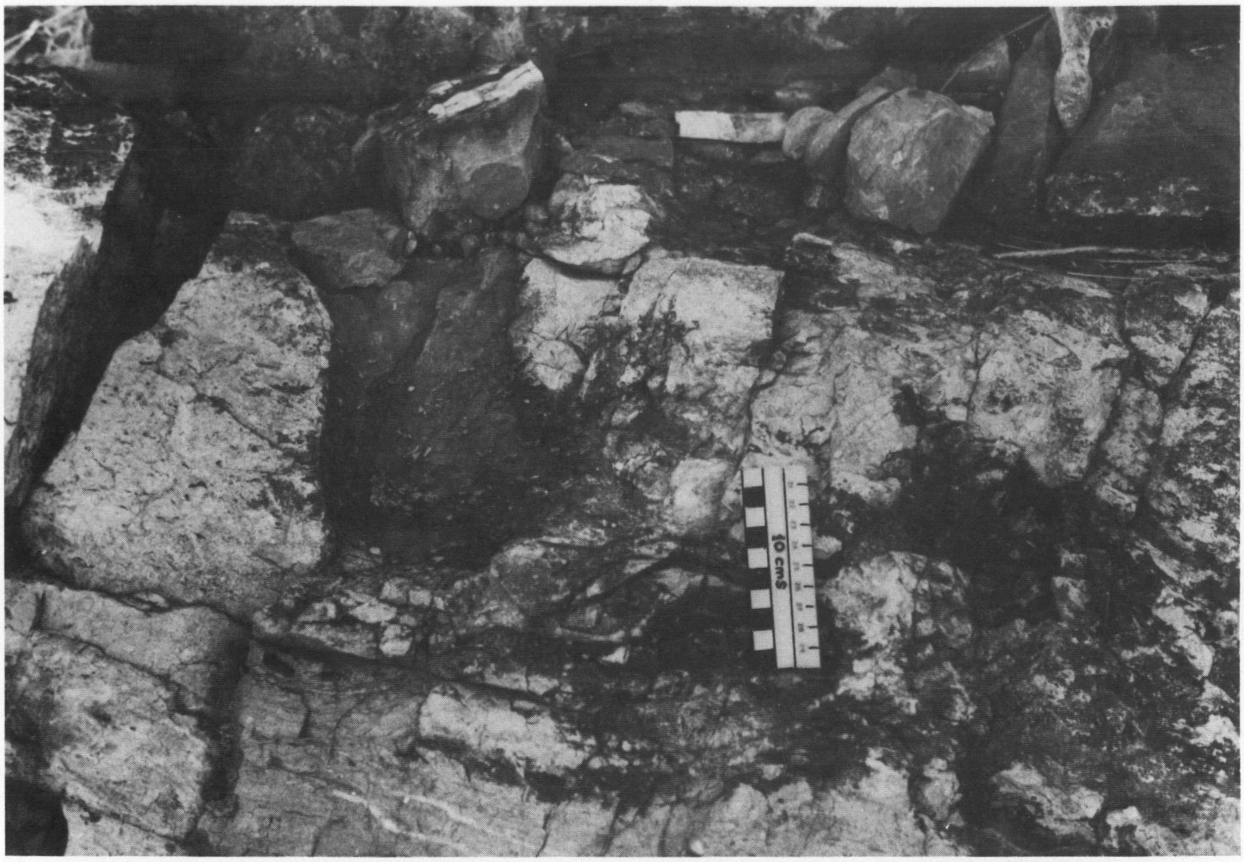

Fig. 149. A pot-hole in a white chert bed in the Amos Formation at the type section is filled with intraclastic sandy dolarenite. The relief on the erosion surface exceeds 20 cm.

Fig. 150. Typical appearance of the upper part of the Amos Formation at the type section: massive stylobrecciated dolostone (pale grey) containing scattered pisoids (a few centimetres to 20 cm).

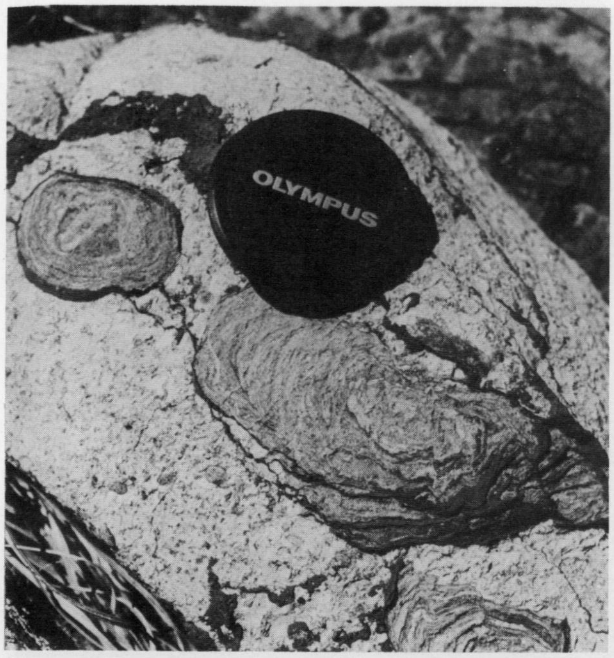

Fig. 151. Large vadose pisoids in the Amos Formation in the Leila Creek area. Note the relation between pisoids and dark grey stylolites, and the presence of small pisoids in the matrix. The diameter of the lens cap is 6 cm. (BMR negative M2551/20A)

upward-fining units near the base) was gradually replaced by a lacustrine or marginal-marine environment (mixed dolostones and clastics in the middle of the unit), which in turn was replaced near the top by a largely unknown environment—now represented by the thick calcreted dolostones formed during a prolonged period of erosion and deep weathering.

The pink beds are potassium-rich, and were originally interpreted as tuffs, similar to those in the Stretton Sandstone and Barney Creek Formation; however, limited follow-up petrographic studies have not provided convincing evidence of a volcanic origin, and an early diagenetic (?evaporitic) origin is possible.

NATHAN GROUP

The name Nathan Group is taken from the informal term 'Nathan subgroup', used by W.H. Johnson in the early 1970s to refer to the units described herein. The component formations of this group were previously included within the McArthur Group (Plumb & Brown, 1973). We have placed them in a separate group for two reasons: (1) a marked unconformity which defines their base has a wide lateral extent; (2) their depositional centres and tectonic controls of sedimentation are quite different from those of the formations in the McArthur Group.

The name is derived from Nathan River homestead in MOUNT YOUNG (GR 457776, *Mantungula*, 5966). The group crops out extensively in a north-trending belt to the west of the homestead, roughly along longitude 135°30′E.

The Nathan Group comprises the Balbirini Dolomite and Dungaminnie Formation. Plumb & Brown (1973) tentatively correlated units previously mapped in BAUHINIA DOWNS and MOUNT YOUNG—'Stott Formation', 'Kookaburra Creek Formation', and 'Mount Birch Sandstone'—with the Balbirini Dolomite and the 'Smythe Sandstone' (now incorporated as a member of the Balbirini Dolomite). This correlation has now been confirmed in sufficient detail that these names may be dropped, and the rocks of these units are included in the Balbirini Dolomite. Identification of diagnostic marker beds also permits tentative correlation of the Nathan Group with the Mount Rigg Group (Walpole & others, 1968) of western Arnhem Land. The new nomenclature and correlations are shown in Figure 152.

Regional unconformities separate the Nathan Group from the underlying McArthur Group and the overlying Roper Group. The Nathan Group is extremely variable in thickness, depending upon the extent of pre-Roper Group erosion. Its maximum thickness, 1600 m, occurs in BAUHINIA DOWNS at the northwestern end of the Abner Range.

The Nathan Group crops out extensively, but not universally, between the McArthur and Roper Groups in south central and western BAUHINIA DOWNS, in western MOUNT YOUNG, and in the Roper River area of southeastern URAPUNGA. It is locally absent from the sequence in western BAUHINIA DOWNS (around Lansen Creek), from southwestern BAUHINIA DOWNS (about Emmerugga Creek and the headwaters of McArthur River), and from eastern BAUHINIA DOWNS and MOUNT YOUNG (about Yalco Creek and farther north).

The type area for the group is along the northwestern side of the Abner Range.

BALBIRINI DOLOMITE

The term Balbirini Dolomite is here proposed for a unit of dolostone, mainly dolarenite, and minor dolomitic sandstone, dolomitic siltstone, potassium-rich mudstone, and volcanic rocks; stromatolites and pseudomorphs after gypsum, anhydrite, and halite are common sedimentary features. The unit was not recognised in the early mapping (Smith, 1964), being confused with the Emmerugga Dolomite and 'Billengarrah Formation'. It was first described by Plumb & Brown (1973), who recognised the regional extent of the basal unconformity but incorrectly included the lower arenites and evaporite unit of the Balbirini Dolomite in the underlying Amos Formation.

Our study has shown that an arenitic unit at the base of the Balbirini Dolomite in the type area correlates with the previously mapped 'Smythe Sandstone' in northern BAUHINIA DOWNS (Smith, 1964), and with the 'Mount Birch Sandstone' in MOUNT YOUNG (Plumb & Paine, 1964) and URAPUNGA (Dunn, 1963c). These are now incorporated into the Balbirini Dolomite as the *Smythe Sandstone Member* (the term 'Mount Birch Sandstone' is no longer used). Although the Smythe Sandstone Member and its equivalents have been identified in the south, they have not been differentiated in Plate 1.

The only other named member of the Balbirini Dolomite, the *Yalwarra Volcanic Member*, is best developed in the Roper River area (URAPUNGA; Dunn, 1963c)—outside the area covered by this Bulletin—where it consists of amygdaloidal basic volcanic rocks and minor breccia, tuff, and intercalated acid volcanic rocks and feldspathic arenites.

The Balbirini Dolomite is named from Balbirini homestead on the McArthur River (GR 788500). The Smythe Sandstone Member is named from Smythe Creek, a tributary of Clarke Creek, which joins Batten Creek in northern BAUHINIA DOWNS; it is best developed in this area. The Yalwarra Volcanic Member is best developed around Yalwarra Lagoon (GR 661728, *Urapunga*, 5868), from which the name is derived.

Distribution and thickness

The *Balbirini Dolomite* is exposed intermittently through the western part of the southern McArthur Basin—from the

WEST ARNHEM LAND	ROPER RIVER	LIMMEN BIGHT	BATTEN CREEK	TYPE AREA BALBIRINI HOMESTEAD
—	—	—	—	DUNGAMINNIE FORMATION (NATHAN GROUP)
MOUNT RIGG GROUP: BESWICK CREEK FORMATION				BALBIRINI DOLOMITE (NATHAN GROUP): Upper siltstones
				Recrystallised unit
				Stromatolitic unit
DOOK CREEK FORMATION	*Kookaburra Creek Formation*	*Kookaburra Creek Formation*	*Stott Formation*	Evaporitic unit
	YALWARRA VOLCANIC MEMBER			
BONE CREEK FORMATION	*Mount Birch Sandstone*	*Mount Birch Sandstone*	*Smythe Sandstone*	Smythe Sandstone Member
~~	~~~~~~	~~~~~~	~~~~~~	~~~~~~
MARGARET HILL CONGLOMERATE		BATTEN SUBGROUP	BATTEN SUBGROUP	BATTEN SUBGROUP
~~	~~~~~~	~~~~~~	~~~~~~	~~~~~~
	VIZARD FORMATION	UMBOLOOGA SUBGROUP	UMBOLOOGA SUBGROUP	UMBOLOOGA SUBGROUP

16/NT/229

Fig. 152. Revised nomenclature for the Nathan Group and associated units in BAUHINIA DOWNS, MOUNT YOUNG, URAPUNGA, and HODGSON DOWNS. Stratigraphic names in italics are no longer valid.

Roper River area in URAPUNGA, through MOUNT YOUNG and BAUHINIA DOWNS, to northern WALLHALLOW (locality map Plate 1).

It is thickest (ca 1500 m) in the Abner Range area, where it surrounds and is folded with the outlier of Roper Group and Cambrian rocks. Elsewhere its thickness is commonly reduced by pre-Roper Group erosion, and, in consequence, its lowermost beds are most commonly preserved.

The *Yalwarra Volcanic Member* is mapped only in URAPUNGA, where it has a maximum thickness of about 150 m to the east of Urapunga homestead. However, its equivalents have been recognised as thin brownish potassium-rich mudstones in MOUNT YOUNG and BAUHINIA DOWNS. The member has not been identified in WALLHALLOW.

The *Smythe Sandstone Member* is mapped in northeastern BAUHINIA DOWNS and through western MOUNT YOUNG to the Roper River area of southeastern URAPUNGA. It has a maximum thickness of about 180 m in the type area about Clarke Creek (Plumb & Brown, 1973), but more generally it is between about 15 and 65 m thick. It lenses out abruptly south of Batten Creek, though equivalent beds have been identified around the southern side of the Abner Range, but they have not been differentiated in Plate 1.

Despite the major unconformity between the Balbirini Dolomite and the Roper Group, the distribution of the two units is similar. The large outliers of Roper Group rocks are everywhere rimmed and underlain by the Nathan Group. In addition, the Nathan and Roper Groups tend to have been deformed by gentle drape-folding rather than by faulting, unlike the older rocks in the area.

Nevertheless, despite these similarities of distribution and tectonic response, the Balbirini Dolomite was intensely silicified and karstically weathered before the Roper Group accumulated. These secondary effects on the rocks of the formation led to large areas of the unit being incorrectly mapped as 'Billengarrah Formation'.

Type sections

Although Plumb & Brown (1973) introduced the name *Balbirini Dolomite*, they did not propose a type section for the formation. We propose that an area south of Balbirini homestead—between the Tablelands Highway and the McArthur River—be designated as the type area. Here, 890 m from the base of the formation was measured as section Mallapunyah 77/04 (Appendix Fig. A42) between GRs 787469 and 793474. The beds above this are not exposed but diamond-drillhole BMR Bauhinia Downs No. 3 (GR 867607)

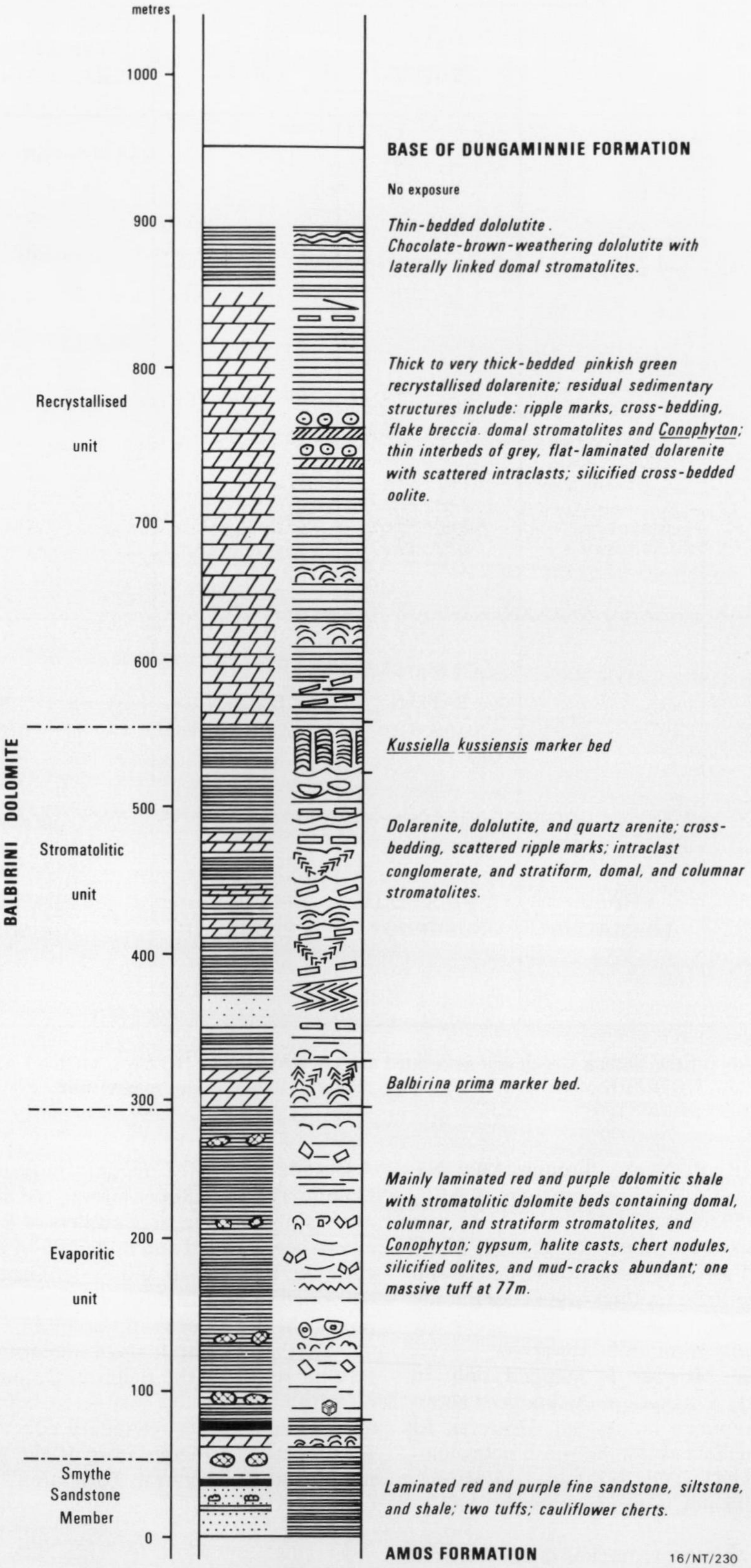

Fig. 153. Condensed and generalised exposed part of the type section of the Balbirini Dolomite (measured section Mallapunyah 77/04), near Balbirini homestead.

penetrated 150 m of redbeds between the topmost dolostone in section Mallapunyah 77/04 and the base of the Dungaminnie Formation. These two sections are together proposed as the type section; the exposed part—Mallapunyah 77/04—is summarised in Figure 153.

Dunn (1963c) did not propose a type section for the *Yalwarra Volcanic Member.* We propose a section near Yalwarra Lagoon (GR 661728, *Urapunga*, 5868) as the type section. We also propose a section at GR 913085 (*Batten*, 6065), about 1 km west of Clarke Yard, as the type section of the *Smythe Sandstone Member*; neither of these sections has been measured in detail.

Stratigraphic relations

The Balbirini Dolomite unconformably overlies the Batten Subgroup and, locally, the Umbolooga Subgroup, both of the McArthur Group. It is conformably overlain by the Dungaminnie Formation in the Abner Range area; elsewhere, it is unconformably overlain by the Roper Group.

Lithology

We have divided the Balbirini Dolomite into five separate units, of which two are formal members. The *Smythe Sandstone Member* at the base is generally about 40 m thick, but may locally reach 65 m around the Abner Range, where it consists largely of sandstone and conglomerate with chert boulders up to 40 cm in diameter derived from the underlying McArthur Group (Appendix Fig. A43). In most places, the matrix of these conglomerates is dolomitic, but in a few places it is a sideritic 'marble'. Elsewhere the member consists of slightly micaceous red siltstone and sandstone with thin (10 cm) beds and lenses of finer-grained chert-pebble conglomerate (Fig. 154). Lithic fragments in the fine-grained arenites are silicified, imparting a curiously whitish appearance to the rock despite the red matrix.

The Smythe Sandstone Member is succeeded by a unit informally referred to as the *evaporitic unit*, which includes most of the beds previously mapped as the 'Stott Formation' in the Batten Creek area, and the lower parts of the 'Kookaburra Creek Formation' and the Dook Creek Formation farther north.

The evaporitic unit, which is about 260 m thick, is characterised by red fine-grained sandstone, siltstone, and dolostone, and contains prominent beds of ripple-marked pink to orange-weathering potassium-rich mudstone (Fig. 155). Hopper halite casts, millet-seed (Fig. 156) and fibrous pseudomorphs after gypsum, small 'pearl' anhydrite casts, (Fig. 157), and botryoidal quartz nodules after anhydrite (cauliflower chert) are present in the fine-grained clastic and dolomitic intervals of this unit. Unusual rhombic moulds

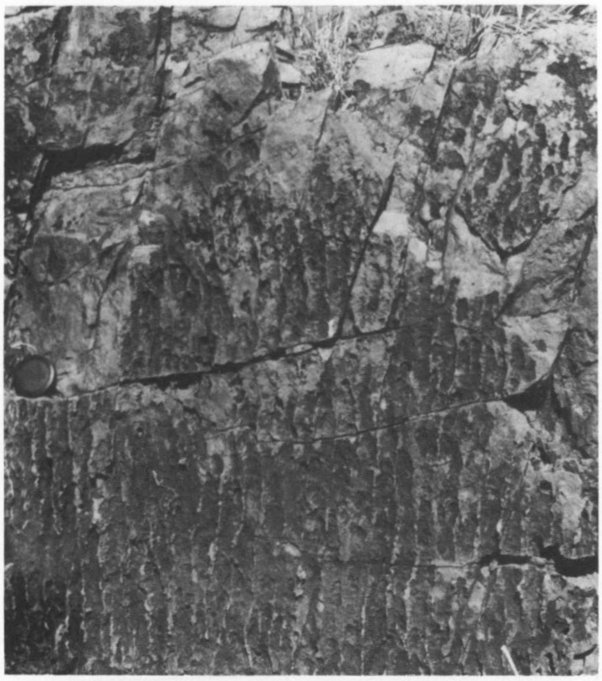

Fig. 155. Ripple-marked top of a pink potassium-rich mudstone in the Balbirini Dolomite along the Tablelands Highway 2 km north of the turn-off to Balbirini homestead. The diameter of the lens cap is 6 cm. (BMR negative M2552/12A)

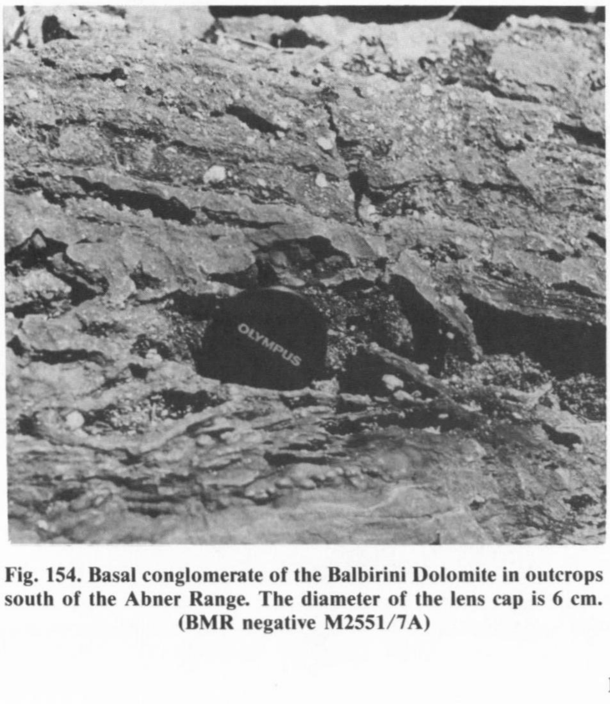

Fig. 154. Basal conglomerate of the Balbirini Dolomite in outcrops south of the Abner Range. The diameter of the lens cap is 6 cm. (BMR negative M2551/7A)

Fig. 156. Millet-seed gypsum crystal casts in fine-grained dolostone with chert nodules in the Balbirini Dolomite at the type section. (BMR negative M2551/21A)

(?shortite) are present in some of the potassium-rich mudstone beds. Thin, usually silicified oolite and stromatolitic dolostone are common near the top of the unit.

The potassium-rich mudstone beds, 1-1.5 m thick, are one of the most conspicuous features of the evaporitic unit. In places, thin red siltstone separates the mudstone into two or, rarely, three thinner beds. The mudstone has a conchoidal fracture, and is very fine-grained. It tends to break into blocks with 15 cm sides. The tops of these mudstone beds are conspicuously ripple-marked (Fig. 155), indicating subaqueous deposition and transportation.

The oolites in the evaporitic unit contain ooids which are commonly silicified. The concentric structure of the ooids is almost perfectly preserved. Each of the ooids appears to have formed on a nucleus of variable nature, and consists of alternations of organic-rich and organic-poor laminae, similar to those described by Davies & others (1978). In places, two or three small ooids are enclosed within a common envelope. Oolites also occur stratigraphically higher in the Balbirini Dolomite, especially in the north, where they are more abundant and thicker-bedded than in the south, and where they may prove to be useful stratigraphic markers.

Overlying the evaporitic unit is a *stromatolitic unit* comprising cyclic dolostone with stromatolitic markers at the base and top. The upper part of the old 'Kookaburra Creek Formation' and the upper part of the stratigraphically equivalent Dook Creek Formation of Arnhem Land are located in this unit, which is divided into upper and lower subunits in the north by the Yalwarra Volcanic Member.

The lower marker of this stromatolitic unit consists of the complex of stromatolites known as *Balbirina prima* (Walter & others, in press), which comprises (Fig. 158)—in sequence—(1) stratiform stromatolites 60 cm thick; (2) 30 × 30 cm domal stromatolites with scattered small cones; (3) about 40 cm of bushy branching columnar stromatolites which have a synoptic height of about 1 cm and columns about 2 cm wide and up to 25 cm high; (4) about 60-80 cm of branching *Conophyton*-like forms which have a synoptic height of 15-20 cm, a diameter of 10-15 cm, and a column height of up to 40 cm; and (5) stratiform stromatolites which contain a well preserved microfossil assemblage (Oehler, 1978).

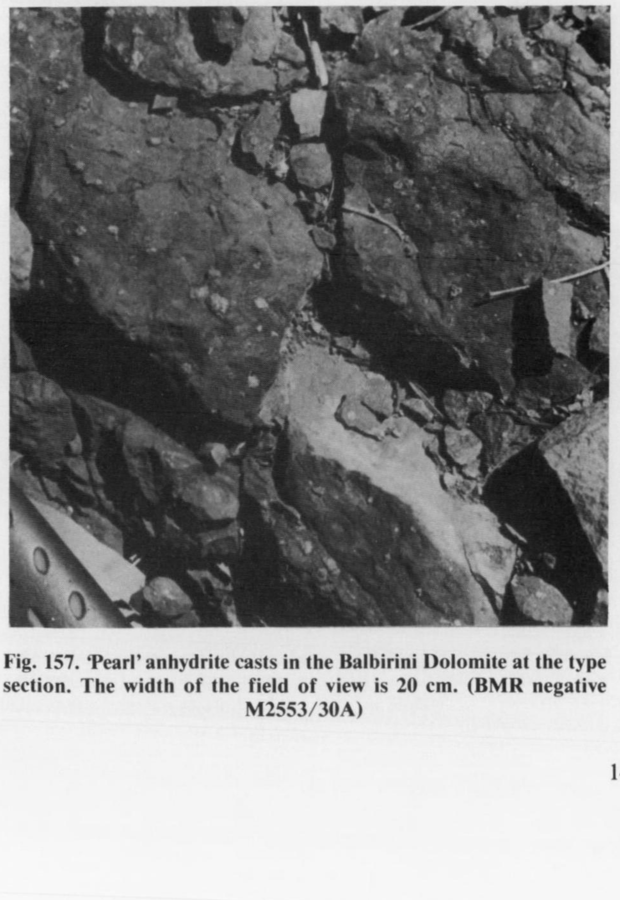

Fig. 157. 'Pearl' anhydrite casts in the Balbirini Dolomite at the type section. The width of the field of view is 20 cm. (BMR negative M2553/30A)

The stromatolite complex in the upper marker bed of this unit has been identified by I. Krylov (USSR Academy of Sciences, personal communication, July 1979) as *Kussiella kussiensis* Krylov. The total complex is 15 m thick in the type section. Its base comprises stratiform stromatolites capping intraclastic breccias, which are followed by cycles of bulbous domal stromatolites up to 50 cm diameter overlain by parallel branching columnar forms in very fine-grained dololutite laminae. The columns vary in size, but have a maximum column height of 60 cm, maximum diameter of about 6 cm, and maximum synoptic height of 3 cm. The domal-columnar sequence varies from place to place, but the cycle is repeated up to four times (Fig. 159).

The stromatolite marker beds are laterally very persistent: the *Balbirina prima* bed occurs in the type area, in the Batten Creek area, and in the Nathan River area; the *Kussiella kussiensis* bed has been mapped south of the Abner Range, at Eastern Creek (MOUNT YOUNG), north of Roper Bar police station (URAPUNGA), and in the Dook Creek Formation at Bulman mine in MOUNT MARUMBA (the 1:250 000 Sheet area immediately north of URAPUNGA).

The section between the two marker beds consists of algal-laminated dololutite, dolarenite, thin cross-bedded quartz arenite, intraclast conglomerates, rare stromatolites, thin oolitic beds (which are invariably silicified), and some evaporite casts, mainly after halite.

The *Yalwarra Volcanic Member*, which also occurs in the interval between the two marker beds, consists of amygdaloidal basic volcanic rocks in which amygdales up to 1 cm in diameter are frequently filled by a bluish green mineral tentatively identified as celadonite; quartz-filled amygdales are rare. Probable basic volcanic breccia and agglomerate, thin shardy tuffs, a few intermediate flows, and minor feldspathic sandstone and pebble conglomerate are interbedded with the basic flows. South of URAPUNGA, thin brown potassium-rich mudstones are probable equivalents of the member.

Overlying the stromatolitic unit is a *recrystallised unit*, comprising bluish grey dolostone that weathers to a pinkish grey, commonly mottled with green. It is developed only in the Abner Range area, and reaches a maximum thickness of at least 340 m. Its extensive recrystallisation obscures much of the original sedimentary textures and structures, which can be detected in places on weathered surfaces. These structures include intraclast conglomerates; quartz sand grains in dolarenite; conical, columnar, and domal stromatolites; wavy bedding; mud-cracks; rare gypsum casts; and more common halite casts. Silicified low-angle cross-bedded oolites in the upper part make useful marker beds.

The uppermost 30 m of this recrystallised unit weathers to a distinctive chocolate-brown, and has not been so severely affected by recrystallisation. It contains stratiform and columnar stromatolites, and a thin development of *Kussiella kussiensis* Krylov.

The base of the uppermost part of the Balbirini Dolomite is exposed only on a track leading due south from Balbirini homestead, where it consists of green thin-bedded fine-grained sandstone. Though no other natural exposures of the uppermost part of the unit are known, it was intersected in BMR Bauhinia Downs No. 3 drillhole (GR 867607), which was spudded into the Dungaminnie Formation and penetrated 150 m of red and green dolomitic fine-grained sandstone and siltstone with dolomite concretions.

Interpretation

The *Smythe Sandstone Member* is distinguished by its variability in grainsize and thickness. The variations are local and unpredictable. The conglomerates are usually unstrati-

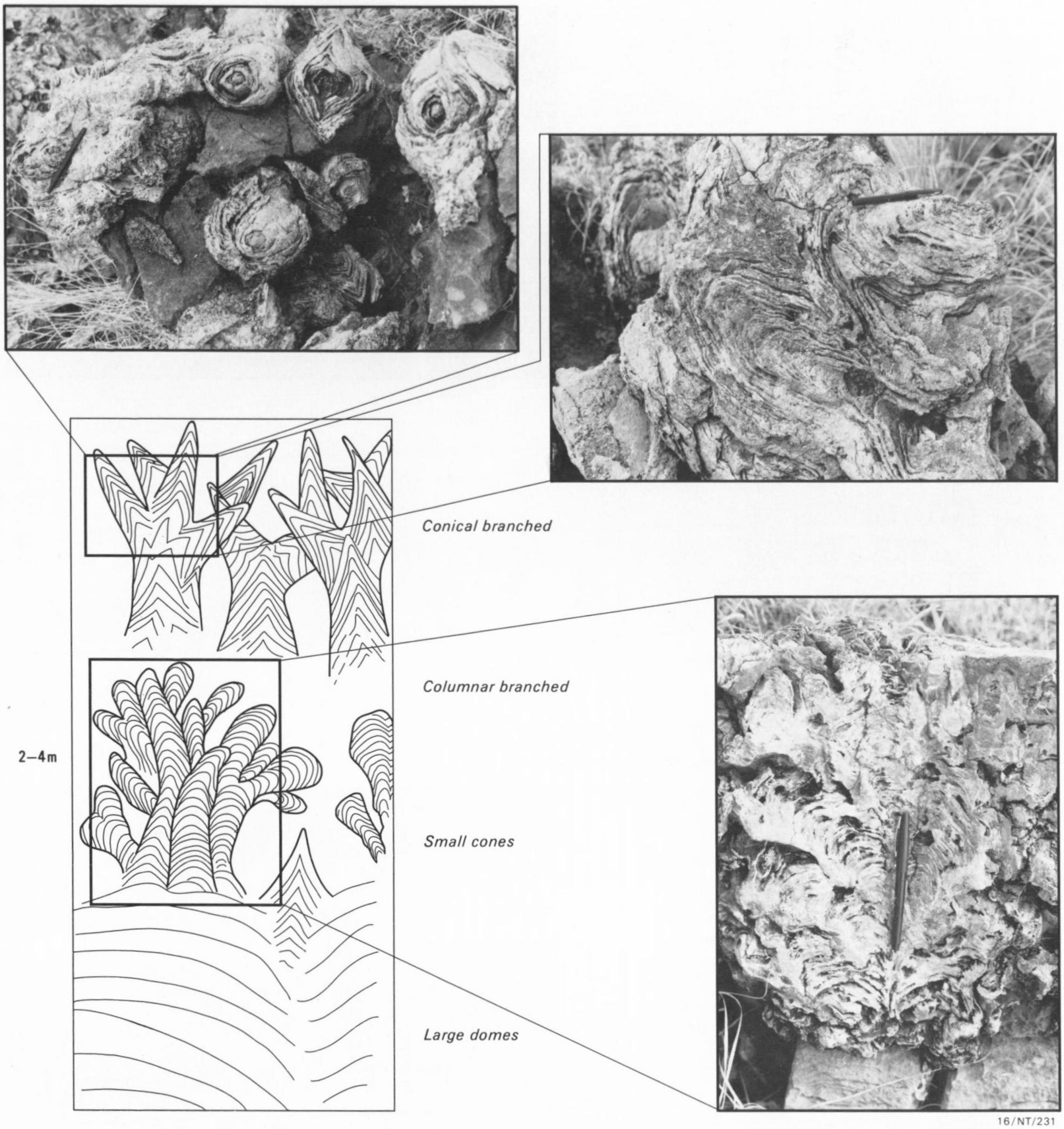

Fig. 158. Part of the *Balbirina prima* stromatolite biostrome in the Balbirini Dolomite at 300 m in the type section.

fied, though in places crude upwards-fining sequences are evident. The finer-grained arenites tend to be micaceous, and poorly sorted, with a few cross-beds at low angles, and parting lineations. These rocks are interpreted as alluvial fan and debris-flow deposits, grading into alluvial braided-stream deposits.

The matrix and cements are dolomitic, and the dolomite content is more abundant higher up in the unit. Some of the thin pebbly conglomerates in the upper part of the unit have a dolarenite matrix which accounts for about 50 per cent by volume of the rock. Thus the depositional environment in which these arenites were laid down was subaqueous and carbonate-precipitating.

The abrupt variations in grainsize and thickness may be due to the proximity of the depositional area to active fault scarps. The depositional environment of this basal arenite of the Balbirini Dolomite may have been analogous to those of the Cooley Dolomite and HYC Pyritic Shale Members of the Barney Creek Formation. The Smythe Sandstone Member, and the stratigraphically equivalent Bone Creek Formation of Arnhem Land, are widely distributed, indicating a period of widespread tectonism which marked the initiation of deposition of the Nathan Group.

The clasts in the Smythe Sandstone Member consist mainly of silicified carbonate. Unaltered carbonate clasts are much rarer, as are quartz arenite fragments and quartz grains in the finer-grained rocks. The carbonate and silicified carbonate clasts are derived from McArthur Group rocks, and the specific formation of origin can be identified for some. The provenance of the rare quartz arenite clasts is not clear: they are too massive to be derived from the Stretton Sandstone, but could be derived from either the Tatoola Sandstone or the Masterton Sandstone. The origin of the scattered mica in the fine sandstone is puzzling: although mica occurs in

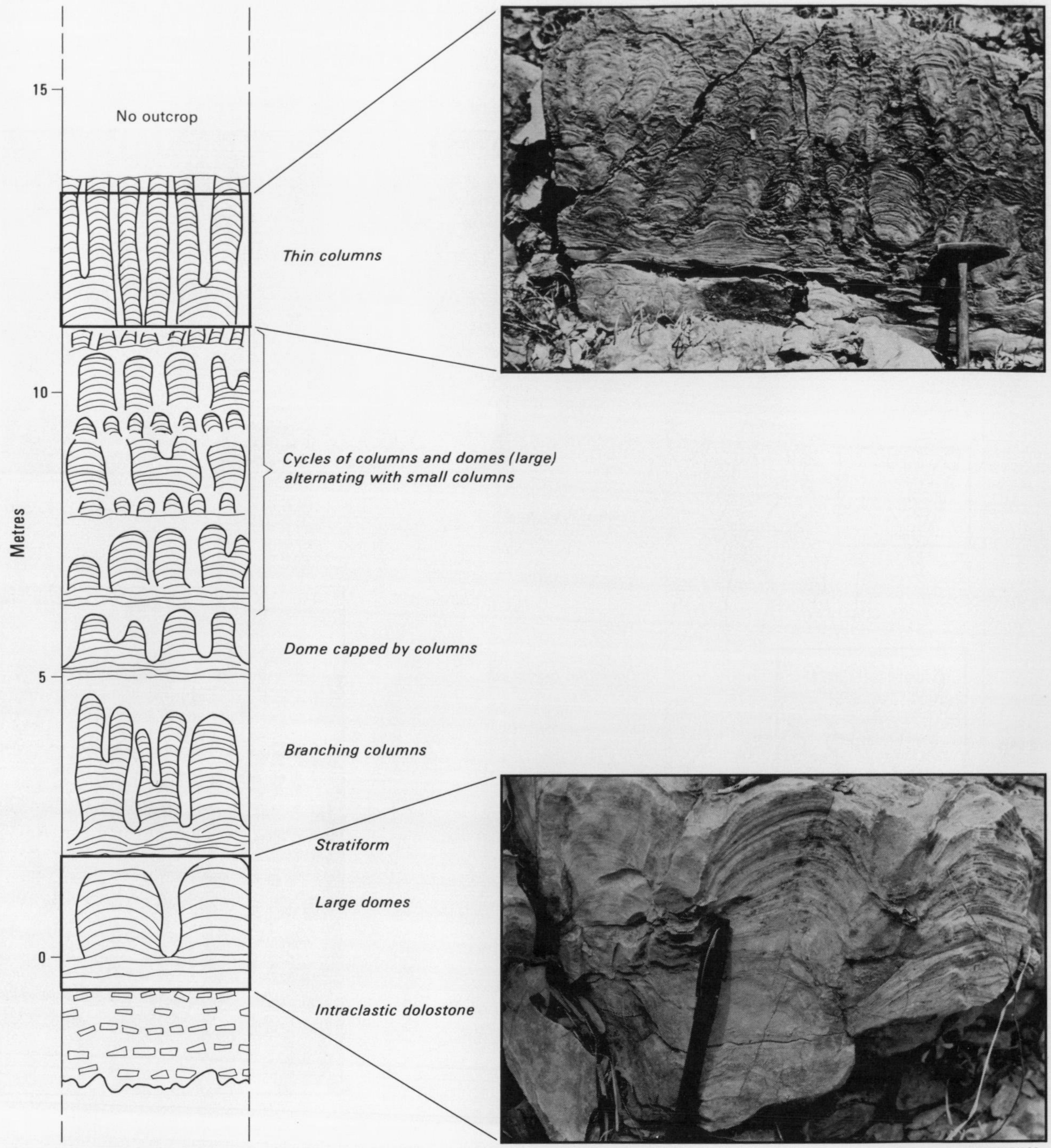

Fig. 159. Part of the *Kussiella kussiensis* stromatolite biostrome in the Balbirini Dolomite at 540 m in the type section.

the Stretton Sandstone in places, it is generally uncommon in the quartz arenites of the McArthur Basin, and the exposed basement rocks of the Urapunga and Murphy Inliers are too remote to be likely sources; the mica may be authigenic, but it occurs as ragged flakes along the bedding and cross-bedding, which suggests a detrital origin.

The *evaporitic unit* is characterised by redbeds and evaporite casts, of which the most abundant are four-sided hopper halite casts contained in thin flat-bedded fine-grained sandstone or siltstone interbedded with flat-laminated dololutite or dolomitic shale. These casts indicate that halite-saturated waters were repeatedly evaporated to dryness so that the sediment surface was exposed to the atmosphere. Repeated seasonal dehydration of shallow-water systems is a feature of lagoons in both continental playa and marginal-marine environments.

Sulphate evaporites occur in the forms of quartz and carbonate nodules after anhydrite, some of which are as small as 0.5 cm in diameter ('pearl' anhydrite—Prof. D.J. Shearman, Imperial College, London, personal communication, 1979), and gypsum crystal casts—some discoidal, some as millet seed gypsum, and some as chert veins replacing fibrous satin spar.

The nodules after anhydrite may be hosted either by red arenites, or by dolostones. They all possess the felted lath texture of blade-like anhydrite crystals on their outer surfaces and as an internal texture. Most are preserved as quartz, but some (unusually for the McArthur Basin) are preserved as carbonate. The nodules originate by precipitation from groundwaters in a sabkha environment—similar to those interpreted for the Mallapunyah Formation.

The discoidal gypsum casts, which occur in fine-grained quartz arenite and dololutite, are identical with those in the Mallapunyah Formation and Amelia Dolomite, and also formed in the littoral zone of a sabkha. Whether the sabkha in which we interpret these deposits accumulated was marginal to a lake or the sea cannot be determined from the present information, but, in the marginal-marine setting of the Abu Dhabi sabkha in the Persian Gulf, both anhydrite and discoidal gypsum precipitate from continental groundwater moving to the sea (Patterson & Kinsman, 1981)—that is, they are totally non-marine in origin.

The millet-seed gypsum casts, which occur in only one bed—a dololutite about 1 m thick at about 85 m in the type section, are elliptical in cross-section, and have a cleavage parallel to the long axis. They are totally silicified, and are associated with veinlets up to 0.5 cm thick of chert with a marked cross-fabric identical with that of satin spar. The morphology of the millet-seed casts is identical with that of gypsum precipitating today in Marion Lake (South Australia) and we envisage a similar origin of precipitation from the waters of a wind-agitated brine pond.

The cross-fibre veinlets associated with the millet-seed gypsum casts are interpreted as products of compaction and dewatering of the dololutite during diagenesis. They are identical with satin spar veins from the so-called 'beef' beds of Dorset, England, described by West (1964).

The potassium-rich mudstone beds are characterised by the presence of irregular rhomboidal crystal casts whose morphology in hand specimen is identical with that of shortite ($Na_2CO_3.CaCO_3$) from the Green River Formation (Eocene) of Colorado (Fahey, 1962). The presence of these crystal casts is critical to an environmental interpretation of the evaporitic unit: since shortite cannot be precipitated by the evaporation of sea water, its possible presence in the potassium-rich mudstones implies a continental origin for the rocks of the evaporitic unit of the Balbirini Dolomite.

The mudstone beds may have a similar origin to shardy tuffs that accumulated in Lake Tecopa, a trona-shortite-precipitating Pleistocene lake in the Amargosa Valley (USA). Sheppard & Gude (1968) have demonstrated that groundwater reactions have progressively altered the fresh tuff in Lake Tecopa to a zeolitic tuff and finally to a pure potassium feldspar or potassium feldspar-searlesite (sodium borosilicate) rock containing no trace of the original shards.

The remaining lithologies of the evaporitic unit are red, purple, and khaki mudstones; stratiform, domal, columnar, and conical stromatolites; and fine-grained silicified oolites. None of these lithologies is incompatible with the continental origin suggested by the evaporites.

The lithology of much of the *stromatolitic unit* (except the Yalwarra Volcanic Member) is similar to that of the evaporitic unit, and can be interpreted in a similar manner. More detailed descriptions and interpretations of the origin of the two stromatolitic biostromes are presented by Walter & others (in press).

Although the *Yalwarra Volcanic Member* originatd as lava flows and pyroclastics, there is no evidence of vents or feeder dykes. The feldspathic sandstone and conglomerate interbedded with the volcanics may be locally derived from the Urapunga Inlier, and may indicate renewed tectonic (?fault) activity in the area at this time.

The overlying unit, the *recrystallised unit*, has been so intensely recrystallised by vadose alteration—possibly in pre-Roper Group times—that it is difficult to interpret. Its residual sedimentary structures liken it to the evaporitic unit, and a similar depositional environment is tentatively suggested for it.

Dungaminnie Formation

The term Dungaminnie Formation is here proposed for a unit of siltstone, fine-grained quartz sandstone, and stromatolitic and detrital dolostones. Rocks of the unit were originally mapped as part of the 'Billengarrah Formation' north and west of the Abner Range (Smith, 1964). The unit was first described by Plumb & Brown (1973), who—in an unfortunate typographic error (table 2, p. 108)—described the formation as unconformably overlying the Balbirini Dolomite.

The formation name is derived from Dungaminnie Creek, which joins Mallapunyah Creek about 8 km south-southeast of Top Crossing.

Distribution and thickness

The Dungaminnie Formation is exposed only in BAUHINIA DOWNS, and is confined to the syncline around the northern end of the Abner Range between Top Crossing in the south, Leila Creek to the north, and the Kilgour River to the east.

In the type section, the thickest measured section, 240 m, is preserved.

Type section

Although Plumb & Brown (1973) introduced the name Dungaminnie Formation, they did not propose a type section for the formation. We propose that measured section Mallapunyah 77/06 (Jackson & others, 1978), between GRs 779552 and 785542, 5 km north of Balbirini homestead be designated as the type section (Fig. 160; Appendix Fig. A44). A partial section of the formation measured 7 km southeast of the type section—Mallapunyah 77/05 (GR 793488)—is nominated as a reference section (Appendix Fig. A45).

Stratigraphic relations

The Dungaminnie Formation overlies the Balbirini Dolomite conformably, and is unconformably overlain by the Roper Group.

Lithology

The lower part of the Dungaminnie Formation (0 to 140 m in the type section, Fig. 160) consists of poorly exposed thin to thick-bedded quartz sandstone. It is mainly flat-bedded though some beds have very low-angle cross-lamination and others are ripple-marked. Striking slump and dewatering structures are exposed along the south side of the road leading to the McArthur River homestead at about the middle of this interval. Interbedded siltstone, granule conglomerate, and dolomitic rocks are evident in the type section (Fig. 160).

The upper part of the formation (140 to 245 m, Fig. 160) consists of dololutite and dolarenite containing stratiform, domal, and conical stromatolites. Flat lamination, intraclastic and oolitic textures, and rare evaporite pseudomorphs are evident in the type section.

A visually striking *Conophyton*-like biostrome about 2 m thick is present at about 150 m in the type section. The biostrome has a sharp planar base, and appears to have a gradational top, although the upper contact is not well

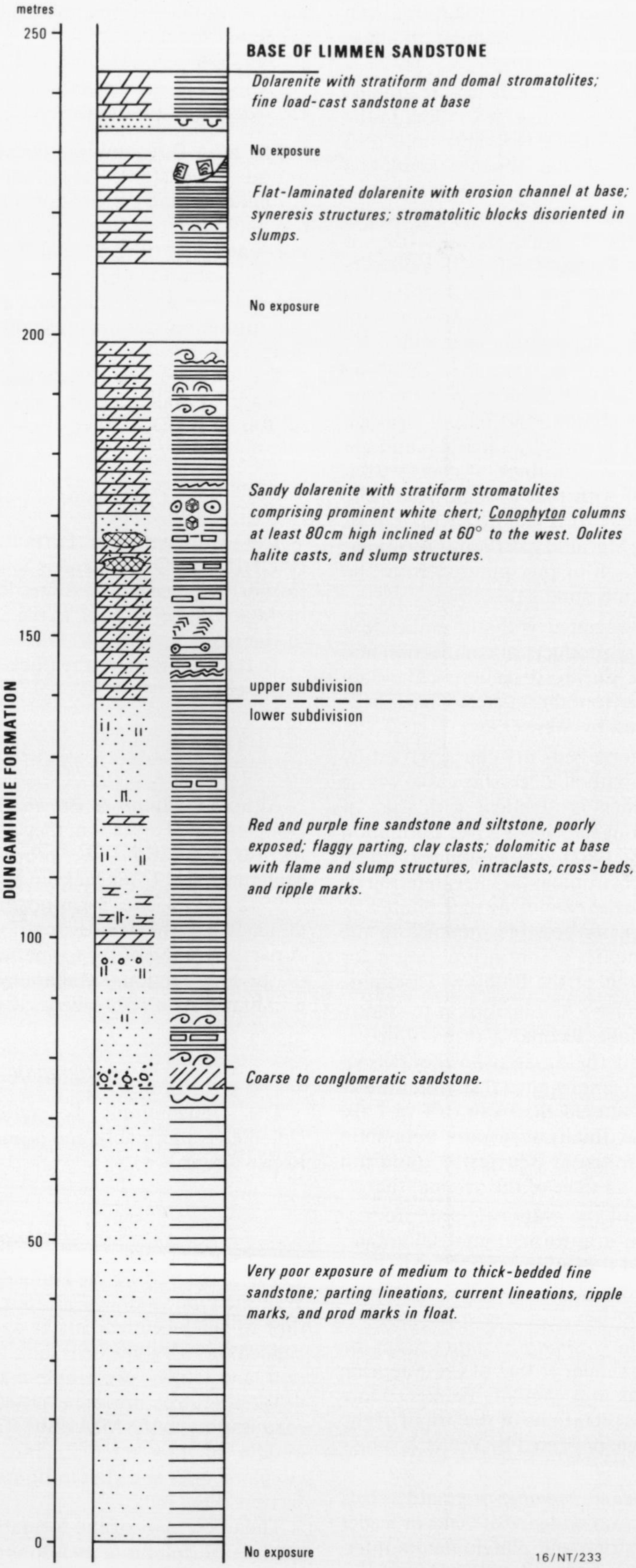

Fig. 160. Generalised type section of the Dungaminnie Formation (measured section Mallapunyah 77/06), east of Balbirini airstrip.

exposed. It rests on a discontinuous breccia bed which infills hollows in an irregular eroded surface at the top of the underlying silty dolostones. These dolostones are mostly flat-laminated, but ripples-in-drift, intraclast breccias, desiccation cracks, and chert evaporite pseudomorphs indicate that the sediments were deposited under shallow-water high-energy conditions before they were exposed and eroded. Individual cones in the biostrome are circular, oval, or tear-shaped in plan; the plane of symmetry in the non-circular forms trends southwest, and the pointed ends of the tear-shaped stromatolites are inclined to the northeast. The individual cones have a uniform size, and a maximum diameter of about 25 cm. Inter-column spaces comprise either fine-grained dololutite or intraclastic debris. Unlike most other specimens of *Conophyton* in the McArthur Basin—which grew vertically—these forms all lean uniformly in one direction; with bedding restored to horizontal, this attitude is 60° (from the vertical) towards the west and southwest (Fig. 161).

Except for the breccia bed the dolostones overlying the biostrome appear to be similar to those below it; sandy dolarenites predominate but thin interbeds of dololutite with stratiform and small domal stromatolites are present. Between 171 and 174 m the rocks are distinctly sandy and oolitic, and contain large halite casts. The only other notable feature in the uppermost part of the formation is a channel (1 m deep × 30 m wide) at 225 m, which contains disoriented clasts of stromatolitic dolostone in slumped dololutite. The channel is cut into fissile thin-bedded dolarenite which contains dewatering structures.

Interpretation

Detailed studies of the Dungaminnie Formation have not been undertaken yet, so only a few generalisations are suggested here. The slump and dewatering structures imply that the lower arenitic unit was deposited more rapidly, and possibly in slightly deeper water, than the Balbirini Dolomite. The presence of granular conglomerates and intraclasts, however, indicates periods of high energy.

Conditions of deposition for the upper dolomitic part of the formation were probably similar to those of the evaporitic unit of the Balbirini Dolomite. The curious attitude of the *Conophyton* is explained by assuming that they leant towards the sediment source, and hence into the prevailing currents. In the absence of features indicative of fluvial environments the channel containing large disoriented blocks of stromatolitic debris may be of tidal-channel origin.

KARNS DOLOMITE

The Karns Dolomite (Yates, 1963; Roberts & others, 1963) is a unit of cherty dolostone, quartz and dolomitic sandstone, siltstone, and oolitic and chamositic dolostone, with abundant evaporite casts. It crops out to the east and south of the Bukalara Plateau in ROBINSON RIVER and CALVERT HILLS. Although we did not make a special study of the formation, we present below a description of it based on two sections that we measured, and on data from open-file reports by Australian Geophysical Pty Ltd (1967, 1968, 1970).

Distribution and thickness

The Karns Dolomite crops out extensively in ROBINSON RIVER, and east of the Bukalara Plateau and north of the Calvert Fault in CALVERT HILLS (part of Ṗm in the locality map, Plate 1). In most places, exposure is poor and the outcrop area of the formation is identified by cherty, dolomitic, oolitic, and stromatolitic rubble.

The upper part of the formation has been stripped by erosion, so the thickness of about 130 m that Roberts & others (1963) estimated must be regarded as a minimum for the formation. Near Calvert Hills homestead it is about 100 m thick, but near the Foelsche River (ROBINSON RIVER) it is possibly 250 m thick.

Fig. 161. Part of inclined *Conophyton*-like biostrome in the Dungaminnie Formation at the type section near Balbirini airstrip. The inclination of the individual stromatolite forms is indicated by the resistant central part of the cone next to the scale (in centimetres). The shaft of the geological pick is vertical, and the notebook lies along the regional bedding.

Type and reference sections

Neither Yates (1963) nor Roberts & others (1963) defined a type section for the formation. We propose that the incomplete measured section Pungalina 79/01 at the Borroloola to Doomadgee Mission road-crossing of the Calvert River (GR 520265, *Pungalina*, 6364) be designated as the type section (Fig. 162). A second easily accessible measured section (Calvert Hills 81/03) in the lower part of the Karns Dolomite on the Little Calvert River 6 km southwest of Calvert Hills homestead (GR 433896, *Calvert Hills*, 6363) is suggested as a reference section (Fig. 163). Unfortunately, both sections contain only the lower part of the formation.

Stratigraphic relations and correlations

The Karns Dolomite unconformably overlies the Masterton Sandstone, which formed an irregular base—apparently a land surface with a relief of about 100 m—on which the Karns Dolomite accumulated. The Karns Dolomite was deposited in valleys between hills formed of the Masterton Sandstone; these depositional relationships are still evident today.

The Karns Dolomite is unconformably overlain by the Limmen Sandstone of the Roper Group. According to Australian Geophysical Pty Ltd (1967) it is also overlain by the Bukalara Sandstone near Calvert Hills homestead; however, the description of the so-called Bukalara Sandstone in this report—grey to white medium-grained cross-bedded sandstone whose basal part is marked by coarse-grained sandstone containing numerous pebble bands—sounds much more like the basal Limmen Sandstone than the Bukalara Sandstone. The Karns Dolomite is unconformably overlain by normal reddish arkosic Bukalara Sandstone in ROBINSON RIVER.

In CALVERT HILLS, the Karns Dolomite crops out only north of the Calvert Fault. Roberts & others (1963) included both their 'Fickling Beds'—now incorporated (as the Walford Dolomite, Mount Les Siltstone, and Doomadgee Formation)

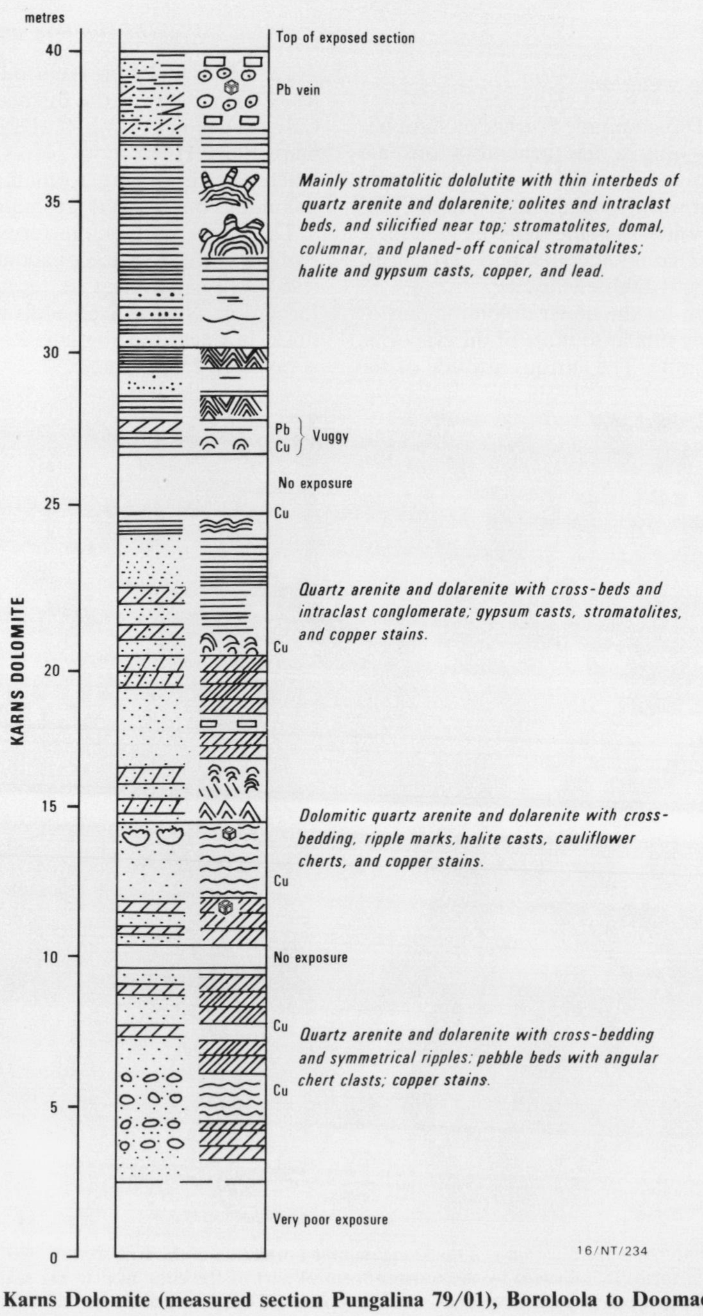

Fig. 162. Type section of the Karns Dolomite (measured section Pungalina 79/01), Boroloola to Doomadgee Mission road-crossing.

in the upper part of the Fickling Group (Sweet, 1981)—south of the Calvert Fault and the Karns Dolomite north of this fault in the McArthur Group. Plumb & Sweet (1974) correlated the Fickling Group (then as the 'Fickling Beds') with the McArthur Group because stratigraphically equivalent sandstones occupy the bases of both: the Masterton Sandstone of the McArthur Group, and the Fish River Formation of the Fickling Group. A unit at the top of the Fickling Group (the manganese-rich arenite-carbonate-chert-bearing Doomadgee Formation) appears to be disconformable in places below the Mount Les Siltstone (Sweet & others, 1981), and may correlate with the Karns Dolomite.

Although the Karns Dolomite may be an attenuated McArthur Group equivalent, correlations between the two are difficult, even where the distance between the outcrops of the two formations is as little as 15 km (southeastern ROBINSON RIVER). Instead, the Karns Dolomite may correlate with the Balbirini Dolomite, which unconformably overlies the McArthur Group. Lithological, geochemical, and metallogenic similarities between these formations support this correlation: (1) the combination of basal arenite overlain by evaporitic and stromatolitic carbonates in the Karns Dolomite is identical with the lower part of the Balbirini Dolomite; (2) both are anomalously high in manganese, and contain small uneconomic residual deposits of pyrolusite and rhodochrosite; and (3) both are hosts to coarse-grained lead (with minor copper) mineral deposits (Eastern Creek and Bulman mines in the Balbirini Dolomite, and numerous small occurrences in the Karns Dolomite).

Lithology

This description of the Karns Dolomite is based mainly on the type section (Fig. 162).

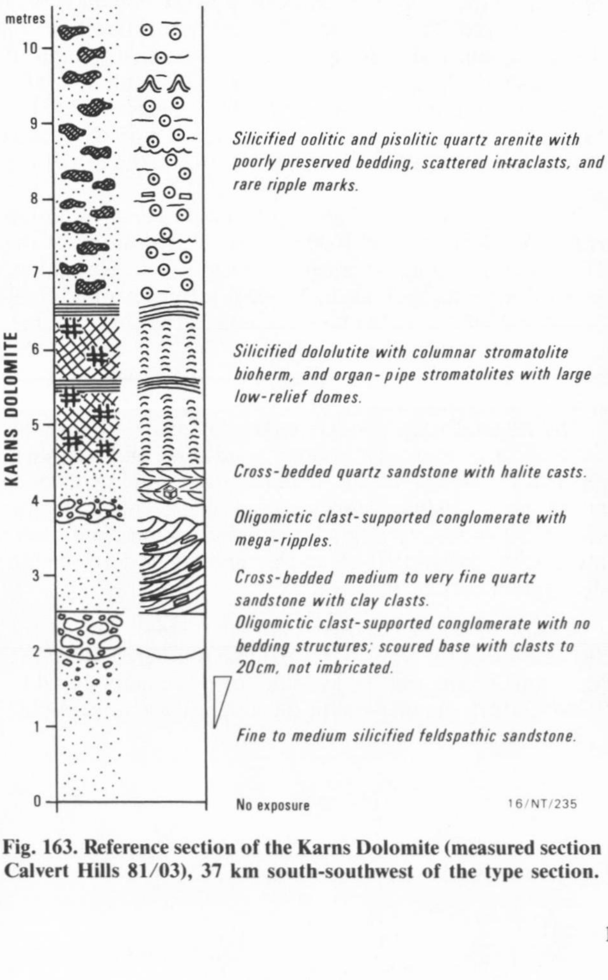

Fig. 163. Reference section of the Karns Dolomite (measured section Calvert Hills 81/03), 37 km south-southwest of the type section.

The lowermost part of the formation—a basal unit with a maximum thickness of 10 m—is lithologically quite variable, being controlled by the topography of the underlying Masterton Sandstone on which it was deposited. The initial sedimentation was largely of coarse clastics—conglomerate, grit, and quartz arenite (with angular chert fragments)—but dolarenite and minor dark grey shale are also present. Features of this basal unit include stromatolites, medium to thick bedding (both planar and cross), ripple marks (mainly symmetrical, some with planed-off tops), and local malachite staining. The following unit comprises about 5 m of cross-bedded dolarenite with interbedded medium to coarse-grained cross-bedded and rippled quartz arenite. Small domal stromatolites, halite casts, and cauliflower chert nodules occur in the dolomitic beds.

The overlying unit—about 13 m thick—consists of coarse to fine quartz arenite, with gypsum casts, interbedded with thin-bedded fissile dolarenite containing intraclast conglomerate and stromatolites (both domal and conical forms). The arenite is flat-bedded or cross-bedded, contains rare ripple marks, and is locally malachite-stained; fine chalcopyrite is disseminated in the dolarenite.

The succeeding unit, at least 13 m thick, contains thin beds of dololutite alternating with shaly or silty dolostone. Conical and domal stromatolites and oolitic and intraclastic beds are common. At two levels the upper parts of *Conophyton* biostromes have been planed off by erosion before the overlying beds were deposited (Fig. 164). The domal stromatolites are linked hemispheres with small pseudocolumnar stromatolites growing on top of them; they commonly contain gypsum pseudomorphs (Fig. 165). The oolitic dolostone is silicified and usually associated with intraclast conglomerate. Disseminated fine-grained galena, and coarser-grained galena in veins and vugs—in places associated with hydrocarbons—occur in this part of the formation at several localities.

The uppermost beds of the Karns Dolomite (not exposed in the type section) consist of thin-bedded purple, khaki, and

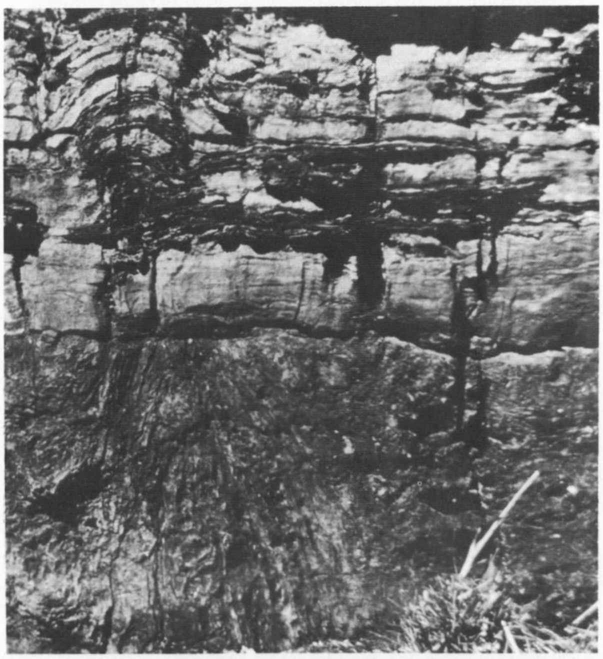

Fig. 164. Vertical section through about 60 cm of stromatolitic dolostone at 28 m in the type section of the Karns Dolomite. *Conophyton* in dark grey dolostone (lower half of photo) has been eroded (?wave-cut platform) before deposition of the overlying dolostones with domal stromatolites. (BMR negative M2573/6A; photo courtesy of Neil Williams.)

Fig. 165. Small gypsum crystal pseudomorphs in laminated dolostone of the Karns Dolomite at its type section. (BMR negative M2573/5A; photo courtesy of Neil Williams.)

dark green silty dolostone, dolomitic siltstone, shale, and chamositic siltstone.

The reference section also contains mixed clastic and carbonate facies. A lower cross-bedded feldspathic sandstone with cobble beds is succeeded by a cherty stromatolitic unit which is overlain by oolitic intraclastic arenites (Fig. 163). The stromatolites are unbranched columnar forms (about 1 cm diameter) at least 1 m thick in the lower part of the bioherm, and broad domal forms in the upper part. A prominent north-south elongation of the bioherm is evident.

Interpretation

Owing to the small amount of information available, interpretations of the depositional environment of the Karns Dolomite are tentative. Even so, the stratigraphic succession at the few outcrops examined indicates that abrupt facies changes are diagnostic of the unit, implying a variety of complexly interfingering environments.

The lowermost clastic unit represents a local infill of topographic lows in the landscape developed in the Masterton Sandstone. The common occurrence of gypsum and halite casts higher up in the formation indicates hypersalinity, and cauliflower cherts are the products of a sabkha-like environment. Planed-off stromatolite bioherms testify to emergence and erosion. Thus—as for most formations in the McArthur and Nathan Groups—extremely shallow-water to emergent hypersaline environments can be inferred.

The lithological differences between the two measured sections may be explained by reference to local syndepositional topography: stromatolitic bioherms probably developed on the less steep basement slopes, while coarser debris accumulated on the steeper slopes (Australian Geophysical Pty Ltd, 1967).

The fine-grained disseminated copper and lead are penecontemporaneous with sedimentation, although they may have crystallised during early diagenesis. The coarse minerals in the cross-cutting veins and those in the vugs precipitated later; they may have been formed by the remobilisation of the syndepositional minerals, or by the introduction of ions from an extraneous source.

ROPER GROUP

The Roper Group, the youngest part of the Proterozoic McArthur Basin sequence, crops out extensively from about latitude 17°S to northern Arnhem Land. It comprises mainly sandstone, siltstone, and shale, and contains subeconomic oolitic ironstone deposits at Sherwin Creek. It unconformably overlies various formations of the Nathan and McArthur Groups, and is generally 2000 m thick within the area described in this Bulletin but about 5 km thick to the southwest (TANUMBIRINI).

Although extensive outcrops of the Roper Group are present in the area, especially along its western edge and in the Abner Range (Plate 1), we have not examined them in any detail. For the sake of completeness, we include a short, mainly descriptive account of the Roper Group; this is based almost exclusively on information published in the explanatory notes for BAUHINIA DOWNS (Smith, 1964), MOUNT YOUNG (Plumb & Paine, 1964), ROPER RIVER/CAPE BEATRICE (Dunn, 1963b), and URAPUNGA (Dunn, 1963c) supplemented by information from Roberts (unpublished), Peat & others (1978), and a few observations we have made. As we have not studied the group systematically, we are unable to provide complete stratigraphic decriptions and definitions of individual formations. However, the names of the twenty-one stratigraphic units constituting the group have been widely published since the early 1960s and our compilation—although lacking nominations for type sections—should be considered as the basis for their formal definition.

BHP Co. Ltd drilled the ironstone at Sherwin Creek in the 1950s, and Cochrane & Edwards (1960) gave an account of its petrography. Peat & others (1978) have reported on micropalaeontological and geochemical studies of organic matter in shales from the McMinn Formation, near the top of the group.

Age

The best estimate of the age of the Roper Group is Kralik's (1982) Rb-Sr isochron of illite separated from the Kyalla Member of the McMinn Formation. The age obtained, 1429 $\pm$ 31 Ma, provides a minimum estimate for diagenesis of the formation, and, thus, an effective younger age limit to the McArthur Basin succession. This date compares with earlier estimates by McDougall & others (1965) of 1390 Ma for glauconite in the Crawford Formation (low in the group) and 1280 Ma for dolerite sills which intrude the top of the group.

The only direct control on the maximum age of the group is Page's (1981) value of 1690^{+29}_{-25} Ma for deposition of the HYC Pyritic Shale Member (Barney Creek Formation, McArthur Group), or Kralik's (1982) estimates of 1537 $\pm$ 52 Ma and 1589 $\pm$ 14 Ma for diagenesis of the same member.

Lithology

The Roper Group consists largely of quartz sandstone, siltstone, and shale; feldspathic sandstone and siltstone; ferruginous sandstone and siltstone; glauconitic sandstone; micaceous sandstone, siltstone, and shale; conglomeratic sandstone; and minor limestone, oolitic ironstone, and chert. Most of the formations are thicker and better developed in the western part of the area.

A simplified geological map (Fig. 166) shows the distribution of the Roper Group in the southern half of the McArthur Basin, and the localities of place names used in Table 7, which summarises the most significant stratigraphic features of the individual formations.

Interpretation

Based on the regional mapping, we interpret the Roper Group as comprising three coarsening-upward cycles, which

TABLE 7. STRATIGRAPHY OF THE ROPER GROUP

Name of unit			*Rock types*	*Sedimentary structures*	*Stratigraphic relations*	*Distribution*	*Thickness (m)*	*Remarks*
COBANBIRINI FORMATION			Flaggy micaceous fine sandstone and silt-stone; minor medium sandstone and shale		Equivalent S of 15°30'S to Maiwok Subgroup; overlies Bessie Creek Sandstone	SW of Borroloola and Abner Range	ca 500 in MOUNT YOUNG; ca 1200 in BAUHINIA DOWNS	Poorly exposed
MAIWOK SUBGROUP	CHAMBERS RIVER FORMATION (comprising four unnamed units)		Ferruginous quartz sandstone	Sandstones are cross-bedded and ripple-marked, and contain clay pellets	Unconformably over-lain by Cambrian rocks	Only in NW of area on W side of Maiwok Sub-basin	ca 800–2000	
			Mainly blocky medium to coarse sandstone					
			Mainly flaggy mica-ceous fine sandstone and siltstone					
			Calcareous and micaceous siltstone					
	McMINN FORMATION	Bukalorkmi Sandstone Member	Medium to coarse friable quartz and ferruginous sandstones	Extensively ripple-marked		The McMinn Forma-tion is confined to the Maiwok Sub-basin in N (URAPUNGA and adjacent areas)	7–10	
		Kyalla Member	Flaggy variegated shale, siltstone, and Kyalla beds of blocky sand-stone and black shale near base, and carbonate near top	Ripple marks, flute casts, current lineation, fine sandstone; inter-cracks, cone-in-cone structures	tool marks, mud-		200–300	
		Sherwin Ironstone Member	Oolitic and pisolitic ironstones and sider-itic sandstone inter-bedded with chloritic sandstone and pyritic carbonaceous shale	Cross-beds, intra-formational conglo-merate	Interbedded with Moroak Sandstone and Kyalla Members		<20	Three separate beds at Sherwin Creek: only one elsewhere
		Moroak Sandstone Member	Blocky fine to medium quartz sandstone and interbedded flaggy siltstone and shale	Cross-beds, ripple marks, flute casts, scour-and-fill, dessica-tion cracks, sandstone dykes, clay pellets, small slumps, numerous fining-up cycles	Conformably overlies Velkerri Formation		100 near Sherwin Creek; thins outwards to 20	Includes one ironstone bed
	VELKERRI FORMATION		Flaggy fissile siltstone and carbonaceous shale		Conformably overlies Bessie Creek Sandstone		300 near Towns; thins to E	

TABLE 7. STRATIGRAPHY OF THE ROPER GROUP (Cont.)

Name of unit		*Rock types*	*Sedimentary structures*	*Stratigraphic relations*	*Distribution*	*Thickness (m)*	*Remarks*
BESSIE CREEK SANDSTONE		Massive blocky friable medium quartz arenite with coarser bands, especially along foresets		Conformably overlies Corcoran Formation	Widespread	360 near Tanumbirini; thins to S and E (180 in Abner Range, only 40 in Emu Fault Zone); also thins to N (50 in Roper River) and lenses out NW of Maiwok Creek	Prominently jointed and well exposed in S and at Ruined City in N
CORCORAN FORMATION		*(upper)* Variegated shale, flaggy micaceous siltstone, and flaggy to blocky medium to fine quartz sandstone	'Pseudo'-mud-cracks	Conformably overlies Abner Sandstone	Widespread; thins and becomes finer-grained to N	ca 150 in centre and N; thickens markedly in S from 20 (E) to 600 (W)	Poorly exposed
		(lower) Minor limestone in N; sericitic siltstone near Tanumbirini					
ABNER SANDSTONE		Medium to coarse massive quartz sandstone		Conformably overlies Crawford Formation	Widespread	Markedly thin in SE where members not recognisable; thickens markedly in S from 80 (E) to 500 (W)	Conspicuously jointed; forms prominent pillars and tower karst; weakly cemented
	Munyi Member	Ferruginous rocks, including sandstone and siltstone	Abundant ripple marks	Conformably overlies Hodgson Sandstone Member	Widespread north of 16°S; probably also present in S but very thin	Up to ca 30	Dark distinctive photo pattern
	Hodgson Sandstone Member	Massive and blocky medium to coarse quartz arenite	Cross-beds and ripple marks	Conformably overlies Jalboi Member where developed	Not recognised in SE of area	Maximum ca 220; thins to NW	Prominently jointed
	Jalboi Member	Flaggy fine micaceous sandstone, siltstone, and shale; interbeds of medium quartz sandstone, which decrease to NW; rare glauconite	Slump rolls, current ripples, load casts, flute casts, clay-pellet impressions, whorl structures	Finer recessive middle member	Not recognised in SE of area	About 80 in S; thickens to NW, forms 75% of formation in far NW	
	Arnold Sandstone Member	Massive to blocky friable quartz arenite with coarse lenses; thin conglomerate beds	Cross-beds and ripple marks	Conformably overlies Crawford Formation	Not recognised in SE of area	Maximum ca 100 in S; thins to NW: only 3 to 5 in Roper River	Prominently jointed

TABLE 7. STRATIGRAPHY OF THE ROPER GROUP (Cont.)

Name of unit		*Rock types*	*Sedimentary structures*	*Stratigraphic relations*	*Distribution*	*Thickness (m)*	*Remarks*
CRAWFORD FORMATION		*(upper)* Blocky to massive fine-medium micaceous and feldspathic sandstones and quartz wackes, in part glauconitic *(lower)* Flaggy, fissile, ferruginous, and micaceous siltstones and wackes	Coarsening-upward cycles	Conformably overlies Mainoru Formation	Widespread throughout area	Variable: increases from ca 100 at Mainoru to over 300 near Three Knobs; from this central zone it thins to SE and NW	Uppermost beds usually resistant; remainder seldom crop out
MAINORU FORMATION		Siliceous siltstone and shale, and micaceous siltstone and sandstone; flaggy to fissile and glauconitic		Conformably overlies Limmen Sandstone	Widespread throughout area	ca 130 in NW; increases to ca 600 in Cox River–Abner Range area; ca 200 at Foelsche River; >1000 at Tanumbirini	Generally poorly exposed; well exposed in far NW
	Wooden Duck Member	Glauconitic micaceous wacke, flaggy micaceous siltstone, blocky silicified quartz sandstone		Middle sandy member along Roper River in N	Only in Roper River area	?20–30	
	Kilgour Sandstone Member	Fine to medium feldspathic sandstone; minor siltstone	Ripple marks	Middle sandy member in Abner Range in S	Only on SE side of Abner Range	About 60	
	Mountain Valley Limestone Member	Interbedded limestone and chert, flaggy siltstone; commonly glauconitic; minor sandstone interbeds	Nodules	Basal member in NW; conformably overlies Limmen Sandstone	Only in NW part of URAPUNGA	About 60	Poorly exposed
LIMMEN SANDSTONE		Mainly fine to medium quartz sandstone, commonly blocky and intensely silicified; basal beds either conglomeratic or silty; flaggy micaceous sandstone and siltstone in places; minor limestone in far NW	Massive cross-stratification; finer beds contain convoluted bedding; large trough-cross-stratification in SW	Unconformably overlies Nathan and McArthur Groups	Widespread basal unit	Fairly constant between 100 and 120 except at Tanumbirini, where it is reported to be 1350 (including basal siltstone about 600); thins to 10–20 in SE BAUHINIA DOWNS	Resistant, usually forms prominent outcrops; *Beltanella*-type jellyfish reported from NW (Flying Fox Creek)

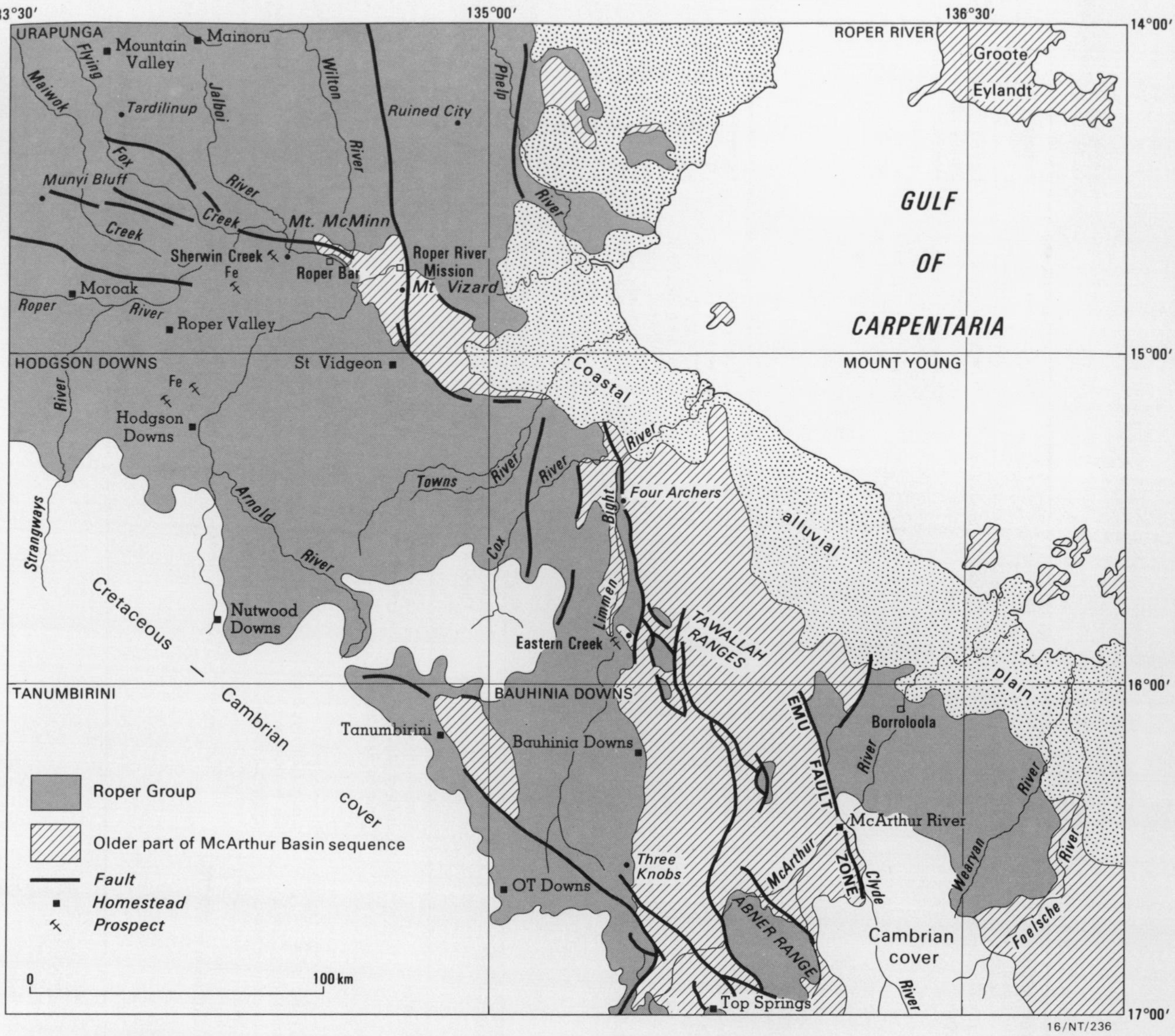

Fig. 166. Distribution of the main Roper Group outcrops, and place names referred to in the text; selected faults are shown.

probably represent major progradational events; these are, by formation name, (1) Mainoru-Crawford-Abner; (2) Corcoran-Bessie Creek; and (3) Velkerri-McMinn. Within the Maiwok Subgroup the Velkerri-Moroak and Kyalla-Bukalorkmi may be similar but smaller progradational events.

From the descriptions available and our limited observations, it would be imprudent of us to suggest environmental interpretations for individual units; however, the overall association of lithologies and structures suggests alternating shallow-marine, littoral, and possibly fluviatile environments. The regional setting of the group is that of a broad epicontinental shelf.

Thick sequences of sandstone and shale in the Victoria River region (Auvergne Group) to the southwest, in the Lawn Hill Platform (South Nicholson Group) to the southeast, and in the Tennant Creek area (Tomkinson Creek beds) to the south are similar to and probably age equivalents of the Roper Group. The distinctly different style of sedimentation shown by these extensive sand-shale sequences, compared with that of the underlying carbonates, suggests that the Roper Group and its probable equivalents should be considered as part of a younger epicontinental basin sequence rather than as a part of the McArthur Basin sequence.

PHANEROZOIC ROCKS

Phanerozoic rocks in the area, which were outside the scope of our study, include the Cambrian Bukalara Sandstone and Top Springs Limestone, the Cretaceous Petrel Formation and Darwin Member of the Bathurst Island Formation, various unnamed limestones, Tertiary laterite, and superficial alluvium, sand, and soil. We have briefly described only the Cambrian and Cretaceous rocks.

CAMBRIAN

Bukalara Sandstone

The Bukalara Sandstone, the basal Cambrian unit, crops out extensively in the eastern parts of BAUHINIA DOWNS and WALLHALLOW, southwestern ROBINSON RIVER, and northwestern CALVERT HILLS, where it forms the

Bukalara Plateau. It is also infolded with the Roper Group in two synclines in the Abner Range, where it reaches a thickness of about 300 m, and is extensively exposed west of the Tawallah Ranges in MOUNT YOUNG and HODGSON DOWNS.

The formation overlies many of the Proterozoic units in the area, demonstrating a variety of contact relationships: karstic infillings in the Amelia Dolomite at the Kilgour copper prospect; angular unconformity on various units—commonly with intensely silicified upper surfaces—in stratigraphic windows in the Bukalara Plateau; and apparently a concordant contact with the Roper Group in the Abner Range. It is overlain unconformably by Cretaceous or younger rocks.

The Bukalara Sandstone consists of red thick to thin-bedded fine to very coarse-grained feldspathic sandstone with scattered pebble trains. Large (several metres in size) trough-cross-beds are a distinctive feature of the unit east of the Mallapunyah Dome.

Although the formation is generally unfossiliferous, it contains medium to coarse-grained arkoses which at five localities in MOUNT YOUNG contain trace fossils that have enabled regional correlations to be suggested (Muir, 1980). The trace fossils include *Skolithos*, and possible *Charniodiscus* Ford 1958 and *Dickinsonia* Glaessner 1966. In addition, meandering burrows 1.5 cm in diameter and 70 cm long, interpreted as feeding burrows, are evident at the same localities. All the fossils have been observed within 20 m of the base of the formation.

The occurrence of *Skolithos* is usually considered to indicate a Phanerozoic age, so the confirmation of the tentative identification of *Charniodiscus* and *Dickinsonia*—which are late Precambrian trace fossils—would present an enigma; reexamination of these localities and collection of material for detailed palaeontological studies are warranted.

The Riversdale Formation and Mount Birnie beds of the Georgina Basin, which are diachronous and transgress the Early and Middle Cambrian (Cook & Shergold, 1978), are stratigraphic equivalents of the Bukalara Sandstone. The Buckingham Bay Sandstone of the Arafura Basin (north of the McArthur Basin), of Early to Middle Cambrian age (Plumb & others, 1976), also contains *Skolithos* and is correlated with the Bukalara Sandstone.

Top Springs Limestone

The Top Springs Limestone, which overlies the Bukalara Sandstone, is a poorly exposed massive cavernous limestone that crops out extensively in southeastern BAUHINIA DOWNS and northeastern WALLHALLOW. It is usually flat-lying, and in the Abner Range area appears to postdate the folding which affected the Bukalara Sandstone. Near Top Spring homestead (GR 7518) the formation has yielded fossils, including *Redlichia* of late Early Cambrian or early Middle Cambrian age (Smith, 1964). Pisoidal structures in outcrops of the formation near Kiana are similar to those described in the Amos Formation, and probably indicate that some sections were intermittently exposed and affected by pedogenic processes.

CRETACEOUS

Cretaceous rocks crop out extensively in the area—in URAPUNGA, MOUNT YOUNG, BAUHINIA DOWNS, and WALLHALLOW. They are usually only a few metres thick, but are as thick as 100 m in places.

Most of the Cretaceous rocks are clay-rich quartz sandstone and claystone, but include a basal conglomerate as thick as 10 m in places. The basal conglomerate contains mainly well rounded arenite boulders less than 1 m in diameter which appear to be derived mainly from the Roper and Tawallah Groups. It is almost invariably silicified, and overlies a regolith which is usually very ferruginous. The regolith is developed on a hard surface which had a relief somewhat similar to that of the present day. In most areas, the Cretaceous rocks are so thin that the morphology of the underlying Proterozoic rocks can be detected on airphotos; thus dips, strikes, folds, and faults can commonly be discerned through the Cretaceous cover.

The Cretaceous rocks were originally referred to the 'Mullaman Group' (Noakes, 1949), but this term was later downgraded by other workers to the 'Mullaman Beds'—a term that was applied to all Mesozoic rocks in the northern part of the Northern Territory, regardless of their age and depositional environment. Skwarko (1966) divided the 'Mullaman Beds' into an 'Inland Belt', covering the southern part of the area (part of BAUHINIA DOWNS and WALLHALLOW), and a 'Coastal Belt', covering the northern part of the area (URAPUNGA, MOUNT YOUNG, ROPER RIVER, and part of BAUHINIA DOWNS). At the bases of both belts, sandstone-conglomerate beds have yielded Neocomian plant fossils. Hughes (1978) correlated these beds with the Petrel Formation; the overlying marine beds containing Aptian Mollusca in the 'Inland Belt' he referred to the Darwin Member of the Bathurst Island Formation.

STRUCTURE

A detailed structural analysis was outside the scope of our study, but a review of previous work and some ideas on structural evolution that were developed are presented here.

Regional Setting

The present structure of the McArthur Basin is dominated by the Batten Fault Zone, a north-trending zone 50 km wide of more intense faulting through the middle of the area (Fig. 167). Stratigraphic reconstructions have shown that this fault zone marks the site of a former syndepositional graben or half-graben, the Batten Trough, in which (according to Plumb & others, 1981) up to 12 km of sediments may have accumulated; this thickness compares with only about 4 km on the Bauhinia and Wearyan Shelves either side of the trough, and about 9 km on the far western Bauhinia Shelf. The Urapunga Fault Zone, along the Roper River at the northern edge of the area, marks an even thinner section above the Urapunga Tectonic Ridge. This general palaeogeographic model (Plumb & others, 1980, 1981) has been confirmed by our study for some parts of the McArthur Basin sequence in the southern area, but inconsistencies have also been noted.

In the southern McArthur Basin, the Batten Trough had the overall form of a graben or half-graben in which the maximum subsidence was near its eastern margin, which is defined by the complex and poorly exposed Emu Fault Zone. The western margin of the Batten Trough is only locally defined—by the Mallapunyah, Hot Spring, Tawallah, and Abner Faults, whose intermittent penecontemporaneous movements locally controlled the thicknesses of some units; for the most part, the McArthur Basin sequence appears to gradually thin westwards from the Tawallah Fault on to the Bauhinia Shelf. The Batten Trough was not evident as a graben during deposition of the Tawallah Group. Typical graben sediments (the Westmoreland Conglomerate) are present along the southeast margin of the McArthur Basin, and indicate early rifting, but this is a long way from the Emu Fault Zone and the orientation of the rift margin was southwesterly—not northerly.

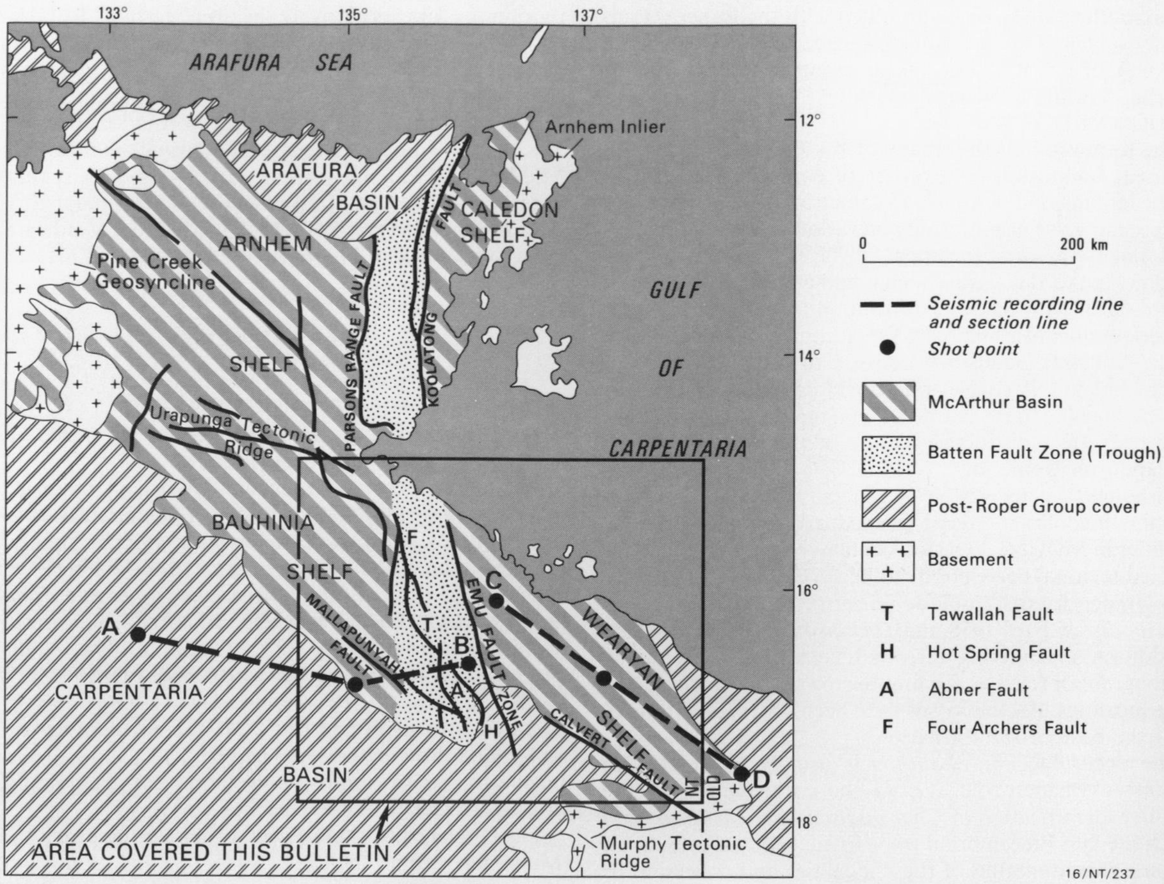

Fig. 167. Major structural and tectonic elements of the McArthur Basin (after Collins, 1983).

Differential subsidence of the Batten Trough probably started during early McArthur Group sedimentation, and continued to a lesser extent during Nathan Group sedimentation. Convincing sedimentological evidence of active fault scarps near the Emu Fault Zone (i.e., along the eastern margin of the Batten Trough) during sedimentation is present only in the Barney Creek and Lynott Formations and Stretton Sandstone. Farther east, on the Wearyan Shelf, a thin Masterton Sandstone and the Karns Dolomite are the only equivalents of the McArthur and Nathan Groups; geophysical studies (Collins, 1983) indicate that they overlie a thin (about 3 km) Tawallah Group section (Fig. 168). Westward of the Abner Range area the McArthur and Nathan Groups appear to wedge out along the western edge of BAUHINIA DOWNS (Fig. 168).

A marked shift of depocentre occurred during sedimentation of the Roper Group, the thickest sections of which (up to 5 km) were deposited on the Bauhinia Shelf—west of the Abner Range area (Fig. 168).

This structural setting of the southern McArthur Basin contrasts with that in the northern McArthur Basin (in Arnhem Land), where the Batten Trough—a graben 12 km deep and broadly symmetrical between easterly and westerly faulted margins—differentially subsided during both Tawallah and McArthur Group sedimentation. Connection between the northern and southern parts of the Batten Trough is obscured by lack of outcrop beneath the coastal plain and sea, about the mouth of the Roper River; indeed, the Batten Trough may comprise two components separated by an easterly extension of the Urapunga Tectonic Ridge (Fig. 167).

Magnetotelluric (Cull, 1982) and seismic (Collins, 1983) studies along a transect across the southern McArthur Basin have provided geophysical support for this regional structure. Further studies, currently (mid-1985) in progress, include a basin-wide interpretation of Landsat, aeromagnetic, and regional gravity data in unexposed areas, to model the deep structure and basement configuration.

The McArthur Basin has been deformed mainly in response to block-faulting along the Batten and Urapunga Fault Zones. Vertical stratigraphic displacements of up to 7.5 km—for example, across the Four Archers Fault in MOUNT YOUNG—have been demonstrated. The block-faulting has had the overall effect of reversing the earlier graben structure (Batten Trough) into a present-day horst or anticlinorium, in which the oldest rocks (Scrutton Volcanics of the basement) are now locally exposed in the middle of the Batten Fault Zone—in the Tawallah Ranges. The shelves are only mildly deformed.

Many folds and broad warps can be directly related to faults. More intense responses to faulting include steep tilting adjacent to faults, minor drag folding, kink folding, shearing, brecciation, veining (both mineralised and non-mineralised), and secondary solution effects. Younger rocks (Nathan Group, Roper Group, Bukalara Sandstone) are commonly drape-folded over contemporaneous underlying fault-blocks in areas such as the Abner Range. Similar synclinal folding has been responsible for many of the sub-basins in the Barney Creek Formation—such as near Top Crossing, and the HYC sub-basin.

The major faults of the area (Mallapunyah, Calvert, Emu, Hot Spring, Tawallah, Abner, and Four Archers Faults), and the Bulman, Parsons Range, Bath Range, and Kootong Faults of Arnhem Land, are all parts of a set of large-scale lineaments across northern Australia (Fig. 169). Considerable strike-slip displacement in the basement before the initiation of the McArthur Basin may be demonstrated for several of them.

Thus, the northwest-trending Mallapunyah–Calvert Fault

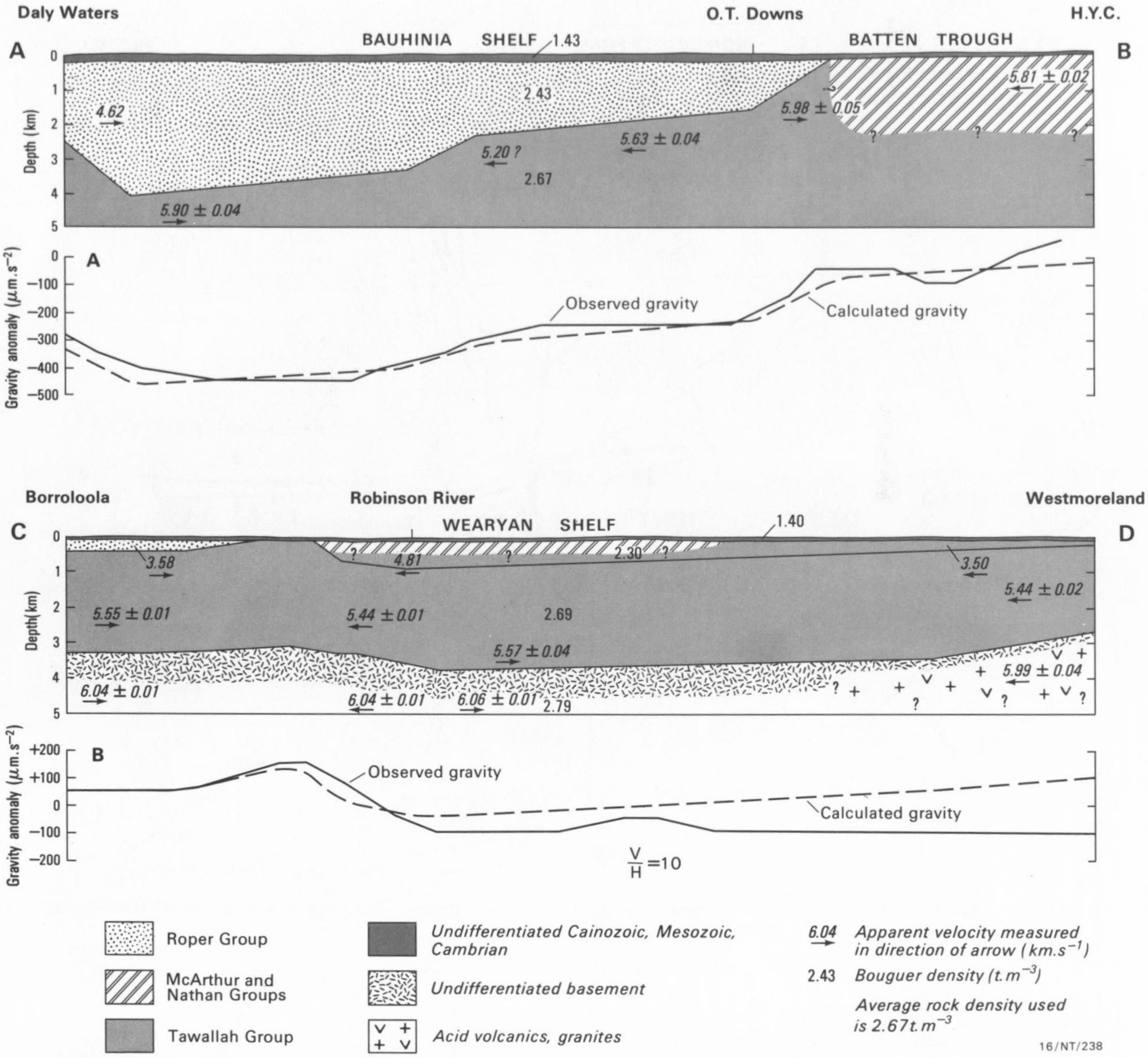

Fig. 168. Cross-section showing a geological interpretation, based largely on seismic results, of the broad stratigraphic subdivisions of the McArthur Basin (see Fig. 167 for location; after Collins, 1983).

system, which is offset by the Batten Trough, has a demonstrated long history of movement, of which the most consistently observed effect is left-lateral strike-slip displacement (though the expression of the Mallapunyah Fault has been complicated by associated vertical movement). Roberts & others (1963) observed 7 km of left-lateral displacement in basement rocks of the Murphy Inlier either side of the Calvert Fault, whereas nearby basin sediments have been displaced by only about 1 km or less. Post-McArthur Group movements along the fault system are relatively small, and include displacements of rocks as young as the Cretaceous along the Calvert Fault. A similar long history of movement is apparent for the parallel Bulman Fault, along which movements amounting to 2.5 km of left-lateral displacement of the McArthur Basin sequence postdated many kilometres of earlier displacemement in the basement rocks of the Pine Creek Geosyncline.

Actual fault traces in the field are seldom exposed but most faults are thought to be generally steep (60°) to vertical. Large vertical displacements are invariably confined to the northerly trending faults defining the Batten Fault Zone (e.g., Emu Fault Zone and Four Archers Fault); some of these may be identified as reverse or steep thrust faults (e.g., Tawallah-Abner Fault system). The very steep faults (e.g., Emu Fault Zone) vary in dip along strike to both east and west. Movements have commonly reversed through time—the obvious example being the Emu Fault Zone, along which the western block (Batten Trough) subsided during deposition and was then uplifted throughout most of its length after deposition had ceased. The character of the faults at depth is unknown; in Plate 1 they have been shown as vertical in the cross-sections for convenience only.

As well as their considerable vertical displacements, the north-trending faults within the Batten Fault Zone also display strike-slip displacements. Tension gashes in the Emu Fault Zone indicate right-lateral displacement of unknown magnitude. Right-lateral strike-slip displacement (inset B, Fig. 169) is also evident in a series of asymmetric domes cut by north-trending faults on the western side of the Batten Trough. In Arnhem Land, right-lateral displacement along faults in the Batten Fault Zone is considerably greater in the basement rocks than it is in the overlying McArthur Basin sequence (Plumb & others, 1980).

In the Urapunga Fault Zone, which is roughly perpendicular to the Batten Fault Zone, symmetrical domes are vertically displaced by probable reverse or thrust faults (inset

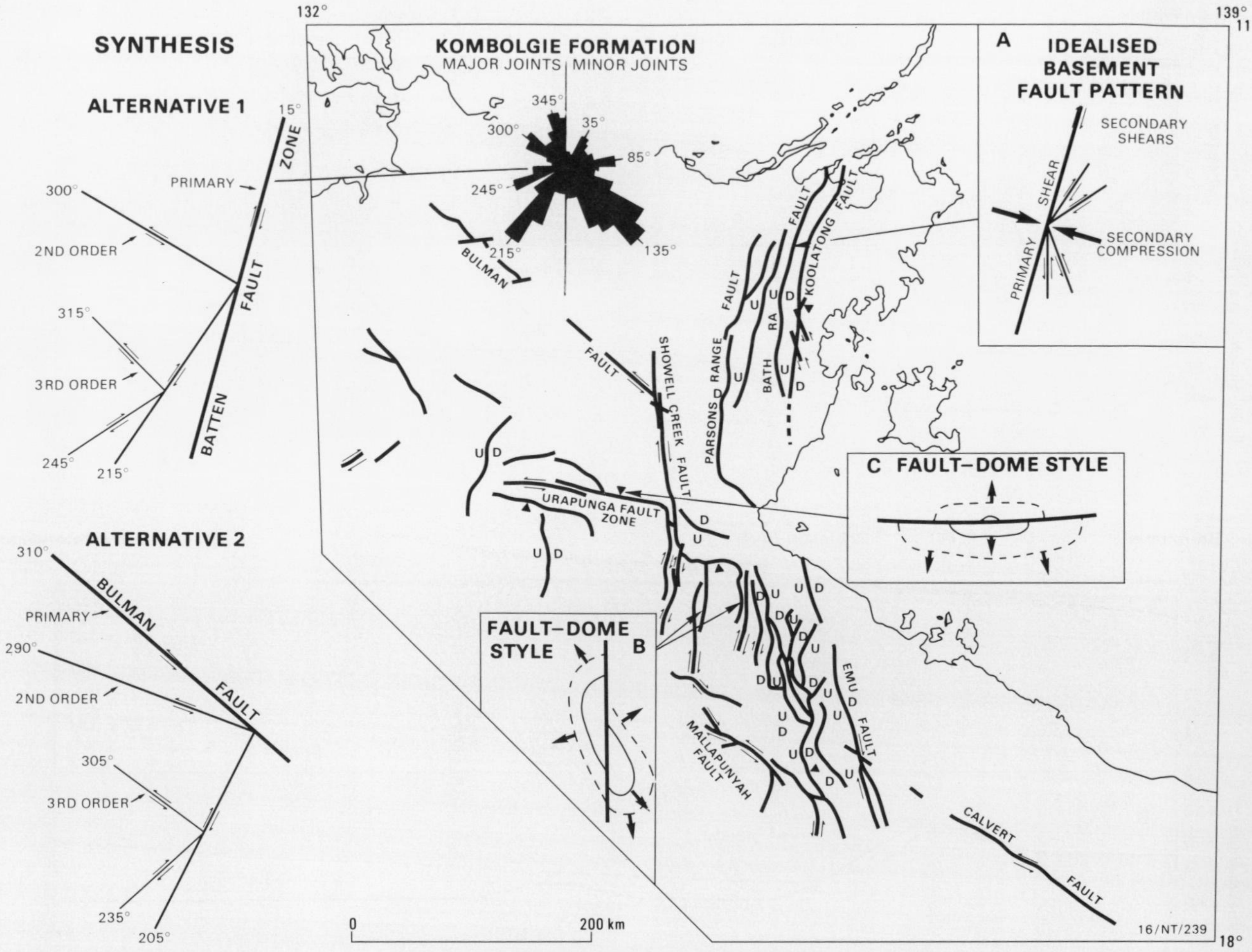

Fig. 169. Simplified regional analysis of the main faults in the McArthur Basin region (after Plumb & others, 1981, fig. 7).

C, Fig. 169). Plumb & others (1980) considered that this structural expression indicates that the Urapunga Tectonic Ridge (below the fault zone) was a rigid block which resisted north–south movements of the surrounding areas.

From the Kombolgie Formation (western Arnhem Land), which is well known for its spectacular jointing, Plumb & others (1980) plotted 10 000 joint measurements in a rose diagram (Fig. 169). According to the classic interpretation of wrench-fault tectonism (Moody & Hill, 1956), these data are compatible with right-lateral displacement parallel to the Batten Fault Zone and with left-lateral displacement parallel to the Bulman–Mallapunyah–Calvert Fault system. However, Plumb & others (1980) could not differentiate, from these data alone, whether the north-northeasterly strike of the Batten Fault Zone or the northwesterly trend of the Bulman Fault was the primary control; they concluded that both operated as part of a continent-wide system, but considered that perhaps the strike of the Batten Fault Zone was dominant in the McArthur Basin.

Since the work of Plumb & others (1980), preliminary analysis of Landsat imagery has suggested that a continent-wide northwesterly structural trend may predominate, and that the Bulman–Mallapunyah–Calvert Fault system is the surface expression of displacements along an ancient pre-McArthur Basin set of fractures deep in the basement.

Structural controls on mineralisation

Studies at McArthur mine (e.g., Logan & Williams, 1984) have indicated that penecontemporaneous faulting along the

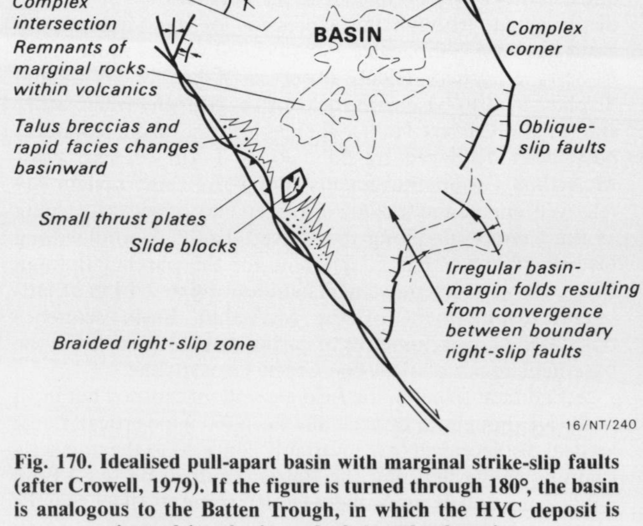

Fig. 170. Idealised pull-apart basin with marginal strike-slip faults (after Crowell, 1979). If the figure is turned through 180°, the basin is analogous to the Batten Trough, in which the HYC deposit is situated just basinward of the talus breccias.

Emu Fault Zone was an important factor controlling the emplacement of the orebody—by providing both a rapidly subsiding euxinic sub-basin and pathways for the mineralising fluids. Viewed in the light of the regional structural information presented above, this apparent relationship between tectonism, sedimentation, and mineralisation suggests to us that movement along strike-slip fault systems and the consequent generation of pull-apart basins may represent the main regional structural controls on the accumulation of HYC-style deposits. The scale and pattern of faulting, and the character of the sediments, are analogous to those in pull-apart basins in the San Andreas and San Gabriel Fault systems of southern California (for example, Fig. 170).

Mineralised tension veins within the Emu Fault Zone and at the Cooleys lead-zinc prospect (immediately west of the Emu Fault Zone) are evidence not only for the release of tension in the oblique splay systems but also for the movement of mineralised groundwaters. These vein deposits thus represent fossil groundwater conduits, and, with the aid of stable isotopes, Rye & Williams (1981) have traced the passage of mineralised groundwaters from the Emu Fault Zone into the HYC deposit.

MINERAL RESOURCES

The McArthur Basin is extensively mineralised with a wide range of metallic elements and a variety of ore deposit types. Even so, there are no working mines in the area at the present time (mid-1985). Though active exploration continues, despite the remoteness and relative inaccessibility of the area, no major ore discovery has been made since Mount Isa Mines Ltd discovered the HYC deposit in the 1950s; however, small deposits (some of which may be economical close to centres of population or to ports) and a large number of base-metal anomalies have been delineated. The more recent exploration activities have been summarised on pp. 8-9. The following account refers to the known mineral occurrences in the area.

LEAD AND ZINC (Fig. 171)

A number of Pb-Zn deposits occur in BAUHINIA DOWNS—including the stratabound and stratiform HYC, W-Fold, Emu Plains, Teena, and Ridge II deposits, and the cross-cutting Cooks, Coxs, Turnbulls, Squib, and Cooley prospects. Other disseminated deposits occur at Reward, Bald Hills, and Barneys prospects. All these deposits occur within a radius of about 30 km of McArthur mine—mainly to the east and south of it. West of the Tawallah Fault, the Great Scott, Mariner, and Apollo prospects contain small quantities of Pb and Zn.

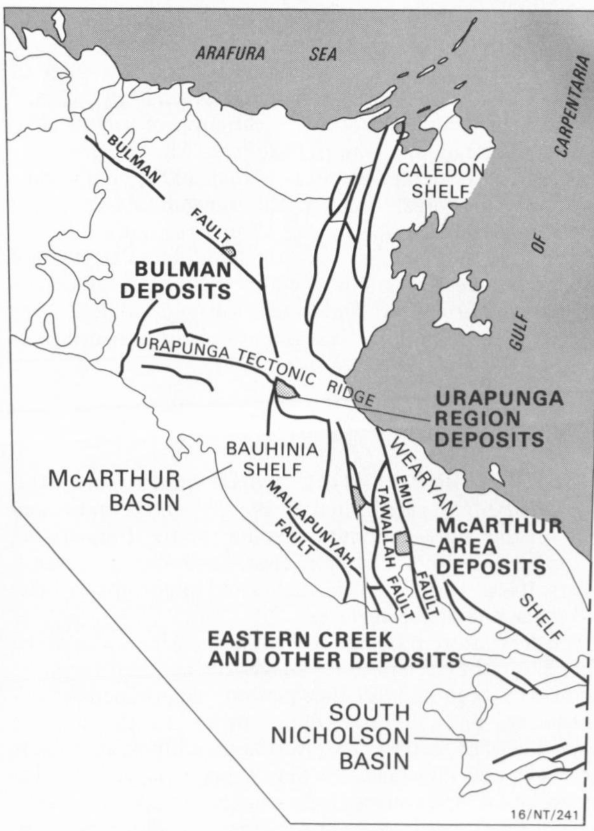

Fig. 171. Locations of significant Pb–Zn occurrences in the McArthur Basin.

Elsewhere, other occurrences of Pb and Zn include: lead-barite in Eastern Creek (MOUNT YOUNG); Pb-Cu in the Mount Vizard area (URAPUNGA); stratabound and stratiform Zn-Pb at the Bulman mine (MOUNT MARUMBA); and disseminated coarse-grained galena in the Karns Dolomite and Fickling Group (CALVERT HILLS and ROBINSON RIVER).

McArthur River area—concordant deposits

HYC (McArthur)

The HYC is a large deposit by world standards. The trial mine is situated at GR 168828 (*Borroloola*, 6165); the gossan and original exploration shaft are about 500 m to the east. The deposit was discovered in 1956 during a mapping, geochemistry, and prospecting program by Mount Isa Mines Ltd (Spratt, 1984). The nearby gossan is a silicified breccia that contains abundant pale blue and white crystals of the zinc silicate, hemimorphite. A diamond-drilling program in 1959 led to the discovery of mineralised pyritic shale and siltstone (of the HYC Pyritic Shale Member, Barney Creek Formation). Bulk samples for metallurgical testing from a shaft sunk near the gossan suggested that the ore would be difficult to treat because of its fine grainsize and high content of organic matter. A natural exposure of the ore beds occurs in Barney Creek at GR 175832 (*Borroloola*, 6165).

The poor exposure of the deposit has necessitated considerable diamond-drilling to define its limits. The most recent estimates are of roughly 227 Mt of ore at grades of 4.1% Pb, 9.2% Zn, 0.2% Cu, and 41 g t^{-1} Ag (Buchanan, 1984). A small area richer in Pb, Cu, and Ag than the bulk of the ore is present near the northern edge of the deposit (Logan & Dennis, 1981).

The ore minerals are principally pyrite, galena, and sphalerite with accessory marcasite, arsenopyrite, chalcopyrite, and freibergite (Croxford & Jephcott, 1972; Murray, 1975; Logan & Dennis, 1981). Their host rocks are dark carbonaceous, tuffaceous, pyritic, and dolomitic siltstone and shale interbedded with breccia. The ore minerals faithfully follow the bedding structures, indicating a syngenetic or early diagenetic origin for the mineralisation. Because of their fine grainsize ($\sim 4\ \mu m$), high-grade ore and barren pyritic shale are difficult to distinguish from one another in hand specimen.

The deposit, occupying an area of about 1.5 km^2 in the HYC sub-basin (Fig. 100), comprises eight ore beds separated by breccias, though only the lower four ore beds are present in the north of the sub-basin, where the upper part of the mineralised zone is dolomitic breccia. Apart from the peripheral areas of the deposit there is little lateral variation in Pb:Zn ratios within individual orebeds; however, there is considerable vertical variation in metal contents and in ratios from orebed to orebed.

Because the HYC deposit is unmetamorphosed (the enclosed organic matter indicates a maximum palaeotemperature between 150 and 170°C) and stratabound, it is regarded as a classic Proterozoic shale-hosted Pb–Zn orebody—the 'McArthur-type' of Williams (1980)—and a genetic model for the Pb–Zn deposit at Mount Isa (Williams, 1980).

Original studies led to the view that the mineralisation was of syngenetic (synsedimentary) origin (Croxford, 1968; Croxford & Jephcott, 1972; Lambert & Scott, 1973; Murray, 1975; Lambert, 1976). Lead and sulphur isotope studies indicate that the pyrite and the Pb–Zn sulphides had different sources (Smith & Croxford, 1973, 1975; Gulson, 1975; Croxford & others, 1975): the pyrite is widely held to be of biogenic origin, wheres the Pb–Zn sulphides were thought to be of volcanic or hydrothermal exhalative origin. More recently, evidence has been presented that suggests that the Pb–Zn mineralisation was of diagenetic (epigenetic) origin, derived from hydrothermal solutions emanating from the Emu Fault Zone and deposited in the HYC Pyritic Shale Member within 10-100 m of the sediment-water interface (Williams, 1976, 1978a, 1978b, 1979, 1980; Rye & Williams, 1981; Williams & Logan, 1981).

W-Fold

A striking vegetation anomaly at W-Fold Hill (GR 107824, *Borroloola*, 6165) reflects the occurrence of a mineral deposit in two separate synclinal structures, plunging in opposite directions, which are believed originally to have been a single depositional basin whose centre was subsequently eroded (Walker & others, 1978). Distinctive tuff beds indicate that the mineralised interval occupies a lower part of the HYC Pyritic Shale Member than the HYC deposit. The deposit averages 2.5% Zn and 0.5% Pb over 30 m; the highest grades are at the top.

Whilst part of the deposit resembles the fine-grained HYC deposit, some sphalerite in the W-Fold deposit occurs as pale straw-yellow beds up to 0.5 mm thick interbedded with grey dolomitic shale (Murray, 1975)—unlike that in the HYC deposit. Coarse-grained red sphalerite with scattered galena crystals occurs in a few thin beds, and these sulphides also occur as concretions. Although the bedding in the mineralised interval is in places slumped and disturbed, inter-ore breccias like those in the HYC deposit are not developed in the W-Fold deposit.

Emu Plains

Little information is available on the Emu Plains deposit, which occurs at roughly GR 167848 (*Borroloola*, 6165). It appears to be of similar style to, and occurs at the same stratigraphic level as the HYC deposit. Grades of 2% Zn and 0.7% Pb were intersected in diamond-drillholes through 50-m-thick sections.

Teena

At Teena (grid square 0682, *Batten*, 6065) a disseminated low-grade deposit of cerussite and anglesite occurs in silicified shale of the Barney Creek Formation. The deposit extends into a silicified breccia, which is probably a fossilised silcrete.

Ridge II

The Ridge II deposit (grid square 1882, *Borroloola*, 6165) has a concordant western part and a discordant eastern part (Williams, 1978a). The concordant part occurs at least 300 m higher in the HYC Pyritic Shale Member than the HYC, W-Fold, and Emu Plains deposits. Its geological setting and associated breccias are similar to those of the HYC deposit, but the lack of chert, presence of rare tuffs, and mineralogical differences distinguish it from the HYC deposit. No grade or tonnage figures are available for it, but from geological sketches (Walker & others, 1978) it appears to be smaller than the other concordant deposits.

McArthur River area—discordant deposits

Coxco

The Coxco deposits are in the Coxco Valley about 10 km southeast of the HYC deposit. The name is a combination of Cooks and Coxs prospects, at GRs 222728 and 225719 respectively, two small high-grade oxidised deposits discovered by prospectors in the 19th century. These deposits—comprising veins and vugs of galena, hydrozincite, cerussite, smithsonite, and amorphous lead carbonate in a ferruginous gossan—were originally described as being hosted by the Amelia Dolomite. Remapping has shown that the deposits are contained within and associated with palaeokarst surfaces in the Mara Dolomite Member of the Emmerugga Dolomite and the Reward Dolomite.

Carpentaria Exploration Co. Pty Ltd has recently explored the Coxco deposits, in which several million tonnes of 2.5% Zn and 0.5% Pb are indicated (Walker & others, 1983). Below the oxidised zone, the Coxco deposits consist of sphalerite, galena, pyrite, and marcasite within brecciated dolostones; sparry dolomite, bitumen, and phosphate (apatite) are the gangue.

The deposit occurs in or close to the Emu Fault Zone, and reflects two stages of mineralisation. In the first stage of mineralisation, colloform sphalerite, galena, pyrite, and marcasite precipitated as crusts on the edges of karst cavities in the Emmerugga and Reward Dolomites. The sulphides were deposited at low temperatures (less than 100°C) in intimate association with organic matter. This mineralised palaeokarst surface was then buried by the Lynott Formation. In the second stage of mineralisation, coarse sulphides crystallised in veins and breccias that cross-cut the Reward Dolomite and the Lynott Formation. Fluid-inclusion and stable-isotope studies indicate that the second-stage sulphides were deposited between 100 and 170°C (Walker, 1980).

Cooley

The Cooley deposits—I, II, and III (grid square 1982, *Borroloola* 6165)—are hosted by breccia matrix and zoned veins in the Mara Dolomite Member of the Emmerugga Dolomite near a branch of the Emu Fault Zone (Walker & others, 1983). They comprise galena and minor hydrozincite and malachite at the surface.

The deposits were studied by Williams (1978a), who noted two phases of brecciation. He suggested that the first phase might have been due to either penecontemporaneous fault movement, or solution collapse owing to the loss of evaporites. The second phase was apparently so intimately associated with mineralisation that Williams suggested it was caused by solution collapse following the introduction of the mineralising fluids into the porous first-generation breccias.

The main part of the deposit comprises coarse-grained sulphide and gangue minerals associated with the matrix of the second-generation breccias, and occurs either in veins or patches scattered throughout the matrix. The sulphide minerals commonly have open-space filling textures and grew perpendicular to the vein walls. Two distinct periods of mineralisation are recognised in the main part of the deposit: the earlier comprising pyrite, marcasite, barite, and dolomite, and the later comprising base-metal sulphides and later dolomite.

One or in places two generations of sulphide-bearing veins cross-cut the main part of the deposit, and may reflect local remobilisation of it.

Rye & Williams (1981) presented sulphur-isotope data which suggest that the temperature range of the mineralising fluids was as high as 275-290°C; however, their oxygen-isotope data indicate a lower temperature range—120-170°C. The light brown colour of the organic matter in the host rocks of the Cooley II deposit (Muir, 1983b) supports the lower temperature of formation.

Ridge

The discordant Ridge I deposit and the eastern part of the Ridge II deposit (grid square 1882, *Borroloola*, 6165) occur within the Cooley Dolomite Member of the Barney Creek Formation, and have similar brecciation and mineralisation features to the Cooley deposits (Williams, 1978a).

Turnbulls

A small oxidised deposit hosted by the Mara Dolomite Member of the Emmerugga Dolomite at GR 235712, Turnbulls deposit was worked before the First World War. Its principal minerals are malachite, galena, and cerussite in veins and vugs.

Squib

The Squib prospect (GR 237702) comprises malachite, cuprite, and chalcocite in veins in the Mara Dolomite Member of the Emmerugga Dolomite. It has been worked in a small way.

Larra Keyah, Star of Bethlehem, Leichhardt (not shown in Plate 1)

Small prospecting pits in oxidised deposits have been excavated at Larra Keyah (Pb and Cu) at GR 250635, and Star of Bethlehem (Pb) and Leichhardt (Ag-Pb), both at about GR 224723. No detailed information about them is available, but all three prospects are mentioned in South Australian Parliamentary Papers of the late 19th century.

The Star of Bethlehem and Leichhardt prospects are both near the Coxco deposits, and may be part of the same mineralisation system. Larra Keyah is near Amelia Spring, and apparently hosted by the Lynott Formation.

Reward

The Reward prospect consists of several shallow workings at GR 027833 (*Batten*, 6065). The deposit, which is confined to the oxidised capping of a hill and dies out abruptly at a depth of about 60 m, consists of cerussite, anglesite, pyromorphite, lead oxides, and minor argentite and cerargyrite. It is described as high grade (Smith, 1964), and is hosted by brecciated Reward Dolomite overlying pyritic shale of the Barney Creek Formation.

Bald Hills, Barneys, and nearby deposits

The Bald Hills (GR 105829) and Barneys or Barneys Hill (GR 145828) deposits—both in *Borroloola* (6165)—are hosted by the lower Teena Dolomite, and contain abundant scattered galena crystals about 3-5 mm in diameter, and yellow to straw-coloured glassy sphalerite in irregular patches of about the same size. Larger patches of sphalerite and galena are present in places, and small prospecting pits at Bald Hills probably indicate the former position of greater concentrations of Pb and Zn. The Barneys prospect (which is close to the old government assay station on Barneys Hill) was drilled in the early years of this century by the McArthur Development Co., which also explored many of the deposits in the Coxco Valley.

In the same area in *Borroloola* (6165) the *Bindawodgie* (GR 078802), *Biondi* (GR 140849), and *Boes Lagoon* (GR 068856) are Pb prospects which appear never to have been worked. The locations given are approximate.

Other areas

Calvert Hills area

Coarse-grained galena occurs as individual crystals and crystalline masses in vuggy Karns Dolomite near Calvert Hills homestead (GR 576957, *Calvert Hills*, 6363); the deposit is restricted to specific stratigraphic levels. Similar concentrations occur within the Karns Dolomite in ROBINSON RIVER. These occurrences have recently been explored by several companies. The galena is commonly associated with solid hydrocarbons and disseminated chalcopyrite.

Also in CALVERT HILLS, veins of galena with malachite stains hosted by the Fickling Group have been prospected from two shallow shafts in Gorge Creek (approximate position at GR 177238, *Seigal*, 6462).

Eastern Creek deposits

At Eastern Creek, in southern MOUNT YOUNG (GR 461484, *Mantungula*, 5966), lead-barite deposits were drilled by CRA Exploration Pty Ltd in 1972-73 (EC1, EC2, and EC3), and a further hole was put down by BMR in 1979 (Mount Young No. 1). An 8.3-m length of core in EC1 contained 2.55% Pb and minor Zn and Ag, but none of the other holes intersected evidence of significant mineralisation.

The barite (Fig. 172) occurs as irregular pods, 3-4 m in maximum length, which apparently peter out at depth. Galena and/or malachite generally occur in the barite in surface exposures, but the galena is quite widespread and occurs independently in chert and carbonate. Barite pods without Pb or Cu are common as far west as the Limmen Bight River (about 7 km away), and as far north as Nathan River homestead (40 km away).

Although mapped as being in the Tooganinie Formation in MOUNT YOUNG (Plumb & Paine, 1964), the lead-barite is hosted by the Balbirini Dolomite (previously the 'Kookaburra Creek Formation') both below and above the *Kussiella kussiensis* stromatolite marker bed. Galena alone is found in silicified oolite beds above the marker bed in a setting identical with that at Bulman (see below).

A study of the genesis of the Eastern Creek deposits has recently been undertaken (Muir & others, 1986). The emplacement temperatures were similar to those interpreted for the Cooley deposits—about 200°C; they were established using a combination of organic maturation, stable-isotope, and fluid inclusion studies. Mineralisation took place in more than one episode: the barite and associated minerals were emplaced in karstic caverns in the pre-Roper Group surface; the galena

Fig. 172. Barite at Eastern Creek lead–barite prospect. The diameter of the lens cap is about 5 cm. (BMR negative M2557/3A)

in the oolite beds appears to have been emplaced at an earlier stage, and its mode of occurrence is similar to that of the galena in the Karns Dolomite in CALVERT HILLS and ROBINSON RIVER.

Great Scott, Mariner, and Apollo

Outlying deposits of oxidised Pb and Zn minerals in BAUHINIA DOWNS—Great Scott (approximate position GR 177131) and Mariner (GR 593208, both in *Batten*, 6065)—and MOUNT YOUNG—Apollo (approximate position GR 663310, *Tawallah Range*, 6066)—have recently been drilled and tested by Carpentaria Exploration Co. Pty Ltd, but no results are available.

Mount Vizard area

Pb and Cu have been found together in URAPUNGA, where several gossanous outcrops occur—most commonly in the Balbirini Dolomite (previously the 'Kookaburra Creek Formation'). Drilling by BHP some years ago failed to locate evidence of any significant mineralisation. The gossans are associated with a fault zone which separates the Balbirini Dolomite from units equivalent to the Umbolooga Subgroup (McArthur Group) at GR 687654 (*Urapunga*, 5868), roughly midway between Mounts Vizard and Birch (locality map, Plate 1). The Balbirini Dolomite is poorly exposed in this area, but the surface is pitted with numerous sinkholes indicating continuing karstic activity. The style of mineralisation may have been similar to that at the lead–barite prospects at Eastern Creek, which are hosted by karstically altered Balbirini Dolomite.

Bulman

Although they occur to the north of the area, we mention the Pb–Zn deposits of Bulman mines for completeness. These deposits, which are essentially concordant, were discovered in the early years of this century, and were sporadically worked for Ag–Pb until about 1925. Exploration and drilling in the 1950s by Zinc Corporation and Enterprise Exploration (now CRA Exploration Pty Ltd) demonstrated that the deposits at the surface are depleted in Zn compared with the unweathered zone.

The Bulman deposits are hosted by the Balbirini Dolomite (formerly mapped as part of the Dook Creek Formation) just below the *Kussiella kussiensis* stromatolite marker bed. Some of the secondary galena is hosted by oolite beds which overlie the marker bed in a stratigraphic position identical with that of some of the lead–barite deposits at Eastern Creek.

The main workings at Bulman mine, and the area that was drilled, are at GR 298897 (*Marumba*, 5770). Other workings are at GRs 322876, 365896, 304904, 224897, and 323933. All but one of the deposits lie in a zone between the northwest-trending Bulman Fault and a parallel fault 7 km to the northeast; the one exception (GR 224897) occurs immediately to the southwest of the Bulman Fault.

At the surface, the deposits consist of coarse-grained galena, oxidised Zn and Pb minerals, and, in places, malachite; gangue minerals are chert, dolomite, and minor talc and asbestos. In the subsurface, the deposits consist of sphalerite (cream to pale yellow), galena, pyrite, and minor pyrrhotite.

BARITE

As mentioned above, barite pods crop out extensively west and north of Eastern Creek. Barite is also fairly common along the Emu Fault Zone, though not in commercial quantities. It occurs in veins and breccias, and in places also infills discoidal pseudomorphs after gypsum in the Amelia Dolomite, and in the Tooganinie Formation in the Masterton Horst. Small crystals of barite occur in a silcrete capping the Amelia Dolomite at Leila Creek (GR 707665). In addition, barite has been reported in fault zones in dolostone of the Mara Dolomite Member of the Emmerugga Dolomite (at GR 696400) and in stromatolitic dolostone of the Mallapunyah Formation (at GR 966100).

COPPER

Copper is not being mined in the area at present, even though Cu deposits are numerous and widely scattered throughout it. There are four principal deposit types: the Redbank-type breccia pipes, volcanic-hosted disseminated, sediment-hosted disseminated, and unconformity-related.

Redbank-type breccia pipes

Copper at Redbank (GR 931987, *Wollogorang*, 6463) occurs mainly in breccia pipes which intersect the Settlement Creek Volcanics, Wollogorang Formation, and Gold Creek Volcanics. An overall resource of about 4 Mt at 2.5% Cu is estimated for the Redbank field. Roberts & others (1963) described these deposits as '. . . ill-defined bodies of secondary copper minerals within gently dipping kaolinized volcanic rocks of the Gold Creek Volcanic Member. There is no pronounced structural control to the mineralization'. The oxidised ore was discovered in 1916 by W. Masterton, who worked it until his death in 1961. Production to 1956 was 947.3 t (932.3 tons of ore; Roberts & others, 1963). The grade of the oxidised ore was 25–52% Cu, and the ore consisted mainly of malachite, chrysocolla, azurite, and chalcocite.

The main breccia pipe deposits in the Redbank area (all in *Wollogorang*, 6463) include Quartzite (GR 956983), Bluff (GR 959981), unnamed (GRs 962982, 964980, 938986, 938984, 948986), Prince (GR 908969), Masterton (GR 915968), Seven Mile (GR 928978), Black Charlie (GR 948962), and Sandy Flat (GR 951959). Other unnamed pipes occur in the area to the north of Wollogorang (Orridge & Mason, 1975; Knutson & others, 1979), and two more occur to the southwest of Wollogorang homestead. Orridge & Mason (1975) established that the location of the pipes seems to be controlled by the intersection of a series of easterly and northeasterly lineaments, which appear to be old basement faults that have been silicified. Individual pipes penetrate the Tawallah Group vertically for at least 330 m.

Beds intruded by the pipes show various types of intrusive relations and disturbances—including dips towards the centres of the pipes, and downward displacements of large blocks indicating that some stoping has occurred. Although some pipes terminate at lower levels, most terminate in the Gold Creek Volcanics.

Rock fragments in the breccias are up to 0.5 m in diameter. Some have moved little from their original stratigraphic position, but others are clearly displaced. All fragments are altered; the volcanic fragments commonly have been bleached and converted to clay minerals. The matrix contains the following minerals: dolomite, calcite, quartz, chlorite, K-feldspar, apatite, celadonite, mica, hematite, rutile, clay minerals, chalcopyrite, and minor pyrite, galena, marcasite, sphalerite, covellite, chalcocite, barite, malachite, and pyrobitumen. A mixture of blue clays, identified by Knutson & others (1979) as trachytic mylonite, also occurs in the matrix, and contains cerium and lanthanum. Chalcopyrite is not confined to the matrix, but also occupies veins and amygdales in the fragments, and occurs along bedding planes of the surrounding Wollogorang Formation, which in many areas contains disseminated chalcopyrite. Both matrix and breccia fragments are markedly potassium-enriched.

Malachite and azurite in kaolin occupy a possible Redbank-type breccia pipe in an open cut on a flat north of Running Creek in ROBINSON RIVER (Battey, 1958).

From their studies of the mineralogy, chemistry (including stable isotopes), and textures of the breccia pipes, and the rocks that they intersect, Knutson & others (1979) suggested that the carbonate-rich material in the Redbank breccia pipes formed from magmatic hydrothermal solutions. They compared the breccia pipes with a number of carbonatites from other continents and concluded that the pipes formed as a result of high-level igneous activity and associated hydrothermal processes. Later circulation of non-magmatic brines modified the original hydrothermal deposits.

Volcanic-hosted

Copper has been mined from several prospects in the Seigal Volcanics, including the Vulcan prospect (GR 109718, *Wollogorang*, 6463), where it occurs as malachite filling amygdales. No published studies of the genesis of these deposits are available, but concentrations at the Chapmans (GR 105540) and Norris (GR 028433) prospects, both in *Seigal* (6462), may have been controlled by proximity to the northwest-trending Calvert Fault. The ore at Norris prospect is chalcopyrite with traces of autunite and torbernite, and is massive in the fault zone.

Sediment-hosted

Disseminated low-grade malachite and chalcopyrite have been reported from many localities, and in several formations.

Wollogorang Formation

Base-metal mineral occurrences are evident at several levels in the Wollogorang Formation outcrop. Visible Cu enrichment confirmed by rock-chip geochemical sampling was reported near the base of the formation in the crystalline dolostone facies (unit 2; see p. 33) at many localities by Rod (1977) and Wyatt (1977) in the Redbank area. Rod reported values of 250 ppm copper in rock-chip samples. He described the occurrences as stratabound, and suggested that they are directly related to the increase in organic matter provided by the prolific algal growth indicated by the stromatolites.

Australian Geophysical Pty Ltd (1968) reported a grade of up to 5% Cu, and chalcopyrite up to 100 μm in size, in polished sections of samples from the unit 2 carbonates around Mallapunyah. Copper in the form of azurite and malachite as vug-infillings is also present near the top of the formation in coarse-grained dolomitic sandstone in the Mallapunyah and Kiana districts.

Mineral exploration drilling by Australian Geophysical Pty Ltd (1970a) and stratigraphic drilling by BMR (Jackson, 1982a) confirmed anomalous Cu, Pb, and Zn at these levels, and also indicated anomalous Pb, Zn, and Cu within organic-rich shale. In general terms, anomalous values for Cu are between 30 and 400 times the background values, whereas Pb and Zn are only about 10 times the background values. Although on their own these values are of little economic significance, Jackson (1981b) pointed out numerous similarities between the black shale facies (facies IV) of the Wollogorang Formation and the HYC Pyritic Shale Member of the Barney Creek Formation, which is the host to the McArthur River deposit. These similarities include lithology, stratification, sedimentary structures, diagenetic structures, nodules after evaporites, mineralogy, and geochemistry. Jackson suggested that the shales of the Wollogorang Formation should be considered a favourable target for exploring for syngenetic base-metal mineral deposits of McArthur River type, especially if a suitable structural environment could be found.

Karns Dolomite

Disseminated chalcopyrite occurs in the Karns Dolomite in CALVERT HILLS and ROBINSON RIVER, where it is associated with disseminated galena and appears to be confined to specific beds (see pp. 147–148).

Amelia Dolomite

Disseminated malachite and chalcopyrite have been reported at two levels in siltstone, dolostone, and quartzite, and concentrated in two fault intersections, in the Amelia Dolomite near Mountain Home (Australian Geophysical Pty Ltd, 1967).

Copper has been mined from the Amelia Dolomite at the Coppermine Creek (Gordons) prospect (GR 571368, *Tawallah Range*, 6066), where about 40 t of ore had been produced up to 1957. Later gouging left a few tonnes of hand-picked high-grade ore on site. A shaft has been sunk on a malachite-stained gossan developed in a 'gypsiferous marble' facies of the Amelia Dolomite at the prospect. Only secondary minerals—malachite and minor azurite—have been worked; the primary minerals are bornite and chalcopyrite. The deposit is located near a small northeast-trending fault, but it also coincides with the pre-Roper Group unconformity, and the concentration of secondary copper minerals may be related to the regolith developed on the Amelia Dolomite.

Leila Sandstone

Disseminated malachite, chalcopyrite, and barite occur in the pore spaces of the Leila Sandstone at a number of localities. Grades are low, of the order of 100 ppm Cu, but may be higher in a suitable trap site.

Mara Dolomite Member of the Emmerugga Dolomite

Stratabound chalcocite and various secondary Cu oxide minerals occur in stromatolitic dolostone of the Mara Dolomite Member near Margoogoo waterhole in the headwaters of Tooganinie Creek (grid square 5242). Visible evidence of mineralisation occurs over about 100 m, but stream-sediment and soil geochemical surveys indicate that the Cu anomaly extends for about 7 km along strike.

About 50 m northeast of Hammers Hut (GR 496467, *Mantungula*, 5966), malachite and chalcopyrite are disseminated and occupy small veins in the highly silicified Mara Dolomite Member in a north-trending fault zone.

Lynott and Yalco Formations

Mystery mine (GR 804444) was dug at the contact between the Lynott and Yalco Formations. Little is known about the mine, which appears to have been dug many years ago; it is thought to represent a former copper occurrence, but little evidence of mineralisation is visible.

Unconformity-related

Although hosted by different formations, these deposits are all developed in permeable zones produced by weathering in the Proterozoic regolith underlying unconformities. Some of them—for example, the Yah Yah and Johnstons deposits—occur along anticlinal crests; at others—for example, the Sly Creek deposit—a nearby fault may have enhanced pore spaces between regolith fragments.

Unconformity-related mineral deposits are more common in the McArthur Basin than has previously been recognised. This is partly because, in the past, breaks in succession in the essentially flat-lying sequence were misinterpreted as being primary cherty formations in their own right—for example, the 'Billengarah Formation' which merely represents weathering profiles of various ages developed on a number of different formations.

During our work in the McArthur Basin, we have generally been able to recognise breaks in the succession by the presence of karstic morphologies, ferruginous and manganiferous stains, and rare terra rossa; the carbonate environment obviously inhibits the development of thick oxidised soil mantles. Although our results are preliminary, we have identified five kinds of mineral deposits at unconformities: (1) disseminated Cu; (2) Cu-rich breccias; (3) Zn-Pb breccias and veins; (4) disseminated Cu-Pb; and (5) disseminated and massive galena-barite. The deposits have been formed mainly by the supergene enrichment of suitable host environments (e.g., breccia-infilled or solution-collapse caves and cavities, or weathered and decomposed beds). Minor disseminated mineral occurrences are present at many levels in the succession, but concentrations into attractive deposits appear to have taken place at some of these former erosion surfaces. The implications for mineral exploration are that target areas can be significantly reduced in size if emphasis is placed on detailed stratigraphic studies aimed at recognising such breaks in the succession. Geophysical techniques may then be required to locate unexposed deposits at these stratigraphic levels.

Yah Yah copper mine (GR 454153, *Bloodwood Creek*, 5963)

Four small collapsed pits are all that now remains of the Yah Yah copper mine. The deposit, which was discovered around 1895 and produced about 40 t of high-grade oxidised ore before 1912, is hosted by brecciated dolomitic siltstone of the Amelia Dolomite disconformably overlain by the Tatoola Sandstone in the crest of a north-northeast-trending anticline. It consists of malachite and chrysocolla, which form the breccia matrix and also occur as veins and on joint planes in the siltstone. In places the malachite forms spherules (up to 5 cm in diameter) of radiating crystals; the chrysocolla is amorphous.

A possibly similar deposit (Balbirini prospect; Daly, 1969) on Sandy Creek, east of Yah Yah, is almost totally concealed beneath the Top Springs Limestone, and its field relations are unknown.

Johnstons prospect (GR 684019, *Batten*, 6065)

This prospect was mined by a Mr Johnston, whose grave is immediately west of the pits. It has been drilled by Carpentaria Exploration Co. Pty Ltd. The deposit here is similar to the one at Yah Yah in its stratigraphic and structural setting, but consists of malachite, azurite, and tenorite, with traces of Pb and Zn.

Sly Creek prospect (GR 473578, *Tawallah Range*, 6066)

At Sly Creek, several small pits have been sunk on a gossan in the Amelia Dolomite which contains malachite, chalcopyrite, and less common azurite. The deposit occupies the regolith immediately below the Balbirini Dolomite basal arenite (previously the 'Mount Birch Sandstone'). A north-south fault nearby may have enhanced the permeability of the host rock. The prospect has not been fully tested.

Kilgour copper mine (GR 830018)

The Kilgour mine had produced about 125 t of ore up to 1955. The host rock is stromatolitic and oolitic Amelia Dolomite overlain by the Bukalara Sandstone. Extensive weathering and erosion—during the Late Proterozoic, before the Bukalara Sandstone accumulated—produced an irregular land surface that shows extensive karsting. The Bukalara Sandstone commonly infills solution or collapse features. High concentrations of malachite occur in joints and in cave breccias containing terra rossa within the Amelia Dolomite. The remains of a massive copper-hematite gossan are present: an analysis of one sample of this revealed a content of 16% Cu. Minor barite is associated with the gossan, which also contains cerussite and bornite.

Darcys Copper King prospect (GR 819259)

The Darcys Copper King prospect occurs at the unconformable contact between the Reward Dolomite and Balbirini Dolomite. A widespread thin ironstone was developed during the Proterozoic karstic weathering that resulted in this unconformity, which is characterised by widespread copper-mineralised rock throughout most of the southern part of BAUHINIA DOWNS (i.e., up to 30 km west and east of Mallapunyah). Minor traces of malachite are invariably present at the unconformity, but one larger concentration of workable copper minerals has been found: Darcys Copper King. At this locality, the copper minerals occur as matrix-filling in breccias that appear to fill solution cavities in the Reward Dolomite. Although much of the deposit has been removed, malachite and chrysocolla are the most conspicuous minerals left, but chalcocite, cuprite, and minor chalcopyrite are present too.

Iron

Several small Fe prospects were identified in the area in the 1950s. Following the discovery of the Hamersley Iron Province in the early 1960s, interest in the Fe deposits of the McArthur Basin has evanesced. However, a brief account of the deposits is given here for completeness.

Tawallah Group—Sly Creek Sandstone

In the Tawallah Ranges (MOUNT YOUNG and BAUHINIA DOWNS), chamositic oolitic sandstone occurs at several locations in the upper part of the Sly Creek Sandstone (Johnstone, 1974), but is not of economic importance.

McArthur Group—Mallapunyah Formation

In the Tawallah Ranges, and north of the police station at Roper Bar (URAPUNGA), quartz-hematite rocks are developed near the contact between the Mallapunyah Formation and the Masterton Sandstone or their equivalents. They are too small to have any economic significance.

Roper Group—Abner Sandstone

The Abner Sandstone in BAUHINIA DOWNS is commonly hematitic, and contains 45% Fe in the north-eastern corner of the Abner Range. The Munyi Member of the Abner Sandstone contains up to 25% Fe in MOUNT YOUNG and URAPUNGA. However, grades are too low to be of economic interest at present.

Roper Group—Sherwin Ironstone Member of the McMinn Formation

The deposits in the Sherwin Ironstone Member are the largest recorded. They were explored by BHP Co. Ltd in the 1950s (Cochrane & Edwards, 1960). The ironstone is best developed at Sherwin Creek (URAPUNGA), where it consists of three beds separated by up to 20 m of sandstone and siltstone. Where fresh, the ironstone consists of ooliths of ochreous hematite, granules of greenalite, and quartz grains in a sideritic cement. The intervening beds are in places dolomitic, and commonly contain abundant organic matter. These deposits are correlated with the Constance Range deposits, south of the Murphy Tectonic Ridge.

Uranium

Several U orebodies occur in the Westmoreland Conglomerate in the Redtree area (northwest *Hedleys Creek*, 6562). Although these are in the basal unit of the McArthur Basin, they are outside the area covered by this Bulletin, and we have not examined them. A summary of the main features of the most significant prospects is presented in Sweet & others (1981).

Gold

Free Au has been reported by prospectors in the Tin Hole Creek and Gold Creek areas in CALVERT HILLS. Small amounts of Au occur in the ores at Pandanus Creek (GR 989427, *Seigal*, 6462) and Cobar II (GR 076616, *Seigal*, 6462) mines.

Manganese

Small amounts of Mn occur as residual deposits in the Nathan Group (BAUHINIA DOWNS) and Karns Dolomite (CALVERT HILLS). The deposits are mainly psilomelane, pyrolusite, and rhodochrosite, and are not of economic importance. No workings are known.

Hydrocarbons

Solid, liquid, and gaseous hydrocarbons, and oil shales, are present in the area. Oil shales occur in the Fickling Group in CALVERT HILLS (Roberts & others, 1963), and highly carbonaceous shales are present in many formations of the Tawallah, McArthur, Nathan, and Roper Groups.

A solid hydrocarbon identified as impsonite was recorded by Dixon (1957) from the Karns Dolomite in the Calvert River and Bluey Creek. Muir & others (1980a) discovered solid hydrocarbons in vuggy carbonates of the Looking Glass Formation in drillcore at Beetle Springs, east of the Abner Range; the solids were acompanied by a small amount of an oily liquid which bled from intergrain pore spaces. At about the same time, Kennecott Exploration Co. encountered a gas pocket in the Teena Dolomite in a mineral exploration hole in the Glyde River area southeast of McArthur mine. Amoco International explored for oil between 1981 and 1985 and undertook stratigraphic drilling and seismic surveys which culminated in the drilling of a dry wildcat well—northeast of Broadmere homestead—in 1984 (Amoco, 1985).

In 1984, BMR started a systematic evaluation of the basin's petroleum potential. Several formations including shales and carbonates contain organic-rich rocks. Potential petroleum source beds at various stages of hydrocarbon generation (maturation) ranging from immature to overmature have been found in drillcore at four different stratigraphic levels—Barney Creek Formation, Lynott Formation, Yalco Formation, and Velkerri Formation. The hydrocarbon-generating capability of the Velkerri Formation was confirmed in June 1985, when live oil was encountered near the base of the formation in BMR Urapunga No. 4 (Jackson & others, 1986).

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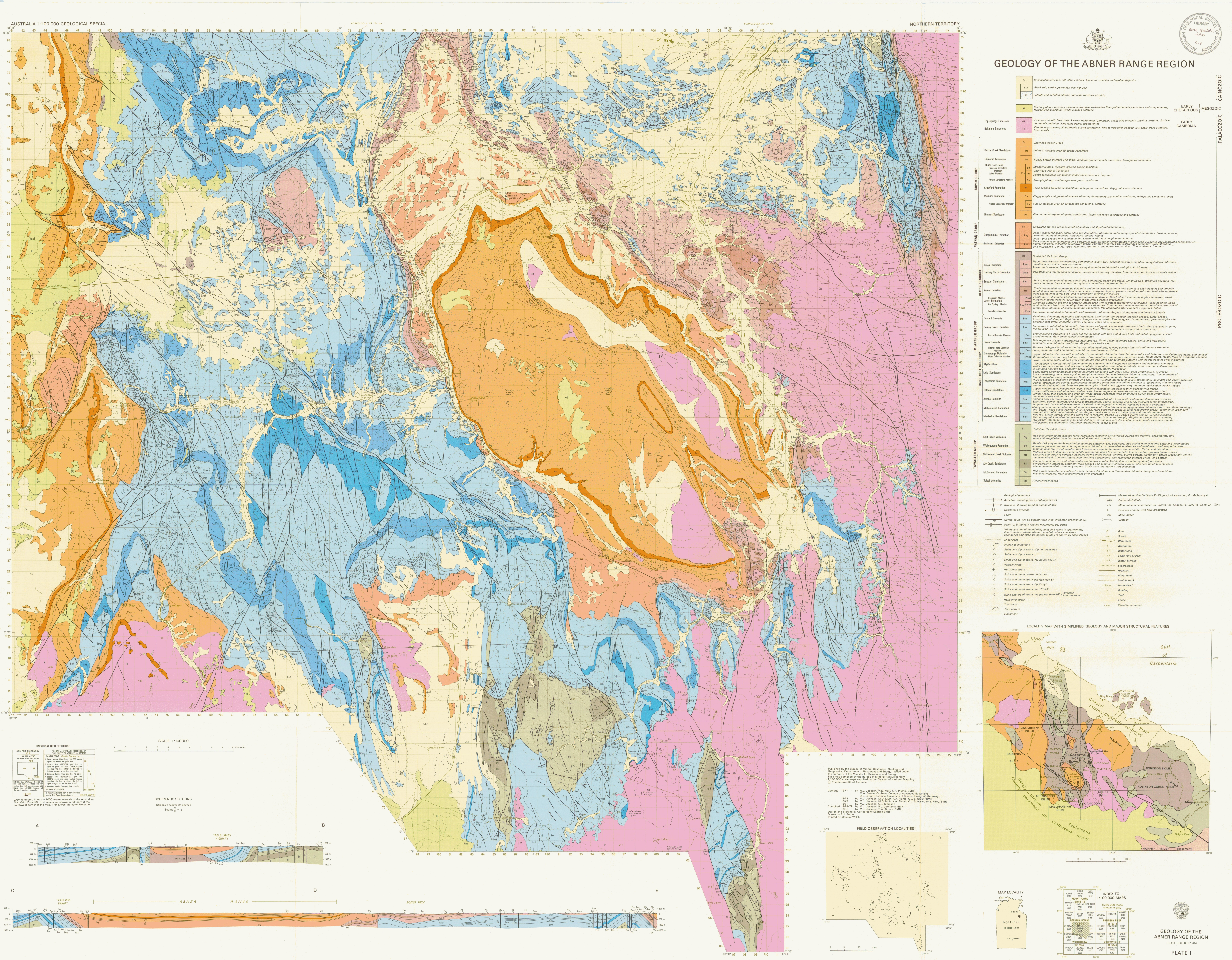
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NORTHERN TERRITORY
GEOLOGY OF THE ABNER RANGE REGION
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MESOZOIC
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PROTEROZOIC
EARLY CRETACEOUS
EARLY CAMBRIAN
SCALE 1:100 000
SCHEMATIC SECTIONS
LOCALITY MAP WITH SIMPLIFIED GEOLOGY AND MAJOR STRUCTURAL FEATURES
Gulf of Carpentaria
FIELD OBSERVATION LOCALITIES
MAP LOCALITY
NORTHERN TERRITORY
INDEX TO 1:100 000 MAPS
ABNER RANGE
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FIRST EDITION 1984
PLATE 1

APPENDIX 1

MEASURED SECTIONS AND DRILLHOLE LOGS

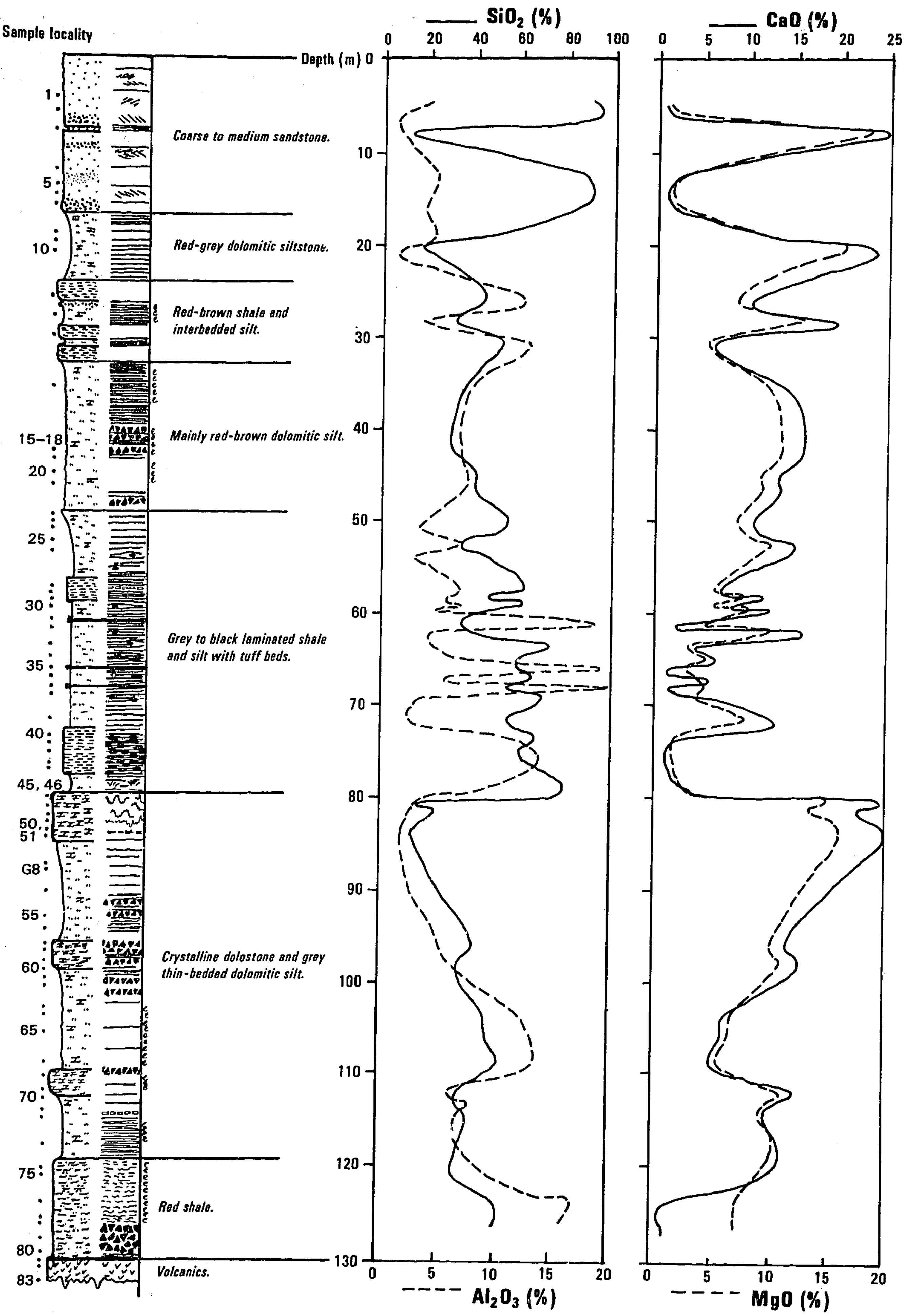


FIG A1 Geochemical characteristics of Wollogorang Formation in diamond drillhole BMR Mt Young No 2 (after Jackson 1982a)

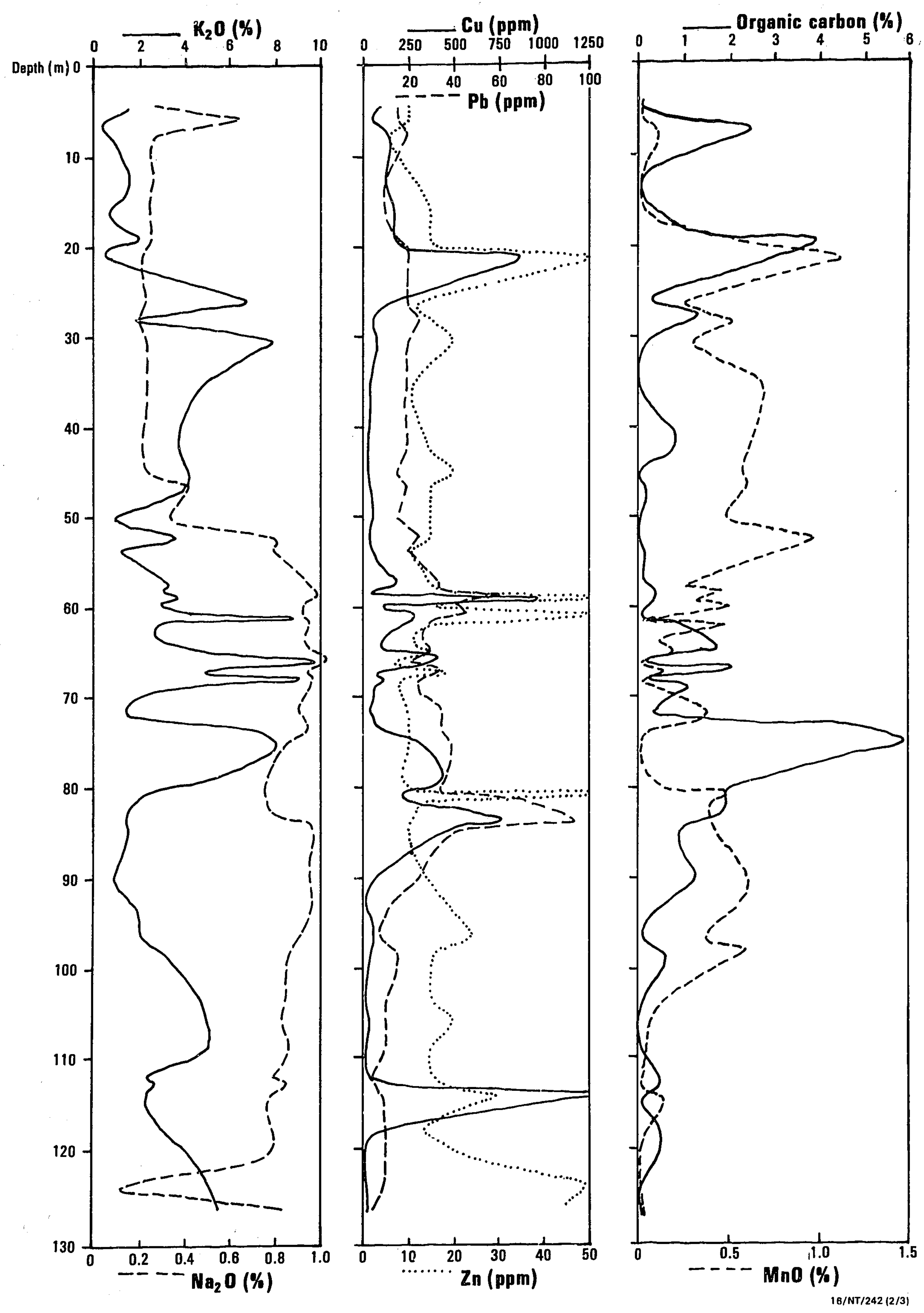
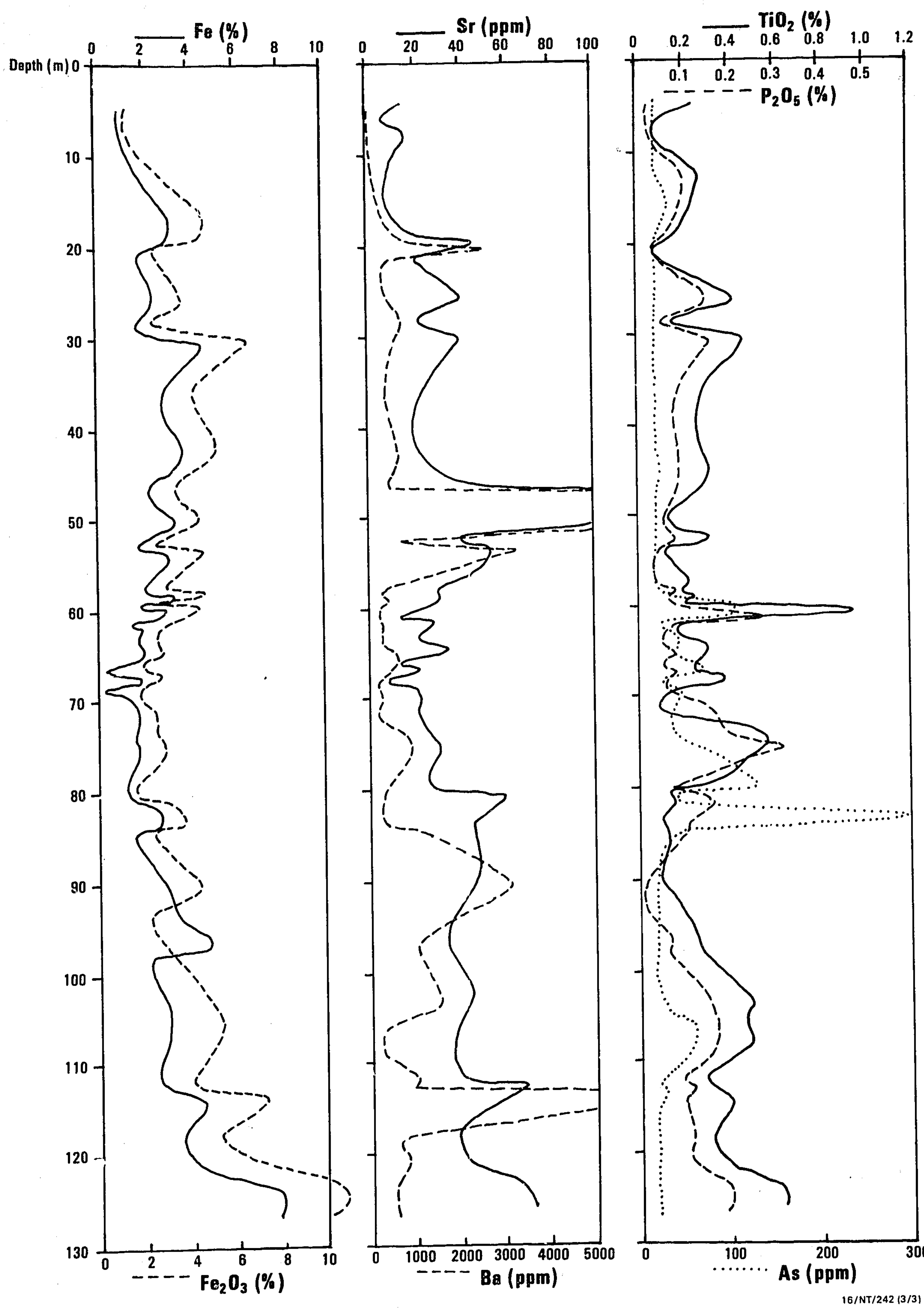


FIG A1 (continued)



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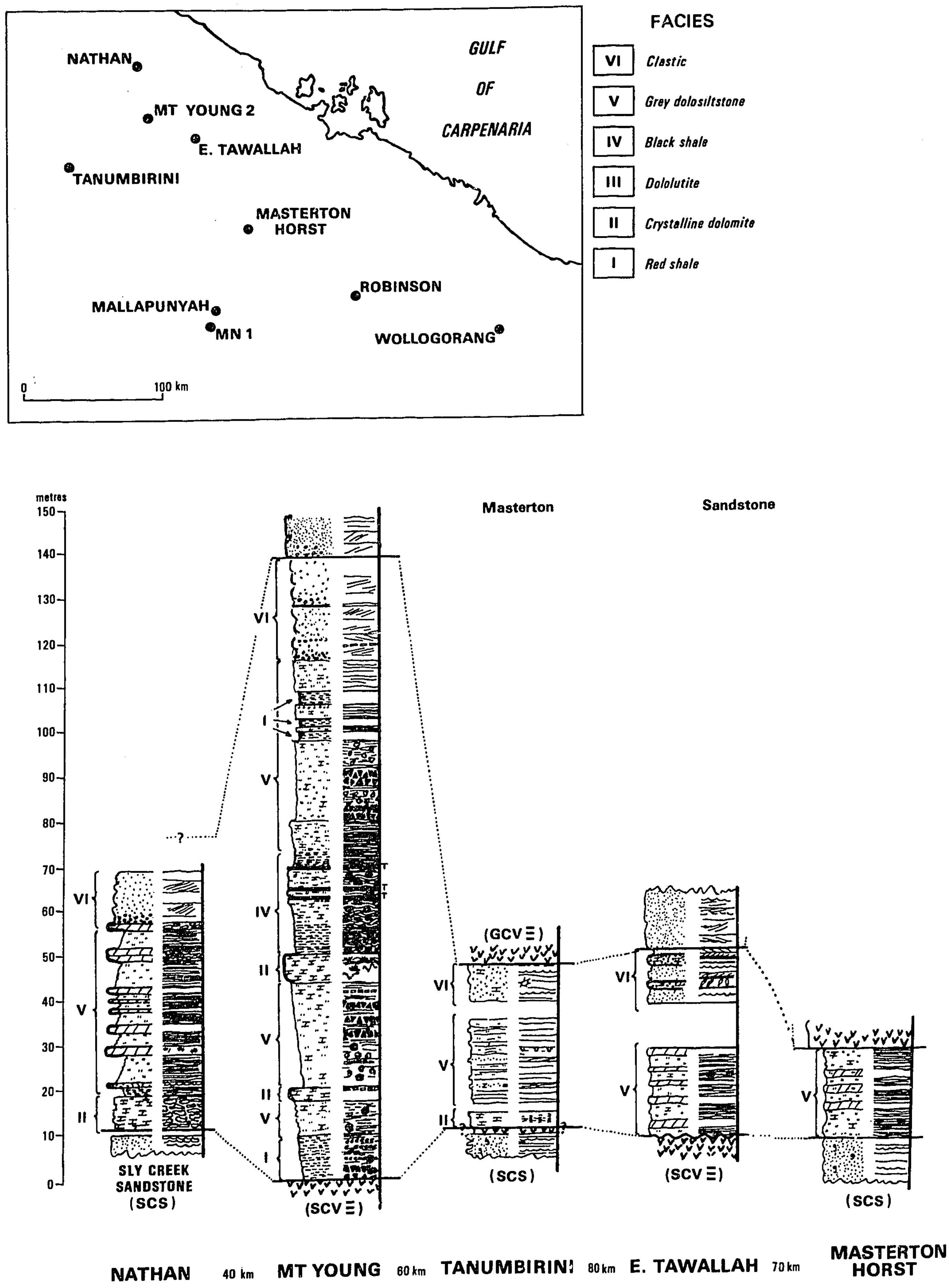


FIG A2 Regional facies and thickness variations in the Wollogorang Formation (after Jackson 1982a)

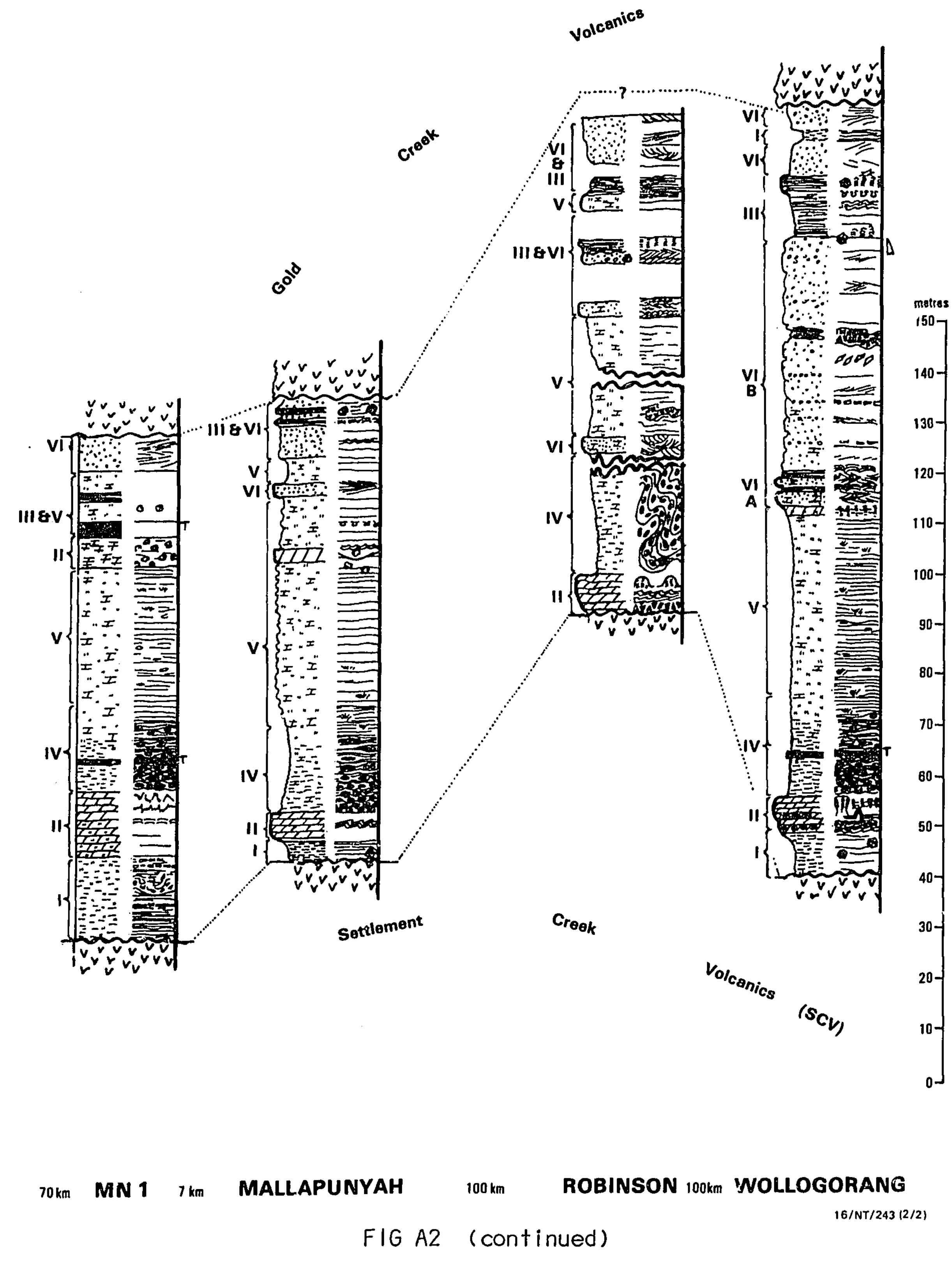


FIG A2 (continued)

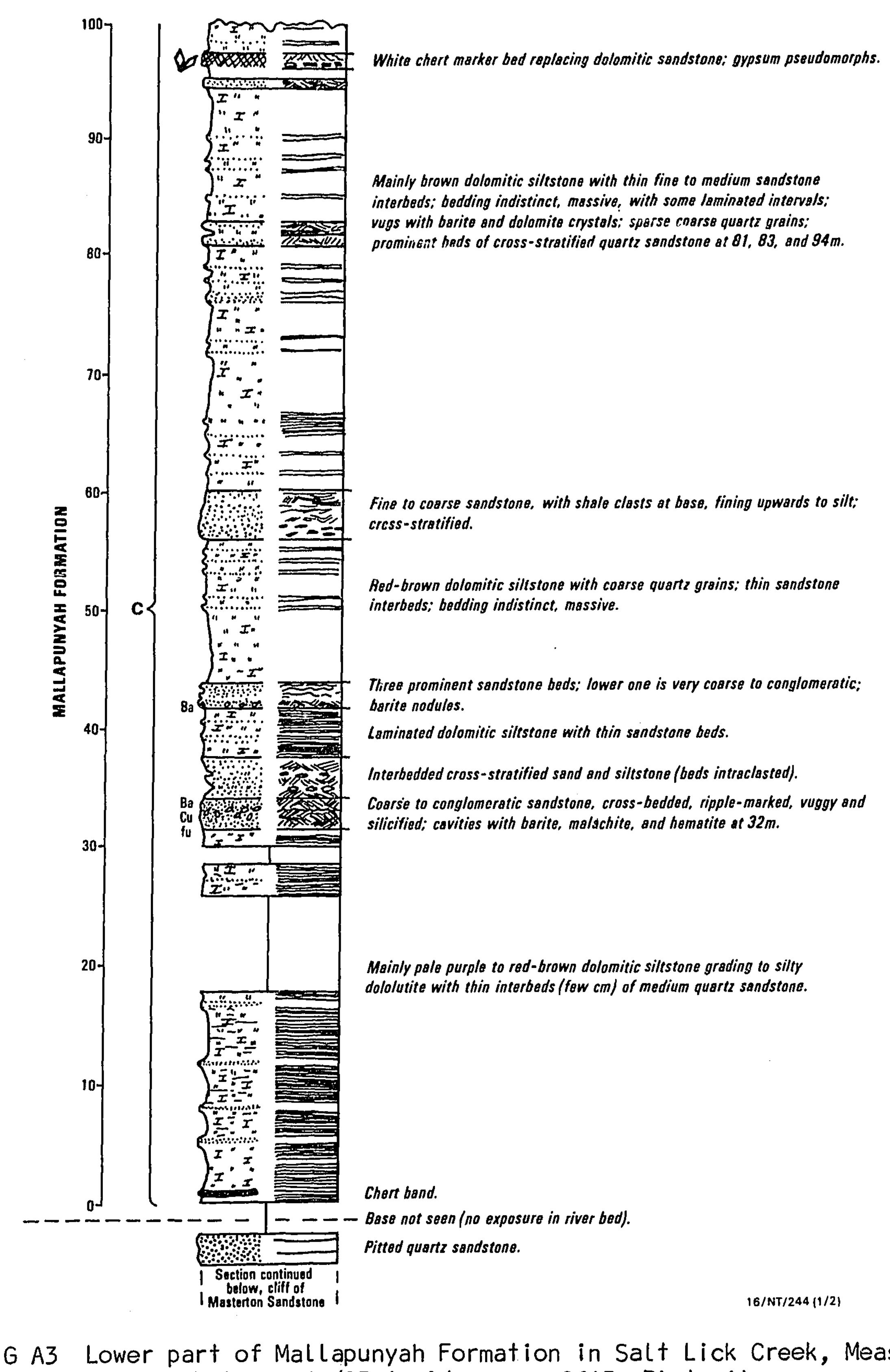


FIG A3 Lower part of Mallapunyah Formation in Salt Lick Creek, Measured Section Kilgour 78/07 (grid square 9615, Plate 1)

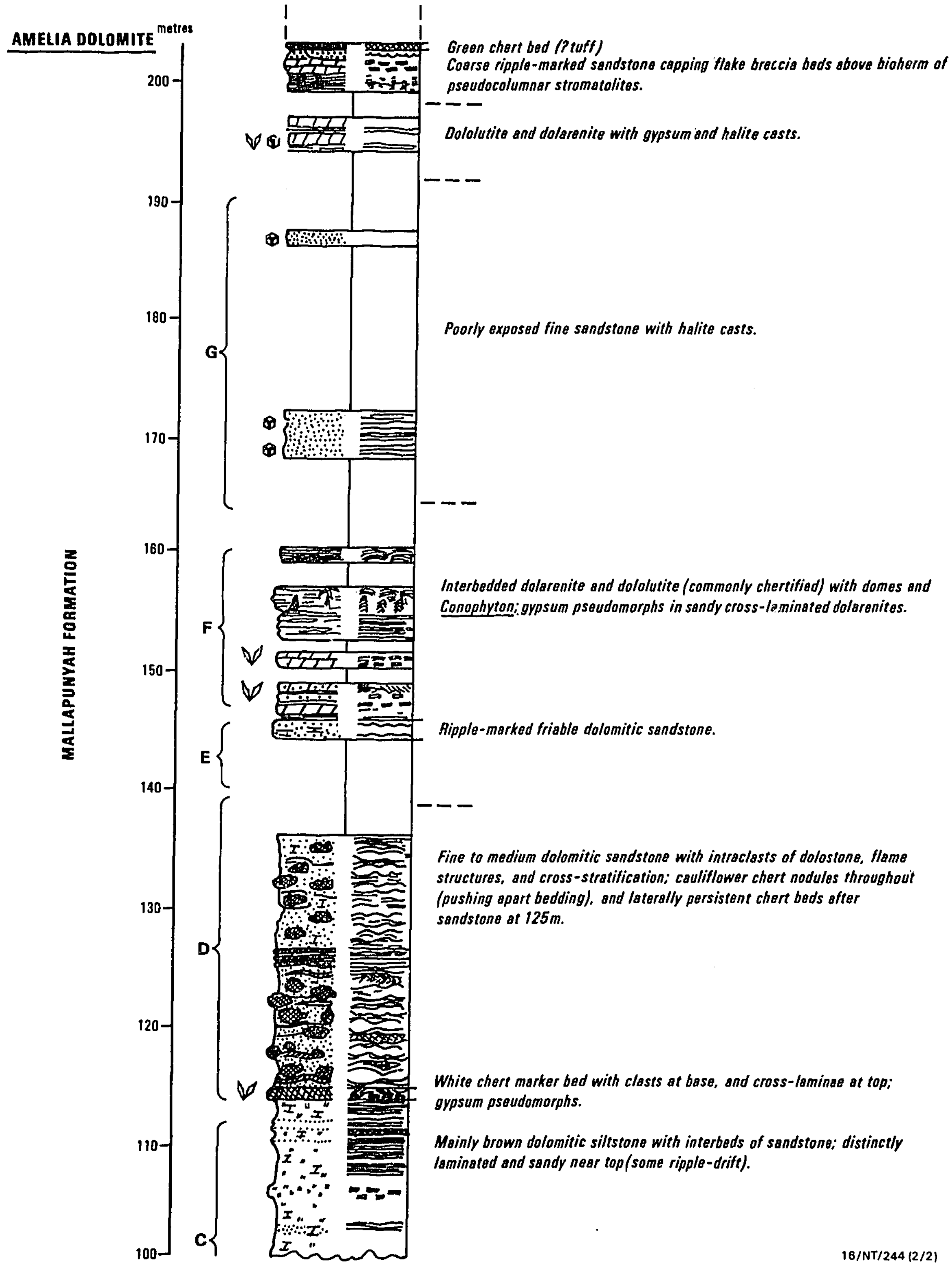


FIG A3 (continued) Upper part of Mallapunyah Formation in Salt Lick Creek, Measured Section Kilgour 78/07 (grid square 9615, Plate 1)

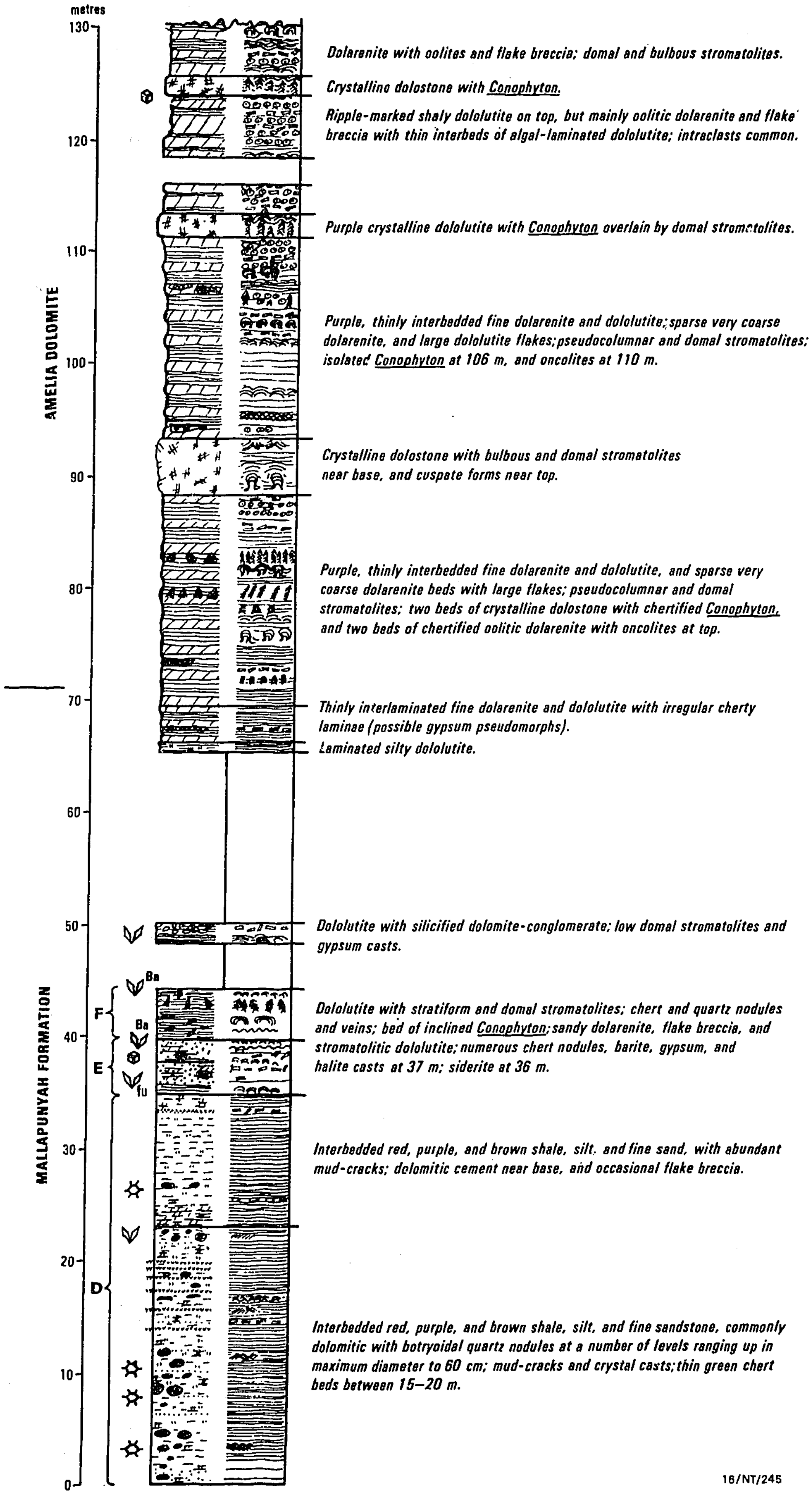


FIG A4 Upper part of Mallapunyah Formation and lower part of Amelia Dolomite in Kilgour River, Measured Section Kilgour 77/10 (grid square 9813, Plate 1)

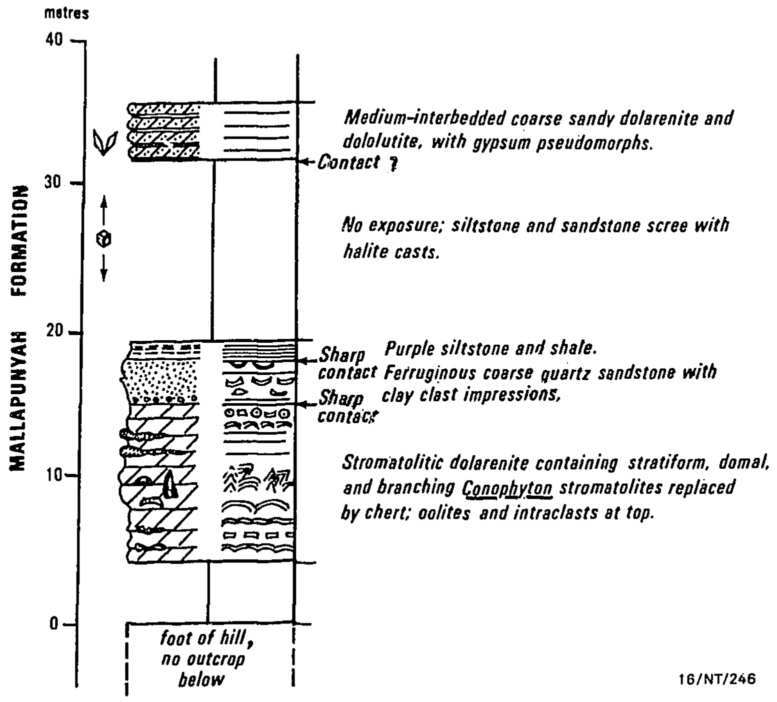


FIG A5 Short section of upper halite beds of Mallapunyah Formation 4km northwest of Kiana homestead, Measured Section Kilgour 78/05 (grid square 0507, Plate 1)

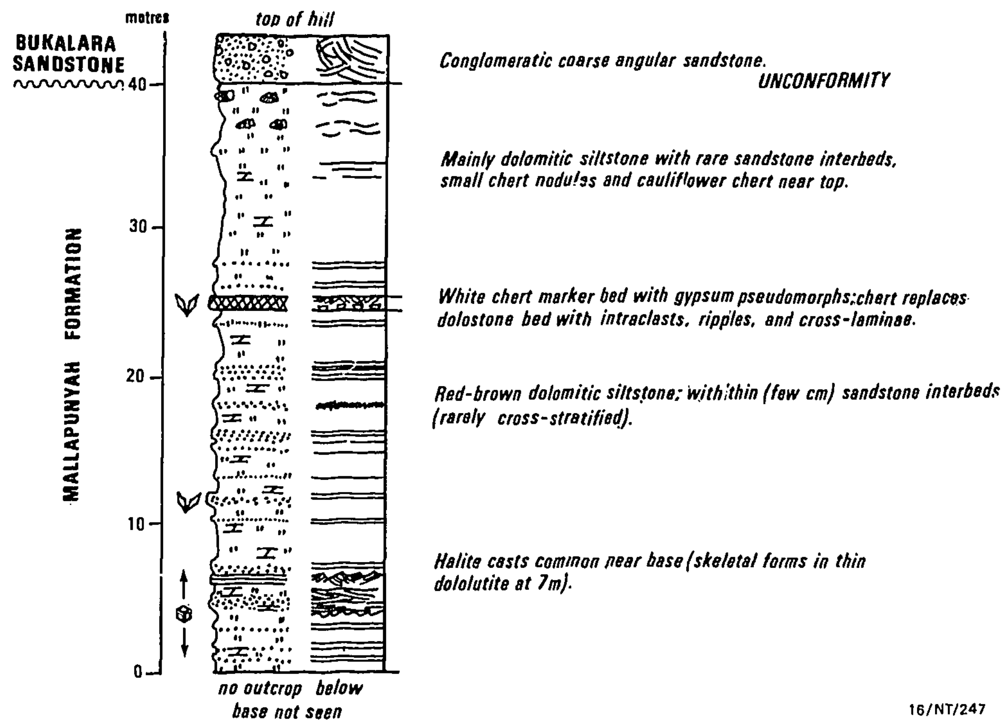


FIG A6 Short section of upper part of Mallapunyah Formation 6km west of Kiana homestead, Measured Section Kilgour 78/04 (grid square 0207, Plate 1)

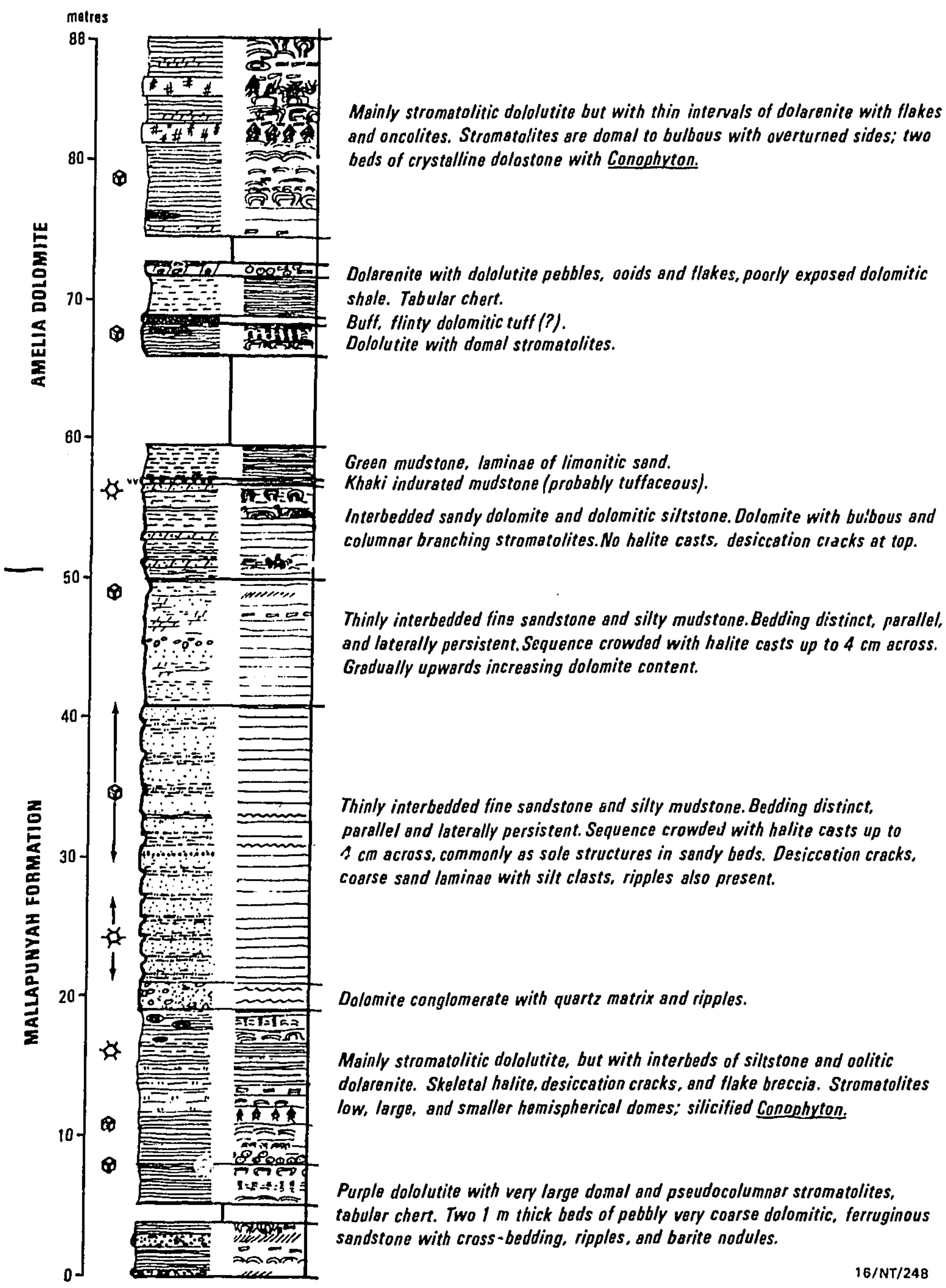


FIG A7 Upper part of Mallapunyah Formation and lower part of Amelia Dolomite in Kilgour Gorge, Measured Section Kilgour 77/12 (grid square 9609, Plate 1)

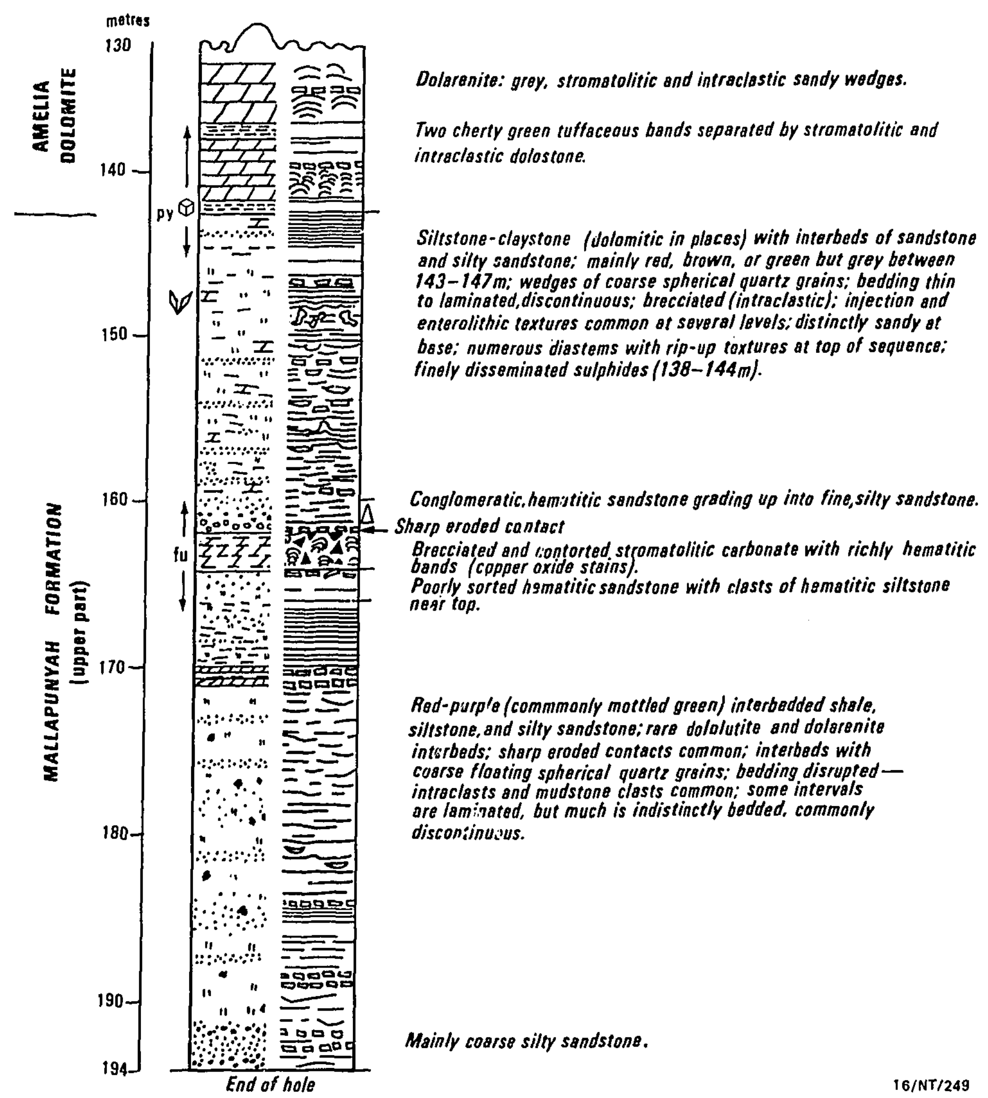


FIG A8 Upper part of Mallapunyah Formation and lowermost Amelia Dolomite in Amoco drillhole No 6, Foelsche Inlier (grid square 5732 on Glyde 6164 map)

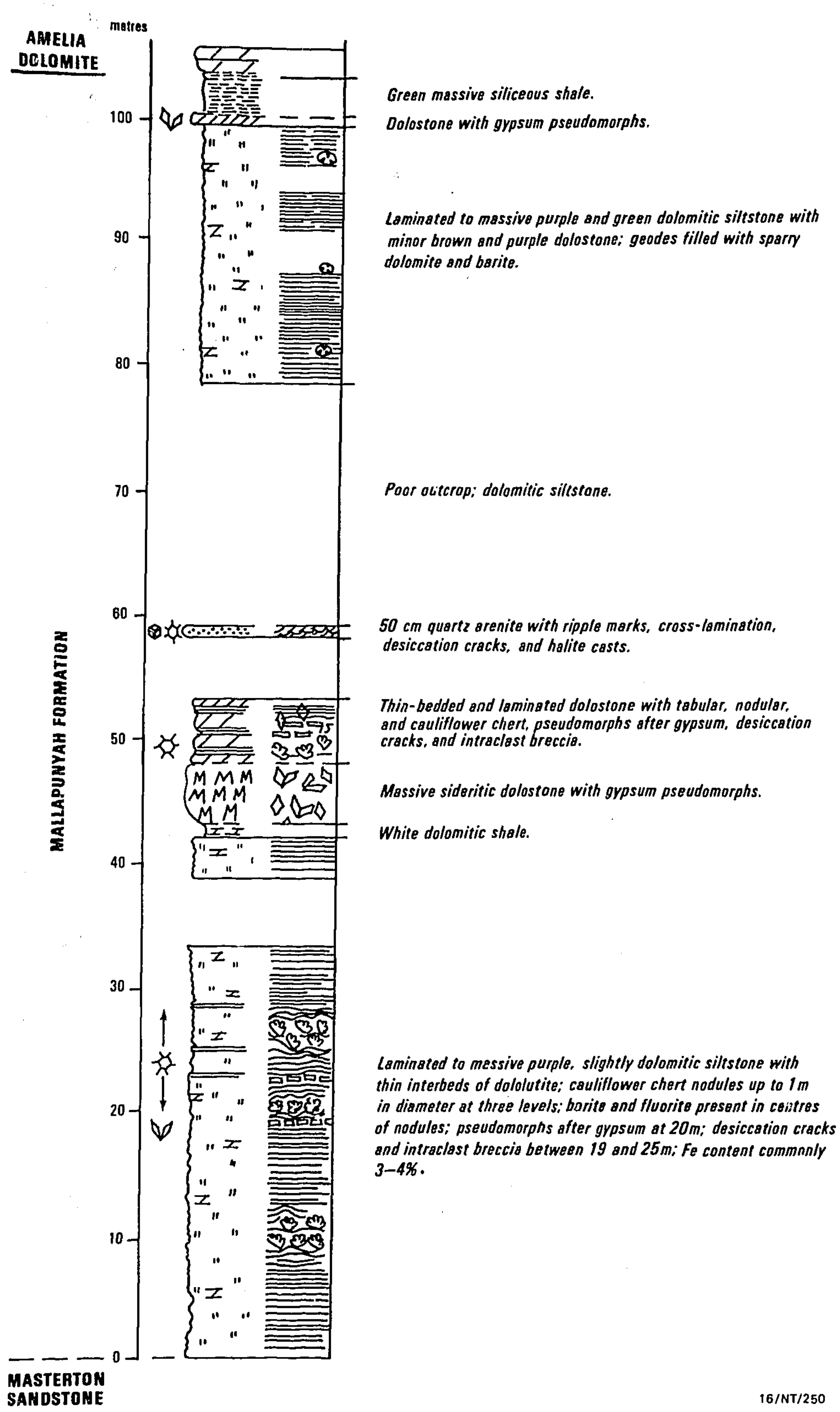


FIG A9 Mallapunyah Formation adjacent to Emu Fault Zone, near McArthur mine (modified after R.N. Walker, CEC Pty Ltd, personal communication 27.3.79); grid square 2076 Borroloola 6165 map).

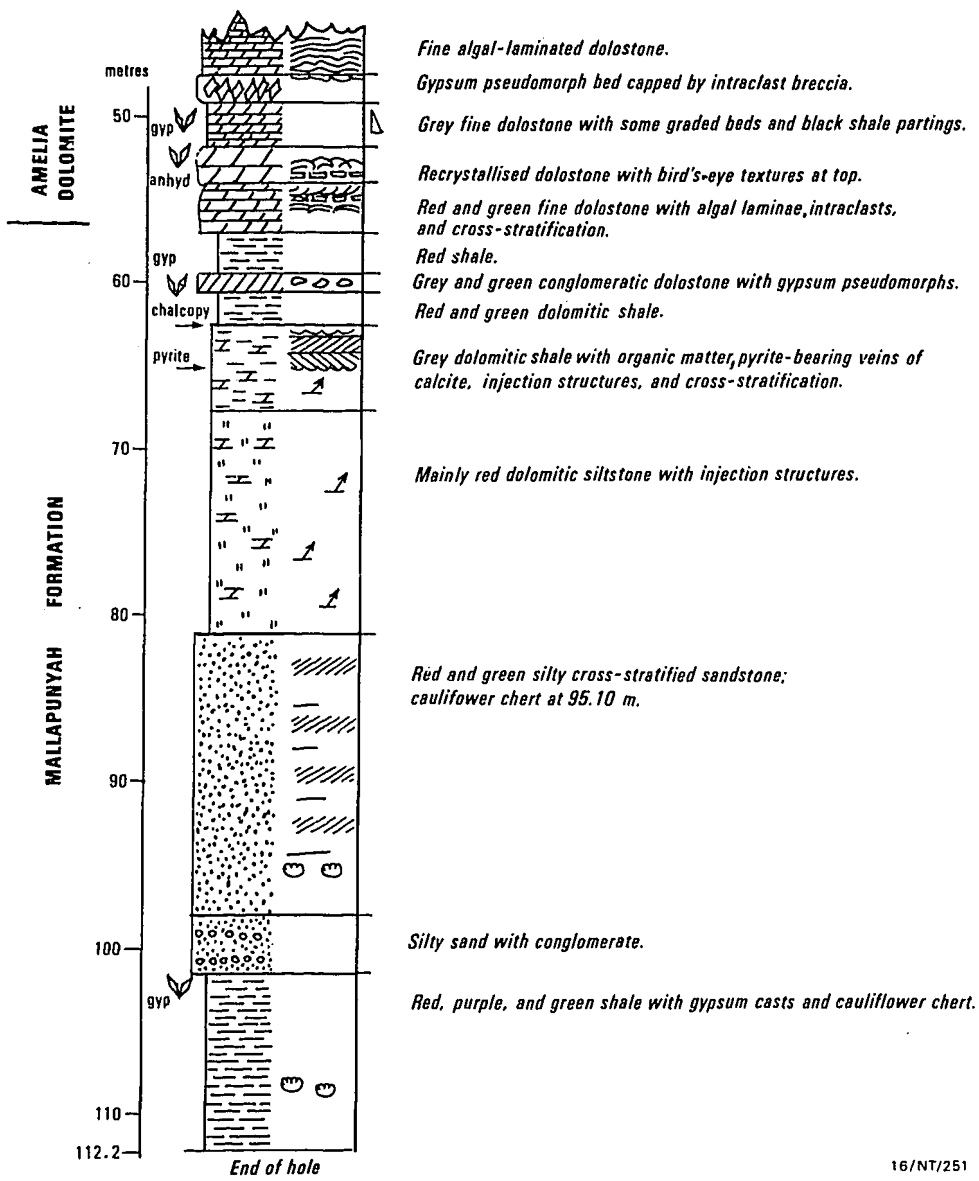


FIG A10 Mallapunyah Formation and lowermost Amelia Dolomite in part of CEC drillhole Tawallah Pocket No 1 (grid reference 690272 Batten 6065 map).

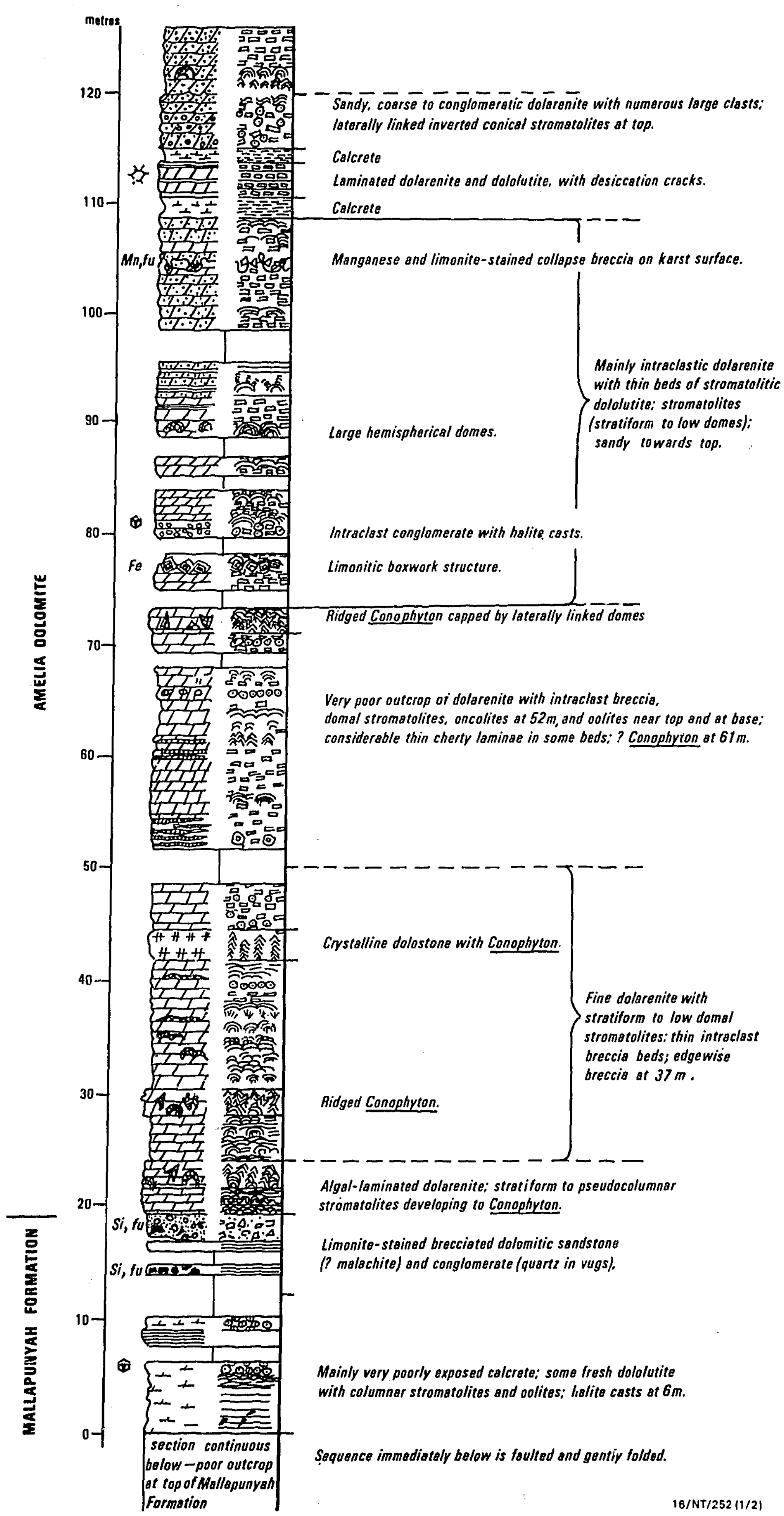


FIG A11 Upper Mallapunyah Formation, Amelia Dolomite and Tatoola Sandstone northwest of Top Spring, Measured Section Kilgour 78/06 (grid square 7119 Plate 1). Reference Section for Amelia Dolomite.

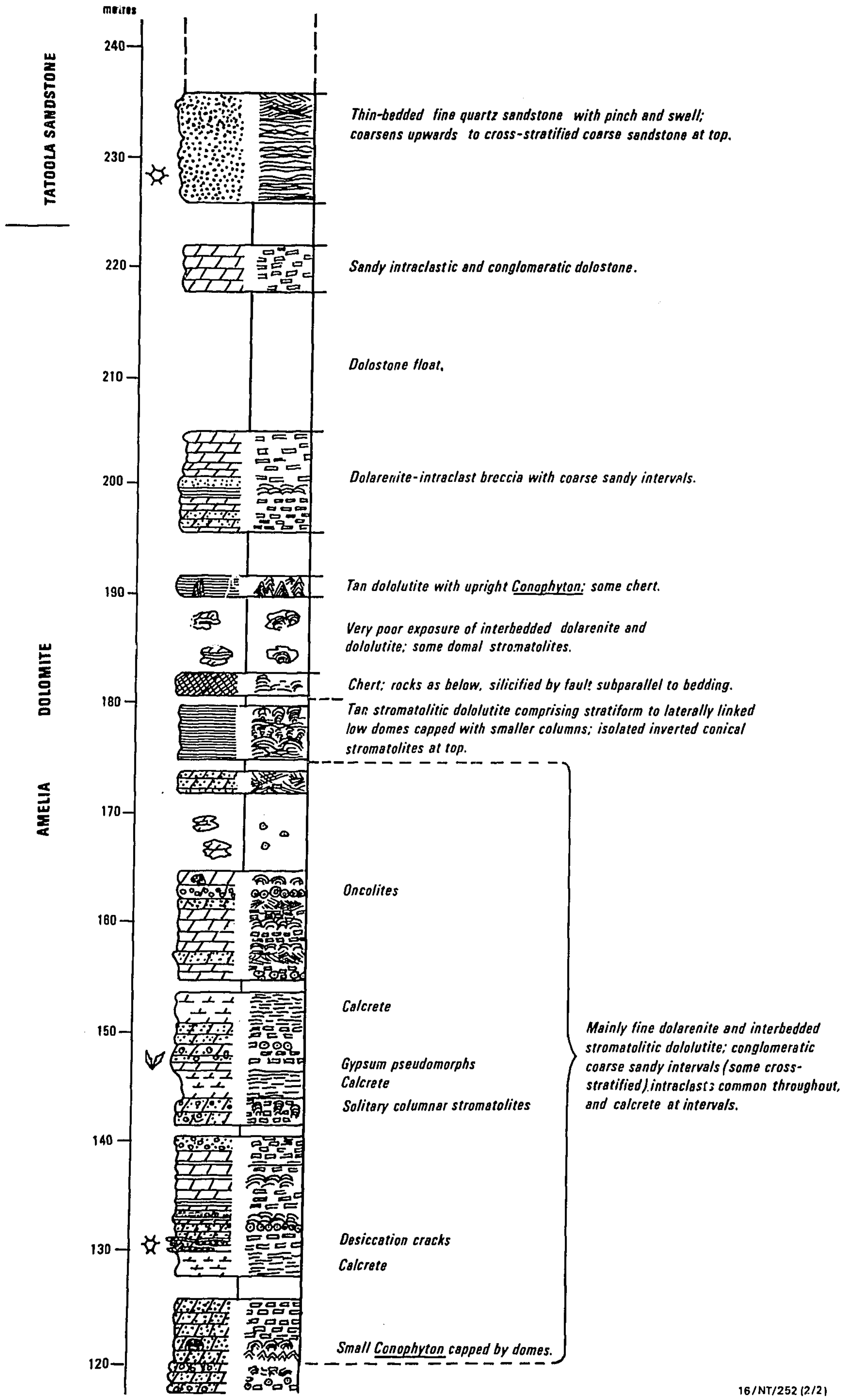


FIG A11 (continued)

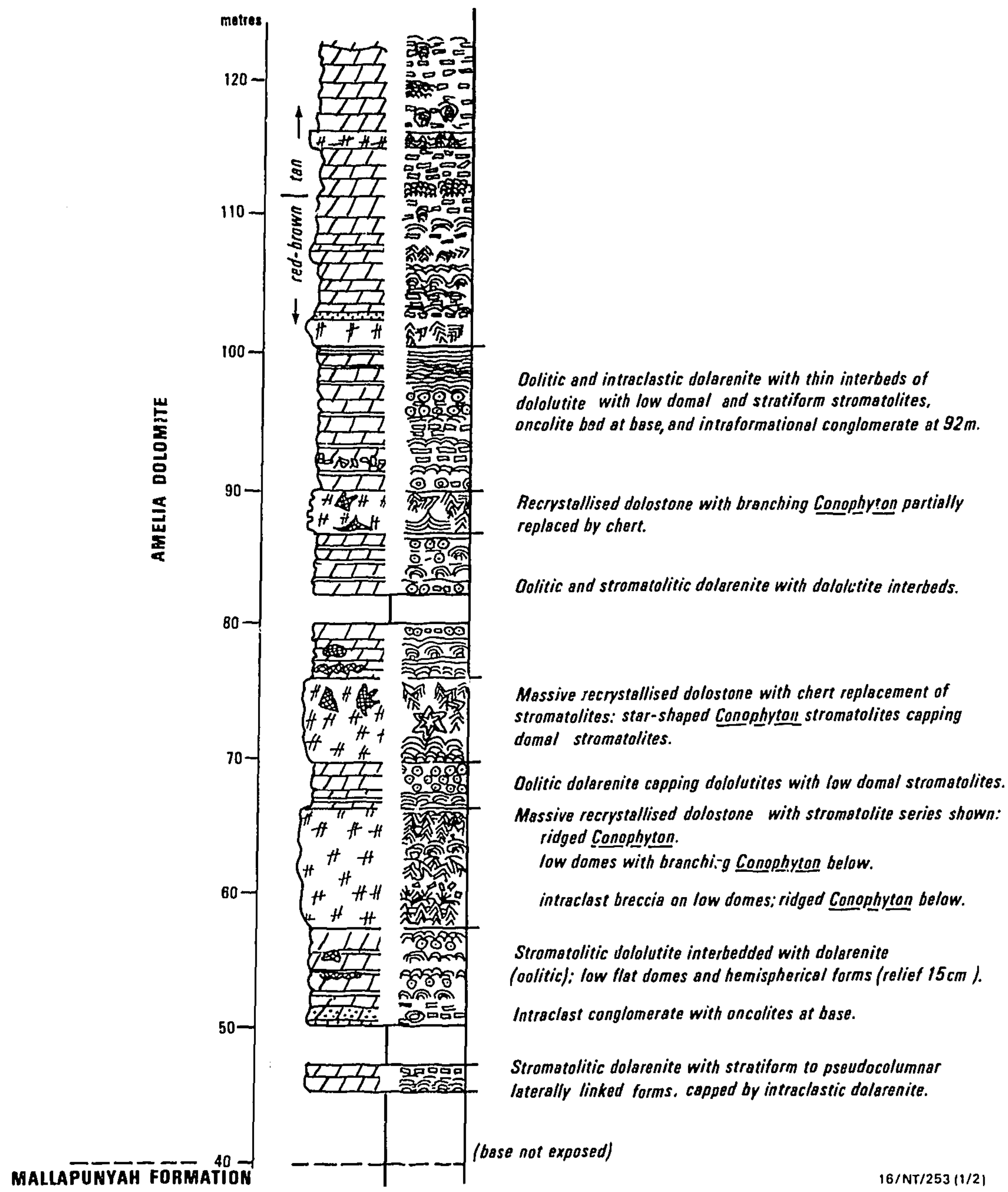


FIG A12 Amelia Dolomite and Tatoola Sandstone, 4km northwest of Kiana homestead, Measured Section Kilgour 78/05 (grid square 0507 Plate 1).

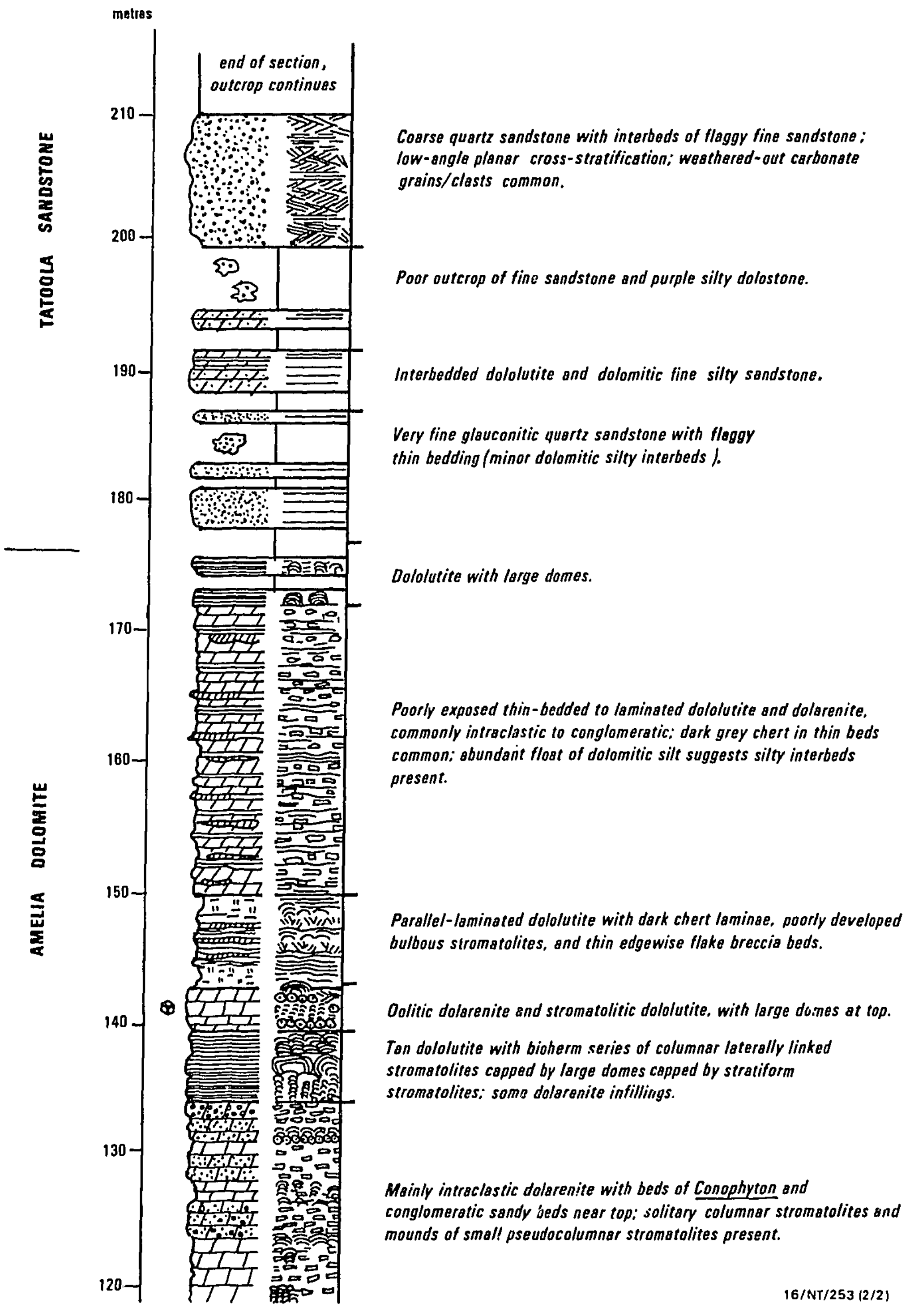


FIG A12 (continued)

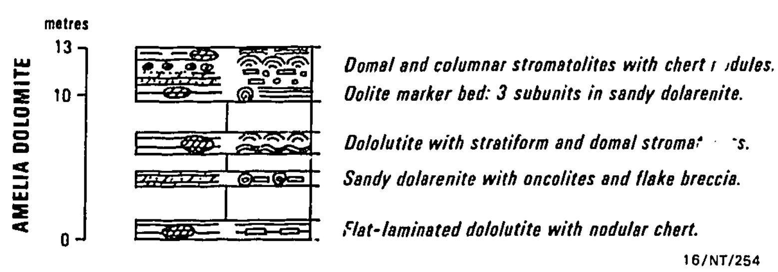


FIG A13 Part of Amelia Dolomite Leila Creek area, Measured Section Mallapunyah 77/07 (grid square 6866 Plate 1).

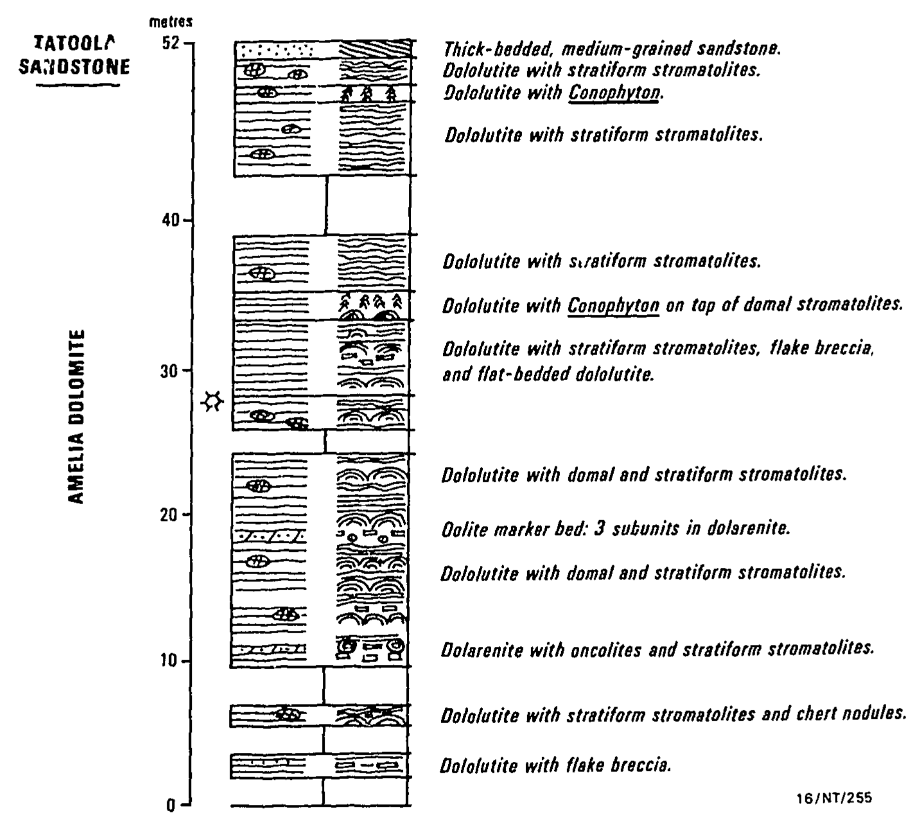


FIG A14 Amelia Dolomite Leila Creek area, Measured Section Mallapunyah 77/08 (grid square 7066 Plate 1).

FIG A15 Evaporitic Amelia Dolomite Leila Creek area, Measured Section Mallapunyah 77/09 (grid square 6966 Plate 1).

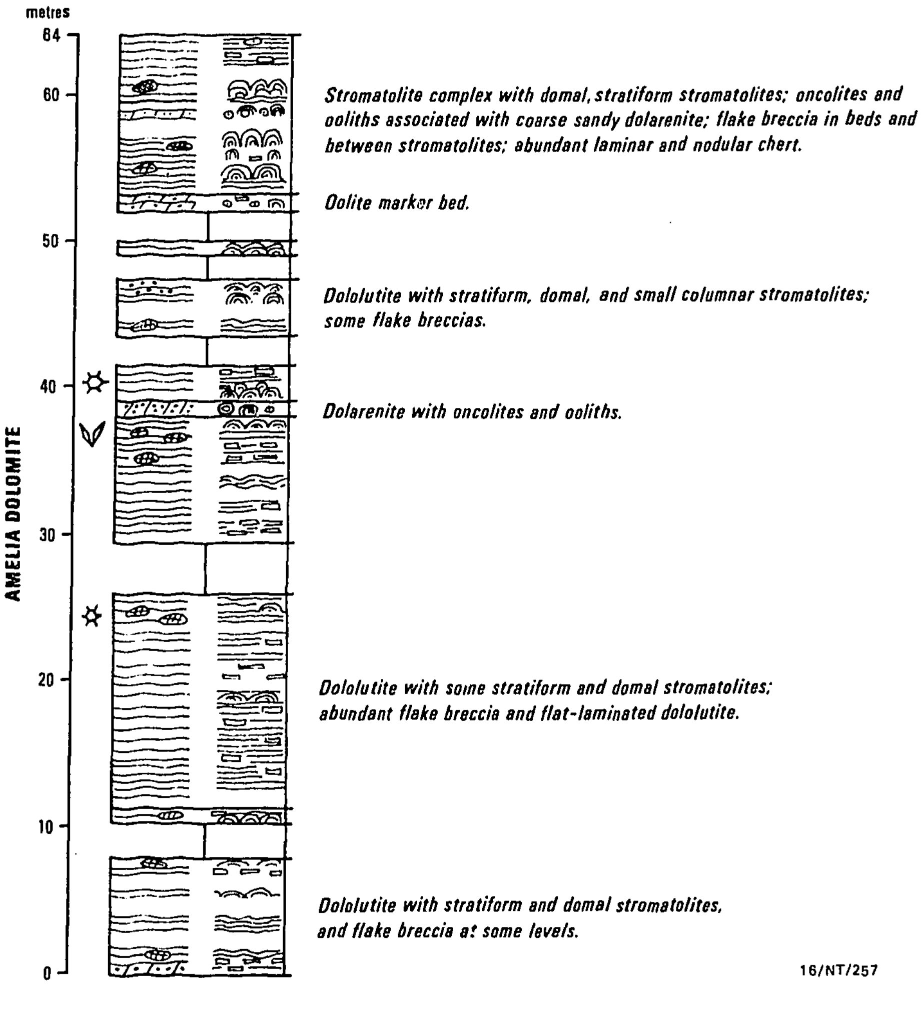


FIG A16 Amelia Dolomite Leila Creek area, Measured Section Mallapunyah 77/10 (grid square 7165 Plate 1).

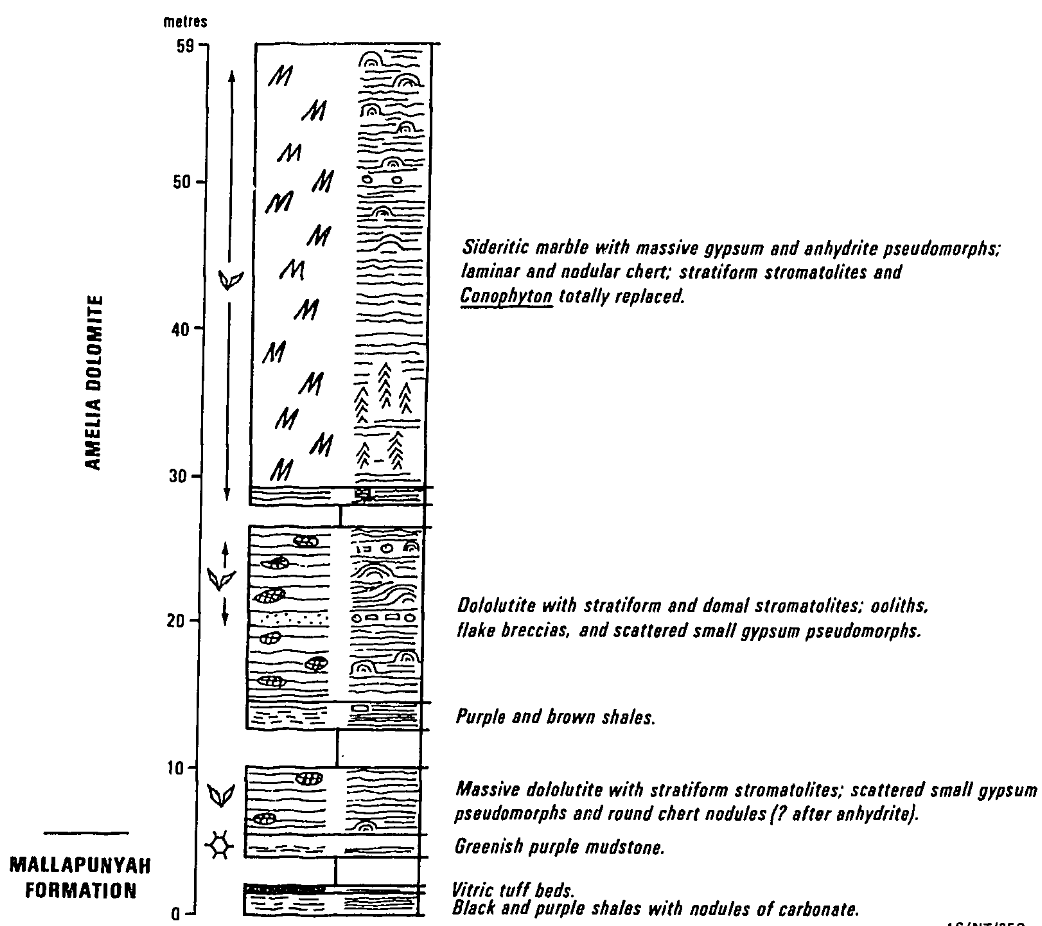


FIG A17 Evaporitic lower Amelia Dolomite, Leila Creek area, Measured Section Mallapunyah 77/11 (grid square 7167 Plate 1).

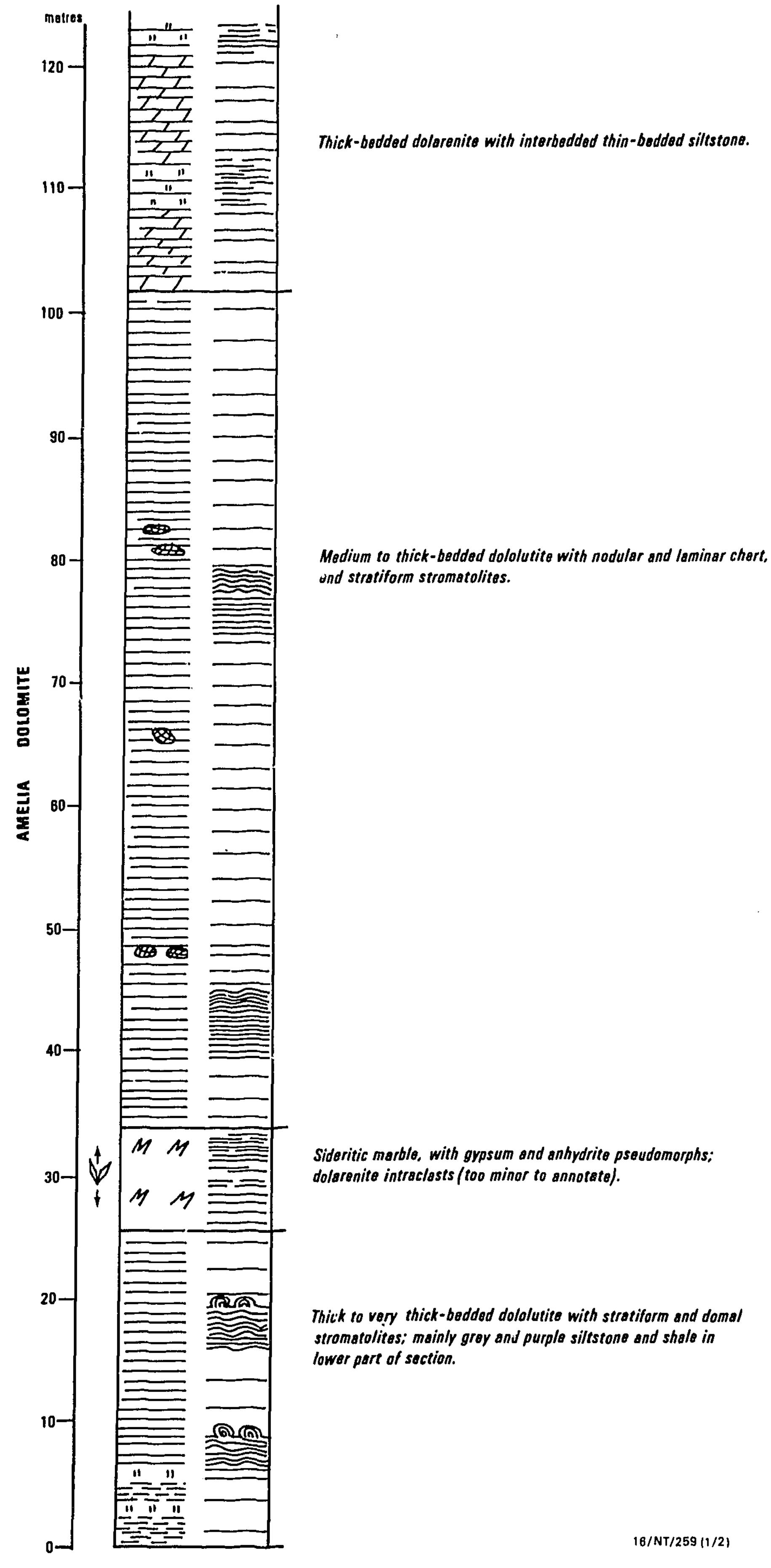


FIG A18 Thick section of Amelia Dolomite, Leila Creek area, Measured Section Mallapunyah 77/12 (grid square 6867 Plate 1).

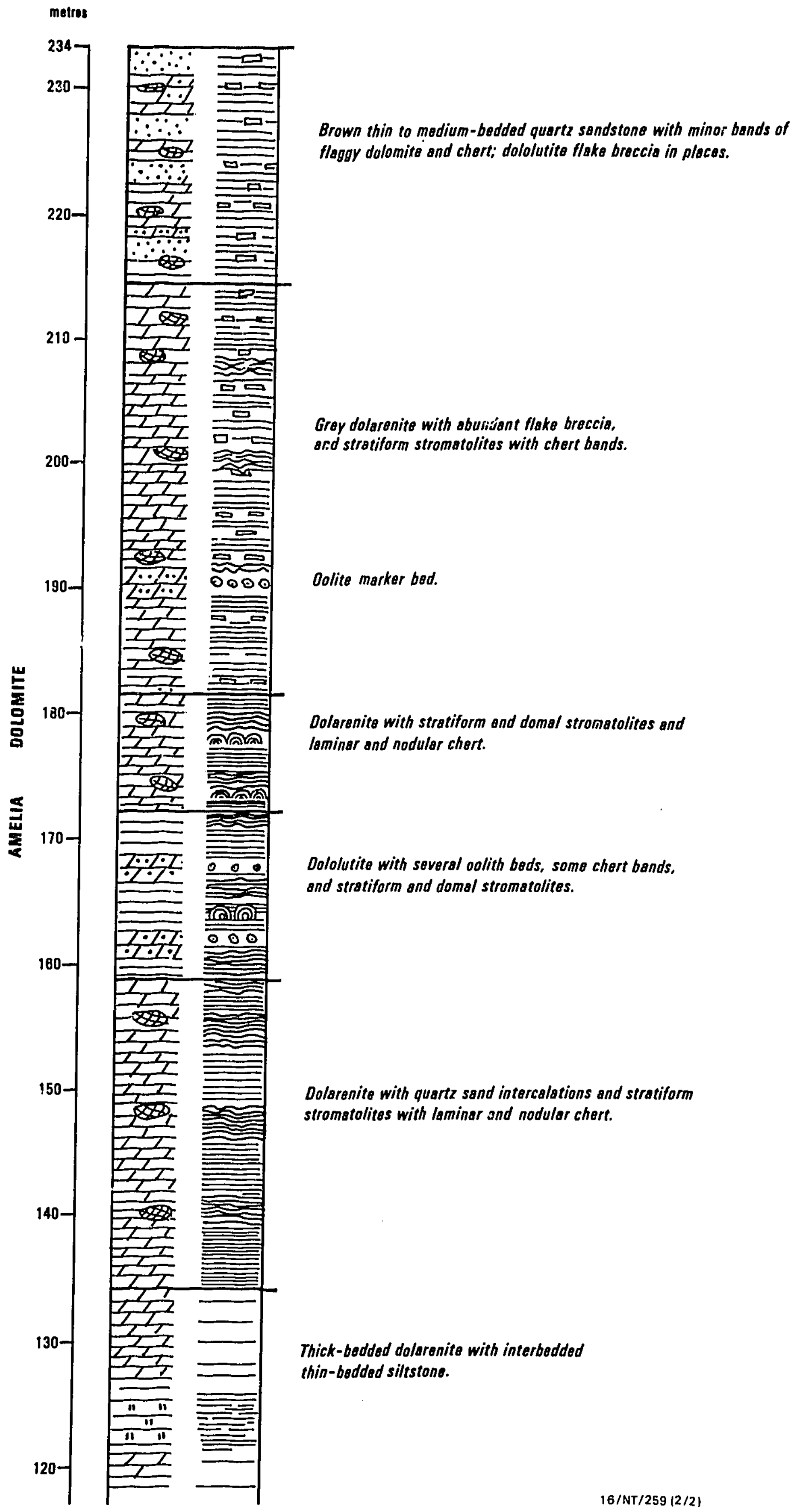


FIG A18 (continued)

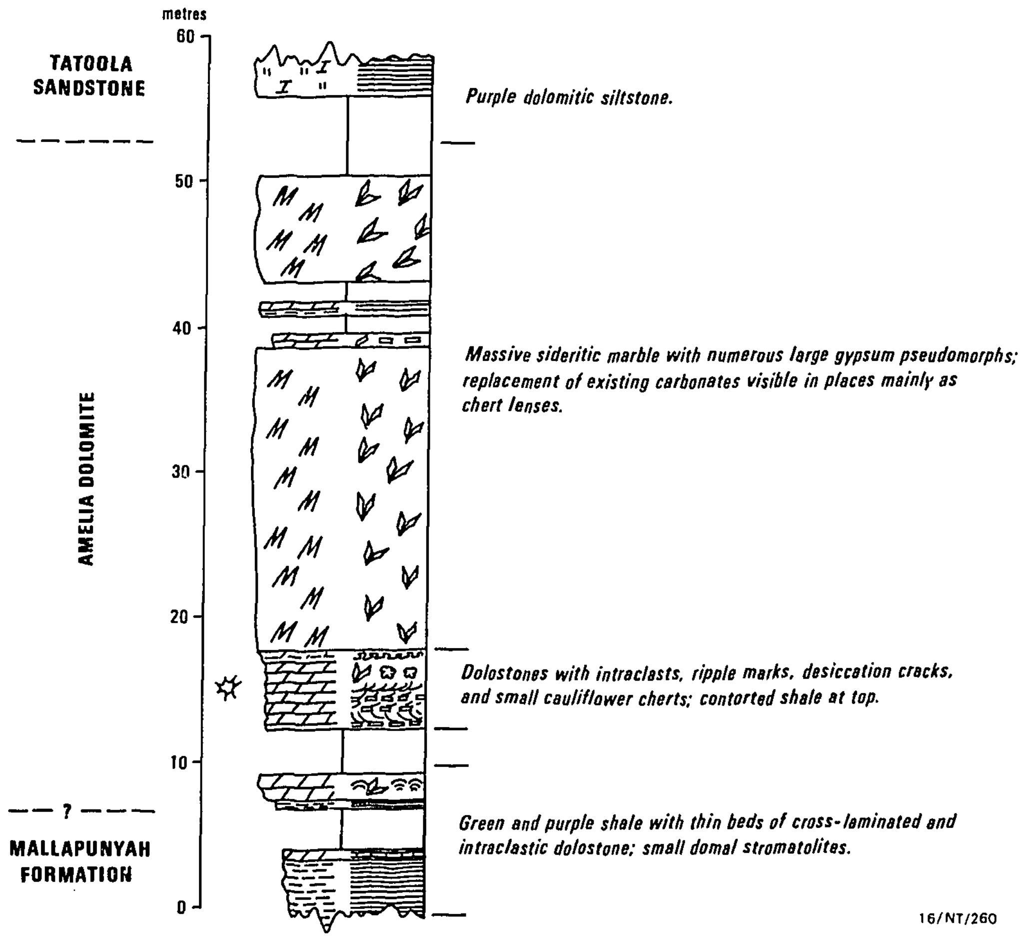


FIG A19 Evaporitic Amelia Dolomite adjacent to Emu Fault Zone, near McArthur mine (modified after R.N. Walker, CEC Pty Ltd, personal communications 27.3.79); grid square 2076 Borroloola 6165 map.

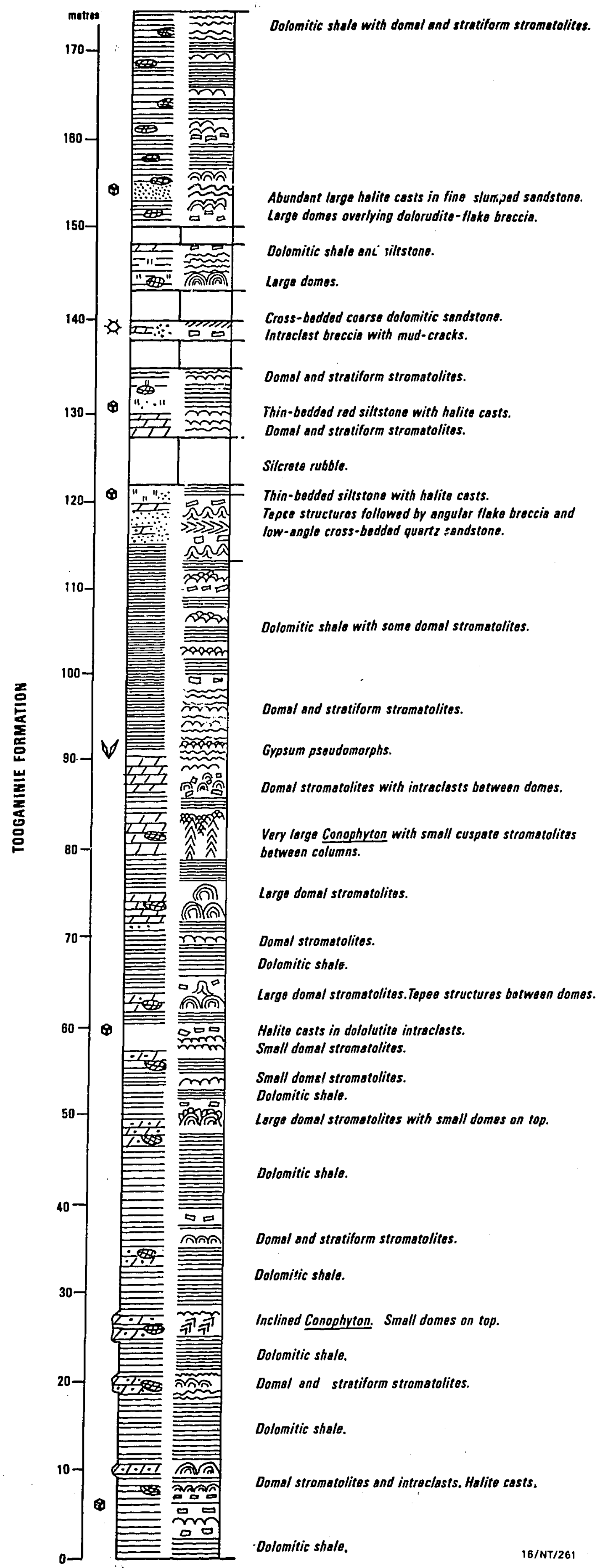


FIG A20 Part of Tooganinie Formation near William Yard, Measured Section Glyde 78/01 (grid square 1927 Plate 1).

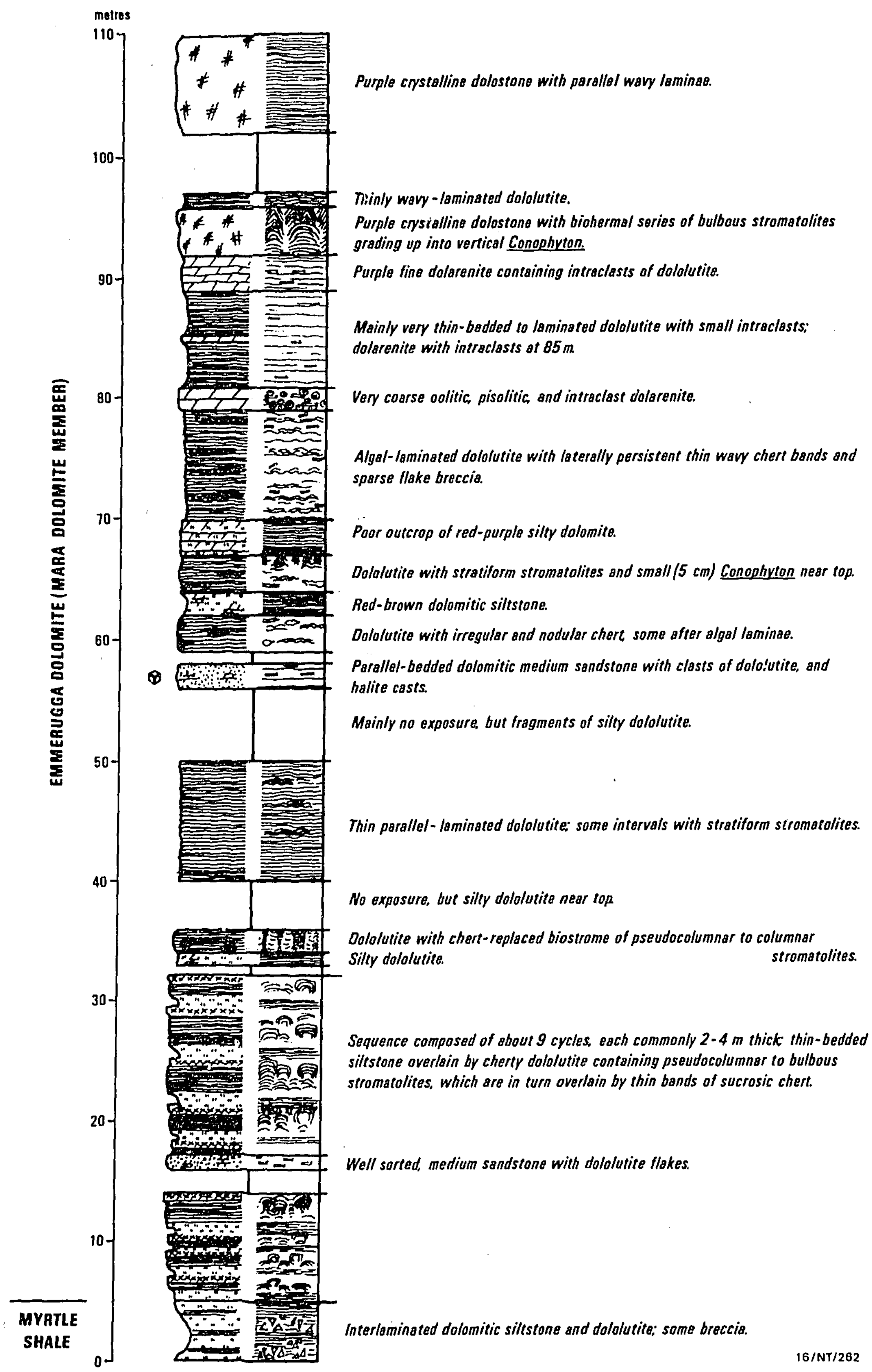


FIG A21 Lower part of Emmerugga Dolomite, east bank Kilgour River, Measured Section Kilgour 77/01 (grid square 0016 Plate 1).

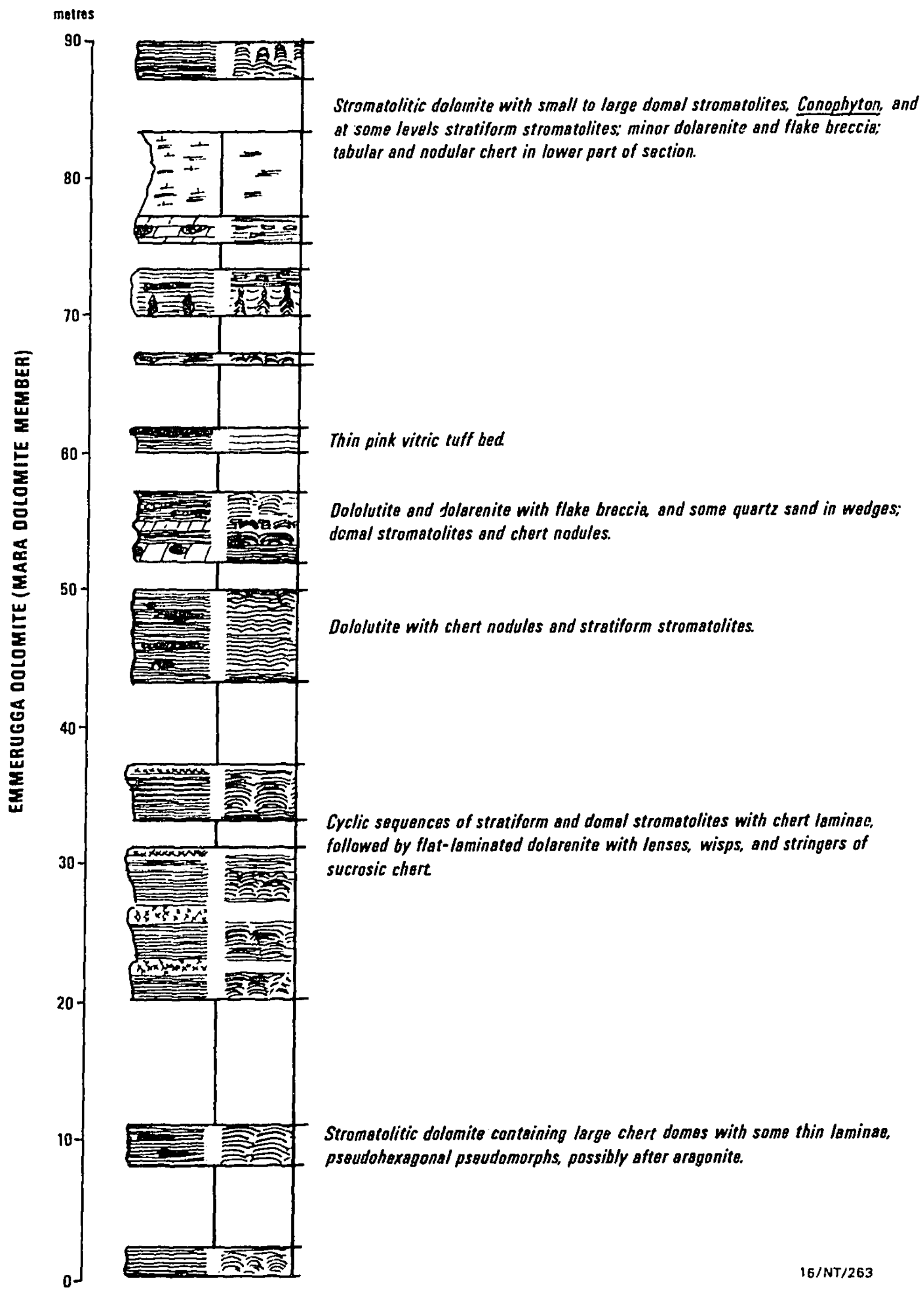


FIG A22 Lower part of Emmerugga Dolomite west bank of Kilgour River 500m northwest of 77/01, Measured Section Kilgour 77/04 (grid square 0017 Plate 1).

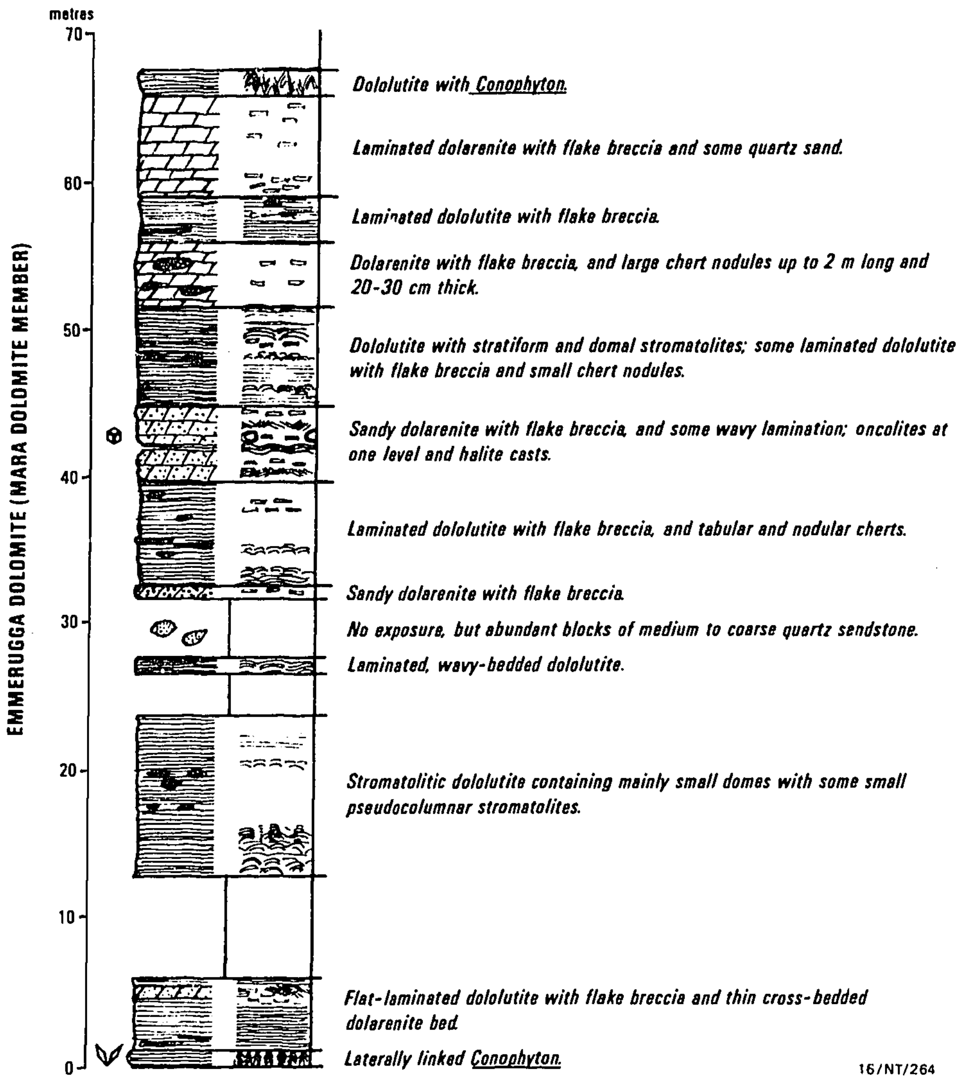


FIG A23 Middle part of Emmerugga Dolomite (1km northeast of MS 77/01), Measured Section Kilgour 77/05 (grid square 0017 Plate 1).

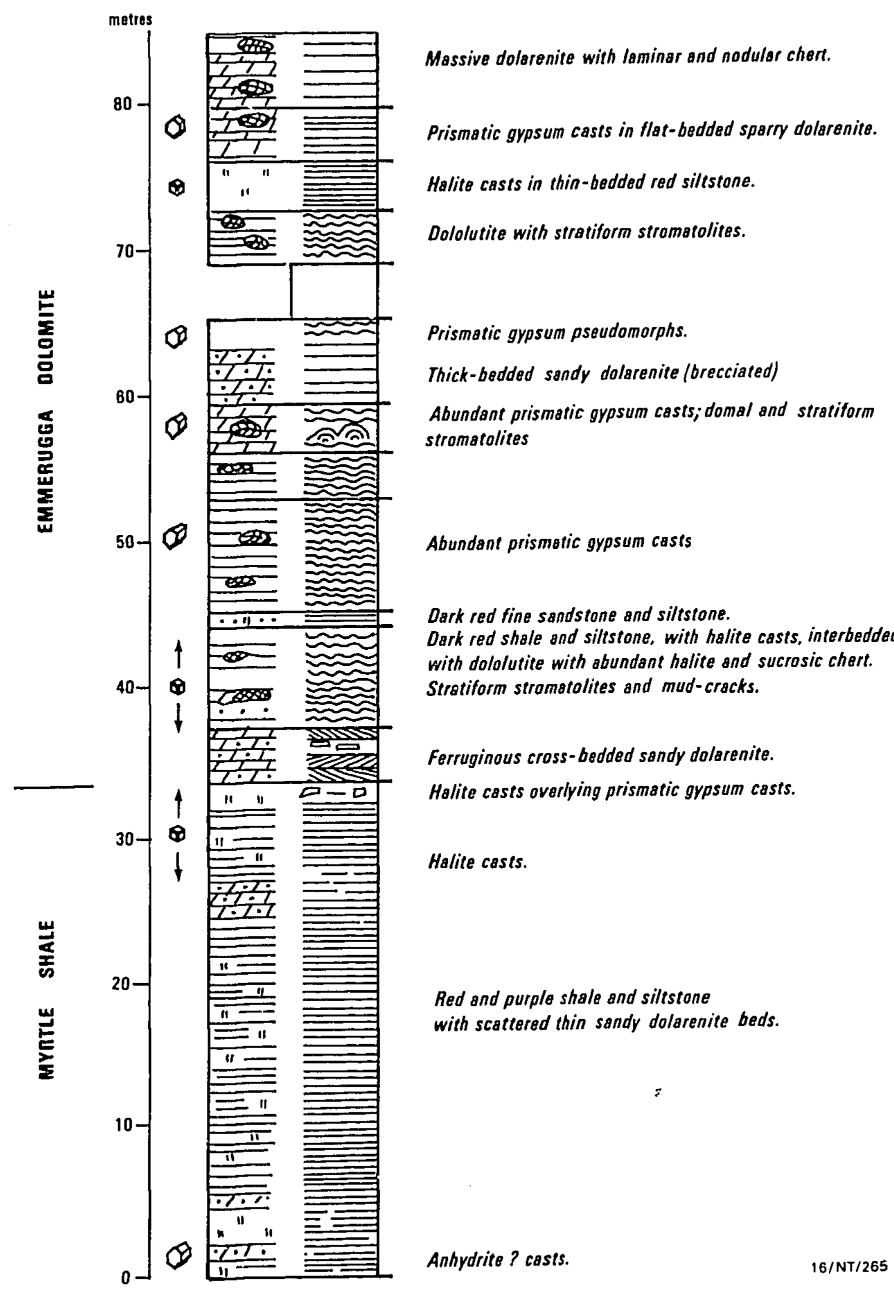


FIG A24 Myrtle Shale and lower Emmerugga Dolomite near William Yard, Measured Section Glyde 78/03 (grid square 1729 Plate 1).

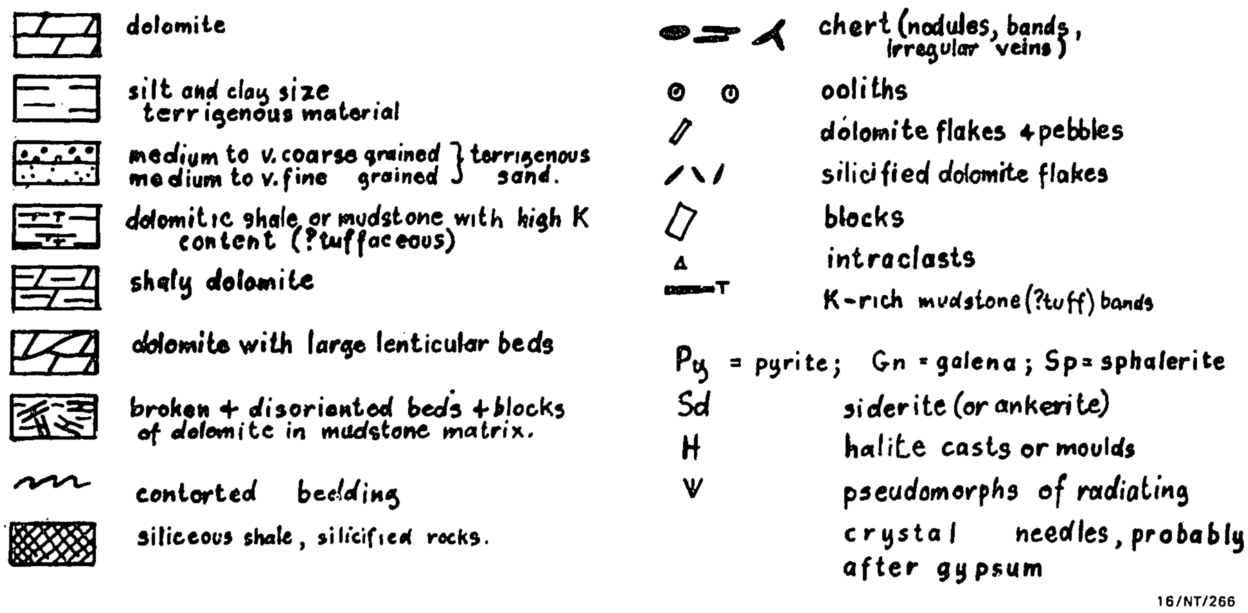


FIG A25 Legend and symbols used on Max Brown's measured sections.

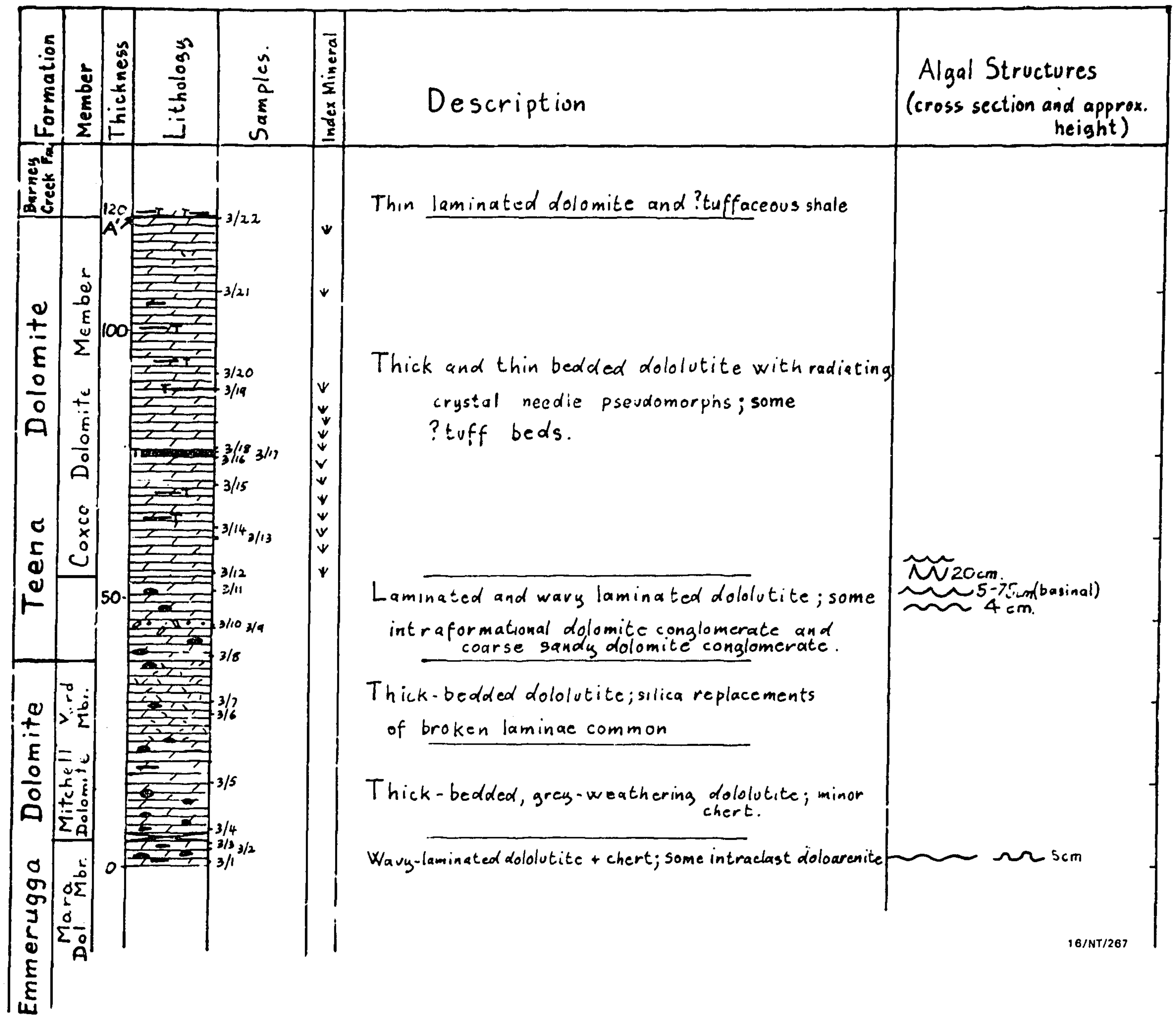


FIG A26 Upper part of Emmerugga Dolomite and Teena Dolomite in Brown's section 3, 3km southwest of Top Crossing (grid square 7843 Plate 1, exact location not shown).

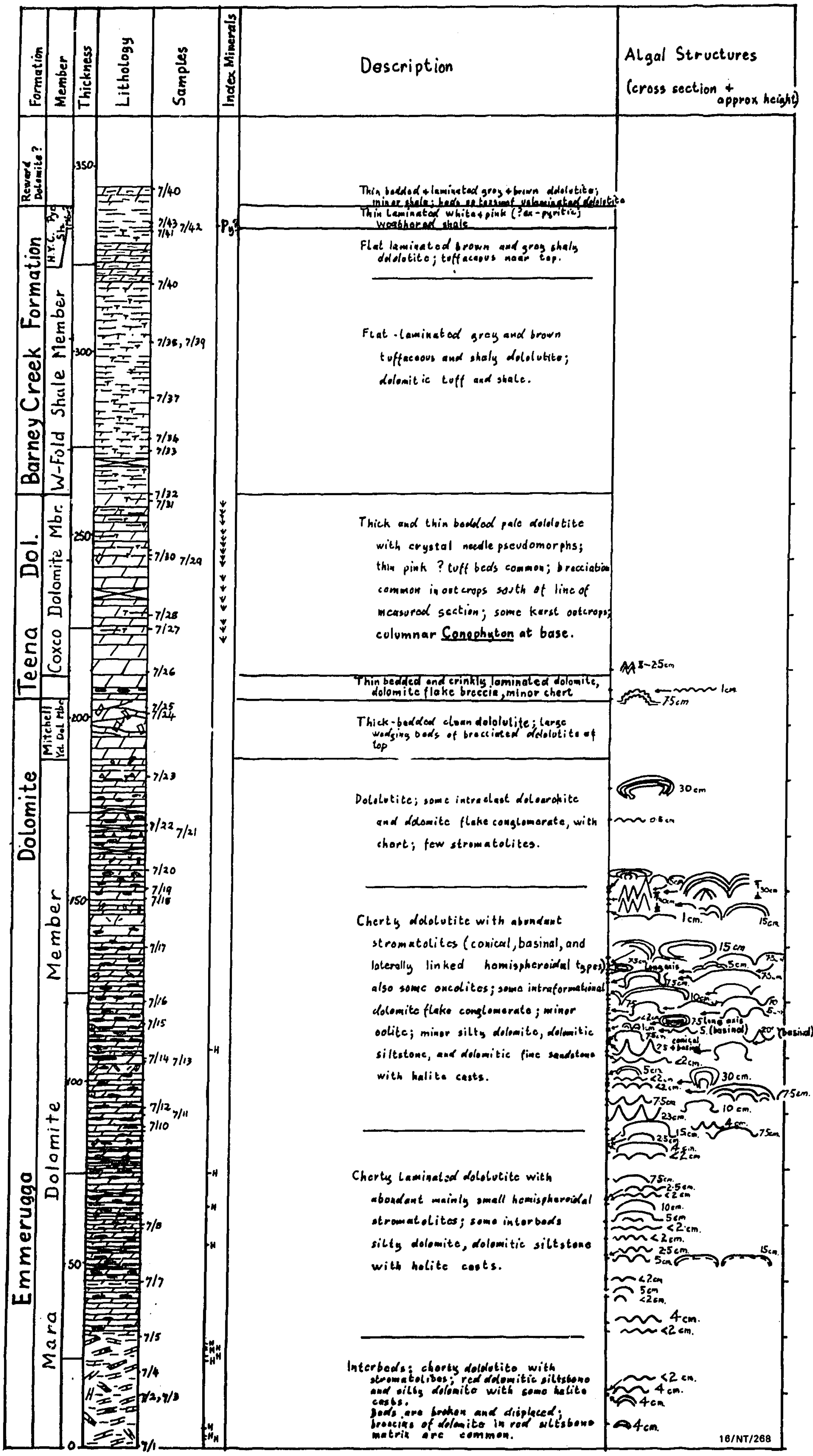


FIG A27 Emmerugga Dolomite, Teena Dolomite and Barney Creek Formation in Brown's section 7, 6.5km east-southeast of Bauhinia Downs homestead (grid ref. not available).

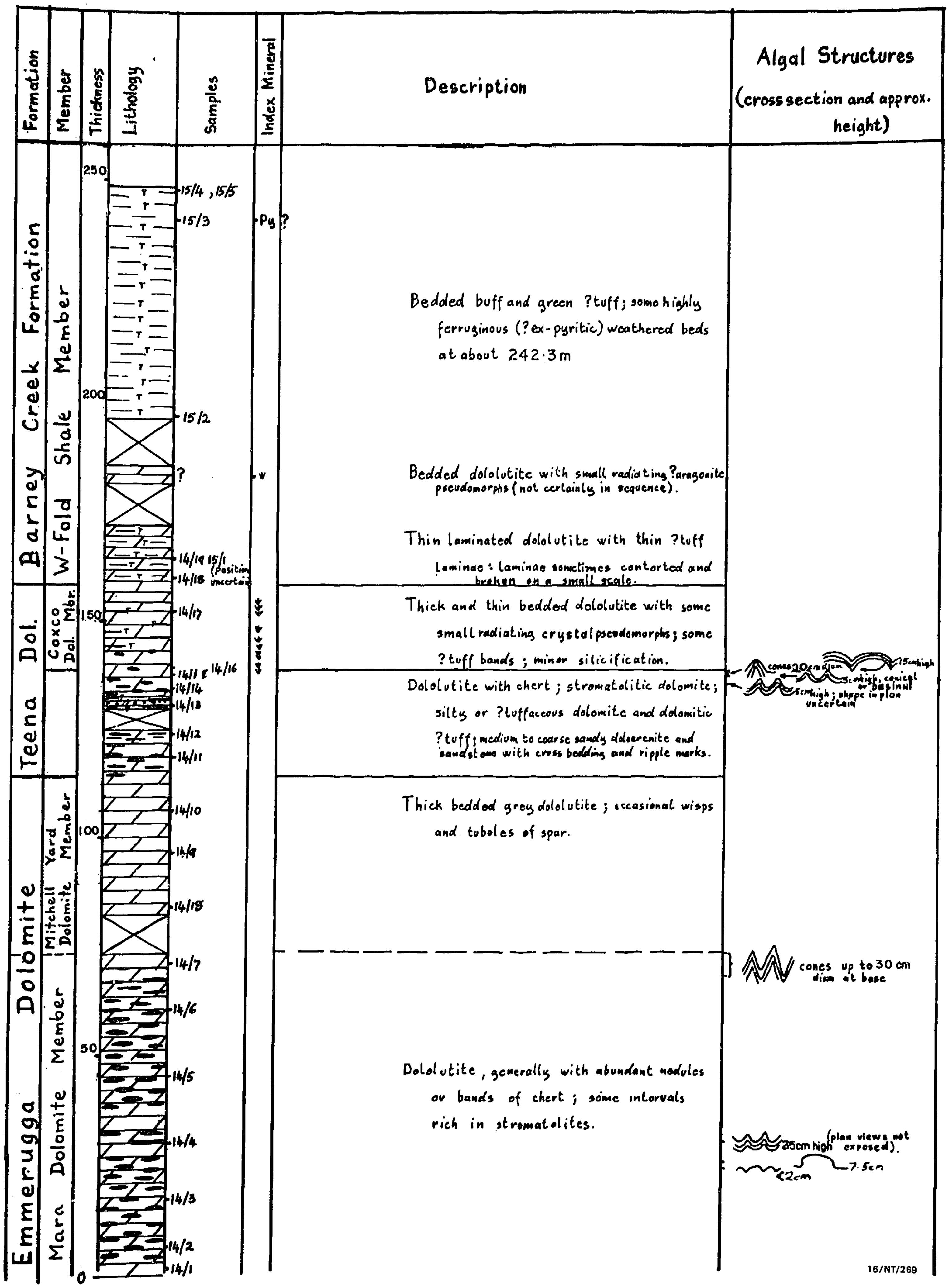


FIG A28 Emmerugga Dolomite, Teena Dolomite and Barney Creek Formation in Brown's Sections 14 & 15 close to HYC deposit (grid ref. not available).

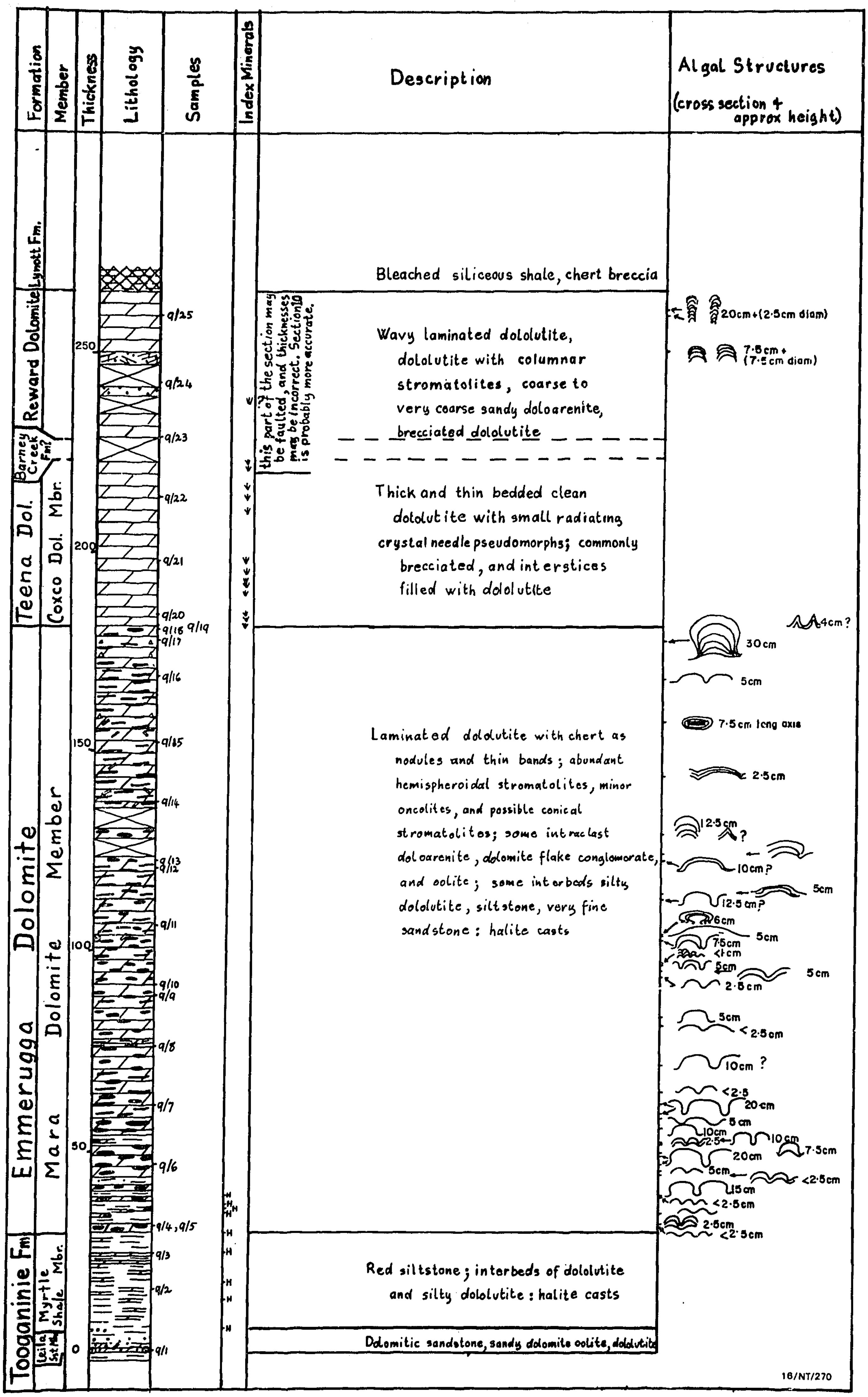


FIG A29 Leila Sandstone, Myrtle Shale, Emmerugga Dolomite, Teena Dolomite, Barney Creek Formation and Reward Dolomite in Brown's Section 9 in Emu Fault Zone near Amelia Spring (grid square 2463, but not shown on Plate 1).

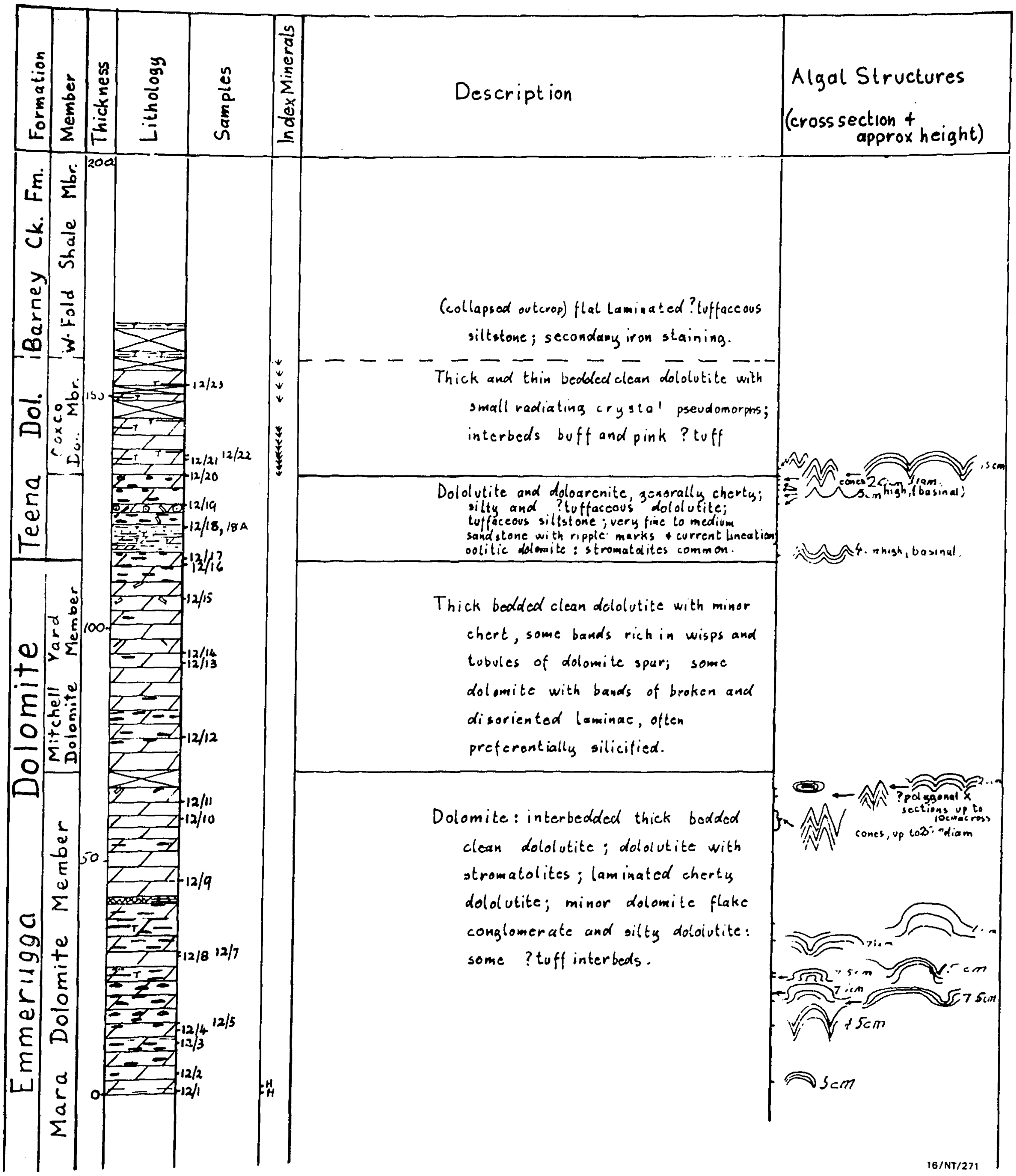


FIG A30 Emmerugga Dolomite, Teena Dolomite and Barney Creek Formation in Brown's section 12, 18km south of McArthur Mine (grid square 1863, not shown on Plate 1).

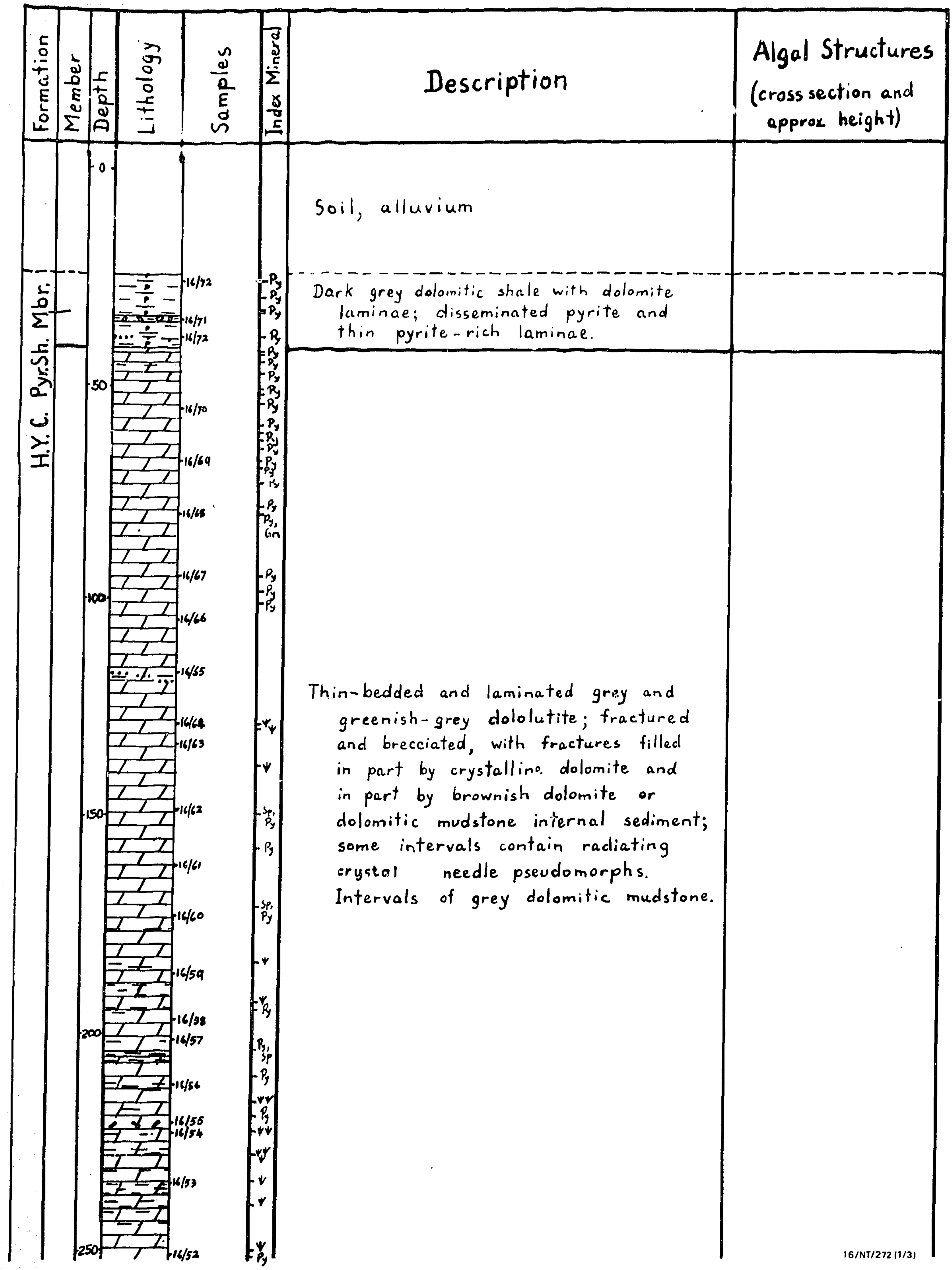
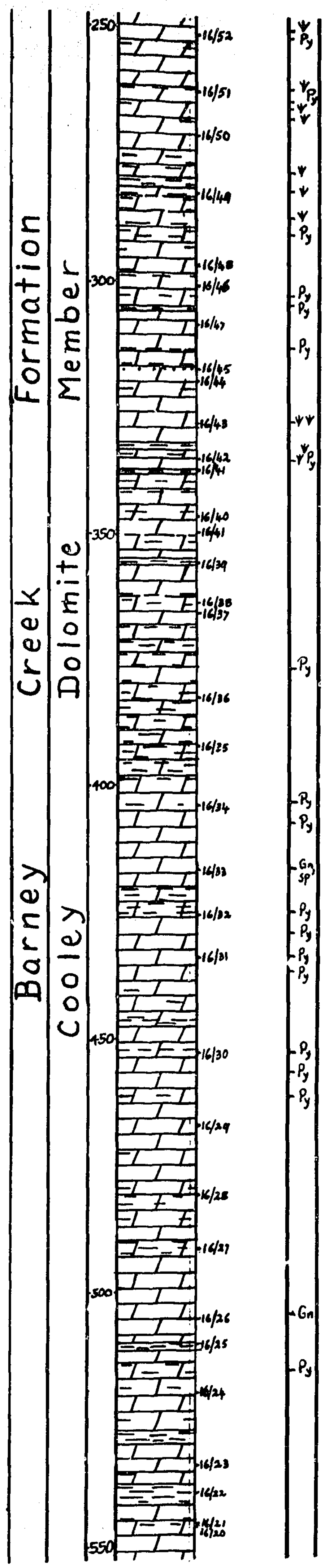


FIG A31 Brown's log of Teena Dolomite and Barney Creek Formation in CEC drillhole le 115 at McArthur River Mine.



Thin-bedded and laminated grey and greenish-grey dololutite; fractured and brecciated, with fractures filled in part by crystalline dolomite and in part by brownish dolomite or dolomitic mudstone internal sediment; some intervals contain radiating crystal needle pseudomorphs. Intervals of grey dolomitic mudstone.

16/NT/272 (2/31)

FIG A31 (continued)

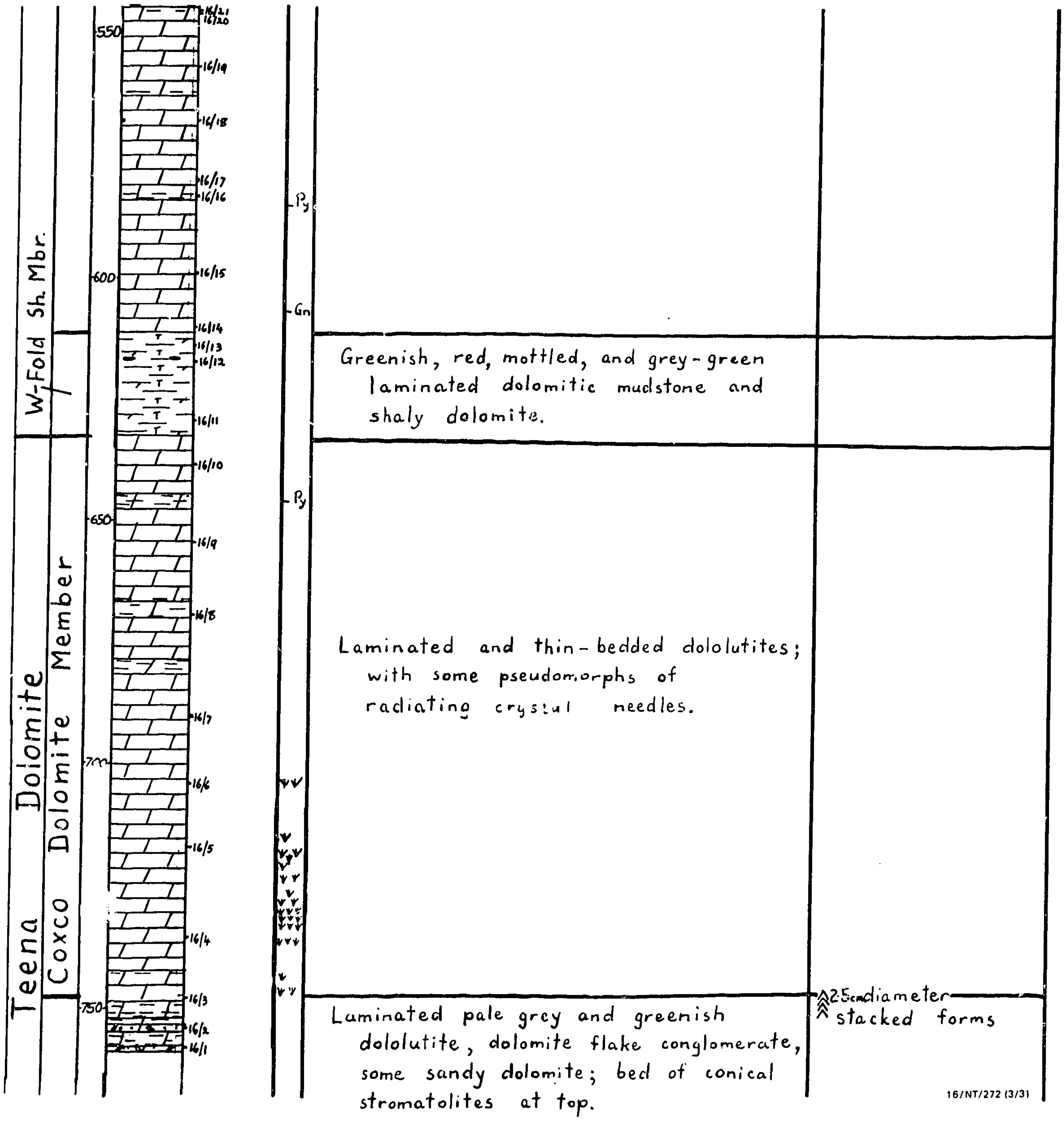


FIG A31 (continued)

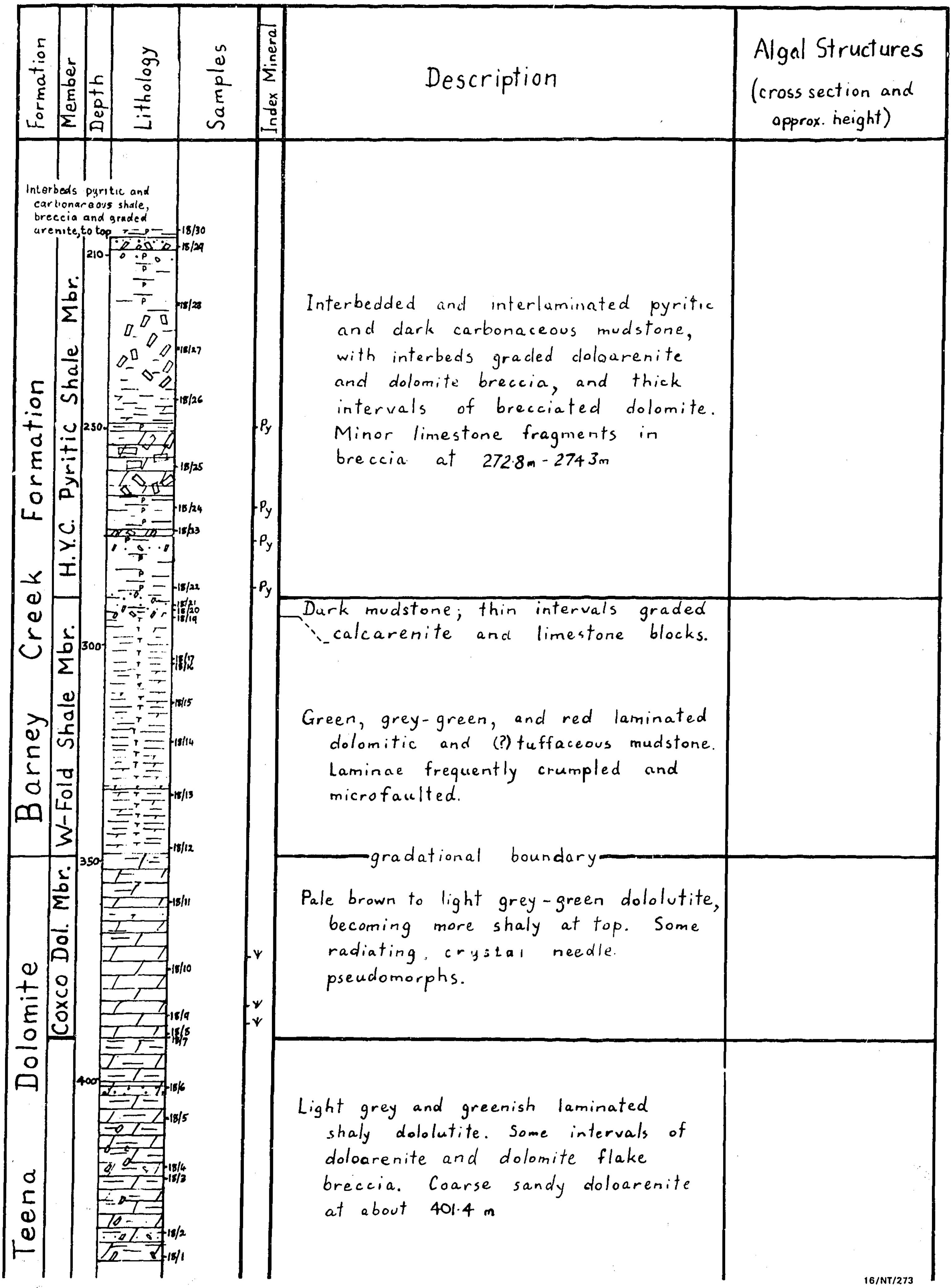


FIG A32 Brown's log of Teena Dolomite and Barney Creek Formation in CEC drillhole Ue 133 at McArthur River Mine.

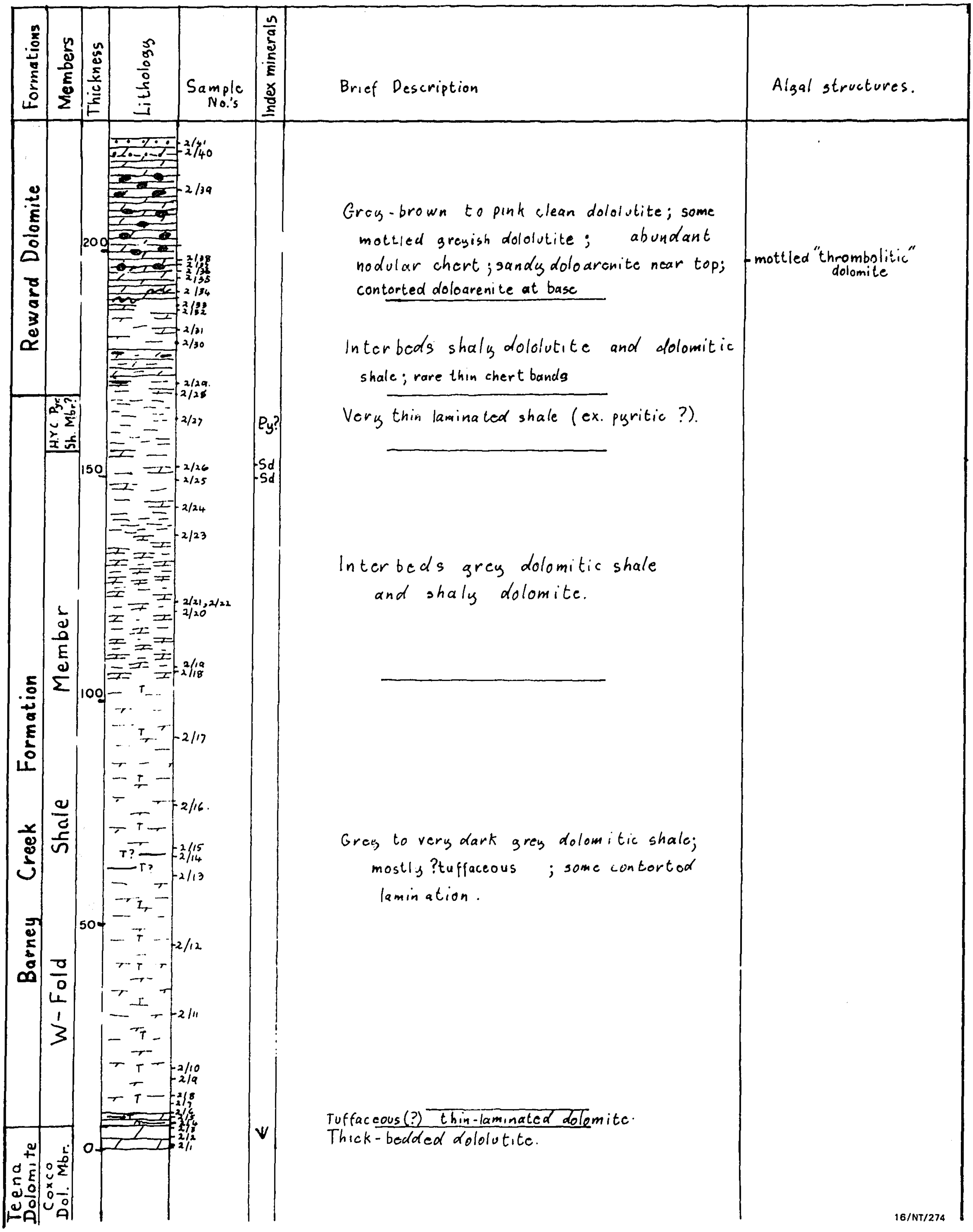


FIG A33 Uppermost Teena Dolomite to Reward Dolomite in Brown's Section 2, about 4km west of Top Crossing (grid square 7743 Plate 1, exact location not shown).

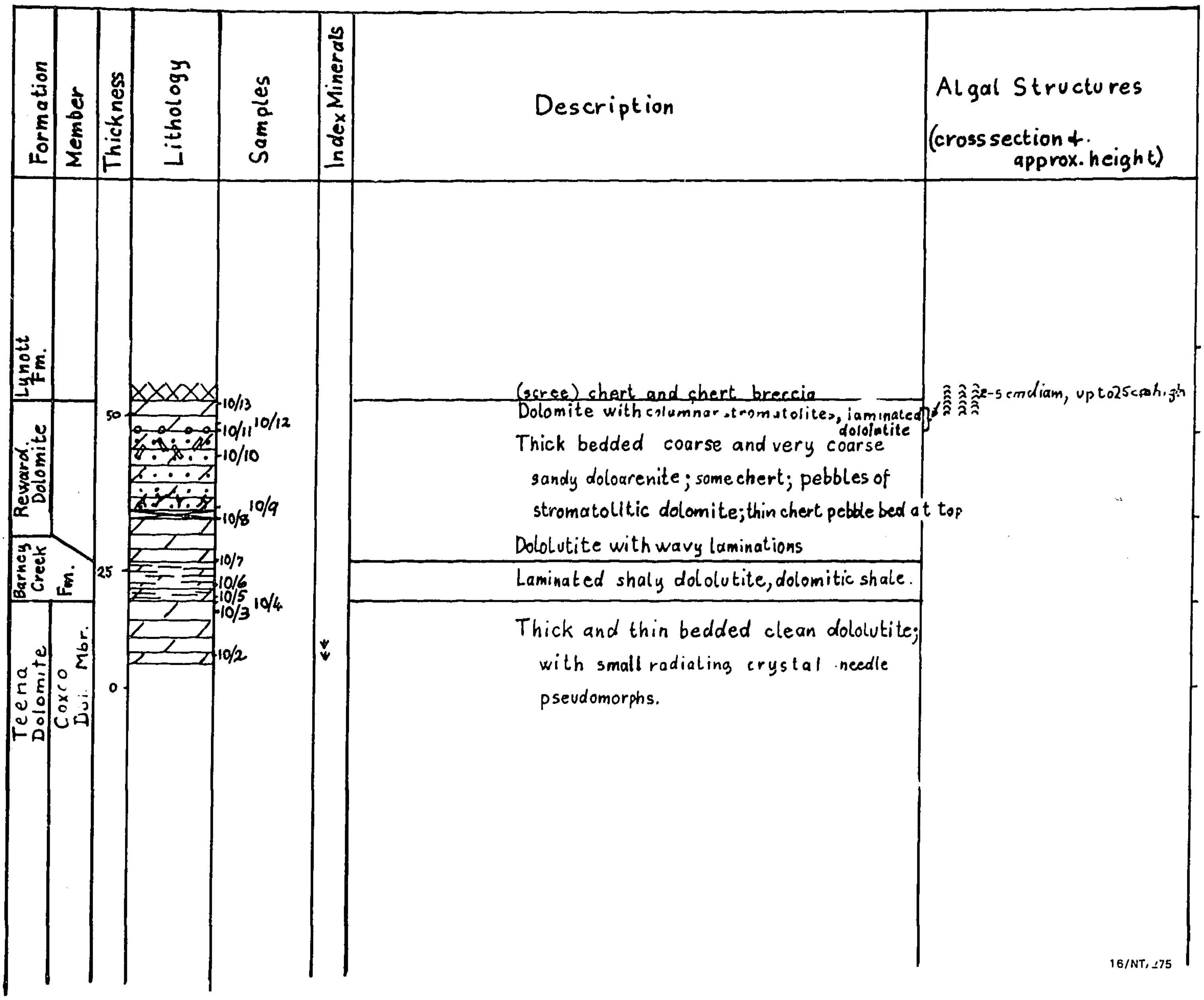


FIG A34 Condensed section of Teena Dolomite to Lynott Formation in Brown's Section 10, in Emu Fault Zone, grid square 2364 Plate 1 (exact location not known).

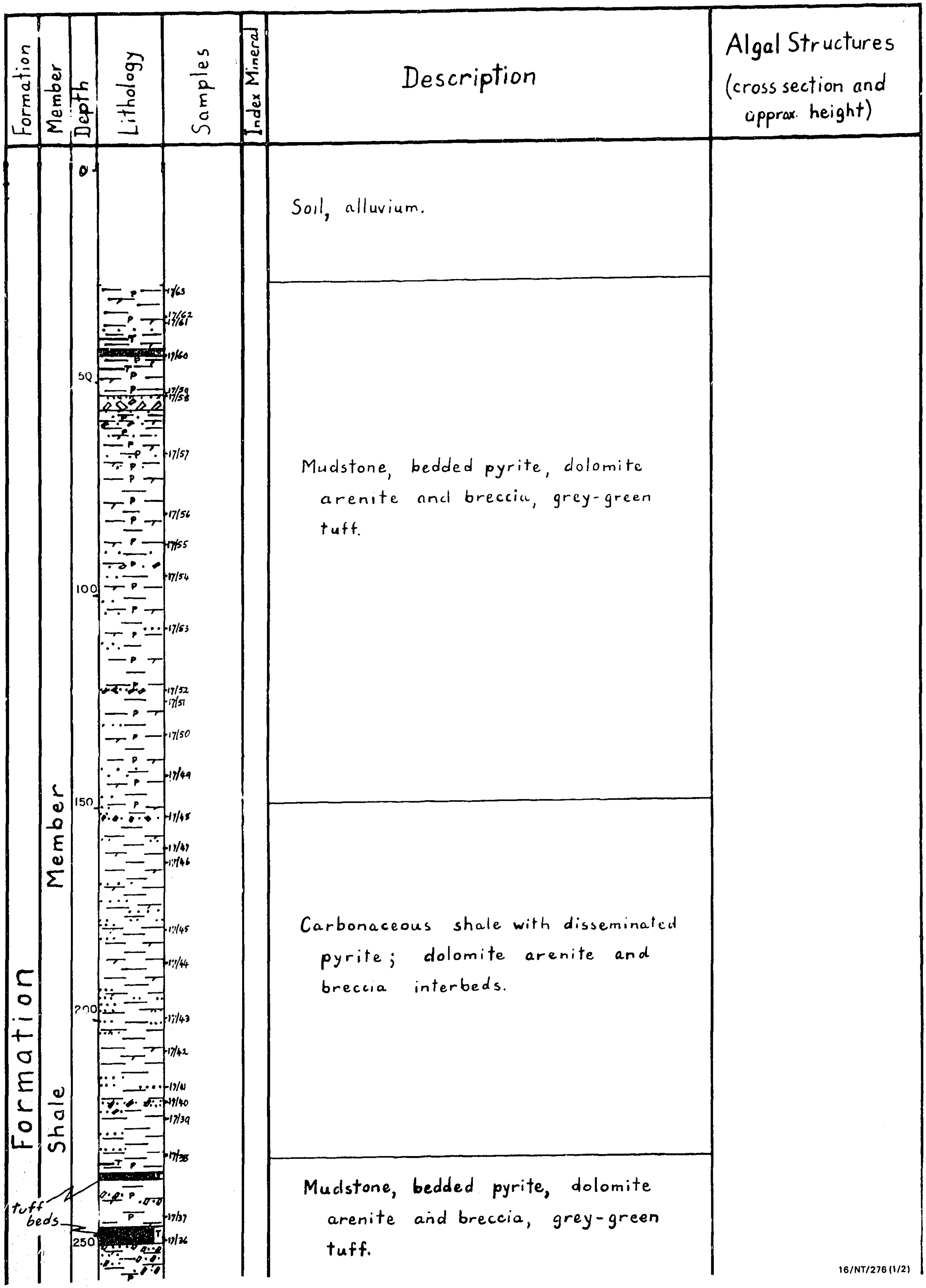
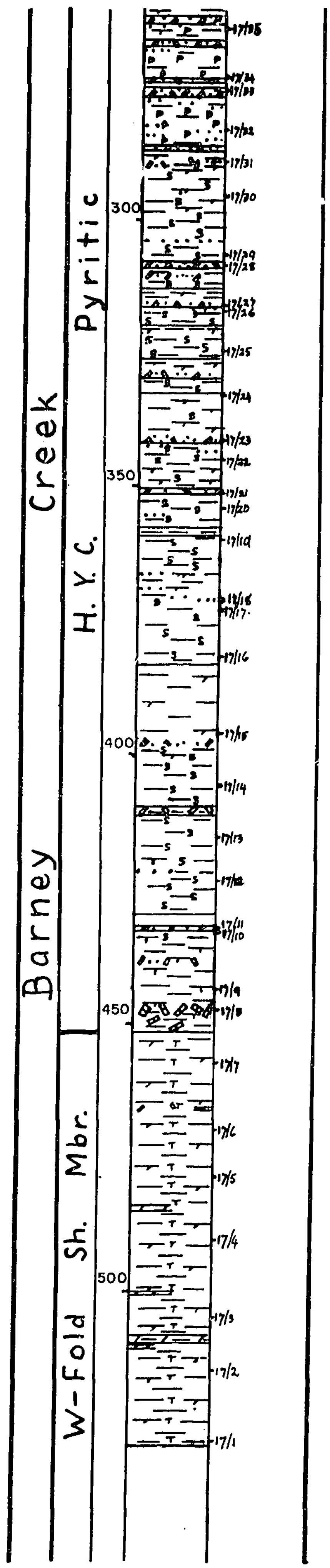


FIG A35 Brown's log of Barney Creek Formation in CEC drillhole Te 115 at McArthur River Mine.



Mudstone, bedded pyrite, dolomite arenite and breccia, grey-green tuff.

Mineralized zone. Bedded sphalerite, galena, pyrite; with grey-green mudstone, carbonaceous shale, dolomite arenite and breccia interbeds.

(N.B. This interval contains steep-dipping sections, and is probably secondarily thickened by slumping).

"S" in lithological column indicates interlayered sphalerite, galena, and pyrite.

Carbonaceous shale, limestone breccia interbeds.

Red and green dolomitic siltstone

18/NT/276 (2/2)

FIG A35 (continued)

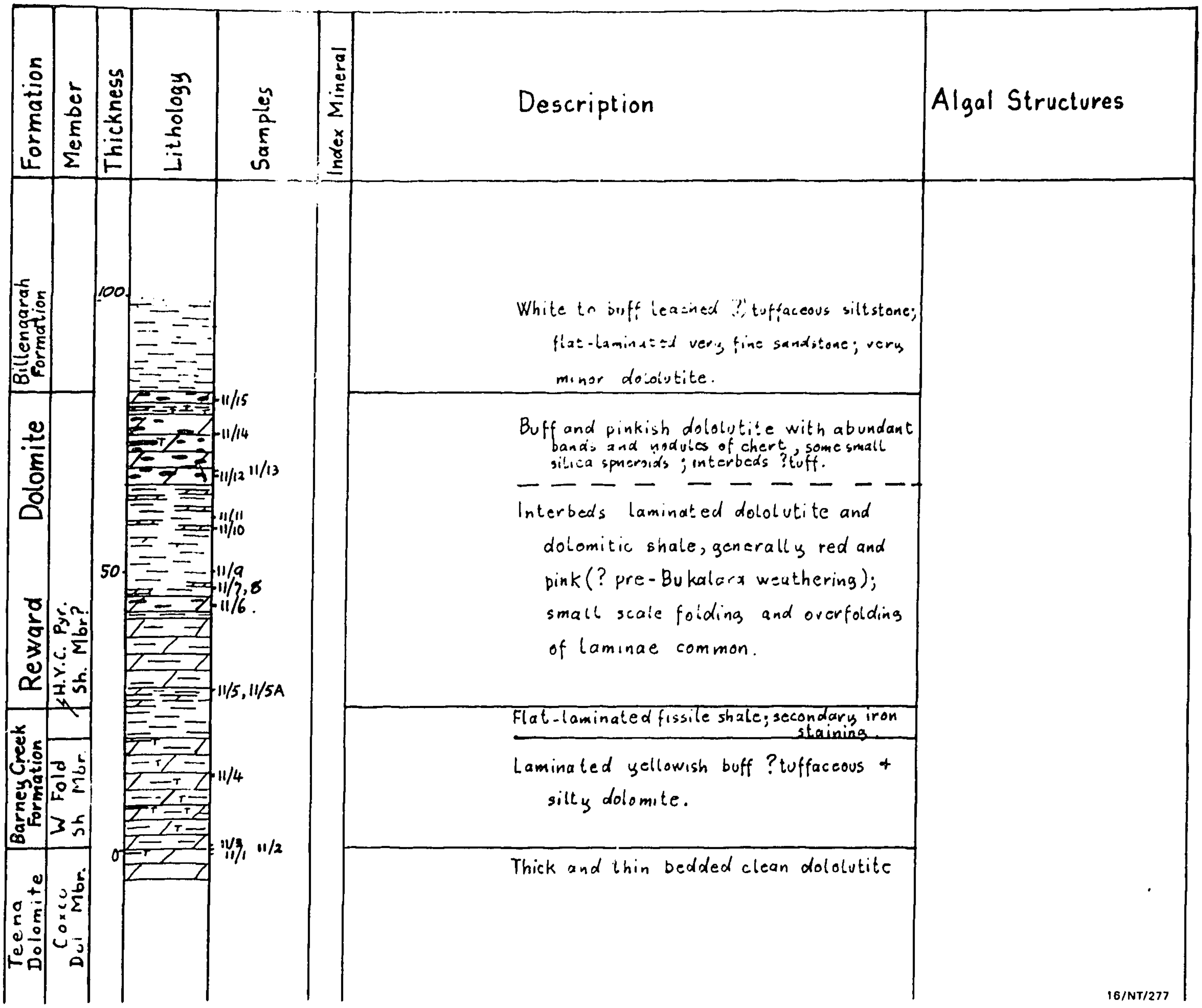


FIG A36 Thin sequence of Teena Dolomite to "Billengarah Formation" in Brown's section 11, east of the Abner Range (grid square 1434 Plate 1, exact location not shown).

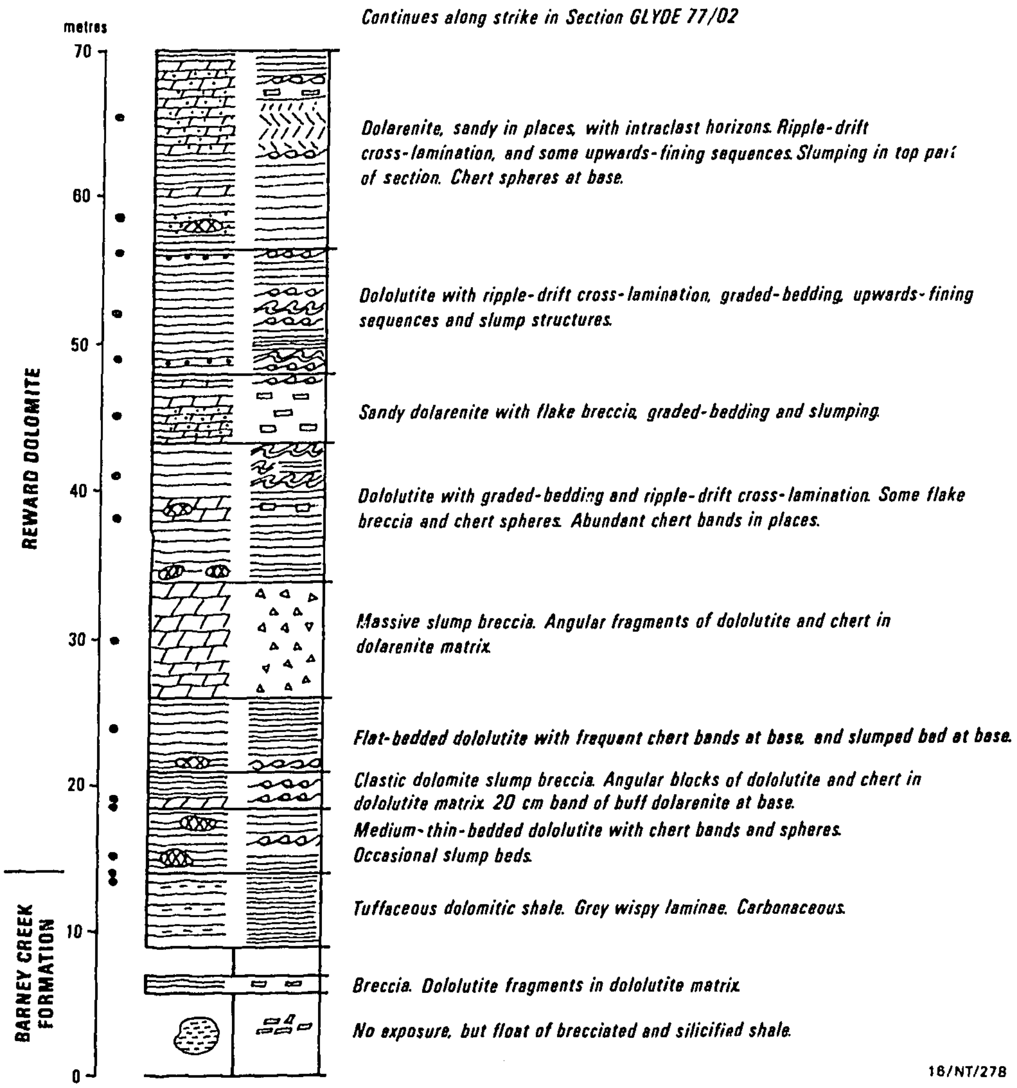


FIG A37 Uppermost Barney Creek Formation and Reward Dolomite in Measured Section Glyde 77/01 (grid square 0759 Plate 1).

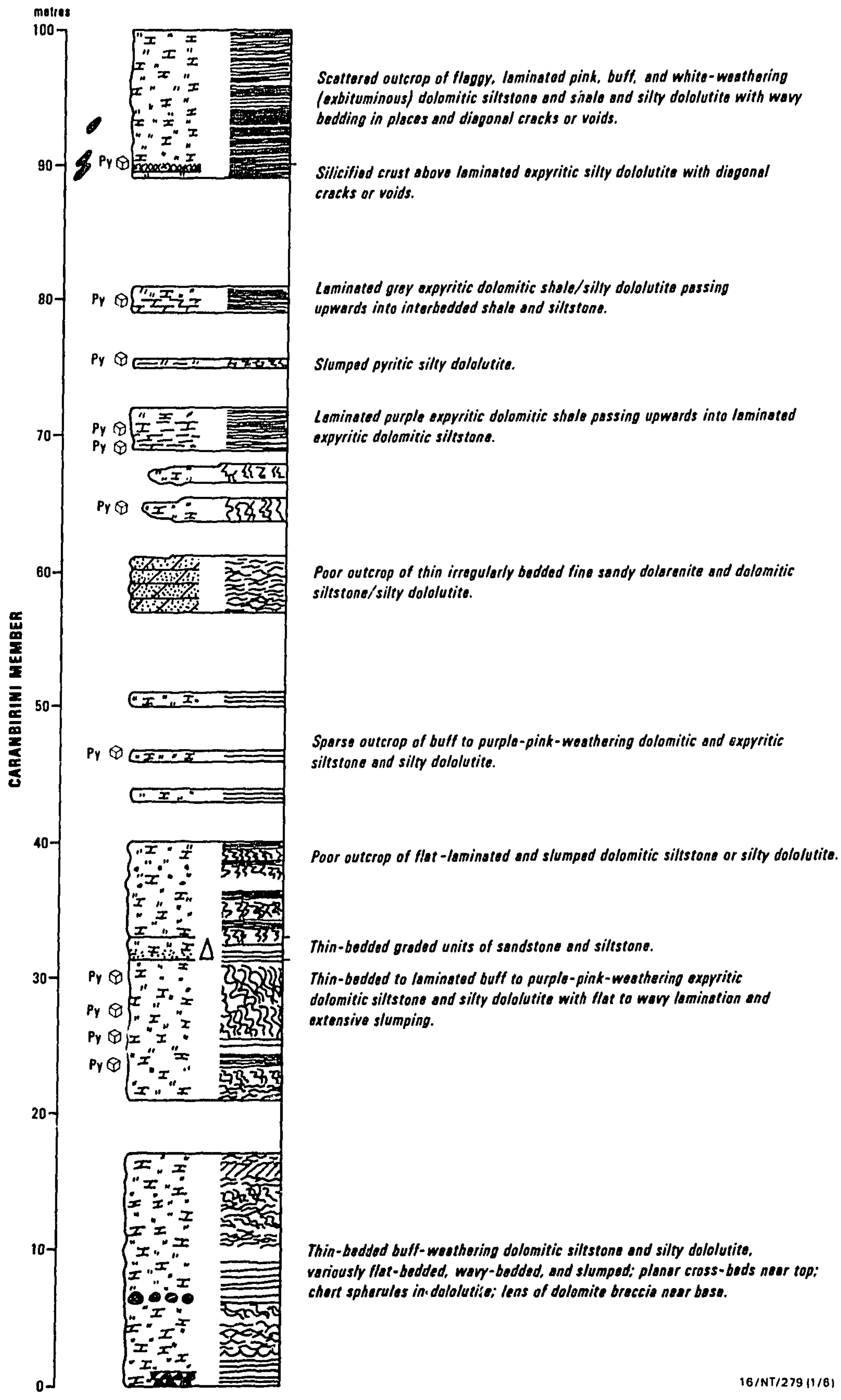


FIG A38 Type Section of Lynott Formation in Measured Section Glyde 77/02 (grid square 0757 Plate 1).

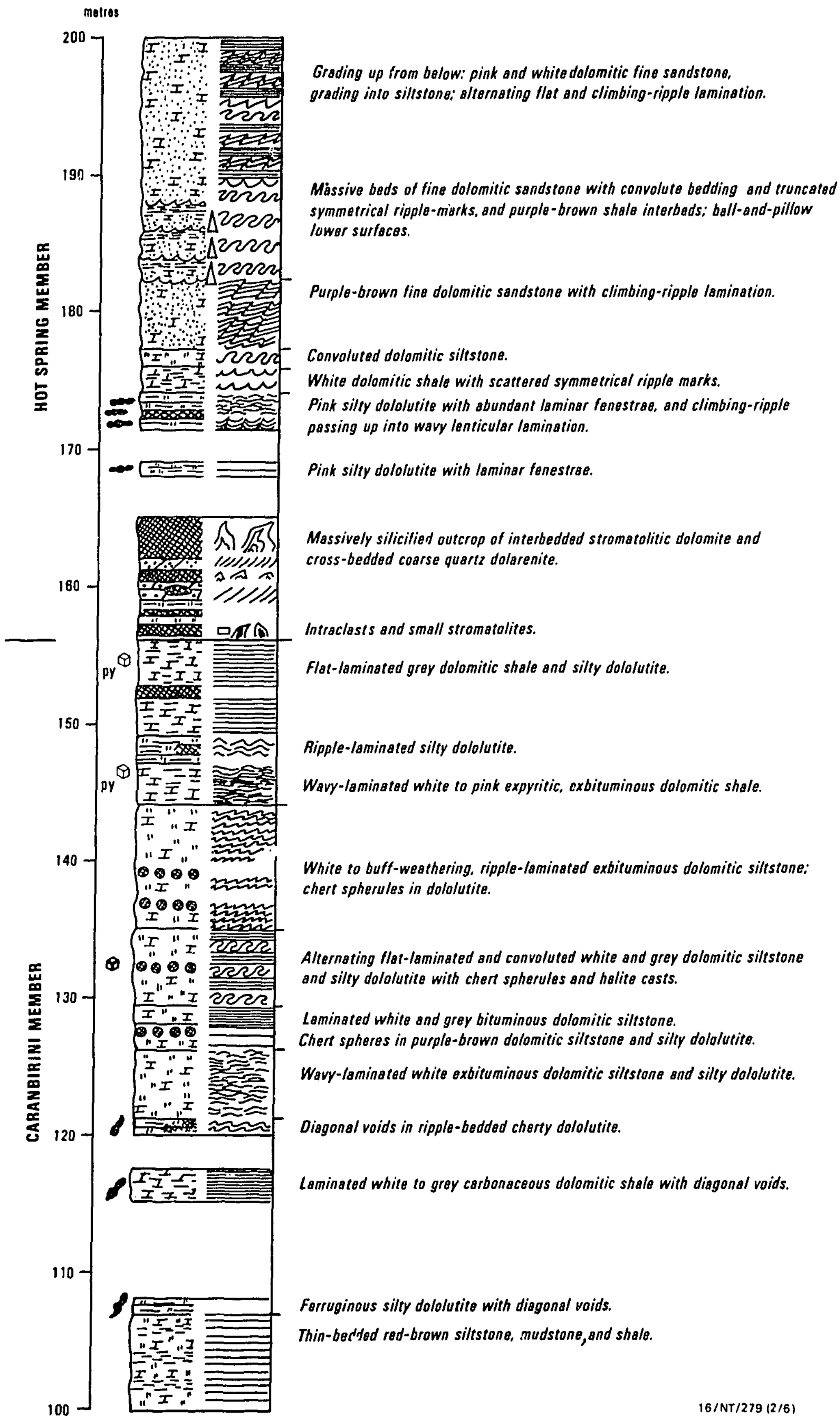


FIG A38 (continued - sheet 2)

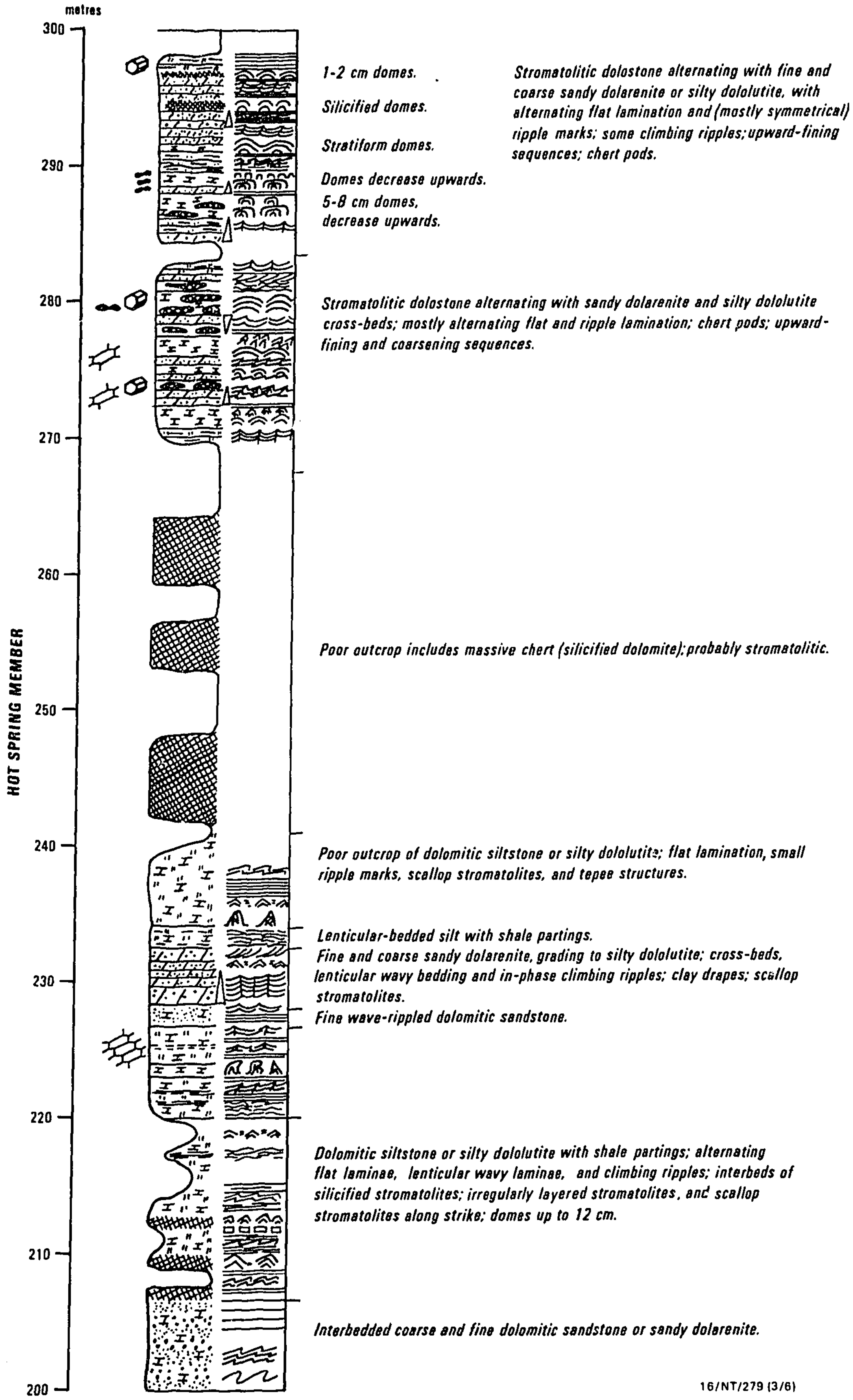
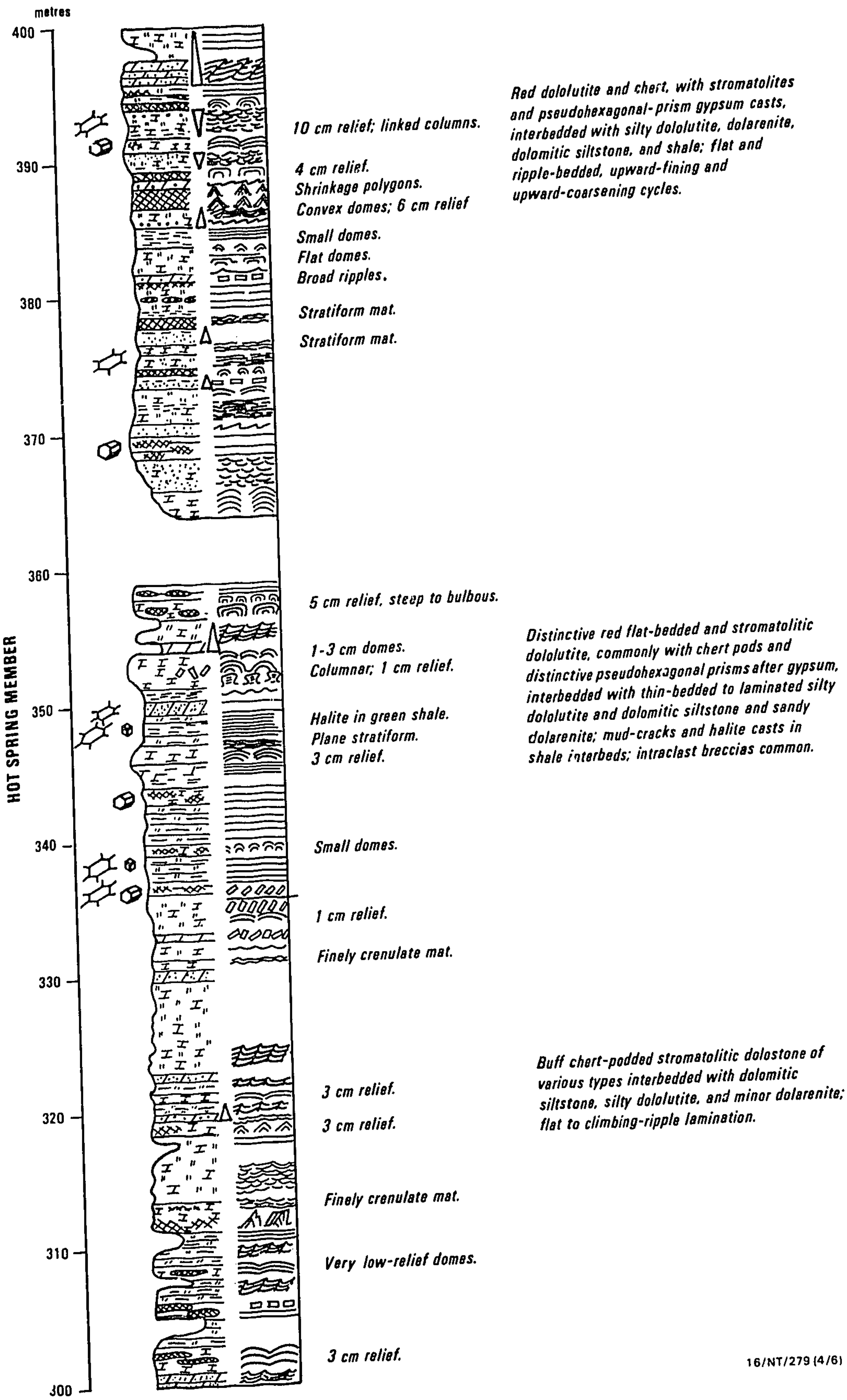


FIG A38 (continued - sheet 3)



16/NT/279 (4/6)

FIG A38 (continued - sheet 4)

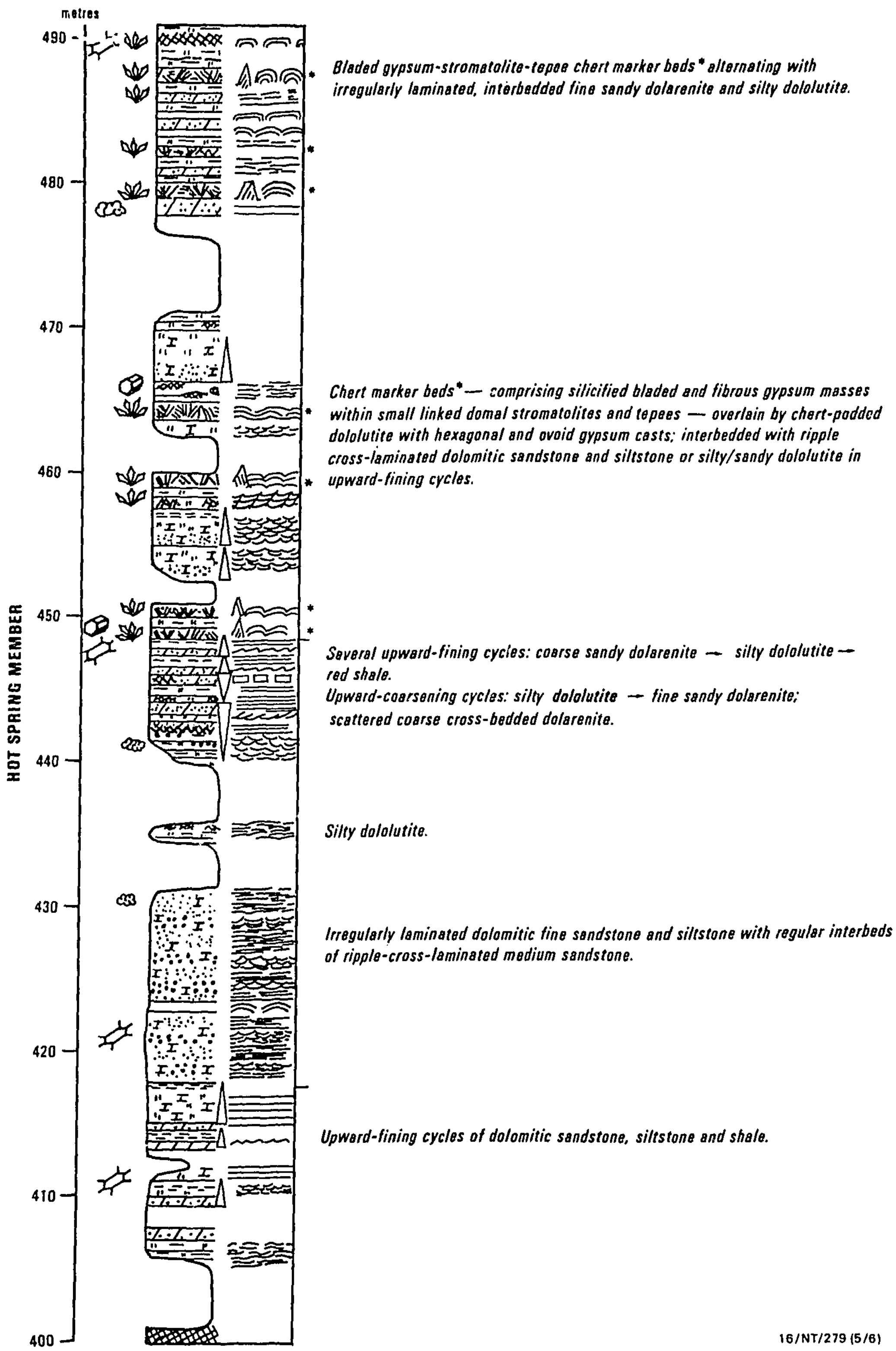


FIG A38 (continued - sheet 5)

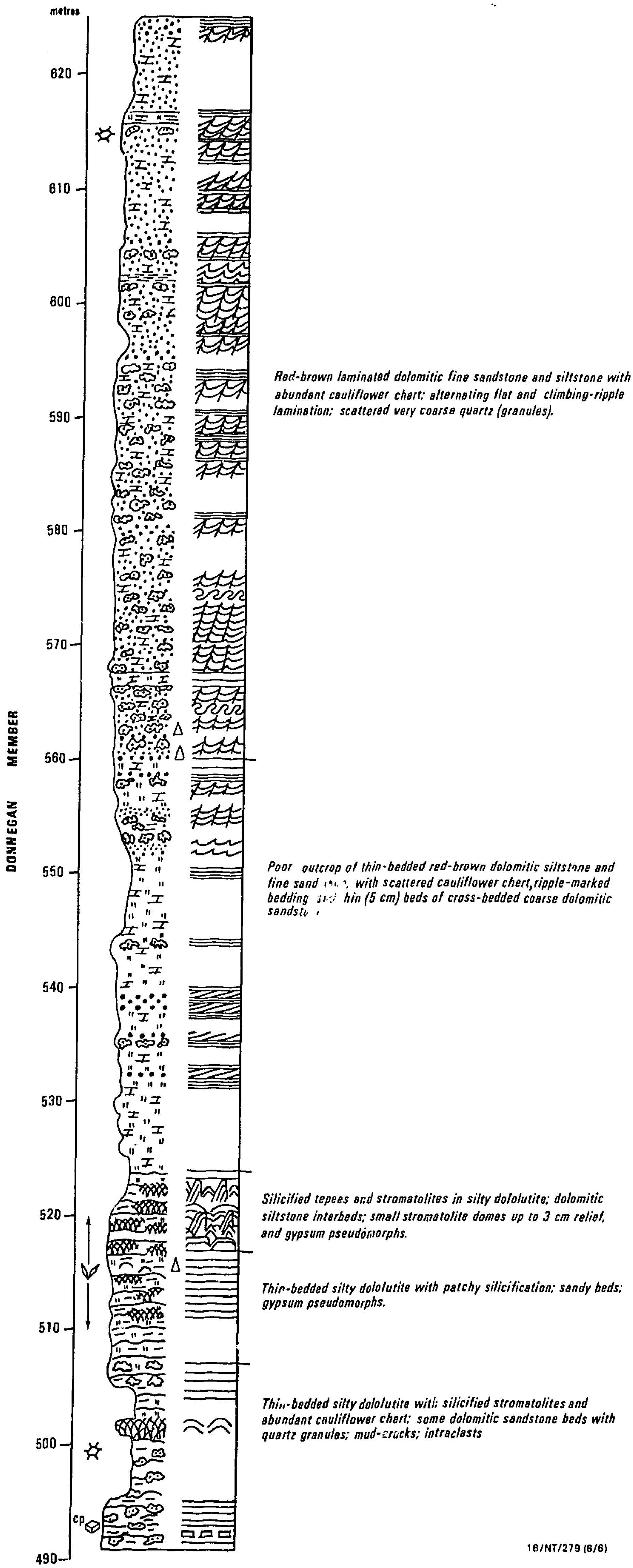


FIG A38 (continued - sheet 6)

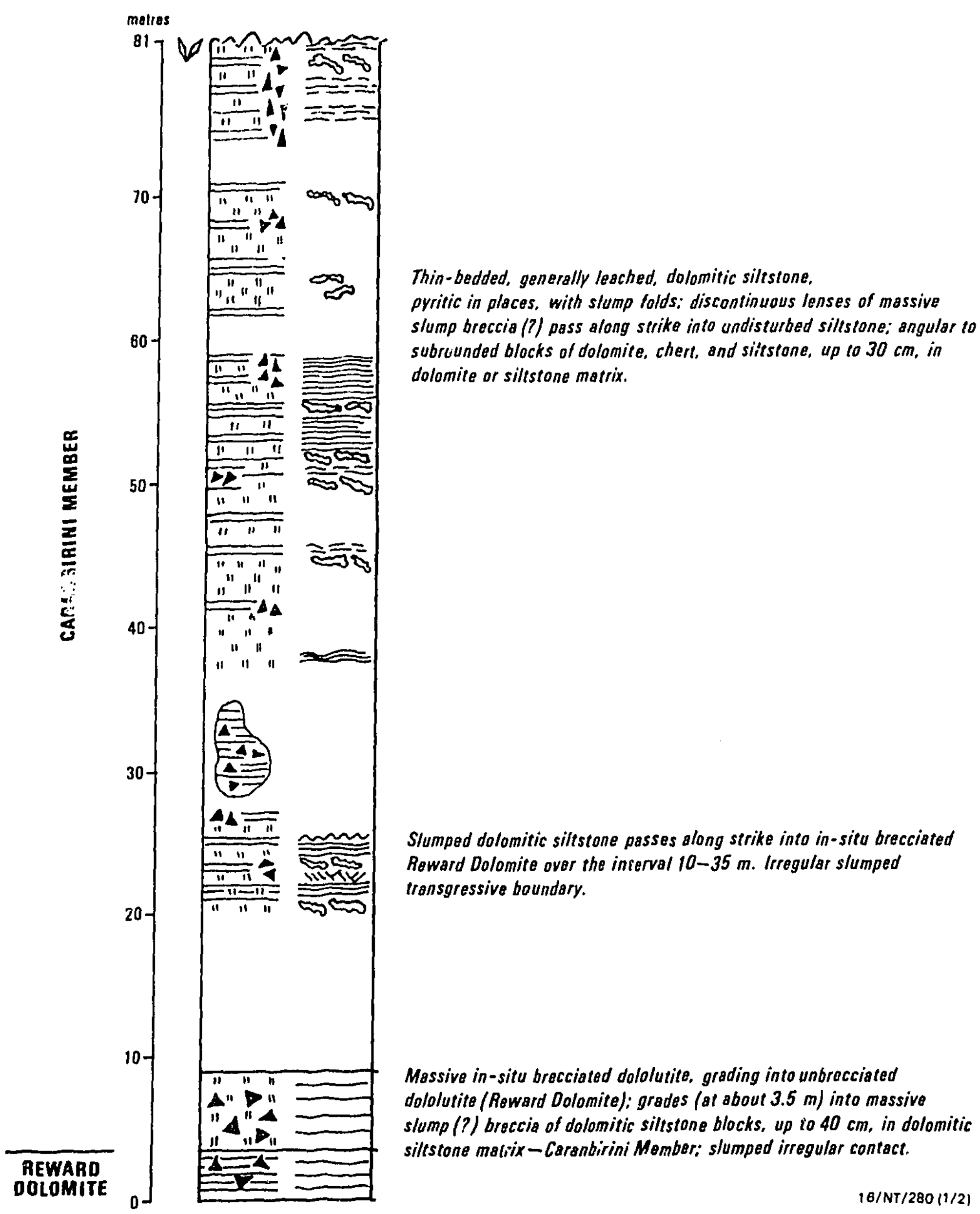


FIG A39 Caranbirini Member (Lynott Formation) in Measured Section Mallapunyah 77/01, 2 km west of type section (grid square 0559 Plate 1).

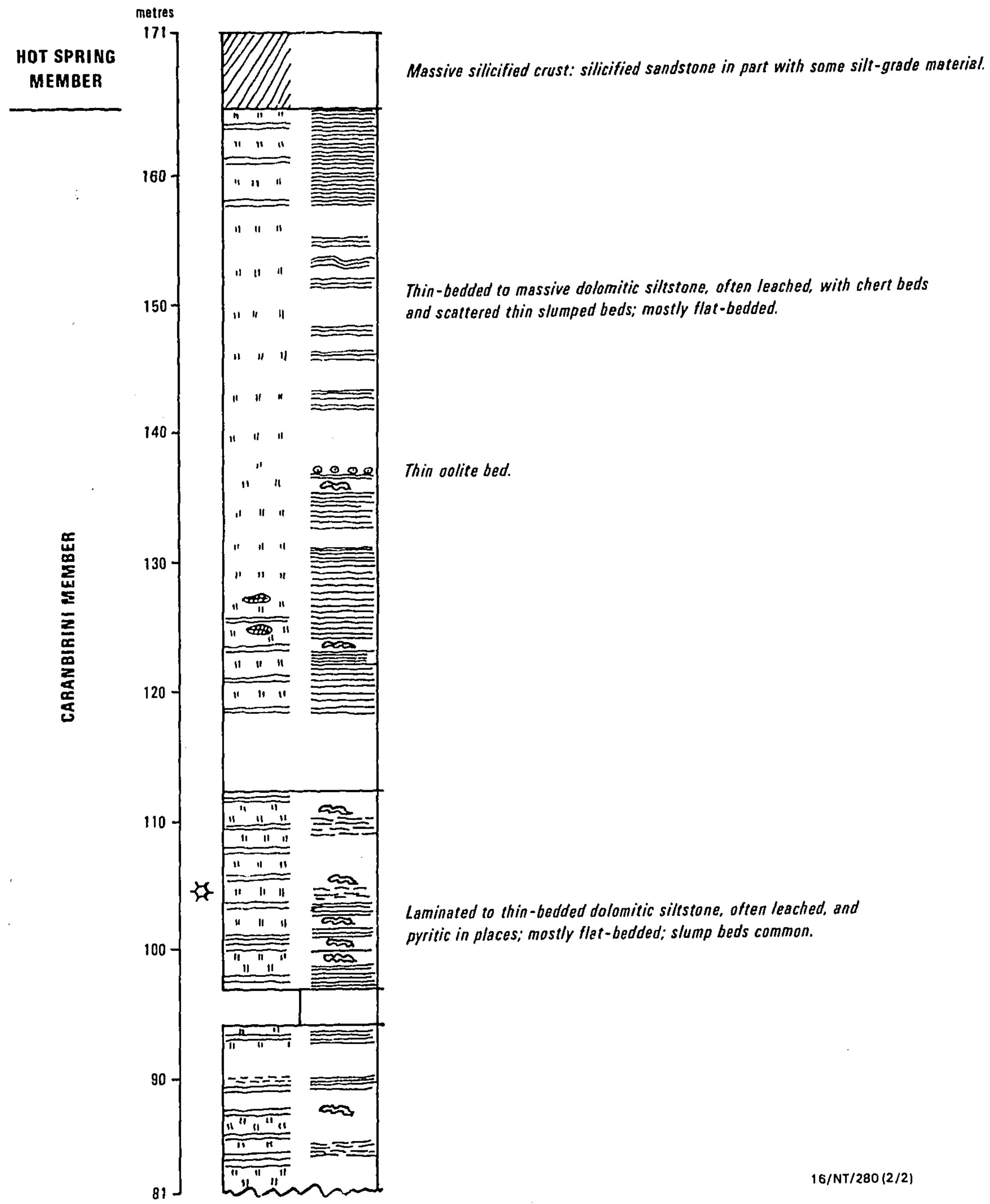


FIG A39 (continued)

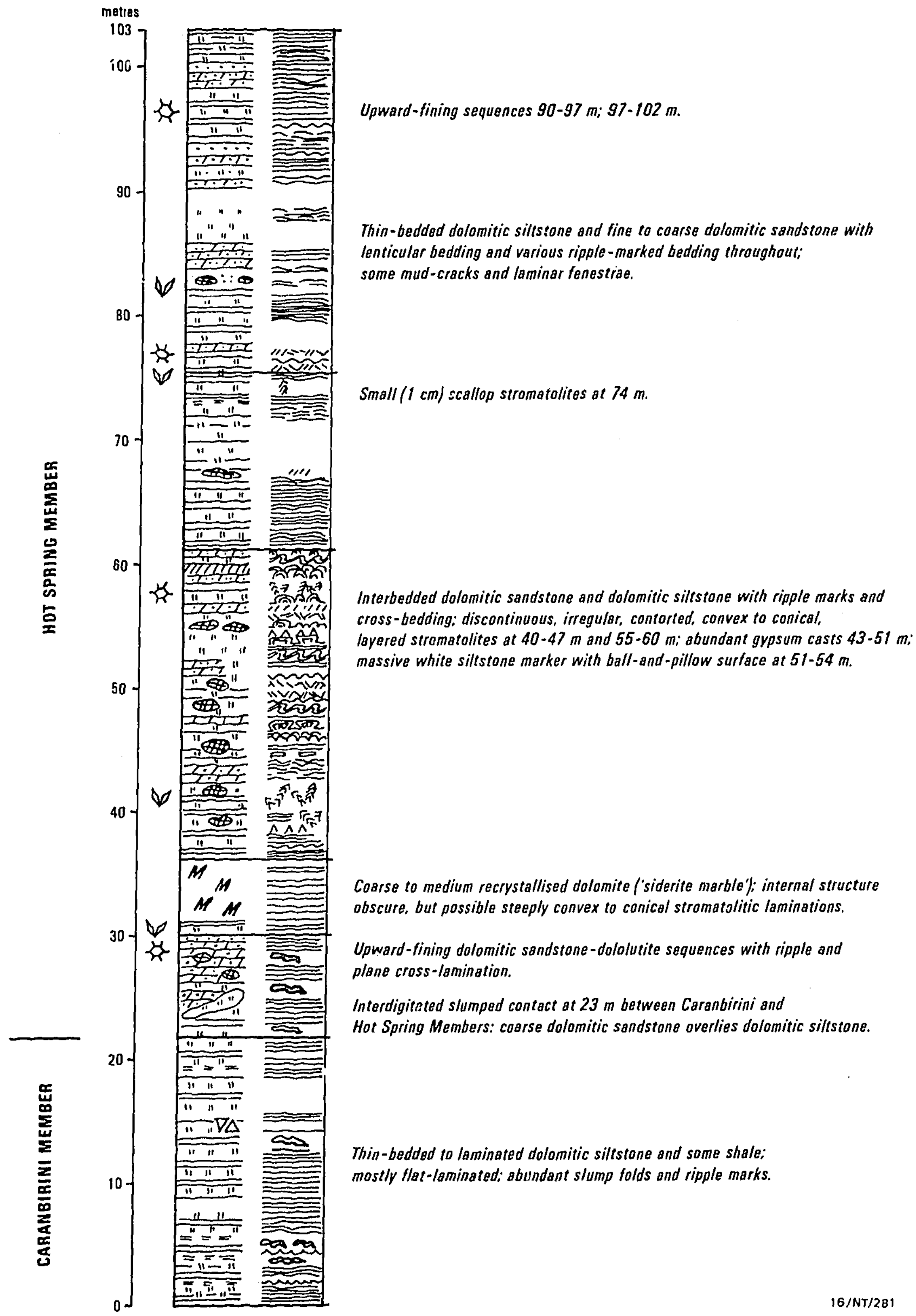


FIG A40 Upper Caranbirini Member and Hot Spring Member (Lynott Formation) in Measured Section Mallapunyah 77/02 (grid square 0258 Plate 1).

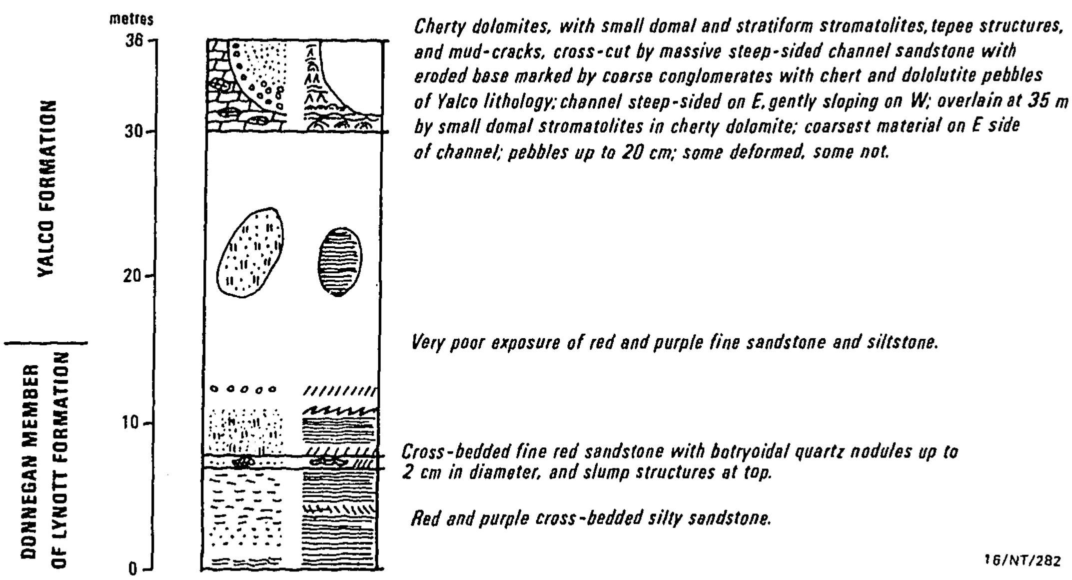


FIG A41 Partial section of Lynott and Yalco Formations in Measured Section Glyde 77/04A (grid square 0755 Plate 1).

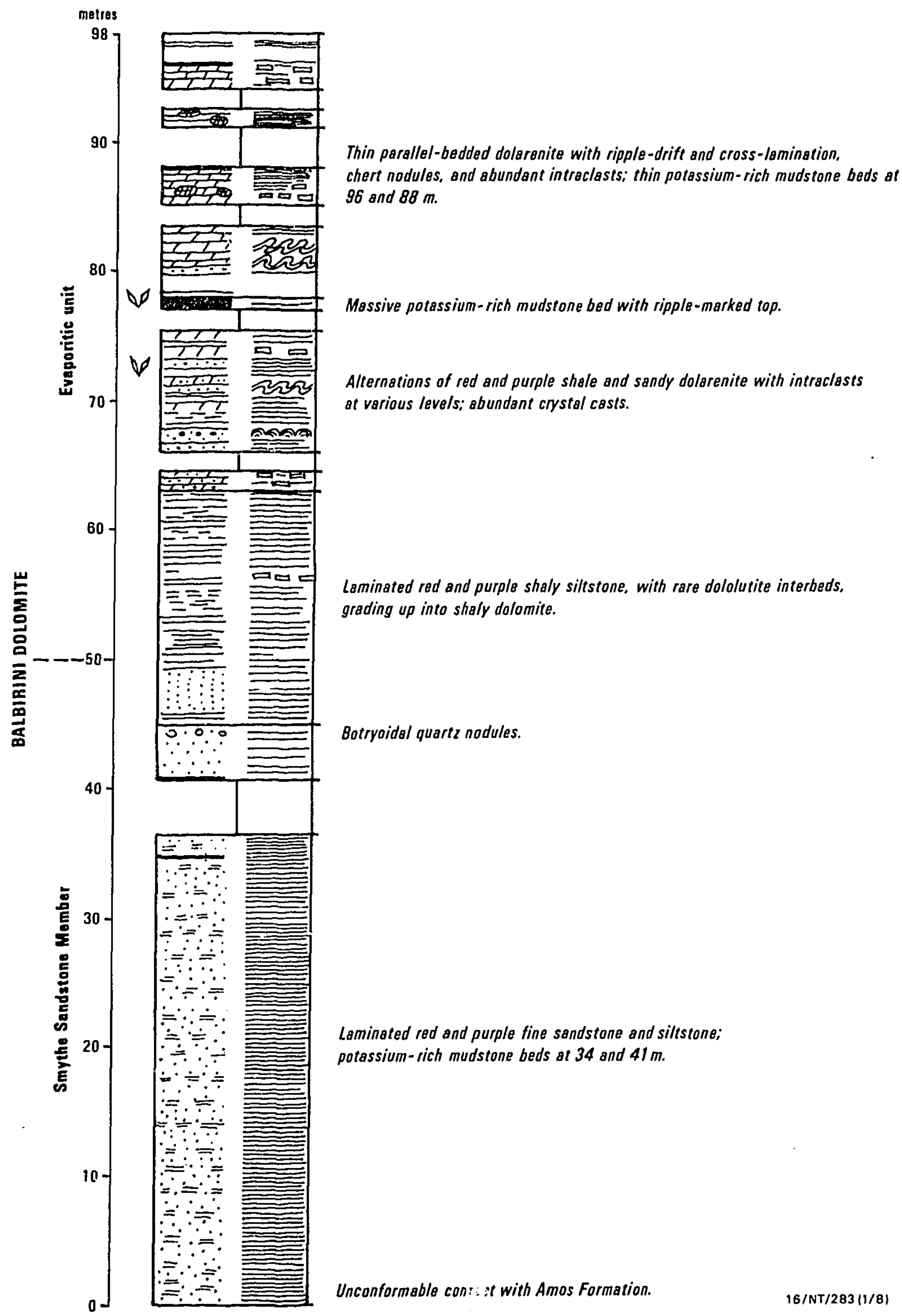


FIG A42 The exposed part of the Type Section of Balbirini Dolomite near Babirini homestead, Measured Section Mallapunyah 77/04 (grid square 7847 Plate 1).

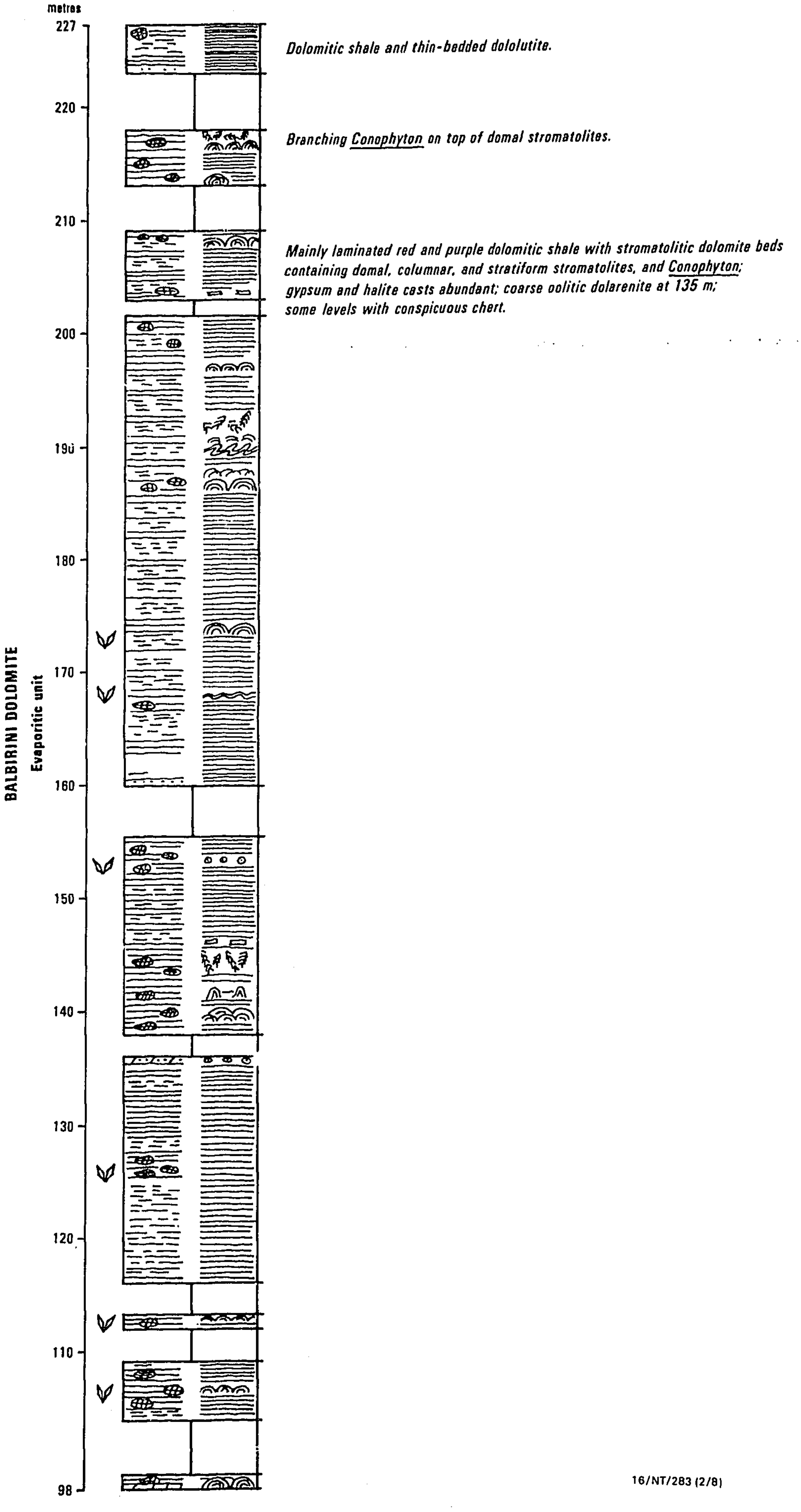


FIG A42 (continued - sheet 2)

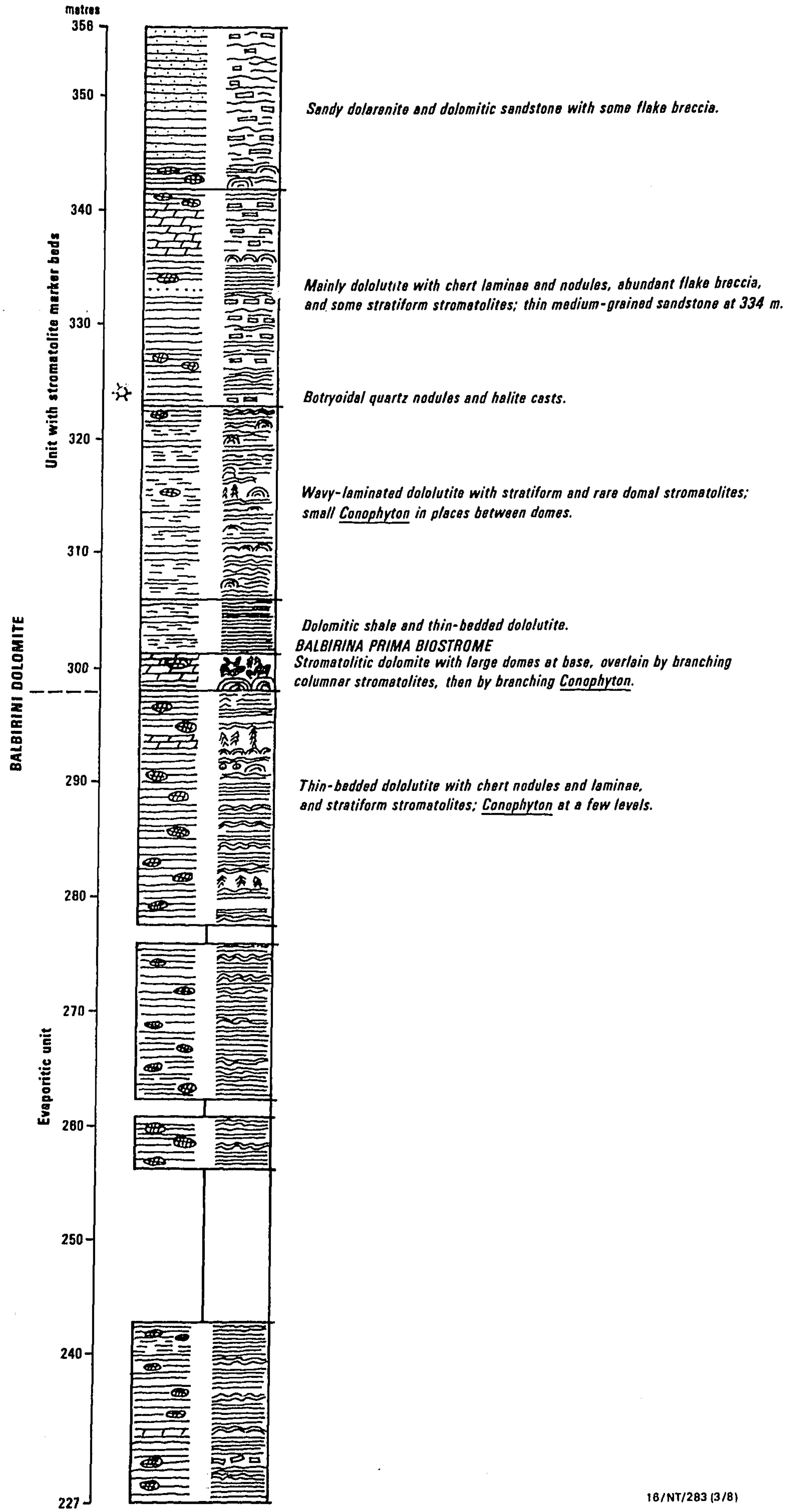


FIG A42 (continued - sheet 3)

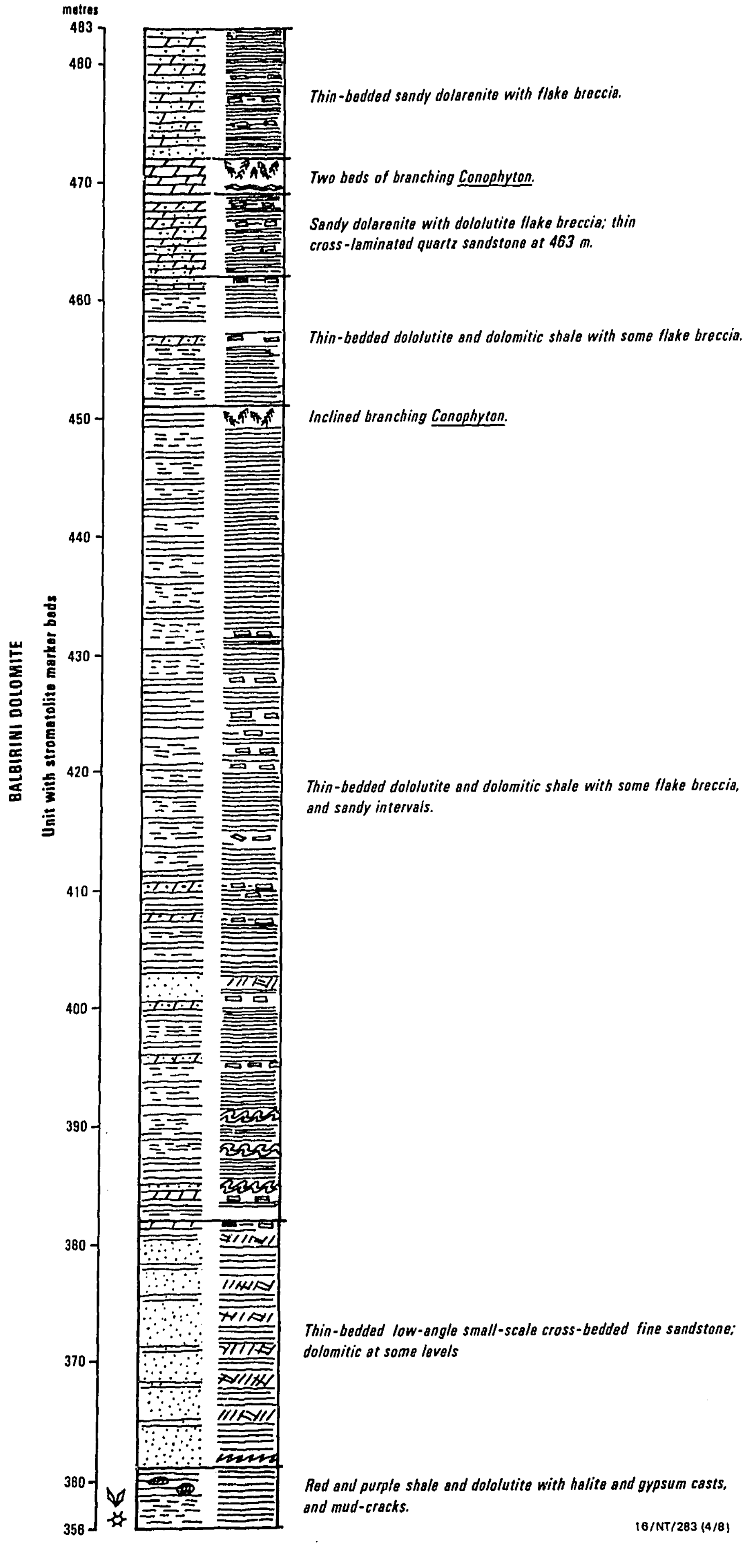
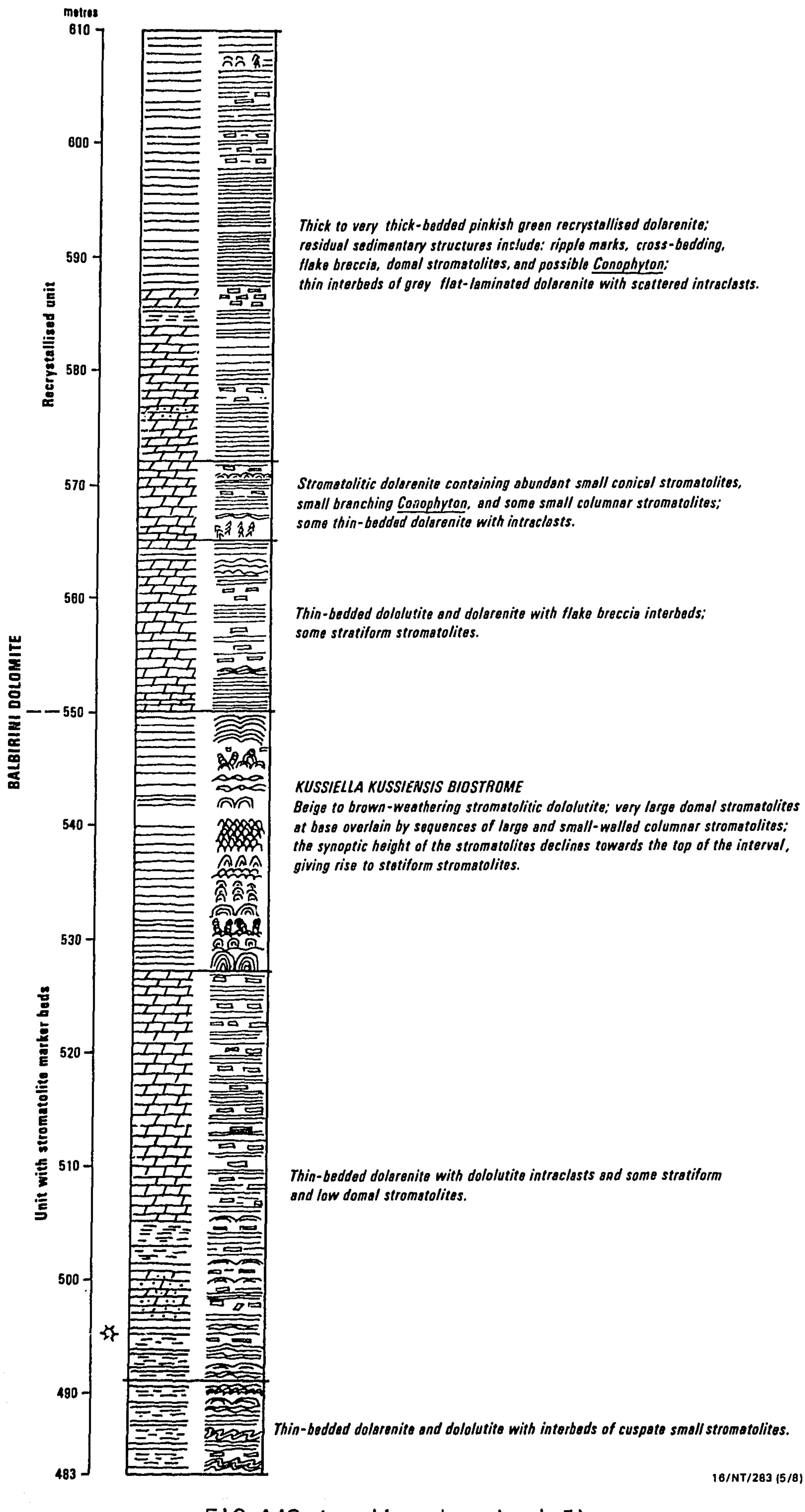
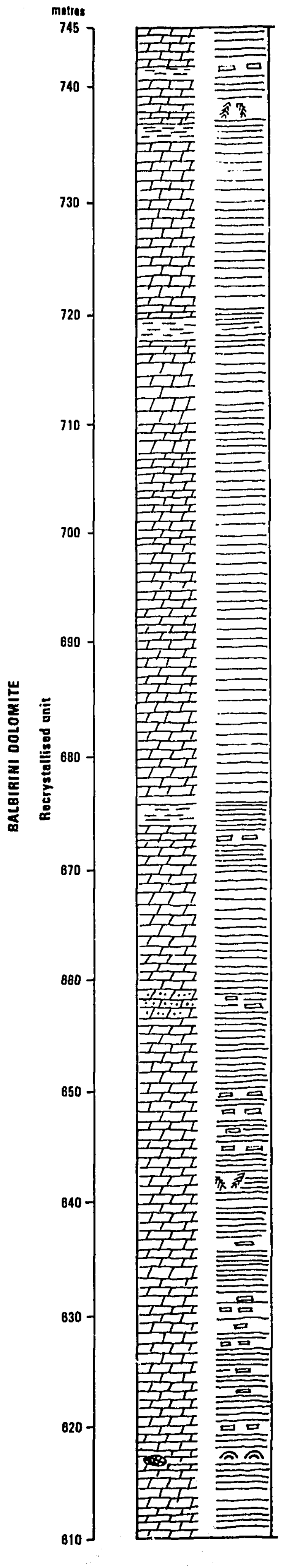


FIG A42 (continued - sheet 4)



16/NT/283 (5/8)

FIG A42 (continued - sheet 5)



Thick to very thick-bedded pinkish green recrystallised dolarenite; residual sedimentary structures include: ripple marks, cross-bedding, flake breccia, domal stromatolites, and possible Conophyton; thin interbeds of grey flat-laminated dolarenite with scattered intraclasts.

16/NT/283 (6/8)

FIG A42 (continued - sheet 6)

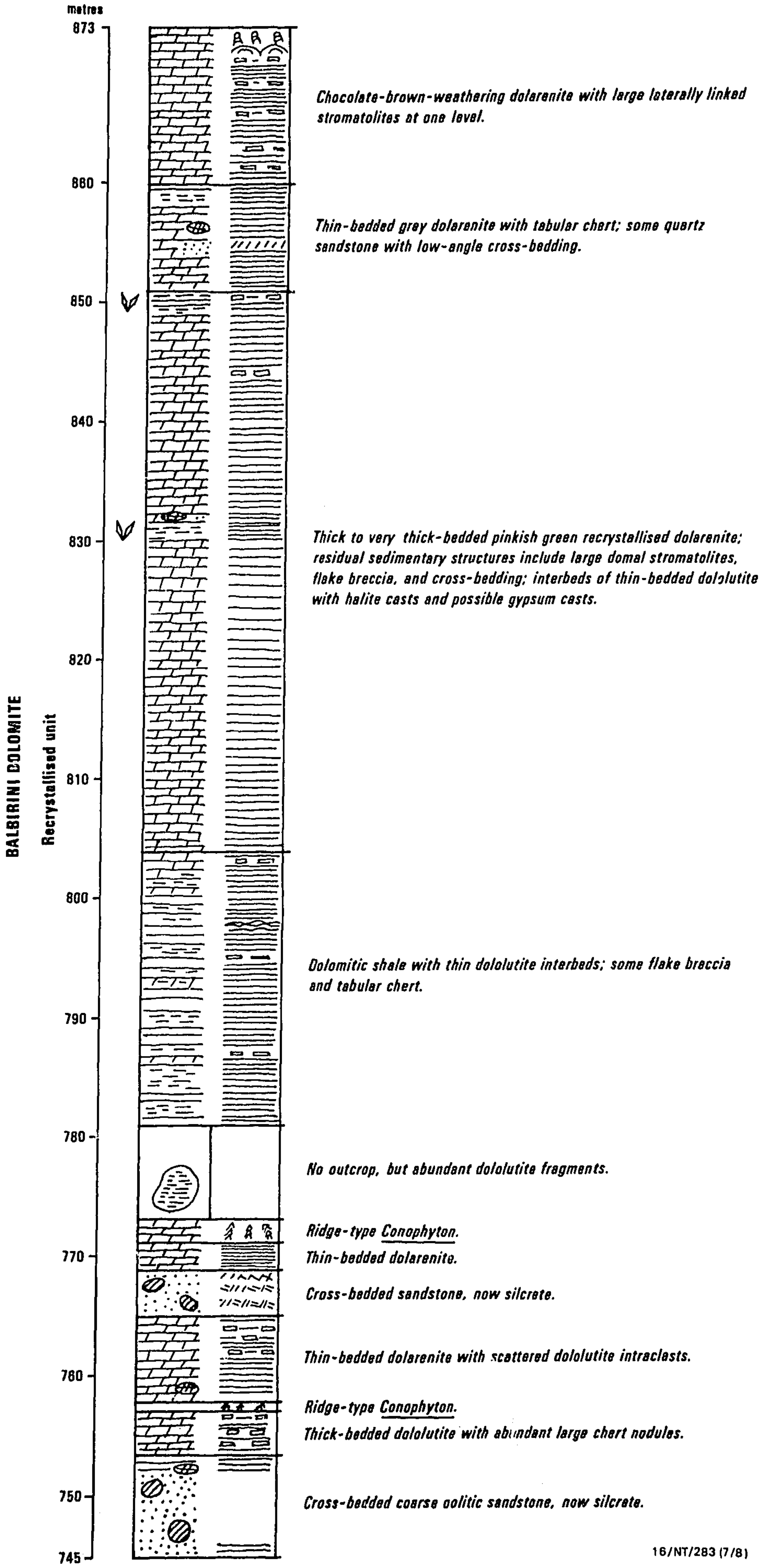


FIG A42 (continued - sheet 7)

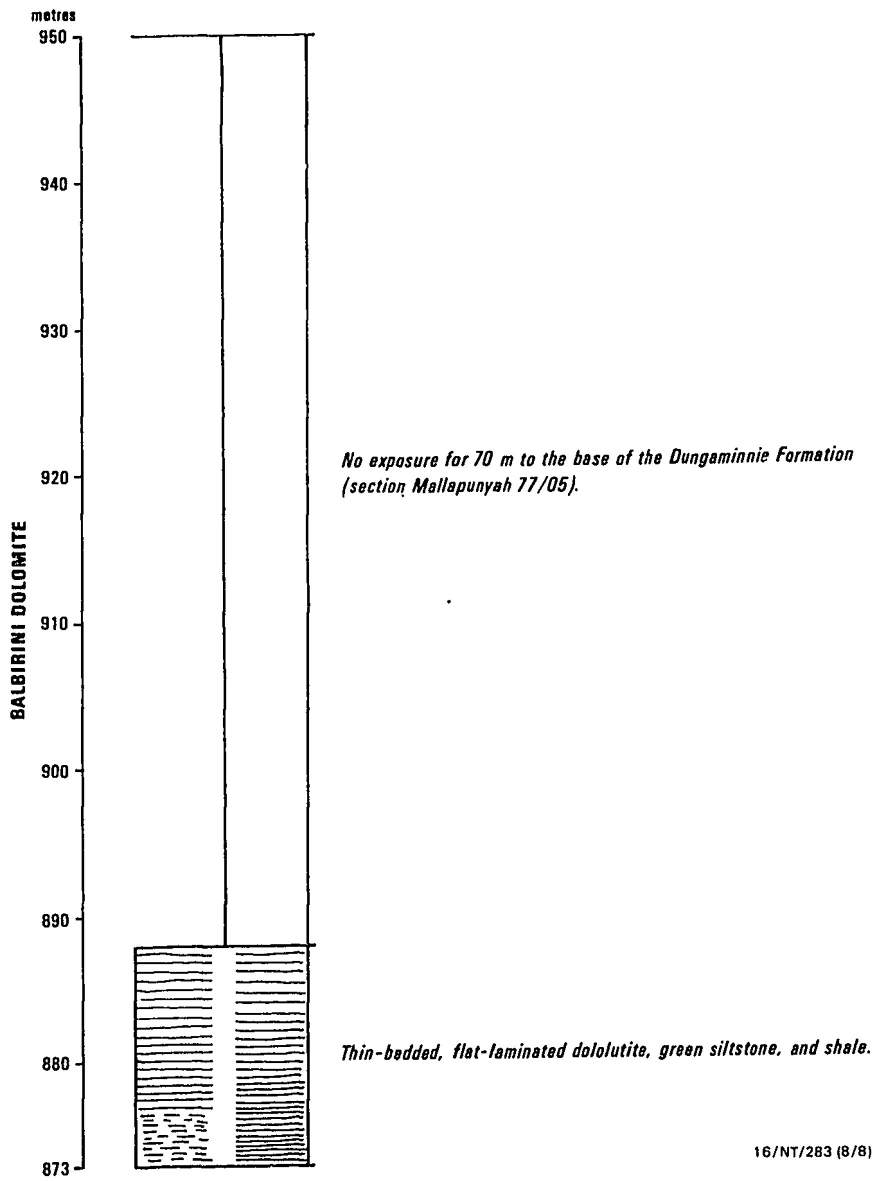


FIG A42 (continued - sheet 8)

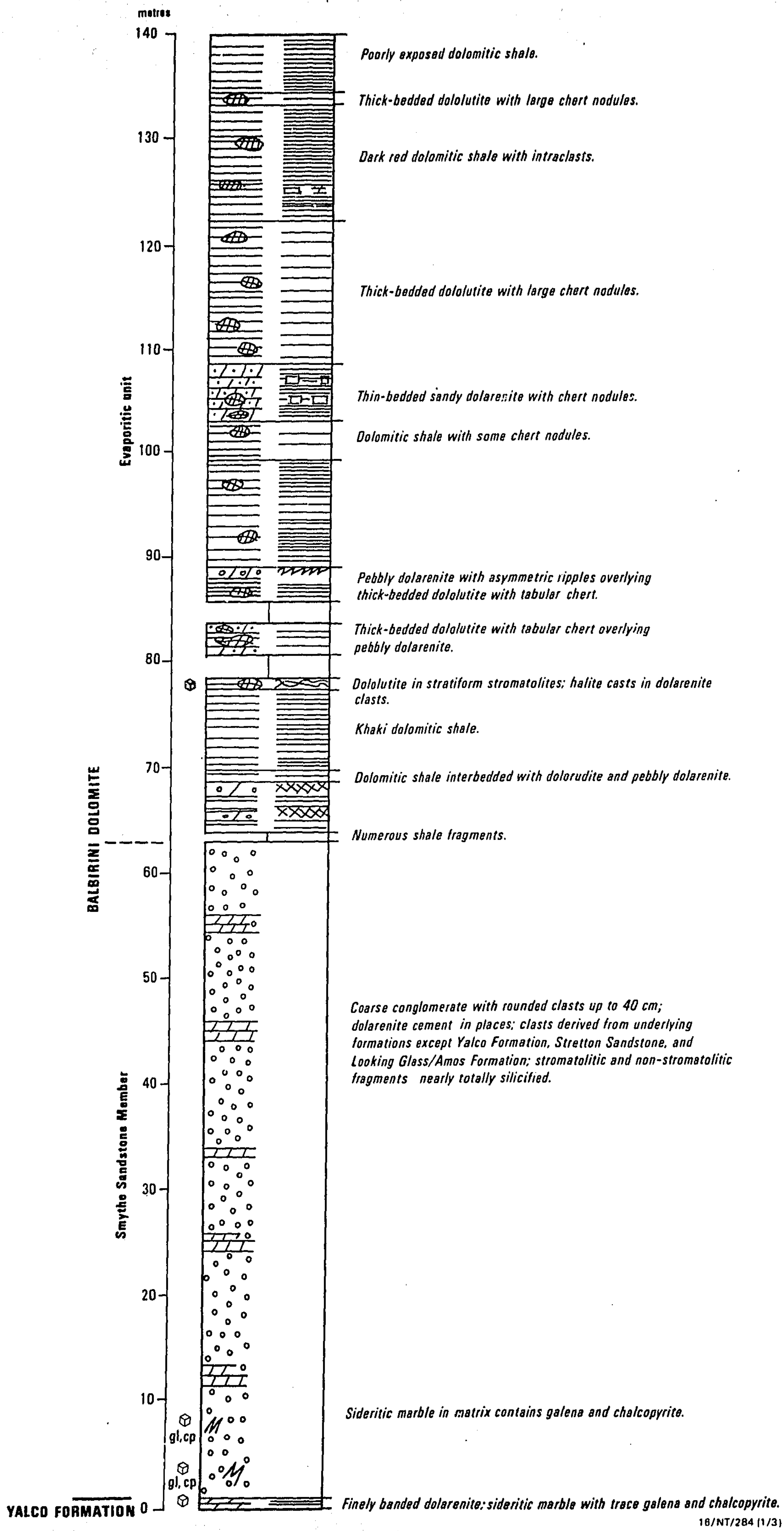


FIG A43 Balbirini Dolomite in Measured Section Mallapunyah 78/03, southeast end of Abner Range (grid square 0623 Plate 1).

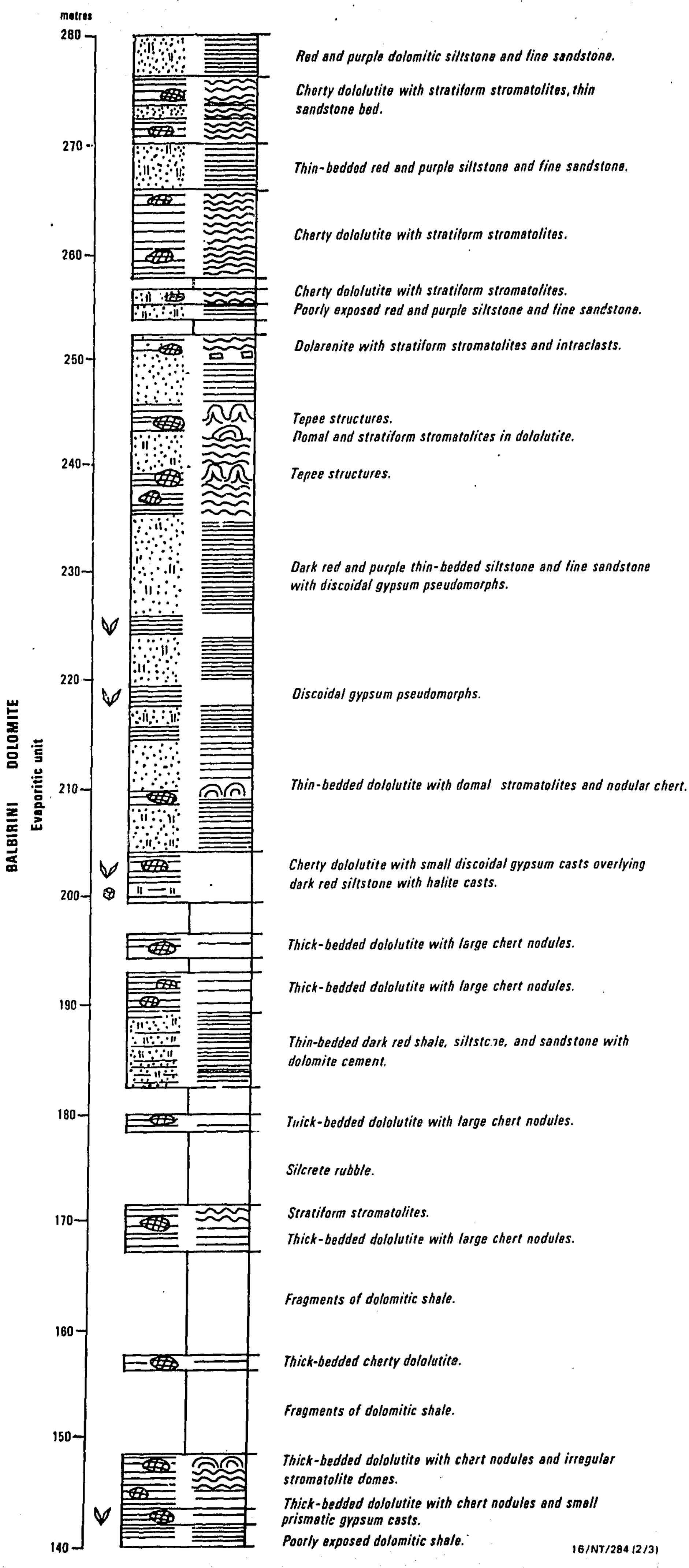


FIG A43 (continued - sheet 2)

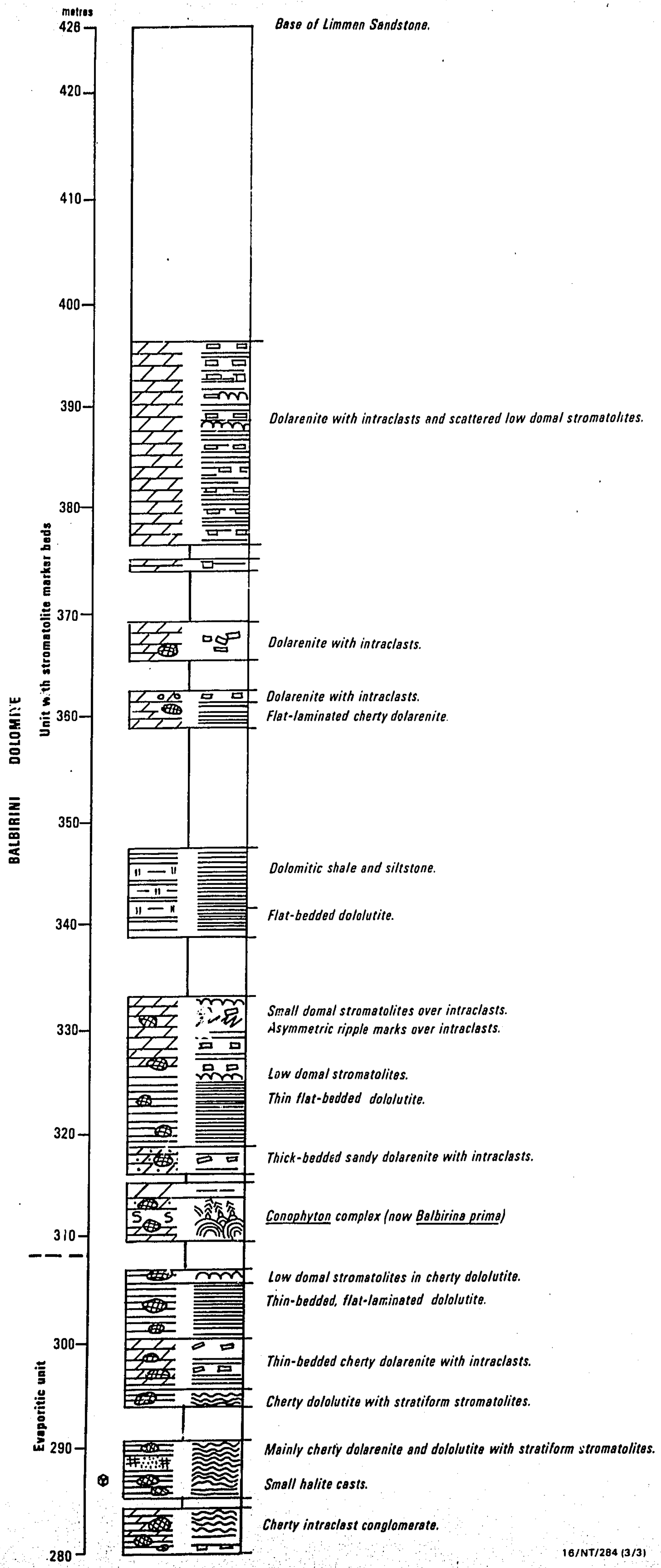


FIG A43 (continued - sheet 3)

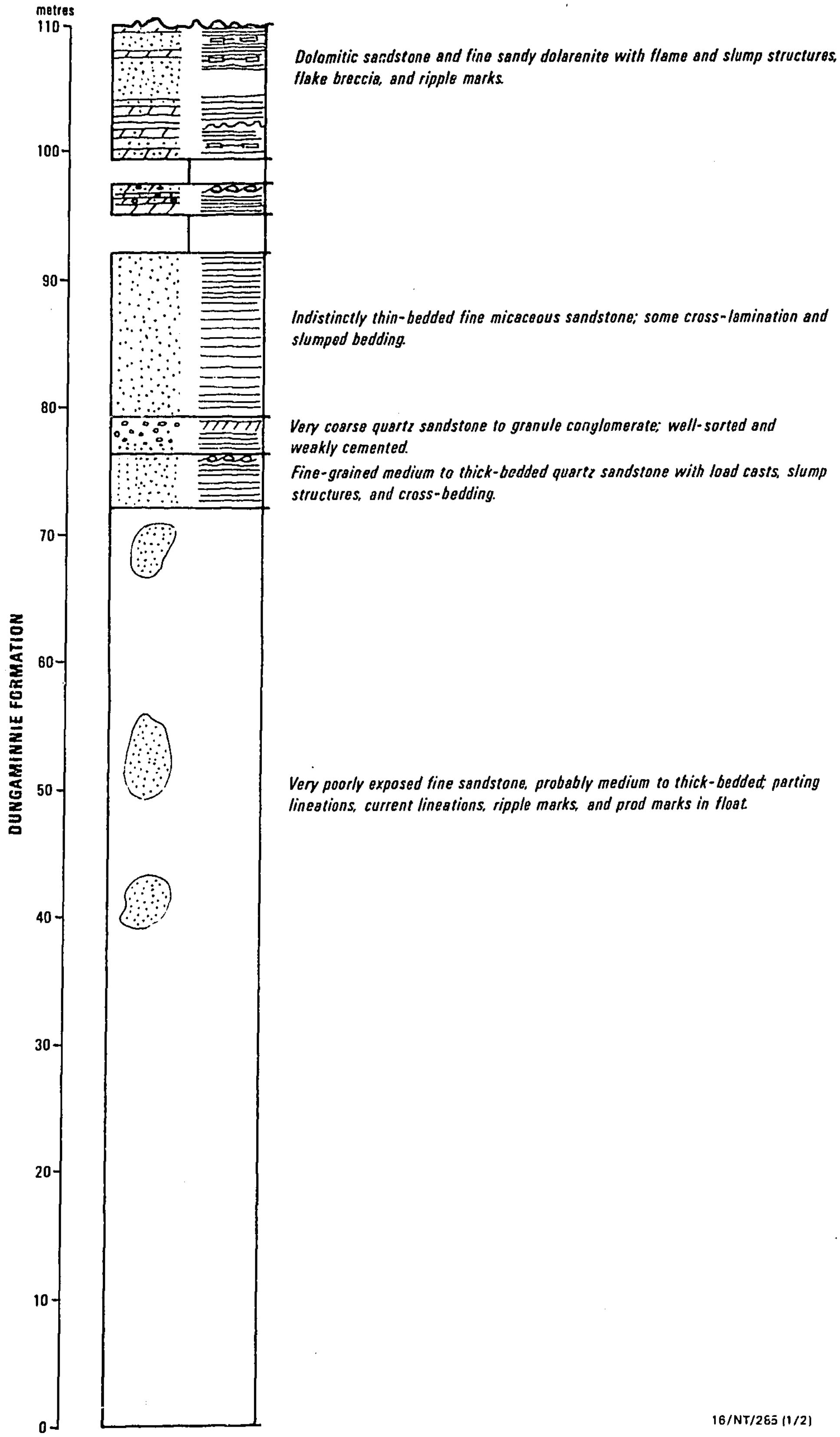


FIG A44 Type Section Dungaminnie Formation near Balbirini homestead air-strip, Measured Section Mallapunyah 77/06 (grid square 7854, Plate 1).

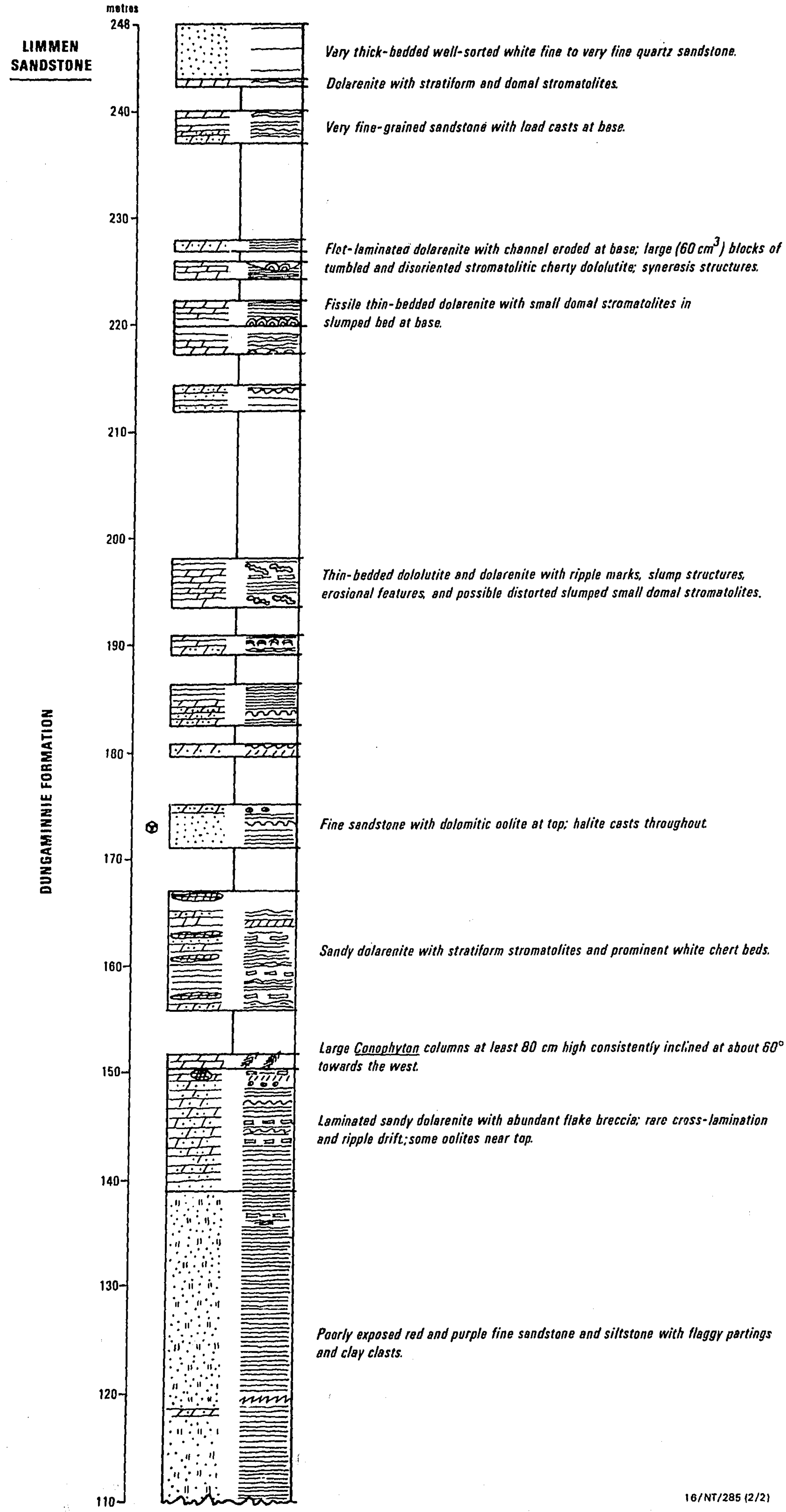


FIG A44 (continued)

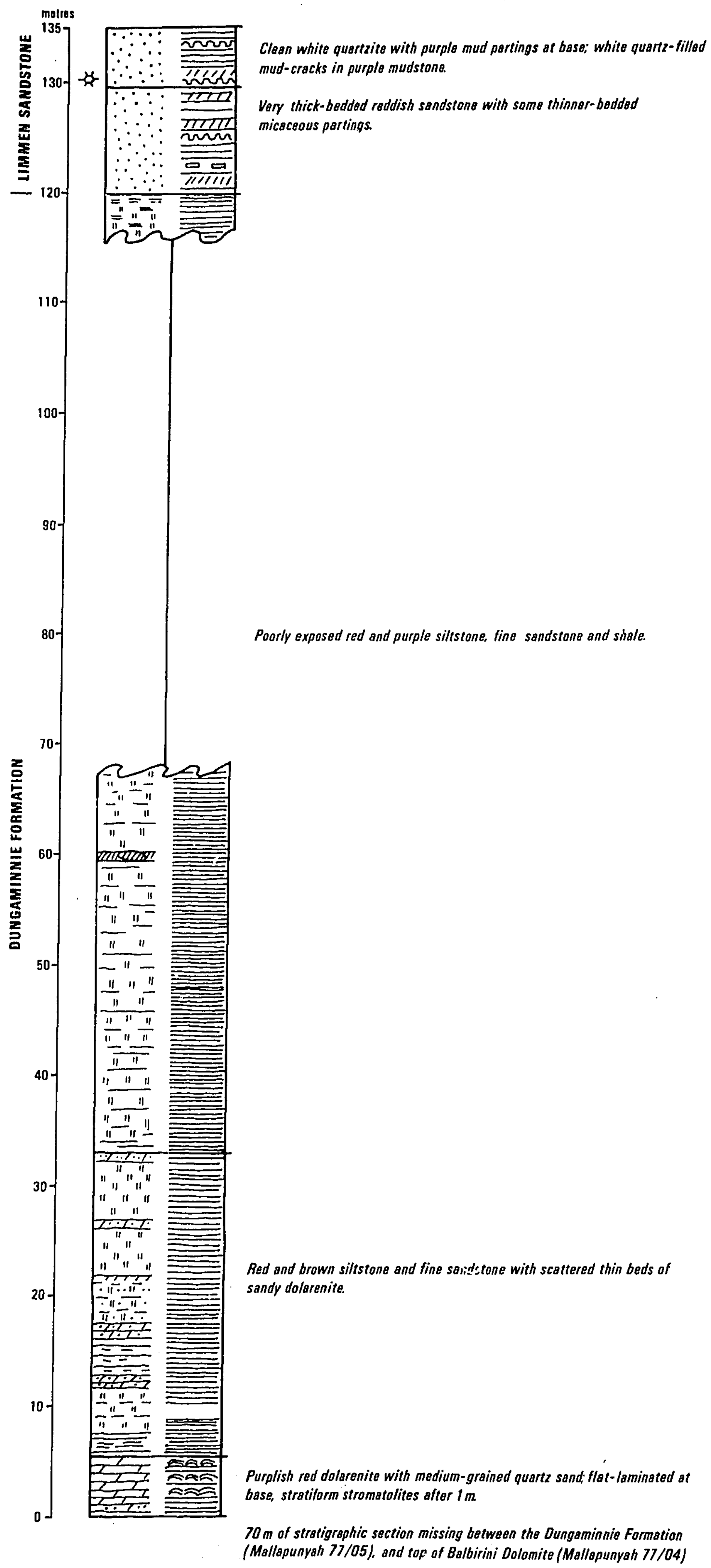


FIG A45 Partial section of Dungaminnie Formation, 1km southeast of Balbirini homestead, Measured Section Mallapunyah 77/05 (grid square 7948 Plate 1).

APPENDIX 2

GEOCHEMICAL INVESTIGATIONS OF THE PROTEROZOIC BARNEY CREEK FORMATION AND SOME ASSOCIATED CARBONATE UNITS OF THE McARTHUR GROUP, NORTHERN TERRITORY*

by

C.W. Claxton

*Originally issued in BMR Record 1969/145 (Brown & others, 1969).

INTRODUCTION

Aims and scope of the geochemical investigations

All (360) samples which M.C. Brown collected for petrographic study have been chemically analysed for Ca, Mg, acid-insoluble residue (AI), K, Fe, Mn, P, Zn, Pb, Cu, Ni, and Co. This appendix presents the analytical data (Table A6), and discusses their significance for interpreting sedimentary environments and exploration indicators. Sample localities and rock types are shown in the stratigraphic sections on the relevant figures (Appendix Figs. A26-36). In the discussion, samples are separated into those from near the HYC deposit and those from outside the known limits of significant Pb-Zn mineralisation.

Brown's samples - selected for petrographic study of representative samples of all the rock types present - do not represent a true statistical sample of the bulk composition of the formation. This must be kept in mind when interpreting the average composition of the sampled formations without reference to the individual rock types collected, although the broad conclusions are probably valid.

Analytical methods

Each sample was reduced to a fine powder by crushing in a jaw-crusher, and grinding in a Sieb-Technik mill. Four aliquots were split from each sample, so that the following determinations could be made:

1. AI (acid insoluble residue), Ca, and Mg
2. Trace elements (Fe, Mn, Ni, Co, Cu, Pb, and Zn)
3. Phosphate
4. K

The first three aliquots were transferred to Pyrex beakers and the last to a platinum dish. All weighings were acid-digested.

To determine the AI content of each sample, the carbonate fraction was dissolved by adding hydrochloric acid (2N) and allowing the reaction to proceed overnight at room temperature; siliceous and sulphide materials are virtually inert under these conditions. The residue was collected on a filter paper, washed, ignited to 800°C, cooled, and weighed. The filtrate was preserved for the determination of Ca and Mg.

An aliquot of the filtrate was treated with ammonium chloride and ammonia solution (1:1) to precipitate Fe, Al, and some Mn, which were then removed by filtration and discarded; complete Mn separation is not necessary before oxalate precipitation (Mellor & Thompson, 1938). The ammonia filtrate was acidified, and Ca precipitated, after buffering the solution with oxalic acid and ammonia and the adding of ammonium oxalate. Because Mg in large amounts is partly precipitated with the Ca, the precipitate was collected, dissolved, and reprecipitated to free it from the occluded Mg before final filtering. The calcium oxalate was then ignited to 1000°C to form calcium oxide, which was weighed.

Magnesium was determined on the combined filtrate from the oxalate separation, which was evaporated to dryness and baked to volatilise the ammonium salts, before redissolving in water. The solution was buffered with ammonia/ammonium chloride solution to prevent interference by any remaining Mn. Excess ethylene-diammine tetra-acetic acid (EDTA) was added and the solution back-titrated with standard magnesium solution, using eriochrome black T to indicate the equivalence point. Only traces of Sr and Ba interfere, and are determined simultaneously. Iron had been previously removed (Schwartzenbach, 1957).

Extraction of the trace elements was incomplete but adequate. The sample was treated with hydrochloric acid (5N) and evaporated to dryness. This was repeated before the final solution was prepared. The hydrochloric acid extraction was supplemented by the addition of nitric acid (15N) if the first residue was markedly discoloured. The nitric acid addition necessitated an additional evaporation. The residue remaining after the extraction was white to light grey and was assumed to be mainly sandy material. The trace elements were determined by atomic absorption spectrophotometry on a Techtron model AA4 spectrophotometer. Non-atomic absorption corrections were made to small readings.

For the determination of phosphate, perchloric acid (21 per cent W/V) was used for digesting the sample. After the digestion, excess perchloric acid was removed by evaporation on a hot plate. The extract was made up to a volume, and an aliquot taken. Ammonium vanadate (4.68 g l^{-1}, 66 ml 70 per cent $HClO_4$ l^{-1}) and ammonium molybdate (70.6 g l^{-1}) reagents were added, and colorimetry performed at a wavelength of 460 nm in a Unicam SP500 spectrophotometer after allowing 30 minutes for colour development. The ferric iron interference was removed by the formation of colourless ferric perchlorate. Manganese was precipitated. All other interferences were too small to have any appreciable effect. The method, according to Charlot (1964), is 'accurate to within 0.1 per cent with natural phosphates'.

For determination of K, the sample was treated with hydrofluoric and perchloric acids and placed on a water bath, where the siliceous material volatilised as SiF_4. Afterwards, the sample was placed on a hot plate to remove the excess perchloric acid. Finally the sample was dissolved in hydrochloric acid (5N). The atomic absorption was measured at a wavelength of 404.4 nm, which enabled K contents down to 0.05 per cent to be evaluated.

Statistical analysis of the results

All analytical results are tabulated in Table A6. Chemical data were punched on 80-column cards for statistical computations on the CSIRO CDC3600 computer. Two programs were used: GESTAT (Garrett, 1967) and FACTORAN (Brown, 1965), for general data screening and factor analysis respectively.

GESTAT is a general - purpose data-screening program which computes summary statistics for each variable (mean, standard deviation, skewness, and kurtosis), as well as a product-moment correlation matrix (containing coefficients of correlation between every pair of variables). The significance level for each correlation coefficient is indicated by a 'Student' t test; in the present study, correlations with less than 95 per cent probability of significance were rejected.

The factor-analysis program (FACTORAN), which uses methods outlined by Harman (1967), was employed to clarify relationships among the variables; ideally this method reduces a large number of observed variables, by linear transformation, to a smaller number of hypothetical variables (factors); rotation of the resulting matrix to 'Simple Structure' (Harman, 1962), giving the best fit to the original variable, allows the factors to be physically interpreted (Fig.A46).

Several separate statistical analyses were carried out: initially individual stratigraphic sections were studied; the total population of samples was analysed; and then each stratigraphic unit was analysed separately.

The small number of samples available for some of these studies limits the statistical reliability of the numerical results, so most of the discussion of the results will be limited to a qualitative assessment of the statistical parameters.

DISCUSSION OF INDIVIDUAL ELEMENTS

Calcium and magnesium

As one would expect from samples of impure dolomites, strong positive correlations are present between Ca and Mg, whilst both show negative relationships with the AI fraction. The close association between calcium and magnesium in carbonate justifies discussing them together.

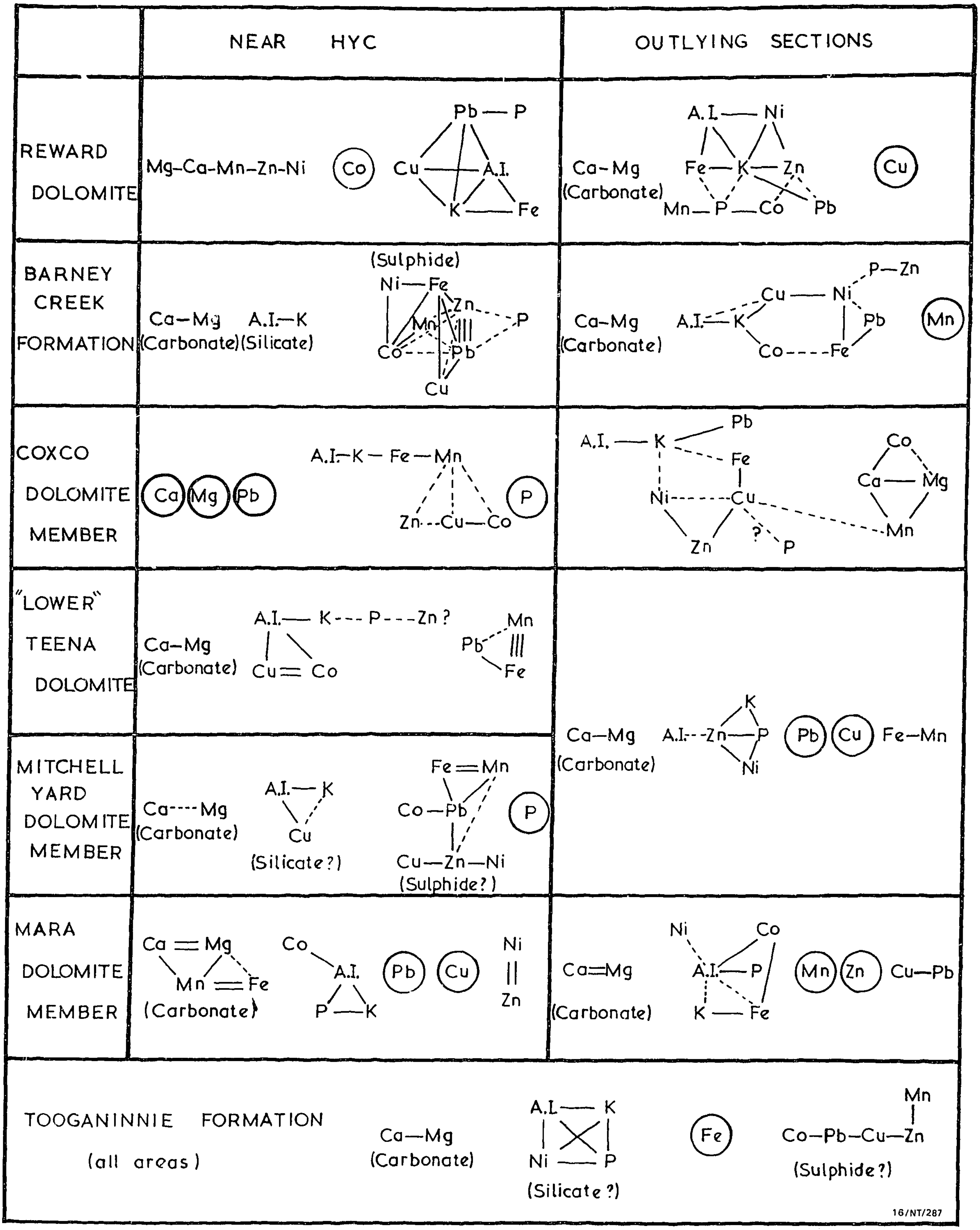


FIG A46 Diagrammatic representation of statistical correlations between elements.

An average Ca:Mg ratio of 1.8 (Table A1) was obtained for the area, which is the same as published values for the Precambrian carbonate rock of the Russian Platform (Vinogradov & others, 1952; cited by Ingerson, 1962). This is slightly higher than the expected ratio of 1.65 in pure dolomite with a 1:1 Ca:Mg molar ratio. Staining of thin sections does not indicate the presence of a separate calcium carbonate phase in the rocks.

TABLE A1. AVERAGE CALCIUM:MAGNESIUM RATIOS IN THE MEASURED SECTIONS

Max Brown's section no.	Ca:Mg
2	2.0
3	1.8
4	1.8
5	1.85
6	2.0
7	1.8
8	1.8
9	1.85
10	2.0
11	2.1
12	1.55
13	1.6
14	1.75
Average (all samples)	1.8

The excess Ca can be partly accounted for by substitution of Fe for Mg in the dolomite lattice. The Reward Dolomite and Barney Creek Formation have generally higher Ca:Mg ratios than the Emmerugga and Teena Dolomites (Table A2), and they also have a higher iron content over most of the region (Table A3). However, many of the rocks with excess calcium still have too little iron to account for all of the excess in this way, so that the carbonate phase must contain, in many cases, excess calcium in the dolomite lattice.

In the immediate area of the HYC mineralisation (Max Brown's sections 13, 14), the Emmerugga and Teena Dolomites show an anomalous deficiency in calcium.

TABLE A2. AVERAGE CALCIUM:MAGNESIUM RATIOS OF ROCK UNITS

Outlying sections	
Reward Dolomite	2.15
Barney Creek Formation	1.85
Teena Dolomite (Coxco Dolomite Member)	1.8
Emmerugga Dolomite (Mara Dolomite Member)	1.8
Sections near HYC	
Reward Dolomite	1.9
Barney Creek Formation	2.0
Teena Dolomite (Coxco Dolomite Member)	1.65
Emmerugga Dolomite (Mara Dolomite Member)	1.7

The Emmerugga Dolomite and Teena Dolomite have Ca:Mg ratios of 1.6 to 1.75; these are closer to a 1:1 dolomite molar ratio than the average for the area as a whole. These rocks have Fe contents (1-4 per cent) which are about five times the content elsewhere in the area. Calculations for five specimens showed molar ratios between 0.973 and 1.14 for Ca:Mg, and 0.933 and 0.970 for Ca:Mg+Fe. This calcium deficiency could be due either to substitution of Ca by Mg and/or Fe in the dolomite lattice, or the presence of separate iron or magnesium carbonate phases.

Iron

Iron contents range from 0.11 to 5.5 per cent; the highest value was found in a sample of the Myrtle Shale consisting of red subaerial siltstone containing hematite-stained terrigenous material. Other values greater than 4 per cent were found in samples of the Barney Creek Formation throughout the area, and from the Mitchell Yard Dolomite Member near the HYC deposit.

Near HYC. The Emmerugga and Teena Dolomites and the Barney Creek Formation all have higher average Fe contents near the HYC deposit than they do in outlying sections (Table A3). This observation has been confirmed by Lambert & Scott (1973), and it clearly reflects the abundance of pyrite in the Barney Creek Formation; in contrast, the lack of hydrogen sulphide liberated during the dissolution of samples from carbonate-rich units shows that they did not contain appreciable amounts of sulphide. The fresh dolomites show no red pigmentation (Fe_2O_3), and most contain too little insoluble residue for the Fe to occur as silicates. The Fe appears to occur in the carbonate fraction as ferroan dolomite. When weathered, the Fe-rich dolomites develop a distinctive red-brown colour.

Product-moment correlation matrices from the Teena and Emmerugga Dolomites show a strong Fe-Mn relationship, suggesting that Mn may also have been deposited as carbonate. Fe-Pb correlation is shown by the Mitchell Yard Dolomite Member and lower Teena Dolomite. The Coxco Dolomite Member shows an Fe-K relationship that probably reflects the Fe content of the K-rich tuffs?, which constitute a significant proportion of the samples from this unit.

TABLE A3. AVERAGE IRON CONTENTS OF ROCK UNITS

Rock unit		% Fe
Reward Dolomite	Outlying	1.05
	Near HYC*	0.78
Barney Creek Formation	Outlying	1.24
	Near HYC	1.62
Coxco Dolomite Member (Teena Dolomite)	Outlying	0.36
	Near HYC	1.46
Mitchell Yard Dolomite Member (Emmerugga Dolomite) and lower Teena Dolomite	Outlying	0.29
Lower Teena Dolomite	Near HYC	1.44
Mitchell Yard Dolomite Member (Emmerugga Dolomite)	Near HYC	1.55
Mara Dolomite Member (Emmerugga Dolomite)	Outlying	0.52
	Near HYC	0.69
Tooganinie Formation and Tatoola Sandstone	All samples	1.33

*The Reward Dolomite is not exposed around the HYC deposit. The near-HYC samples are from sections 8, 9, and 10, about 20 km from the deposit.

Iron, particularly the oxide but also the sulphide, has the ability to scavenge other ions from solution (Krauskopf, 1957). The relationships inferred in the product-moment correlation matrix for the Barney Creek Formation show that deposition of Ni, Co, Cu, Pb, and Zn is related to the Fe content.

In the Reward Dolomite, Fe-Al and Fe-K correlations reflect the abundance of tuffaceous material in the unit near the HYC deposit.

Manganese

The Mn content of the rocks varies from less than 50 ppm to more than 1.2 per cent; the average value (1030 ppm Mn; 1330 ppm MnO) compares favourably with carbonate rocks on the Russian Platform (Ronov & Erminshkina, 1959).

Manganese oxides, like Fe, have the ability to scavenge ions from solution by absorption. They are usually deposited as a hydrated oxide after migration in suspension, as adsorbed cations on colloidal particles such as clay minerals, and partly in solution from the breakdown of igneous and metamorphic rocks by chemical weathering.

Widespread correlations of Mn with Ca and Mg, and in places with Zn and Fe, in the carbonates of most units suggest that Mn, as well as Fe and probably Zn, have substituted for Ca and possibly Mg in the dolomite crystal lattices.

Near HYC. Strong Fe-Mn correlation was found throughout the Fe-rich carbonate of the Emmerugga and Teena Dolomites. The Mitchell Yard Dolomite Member also shows Mn-Pb correlation and weaker Mn-Zn correlation, while the lower Teena Dolomite shows only weak Mn-Pb correlation.

Outlying sections. The Fe-Mn correlation is weak in the Mitchell Yard Dolomite Member and lower Teena Dolomite. This perhaps reflects different pH and Eh conditions away from the mineralised area, allowing geochemical differentiation of manganese and iron as proposed by Krauskopf (1957).

In the Myrtle Shale, Mn correlates with Zn, probably because manganese oxides adsorb Zn in the Fe-rich terrigenous siltstones.

Cobalt

The values obtained for Co in samples of McArthur Basin carbonates are significantly lower than those reported for carbonates elsewhere. Graf (1962) determined an average value of 4.3 ppm Co for Scottish, Russian, and New Zealand rocks. The McArthur Basin samples average 3.1 ppm Co, although some contain as much as 43 ppm. In the Coxco Dolomite Member, none of the thirty-four samples analysed has Co values above the detection limit (2.5 ppm).

In all other units, apart from the Barney Creek Formation, the number of Co values which lie above the detection limit is too small for reliable inferences to be drawn. However, from a statistical evaluation of the entire sample population, an Fe-Co correlation can be inferred. In the Barney Creek Formation, which shows the highest Co values, the Fe-Co correlation weakens away from the HYC deposit (Students t-test values decreasing). This probably indicates that the Co either occurs in the sediments as sulphide, or is adsorbed onto pyrite or iron oxides.

Nickel

Statistical analysis failed to establish any general correlations between Ni and other elements. Each unit or area tends to show different correlations, suggesting that Ni was introduced independently into the sediments.

Near HYC. Ni-Zn correlations are apparent in the Emmerugga and Reward Dolomites and, in the latter, appear to be related to the carbonate fraction. The Barney Creek Formation shows correlations of Ni with Fe, Mn, and Co; these elements, in turn, are associated with the economic metals (Pb-Zn) of the HYC deposit.

Around Amelia Creek, only the Mara Dolomite Member is of significance, as all other units exhibit either no Ni correlations or nickel contents below the detection limit. Here Ni is associated with Cu and, to a lesser degree, Zn, possibly in sulphides.

Outlying sections. Ni-Zn correlations here show up in the Mitchell Yard Dolomite Member, lower Teena Dolomite, Coxco Dolomite Member, and Reward Dolomite where they appear to be associated more with the non-carbonate fractions of the rocks. A relationship is inferred between Ni, AI, and K in the Tooganinie Formation, Reward Dolomite, and (weakly) Coxco Dolomite Member, while an ill-defined relationship between Ni and AI is inferred in the Mara Dolomite Member. These associations suggest transportation and precipitation of Ni with terrigenous material, perhaps by adsorption on clays, etc.

In the Top Crossing area the Reward Dolomite and Barney Creek Formation show correlations of Ni with Fe, K, and Zn. Lower in the sequence, the Coxco Dolomite Member retains its strong Ni-Zn correlation, but Ni-Fe and Ni-K correlations weaken, and additional associations are apparent between Ni-AI and Ni-P. In the Mara Dolomite Member, Ni is associated with the sulphide cations, Cu, and Co; the Ni-Fe correlation is re-established (perhaps as a result of adsorption effects in the non-carbonate rocks); the phosphate and AI residue relationships remain; but the Ni-Zn correlation is weaker. The upper half of the Tooganinie Formation shows Ni associated with P, K, AI, and Zn, but these do not continue into the lower Tooganinie Formation, where Ni correlates with Pb and weakly with Fe and Co.

Lead and zinc

Lead and zinc are the major economic metals in the sulphide orebodies of the HYC Pyritic Shale Member. Although a general correlation between these elements is apparent throughout the area, only in the mineralised parts of the HYC Pyritic Shale Member is the Pb-Zn association strong. Significant but weaker Pb-Zn correlations also occur in the Mitchell Yard Dolomite Member and lower Teena Dolomite near the HYC deposit.

For most formations, Pb and Zn associations near the HYC deposit are quite different from those in outlying sections.

The average values for all units are 110 ppm Zn and 20 ppm Pb; averages of individual units are shown in Table A4. The only major anomalies apparent are in the mineralised parts of the Barney Creek Formation, at or near the HYC deposit. If these anomalous results are removed from the overall averages, the averages reduce to 15 ppm Zn and 10 ppm Pb. The average values for the Barney Creek Formation in the outlying sections are only 20 ppm Zn and 10 ppm Pb, similar to the values in the other units. The Pb and Zn contents of all units are relatively constant throughout the sequence, except for a slight enrichment of Zn in those units immediately underlying and overlying the Barney Creek Formation in outlying sections.

Near HYC. A strong Zn-Ni correlation is apparent in the Mara Dolomite Member, but associations are more complex in the Mitchell Yard Dolomite Member, where the Pb-Zn shows interrelated correlations with the (sulphide?) elements Cu, Ni, Co, Fe, and Mn.

TABLE A4. AVERAGE LEAD AND ZINC CONTENTS OF ROCK UNITS

Rock unit		Zn(ppm)	Pb(ppm)
Reward Dolomite	Near HYC	30	10
	Outlying	10	10
Barney Creek Formation	Near HYC	1890	320
	Outlying	20	10
Coxco Dolomite Member (Teena Dolomite)	Near HYC	20	10
	Outlying	20	10
Lower Teena Dolomite	Near HYC	10	10
Mitchell Yard Dolomite Member (Emmerugga Dolomite)	Near HYC	10	10
Mitchell Yard Dolomite Member (Emmerugga Dolomite) and lower Teena Dolomite	Outlying	10	10
Mara Dolomite Member (Emmerugga Dolomite)	Near HYC	10	10
	Outlying	10	10
Tooganinie Formation and Tatoola Sandstone		20	10

In the lower Teena Dolomite, a correlation is inferred only between Pb-Fe and Pb-Mn (weak), while the Coxco Dolomite Member shows weak relationships between Zn, Mn, Cu, and Co. These associations may reflect adsorption of trace elements on Mn and Fe oxides.

Complex associations are also apparent in the Barney Creek Formation, where the strongly interrelated Pb and Zn are related to the sulphide elements Fe and Cu, and show a weak correlation with Cu, Mn, and P.

In the Reward Dolomite, Pb and Zn are again independent. Zinc is correlated with Mn and Ni, and, through them, with Ca and Mg; Pb is related to the terrigenous component, being correlated with K, AI residue, Fe, Cu, and P, perhaps reflecting adsorption of the trace elements on clays.

Outlying sections. In the Tooganinie Formation, scavenging of trace elements by manganese oxides apparently explains the inferred complex associations of Zn with Mn and Cu, of Pb with Cu and Co, and (indirectly through Cu) of Pb with Zn and Mn.

The Mara Dolomite Member shows correlation only between Pb and Zn. In the Mitchell Yard Dolomite Member and lower Teena Dolomite a Zn-K-P-Ni relationship, and a weak Zn-AI correlation, apparently reflect transportation and deposition with terrigenous material, whilst Pb appears to have been adsorbed onto hydrated iron and manganese oxides. Transportation of terrigenous material is again reflected in the complex relationships of the Coxco Dolomite Member, which evinces direct Zn-Ni, Zn-Cu, and Pb-K correlations; indirect correlations (through K) of Pb and AI; and indirect correlations (through Cu, Fe, and K) of Zn and Pb.

The Barney Creek Formation shows independent correlations of Zn with P, and Pb with Fe; these appear to occur in the non-carbonate fraction of the rocks.

The Reward Dolomite again shows weak but direct Pb-Zn correlation, direct correlation of Zn with Ni and K, and - through them - tenuous relationships of Zn with all the non-carbonate elements of the rock.

Copper

Copper, like Ni, does not show any general correlations. Its overall average is about 10 ppm, and its content varies little between the rock units. The highest average - 20 ppm - is from the Tooganinie Formation, though four mineralised samples of the Barney Creek Formation from near the HYC deposit averaged 26 ppm.

Near HYC. No significant correlations are apparent in the Mara Dolomite Member, but the Mitchell Yard Dolomite Member shows weak correlations of Cu with AI residues and K. In the lower Teena Dolomite, Cu maintains its correlation with AI residue and (through that) with K, and has a strong Co correlation. The Co correlation continues up into the Coxco Dolomite Member, where weak correlations of Cu with Mn and Zn are apparent.

The Barney Creek Formation evinces Cu-Fe, Cu-Pb, and weak Cu-Zn correlations which are not evident lower in the sequence. The Cu-Pb correlation continues up into the Reward Dolomite, where correlations are also apparent between Cu-K and Cu-AI.

Copper therefore exhibits two general types of association near the HYC deposit:

- with AI and K in the carbonate-rich units, reflecting the introduction of Cu with the terrigenous components;
- with the principal sulphide components in the Barney Creek Formation, and to a lesser extent the Coxco Dolomite Member, reflecting a swamping of the terrigenous association by the introduction of Cu with the mineralising fluids.

Outlying sections. No significant correlations are evident in the Mitchell Yard Dolomite Member, lower Teena Dolomite, or Reward Dolomite. The Tooganinie Formation shows significant Cu-Pb and Cu-Zn correlations, and the Mara Dolomite

Member shows a Cu-Pb correlation. The Coxco Dolomite Member maintains oxide or sulphide metal associations, shown by its Cu-Fe, Cu-Zn, and weak Cu-Ni and Cu-Mn correlations. In the Barney Creek Formation, correlations of Cu with K, AI, and Ni in the outlying sections are in marked contrast to the correlations of the formation in the mineralised area.

Copper away from the HYC deposit, therefore, seems to be dominated by its association with the terrigenous fraction. The significant association of Cu with Pb and Zn in the Tooganinie Formation, may indicate that the abundant redbeds in this unit were a favourable facies for primary copper sulphide mineralisation.

Potassium

Potassium is contained in the non-carbonate materials of the sediments, and correlates strongly with the AI residue and phosphorus. The Emmerugga Dolomite, lower Teena Dolomite, Barney Creek Formation, and Reward Dolomite contain beds of fine-grained buff to pink non-carbonate rocks with abnormally high K contents, interpreted as tuffs. The inclusion of samples of these beds in calculations of average K contents has probably produced results which are too high.

Fresh rocks from the Barney Creek Formation yielded values ranging from 0.8 to 10 per cent K, the lower values mainly in dolomite-rich samples; the K content, expressed as a percentage of the AI residue fraction, has a range of about 3-11 per cent. One thin tuff? bed in the Coxco Dolomite Member contains 12 per cent K, and one sample from the Reward Dolomite (2/32) has a value of 6 per cent K. These values are higher than those normally found in igneous rocks, so if they are tuffs, additional K must have been added from some other source.

TABLE A5. AVERAGE POTASSIUM CONTENTS OF ROCK UNITS

Outlying sections

Rock unit	% K
Reward Dolomite	1.4
Barney Creek Formation	3.79
Coxco Dolomite Member (Teena Dolomite)	1.9
Lower Teena Dolomite and Mitchell Yard Dolomite Member (Emmerugga Dolomite)	0.18
Mara Dolomite Member (Emmerugga Dolomite)	0.50

Sections near HYC

Rock unit	% K
Reward Dolomite	1.24
Barney Creek Formation	2.94
Coxco Dolomite Member (Teena Dolomite)	0.89
Lower Teena Dolomite	1.65
Mitchell Yard Dolomite Member (Emmerugga Dolomite)	0.29
Tooganinie Formation and Tatoola Sandstone	1.62

The average K contents of some units near the HYC deposit contrast with those in outlying sections, but the variation is not systematic and simply reflects sample bias (Table A5).

Potassium almost invariably correlates strongly with AI, and less commonly with P in a three-way relationship. Some sections show strong K-Fe-AI correlations, mostly in place of K-P correlations. Potassium correlates with a variety of trace elements, particularly in places that were outside the influence of sulphide mineralisation, indicating that the ions of these elements are incorporated in the normal rock minerals rather than in distinct sulphide phases in these places.

Acid insoluble residue

The samples show a wide range of compositions, from almost pure carbonates to rocks composed almost entirely of AI residue; the overall average content of AI residue is 28 per cent. The AI residue comprises terrigenous silt, clay, sand, and pebbles, and authigenic minerals such as chert, K-feldspar, and sulphides.

As described previously, the AI residue always correlates with K, and less commonly with phosphate and Fe. No other significant correlations are apparent.

Away from the HYC deposit, the trace-element associations within the AI residue component of the rock are diffuse and complex; most of the non-carbonate elements show common complex groupings in all units. Near the HYC deposit, associations in the carbonate-rich units become more divergent, and can be grouped into distinct silicate? and sulphide? fractions.

Phosphorus

The overall average phosphorus content is 520 ppm. In general, samples from near the HYC deposit have higher P contents than samples from outlying sections, perhaps reflecting additional phosphate that was taken into solution when P-bearing organic material decomposed (Ronov & Korzina, 1960).

The Coxco Dolomite Member and part of the Barney Creek Formation have P contents roughly two to four times the overall average. In the upper part of the Coxco Dolomite Member, some samples with low AI residues have P contents of up to 4700 ppm - about eight times the overall average.

CONCLUSIONS

The principal results of the geochemical investigations are:

(1) Ca:Mg ratios confirm that dolomite is the major carbonate phase throughout the sequence, but there are significant departures from the 1:1 molar ratio of pure dolomite. In most samples, Ca:Mg ratios indicate a significant Ca excess, but locally there are anomalous Ca deficiencies. Substitution of Fe or Mn for Mg in the dolomite lattice cannot, alone, explain the Ca excess.

(2) The Emmerugga and Teena Dolomites show the following significant compositional differences near the HYC deposit, compared with outlying areas:

   (i) Fe and Mn contents are much greater

   (ii) Ca:Mg+Fe molar ratios are less than 1; this Ca deficiency may be explained by substitution of Fe or Mg for Ca in the lattice, or by the presence of separate Fe or Mg carbonate phases.

(3) Potassium contents are generally high, particularly in the Barney Creek Formation (up to 10 per cent K) and in tuff? beds in dolomite units (up to 12 per cent K). These exceed values for normal igneous rocks, indicating addition of potassium from other sources.

(4) Anomalous Pb and Zn contents are present only in the mineralised part of the Barney Creek Formation, at or near the HYC deposit. All other units, and the Barney Creek Formation away from the HYC deposit, show low and relatively constant abundances of around 15 ppm Zn and 10 ppm Pb.

(5) Phosphorus is nowhere in economically interesting concentrations. Phosphorus contents are generally higher near the HYC deposit in all units. Concentrations of P in the upper Coxco Dolomite Member are about eight times the average for the area, and may indicate chemical precipitation of apatite during sedimentation.

(6) For most units, the element correlation patterns of a unit differ for samples near and away from the HYC deposit, but consistent or significant variation trends are not evident.

(7) Mineralised units (near the HYC deposit) tend to show more complex groupings of 'sulphide' elements, and partitioning into sulphide and silicate fractions, than units in outlying sections, where the various trace elements are presumably absorbed into mineral lattices rather than being associated with sulphides.

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TABLE A6. RESULTS OF CHEMICAL ANALYSES

- LEGEND -

No	=	Sample Number
1501	=	Section 15, sample 1, etc.
FM	=	Formation/member
TA	=	Tatoola Sandstone
TL	=	Leila Sandstone
TU	=	Tooganinie Formation undifferentiated
TM	=	Myrtle Shale
EM	=	Emmerugga Dolomite, Mara Dolomite Member
EY	=	Emmerugga Dolomite, Mitchell Yard Dolomite Member
TD	=	Teena Dolomite
TC	=	Teena Dolomite, Coxco Dolomite Member
BW	=	Barney Creek Formation, W-Fold Shale Member
BH	=	Barney Creek Formation, HYC Pyritic Shale Member
RD	=	Reward Dolomite
LI	=	Lithology
BD	=	Dolomite breccia
C	=	Chert
CD	=	Cherty dolomite
DA	=	Dolarenite
DL	=	Dololutite
DT	=	Dolomitic tuff
PS	=	Ex-pyritic shale (weathered)
S	=	Shale
SD	=	Shaly, silty, or sandy dolomite
Sl	=	Siltstone
T	=	Tuff band
TD	=	Tuffaceous dolomite
TS	=	Tuffaceous shale or siltstone
Ca	=	Calcium, per cent
Mg	=	Magnesium, per cent
AI	=	Percentage residue after acid treatment
K	=	Potassium, per cent
Fe	=	Iron, per cent*
Mn	=	Manganese, per cent*
P	=	Phosphorus, ppm
Zn	=	Zinc, ppm*
Pb	=	Lead, ppm*
Cu	=	Copper, ppm*
Ni	=	Nickel, ppm*
Co	=	Cobalt, ppm*
*	=	Extracted by hot 5N hydrochloric acid

NO	FM	LI	CA	MG	AL	K	FE	MN	P	ZN	PB	CU	NI	CO
1501	BW	TD	11.60	5.35	48.20	2.85	1.76	0.25	1690	118	18	49	3	6
1502	BW	DT	4.90	0.41	92.00	4.10	1.89	0.20	2630	175	43	5	10	5
1503	BW	PS	12.80	0.93	52.00	1.30	4.64	1.21	240	4690	1045	35	30	5
1504	BW	DT	0.40	0.30	95.10	3.10	0.55	0.03	590	1095	41	17	20	40
1401	EM	DL	19.20	11.30	6.45	0.35	2.14	0.19	580	6	10	4	3	1
1402	EM	CD	18.60	11.60	8.25	0.35	1.13	0.11	350	16	16	345	3	1
1403	EM	CD	12.60	7.80	37.50	1.05	0.71	0.07	310	9	7	50	3	1
1404	EM	CD	19.20	11.20	4.95	0.08	2.75	0.22	370	5	4	18	3	1
1405	EM	CD	16.80	10.60	17.20	0.24	0.89	0.10	310	6	27	3	3	1
1406	EM	CD	18.90	11.80	6.85	0.35	1.28	0.14	800	112	13	9	9	1
1407	EM	DL	18.80	11.50	3.65	0.10	3.00	0.30	350	10	10	6	3	1
1408	EY	DL	19.20	11.50	2.90	0.08	2.75	0.30	390	11	6	4	3	1
1409	EY	DL	20.10	12.00	2.90	0.07	3.10	0.34	80	4	21	3	3	1
1410	EY	DL	20.00	11.20	1.00	0.07	4.13	0.46	50	6	22	3	3	1
1411	TD	CD	19.00	9.40	10.80	0.50	3.43	0.40	50	8	71	5	3	1
1412	TD	CD	13.40	7.00	40.80	0.65	0.91	0.09	580	6	8	4	3	1
1413	TD	DA	12.50	6.10	44.30	0.43	1.30	0.13	50	5	2	4	3	1
1414	TD	CD	18.60	9.25	15.50	0.90	2.35	0.29	50	6	6	3	3	1
1415	TD	CD	19.50	10.90	7.75	0.65	3.48	0.45	350	48	7	4	3	1
1416	TC	DL	17.20	9.15	7.00	1.50	3.70	0.50	380	23	2	5	20	1
1417	TC	DL	18.00	10.20	12.30	1.15	2.75	0.37	580	15	7	3	3	1
1418	BW	TD	15.20	9.15	26.40	1.95	1.59	0.24	950	8	2	3	3	1
1419	BW	TD	15.60	9.50	26.30	1.95	1.38	0.23	1190	7	2	3	3	1
1301	EM	SD	18.90	12.00	9.80	0.58	0.51	0.07	340	19	2	4	3	1
1302	EM	DL	20.90	12.80	1.50	0.07	1.50	0.24	220	3	2	3	3	1
1303	EM	DL	17.00	10.50	21.20	1.45	0.91	0.12	780	3	12	7	3	1
1304	EM	DL	18.40	11.70	13.10	0.22	1.18	0.14	490	6	30	8	10	1
1305	EY	BD	16.30	9.80	21.00	1.45	1.89	0.23	260	10	21	7	3	1
1306	EY	DL	18.90	12.60	1.65	0.20	1.69	0.21	680	5	2	3	3	1
1307	EY	DL	19.30	12.20	1.00	0.10	2.19	0.29	600	4	4	3	3	1
1308	EY	DL	19.70	12.00	1.60	0.20	2.21	0.32	1550	4	8	3	3	1
1309	EY	DL	20.00	12.90	1.25	0.10	1.91	0.26	350	4	4	3	3	1
1310	EY	DL	20.00	12.60	0.60	0.05	1.53	0.17	120	5	6	3	3	1
1311	EY	DL	19.60	12.60	1.05	0.05	1.85	0.21	450	7	6	3	3	1
1312	EY	DL	20.00	12.80	0.55	0.05	1.69	0.19	610	5	4	3	3	1
1313	EY	DL	19.30	12.00	2.90	0.32	2.21	0.28	300	7	6	3	3	1
1314	EY	DL	19.30	11.80	3.75	0.42	2.26	0.29	610	19	24	4	5	4
1315	EY	BD	18.30	10.70	7.65	0.83	2.86	0.37	230	35	15	6	5	1
1316	TD	DL	17.40	11.80	3.10	0.28	2.78	0.37	230	15	19	3	5	1
1317	TD	TD	11.90	7.40	40.50	2.15	0.86	0.12	490	8	2	3	5	1
1318	TD	CD	11.80	8.25	30.20	2.20	1.33	0.17	600	169	38	14	4	4
1319	TD	DL	17.20	11.40	7.90	0.53	2.53	0.41	270	10	7	7	3	1
1320	TD	TD	11.40	6.95	40.20	3.65	1.58	0.22	820	14	5	3	3	1
1321	TC	TD	16.20	10.90	12.70	1.20	1.71	0.33	360	10	2	4	3	1
1322	TC	DL	16.00	9.80	14.60	0.90	2.65	0.47	380	39	14	6	3	1
1323	TC	DL	16.00	9.95	15.50	1.50	2.40	0.58	700	48	6	9	3	4
1324	BW	TD	13.00	7.90	33.00	2.80	2.19	0.41	1450	45	2	10	4	4
1325	BW	TS	0.30	0.50	85.60	8.60	0.76	0.14	260	68	30	10	4	1
1326	BW	TD	14.70	8.90	21.50	1.35	3.10	0.62	1200	42	280	27	10	1
1327	BW	TD	11.10	4.40	48.70	3.15	3.56	0.59	2790	27500	4200	38	10	20
1201	EM	SD	15.20	9.95	23.70	1.15	0.79	0.06	280	10	2	3	3	1
1202	EM	DL	20.50	14.00	0.68	0.05	0.51	0.06	250	15	2	3	3	1
1203	EM	CD	18.90	12.60	8.60	0.38	0.69	0.09	250	6	2	3	3	1
1204	EM	DL	18.80	12.40	8.60	0.35	1.26	0.12	310	4	5	3	3	1
1205	EM	CD	21.30	13.60	1.80	0.05	0.96	0.18	100	10	2	3	3	1
1207	EM	DL	20.60	14.00	1.50	0.05	0.87	0.09	110	3	2	3	3	1

NO	FM	LI	CA	MG	AL	K	FE	MN	P	ZN	PB	CU	NI	CO
1208	EM	DL	19.20	11.60	5.85	0.05	0.72	0.14	80	12	2	3	3	1
1209	EM	DL	20.20	11.80	2.10	0.05	1.49	0.15	270	15	2	3	4	1
1210	EM	DL	19.80	11.70	2.55	0.05	1.70	0.15	1100	11	5	3	3	1
1211	EM	DL	21.70	11.90	1.15	0.05	0.96	0.13	140	7	2	3	4	1
1212	EY	CD	20.20	11.60	4.60	0.10	0.43	0.08	260	5	2	3	7	1
1213	EY	DL	20.20	11.90	1.85	0.13	0.75	0.11	150	10	2	3	3	1
1215	EY	DL	21.30	14.00	2.00	0.13	0.54	0.09	80	3	2	3	3	1
1216	EY	CD	15.40	12.00	15.20	0.37	0.55	0.06	120	4	14	3	3	1
1217	TD	CD	14.00	10.50	21.50	1.20	0.60	0.05	60	3	4	3	3	1
1218	TD	TD	9.30	6.90	49.70	1.65	0.90	0.04	200	4	9	11	3	1
1219	TD	CD	13.60	9.85	30.70	0.75	1.09	0.06	170	4	14	13	5	1
1220	TD	DL	18.40	12.90	4.65	0.17	0.32	0.04	110	3	2	5	3	1
1221	TC	DL	18.10	12.70	7.70	0.42	0.53	0.07	80	3	5	3	3	1
1222	TC	TD	16.70	11.60	15.50	0.86	0.51	0.07	340	4	16	3	3	1
1223	TC	TD	15.30	11.00	11.00	0.67	0.58	0.07	330	4	5	3	3	1
1101	TC	TC	19.60	9.50	13.90	1.60	0.50	0.08	4380	4	2	13	3	1
1102	TC	TD	18.70	9.50	15.70	1.75	0.59	0.09	250	5	2	10	3	1
1103	BW	TD	10.80	5.25	52.50	2.35	0.55	0.11	1640	13	2	8	5	1
1104	BW	TD	14.00	6.65	38.20	2.60	1.78	0.08	650	12	2	7	8	1
1105	RD	DS	12.20	5.25	46.50	2.70	1.22	0.11	940	12	2	20	3	1
1105	RD	DL	13.70	6.65	38.50	2.50	0.87	0.17	1000	5	2	5	3	1
1106	RD	SD	17.40	9.10	21.80	1.05	0.97	0.16	450	4	2	5	5	1
1107	RD	SD	21.90	2.10	38.30	1.35	0.72	0.25	450	8	2	20	5	1
1108	RD	SD	15.60	6.85	34.20	1.45	1.30	0.19	500	5	2	5	7	1
1109	RD	S	0.43	0.14	96.70	1.75	2.75	0.01	590	3	2	13	3	1
1110	RD	DS	11.40	5.90	49.40	2.10	2.35	0.14	600	5	2	7	3	1
1111	RD	DS	13.70	5.10	38.60	1.55	1.19	0.16	750	7	2	8	3	1
1112	RD	CD	19.80	9.90	21.40	0.66	0.96	0.29	1190	49	7	6	5	1
1113	RD	CD	18.50	11.30	10.60	0.24	0.88	0.18	290	15	2	3	3	1
1114	RD	CD	18.30	11.50	12.00	0.30	0.94	0.15	270	5	2	5	3	1
1115	RD	CD	14.00	9.70	26.90	1.46	0.71	0.11	450	5	2	6	4	1
1002	TC	DL	15.90	7.75	18.90	1.35	1.80	0.10	2530	40	2	3	8	1
1003	TC	DL	20.50	10.40	7.25	0.75	0.68	0.12	250	30	2	3	3	1
1004	BW	SD	17.10	8.75	21.40	1.20	0.68	0.11	350	30	2	3	3	1
1005	BW	SD	19.20	10.00	11.40	1.10	0.68	0.13	50	23	2	3	7	1
1006	BW	SD	13.70	6.90	26.80	2.20	1.28	0.15	1440	18	2	3	3	1
1007	BW	SD	19.60	9.80	11.80	0.75	0.75	0.12	300	45	2	5	3	1
1008	RD	DL	17.20	8.60	23.10	1.35	1.40	0.12	150	50	2	3	5	1
1009	RD	DA	16.60	8.50	25.00	0.40	0.94	0.12	1150	20	2	3	3	1
1010	RD	DA	18.30	9.20	16.60	0.25	0.94	0.10	250	28	2	5	3	1
1012	RD	DL	18.90	9.65	14.60	0.60	0.37	0.08	150	88	2	10	5	1
1013	RD	DL	21.80	11.10	1.55	0.10	0.64	0.10	50	150	2	5	5	1
901	TL	SD	15.40	7.95	22.50	0.85	1.13	0.83	500	80	13	3	3	1
902	TM	SL	6.20	2.75	72.60	2.55	5.50	0.04	600	23	13	3	5	1
903	TM	SD	19.80	9.65	13.10	0.05	1.19	0.10	50	9	18	3	7	5
904	EM	DL	21.50	9.90	6.55	0.10	1.09	0.08	50	1	23	13	20	1
905	EM	CD	7.70	3.60	67.90	0.05	0.31	0.02	50	6	13	8	10	1
906	EM	DL	21.90	10.50	4.05	0.05	0.53	0.07	50	18	23	3	10	1
907	EM	DL	19.00	11.10	9.25	0.05	0.31	0.04	50	8	23	3	5	1
908	EM	DL	19.40	11.30	6.15	0.10	0.46	0.08	50	10	23	3	5	1
909	EM	DL	19.40	12.00	4.60	0.05	0.41	0.07	50	6	18	3	8	1
910	EM	DL	18.50	10.70	9.75	0.03	0.50	0.10	50	3	23	3	10	1
911	EM	DL	20.60	12.40	2.00	0.05	0.27	0.05	50	22	23	3	5	1
912	EM	DL	19.80	12.00	5.70	0.05	0.25	0.05	50	3	18	3	5	5
913	EM	DL	18.10	10.30	12.40	0.10	0.25	0.05	50	5	23	3	3	1
914	EM	DL	19.60	12.00	5.70	0.05	0.23	0.05	50	7	18	3	3	1

NO	FM	LI	CA	MG	AL	K	FE	MN	P	ZN	PB	CU	NI	CO
915	EM	DL	19.40	11.60	7.60	0.15	0.47	0.10	50	98	2	50	500	1
916	EM	CD	16.70	10.20	18.10	0.05	0.30	0.05	50	108	2	65	300	1
917	EM	DL	19.70	11.80	6.65	0.05	0.35	0.07	50	38	2	23	70	1
918	EM	DL	18.40	11.20	10.90	0.10	0.60	0.08	50	23	2	10	30	1
919	EM	DL	20.40	10.30	6.95	0.25	0.66	0.13	150	25	2	7	10	1
920	TC	DL	20.00	10.00	9.65	0.30	0.40	0.08	850	20	2	3	3	1
921	TC	DL	20.50	10.40	6.05	0.10	1.25	0.13	4710	38	2	3	5	1
922	TC	DL	20.70	10.30	6.60	0.40	0.68	0.12	2640	23	2	5	3	1
923	RD	DL	21.10	10.80	3.70	0.25	0.93	0.17	200	28	2	5	5	1
924	RD	DA	16.90	8.75	22.70	0.15	1.10	0.09	550	15	2	5	3	1
925	RD	DL	17.60	9.05	19.60	0.50	0.68	0.12	400	218	2	5	10	1
801	EM	DB	19.40	11.50	13.40	0.23	0.30	0.03	50	3	11	5	3	1
802	EM	C	2.70	1.25	88.00	0.10	0.49	0.04	900	10	21	9	8	3
803	EM	CD	14.80	8.10	34.00	0.85	0.48	0.03	250	5	30	8	3	3
804	EM	DL	19.10	11.80	14.30	0.65	0.40	0.03	50	4	3	4	3	1
805	EM	DL	21.30	12.50	5.50	0.10	0.26	0.02	1000	5	2	3	3	1
806	EM	C	8.25	4.20	65.00	4.00	0.19	0.02	1700	6	2	5	3	1
807	EM	DL	20.90	12.00	7.50	0.25	0.23	0.03	400	4	2	3	3	1
808	EM	C	8.45	4.65	63.00	0.10	0.26	0.03	1000	6	2	3	4	1
809	EM	DL	20.80	11.90	7.70	0.23	0.22	0.03	50	3	2	3	3	1
810	EM	CD	15.30	9.95	20.20	0.85	0.31	0.03	250	3	19	4	5	1
811	EM	DA	19.50	10.70	14.30	0.40	0.31	0.03	750	2	2	4	5	6
812	EM	CD	10.00	4.80	56.20	0.23	0.27	0.03	1100	11	2	3	3	1
813	EM	CD	15.90	8.90	25.50	0.80	0.42	0.02	250	5	6	6	3	9
814	EM	DL	21.00	11.80	4.40	0.10	0.39	0.05	50	2	2	3	3	1
815	EM	SD	14.40	7.70	33.20	2.20	0.63	0.04	50	4	13	9	5	3
816	EY	DL	20.00	11.30	7.05	0.10	0.42	0.04	500	9	5	8	3	1
817	EY	DL	21.30	12.00	2.65	0.10	0.30	0.04	50	2	2	3	3	1
818	EY	DL	21.30	12.30	2.35	0.20	0.48	0.06	500	2	2	3	3	1
819	EY	DL	21.40	12.00	2.30	0.30	0.57	0.06	50	2	2	3	3	1
820	EY	DL	21.30	11.80	3.00	1.40	0.57	0.06	100	2	2	3	3	1
821	EY	DL	19.10	10.60	13.40	0.20	0.30	0.03	50	3	2	3	3	1
822	TD	SD	15.90	8.60	26.20	1.85	0.45	0.03	250	9	2	4	5	1
823	TD	DL	19.40	10.20	1.70	0.50	0.57	0.04	50	2	2	5	3	1
823	TD	DS	13.80	7.10	38.60	0.75	0.62	0.03	250	2	2	3	5	1
824	TD	DL	19.10	10.20	13.40	0.45	1.00	0.06	50	8	8	4	5	1
825	TD	TS	0.21	0.48	96.30	5.35	2.47	0.17	450	3	18	58	4	30
826	TD	SD	14.30	7.60	35.60	2.75	0.95	0.05	350	3	8	16	3	1
827	TD	TS	0.17	0.06	97.30	7.60	0.06	0.09	250	55	5	16	3	1
828	BW	TS	5.70	2.50	73.70	4.85	0.85	0.38	1350	18	18	15	5	1
829	BW	TS	0.30	0.09	96.90	4.50	0.87	0.05	870	4	8	6	5	1
830	BW	TS	3.95	1.55	81.60	4.40	0.87	0.11	1140	71	10	8	5	1
831	BW	TD	12.20	6.40	43.40	2.00	1.55	0.10	1740	6	40	10	20	10
832	BW	TD	14.00	7.20	37.20	2.20	1.00	0.09	650	23	2	9	4	1
832	BW	DL	19.40	10.80	12.00	0.50	0.65	0.10	400	21	13	3	3	1
833	RD	TD	11.30	6.00	49.40	3.60	0.70	0.07	700	30	8	8	3	1
834	RD	TD	12.00	6.20	45.80	3.10	0.73	0.07	550	5	2	5	3	1
835	RD	TS	0.09	0.03	98.40	3.55	1.58	0.04	500	5	30	9	6	1
836	RD	TD	12.30	7.40	45.20	3.45	0.80	0.05	800	3	13	10	5	3
837	RD	DL	19.40	10.50	13.80	0.60	0.54	0.05	50	2	5	6	3	3
839	RD	DL	16.30	10.00	28.30	1.25	0.90	0.07	500	3	13	10	5	3
840	RD	DA	18.90	11.80	17.30	0.65	0.47	0.05	3100	2	13	3	3	1
841	RD	CD	17.20	11.50	24.20	0.35	0.45	0.05	50	1	2	3	3	3
842	RD	SD	15.40	10.10	32.10	1.65	0.53	0.05	150	3	2	3	3	1
844	RD	SD	13.00	7.83	40.30	2.70	0.95	0.03	2730	75	53	11	3	1
845	RD	TD	16.00	10.20	30.00	2.05	1.28	0.07	700	23	8	8	5	1

NO	FM	LI	CA	MG	AL	K	FE	MN	P	ZN	PB	CU	NI	CO
846	RD	DL	19.30	11.70	14.60	0.45	0.73	0.07	1540	2	13	4	3	1
847	RD	DL	19.20	11.60	15.00	0.50	0.63	0.07	200	3	2	4	9	1
848	RD	DA	16.30	8.30	28.70	1.60	0.63	0.05	300	3	18	8	5	1
849	RD	DL	22.00	10.90	3.35	0.05	0.40	0.07	400	3	18	5	3	1
850	RD	DL	19.20	12.30	13.40	0.05	0.44	0.06	450	5	5	5	3	1
851	RD	DB	15.20	7.85	3.48	1.00	0.75	0.08	1150	4	23	7	3	1
852	RD	TD	11.50	5.05	50.50	1.40	0.63	0.05	1250	2	13	8	3	1
853	RD	SD	12.20	5.65	48.10	1.30	0.68	0.05	1930	3	13	7	5	1
854	RD	SD	12.60	6.15	46.40	2.40	1.16	0.07	700	4	35	13	3	1
701	EM	SD	14.90	7.70	33.30	1.05	0.80	0.05	200	9	2	7	5	5
702	EM	DL	20.90	11.50	7.00	0.17	0.69	0.05	50	10	7	5	5	5
703	EM	C	6.10	3.05	72.30	0.00	0.28	0.03	50	11	2	5	10	1
704	EM	DS	8.60	4.70	59.80	3.65	2.19	0.03	700	21	8	5	5	5
705	EM	SD	14.30	7.20	35.30	2.10	0.76	0.04	1840	20	5	2	7	5
707	EM	DL	21.00	12.20	0.86	0.21	0.88	0.06	50	9	7	5	5	1
708	EM	CD	17.90	10.40	20.30	0.00	0.54	0.03	100	22	25	8	8	1
710	EM	DL	22.50	12.10	2.90	0.10	0.60	0.06	150	25	38	18	7	5
711	EM	DL	20.80.	12.30	6.10	0.17	0.40	0.04	200	44	20	7	5	5
713	EM	DL	21.90	13.00	2.10	0.14	0.78	0.09	150	10	2	10	10	1
715	EM	CD	19.20	11.30	13.70	0.22	0.41	0.04	150	8	2	15	10	1
716	EM	DL	22.20	12.60	0.91	0.00	0.40	0.05	50	6	2	7	10	1
717	EM	DL	22.20	11.20	1.20	0.10	0.56	0.08	140	181	2	5	10	1
718	EM	DL	21.70	12.20	2.65	0.17	0.28	0.04	250	10	2	5	10	1
719	EM	DL	22.20	12.20	1.65	0.13	0.37	0.05	50	5	2	3	8	1
720	EM	DL	21.80	12.50	1.60	0.05	0.28	0.04	100	10	2	3	10	1
721	EM	DL	21.60	11.90	4.10	0.05	0.87	0.09	1110	17	2	3	10	1
723	EM	DL	21.80	12.20	3.15	0.13	0.42	0.06	150	24	2	3	10	1
724	EY	DL	22.30	12.60	1.45	0.13	0.00	0.04	390	7	2	3	10	1
725	EY	DL	20.90	11.60	7.10	0.70	0.00	0.05	1360	20	2	3	10	1
726	TC	DL	20.30	11.40	9.95	0.45	0.00	0.05	1080	9	2	5	10	1
727	TC	DL	20.80	12.00	7.20	0.60	0.00	0.06	1150	12	2	5	10	1
728	TC	DL	20.50	11.50	6.45	0.53	0.00	0.06	780	20	2	3	10	1
729	TC	DL	21.10	11.10	8.85	0.45	0.47	0.06	1790	18	2	3	10	1
730	TC	TS	3.95	1.80	83.40	6.70	0.13	0.02	1090	6	2	3	8	1
731	TC	DL	21.70	11.90	4.60	0.25	0.46	0.07	390	134	2	15	10	1
732	BW	TD	9.40	4.55	57.40	4.80	0.53	0.04	2190	49	2	15	10	1
733	BW	TD	9.35	5.40	59.80	4.95	1.45	0.05	1960	18	2	18	20	1
734	BW	TD	13.90	5.90	39.70	3.25	0.68	0.05	2400	43	13	25	20	1
737	BW	TS	6.70	4.10	68.30	5.75	0.69	0.04	1740	43	8	5	5	1
738	BW	TD	12.70	7.20	44.30	3.38	0.58	0.06	700	39	7	5	3	1
739	BW	TS	3.40	1.65	86.90	9.40	0.18	0.02	980	10	2	3	5	1
740	BW	TD	12.50	6.55	44.80	2.65	0.68	0.13	940	19	2	5	3	1
741	BW	TS	0.25	0.12	97.80	4.35	0.11	0.00	400	6	2	10	5	1
742	BW	TS	0.57	0.30	95.60	10.00	2.38	0.03	290	15	28	58	20	20
743	BW	TD	12.50	5.90	44.30	2.60	1.50	0.06	750	7	13	18	10	1
744	BW	TD	12.10	6.00	45.70	2.35	1.31	0.04	900	9	13	10	5	10
601	TA	SL	1.65	0.57	93.70	3.00	0.94	0.04	250	8	2	25	8	3
602	TA	SL	6.00	2.15	72.00	4.65	1.83	0.04	790	4	45	18	20	3
603	TU	DL	18.20	8.85	19.40	0.80	1.28	0.10	300	10	2	43	3	3
604	TU	DA	18.00	10.00	15.50	0.37	1.31	0.11	100	65	68	375	10	5
605	TU	CD	16.20	8.75	25.90	0.46	1.89	0.09	100	9	45	60	10	30
606	TU	SD	14.30	7.70	33.40	0.40	0.89	0.06	100	6	20	10	5	1
607	TU	SD	10.70	6.20	46.50	2.60	1.23	0.05	700	15	2	7	7	1
608	TU	SD	16.80	9.00	20.70	1.20	1.16	0.05	150	9	2	18	5	5
609	TU	DA	18.20	10.10	14.60	0.45	0.90	0.05	100	6	18	8	8	1
610	TU	SD	15.40	8.05	28.50	1.50	1.50	0.06	250	13	25	40	7	10

NO	FM	LI	CA	MG	AL	K	FE	MN	P	ZN	PB	CU	NI	CO
611	TU	CD	17.50	9.05	19.50	0.27	1.23	0.06	50	7	2	23	3	1
501	TU	SL	8.60	5.70	57.40	2.55	2.10	0.05	500	19	10	10	6	4
502	TU	DS	10.30	5.55	51.00	2.45	2.20	0.05	790	19	3	5	10	4
503	TU	DS	9.60	4.90	54.90	3.30	1.53	0.05	550	14	13	15	9	3
504	TU	DS	7.70	3.30	63.10	3.20	1.65	0.03	750	16	9	19	10	3
505	TU	DL	19.10	10.50	11.50	0.17	1.90	0.07	250	14	2	4	3	3
506	TU	SD	15.80	8.50	28.30	0.40	1.78	0.07	100	11	10	29	3	1
507	TU	SD	16.80	8.85	22.20	0.80	1.90	0.07	250	8	3	6	3	4
508	TU	DS	8.60	4.60	59.40	2.55	1.50	0.03	700	13	5	68	3	3
509	TU	DL	20.10	10.60	7.80	0.25	1.50	0.05	550	14	2	8	3	3
510	TU	C	3.80	1.90	81.20	0.00	1.15	0.04	250	15	5	9	9	1
511	TU	DS	10.10	5.10	52.10	3.65	1.58	0.03	700	13	3	18	9	1
512	TU	DL	20.80	11.30	6.25	0.00	1.80	0.07	50	9	5	4	3	1
513	TU	SD	12.90	6.95	40.90	2.30	1.73	0.04	700	12	2	13	10	1
514	TU	DL	20.80	11.10	5.05	0.06	1.50	0.07	100	14	2	10	3	1
515	TU	C	2.75	0.47	87.80	0.09	0.80	0.03	150	9	5	44	10	6
516	TU	SD	15.30	8.15	28.50	1.05	1.45	0.05	350	11	5	8	3	1
517	TU	SD	16.50	8.80	24.00	1.15	1.24	0.06	150	20	23	28	4	8
518	TU	DL	18.20	9.60	16.20	0.32	1.24	0.06	50	11	18	3	3	3
519	TU	SL	3.90	1.25	78.70	4.45	2.22	0.03	840	23	10	5	9	4
520	TU	SD	16.30	8.70	23.50	0.28	1.24	0.07	50	6	23	7	3	1
521	TU	C	6.45	3.05	70.70	0.15	0.58	0.03	100	10	10	5	3	4
523	TL	SD	17.90	8.55	19.30	0.28	1.89	0.11	300	5	55	8	3	10
524	TL	SD	13.30	10.30	37.60	0.25	0.85	0.07	150	5	18	15	3	3
525	TL	SD	10.90	8.05	48.10	1.90	1.20	0.06	750	12	28	33	6	10
526	TL	SD	17.70	14.20	19.10	0.80	0.10	0.08	1050	6	33	7	4	10
527	TM	CD	15.70	7.60	29.60	0.73	0.10	0.07	300	13	8	8	3	8
528	TM	DS	8.30	3.40	61.70	3.00	0.11	0.06	700	12	23	10	9	10
529	TM	SL	6.10	2.35	70.80	4.10	0.20	0.05	1000	29	10	3	10	10
530	TM	DS	7.80	3.30	62.80	3.75	0.10	0.05	800	27	10	3	10	10
531	TM	SL	5.30	1.90	75.50	4.45	0.20	0.03	950	27	5	3	10	10
532	EM	DS	8.55	3.25	61.50	3.80	0.11	0.07	700	17	10	3	6	4
533	EM	C	4.90	2.25	77.10	0.05	0.00	0.03	300	8	10	3	3	9
534	EM	DL	21.30	11.20	5.80	0.12	0.00	0.05	50	10	23	3	3	3
535	EM	TD	14.80	7.10	34.70	2.75	0.00	0.03	200	42	33	3	4	10
401	TM	SL	9.30	5.20	56.50	3.25	1.73	0.02	700	18	2	3	8	1
402	EM	CD	12.50	7.30	34.70	0.15	0.53	0.02	200	6	2	4	6	1
403	EM	CD	15.50	8.20	31.80	0.76	0.65	0.03	50	5	2	5	4	1
404	EM	SD	13.60	7.10	40.10	0.83	1.28	0.03	450	8	2	3	4	1
405	EM	SD	8.50	4.60	60.80	2.70	1.68	0.02	950	11	2	5	6	5
406	EM	DL	18.80	9.95	14.70	0.42	0.60	0.03	100	5	18	4	3	1
407	EM	DL	20.90	12.30	3.95	0.42	0.68	0.03	250	9	2	5	3	1
408	EM	DL	20.00	11.30	7.13	0.11	0.50	0.02	200	6	2	3	3	1
409	EM	C	1.90	0.40	90.80	0.00	0.45	0.03	1850	14	5	5	6	3
411	EM	CD	17.90	10.20	18.60	0.05	0.31	0.02	250	6	2	3	3	1
412	EM	DL	21.30	12.30	2.80	0.05	0.43	0.02	50	8	2	3	3	1
413	EM	SD	12.80	7.60	40.90	0.50	0.60	0.02	150	12	18	5	4	1
414	EM	DL	19.70	11.40	9.70	0.65	0.55	0.02	100	4	2	4	3	1
415	EM	C	3.45	1.80	84.30	0.06	0.38	0.02	550	7	13	4	6	1
416	EM	SD	16.80	10.10	23.40	0.38	0.50	0.02	50	5	10	4	4	1
417	EM	BD	19.00	10.70	13.60	0.36	0.60	0.02	50	5	23	12	5	3
418	EM	DS	10.20	5.80	51.40	1.35	0.68	0.02	350	7	23	10	6	4
419	EM	SD	11.90	6.70	47.10	0.73	0.40	0.02	400	6	2	4	4	1
421	EM	DL	18.10	10.10	18.10	0.61	0.35	0.02	50	10	2	3	4	1
422	EM	DL	21.70	12.50	0.11	0.00	0.35	0.02	50	9	2	3	3	1
423	EM	C	6.70	4.15	68.60	0.08	0.45	0.02	200	6	2	15	9	1

NO	FM	LI	CA	MG	AL	K	FE	MN	P	ZN	PB	CU	NI	CO
424	EM	DL	20.40	11.30	6.00	0.20	0.55	0.02	100	5	2	3	3	1
425	EM	DL	20.80	11.80	4.60	0.06	0.28	0.01	50	4	2	4	3	1
426	EM	C	4.30	2.00	78.70	0.00	0.33	0.01	600	5	2	4	9	4
427	EM	SD	16.90	8.85	24.20	0.08	0.30	0.02	100	13	2	7	3	1
428	EM	DL	19.10	10.70	13.60	0.06	0.28	0.02	50	9	2	3	3	9
429	EM	DL	21.10	12.10	4.50	0.00	0.75	0.34	620	5	2	3	3	1
430	EM	DL	21.10	12.00	3.80	0.00	0.20	0.02	300	5	2	3	3	1
431	EM	DA	21.40	12.20	2.55	0.00	0.25	0.02	50	3	2	8	3	1
432	EM	C	1.90	1.10	90.90	0.00	0.40	0.01	250	4	2	5	8	6
433	EM	CD	14.90	8.05	32.20	0.00	0.24	0.03	50	4	2	3	3	1
434	EM	DL	20.70	11.30	5.95	0.00	0.24	0.03	350	4	2	3	3	1
435	EM	DL	21.80	11.90	0.95	0.00	0.28	0.02	50	5	13	3	3	1
436	EM	DL	21.10	12.80	1.75	0.00	0.23	0.02	50	5	8	3	5	1
437	EM	C	0.19	0.13	96.80	0.06	0.75	0.07	400	6	2	3	10	9
438	EM	DL	21.10	11.70	1.60	0.00	0.48	0.05	50	4	2	3	3	1
439	EM	DL	19.00	10.10	9.70	0.00	0.29	0.03	100	5	2	6	3	1
440	EM	DL	21.20	11.90	0.95	0.00	0.18	0.02	250	4	2	3	3	1
441	EY	DL	21.60	12.80	2.30	0.00	0.95	0.08	100	3	2	3	3	1
442	EY	DL	21.00	12.80	1.40	0.00	0.40	0.02	150	4	2	3	3	1
443	EY	DL	21.60	12.00	0.35	0.00	0.27	0.02	50	3	2	3	3	1
444	EY	DL	21.50	12.10	0.80	0.00	0.16	0.02	50	4	2	3	3	1
445	EY	DL	21.50	12.90	0.80	0.00	0.16	0.02	250	3	10	3	3	1
446	EY	DL	20.70	12.80	3.35	0.00	0.25	0.02	50	3	2	3	3	1
301	EM	DL	21.20	11.10	2.60	0.00	0.23	0.01	50	9	2	3	3	1
302	EM	DL	20.00	11.60	9.10	0.10	0.80	0.00	19	10	2	9	3	1
303	EM	DL	21.40	11.10	3.65	0.05	0.25	0.02	350	9	9	3	8	1
304	EY	DL	18.60	11.30	14.30	0.00	0.33	0.02	50	6	2	3	5	1
305	EY	DL	21.30	12.20	4.15	0.00	0.38	0.03	50	8	2	3	5	1
306	EY	CD	16.00	9.65	27.70	0.00	0.31	0.02	200	12	6	3	9	1
307	EY	DL	21.50	11.90	2.40	0.00	0.28	0.02	50	7	2	3	9	1
308	TD	DL	20.20	13.00	8.40	0.60	0.34	0.03	100	8	3	3	3	1
309	TD	DL	20.80	12.30	5.70	0.49	0.29	0.02	200	10	15	3	3	1
310	TD	DL	18.70	11.70	14.60	0.60	0.31	0.02	250	14	2	3	5	1
311	TD	DL	20.50	12.00	7.50	0.38	0.25	0.02	200	9	4	4	3	1
312	TC	DL	20.80	12.70	8.30	0.25	0.40	0.03	500	5	3	7	3	1
314	TC	TS	3.50	1.70	84.00	5.75	0.17	0.01	500	12	5	3	8	1
316	TC	DL	20.00	11.70	6.85	0.38	0.44	0.03	750	12	6	3	3	1
317	TC	T	0.00	0.05	97.10	12.00	0.13	0.00	1400	21	11	14	20	1
320	TC	DL	20.00	11.40	79.00	0.57	0.45	0.03	690	8	8	3	4	1
321	TC	DL	20.20	11.50	7.25	0.30	0.44	0.03	300	13	8	3	3	1
322	TC	DL	20.20	10.90	7.30	0.44	0.53	0.05	500	10	2	8	5	1
201	TC	DL	20.40	12.20	6.40	0.39	0.40	0.02	600	13	3	3	4	1
202	TC	DL	20.40	12.30	4.90	0.22	0.38	0.03	50	6	2	3	6	1
203	TC	TD	16.60	10.10	28.10	2.05	0.45	0.04	500	11	2	10	3	1
204	BW	TD	9.40	5.60	55.90	3.85	0.55	0.01	1790	22	4	19	9	1
205	BW	TD	15.60	10.10	23.20	1.45	0.64	0.04	50	8	2	4	5	1
206	BW	TD	13.00	7.80	39.40	2.45	2.70	0.08	890	18	19	13	10	4
207	BW	DT	6.00	2.80	67.50	6.65	0.95	0.03	1090	26	3	9	9	1
208	BW	DT	5.10	2.90	72.00	5.45	1.53	0.03	2000	15	10	8	4	4
209	BW	DT	7.50	4.30	59.80	4.15	1.28	0.03	1180	18	2	8	9	1
210	BW	DT	4.00	2.10	77.00	5.15	1.90	0.03	2380	17	2	20	10	4
211	BW	DT	8.20	4.30	58.40	4.45	1.63	0.05	1580	19	5	19	8	1
213	BW	TD	12.00	5.60	43.40	2.55	1.46	0.65	100	18	5	13	8	1
214	BW	DT	9.10	5.30	56.40	3.70	1.65	0.45	1590	12	4	13	8	3
215	BW	DT	7.80	3.70	62.60	6.15	1.17	0.36	690	11	5	6	10	1
216	BW	TD	12.10	7.00	41.50	2.20	1.55	0.60	1500	13	2	10	10	1

NO	FM	LI	CA	MG	AL	K	FE	MN	P	ZN	PB	CU	NI	CO
217	BW	TD	10.00	6.20	49.80	1.70	1.24	0.31	300	17	11	14	8	1
218	BW	TD	15.20	9.10	26.00	1.20	1.05	0.22	200	14	4	9	4	1
219	BW	DS	11.60	6.90	42.20	1.45	1.23	0.18	500	24	2	10	5	5
220	BW	DS	10.90	6.60	44.80	1.55	0.83	0.08	300	13	5	5	4	1
221	BW	DS	15.10	8.60	27.00	1.15	1.15	0.17	400	15	2	10	4	1
222	BW	DS	12.60	7.80	37.50	1.45	0.93	0.13	450	24	2	6	9	1
223	BW	DS	11.10	6.90	44.50	1.45	0.84	0.11	200	12	3	5	9	1
224	BW	DS	5.70	2.90	72.70	4.85	4.45	0.07	200	10	89	10	10	1
225	BW	DS	5.95	2.40	71.80	7.00	0.80	0.14	300	14	3	30	6	1
226	BW	DS	7.50	3.00	64.50	5.85	0.81	0.16	100	9	2	19	8	1
227	BH	S	0.00	0.00	96.10	4.10	2.72	0.02	550	12	11	10	8	1
228	RD	SD	12.10	5.50	40.50	1.65	1.50	0.10	600	16	5	13	4	1
229	RD	SD	13.70	6.05	36.30	1.15	1.35	0.10	50	9	5	5	3	1
230	RD	SD	13.30	7.40	63.00	2.80	1.28	0.04	150	60	2	6	30	1
231	RD	DS	16.00	3.95	41.00	1.05	1.18	0.08	250	32	2	6	10	4
232	RD	TS	0.00	0.00	99.50	6.00	2.10	0.07	600	47	20	26	20	1
233	RD	DS	14.60	6.20	32.00	1.85	0.70	0.03	200	10	2	6	3	1
234	RD	CD	17.10	7.25	21.50	0.81	0.53	0.04	50	7	5	91	3	1
235	RD	CD	18.40	7.95	14.40	0.51	0.60	0.04	250	8	14	5	6	1
237	RD	DL	20.40	8.70	7.80	0.17	0.30	0.05	400	8	3	5	6	1
238	RD	DL	20.40	11.60	5.00	0.34	0.28	0.03	150	7	2	3	4	1
239	RD	DL	21.00	11.80	5.35	0.17	0.41	0.03	50	9	4	3	6	1
240	RD	DL	21.40	12.20	4.50	0.08	0.44	0.03	50	8	8	4	3	1
241	RD	SD	16.80	10.00	23.00	0.42	0.40	0.03	50	10	4	3	3	1

APPENDIX 3

ROCK GEOCHEMISTRY STUDY,

McARTHUR BASIN PROJECT, 1978

D.E. Large+

+statistical analysis by S. Rehder & G.v.d. Boom

From Bundesanstalt fur Geowissenschaften und Rohstoffe, Hannover,

Archive Number 82032

1. INTRODUCTION

A total of 210 rock samples was taken from various stratigraphic formations of the Middle Proterozoic McArthur Group. The lithologies sampled include dolostone, dololutite, dolarenite, dolomitic and tuffaceous siltstone, tuffite? (K-rich mudstone), and minor sandstone.

The purposes of the sampling program were to:

determine the geochemical background of selected formations within the McArthur Group;

determine if the geochemistry of t' ... k Formation away from the HYC deposit reflects the strati ... on; and

determine if the evaporitic facies of ... melia Dolomite, in which the original evaporitic minerals have been replaced by dolomite, can be geochemically distinguished from the laterally equivalent non-evaporitic facies, which consists of dololutite and dolarenite.

2. SAMPLING

Grab samples from outcrop were taken during fieldwork, and sample locations were determined by the logistics of the fieldwork. No attempt was made to collect samples from widely spaced locations, but the emphasis was placed upon sampling a vertical section through a formation, usually in connection with measured geological sections. However, it was possible to collect sample suites from several locations of the Amelia Dolomite, Tooganinie Formation, and Barney Creek Formation, so that some lateral trends may be distinguished.

The dolomitic rocks of the McArthur Group are generally fresh at outcrop, although the silty - and especially the pyritic - lithologies are often more deeply weathered. Samples were numbered according to the BMR system, which - however - proved to be incompatible with the analytical and statistical procedures at BGR and new numbers had to be alloted. The BMR and corresponding BGR numbers are listed in Table A7.

3. SAMPLE DISTRIBUTION

The following formations were sampled:

Mallapunyah Formation - group 1	25 samples
Amelia Dolomite - group 2	46
Tatoola Sandstone - group 3	8
Tooganinie Formation - group 4	25
Emmerugga Dolomite/Teena Dolomite - group 5	15
Barney Creek Formation - group 6	56

In addition samples were collected from:

tuffite? (K-rich mudstone) horizons - group 7	13
'others' (mineralised localities, etc.)	18
samples not analysed (high S from mineralised localities)	4

The numbers assigned to the samples in each of these groups are listed in Table A8.

4. SAMPLE PREPARATION AND ANALYSIS

The samples were crushed at BMR, Canberra, and ground in an agate mill to - 200 mesh (-75 μm) at BGR, Hannover. All the samples were analysed by X-ray fluorescence for the following in the laboratories at BGR:

oxides of major elements - SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5;

minor and trace elements - Ba, Ce, Co, Cr, Cu, La, Mn, Nb, Ni, Pb, Rb, Sc, Sr, Th, V, Y, Zn, Zr.

5. ANALYTICAL RESULTS AND EVALUATION

The results for each formation (groups 1-6) and for the tuffites? (group 7) have been statistically analysed. The samples in the 'others' category (see Table A8) were not included in the statistical analysis, as this category included mineralised samples which should not be compared with the normal lithologies.

The statistical analysis was simple - because the number of samples was insufficient for an elaborate study - and included calculation of the arithmetic mean, standard deviation, and variance of each element for the groups 1-7 and for the total population excluding 'others' - a total of 188 samples. However, tentative comparisons of the geochemistry of the formations can be made. The analytical data and an analysis of the variance for each of the oxides and elements analysed in the seven groups are tabulated at the back of this appendix. Until more detailed sampling is undertaken, the mean contents of the various elements in each formation could be used as the geochemical background.

5.1 Major-element geochemistry

Of the formations, the Barney Creek Formation is characterised by the highest mean contents of TiO_2, Al_2O_3, Fe_2O_3, MnO, K_2O, and P_2O_5, and the lowest mean content of Na_2O. Not surprisingly the carbonate formations (Amelia Dolomite, Tooganinie Formation, and Emmerugga and Teena Dolomites) have the highest mean CaO and MgO contents.

The high mean K_2O content (5.3%) of the Barney Creek Formation is related to the presence of abundant tuffaceous? material in the dolomitic siltstone that characterises the formation. The relatively high P_2O_5 content (0.16%) is characteristic of black shale formations, and may be associated with organic material.

The tuffites? are characterised by their very high K_2O content (mean of 11.9%). This is significantly greater than the average composition of alkalic and intermediate igneous rocks, for which the K_2O content varies between about 2 and 7.5 per cent - depending on the rock type. Sample MA 110, containing 15.87 per cent K_2O, must be almost pure $KAlSi_3O_8$ (16.7% K_2O). Similar compositions have been reported from tuffs of the Green River Formation in Wyoming (Surdam & Parker, 1972).

5.2 Minor and trace-element geochemistry

The mean contents of Ba and Sr are both high within the Mallapunyah Formation (1018 and 85.3 ppm respectively). The Tooganinie Formation also has a high mean Ba content (1135 ppm), but its mean Sr content (38 ppm) is close to the average for the whole population (45 ppm). Barite nodules in both formations undoubtedly account for the high Ba content of the formations. Minor malachite staining is commonly associated with these barite nodules, and the Mallapunyah Formation has the highest mean Cu content (209 ppm) of all the analysed formations; none of the other formations has a mean Cu content greater than 73 ppm. The mean Cr and Ni contents of the Mallapunyah Formation are also the highest of all the analysed formations.

The Barney Creek Formation has the highest mean content of the following trace elements: Ce, Co, Nb, Rb, Sc, Th, V, and Y.

Manganese is an element that is commonly found as a halo to stratiform mineral deposits (Gwodsz & Krebs, 1977). The range of the mean contents of Mn in the various formations is not great - 583 to 1686 ppm - and the variance of the Mn values within the different groups is very high. However, of the 35 samples containing more than 1500 ppm Mn (excluding those samples from the 'others' group), 14 are from the Barney Creek Formation, and 11 are from the Amelia Dolomite. The high Mn content of the Amelia Dolomite is definitely correlated with an evaporite-rich component of that formation (see 5.3). The remaining 10 samples with an Mn content of more than 1500 ppm are from the Mallapunyah Formation (5), Tooganinie Formation (3), and Tatoola Sandstone (2).

Lead and zinc have low mean contents in all the formations except for the Barney Creek Formation (mean of 146 ppm Pb, 270 ppm Zn). The variance of the Pb and Zn within the Barney Creek Formation samples is very high, and further work will be required to determine the probable presence of two populations and thus a meaningful background. Of the three samples that exceed 500 ppm Pb, all are from the Barney Creek Formation and located within 5 km of the McArthur River deposit; the same is true for the three samples exceeding 1000 ppm Zn.

Compared with samples from groups 1-6, the tuffite? samples have higher mean contents of the following elements: Co, La, Nb, Rb, Th, Y, and Zr. Also in the tuffites?, base-metal contents are similar to those found in groups 1-5, and their manganese content is significantly lower than any found in groups 1-6.

5.3 Amelia Dolomite

In an attempt to distinguish geochemically between evaporite-rich and non-evaporitic components of the Amelia Dolomite, a controlled set of samples was collected from these two components (MA 113-128 from the evaporite-rich and MA 129-136 from the non-evaporitic beds). The evaporite-rich component is recognised by the presence of dolomitic pseudomorphs after gypsum and anhydrite. Of the samples from the evaporitic component, samples MA 114, 116, 120, 122, 125, 126, 127, and 128 contain definite evidence of the evaporitic origin of the rocks (e.g., gypsum and anhydrite pseudomorphs). The other samples are from the inter-evaporitic beds, but lack obvious pseudomorphs.

The trace and minor elements (with the exception of Mn, as noted above) do not show any systematic variation between the evaporitic and non-evaporitic samples. The evaporitic samples appear to be enriched in Cu and depleted in Ba, but the results for both these elements have a high variance.

REFERENCES

GWODSZ, W., & KREBS, W., 1977 - Manganese halo surrounding Meggen ore deposit, Germany. Transactions of the Institute of Mining and Metallurgy, 86 B, 73-77.

SURDAM, R.C., & PARKER, R.B., 1972 - Authigenic aluminosilicate minerals in the tuffaceous rocks of the Green River Formation, Wyoming. Bulletin of the Geological Society of America, 83(3), 689-750.

TABLE A7. CORRESPONDING MA (BGR) AND BMR SAMPLE NUMBERS

MA	BMR	MA	BMR	MA	BMR	MA	BMR
001	011A	055	080A	109	139B	163	219B
002	011B	056	080B	110	101F	164	219C
003	012A	057	080C	111	101G	165	304A
004	012B	058	080D	112	101H	166	304B
005	014A	059	080E	113	006A	167	304C
006	015A	060	080F	114	006B	168	305A
007	015B	061	080G	115	006C	169	305B
008	015C	062	081B	116	006D	170	406A
009	018A	063	081D	117	006E	171	306B
010	021A	064	081F	118	006F	172	306C
011	022B	065	081I	119	006G	173	307A
012	022C	066*	081J*	120	006H	174	332A
013	022F	067	083A	121	006I	175	305C
014	025A	068	083B	122	006J	176	332B
015	025B	069	083C	123	006K	177	332C
016	025C	070	087A	124	006L	178	333A
017	025D	071	087B	125	006M	179	333B
018	028A	072	093A	126	006N	180	336A
019	031A	073	101A	127	006O	181	390A
020	031B	074	101B	128	006P	182	391A
021	036A	075	103A	129	009A	183	391B
022	036B	076	103B	130	009B	184	391C
023	036C	077	103C	131	009C	185	399A
024	037A	078	103D	132	009D	186	399B
025	038C	079	106A	133	009E	187	488A
026	040A	080	106B	134	009F	188	488B
027	043C	081	106C	135	009G	189	488C
028	047B	082	106E	136	009H	190	488D
029	051A	083	106F	137	148A	191	488E
030	051B	084	106G	138	148B	192	488F
031	053A	085	106H	139	151C	193	488G
032	053C	086	106I	140	157B	194	488H
033	053D	087	108A	141	157C	195	488I
034	053F	088	108B	142	148D	196	496A
035	053H	089	108C	143	148E	197	496B
036	064A	090	108D	144	165A	198	496C
037	064B	091	110A	145	165B	199	496D
038	069B	092	110B	146	165C	200	496E
039	069C	093	110C	147	167A	201	496F
040	069D	094	110D	148	175A	202	496G
041	069E	095*	111A*	149	175B	203	406H
042	069F	096	119E	150	175C	204	502A
043	069G	097	119F	151	179A	205	514A
044*	069H*	098	119G	152	180A	206	668A
045*	069I*	099	119H	153	180B	207	668B
046	071D	100	119I	154	180C	208	672A
047	071E	101	119J	155	180D	209	673A
048	071G	102	119K	156	183A	210	673B
049	071H	103	119L	157	183B		
050	073D	104	119M	158	184A		
051	073E	105	119N	159	189A		
052	073G	106	119B	160	189B		
053	076A	107	138A	161	217B		
054	076B	108	139A	162	218A		

TABLE A8. SAMPLE GROUPS

Group 1: MALLAPUNYAH FORMATION (25 samples)

MA 055	MA 079	MA 088
056	080	089
057	081	090
058	082	091
059	083	092
060	084	093
061	085	094
070	086	
071	087	

Group 2: AMELIA DOLOMITE (46 Samples)

MA 007	MA 102	MA 124
008	103	125
062	104	126
063	105	127
064	113	128
065	114	129
067	115	130
068	116	131
069	117	132
072	118	133
096	119	134
097	120	135
098	121	136
099	122	206
100	123	207
101		

Group 3: TATOOLA SANDSTONE (8 samples)

MA 001	MA 005	MA 052
002	050	165
004	051	

Group 4: TOOGANINIE FORMATION (25 samples, including Leila Sandstone and Myrtle Shale)

MA 026	MA 035	MA 108
027	046	109
028	047	144
029	048	145
030	049	146
031	053	147
032	054	166
033	107	167
034		

Group 5: EMMERUGGA DOLOMITE AND TEENA DOLOMITE (15 samples)

MA 018	MA 023	MA 157
019	024	158
020	025	176
021	074	177
022	156	196

Group 6: BARNEY CREEK FORMATION (56 samples)

MA 009	MA 078	MA 162	MA 180	MA 195
010	112	163	182	197
011	140	164	183	198
012	141	168	184	199
013	151	169	185	200
014	152	170	186	201
015	153	171	188	202
016	154	172	189	203
017	155	173	190	
075	159	174	191	
076	160	175	192	
077	161	178	194	

Group 7: TUFF? SAMPLES (13 samples)

MA 003	Tatoola Sandstone
006	Amelia Dolomite
073	Teena Dolomite
106	Amelia Dolomite
110	Teena Dolomite
111	Barney Creek Formation
139	Batten Subgroup?
148	Reward Dolomite
179	Barney Creek Formation
181	Teena Dolomite
187	Barney Creek Formation
193	Barney Creek Formation
204	Amos Formation

Others:

REWARD DOLOMITE, MA 149, 150, 205
BALBIRINI DOLOMITE, MA 036, 037
DARCYS COPPER KING PROSPECT, MA 038, 039, 040, 041, 042, 043
HEMATITIC VEINS IN AMOS FORMATION, MA 137, 138, 142, 143
YAH YAH COPPER MINE, MA 208, 209, 210

ANALYTICAL DATA

AND

ANALYSIS OF VARIANCE

MC ARTHUR AUSTRALIA AJOR ELEMENTS (CONCENTRATIONS IN %)

SPL. NO.		SIO2	TIO2	AL2O3	FE2O3	MNO	MGO	CAO	NA2O	K2O	P2O5
MA	1	72.32	0.43	12.97	2.51	0.01	1.38	0.17	0.19	7.73	0.12
MA	2	80.20	0.25	9.14	2.04	0.05	0.41	0.06	0.19	6.6[illegible]	0.09
MA	3	69.24	0.38	14.87	1.91	0.01	0.93	0.14	0.23	10.30	0.12
MA	4	86.50	0.19	6.22	0.92	0.01	0.42	0.07	0.17	4.43	0.08
MA	5	98.08	0.04	0.64	0.35	0.01	0.04	0.02	0.10	0.14	0.04
MA	6	54.98	0.43	13.23	2.41	0.07	4.92	4.81	0.26	10.13	0.12
MA	7	62.69	0.58	15.57	3.94	0.02	3.82	0.45	0.20	8.10	0.21
MA	8	38.34	0.37	8.85	5.51	0.15	11.02	11.57	0.21	3.61	0.11
MA	9	62.31	0.20	9.77	1.20	0.23	3.49	5.54	0.22	7.79	0.14
MA	10	61.97	0.36	9.29	12.76	0.19	0.20	2.64	0.25	7.31	1.81
MA	11	81.24	0.22	8.49	1.58	0.14	0.43	0.10	0.20	5.70	0.10
MA	12	50.05	0.31	15.30	16.30	0.39	3.05	0.08	0.37	6.47	0.09
MA	13	72.47	0.30	7.84	6.01	0.23	0.86	0.06	0.67	3.01	0.23
MA	14	25.27	0.20	5.01	15.09	0.31	7.50	13.95	0.95	3.25	0.13
MA	15	28.10	0.12	3.04	2.86	0.26	11.26	19.00	0.68	1.96	0.08
MA	16	58.95	0.17	0.77	33.14	0.16	0.01	0.23	0.24	0.07	0.18
MA	17	2.05	0.02	0.34	2.02	0.23	19.47	29.81	0.28	0.16	0.04
MA	18	42.00	0.37	7.53	3.19	0.04	9.15	12.49	0.27	4.75	0.12
MA	19	0.37	0.01	0.13	2.08	0.14	31.83	16.66	0.19	0.01	0.04
MA	20	0.59	0.02	0.28	0.43	0.06	21.36	30.23	0.25	0.01	0.04
MA	21	6.13	0.05	0.85	0.83	0.12	19.32	28.23	0.26	0.46	0.05
MA	22	71.97	0.03	0.47	0.52	0.06	5.67	8.26	0.17	0.18	0.06
MA	23	15.86	0.12	2.38	0.55	0.07	14.31	27.21	0.24	1.37	0.07
MA	24	30.06	0.04	0.66	0.72	0.09	14.43	21.04	0.22	0.35	0.06
MA	25	4.67	0.03	0.37	0.54	0.12	19.88	29.09	0.24	0.19	0.05
MA	26	87.75	0.04	0.99	0.78	0.02	1.53	2.84	0.16	0.47	0.08
MA	27	10.14	0.03	0.51	0.95	0.35	18.35	26.97	0.27	0.23	0.05
MA	28	4.64	0.03	0.52	0.96	0.25	19.69	28.89	0.01	0.24	0.01
MA	29	4.61	0.03	0.54	0.97	0.25	19.70	28.96	0.30	0.24	0.06
MA	30	6.04	0.02	0.22	1.36	0.09	19.68	29.32	0.25	0.09	0.05
MA	31	21.81	0.03	0.61	1.62	0.08	15.59	23.54	0.01	0.29	0.02
MA	32	21.03	0.03	0.58	1.57	0.08	15.04	22.82	0.20	0.27	0.06
MA	33	40.07	0.04	0.85	1.17	0.07	11.88	17.84	0.22	0.52	0.05
MA	34	18.78	0.12	2.76	1.58	0.08	15.36	22.87	0.24	1.66	0.06
MA	35	22.06	0.04	0.72	1.44	0.09	15.54	23.10	0.23	0.36	0.06
MA	36	1.92	0.02	0.25	3.45	0.45	19.93	28.75	0.30	0.06	0.04
MA	37	4.16	0.02	0.25	0.80	0.26	19.94	28.92	0.31	0.09	0.05
MA	38	5.12	0.04	0.80	0.48	0.09	19.85	28.36	0.24	0.54	0.05
MA	39	35.60	0.22	5.65	2.16	0.04	0.90	27.48	0.32	3.40	0.06
MA	40	54.14	0.26	7.14	1.32	0.01	0.73	16.72	0.28	4.79	0.06

MC ARTHUR AUSTRALIA MAJOR ELEMENTS (CONCENTRATIONS IN %)

SPL. NO.		SIO2	TIO2	AL2O3	FE2O3	MNO	MGO	CAO	NA2O	K2O	P2O5
MA	41	60.78	0.39	11.40	1.67	0.01	1.46	1.01	0.54	6.58	0.07
MA	42	95.87	0.04	1.13	0.11	0.01	0.13	0.25	0.15	0.15	0.11
MA	43	24.10	0.07	0.83	69.60	0.15	0.29	0.23	0.26	0.05	0.13
MA	46	16.75	0.04	0.76	0.54	0.13	17.29	24.91	0.25	0.45	0.05
MA	47	57.90	0.39	7.93	5.11	0.05	5.12	6.68	0.25	5.04	0.11
MA	48	55.41	0.35	8.39	3.95	0.06	5.85	7.51	0.30	5.41	0.12
MA	49	53.70	0.42	10.65	5.69	0.07	5.94	5.76	0.26	5.49	0.13
MA	50	30.56	0.19	3.89	2.89	0.29	10.90	19.57	0.31	2.52	0.07
MA	51	83.92	0.18	4.86	1.34	0.07	0.61	1.99	0.26	3.53	0.06
MA	52	89.97	0.11	4.69	0.44	0.06	0.14	0.04	0.17	3.28	0.05
MA	53	7.79	0.04	0.78	1.29	0.09	18.68	27.63	0.28	0.43	0.05
MA	54	29.78	0.03	0.55	1.26	0.08	14.04	21.08	0.20	0.25	0.04
MA	55	70.58	0.19	7.09	2.66	0.10	2.86	3.64	0.24	5.45	0.11
MA	56	47.80	0.24	6.18	2.04	0.24	8.79	11.47	0.25	4.06	0.13
MA	57	78.58	0.12	4.17	0.94	0.07	3.30	2.93	0.23	2.66	0.08
MA	58	50.68	0.04	0.75	0.41	0.16	10.26	14.47	0.21	0.27	0.07
MA	59	88.65	0.07	1.34	0.38	0.04	1.90	1.95	0.16	0.57	0.09
MA	60	65.32	0.32	7.79	2.03	0.10	4.41	5.01	0.30	5.02	0.13
MA	61	81.17	0.02	0.20	0.30	0.06	3.42	5.17	0.15	0.05	0.04
MA	62	2.08	0.02	0.21	1.17	0.15	20.21	29.41	0.28	0.11	0.04
MA	63	6.95	0.03	0.46	1.30	0.14	18.56	28.49	0.26	0.25	0.05
MA	64	57.28	0.04	0.65	0.76	0.08	8.02	12.23	0.23	0.35	0.07
MA	65	5.91	0.04	0.95	1.44	0.16	18.87	27.80	0.32	0.67	0.06
MA	67	46.02	0.08	1.80	1.00	0.07	10.23	15.26	0.18	0.94	0.06
MA	68	60.89	0.06	1.32	0.75	0.09	7.53	11.05	0.16	0.68	0.06
MA	69	25.86	0.21	5.20	1.19	0.05	6.12	28.63	0.30	2.97	0.14
MA	70	27.76	0.08	1.02	2.07	0.20	9.25	14.68	0.47	0.19	0.06
MA	71	32.70	0.27	6.59	1.99	0.19	11.11	16.14	0.26	4.18	0.16
MA	72	14.17	0.03	0.58	10.87	0.45	14.48	21.26	0.24	0.24	0.04
MA	73	57.05	0.42	13.26	3.02	0.08	2.51	4.45	0.25	11.13	0.13
MA	74	8.34	0.06	1.30	0.79	0.08	18.48	27.21	0.28	1.03	0.09
MA	75	47.52	0.34	8.23	2.24	0.08	7.43	10.71	0.27	5.58	0.15
MA	76	38.72	0.27	6.75	2.11	0.19	9.62	14.22	0.32	4.69	0.14
MA	77	41.57	0.29	7.35	2.03	0.15	8.62	13.05	0.26	5.14	0.16
MA	78	74.14	0.38	9.32	3.18	0.10	0.63	1.23	0.26	6.78	0.22
MA	79	76.38	0.05	0.97	18.47	0.03	0.06	0.07	0.24	0.33	0.07
MA	80	83.12	0.14	2.01	1.51	0.07	2.22	3.01	0.25	1.39	0.09
MA	81	49.00	0.35	9.48	4.74	0.06	7.11	8.17	0.24	5.69	0.10
MA	82	30.48	0.24	6.14	2.94	0.08	12.11	16.90	0.25	3.66	0.07
MA	83	79.08	0.08	1.14	0.45	0.13	3.55	5.03	0.26	0.59	0.06

M C A R T H U R   A U S T R A L I A   M A J O R E L E M E N T S   (CONCENTRATIONS IN %)

SPL. NO.		SIO2	TIO2	AL2O3	FE2O3	MNO	MGO	CAO	NA2O	K2O	P2O5
MA	84	52.85	0.35	9.10	5.13	0.17	5.80	7.44	0.27	5.57	0.12
MA	85	72.84	0.15	3.58	1.04	0.17	4.48	5.81	0.21	1.86	0.08
MA	86	45.82	0.40	9.54	4.41	0.21	7.48	9.69	0.28	5.51	0.13
MA	87	68.89	0.23	7.94	1.12	0.10	4.66	3.67	0.19	5.51	0.11
MA	88	43.41	0.29	7.76	3.91	0.16	10.23	10.81	0.27	4.61	0.10
MA	89	33.23	0.04	0.73	0.37	0.39	13.63	19.37	0.27	0.20	0.05
MA	90	66.12	0.06	1.21	0.34	0.06	6.76	9.34	0.23	0.59	0.08
MA	91	53.47	0.31	6.17	2.51	0.17	8.71	8.83	0.33	3.64	0.15
MA	92	45.18	0.30	6.28	1.42	0.21	8.91	12.46	0.31	4.60	0.17
MA	93	74.27	0.15	4.55	1.22	0.06	4.01	4.40	0.24	3.02	0.11
MA	94	60.47	0.20	5.19	1.56	0.10	7.05	8.01	0.24	3.18	0.15
MA	96	7.32	0.03	0.41	1.95	0.30	18.89	27.65	0.30	0.23	0.05
MA	97	2.80	0.05	0.65	1.40	0.24	16.44	24.95	0.46	0.10	0.05
MA	98	44.32	0.22	5.33	3.62	0.14	9.00	12.77	0.28	3.63	0.12
MA	99	35.13	0.07	1.70	1.32	0.20	12.56	18.53	0.21	1.14	0.06
MA	100	62.63	0.12	2.89	1.80	0.11	6.34	9.09	0.22	1.81	0.08
MA	101	34.19	0.07	1.77	1.00	0.17	12.80	18.64	0.23	1.19	0.07
MA	102	46.07	0.32	9.31	2.64	0.13	7.15	10.05	0.27	6.50	0.11
MA	103	52.99	0.37	9.23	5.16	0.09	5.96	6.98	0.29	5.59	0.13
MA	104	40.99	0.31	6.90	4.51	0.15	9.02	12.68	0.28	4.57	0.14
MA	105	12.95	0.06	1.18	2.70	0.42	16.89	25.40	0.31	0.77	0.13
MA	106	65.57	0.50	14.80	4.01	0.01	0.60	0.09	0.01	11.52	0.08
MA	107	23.11	0.03	0.44	1.91	0.13	15.06	23.16	0.25	0.27	0.13
MA	108	12.95	0.06	1.58	1.90	0.08	16.60	25.64	0.30	1.00	0.06
MA	109	5.17	0.02	0.33	2.31	0.09	18.86	28.28	0.27	0.20	0.04
MA	110	61.07	0.41	17.67	1.93	0.08	0.03	0.20	0.01	15.87	0.17
MA	111	60.84	0.49	12.25	1.54	0.03	2.25	4.33	0.03	10.00	0.28
MA	112	35.47	0.20	4.92	1.48	0.10	10.41	17.61	0.28	3.50	0.12
MA	113	20.76	0.03	0.37	1.04	0.09	16.29	23.93	0.30	0.21	0.05
MA	114	4.00	0.03	0.44	4.03	0.25	19.10	27.34	0.27	0.29	0.04
MA	115	63.58	0.25	4.39	1.04	0.07	5.75	8.01	0.28	3.27	0.11
MA	116	15.93	0.05	0.90	7.56	0.22	29.03	6.50	0.16	0.56	0.04
MA	117	44.32	0.09	1.93	1.17	0.07	11.00	15.70	0.19	1.14	0.06
MA	118	5.62	0.02	0.40	9.97	0.31	29.62	9.15	0.20	0.27	0.03
MA	119	40.31	0.08	1.86	1.40	0.09	11.86	16.93	0.20	0.96	0 06
MA	120	4.89	0.22	0.33	3.47	0.21	18.70	27.64	0.31	0.20	0 04
MA	121	10.98	0.08	1.26	6.04	0.19	32.91	4.72	0.20	0.80	0 07
MA	122	11.94	0.04	0.77	5.12	0.17	16.90	25.04	0.27	0.50	0 05
MA	123	11.63	0.11	2.39	0.50	0.02	12.73	31.67	0.23	1.00	0 06
MA	124	16.33	0.05	1.20	1.36	0.12	16.84	24.93	0.25	0.81	0 05

M C A R T H U R   A U S T R A L I A   M A J O R E L E M E N T S   (CONCENTRATIONS IN %)

SPL. NO.		SIO2	TIO2	AL2O3	FE2O3	MNO	MGO	CAO	NA2O	K2O	P2O5
MA	125	35.54	0.04	0.82	1.12	0.08	12.81	18.98	0.21	0.51	0 05
MA	126	23.83	0.04	1.34	6.63	0.17	14.55	20.04	0.22	1.06	0 04
MA	127	41.08	0.03	0.49	2.07	0.13	11.71	17.03	0.21	0.24	0 05
MA	128	13.00	0.07	1.42	6.67	0.24	21.11	16.70	0.24	0.98	0 09
MA	129	7.42	0.03	0.51	1.34	0.10	18.48	27.30	0.28	0.33	0 04
MA	130	21.02	0.04	0.70	1.10	0.08	16.11	23.44	0.29	0.51	0 04
MA	131	32.86	0.11	2.37	1.03	0.07	13.20	19.00	0.22	1.70	0 06
MA	132	2.95	0.02	0.28	1.11	0.09	20.01	29.20	0.31	0.19	0 04
MA	133	29.31	0.11	2.56	1.33	0.08	14.00	19.77	0.19	1.45	0 06
MA	134	6.28	0.03	0.41	1.18	0.10	18.96	27.60	0.25	0.26	0 04
MA	135	11.35	0.02	0.33	1.06	0.09	18.34	26.68	0.22	0.22	0 04
MA	136	12.43	0.06	1.38	1.04	0.11	17.79	25.71	0.26	0.96	0 05
MA	137	9.86	0.05	1.29	6.36	1.47	10.16	32.48	0.25	0.36	0 11
MA	138	12.73	0.09	1.94	3.41	0.33	5.36	38.41	0.27	0.43	0 10
MA	139	66.98	0.30	16.33	0.60	0.02	0.04	0.05	0.01	14.48	0 03
MA	140	20.50	0.15	3.24	1.58	0.09	15.31	21.93	0.23	2.20	0 11
MA	141	49.97	0.29	13.81	1.52	0.05	4.58	6.72	0.22	11.32	0 18
MA	142	6.57	0.09	1.84	64.84	0.06	0.09	0.01	0.55	0.07	0 29
MA	143	4.21	0.04	1.16	81.59	0.08	0.12	0.10	0.30	0.04	0 33
MA	144	8.12	0.05	1.30	1.65	0.12	18.10	27.47	0.27	0.87	0 05
MA	145	9.65	0.03	0.91	2.05	0.16	17.79	26.99	0.27	0.62	0 04
MA	146	19.19	0.03	0.43	3.43	0.20	15.47	23.97	0.22	0.04	0 06
MA	147	44.14	0.05	1.02	1.41	0.07	10.47	16.04	0.23	0.65	0 06
MA	148	75.49	0.15	11.30	0.17	0.02	0.22	0.40	0.17	9.65	0 10
MA	149	37.49	0.08	1.62	0.97	0.15	12.24	18.03	0.23	1.13	0 06
MA	150	25.30	0.09	2.95	0.83	0.13	14.38	21.23	0.22	2.40	0 07
MA	151	21.55	0.12	2.89	1.31	0.15	15.11	22.11	0.24	2.03	0 07
MA	152	71.29	0.29	13.41	1.05	0.05	0.26	0.20	0.21	10.93	0 12
MA	153	32.74	0.17	4.39	1.52	0.58	11.86	17.78	0.28	2.87	0 09
MA	154	32.52	0.16	3.51	1.41	0.32	12.74	18.39	0.27	2.02	0 09
MA	155	53.42	0.16	12.32	0.97	0.10	4.44	6.79	0.27	10.28	0 07
MA	156	35.78	0.03	0.44	0.36	0.02	13.35	19.32	0.23	0.22	0 05
MA	157	33.27	0.22	5.24	0.85	0.04	12.01	17.31	0.28	3.65	0 08
MA	158	2.84	0.02	0.28	0.14	0.02	20.62	29.59	0.28	0.14	0 04
MA	159	65.24	0.47	12.77	1.47	0.05	1.91	1.81	0.33	9.16	0 30
MA	160	40.73	0.29	7.66	2.21	0.20	9.08	12.79	0.27	5.28	0 13
MA	161	42.99	0.18	4.00	1.78	0.17	10.42	14.85	0.23	2.20	0 09
MA	162	32.82	0.23	5.59	1.89	0.25	11.22	17.08	0.30	4.10	0 11
MA	163	39.43	0.29	7.45	2.53	0.12	9.28	13.66	0.01	5.25	0 10
MA	164	37.55	0.26	7.47	38.71	4.83	0.39	0.07	0.01	4.78	0 23

M C A R T H U R   A U S T R A L I A   M A J O R   E L E M E N T S   (CONCENTRATIONS IN %)

SPL. NO.		SIO2	TIO2	AL2O3	FE2O3	MNO	MGO	CAO	NA2O	K2O	P2O5
MA	165	9.54	0.04	0.60	10.77	0.34	15.74	24.68	0.24	0.25	0 05
MA	166	38.63	0.31	7.25	2.33	0.13	10.00	14.15	0.23	4.25	0 12
MA	167	42.16	0.39	10.25	4.82	0.08	8.50	10.27	0.23	4.59	0 13
MA	168	71.99	0.25	12.09	0.88	0.09	0.06	0.55	0.23	9.88	0 16
MA	169	40.09	0.29	7.60	1.72	0.06	9.20	13.43	0.26	5.82	0 25
MA	170	51.34	0.38	9.69	2.01	0.05	5.28	8.26	0.25	7.24	0 18
MA	171	62.56	0.33	12.32	3.83	0.04	1.44	3.15	0.23	9.76	0 51
MA	172	41.43	0.36	8.32	2.67	0.07	8.01	12.02	0.01	6.08	0 16
MA	173	48.93	0.39	10.09	2.87	0.06	6.16	8.50	0.01	6.94	0 16
MA	174	59.71	0.43	14.58	3.04	0.05	1.68	2.57	0.01	12.69	0 17
MA	175	15.48	0.07	3.05	0.51	0.08	16.49	24.10	0.01	2.57	0 04
MA	176	18.33	0.11	2.59	0.66	0.06	16.24	23.65	0.01	1.80	0 09
MA	177	7.29	0.06	1.38	0.73	0.08	19.06	27.81	0.01	0.99	0 05
MA	178	46.76	0.39	9.54	2.48	0.06	6.83	9.86	0.01	6.91	0 12
MA	179	51.86	0.23	9.23	1.51	0.11	5.32	8.82	0.01	7.92	0 08
MA	180	49.71	0.38	9.23	1.99	0.07	5.97	9.03	0.01	7.28	0 12
MA	181	60.69	0.39	17.48	0.20	0.01	0.60	1.51	0.01	15.71	0 06
MA	182	53.47	0.29	7.89	0.95	0.02	6.59	9.13	0.01	5.98	0 16
MA	183	34.91	0.35	7.32	2.30	0.09	10.07	15.11	0.01	5.22	0 10
MA	184	55.28	3.79	14.06	11.28	0.02	1.15	0.31	0.01	11.08	0 19
MA	185	35.48	0.35	7.29	3.41	0.08	9.77	15.00	0.01	5.10	0 13
MA	186	43.42	0.50	8.74	2.26	0.07	7.77	11.14	0.01	6.22	0 16
MA	187	58.57	0.27	16.59	1.22	0.02	1.41	2.71	0.01	14.97	0 08
MA	188	6.17	0.05	1.01	0.83	0.07	19.13	28.58	0.01	0.72	0 01
MA	189	22.69	0.18	4.01	1.42	0.07	14.44	21.38	0.01	2.90	0 08
MA	190	34.84	0.26	6.30	1.20	0.06	10.84	16.22	0.01	4.72	0 18
MA	191	39.49	0.33	7.66	1.74	0.07	8.82	13.65	0.01	5.67	0 24
MA	192	10.17	0.09	1.92	1.14	0.06	18.15	26.46	0.01	1.34	0 02
MA	193	56.88	0.23	15.63	1.39	0.02	2.17	3.81	0.01	13.96	0 04
MA	194	13.02	0.10	2.46	1.03	0.09	17.52	25.34	0.01	1.70	0 03
MA	195	8.59	0.08	1.74	0.70	0.10	18.75	26.84	0.01	1.20	0 02
MA	196	9.03	0.07	1.64	0.73	0.06	18.75	26.68	0.01	1.14	0 03
MA	197	24.48	0.19	4.68	1.24	0.06	14.38	20.34	0.01	3.15	0 13
MA	198	32.31	0.29	6.50	2.24	0.08	11.41	16.18	0.01	4.69	0 11
MA	199	41.38	0.36	7.21	3.12	0.07	9.76	12.56	0.01	4.77	0 17
MA	200	43.76	0.27	6.65	2.46	0.07	9.23	12.73	0.01	4.42	0 12
MA	201	30.86	0.23	5.78	1.65	0.11	12.38	17.22	0.01	4.05	0 08
MA	202	22.17	0.14	3.50	0.96	0.19	15.00	21.63	0.01	2.52	0 05
MA	203	68.71	0.26	15.29	0.75	0.20	0.05	0.06	0.01	13.59	0 03
MA	204	77.67	0.12	10.95	0.30	0.01	0.04	0.03	0.01	9.49	0 02

M C A R T H U R   A U S T R A L I A   M A J O R   E L E M E N T S   (CONCENTRATIONS IN %)

SPL. NO.	SIO2	TIO2	AL2O3	FE2O3	MNO	MGO	CAO	NA2O	K2O	P2O5
MA 205	33.35	0.05	1.40	0.88	0.33	13.36	19.70	0.01	0.77	0 02
MA 206	12.47	0.04	0.71	3.56	0.21	16.63	25.83	0.01	0.33	0 01
MA 207	1.45	0.02	0.22	3.84	0.19	18.83	29.44	0.01	0.09	0 01
MA 208	76.41	0.56	8.12	5.87	0.14	0.52	0.09	0.01	3.69	0 05
MA 209	73.39	0.31	12.83	0.52	0.01	0.13	0.10	0.01	10.96	0 02
MA 210	81.63	0.51	7.79	2.44	0.06	0.18	0.03	0.01	5.79	0 02

M C A R T H U R   A U S T R A L I A   T R A C E   E L E M E N T S   1   (CONCENTRATIONS IN PPM)

SPL. NO.		BA	CE	CO	CR	CU	LA	MN	NB	NI	PB
MA	1	361	98	1	46	1	47	45	20	30	11
MA	2	386	55	2	20	21	24	331	18	23	76
MA	3	277	101	29	32	1	50	42	25	35	5
MA	4	276	30	2	18	1	7	11	1	17	1
MA	5	51	32	1	2	1	17	2	8	12	14
MA	6	297	74	4	4	1	31	519	32	31	11
MA	7	247	51	23	96	43	26	86	12	60	24
MA	8	160	58	16	54	3	19	1224	6	59	6
MA	9	522	92	1	12	1	42	1812	19	19	19
MA	10	398	78	38	37	68	33	1443	10	130	148
MA	11	344	95	1	2	1	129	1026	14	21	146
MA	12	283	229	10	18	3	160	3050	16	37	53
MA	13	200	118	31	52	39	58	1677	11	66	2
MA	14	192	63	34	32	166	25	2585	1	50	3753
MA	15	253	36	13	13	71	16	2205	4	26	1494
MA	16	240	50	12	23	120	11	1146	1	14	1885
MA	17	58	17	1	3	5	1	2080	3	14	96
MA	18	977	52	4	34	5	31	314	15	26	13
MA	19	106	17	2	6	1	1	1291	4	11	1
MA	20	19	21	1	3	1	1	472	1	17	1
MA	21	44	30	1	7	1	9	1089	8	14	5
MA	22	61	23	1	6	1	1	446	8	15	1
MA	23	107	32	2	11	113	9	553	6	25	10
MA	24	42	21	2	3	1	1	748	4	15	1
MA	25	44	23	1	2	1	1	1047	8	19	1
MA	26	625	18	1	11	1	10	137	6	11	27
MA	27	29	23	1	5	1	1	3115	3	16	1
MA	28	6123	1	8	1	68	5	739	1	26	35
MA	29	32	16	6	11	1	1	2141	1	18	67
MA	30	39	21	1	1	1	1	735	2	16	1
MA	31	1423	13	4	5	3	4	759	5	18	8
MA	32	236	33	1	5	35	4	679	4	22	34
MA	33	2878	5	2	6	124	8	534	9	16	1
MA	34	140	42	4	10	138	13	618	8	15	1
MA	35	5792	1	4	4	19	1	714	3	20	6
MA	36	25	24	11	9	24	1	4090	4	33	1
MA	37	21	7	3	11	7	1	2379	3	18	40
MA	38	57	4	3	4	1	1	806	1	23	1
MA	39	188	37	36	19	4687	10	285	5	37	225
MA	40	258	43	1	20	1007	17	15	10	22	16

MC ARTHUR AUSTRALIA TRACE ELEMENTS 1 (CONCENTRATIONS IN PPM)

SPL. NO.		BA	CE	CO	CR	CU	LA	MN	NB	NI	PB
MA	41	307	43	16	34	7	13	27	8	22	47
MA	42	81	137	1	9	1	77	4	1	11	13
MA	43	184	53	154	26	269	1	995	4	80	184
MA	46	95	17	8	10	35	1	1155	3	19	1
MA	47	376	70	6	32	140	38	387	17	27	7
MA	48	592	77	7	25	201	37	438	14	30	10
MA	49	359	75	11	39	1	35	519	14	36	7
MA	50	194	37	3	25	1	18	2583	8	19	19
MA	51	416	47	1	19	6	12	571	8	16	13
MA	52	333	36	1	10	1	11	421	1	16	1
MA	53	62	33	1	7	1	1	775	1	19	1
MA	54	1051	11	1	1	1	1	659	6	18	12
MA	55	415	141	4	10	10	74	744	14	20	1
MA	56	208	47	2	28	212	21	2029	9	27	13
MA	57	223	37	2	12	56	7	499	9	15	2
MA	58	161	30	1	8	1	4	1300	4	14	1
MA	59	272	17	1	6	1	1	236	7	11	1
MA	60	307	55	2	30	1	30	778	14	29	2
MA	61	3209	1	1	1	9	1	428	4	11	8
MA	62	18	20	6	3	32	1	1340	1	16	8
MA	63	45	18	1	3	1	1	1239	5	18	5
MA	64	1	1	4	1	373	1	593	1	18	1
MA	65	631	16	5	5	118	4	1388	4	23	25
MA	67	959	25	1	9	33	7	598	8	20	1
MA	68	1102	19	1	9	1	1	675	7	12	3
MA	69	255	73	1	27	218	34	332	9	25	4
MA	70	12	1	3	1	26	1	1001	1	18	6
MA	71	594	60	11	28	3038	29	1589	13	31	32
MA	72	40	21	18	1	71	1	3945	1	21	7
MA	73	794	95	8	7	46	52	644	20	29	17
MA	74	63	25	1	11	251	1	609	5	22	1
MA	75	319	76	1	38	43	24	653	11	28	10
MA	76	271	71	1	29	35	23	1561	11	30	18
MA	77	271	49	1	37	55	26	1172	14	24	11
MA	78	534	57	7	45	32	24	778	14	41	30
MA	79	1	1	4	1	18	7	174	1	18	3
MA	80	121	38	2	10	9	13	515	4	16	3
MA	81	531	68	3	44	113	26	440	12	28	4
MA	82	217	64	5	24	434	27	620	1	27	9
MA	83	7791	1	2	7	535	3	966	5	17	9

M C A R T H U R   A U S T R A L I A   T R A C E E L E M E N T S 1   (CONCENTRATIONS IN PPM)

SPL. NO.		BA	CE	CO	CR	CU	LA	MN	NB	NI	PB
MA	84	781	60	11	33	391	25	1437	17	29	3
MA	85	163	51	5	21	40	9	1429	[illegible]	21	1
MA	86	379	74	10	46	28	35	1723	15	27	3
MA	87	844	108	15	26	16	58	810	16	27	1
MA	88	433	67	16	38	23	22	1326	9	29	11
MA	89	7190	1	4	519	5	1	3329	1	387	1
MA	90	77	18	1	9	45	6	448	9	14	1
MA	91	1047	56	18	26	145	21	1351	15	33	5
MA	92	239	57	2	33	17	20	1724	5	20	1
MA	93	109	36	4	13	15	22	448	12	22	1
MA	94	127	61	5	22	40	26	787	11	26	2
MA	96	133	37	3	13	219	3	2649	1	17	12
MA	97	8	1	1	1	36	1	1494	1	19	1
MA	98	232	41	1	23	35	24	1114	7	19	20
MA	99	795	27	4	13	33	3	1640	1	19	1
MA	100	1060	31	1	10	13	12	805	9	17	1
MA	101	3243	1	4	8	27	2	1462	5	19	1
MA	102	1784	56	2	36	15	28	1038	18	28	6
MA	103	1614	68	14	37	19	47	649	15	33	5
MA	104	1432	55	6	26	31	23	1189	12	25	9
MA	105	527	37	8	14	6	4	3740	5	19	1
MA	106	3241	9	75	78	210	20	36	5	66	30
MA	107	187	37	4	8	[illegible]	3	1203	1	20	10
MA	108	94	23	9	9	174	7	697	1	20	20
MA	109	27	48	1	4	36	3	821	3	17	9
MA	110	1011	454	13	1	8	311	683	19	27	16
MA	111	443	86	1	55	29	48	193	15	29	12
MA	112	230	57	5	26	672	19	795	9	29	13
MA	113	4744	1	1	1	259	1	751	2	13	1
MA	114	299	22	7	1	296	1	2202	1	18	5
MA	115	342	51	1	21	21	25	591	11	15	1
MA	116	223	21	6	6	41	1	1952	1	13	1
MA	117	104	38	1	14	42	1	506	8	16	1
MA	118	26	18	11	1	31	1	2811	8	17	1
MA	119	97	40	1	14	12	1	666	2	15	8
MA	120	52	35	8	7	28	2	1920	2	17	7
MA	121	49	31	20	4	353	9	1699	12	19	8
MA	122	61	28	7	3	26	1	1491	1	19	1
MA	123	147	30	1	17	36	1	79	11	19	1
MA	124	231	17	1	5	11	1	954	1	12	1

M C A R T H U R   A U S T R A L I A   T R A C E E L E M E N T S 1   (CONCENTRATIONS IN PPM)

SPL. NO.		BA	CE	CO	CR	CU	LA	MN	NB	NI	PB
MA	125	51	22	1	6	28	1	657	1	16	1
MA	126	125	24	8	3	131	2	1408	3	17	1
MA	127	195	24	1	3	15	1	1086	3	15	1
MA	128	65	38	14	1	245	1	2137	1	15	5
MA	129	1	1	1	1	36	1	832	1	18	5
MA	130	226	27	1	7	31	1	635	3	18	1
MA	131	242	19	1	9	10	4	548	8	15	1
MA	132	1812	7	2	8	21	4	811	1	17	1
MA	133	106	36	4	15	58	6	631	13	13	1
MA	134	9184	1	1	4	8	1	813	2	11	12
MA	135	104	25	2	3	69	1	679	11	13	1
MA	136	63	18	1	9	7	1	878	8	15	1
MA	137	4009	1	48	9	149	4	12878	4	46	3
MA	138	846	21	12	17	80	5	2902	1	33	5
MA	139	354	70	1	7	1	33	74	19	13	3
MA	140	112	31	3	20	4	8	784	5	15	1
MA	141	138	142	1	11	15	86	322	20	15	1
MA	142	11	1	61	1	24	1	196	1	64	3
MA	143	1	1	100	1	35	1	409	1	95	32
MA	144	110	5	1	7	1	1	1061	1	12	1
MA	145	89	32	1	9	2	1	1407	1	13	5
MA	146	222	31	12	10	36	1	1878	10	19	38
MA	147	6541	1	1	1	2	2	562	5	12	1
MA	148	594	156	1	1	1	79	153	18	12	1
MA	149	116	27	1	8	13	1	1313	1	14	2
MA	150	157	20	1	12	1	1	1122	8	12	14
MA	151	143	38	1	23	7	1	1267	6	16	1
MA	152	312	185	1	13	1	132	337	22	16	5
MA	153	159	33	4	17	40	14	5096	14	14	5
MA	154	161	42	1	20	1	15	2814	14	19	2
MA	155	227	157	4	3	16	90	805	35	15	8
MA	156	549	13	2	1	1	1	159	3	11	6
MA	157	234	47	4	21	59	12	253	16	17	13
MA	158	25	24	1	12	1	1	141	9	11	16
MA	159	394	59	4	53	1	26	340	20	32	7
MA	160	242	52	5	34	36	28	1717	19	24	6
MA	161	272	38	10	23	36	16	1414	9	22	5
MA	162	286	51	2	28	1	13	2164	7	15	1
MA	163	262	65	24	19	114	41	36886	13	41	22
MA	164	271	65	5	34	80	24	1032	14	25	17

M C A R T H U R   A U S T R A L I A   T R A C E E L E M E N T S 1   (CONCENTRATIONS IN PPM)

SPL. NO.	BA	CE	CO	CR	CU	LA	MN	NB	NI	PB
MA 165	182	19	20	3	4	1	3073	4	23	1
MA 166	325	54	2	35	1	20	1062	5	23	15
MA 167	934	52	9	45	46	35	672	11	30	5
MA 168	866	103	5	10	1	51	638	33	24	19
MA 169	230	38	10	35	12	8	425	19	40	16
MA 170	303	82	3	50	19	37	373	24	22	7
MA 171	408	41	6	34	39	14	225	25	44	17
MA 172	318	57	3	46	21	33	517	17	32	31
MA 173	309	63	5	43	9	32	411	17	31	12
MA 174	466	213	3	29	54	121	324	16	20	5
MA 175	166	23	1	5	1	1	596	5	11	1
MA 176	129	34	1	21	64	4	475	9	11	17
MA 177	53	21	1	15	3	4	595	2	13	1
MA 178	308	65	6	43	6	28	435	18	26	14
MA 179	171	89	4	22	28	50	868	22	17	1
MA 180	352	70	7	40	11	30	519	20	27	1
MA 181	797	194	1	1	5	141	48	21	16	1
MA 182	328	37	1	52	1	10	168	19	17	6
MA 183	215	55	8	39	2	18	833	16	30	17
MA 184	336	226	34	33	411	148	108	51	139	132
MA 185	205	68	11	39	247	29	649	25	41	11
MA 186	265	84	3	46	70	29	530	22	29	7
MA 187	174	169	1	3	19	98	95	10	14	10
MA 188	31	28	2	9	1	1	622	5	17	22
MA 189	129	39	6	30	4	5	565	1	19	3
MA 190	181	43	7	32	1	9	475	17	26	14
MA 191	260	76	7	48	3	38	569	16	33	7
MA 192	47	32	2	19	1	1	550	9	14	9
MA 193	178	178	1	1	5	105	113	26	15	15
MA 194	86	38	2	22	6	4	733	8	12	6
MA 195	92	21	1	9	21	1	913	1	12	13
MA 196	52	16	1	9	1	1	564	9	14	5
MA 197	116	37	1	31	1	7	495	16	19	18
MA 198	169	49	5	38	30	1	636	6	20	7
MA 199	186	20	7	37	61	1	542	11	21	1
MA 200	176	76	2	31	1	27	518	12	18	13
MA 201	150	53	5	20	1	13	913	17	21	3
MA 202	184	65	7	15	1	25	1639	21	20	9
MA 203	540	109	4	14	1	51	1570	24	13	8
MA 204	359	47	1	2	1	45	1	19	10	1

M C A R T H U R A U S T R A L I A T R A C E E L E M E N T S 1 (CONCENTRATIONS IN PPM)

SPL. NO.	BA	CE	CO	CR	CU	LA	MN	NB	NI	PB
MA 205	54	16	4	16	12	1	2877	3	17	12
MA 206	40	9	4	3	77	1	1843	1	18	8
MA 207	38	16	19	2	101	1	1731	4	16	17
MA 208	394	64	418	42	4284	44	1099	5	36	149
MA 209	496	33	1	14	1	3	14	26	13	1
MA 210	432	65	9	29	47	43	461	13	15	4

M C A R T H U R   A U S T R A L I A   T R A C E E L E M E N T S 2   (CONCENTRATIONS IN PPM, HG IN PPB)

SPL. NO.		PB	SC	SR	TH	V	Y	ZN	ZR	HG
MA	1	205	7	21	15	35	34	11	226	
MA	2	133	6	18	5	15	23	1	166	
MA	3	197	4	20	12	29	48	6	221	
MA	4	97	1	12	1	10	16	1	152	
MA	5	2	1	2	1	5	12	1	65	
MA	6	132	11	9	10	26	79	1	317	
MA	7	245	14	15	2	128	21	24	120	
MA	8	141	22	33	9	88	23	35	86	
MA	9	189	5	22	9	17	30	1	112	
MA	10	134	9	14	9	55	22	158	192	
MA	11	196	1	16	20	8	43	1365	144	
MA	12	220	8	6	22	22	25	8229	150	
MA	13	93	2	14	12	43	29	3	96	
MA	14	62	5	10	12	74	23	3	64	
MA	15	37	9	23	11	17	19	2	48	
MA	16	1	1	1	11	80	4	3361	60	
MA	17	1	1	50	40	5	7	555	8	
MA	18	143	8	50	6	35	13	15	123	
MA	19	1	2	56	1	3	2	1	1	
MA	20	1	1	16	1	7	8	1	12	
MA	21	8	1	41	1	11	8	4	15	
MA	22	1	1	11	1	4	9	4	38	
MA	23	29	3	63	3	14	11	5	[illegible]	
MA	24	3	1	23	1	9	12	3	35	
MA	25	1	1	25	1	5	9	1	5	
MA	26	14	1	5	1	14	10	47	28	
MA	27	2	1	20	3	8	6	1	9	
MA	28	9	1	88	1	4	14	1	69	
MA	29	5	1	22	1	17	3	656	16	
MA	30	1	1	25	1	7	7	1	8	
MA	31	1	1	46	1	10	10	1	10	
MA	32	3	1	37	1	17	18	1	22	
MA	33	9	5	42	1	7	10	1	63	
MA	34	41	1	33	1	15	12	1	64	
MA	35	6	1	61	1	7	7	1	43	
MA	36	1	1	44	1	19	5	3	3	
MA	37	1	1	15	1	6	1	414	1	
MA	38	4	1	22	1	6	8	6	15	
MA	39	71	7	17	13	34	21	35	162	
MA	40	105	3	20	8	20	17	16	177	

M C A R T H U R   A U S T R A L I A   T R A C E   E L E M E N T S   2   (CONCENTRATIONS IN PPM, HG IN PPB)

SPL. NO.		RB	SC	SR	TH	V	Y	ZN	ZR	HG
MA	41	104	6	19	17	69	21	1	150	
MA	42	1	1	123	1	11	7	1	9	
MA	43	1	2	1	9	142	7	604	36	
MA	46	4	[illegible]	54	1	16	12	8	10	
MA	47	141	[illegible]	47	4	37	24	13	157	
MA	48	141	6	44	7	26	27	12	135	
MA	49	237	1	36	4	46	22	36	203	
MA	50	62	[illegible]	27	6	14	14	43	132	
MA	51	84	2	22	1	8	15	1	262	
MA	52	63	1	15	1	6	12	1	220	
MA	53	8	4	32	1	8	9	1	16	
MA	54	1	2	33	1	5	12	1	10	
MA	55	93	4	16	9	16	12	1	112	
MA	56	130	6	44	1	25	16	14	91	
MA	57	63	2	15	1	12	9	4	53	
MA	58	2	2	90	1	13	6	0	4	
MA	59	18	1	11	1	6	7	1	25	
MA	60	144	12	26	4	20	24	12	247	
MA	61	1	1	29	1	1	7	1	1	
MA	62	1	1	22	2	7	3	1	1	
MA	63	1	1	25	6	8	5	1	8	
MA	64	1	3	56	1	1	3	1	20	
MA	65	8	1	33	1	10	2	25	18	
MA	67	21	1	33	1	10	12	1	29	
MA	68	16	4	28	1	11	12	1	44	
MA	69	95	8	45	8	23	8	3	81	
MA	70	1	5	698	1	1	3	1	48	
MA	71	93	9	44	1	47	21	7	73	
MA	72	1	1	21	7	3	1	1	6	
MA	73	93	2	13	14	5	23	1	260	
MA	74	2	1	62	1	16	11	1	20	
MA	75	131	10	42	5	53	24	7	151	
MA	76	98	10	45	1	47	21	3	125	
MA	77	103	6	42	8	52	20	1	136	
MA	78	138	3	21	11	31	19	10	237	
MA	79	1	1	209	6	8	3	1	30	
MA	80	41	3	29	1	16	14	1	132	
MA	81	144	9	93	3	40	20	12	110	
MA	82	99	6	108	1	29	15	10	84	
MA	83	3	1	148	1	2	16	1	187	

MC ARTHUR AUSTRALIA TRACE ELEMENTS 2 (CONCENTRATIONS IN PPM, HG IN PPB)

SPL. NO.		RB	SC	SR	TH	V	Y	ZN	ZR	HG
MA	84	136	14	49	11	53	16	17	134	
MA	85	60	5	23	1	176	17	8	136	
MA	86	163	7	44	8	47	21	18	155	
MA	87	89	5	24	15	27	27	12	130	
MA	88	121	8	41	1	35	20	26	89	
MA	89	1	1	199	1	15	3	1	2	
MA	90	20	3	33	1	5	9	1	21	
MA	91	110	5	49	4	21	23	19	350	
MA	92	113	10	57	2	20	15	7	210	
MA	93	79	1	29	3	14	10	1	59	
MA	94	113	4	31	1	23	11	15	70	
MA	96	1	1	42	1	10	1	80	9	
MA	97	1	1	634	1	1	1	24	1	
MA	98	75	6	30	1	25	8	32	72	
MA	99	17	3	35	4	13	1	1	14	
MA	100	41	7	33	6	10	14	9	150	
MA	101	13	5	64	1	10	7	1	38	
MA	102	119	9	70	6	36	23	12	127	
MA	103	156	11	58	10	40	30	20	219	
MA	104	111	10	58	1	34	24	12	125	
MA	105	10	1	61	1	18	10	1	25	
MA	106	132	15	39	1	182	9	2	97	
MA	107	2	5	20	1	12	5	1	18	
MA	108	16	1	28	1	21	9	1	27	
MA	109	1	1	18	1	10	14	1	10	
MA	110	134	4	15	34	6	40	1	306	
MA	111	141	9	27	9	100	31	1	160	
MA	112	76	3	37	8	32	17	2	108	
MA	113	1	1	143	1	3	1	1	2	
MA	114	1	1	38	2	9	8	1	12	
MA	115	71	7	28	1	15	17	1	162	
MA	116	9	2	21	1	12	6	1	18	
MA	117	24	3	43	1	11	11	1	36	
MA	118	1	4	18	1	8	6	1	7	
MA	119	20	1	32	1	12	8	1	23	
MA	120	1	1	32	26	5	1	1	8	
MA	121	10	4	12	4	8	11	1	88	
MA	122	4	1	38	1	7	9	1	18	
MA	123	30	1	43	1	10	4	1	39	
MA	124	8	1	44	2	6	11	1	16	

M C A R T H U R   A U S T R A L I A   T R A C E   E L E M E N T S   2   (CONCENTRATIONS IN PPM, HG IN PPB)

SPL. NO.	RB	SC	SR	TH	V	Y	ZN	ZR	HG
MA 125	6	5	36	1	9	6	1	15	
MA 126	3	2	93	5	4	7	1	19	
MA 127	2	1	33	1	6	10	1	21	
MA 128	9	2	62	3	10	8	1	36	
MA 129	1	1	262	1	1	8	1	1	
MA 130	2	1	30	1	8	1	1	9	
MA 131	29	2	64	2	13	12	1	32	
MA 132	1	2	72	1	2	9	1	5	
MA 133	36	3	46	1	13	7	4	35	
MA 134	1	3	187	1	1	9	4	24	
MA 135	1	1	37	12	4	1	1	8	
MA 136	11	2	37	1	19	6	1	20	
MA 137	13	1	20	4	18	7	74	37	
MA 138	12	1	1	1	19	19	7	60	
MA 139	122	1	12	19	12	40	1	172	
MA 140	28	6	17	3	20	16	1	52	
MA 141	125	1	16	29	12	33	1	297	
MA 142	1	1	123	15	1	1	39	36	
MA 143	1	1	5	22	15	6	65	43	
MA 144	12	1	29	17	9	6	1	19	
MA 145	6	2	27	1	10	5	1	15	
MA 146	1	7	35	1	14	12	1	25	
MA 147	11	4	89	1	7	6	1	72	
MA 148	121	1	5	9	6	16	1	97	
MA 149	20	5	161	4	9	9	1	130	
MA 150	27	2	67	1	7	7	1	84	
MA 151	34	9	22	1	15	9	1	46	
MA 152	141	8	7	38	12	44	1	238	
MA 153	69	8	108	1	18	11	1	99	
MA 154	55	8	36	1	17	14	1	99	
MA 155	140	10	8	28	4	39	1	230	
MA 156	1	4	41	1	9	1	1	17	
MA 157	75	2	50	1	31	7	1	75	
MA 158	1	1	47	1	6	1	1	10	
MA 159	152	3	20	15	69	24	1	134	
MA 160	120	8	27	3	41	21	6	131	
MA 161	65	1	31	1	23	20	1	137	
MA 162	73	10	17	4	34	16	1	98	
MA 163	85	7	54	31	55	25	2	100	
MA 164	113	11	27	1	89	32	1	117	

M C A R T H U R   A U S T R A L I A   T R A C E   E L E M E N T S 2   (CONCENTRATIONS IN PPM, HG IN PPB)

SPL. NO.		PB	SC	SR	TH	V	Y	ZN	ZR	HG
MA	165	2	1	29	1	12	5	1	14	
MA	166	104	7	36	1	36	22	4	83	
MA	167	194	14	56	15	52	17	13	107	
MA	168	87	3	22	22	16	50	1	205	
MA	169	86	13	25	1	81	23	1	117	
MA	170	133	2	32	10	80	25	1	143	
MA	171	125	9	33	8	86	22	7	93	
MA	172	114	15	40	22	149	22	1	117	
MA	173	144	11	39	18	95	21	6	151	
MA	174	113	4	9	18	40	55	1	259	
MA	175	20	4	33	1	15	14	1	53	
MA	176	27	4	43	4	68	16	1	47	
MA	177	7	4	25	3	16	6	1	25	
MA	178	151	9	71	7	77	24	1	150	
MA	179	97	3	36	17	33	22	1	103	
MA	180	130	7	28	6	59	21	4	149	
MA	181	143	1	12	28	3	24	1	196	
MA	182	78	9	22	1	36	16	1	95	
MA	183	102	7	39	1	93	23	1	108	
MA	184	122	8	12	1	162	42	1	320	
MA	185	103	14	36	8	87	8	3	102	
MA	186	117	8	39	12	102	20	1	120	
MA	187	143	1	7	44	7	21	1	197	
MA	188	7	1	29	1	11	1	1	19	
MA	189	44	3	28	9	22	9	1	82	
MA	190	75	6	28	9	33	22	1	85	
MA	191	104	17	43	17	39	36	1	107	
MA	192	17	1	11	1	16	13	1	34	
MA	193	123	1	3	38	13	27	1	228	
MA	194	29	4	11	1	9	9	1	45	
MA	195	14	1	4	1	9	10	1	33	
MA	196	8	6	31	1	16	12	1	23	
MA	197	46	1	22	21	17	11	1	63	
MA	198	78	8	34	9	23	8	1	99	
MA	199	81	7	19	10	29	10	2	82	
MA	200	77	7	21	19	26	18	1	86	
MA	201	74	8	25	11	17	13	1	98	
MA	202	34	7	22	20	13	21	1	60	
MA	203	106	2	2	18	8	30	1	158	
MA	204	67	1	6	17	1	15	1	111	

M C A R T H U R   A U S T R A L I A   T R A C E E L E M E N T S 2   (CONCENTRATIONS IN PPM, HG IN PPB)

SPL. NO.	RB	SC	SR	TH	V	Y	ZN	ZR	HG
MA 205	19	2	50	1	9	10	10	42	
MA 206	2	1	14	1	7	1	1	54	
MA 207	1	1	33	8	10	2	1	10	
MA 208	97	5	87	56	49	18	23	238	
MA 209	118	6	5	21	13	31	1	215	
MA 210	112	12	21	12	26	23	1	286	

SiO_2

A N A L Y S I S   O F   V A R I A N C E

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	1477.8500	59.1140	18.1499	7906.0824	(25)
2.	AMELIA DLMT	1160.8600	25.2361	19.4152	16962.7013	(46)
3.	TATOOLA SANDSTONE	551.0900	68.8863	31.5407	6963.7278	(8)
4.	TOOGANINIE FORM.	661.3800	26.4552	21.1704	10756.4408	(25)
5.	EMMERUGGA TEENA DLMT	286.5300	19.1020	20.0371	5620.7952	(15)
6.	BARNEY CREEK FORM.	2329.7800	41.6032	18.5138	18851.8526	(56)
7.	TUFF	816.8900	62.8377	7.7829	726.8778	(13)
	TOTAL	7284.3800	38.7467	24.4064	111390.5436	(188)

A N O V A   T A B L E

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	43602.0656	(6)	7267.0109
WITHIN GROUPS	67788.4780	(181)	374.5220
TOTAL	**********	(187)	

F = 19.4034   SIG. = .0000

TiO_2

A N A L Y S I S   O F   V A R I A N C E

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	4.6900	.1876	.1157	.3213	(25)
2.	AMELIA DLMT	4.7900	.1041	.1197	.6447	(46)
3.	TATOOLA SANDSTONE	1.4300	.1788	.1263	.1117	(8)
4.	TOOGANINIE FORM.	2.6500	.1060	.1382	.4582	(25)
5.	EMMERUGGA TEENA DLMT	1.2400	.0827	.0960	.1291	(15)
6.	BARNEY CREEK FORM.	17.8200	.3182	.4845	12.9112	(56)
7.	TUFF	4.3200	.3323	.1245	.1860	(13)
	TOTAL	36.9400	.1965	.2982	16.6277	(188)

A N O V A   T A B L E

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	1.8655	(6)	.3109
WITHIN GROUPS	14.7622	(181)	.0816
TOTAL	16.6277	(187)	

F = 3.8121   SIG. = .0013

ANALYSIS OF VARIANCE

Al_2O_3

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	117.5200	4.7008	3.1267	234.6268	(25)
2.	AMELIA DLMT	104.7400	2.2770	3.1202	438.1004	(46)
3.	TATOOLA SANDSTONE	43.0100	5.3763	4.1530	120.7338	(8)
4.	TOOGANINIE FORM.	60.8700	2.4348	3.3885	275.5666	(25)
5.	EMMERUGGA TEENA DLMT	25.5400	1.7027	2.0910	61.2121	(15)
6.	BARNEY CREEK FORM.	411.4500	7.3473	3.8675	822.6459	(56)
7.	TUFF	183.5900	14.1223	2.6634	85.1240	(13)
	TOTAL	946.7200	5.0357	4.6825	4100.1906	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	2062.1810	(6)	343.6968
WITHIN GROUPS	2038.0096	(181)	11.2597
TOTAL	4100.1906	(187)	

F = 30.5245 SIG. = .0000

ANALYSIS OF VARIANCE

Fe_2O_3

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	63.9600	2.5584	3.6048	311.8687	(25)
2.	AMELIA DLMT	129.8100	2.8220	2.4930	279.6791	(46)
3.	TATOOLA SANDSTONE	21.2600	2.6575	3.4073	81.2663	(8)
4.	TOOGANINIE FORM.	52.0500	2.0820	1.4061	47.4506	(25)
5.	EMMERUGGA TEENA DLMT	13.1200	.8747	.7691	8.2808	(15)
6.	BARNEY CREEK FORM.	222.8300	3.9791	7.0359	2722.7177	(56)
7.	TUFF	20.2100	1.5546	1.1385	15.5539	(13)
	TOTAL	523.2400	2.7832	4.4089	3634.9189	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	168.1017	(6)	28.0170
WITHIN GROUPS	3466.8172	(181)	19.1537
TOTAL	3634.9189	(187)	

F = 1.4627 SIG. = .1934

MnO

ANALYSIS OF VARIANCE

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	3.3300	.1332	.0812	.1583	(25)
2.	AMELIA DLMT	6.8600	.1491	.0915	.3770	(46)
3.	TATOOLA SANDSTONE	.8400	.1050	.1324	.1228	(8)
4.	TOOGANINIE FORM.	2.9000	.1160	.0747	.1338	(25)
5.	EMMERUGGA TEENA DLMT	1.0600	.0707	.0356	.0177	(15)
6.	BARNEY CREEK FORM.	11.9300	.2130	.6363	22.2708	(56)
7.	TUFF	.4900	.0377	.0344	.0142	(13)
	TOTAL	27.4100	.1458	.3554	23.6244	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	.5298	(6)	.0883
WITHIN GROUPS	23.0946	(181)	.1276
TOTAL	23.6244	(187)	

F = .6920 SIG. = .6564

MgO

ANALYSIS OF VARIANCE

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	162.0700	6.4828	3.5235	297.9603	(25)
2.	AMELIA DLMT	687.1700	14.9385	6.2510	1758.3964	(46)
3.	TATOOLA SANDSTONE	29.6400	3.7050	6.0873	259.3836	(8)
4.	TOOGANINIE FORM.	350.1300	14.0052	5.2057	650.3942	(25)
5.	EMMERUGGA TEENA DLMT	254.4600	16.9640	6.0818	517.8294	(15)
6.	BARNEY CREEK FORM.	465.9100	8.3198	5.6912	1781.4679	(56)
7.	TUFF	21.0400	1.6185	1.7831	38.1534	(13)
	TOTAL	1970.4200	10.4810	7.0172	9208.0952	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	3904.5101	(6)	650.7517
WITHIN GROUPS	5303.5851	(181)	29.3016
TOTAL	9208.0952	(187)	

F = 22.2088 SIG. = .0000

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CaO

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	208.4700	8.3388	5.1448	635.2489	(25)
2.	AMELIA DLMT	901.3700	19.5950	8.1225	2968.8776	(46)
3.	TATOOLA SANDSTONE	46.6000	5.8250	10.1745	724.6418	(8)
4.	TOOGANINIE FORM.	516.6900	20.6676	8.2060	1616.1209	(25)
5.	EMMERUGGA TEENA DLMT	344.7800	22.9853	6.8158	650.3714	(15)
6.	BARNEY CREEK FORM.	683.7600	12.2100	8.4869	3961.4686	(56)
7.	TUFF	31.3500	2.4115	2.7119	88.2496	(13)
	TOTAL	2733.0200	14.5373	9.7054	17614.2531	(188)

* * * * * * * * * * * * * * A N O V A   T A B L E * * * * * * * * * * * * * *

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	6969.2745	(6)	1161.5457
WITHIN GROUPS	10644.9786	(181)	58.8120
TOTAL	17614.2531	(187)	

F = 19.7501   SIG. = .0000

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Na_2O

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	6.3500	.2540	.0609	.0890	(25)
2.	AMELIA DLMT	11.0100	.2393	.0724	.2361	(46)
3.	TATOOLA SANDSTONE	1.6300	.2038	.0646	.0292	(8)
4.	TOOGANINIE FORM.	5.7000	.2280	.0735	.1298	(25)
5.	EMMERUGGA TEENA DLMT	2.9400	.1960	.1013	.1438	(15)
6.	BARNEY CREEK FORM.	9.3400	.1668	.1935	2.0592	(56)
7.	TUFF	1.0200	.0785	.1055	.1336	(13)
	TOTAL	37.9900	.2021	.1316	3.2377	(188)

* * * * * * * * * * * * * * A N O V A   T A B L E * * * * * * * * * * * * * *

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	.4171	(6)	.0695
WITHIN GROUPS	2.8206	(181)	.0156
TOTAL	3.2377	(187)	

F = 4.4606   SIG. = .0003

K_2O

ANALYSIS OF VARIANCE

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	72.4000	2.8960	2.0951	105.3486	(25)
2.	AMELIA DLMT	62.2900	1.3541	1.7910	144.3401	(46)
3.	TATOOLA SANDSTONE	28.4900	3.5613	2.7061	51.2617	(8)
4.	TOOGANINIE FORM.	33.9300	1.3572	1.8789	84.7285	(25)
5.	EMMERUGGA TEENA DLMT	16.2900	1.0860	1.3919	27.1224	(15)
6.	BARNEY CREEK FORM.	298.0400	5.3221	3.1801	556.2169	(56)
7.	TUFF	155.1300	11.9331	2.6978	87.3389	(13)
	TOTAL	666.5700	3.5456	3.7213	2589.5860	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	1533.2289	(6)	255.5382
WITHIN GROUPS	1056.3571	(181)	5.8362
TOTAL	2589.5860	(187)	

F = 43.7848 SIG. = .0000

P_2O_5

ANALYSIS OF VARIANCE

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	2.5100	.1004	.0355	.0303	(25)
2.	AMELIA DLMT	3.0600	.0665	.0386	.0670	(46)
3.	TATOOLA SANDSTONE	.5600	.0700	.0262	.0048	(8)
4.	TOOGANINIE FORM.	1.6900	.0676	.0349	.0293	(25)
5.	EMMERUGGA TEENA DLMT	.9200	.0613	.0245	.0084	(15)
6.	BARNEY CREEK FORM.	9.1600	.1636	.2380	3.1167	(56)
7.	TUFF	1.3100	.1008	.0687	.0567	(13)
	TOTAL	19.2100	.1022	.1396	3.6460	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	.3329	(6)	.0555
WITHIN GROUPS	3.3131	(181)	.0183
TOTAL	3.6460	(187)	

F = 3.0307 SIG. = .0076

- - - - - A N A L Y S I S   O F   V A R I A N C E - - - - -

Ba

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	25451.0000	1018.0400	2049.4576	************	(25)
2.	AMELIA DLMT	32913.0000	715.5000	1565.5567	************	(46)
3.	TATOOLA SANDSTONE	2199.0000	274.8750	124.4123	108348.8750	(8)
4.	TOOGANINIE FORM.	28381.0000	1135.2400	1991.7639	************	(25)
5.	EMMERUGGA TEENA DLMT	2505.0000	167.0000	260.6999	951502.0000	(15)
6.	BARNEY CREEK FORM.	14516.0000	259.2143	142.1022	1110617.4286	(56)
7.	TUFF	8690.0000	668.4615	818.6542	8042337.2308	(13)
	TOTAL	114655.0000	609.8670	1346.1626	************	(188)

A N O V A   T A B L E

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	**********	(6)	**********
WITHIN GROUPS	**********	(181)	**********
TOTAL	**********	(187)	

F = 2.1300 SIG. = .0520

- - - - - A N A L Y S I S   O F   V A R I A N C E - - - - -

Ce

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	1150.0000	46.0000	34.2162	28098.0000	(25)
2.	AMELIA DLMT	1255.0000	27.2826	17.7735	14215.3261	(46)
3.	TATOOLA SANDSTONE	354.0000	44.2500	24.2708	4123.5000	(8)
4.	TOOGANINIE FORM.	741.0000	29.6400	22.8890	12573.7600	(25)
5.	EMMERUGGA TEENA DLMT	399.0000	26.6000	10.9401	1675.6000	(15)
6.	BARNEY CREEK FORM.	3957.0000	70.6607	49.1063	132628.5536	(56)
7.	TUFF	1722.0000	132.4615	110.8465	147443.2308	(13)
	TOTAL	9578.0000	50.9468	51.4949	495873.4681	(188)

A N O V A   T A B L E

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	**********	(6)	25852.5829
WITHIN GROUPS	**********	(181)	1882.6407
TOTAL	**********	(187)	

F = 13.7321 SIG. = .0000

Co

ANALYSIS OF VARIANCE

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	134.0000	5.3600	5.0570	613.7600	(25)
2.	AMELIA DLMT	245.0000	5.3261	6.0039	1622.1087	(46)
3.	TATOOLA SANDSTONE	31.0000	3.8750	6.5561	300.8750	(8)
4.	TOOGANINIE FORM.	106.0000	4.2400	3.5856	308.5600	(25)
5.	EMMERUGGA TEENA DLMT	25.0000	1.6667	1.0465	15.3333	(15)
6.	BARNEY CREEK FORM.	385.0000	6.8750	8.7012	4164.1250	(56)
7.	TUFF	140.0000	10.7692	20.8772	5230.3077	(13)
	TOTAL	1066.0000	5.6702	8.3376	12999.5532	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	744.4835	(6)	124.0806
WITHIN GROUPS	12255.0697	(181)	67.7076
TOTAL	12999.5532	(187)	

F = 1.8326 SIG. = .0950

Cr

ANALYSIS OF VARIANCE

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	996.0000	39.8400	100.7103	243421.3600	(25)
2.	AMELIA DLMT	557.0000	12.1087	16.8302	12746.4565	(46)
3.	TATOOLA SANDSTONE	143.0000	17.8750	14.0554	1382.8750	(8)
4.	TOOGANINIE FORM.	301.0000	12.0400	12.5979	3808.9600	(25)
5.	EMMERUGGA TEENA DLMT	162.0000	10.8000	8.9618	1124.4000	(15)
6.	BARNEY CREEK FORM.	1564.0000	27.9286	13.9256	10665.7143	(56)
7.	TUFF	214.0000	16.4615	24.5378	7225.2308	(13)
	TOTAL	3937.0000	20.9415	40.0191	299486.3564	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	19111.3598	(6)	3185.2266
WITHIN GROUPS	**********	(181)	1549.0331
TOTAL	**********	(187)	

F = 2.0563 SIG. = .0605

Cu

- - - - - - - - - - - - - - - - - A N A L Y S I S   O F   V A R I A N C E -

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	5228.0000	209.1200	607.3885	8854098.6400	(25)
2.	AMELIA DLMT	3320.0000	72.1739	96.2128	416560.6087	(46)
3.	TATOOLA SANDSTONE	36.0000	4.5000	6.9282	336.0000	(8)
4.	TOOGANINIE FORM.	1088.0000	43.5200	61.2087	89916.2400	(25)
5.	EMMERUGGA TEENA DLMT	504.0000	33.6000	68.8972	66455.6000	(15)
6.	BARNEY CREEK FORM.	2700.0000	48.2143	108.8313	651433.4286	(56)
7.	TUFF	355.0000	27.3077	56.7353	38626.7692	(13)
	TOTAL	13231.0000	70.3777	239.4677	************	(188)

* * * * * * * * * * * * * * * * A N O V A   T A B L E * * * * * * * * * * * * * * * *

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	**********	(6)	**********
WITHIN GROUPS	**********	(181)	55897.3883
TOTAL	**********	(187)	

F = 1.8070 SIG. = .1000

La

- - - - - - - - - - - - - - - - - A N A L Y S I S   O F   V A R I A N C E -

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	489.0000	19.5600	17.8070	7610.1600	(25)
2.	AMELIA DLMT	313.0000	6.8043	10.7654	5215.2391	(46)
3.	TATOOLA SANDSTONE	137.0000	17.1250	13.9738	1366.8750	(8)
4.	TOOGANINIE FORM.	234.0000	9.3600	12.8189	3943.7600	(25)
5.	EMMERUGGA TEENA DLMT	78.0000	5.2000	8.0285	902.4000	(15)
6.	BARNEY CREEK FORM.	1858.0000	33.1786	38.2585	80504.2143	(56)
7.	TUFF	1063.0000	81.7692	76.9385	71034.3077	(13)
	TOTAL	4172.0000	22.1915	36.0627	243197.1064	(188)

* * * * * * * * * * * * * * * * A N O V A   T A B L E * * * * * * * * * * * * * * * *

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	72620.1503	(6)	12103.3584
WITHIN GROUPS	**********	(181)	942.4141
TOTAL	**********	(187)	

F = 12.8429 SIG. = .0000

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Mn

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	26131.0000	1045.2400	703.1022	************	(25)
2.	AMELIA DLMT	57511.0000	1250.2391	834.6348	************	(46)
3.	TATOOLA SANDSTONE	7037.0000	879.6250	1227.0924	************	(8)
4.	TOOGANINIE FORM.	23467.0000	938.6800	635.5019	9692705.4400	(25)
5.	EMMERUGGA TEENA DLMT	8756.0000	583.7333	338.1725	1601048.9333	(15)
6.	BARNEY CREEK FORM.	94452.0000	1686.6429	4869.0841	************	(56)
7.	TUFF	3449.0000	265.3077	299.5186	1076536.7692	(13)
	TOTAL	220803.0000	1174.4840	2739.5876	************	(188)

* * * * * * * * * * * * * * * A N O V A   T A B L E * * * * * * * * * * * * * * *

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	**********	(6)	**********
WITHIN GROUPS	**********	(181)	**********
TOTAL	**********	(187)	

F = .7362 SIG. = .6211

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Nb

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	218.0000	8.7200	5.1601	639.0400	(25)
2.	AMELIA DLMT	248.0000	5.3913	4.6115	956.9565	(46)
3.	TATOOLA SANDSTONE	68.0000	8.5000	7.1314	356.0000	(8)
4.	TOOGANINIE FORM.	135.0000	5.4000	4.6904	528.0000	(25)
5.	EMMERUGGA TEENA DLMT	107.0000	7.1333	4.3072	259.7333	(15)
6.	BARNEY CREEK FORM.	827.0000	14.7679	9.0674	4521.9821	(56)
7.	TUFF	251.0000	19.3077	6.8360	560.7692	(13)
	TOTAL	1854.0000	9.8617	7.9794	11906.4043	(188)

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	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	4083.9230	(6)	680.6538
WITHIN GROUPS	7822.4812	(181)	43.2181
TOTAL	11906.4043	(187)	

F = 15.7493 SIG. = .0000

ANALYSIS OF VARIANCE

Ni

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	917.0000	36.6800	73.2744	128859.4400	(25)
2.	AMELIA DLMT	897.0000	19.5000	9.5539	4107.5000	(46)
3.	TATOOLA SANDSTONE	156.0000	19.5000	5.6315	222.0000	(8)
4.	TOOGANINIE FORM.	493.0000	19.7200	6.1476	907.0400	(25)
5.	EMMERUGGA TEENA DLMT	241.0000	16.0667	4.9780	346.9333	(15)
6.	BARNEY CREEK FORM.	1596.0000	28.5000	23.2081	29624.0000	(56)
7.	TUFF	314.0000	24.1538	15.1319	2747.6923	(13)
	TOTAL	4614.0000	24.5426	30.5396	174408.6596	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	7594.0539	(6)	1265.6757
WITHIN GROUPS	**********	(181)	921.6277
TOTAL	**********	(187)	

F = 1.3733 SIG. = .2276

ANALYSIS OF VARIANCE

Pb

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	124.0000	4.9600	6.6425	1058.9600	(25)
2.	AMELIA DLMT	233.0000	5.0652	6.1079	1678.8043	(46)
3.	TATOOLA SANDSTONE	136.0000	17.0000	24.8251	4314.0000	(8)
4.	TOOGANINIE FORM.	323.0000	12.9200	16.0414	6175.8400	(25)
5.	EMMERUGGA TEENA DLMT	92.0000	6.1333	6.0459	511.7333	(15)
6.	BARNEY CREEK FORM.	8188.0000	146.2143	583.9243	************	(56)
7.	TUFF	123.0000	9.4615	8.7046	909.2308	(13)
	TOTAL	9219.0000	49.0372	323.1116	************	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	**********	(6)	**********
WITHIN GROUPS	**********	(181)	**********
TOTAL	**********	(187)	

F = 1.2138 SIG. = .3011

ANALYSIS OF VARIANCE

Rb

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	1838.0000	73.5200	54.7107	71838.2400	(25)
2.	AMELIA DLMT	1359.0000	29.5435	51.1671	117813.4130	(46)
3.	TATOOLA SANDSTONE	648.0000	81.0000	67.0948	31512.0000	(8)
4.	TOOGANINIE FORM.	970.0000	38.8000	67.5481	109506.0000	(25)
5.	EMMERUGGA TEENA DLMT	308.0000	20.5333	39.2025	21515.7333	(15)
6.	BARNEY CREEK FORM.	5090.0000	90.8929	49.4794	134651.3571	(56)
7.	TUFF	1645.0000	126.5385	30.8724	11437.2308	(13)
	TOTAL	11858.0000	63.0745	60.8700	692864.9574	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	**********	(6)	32431.8305
WITHIN GROUPS	**********	(181)	2752.8949
TOTAL	**********	(187)	

F = 11.7810 SIG. = .0000

ANALYSIS OF VARIANCE

Sc

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	125.0000	5.0000	3.6856	326.0000	(25)
2.	AMELIA DLMT	164.0000	3.5652	4.1721	783.3043	(46)
3.	TATOOLA SANDSTONE	25.0000	3.1250	2.6959	50.8750	(8)
4.	TOOGANINIE FORM.	88.0000	3.5200	3.5838	308.2400	(25)
5.	EMMERUGGA TEENA DLMT	40.0000	2.6667	2.1602	65.3333	(15)
6.	BARNEY CREEK FORM.	359.0000	6.4107	3.9256	847.5536	(56)
7.	TUFF	54.0000	4.1538	4.5979	233.6923	(13)
	TOTAL	855.0000	4.5479	3.9897	2976.5691	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	341.5706	(6)	56.9284
WITHIN GROUPS	2634.9986	(181)	14.5580
TOTAL	2976.5691	(187)	

F = 3.9105 SIG. = .0011

Sr

ANALYSIS OF VARIANCE

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	2133.0000	85.3200	138.5435	460663.4400	(25)
2.	AMELIA DLMT	2894.0000	62.9130	96.9327	422817.6522	(46)
3.	TATOOLA SANDSTONE	146.0000	18.2500	8.6808	527.5000	(8)
4.	TOOGANINIE FORM.	963.0000	38.5200	19.7571	9368.2400	(25)
5.	EMMERUGGA TEENA DLMT	584.0000	38.9333	16.3640	3748.9333	(15)
6.	BARNEY CREEK FORM.	1512.0000	27.0000	17.7549	17338.0000	(56)
7.	TUFF	204.0000	15.6923	11.6432	1626.7692	(13)
	TOTAL	8436.0000	44.8723	73.4238	1008126.9362	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	92036.4014	(6)	15339.4002
WITHIN GROUPS	**********	(181)	5061.2737
TOTAL	**********	(187)	

F = 3.0307 SIG. = .0076

Th

ANALYSIS OF VARIANCE

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	80.0000	3.2000	3.7639	340.0000	(25)
2.	AMELIA DLMT	151.0000	3.2826	4.4804	903.3261	(46)
3.	TATOOLA SANDSTONE	31.0000	3.8750	4.9407	170.8750	(8)
4.	TOOGANINIE FORM.	69.0000	2.7600	4.2454	432.5600	(25)
5.	EMMERUGGA TEENA DLMT	27.0000	1.8000	1.5213	32.4000	(15)
6.	BARNEY CREEK FORM.	618.0000	11.0357	9.8035	5285.9286	(56)
7.	TUFF	252.0000	19.3846	12.8357	1977.0769	(13)
	TOTAL	1228.0000	6.5319	8.6330	13936.8085	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	4794.6419	(6)	799.1070
WITHIN GROUPS	9142.1666	(181)	50.5092
TOTAL	13936.8085	(187)	

F = 15.8210 SIG. = .0000

ANALYSIS OF VARIANCE

V

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	672.0000	26.8800	34.3430	28306.6400	(25)
2.	AMELIA DLMT	699.0000	15.1957	22.2007	22179.2391	(46)
3.	TATOOLA SANDSTONE	105.0000	13.1250	9.5385	636.8750	(8)
4.	TOOGANINIE FORM.	415.0000	16.6000	12.9968	4054.0000	(25)
5.	EMMERUGGA TEENA DLMT	250.0000	16.6667	16.9565	4025.3333	(15)
6.	BARNEY CREEK FORM.	2395.0000	42.7679	35.5528	69519.9821	(56)
7.	TUFF	423.0000	32.5385	51.9898	32435.2308	(13)
	TOTAL	4959.0000	26.3777	31.6787	187662.1862	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	26504.8858	(6)	4417.4810
WITHIN GROUPS	**********	(181)	890.3718
TOTAL	**********	(187)	

F = 4.9614 SIG. = .0001

ANALYSIS OF VARIANCE

Y

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	345.0000	13.8000	6.9101	1146.0000	(25)
2.	AMELIA DLMT	389.0000	8.4565	6.9273	2159.4130	(46)
3.	TATOOLA SANDSTONE	131.0000	16.3750	8.7004	529.8750	(8)
4.	TOOGANINIE FORM.	299.0000	11.9600	6.4710	[illegible]004.9600	(25)
5.	EMMERUGGA TEENA DLMT	126.0000	8.4000	4.4529	[illegible]77.6000	(15)
6.	BARNEY CREEK FORM.	1204.0000	21.5000	11.2831	7002.0000	(56)
7.	TUFF	395.0000	30.3846	18.3146	4025.0769	(13)
	TOTAL	2889.0000	15.3670	11.4387	24467.6755	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	8322.7506	(6)	1387.1251
WITHIN GROUPS	16144.9250	(181)	89.1985
TOTAL	24467.6755	(187)	

F = 15.5510 SIG. = .0000

ANALYSIS OF VARIANCE

Zn

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	191.0000	7.6400	7.4492	1331.7600	(25)
2.	AMELIA DLMT	317.0000	6.8913	14.2083	9084.4565	(46)
3.	TATOOLA SANDSTONE	60.0000	7.5000	14.7648	1526.0000	(8)
4.	TOOGANINIE FORM.	806.0000	32.2400	130.4535	408434.5600	(25)
5.	EMMERUGGA TEENA DLMT	41.0000	2.7333	3.6736	188.9333	(15)
6.	BARNEY CREEK FORM.	13765.0000	245.8036	1189.5443	************	(56)
7.	TUFF	19.0000	1.4615	1.3914	23.2308	(13)
	TOTAL	15199.0000	80.8457	655.8310	************	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	**********	(6)	**********
WITHIN GROUPS	**********	(181)	**********
TOTAL	**********	(187)	

F = .8424 SIG. = .5387

ANALYSIS OF VARIANCE

Zr

CODE	VALUE LABEL	SUM	MEAN	STD DEV	SUM OF SQ	N
1.	MALLAPUNYAH FORM.	2553.0000	102.1200	83.0107	165378.6400	(25)
2.	AMELIA DLMT	1913.0000	41.5870	49.3358	109531.1522	(46)
3.	TATOOLA SANDSTONE	1237.0000	154.6250	83.9676	49353.8750	(8)
4.	TOOGANINIE FORM.	1239.0000	49.5600	52.2271	65464.1600	(25)
5.	EMMERUGGA TEENA DLMT	485.0000	32.3333	31.4067	13809.3333	(15)
6.	BARNEY CREEK FORM.	6642.0000	118.6071	65.7982	238117.3571	(56)
7.	TUFF	2465.0000	189.6154	75.9962	69305.0769	(13)
	TOTAL	16534.0000	87.9468	77.4135	1120663.4681	(188)

ANOVA TABLE

	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE
BETWEEN GROUPS	**********	(6)	68283.9789
WITHIN GROUPS	**********	(181)	3927.9536
TOTAL	**********	(187)	

F = 17.3841 SIG. = .0000