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Middle and Upper Cambrian Sedimentary Rocks in the Northern Part of the Northern Territory

by

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NORTHERN PART OF THE NORTHERN TERRITORY

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CONTENTS

TEXT FIGURES

2

INTRODUCTION

Carbonate rocks, siltstone, and sandstone of Middle to (?) Upper Cambrian age and post-dating an early Cambrian volcanic episode occur in three main areas in the northern part of the Northern Territory - the Daly Basin, the Wiso Basin and the Georgina Basin (Fig. 1). This report deals mainly with the petrology of Middle to (?) Upper Cambrian rocks of the Beetaloo and Helen Springs Sheet areas, in the northwest part of the Georgina Basin, mapped by the Bureau of Mineral Resources in 1965 (Brown & Randal, 1969; Randal & Brown, 1969) and of the northern part of the Wiso Basin and southern part of the Daly River Basin, mapped in 1966 (Randal & Brown, 1967). In considering the environment of deposition of these rocks a knowledge of the regional stratigraphy is essential, and reference will be made to other areas of Cambrian rocks.

Over most of the region the Middle to (?) Upper Cambrian rocks are covered by younger sedimentary rocks (Mostly Lower Cretaceous sandstone and mudstone) and superficial deposits. In most areas the Cambrian outcrops consist merely of scree and blocks of the more resistant rock types, commonly silicified or ferruginized. The best surface exposures of the Cambrian rocks in this area are in the dissected country of the northwestern half of the Daly Basin and northwest margin of the Wiso Basin.

Because of the poor exposures and the cover of younger sedimentary rocks, the lithology of the Middle Cambrian rocks over much of the area is known only from borehole cuttings and cores. The more important boreholes are shown on Figure 1. Many of the drillers' logs of water bores are difficult to interpret, but the cuttings from some bores have been examined by geologists (including the author) and some scouthole and stratigraphic drilling has been done for the Bureau of Mineral Resources and oil companies.

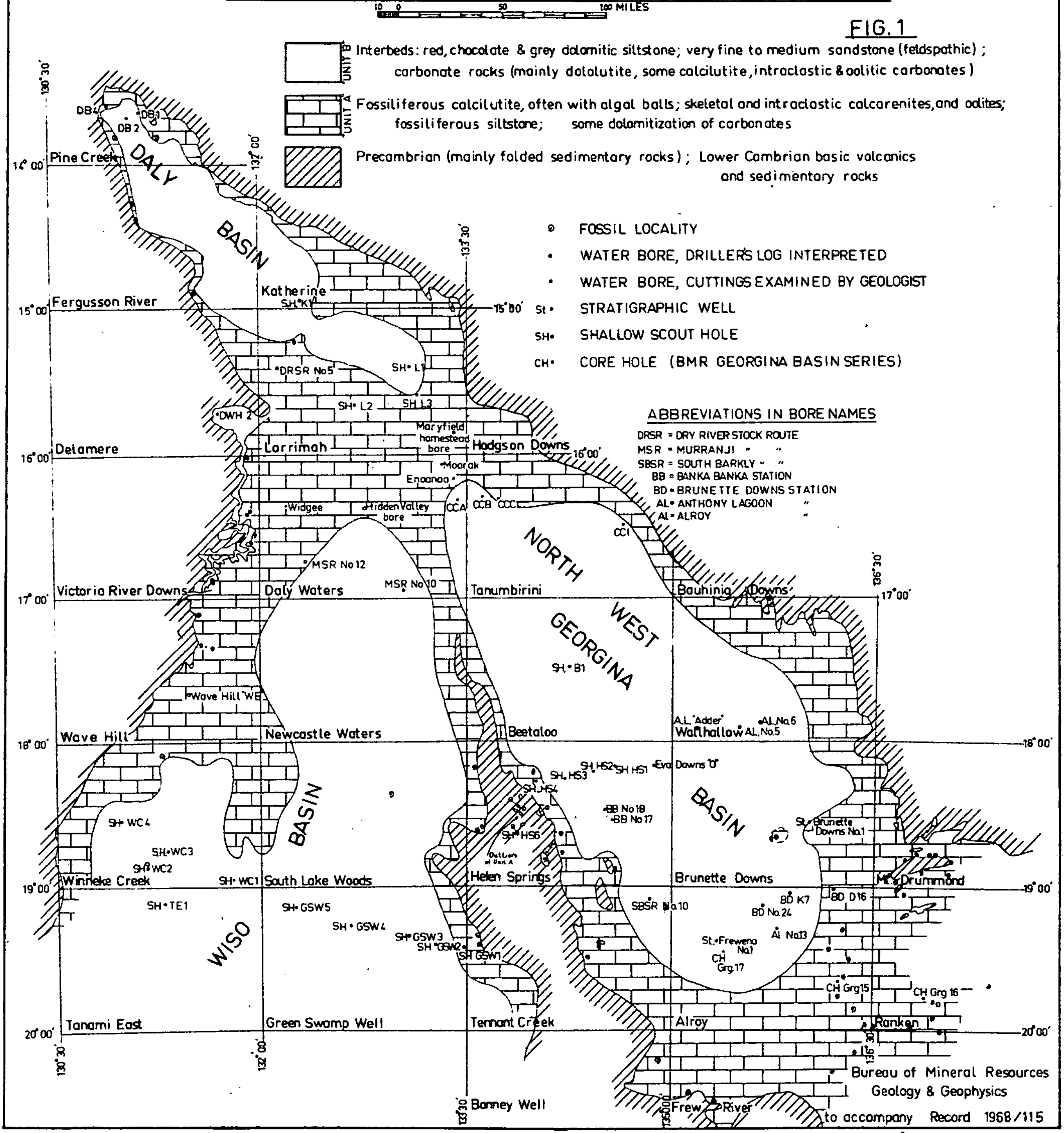
Cuttings from boreholes were examined under a binocular microscope. Samples from both bore cores and outcrops, and some cuttings have been thin-sectioned and examined under a petrographic microscope. A weakly acid solution of Alizarin Red S was used to distinguish dolomite from calcite in uncovered thin sections, cuttings, and hand specimens. Some outcrop and borehole samples have been chemically analysed by the Australian Mineral Development Laboratories; and approximate determinations of calcite, dolomite, and insoluble residue have been carried out at the B.M.R. core and cuttings laboratory on material from some of the B.M.R. scoutholes.

STRATIGRAPHY

Cambrian sedimentary rocks younger than the early Cambrian basic volcanics in the northern part of the Northern Territory can be broadly subdivided into two rock bodies which for brevity will be referred to as unit "A" and unit "B" respectively. Unit A is characterized by an abundance of shelly fossils (of early Middle Cambrian forms) and algal balls, and consists mainly of limestone with some dolomite and siltstone; in unit B shelly fossils are rare or absent and the main rock types are red, chocolate and grey dolomitic siltstone, dolomite with algal stromatolites, and fine to very fine grained feldspathic sandstone. Figure 1 shows the distribution of outcrops of these two units and their subcrop beneath the younger deposits; it also shows the contacts with the basement of Precambrian rocks and early Cambrian basic volcanics.

Unit A comprises the following formally named units: the Tindall Limestone of the Daly Basin; the Montejinni Limestone of the northern part of the Wiso Basin; the lower dolomite of the Merrina Beds of the Wiso Basin; the Gum Ridge Formation of the Tennant Creek, Bonney Well, Helen Springs, and Beetaloo 1:250,000 Sheet areas; the Top Springs Limestone of the Wallhallow and Bauhinia Downs 1:250,000 Sheet areas; the Wonarah Beds of the Alroy 1:250,000 Sheet area; the Burton Beds of the Mount Drummond 1:250,000 Sheet area; the Ranken Limestone of the Ranken 1:250,000 Sheet area; and the lower part of the Anthony Lagoon Beds of the Brunette Downs 1:250,000 Sheet area. Unit B comprises most of the Jinduckin Formation of the Daly Basin (not including the Ordovician glauconitic sandstone at the top); the upper (siltstone and sandstone) part of the Merrina Beds of the Wiso Basin; and the major part of the Anthony Lagoon Beds of the northwest Georgina Basin.

GENERALIZED MIDDLE and ?UPPER CAMBRIAN OUTCROP & SUBCROP (POST-CAMBRIAN OMITTED)
NORTHERN PART of the NORTHERN TERRITORY



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The fossiliferous unit A occurs between areas of unit B and basement rocks. There are two main ways of interpreting the three-dimensional relationships: firstly that the two units are lateral equivalents, and secondly that unit A is older and dips away from the basement areas below the areas of unit B. These two alternative hypotheses were put forward by Milligan et al.(1966) to explain the results of B.M.R. scout drilling in the Merrina Beds in the central part of the Wiso Basin. In the northwestern part of the Georgina Basin Plumb & Rhodes (1964) show the Anthony Lagoon Beds (largely unit B) interfingering with the Top Springs Limestone (unit A), on the rock relationship diagram for the Wallhallow 1:250,000 geological Sheet. In the Daly Basin the Jinduckin Formation (unit B) is shown overlying the Tindall Limestone (unit A) (Randal 1962, 1963).

Lateral equivalence of the two units implies a palaeogeography in which the present margins of the Middle Cambrian outcrops are close to the original depositional margin, with units A and B representing sedimentation near-shore and off-shore respectively. The depositional environments of the sediments, to be discussed in more detail later, do not fit such a palaeogeography. Unit A consists mainly of sediments deposited below low tide level in freely-circulating sea water, while unit B consists mostly of supratidal to intertidal sediments, and cannot be an off-shore facies of unit A. Mainly for this reason I consider it much more likely that unit A underlies unit B. There is some other, more direct, evidence. In the Daly Basin the exposures are good enough for measurement of dips, and the Tindall Limestone (unit A) clearly dips below the Jinduckin Formation (unit B); also some recent boreholes starting in the Jinduckin Formation (DB2, K1, and L1) have intersected Tindall Limestone at depth. Several bores in the northwest Georgina Basin are known to have penetrated sections with interbeds of carbonate rocks, red and chocolate siltstone, and fine-grained sandstone, passing down into more uniform carbonate rocks (Frewena No.1, CCA, CCB, South Barkly Stock Route No.10,* and several waterbores on the Brunette Downs Sheet area).

*Labelled "No.10, SBSR" on Fig.1.

The detailed sequences in the two units, and their thicknesses, are not well known. Unit A appears to be thicker in the southeast than elsewhere. The Montejinni Limestone is about 250 feet thick and the Tindall Limestone may be up to 500 feet thick. In Brunette Downs No.1 well in the southeast the section from below superficial clays to 1044 feet can be referred to unit A. This may be close to the total thickness of unit A in the area, since logs of nearby waterbores indicate that the site of the well is close to the boundary of units A and B. The maximum thickness and the nature of the upper limit of unit B is not known. Scouthole K1 (Randal & Brown, 1967) shows the relationships of the Jinduckin Formation (unit B) with the Tindall Limestone (unit A) and indicates some vertical variations in the former. The two units appear to be conformable. The bottom 300 feet of the Jinduckin Formation here consists of interbeds of red, chocolate, and grey siltstone and dolomite. The top of the Tindall Limestone is placed arbitrarily at the base of the lowest interbed of siltstone. The alternating dolomite-siltstone sequence is overlain, at the top of the hole, by about 50' of interbedded very fine to fine-grained sandstone and chocolate to red siltstone. B.M.R. scoutholes in the Wiso Basin (Milligan _et al._, 1966) indicate a similar vertical sequence in the Merrina Beds, although no one hole penetrates all parts of the sequence. In GSW4 about 350 feet of sandstone, red siltstone, and minor dolomite overlies 250 feet of siltstone with dolomite interbeds, which continues to total depth of 590 feet. In the northwest Georgina Basin the vertical sequence in unit B is not known.

The surface on which the sediments were deposited had some topographic relief, up to a few hundred feet. This is best seen in areas such as the Ashburton and Davenport Ranges where the fossiliferous Middle Cambrian sediments occur in erosional valleys between strike ridges of resistant Precambrian sandstone. Along the northwest margin of the Wiso Basin (Randal & Brown, 1967) an early limestone member of the Montejinni Limestone, about 100 feet thick, locally wedges out against a topographic high in the underlying early Cambrian volcanics; an overlying red siltstone interbed in the Montejinni continues across without evident change in thickness.

7

Excluding the above examples of buried topography, the present variations in altitude of the base of the sequence appear to be due mainly to post-depositional warping. The base of the Tindall Limestone is known to vary in altitude by at least 800 feet, and that of the Montejinni by at least 300 feet. Deposition of carbonate sediments over surfaces with the above order of relief would have produced very marked lateral facies changes, unless the sediments were all deposited in deep water below the depth of penetration of sunlight. Neither of these factors applies. The Tindall Limestone and the Montejinni Limestone appear to be remarkably uniform over large areas, and were deposited mainly in shallow water in which sunlight penetrated to the bottom. Further south and southeast there are large areas in which there is no available information on either the magnitude of the regional relief of the basement surface, or of the lithology of unit A in the structurally low areas. Stratigraphic drilling will be necessary to provide information from these areas, but there is no reason to suspect that the present relief of the basement surface existed before deposition of the Middle Cambrian sediments.

The age of unit A is reliably dated by trilobites, identified by A.A. Öpik (1956; in Plumb & Rhodes, 1964; in Milligan et al., 1966; in Randal, 1962, 1963), and C.G. Gatehouse (in Randal, Brown & Doutch, 1966; in Randal & Brown, 1967). Redlichia, Xystridura and other forms are present and indicate an early Middle Cambrian age, although the Top Springs Limestone may extend down into the uppermost Lower Cambrian. Unit B, being probably conformable with unit A, is thus at least in part of Middle Cambrian age. Some organic remains have been found in carbonate interbeds in unit B, but are either unidentifiable or not diagnostic. In the Daly Basin Lower Ordovician fossils occur in glauconitic sandstone at the top of the Jinduckin Formation and in the overlying Ooloo Limestone (Öpik, 1964; P. Jones, B.M.R. pers.comm.) and in the Wiso Basin the Hanson River Beds (limestone and sandstone) which overlie the Merrina Beds, contain Lower to Middle Ordovician fossils (Milligan et al., 1966). In both cases it is not yet known if there are important hiatuses in the sequence between the fossiliferous Middle Cambrian rocks and the Ordovician. It should however be noted that in the original mapping of the Daly Basin (Randal, 1962;

1963) unconformities were not recognized in the post-Lower Cambrian Palaeozoic sequence. It seems likely that the Jinduckin Formation below the Lower Ordovician glauconitic sandstone may include some Upper Cambrian as well as Middle Cambrian rocks. Likewise, Milligan et al. (1966) suggested that the sandy upper part of the Merrina Beds may correlate with the Upper Cambrian to Lower Ordovician Tomahawk Beds of the southern part of the Georgina Basin (Smith, 1967). In the northwest Georgina Basin the upper limit to the age of unit B is not known, except that it is overlain unconformably by fossiliferous Lower Cretaceous sediments; Ordovician sediments have not been recorded but could be present.

To summarise the stratigraphy: (A) Deposition of fossiliferous lower Middle Cambrian carbonate sediments was followed by the deposition of a largely unfossiliferous sequence of interbedded mainly red siltstone, carbonate rocks, and fine-grained sandstone; (b) The present distribution of the Middle Cambrian rocks and basement outcrops is due largely to post-depositional warping, followed by the preferential erosion of structural highs; (c) Following from (b), and the lack of evidence of facies changes related to structure, it can be inferred that the present outcrop and subcrop margins are not limits of Middle Cambrian deposition, and sedimentation during the Middle Cambrian extended well beyond the present margins.

DESCRIPTIONS OF ROCK TYPES

Introduction

The carbonate rocks in the region have been affected by a variable degree of diagenesis since their deposition, but in most cases the nature of the original sediment can be inferred and the rocks can be described and classified according to their depositional texture. Terms which will be used frequently in descriptions are defined below. References to authors will be given for other terms except where they are well known and their meaning is not ambiguous.

Aphanatic limestone (or dolomite): limestone (or dolomite) composed of microcrystalline to cryptocrystalline carbonate crystals.

9

Calcilutite (or dololutite): limestone (or dolomite) deposited originally as a carbonate mud.

Grains: original sedimentary particles; generally refers to sand size and coarser particles.

Calcarenite (dolarenite): limestone (or dolomite) deposited as dominantly sand size carbonate grains.

Skeletal limestone: limestone, deposited mainly as an accumulation of calcareous organic skeletons or fragments of skeletons.

Stromatolitic limestone (or dolomite): limestone (or dolomite), originally deposited as sediment trapped in algal mats, characterized by wavy and sometimes impersistent laminations.

Intraclast: sedimentary particle formed by breaking-up and transport of previously deposited carbonate sediment (a narrower meaning than that in Folk, 1959).

Pellet: rounded sand-size grain composed of aphanitic carbonate, and having various possible modes of origin; may include rounded intraclasts, fecal grains, and skeletal grains or ooliths converted to aphanitic carbonate by algal boring (Bathurst, 1964). This is a broader definition than that in Folk, 1959.

Composite grain: sedimentary particle formed by aggregation of smaller grains such as pellets, ooliths, or intraclasts.

Spar: clear crystalline calcite (called "dolomite spar" if dolomite), usually a cement or cavity fill.

Microspar: microcrystalline calcite (crystals generally of silt size), often formed by recrystallization of finer carbonate, but sometimes a cavity fill.

Recrystallization: change in size of crystals in a carbonate rock or sediment (usually coarsening) without major change in bulk chemistry, usually tending to obscure depositional textures.

Crystalline limestone (or dolomite): limestone (or dolomite) in which recrystallization has obliterated depositional textures.

Dedolomite: limestone formed by replacement of a dolomite rock by calcite.

Fossiliferous calcilutites:

Fossiliferous calcilutites, and their silicified or dolomitized equivalents, are characteristic of unit A, but some interbeds are known in unit B, as near bore WC2 in the Wiso Basin (Milligan et al., 1966). They consist of shells and shell fragments, often with algal balls, in a matrix of unlaminated calcilutite. The shells include molluscs (mainly Biconulites sp. and other hyolithids), echinoderm ossicles, trilobites, and phosphatic brachiopods. They are often broken but usually not abraded. The algal balls (usually recorded as Girvanella in the field) are usually about one inch in diameter, but sometimes larger. A concentric laminated structure is evident on weathered surfaces; some algal filaments can be identified in thin section, but the fine structure is often obscured by recrystallization. Algal balls have commonly formed around a shell (often a hyolithid or gastropod) as nucleus; large algal balls with a gastropod as nucleus are common in silicified limestone of the Gum Ridge Formation.

The lack of lamination in the calcilutite matrix appears to be due to reworking of the original lime mud sediment by animals.

Traces of burrows are common on weathered surfaces and can also be seen in thin sections as tubular cavities, with fills of internal sediment or clear crystalline calcite.

The fossiliferous calcilutites are often partly recrystallized, dolomitized, or silicified. A common rock type (especially in the upper unit of Montejinni Limestone and Tindall Limestone) is a mottled limestone consisting of a grey calcilutite with patches about 1 inch across of yellowish to reddish partly recrystallized limestone with scattered dolomite rhombs. The grey calcilutite is usually cryptocrystalline ("micrite" of Folk, 1959) and has sharp boundaries with shells, while the paler patches are a cloudy microspar in which outlines of shells are not well defined. The lower part of the lower unit of the Montejinni Limestone, which was apparently originally a lime mud sediment with fairly rare shell remains, is in some areas almost entirely recrystallized to a microspar with variable grain size.

Fossiliferous dolomite, probably dolomitized fossiliferous calcilutite, occurs in the basal part of the Merrina Beds in Scouthole GSW1 and in an interbed in Merrina Beds siltstone near Scouthole WC2 (Milligan et al., 1966).

Silicified fossiliferous calcilutite is common in outcrops of the Gum Ridge Formation. Fossils in the Montejinni Limestone are commonly preferentially silicified, and the limestone typically contains chert nodules formed by replacement.

The fossiliferous calcilutites must have been deposited in sea water of normal or near-normal salinity containing a good supply of nutrients, in order to support the abundant and varied fauna of marine invertebrates. The common presence of algal balls indicates that sunlight penetrated to the bottom, permitting algal growth, and that the water was mildly agitated so that the algal growths were rolled about to form their concentric layering and spherical shape. The presence of abundant lime mud and the lack of abrasion of shells and shell fragments implies that the bottom water was not strongly agitated. According to Logan et al. (1964) algal balls (oncolites) form below low tide level; this is consistent with the other characteristics of the sediment.

Deposition of near-pure carbonate sediments implies warm water and a lack of influx of terrigenous material. The lime mud was deposited in an environment favourable to organisms and was very probably precipitated as a result of photosynthesis by algae in water saturated or near-saturated with calcium carbonate.

Skeletal Limestones

Skeletal limestones (usually referred to as coquinites by field geologists) are fairly common in the Tindall Limestone; and also in the Burton Beds, the Wonarah Beds, and the Gum Ridge Formation, where they occur as fragments of silicified limestone in surface scree. The skeletal remains are of marine invertebrates (usually molluscs, trilobites, echinoderms, and brachiopods) and they are usually somewhat fragmented and abraded.

A thin section from Tindall Limestone in BMR Scouthole L1 (66670725)* shows close packed broken and worn skeletal grains, together with some pellets and some microspar matrix (probably originally carbonate mud). Original pore spaces are filled with a clear calcite spar cement. In the terminology of Folk (1962) this rock would be a poorly washed biosparite.

The depositional environment of these limestones is similar to that of the fossiliferous calcilutites, except that the water has been agitated enough to move and abrade shell fragments and winnow out lime mud. They may have been deposited on shallow shoals subject to more intensive wave and current agitation than the more common fossiliferous calcilutites.

Fossiliferous siltstone

Siliceous siltstone with well preserved fossils, usually trilobites, is common as scree in outcrops of the Gum Ridge Formation, the Wonarah Beds, and the Burton Beds. This surface material appears to have resulted from leaching and silicification of calcareous siltstone and silty calcilutite. In BMR Scouthole HS6, the surface scree of siliceous siltstone (and silicified limestone) was underlain by about 70 feet of completely kaolinized siltstone resting on underlying Lower Cambrian sandstone. Similar strongly weathered material was found beneath surface scree of siliceous siltstone in BMR Corehole GRG 15, (Milligan, 1963). Cuttings from a nearby waterbore are of grey calcareous siltstone and silty limestone, apparently the original unweathered rock.

The marine fauna again suggests that these siltstones were deposited in sea water of normal salinity, and their fine grainsize suggests weak current and wave action. Conditions were less favourable to precipitation of carbonate than the fossiliferous calcilutites; they

*BMR Registered Number of thin section.

were probably deposited in deeper water, less favourable for algal precipitation of carbonates.

Intraclast and pellet limestones and dolomites

Limestones and dolomites deposited as accumulations of intraclasts or pellets are present in both of units A and B. They make up the upper part of the lower unit of the Montejinni Limestone, and have been recorded from the Anthony Lagoon Beds in outcrop samples from near Eva Downs "D" bore, in limestone interbedded with buff and red siltstone between 90 feet and 130 feet in Scouthole HS2 and in limestone at a depth of 250 feet in Scouthole B1.

The upper part of the lower unit of the Montejinni Limestone consists of well-bedded intraclast limestone with some interbeds of calcilutite and disrupted calcilutite. At Mount Wallaston the traces of small scale cross-lamination and ripple bedding can be seen on weathered vertical surfaces. Thin sections of the less recrystallized rocks (6667510la, 66675116) show that they are composed of intraclasts of microcrystalline carbonate with a variable amount of rounding, together with some ooliths and probable shell fragments, set in a clear calcite spar cement. In parts of some thin sections (6667510a) the intraclasts are recrystallized to a microspar, and their boundaries with original cement are not sharp. Specimens from the same unit in outcrops north and northwest of Top Springs and in BMR Scouthole L1 are recrystallized and partially dolomitized, and little remains of the depositional texture.

These rocks were probably deposited in an environment in which lime mud was being precipitated, but in which currents or wave action were strong enough to break up previously deposited mud into fragments and to abrade and sort them into a carbonate sand sediment. The fauna seems to have been restricted in abundance, probably owing to a poor supply of nutrients or to increased salinity.

The petrography of intraclast limestone from the Anthony Lagoon Beds near Eva Downs "D" bore (6567 H17A) is similar to that from the Montejinni Limestone; and a rock from between "L" and "M" bores, Eva Downs Station, (6567 H57) shows similar textures but is a dolomite.

The limestone from Scouthole B1 consists of rounded grains, mainly of very fine sand size, set in a microspar cement. About one-third of the grains consist either of spar, or spar with a rim of cryptocrystalline calcite. The origin of these is not clear, and they could be abraded skeletal fragments, fragments of crystalline limestone, or recrystallized pellets. The other grains are rounded pellets of cryptocrystalline calcite. Dolomite overlying the limestone has similar textures and was probably formed by dolomitization of pellet limestone. Because pellets can form in several ways the environment of deposition of this rock is uncertain.

Some of the intraclast limestones from BMR Scouthole HS2 contain large amounts of terrigenous sand. One specimen has some unusual features: it consists of intraclasts, ooliths, and terrigenous grains in a matrix of aphanitic limestone (micrite), presumably originally a carbonate mud. The intraclasts include worn fragments of calcilutite and silty calcilutite, and some composite grains of spar-cemented intraclasts and ooliths. The intraclasts appear to have been well-cemented before incorporation in the sediment, and may have been derived from a previously-consolidated carbonate rock (perhaps a beach rock).

Oolites

Rocks deposited as accumulations of ooliths seem to be fairly uncommon. A recrystallized sandy oolite was collected from the lower unit of the Montejinni Limestone at Fraynes Knob near its northern outcrop limit where it wedges out against a low rise in the basal unconformity surface; and a cobble of silicified oolite was collected from scree mapped as Anthony Lagoon Beds about 3 miles east of Helen Springs No.2 bore. Oolite and silicified oolite has also been recorded from the Wonarah Beds and Burton Beds (Randal and Brown, 1962a).

The oolite from Fraynes Knob (66673230a) is now coarsely recrystallized, but the outlines of original oolites, and their concentric structure, is shown by concentric narrow zones of impurities, sometimes around a terrigenous sand grain (commonly quartz or basalt) as nucleus.

The silicified oolite from the Anthony Lagoon Beds(6567H333) has its depositional textures preserved. The original sediment grains were ooliths and intraclasts, now replaced by microcrystalline silica. They are now enclosed in brownish fibrous chalcedony which preferentially weathers out on exposed surfaces. The ooliths (about 0.4 mm diameter) commonly have a quartz grain or an intraclast as a nucleus.

By analogy with modern oolitic sands, these oolites were probably deposited from shallow water, possibly in part intertidal, subject to strong tidal currents or wave agitation. Compared with the fossiliferous limestones, the fauna was restricted in abundance.

Stromatolitic limestone and dolomite

Stromatolitic limestones and dolomites are commonly found in outcrops; they are not easily recognizable in bore cuttings or cores since the identification of the laminae as algal laminae often depends upon the larger scale features of the rock.

The most common type of algal layering seems to be the laterally-linked hemispheroidal type (type LLH of Logan et al., 1964); on surfaces parallel to bedding the laminae are seen to be arched up into domes, and in cross section the laminae are wavy but generally continuous between domes. Laminae of this type are produced, in modern areas of carbonate sedimentation, by the binding of carbonate mud by blue-green algae.

Limestone with type LLH stromatolites has been found in the Montejinni Limestone in two thin but laterally persistent beds, separated by an interbed of red and buff dolomitic siltstone. These stromatolites are common in carbonate rocks (mainly dolomite) interbedded with red and grey dolomitic siltstone in the Jinduckin Formation. According to Logan et al., (1964) this type of algal layering occurs in marine intertidal areas sheltered from wave attack, and also in shallow impermanent saline lakes.

Gypsiferous carbonates

Gypsum, and solution cavities probably after gypsum, occur in carbonate rocks of unit B in dolomite of the Merrina Beds (Milligan et al., op. cit.), and the Anthony Lagoon Beds (in BMR Scouthole HS1).

Drillers' logs of some waterbores in the Anthony Lagoon Beds record gypsum (Randal, 1967) and it has also been found in Frewena No.1 bore in several intervals between 360 feet and 750 feet. A specimen of laminated calcilutite from near Warloch Ponds north of Larrimah, mapped as Tindall Limestone, (66672002) contains two layers with prismatic and rhomb shape patches of calcite and dolomite microspar which appear to be replacements of original gypsum crystals.

The presence of gypsum in the carbonate sediments of unit B indicates raised salinity during their deposition. Precipitation of gypsum during deposition would have raised the ratio of magnesium to calcium in the water, probably causing dolomitization of calcium carbonate sediments. The reverse reaction, between dolomite and groundwater solutions rich in Ca^{++} and SO_4^{--} ions, causes replacement of dolomite by calcite; it may have been responsible for the examples of dedolomitization which have been observed in carbonates of unit A, and also for some anomalously high $Mg^{++}: Ca^{++}$ ratios in sulphate-bearing groundwater of the Barkly Tableland noted by Randal (1967).

Crystalline limestones and dolomites, and silicified limestones

In some limestones, particularly the lower unit of the Montejinni Limestone, in the area north and west of Top Springs and in Scouthole L1, recrystallization has been extensive enough to obscure or obliterate the depositional textures. The lower part of this unit, probably originally a calcilutite, is now a microcrystalline limestone. Small lenses and ellipsoids with coarser calcite crystals and a lower content of terrigenous silt and clay are elongated parallel to the bedding. They are darker in tone than the remainder of the rock and give it a mottled appearance. The upper part of the lower unit of the Montejinni, at many localities, consists of a coarse mosaic of calcite crystals up to 1 cm. across, enclosing dolomite crystals or dolomitized intraclasts. Original dolomite rhombs in these rocks are often partially, and sometimes completely, replaced by calcite - a process of dedolomitization. The reason for the recrystallization of the lower unit of the Montejinni in this area is not very clear. The upper limestone unit, as described previously, has small patches only of weak recrystallization.

Crystalline dolomite, showing few or no traces of depositional textures, is common in the Merrina Beds, in some outcrops of the Montejinni Limestone, in the upper part of the Tindall Limestone in some areas, in carbonate interbeds in the Jinduckin Formation (Manbulloo Limestone Member), and in carbonate interbeds in the Anthony Lagoon beds. Most thin sections of limestone have a few euhedral dolomite rhombs replacing the original fabric. Dolomitization of carbonate interbeds in unit B is probably for the most part early diagenetic and is due to the reaction of calcium carbonate sediments with Mg-rich solutions produced by evaporation of sea water with precipitation of gypsum. Details of this type of dolomitization in modern areas of carbonate sedimentation are discussed by contributors in Pray & Murray (1965). The patchy dolomitization of normal marine limestones such as the bulk of the Tindall Limestone, and the upper part of the Montejinni Limestone, may be late diagenetic and produced beneath a considerable cover of younger sediments by reaction of limestone with Mg rich saline groundwater.

Silicification in places destroys depositional fabrics. Quartz rock consisting of a mosaic of crystalline and microcrystalline quartz, with some relic patches of crystalline limestone or leached-out cavities, commonly occurs at the top of the lower unit of the Montejinni Limestone below the red and buff siltstone interbed.

Dolomitic siltstone and claystone

Dolomitic siltstone and minor claystone, dominantly chocolate-brown and red, but also buff and grey-green, is characteristic of unit B. It occurs interbedded with dolomite and limestone or fine-grained sandstone in the Jinduckin Formation, Anthony Lagoon Beds, and the Merrina Beds above the basal dolomite. It also occurs as an interbed about 40 feet thick in the Montejinni Limestone (Randal & Brown, 1967), and a small thickness of red siltstone has been found at the base of the Gum Ridge Formation near Helen Springs homestead.

The rocks show thin laminations with variable proportions of clay and silt, but the laminations in many specimens are broken and disoriented, and some outcrops have a massive unbedded appearance. Halite pseudomorphs occur in siltstone in the Jinduckin Formation

(Randal, 1962; 1963). In the red and chocolate brown rocks the pigmentation is mainly in the clay fraction, and laminae and lenses of well-sorted coarse siltstone are usually white to buff. The silt-size terrigenous grains are mainly quartz (and chert), muscovite,microcline, biotite, and chlorite, with the usual accessories such as tourmaline* Some sodic plagioclase may also be present. The clay fraction of three samples has been semi-quantitatively determined by E.C. Stock of Australian Mineral Development Laboratories, with the following results:

(a) Smectite sub-dominant (20%-50%) illite sub-dominant, kaolin accessory (<20%), chlorite trace (< 10%).

(b) Illite dominant (<50%), random mixed layer smectite-chlorite subdominant, chlorite accessory.

(c) Illite subdominant, regular mixed-layer smectite-chlorite subdominant.

Results (a) and (b) were from red siltstones, (a) from about 200 feet in Scouthole B1 and (b) from 17 feet in Scouthole K1; (c) was from a grey siltstone from 102 feet in Scouthole K1.

Dolomite occurs as silt-size grains, generally the same size as quartz and feldspar grains in the same sedimentary laminae. These grains are frequently euhedral rhombs, but rhombs with rounded corners are common, and rounded grains with a post-depositional overgrowth rim occur. They seem to be detrital, like the silt-size silicate grains. Calcite occurs in places as a cement in well-sorted siltstone and also as a fracture filling.

The environment of deposition of these rocks needs some discussion. The occasional presence of halite pseudomorphs and their association with stromatolitic carbonates suggests an intertidal to supratidal marine or perhaps an intermittent saline lake environment. Breaking-up of clayey laminae may be due to dessication of the sediment during exposure; and the lack of fossils suggests rigorous conditions.

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*Silt size terrigenous grains, mainly quartz, are present in variable amounts in the carbonate rocks described above. They have not been mentioned in the descriptions to avoid undue repetition.

The reason for the vertical alternations of carbonate rocks with siltstone is not clear, but there are some grounds for concluding that the siltstones are essentially subaerial sediments, only occasionally covered by water, whereas the interbedded carbonate sediments were frequently covered by water. The Montejinni Limestone shows a vertical sequence (from the base up) of shallow water but subtidal carbonate sediments, intertidal stromatolitic carbonates, red and buff dolomitic siltstone, intertidal stromatolitic carbonates, and shallow water normal marine carbonates. A supratidal to subaerial environment for the red and buff siltstone would explain the vertical changes simply as a regression and subsequent transgression. The common red pigmentation in the siltstones, under such an environment, would have resulted from their oxidation during exposure, as well as a lack of organic material.

The sediment grains in the siltstone, including the dolomite grains, are of sizes which could have been carried as wind-blown dust. Considerations of the regional palaeogeography, to be discussed later, suggest that this may have been the dominant mode of transport, since the climate was probably semi-arid, relief was low, and possible sources of terrigenous sediment were at least many hundreds of miles distant.

Sandstones

Sandstones occur interbedded with chocolate-brown, red, and buff siltstones in the Jinduckin Formation, Anthony Lagoon Beds, and the upper part of the Merrina Beds. They have also been recorded in the Gum Ridge Formation. They are often weakly cemented, porous and friable, but sometimes cemented by overgrowths. They are generally flat laminated and flaggy with primary current lineations on bedding surfaces, or have bedding surfaces with oscillation ripples. Milligan et al.(1966), illustrate a sandstone from the Merrina Beds with small scale cross lamination, probably formed by migration of asymmetrical ripples during sedimentation. Randal (1962, 1963) records halite pseudomorphs in sandstone of the Jinduckin Formation.

In thin section the sandstones are seen to be well sorted. The grain size in different specimens varies from very fine to medium sand. The sand grains are mainly quartz with some chert, but feldspar (mainly microline) muscovite, biotite, and tourmaline, are also important. Clasts of partly dolomitized calcilutite are abundant in sandstone from BMR Scouthole HS2, interbedded with calcilutite and 20 sandy calcarenite. Some surface exposures of sandstone have abundant small equidimensional cavities, apparently weathered-out carbonate clasts.

The environment of most of these sandstones seems to be intertidal. Flat laminations and primary current lineation form in fast-flowing shallow water, and these hydrodynamic conditions can occur on beaches, intertidal sand flats, and shallow streams and flood plains. Shallow stream and flood plain environments are considered unlikely to be important; halite pseudomorphs suggest that tidal flats and beaches are the more likely environments.

The provenance of the terrigenous sand and its mode of transport to the depositional site is not known, especially for unit B. The regional palaeogeography suggests that sources to the south-west, possibly the Archaean shield areas, are the most likely. The sand has probably been transported by longshore drift and perhaps by tidal currents, but some transport by wind and by rain water runoff would also have occurred during periods of exposure. The minor occurrences of sandstone in the Gum Ridge Formation are probably from local sources such as outcrops of Precambrian and Lower Cambrian sandstone not covered during early stages of the Middle Cambrian transgression.

CORRELATIONS, REGIONAL PALAEOGEOGRAPHY AND PALAEOENVIRONMENTS

Palaeontological studies of the Cambrian rocks have provided a sound basis for regional correlations, which are necessary for an interpretation of the regional palaeogeography and the regional palaeoenvironments of sedimentation.

The Middle to (?) Upper Cambrian rocks of the area covered by Figure 1 are continuous with Cambrian rocks to the southeast, the stratigraphy of which has been summarised by Smith (1967). The unit A of this report is the same age as several named units to the southeast (Border Waterhole Formation, Beetle Creek Formation, Thorntonia Limestone, "Yelvertoft Beds"), as well as unnamed units encountered in boreholes. The rock types in these units are dark calcareous siltstones, bedded dark limestone and minor dolomite (sometimes with Girvanella), bedded cherts and siliceous shales rich in organic matter,

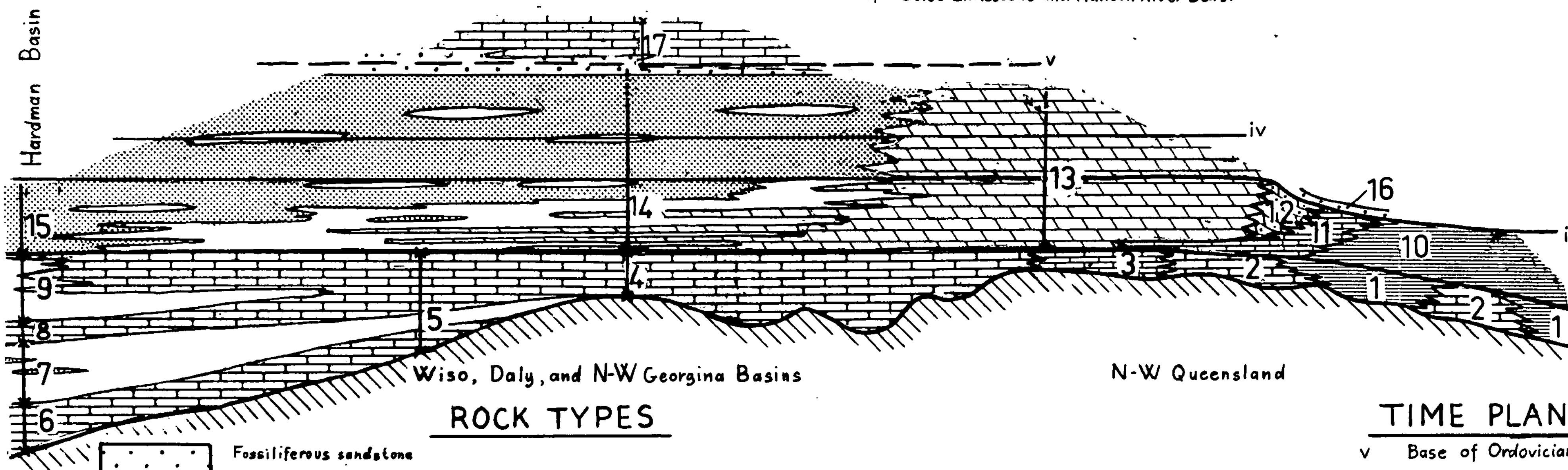
21

SCHEMATIC SECTION OF MIDDLE CAMBRIAN ROCKS, EAST KIMBERLEYS TO N-W QUEENSLAND (POST MIDDLE CAMBRIAN WARPING REMOVED)

FIG. 2

NAMED MAP UNITS

1 Beetle Creek Formation
2 Thorntonia Limestone
3 Border Waterhole Formation
4 Ranken Limestone; Burton, Wonarah, and lower Merrina Beds; Gum Ridge Formation; Top Springs and Tindall Limestones (Unit A)
5 Montejinni Limestone (Unit A)
6 Headleys Limestone
7 Nelson Shale
8 Linnekar Limestone
9 Panton Formation
10 Inca Formation
11 Currant Bush, V-Creek, and Mail Change Limestones
12 Age Creek Formation
13 Camooweal Dolomite
14 Jinduckin Formation, upper parts of Merrina Beds and Anthony Lagoon Beds (Unit B)
15 Hudson Formation
16 Split Rock Sandstone
17 Ooloo Limestone and Hanson River Beds.



ROCK TYPES

- Fossiliferous sandstone
- Red + buff dolomitic sandstone, mainly fine grained, with ripples or flat laminations and parting lineation; some halite casts
- Red + brown (minor buff + grey) dolomitic siltstone, some fine sandstone + silty dolomite; halite casts
- Dololutite, sometimes with stromatolites; some intraclast and oolitic doloarenite, some dolomitic sandstone and siltstone; some gypsum casts
- Fossiliferous calcilutite, commonly with algal balls; some skeletal + intraclast doloarenite + oolite, fossiliferous siltstone; sometimes dolomitized
- Sandy intraclast doloarenite and limestone, with very large scale cross beds
- Fossiliferous thin-bedded dark limestone, siltstone, chert
- Fossiliferous siltstone, thin bedded dark limestone, bedded chert, phosphorite.

TIME PLANES

v Base of Ordovician
iv Top of Middle Cambrian
iii Top of Ptychagnostus punctuosus zone
ii Top of Xystridura templetonensis zone
i Basal unconformity (diachronous)

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to accompany Record 1968/115

AUST/244

and phosphate rocks. They contain a rich and varied fauna of marine invertebrates, indicating a well-circulated marine environment. The trilobite species, according to Öpik (1956) are different from those of the same age in areas covered by this report; and outcrops in the two areas are separated by a northsouth trending belt of unfossiliferous dolomite (the Camooweal Dolomite). Öpik (1956) concluded that the dolomite was older than the fossiliferous rocks, and formed a physical barrier (the "meridional divide") between two faunal provinces. Field evidence collected by Randal & Brown (1962b), and borehole evidence (summarized in Smith, 1967) has shown that the dolomite is not older than the fossiliferous rocks and hence could not have formed a topographic ridge between the two provinces. It seems more likely that the differences in the faunas are controlled by environment: in the northwestern areas the water was probably warmer, shallower and slightly more saline.

Middle Cambrian units conformably overlying the lateral equivalents of unit A in the southeastern part of the Georgina Basin (and hence equivalent in part to unit B) include the Age Creek Formation, Currant Bush Limestone, V-Creek Limestone, Mail Change Limestone, Split Rock Sandstone, and probably most of the Camooweal Dolomite. Randal & Brown (1962b) have shown that the unfossiliferous Camooweal Dolomite is in part laterally equivalent to the other units, which contain Middle Cambrian fossils younger than the Xystridura and Redlichia faunas. The Camooweal Dolomite passes eastward into the Age Creek Formation, which in turn passes to the south and east into the limestone units and then into a shaly unit, the Inca Formation. The petrology of the Camooweal Dolomite is discussed by Brown (1962) and Nichols (1966). It consists of pelletal and microcrystalline dolomite with a variable content of terrigenous sand; it is in places cross laminated, and in places contains algal stromatolites. Nichols (op. cit.) concludes that it was deposited under very shallow water and that dolomitization probably occurred during periods of exposure, a similar environment to that postulated for unit B above. The other units have a varied marine fauna and appear to be open water marine sediments. Depth of water appears to have increased eastward, giving a lateral change from predominantly coarse pelletal and sandy dolomite with large cross beds (Age Creek Formation) to finer grained bituminous calcarenite and calcilutites (Currant Bush, V-Creek, and Mail Change Limestone) to bituminous siliceous and calcareous shales (Inca Formation).

To the west of the area of Figure 1, on the N.T.-W.A. border, the Hardman, Argyle, and Rosewood Basins contain a thick sequence of Cambrian sediments (the Negri Group) overlying the Lower Cambrian volcanics. The Hardman Basin sequence, as described by Traves (1955) and Dow (in prep.) contains rock types similar to those of the Daly, Wiso, and Northwest Georgina Basins, and some correlations, based on trilobite faunas, can be made. The first 1300 feet which comprises the Headleys Limestone, Nelson Shale, Linnekar Limestone, and Panton Formation of Dow (in prep.) can be correlated with unit A; it consists mostly of unfossiliferous red, brown, and grey shale and siltstone (sometimes with gypsum). Three intervals of limestone and grey fossiliferous shale with thickness totalling about 350 feet, are present; and they are apparently similar in lithology and depositional environment to the limestones and fossiliferous siltstones of unit A. The 150-foot thick basal limestone is apparently identical with the basal unit of the Montejinni Limestone; the second interval is a limestone with <u>Redlichia</u> and <u>Girvanella</u>, and the uppermost consists of fossiliferous limestone and shale with <u>Redlichia</u> and <u>Xystridura</u>.

Dow (in prep.) reports that the units of the Negri Group discussed above are thinner in the east than the west; and limestone makes up a greater proportion of the section in the east.

Overlying the Panton Formation is the Hudson Formation, a unit about 500 feet thick consisting of interbeds of red, brown, and minor green fine to medium grained flaggy sandstone, and red and green siltstone and shale. It contains a thin interbed of limestone with <u>Biconulites</u> but is otherwise unfossiliferous. The unit is overlain (unconformably according to Dow, in prep.) by the Elder Sandstone, a unit formerly regarded as Cambrian but now regarded by Dow as Upper Devonian. The Hudson Formation, being conformable with the underlying early Middle Cambrian rocks, is of Middle Cambrian age (at least in part); and probably can be correlated with unit B of this report.

Figure 2 is a diagrammatic cross section from the East Kimberleys to the Camooweal area showing the relationships between various rock types in the Middle Cambrian. Figures 3 and 4 are attempts to show in plan for the Australian continent the distribution of rock types in the early Middle Cambrian and the remainder of the Middle Cambrian respectively; using information from the Cambrian areas of the Amadeus Basin (Wells et al., 1967), the Flinders Ranges (Daily, 1957), Victoria (Thomas & Singleton, 1957), and Tasmania (Banks, 1962). The position of the Cambrian palaeoequator is after Irving (1964).

Both Figs 3 and 4 show trends of facies belts varying from meridional to a north-northwesterly; open water marine sediments are more abundant in the east, and supratidal to intertidal or saline lake sediments are more abundant in the west. Middle Cambrian volcanic rocks occur associated with marine sediments in Victoria (basic volcanics) and Tasmania (acid and basic volcanics).

During the early Middle Cambrian, marine transgressions covered at least the eastern two-thirds of the continent at their maximum extent. In the east Kimberleys and the northern Wiso Basin, there is evidence for regressions with deposition of intertidal to subaerial sediments between periods of maximum transgression. The sediments deposited in the Northern Territory during periods of maximum transgression are often remarkably uniform in lithology and fauna over large areas; this applies particularly to the later phases of transgression (e.g. the upper unit of the Montejinni Limestone), after early phases of deposition had levelled off pre-existing topography. The basal limestone unit of the Montejinni limestone, and the Headleys Limestone at the base of the Negri Group contains few fossils, and may have been deposited from water of somewhat raised salinity or a restricted supply of nutrients, possibly due to some restrictions of the circulation produced by low hills and ridges on the surface transgressed by the sea. Later units have a rich and varied fauna which includes forms such as echinoderms which, at present, have a low tolerance for variations in salinity from that of normal sea water. This implies a lack of barriers to circulation. Towards the Queensland border and farther eastward, water depth during the early Middle

Cambrian probably increased, so that the environment became less favourable for carbonate precipitation, the supply of terrigenous material was limited by the great distance to possible sources to the west, and hence conditions were favourable for the accumulation of sediments rich in phosphate, organic matter, and silica.

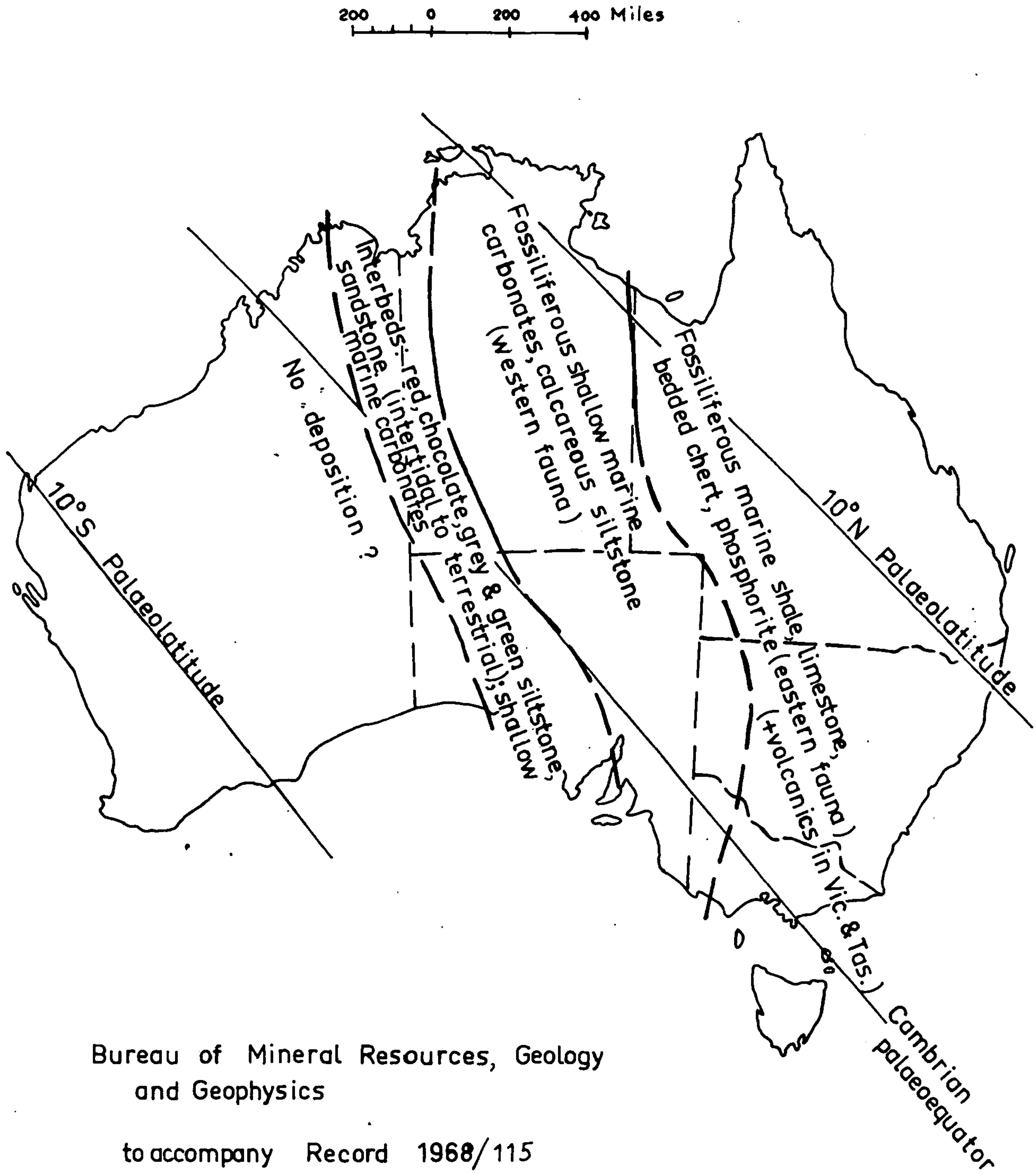
The western limit of marine transgression during the early Middle Cambrian is not known, except probably for the Amadeus Basin where Wells et al. (1967) show a western limit about 150 miles east of the Western Australia-Northern Territory border.

In the Middle Cambrian after the time of Xystridura the sea regressed from most of the northern part of the Northern Territory; normal marine sediments are known only from the southern and eastern parts of the Georgina Basin. Sediments in areas further west were deposited for the most part on an extensive, nearly flat surface close to mean sea level. Immediately west of the area of normal marine sedimentation carbonate sediments (the Camooweal Dolomite) were deposited on intertidal mud flats, in saline lagoons connected with the sea and possibly in shallow impermanent saline lakes not connected with the sea. Early diagenetic dolomitization occurred during periods of exposure. Further west deposition of terrigenous material was more important; silts and clays were deposited on surfaces probably exposed to the air for most of the time, and fine sands were deposited on shorelines of salt lakes or lagoons and possibly in part from streams and sheet floods.

The most likely source of the terrigenous material is the Precambrian shield area of Western Australia which, during deposition of the Middle Cambrian sediments, was probably exposed well to the west of the present preserved areas of Middle Cambrian sediments. Soon after the first phase of marine transgression in the Middle Cambrian, local sources of terrigenous sediments such as the sandstone strike ridges of the Ashburton Range became covered by carbonate sediments. With the regression at the close of Xystridura time, terrigenous sediments spread eastward across a near-flat surface underlain largely by carbonate sediments. The silts and clays spread most widely at first - terrigenous sands seem to have entered the stratigraphic section later in the east than the west.

DISTRIBUTION OF ROCK TYPES AND DEPOSITIONAL ENVIRONMENTS (EARLY MIDDLE CAMBRIAN)

FIG. 3



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to accompany Record 1968/115

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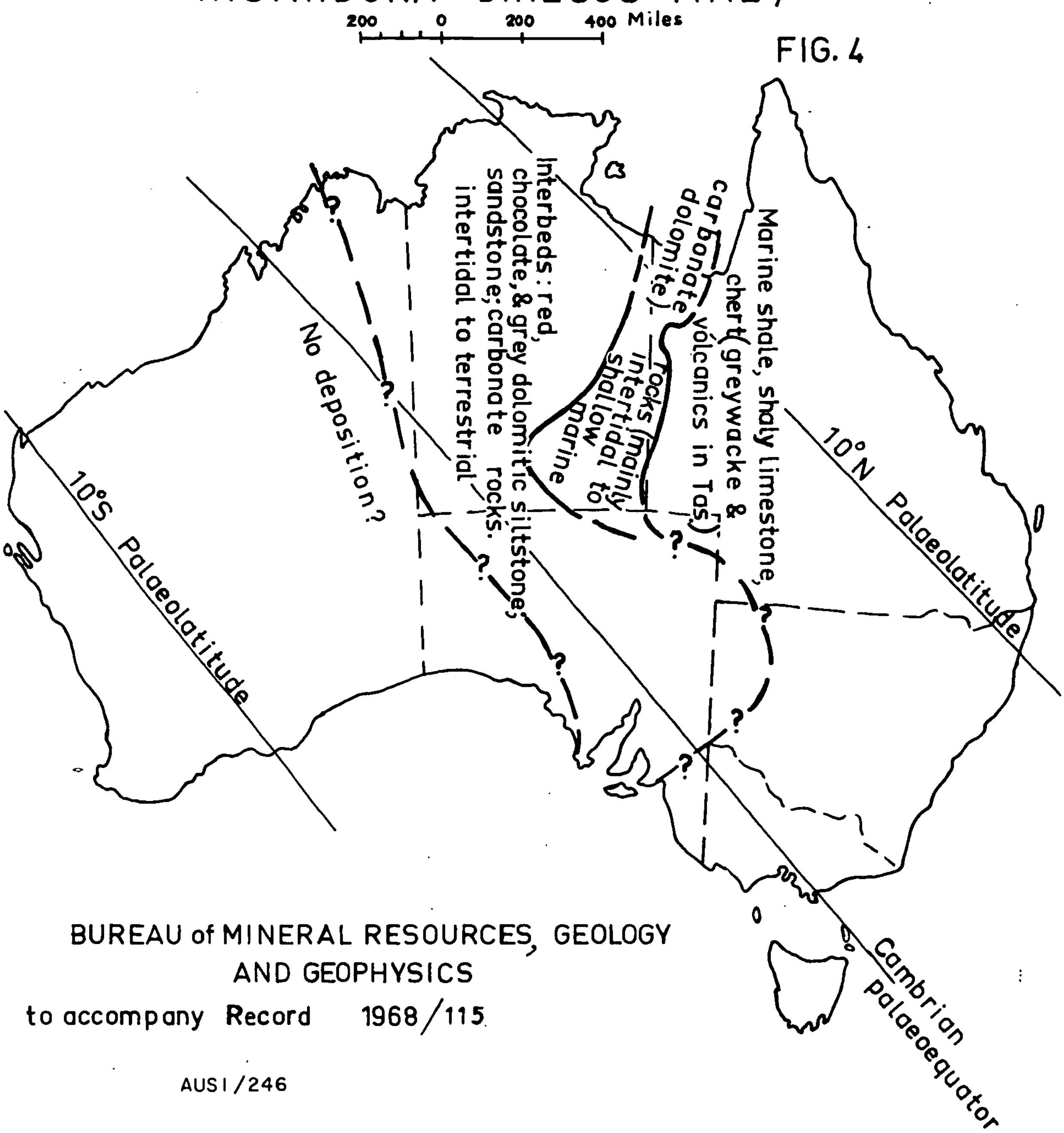
DISTRIBUTION OF ROCK TYPES AND DEPOSITIONAL ENVIRONMENTS, MIDDLE CAMBRIAN (AFTER XYSTRIDURA - DINESUS TIME)

FIG. 4



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AUS I/246

The climate in northern Australia during the Middle Cambrian seems to have been tropical, with evaporation exceeding precipitation. This can be inferred from the abundance of carbonate sediments and the evidence for raised salinity in areas of restricted marine circulation. This is in accord with the palaeomagnetic results for the Cambrian of Australia which indicate that most of the known Middle Cambrian sedimentary rocks in Australia lie within 10° latitude of the Cambrian palaeoequator.

With the climate and palaeogeography discussed above, terrigenous sediments would have had a complex history of transport and deposition. The semi-arid climate, low relief, and the substrate of porous carbonate sediments would probably not have supported permanent streams on exposed areas, but some fluvial transport would probably have occurred during sheet floods following rainstorms. Some silt and clay was probably carried in suspension in the water of salt lakes or lagoons, and some sand transported by long-shore drift. Transport of sediment by wind (silt and clay in suspension, and sand by saltation) was probably important but is difficult to prove. Sand dunes are not known; if they formed they must have been reworked by water before being buried by later sediment. The ubiquitous silt-size terrigenous grains in the carbonate sediments, far from possible sources, and the materials of the red and chocolate siltstone, probably deposited on surfaces exposed to the air for most of the time, may have been transported largely by wind. It is tempting to speculate that the dolomite grains in the siltstones, which seem to have been transported and sorted with the terrigenous fraction, may also have been wind transported. Their most likely source would be supratidal dolomite mud flats which would probably have been exposed eastward of areas of siltstone deposition.

The only available information on wind directions in the Cambrian of northern Australia is from ancient longitudinal dunes interbedded with the lavas of the Lower Cambrian Antrim Plateau Volcanics (Randal & Brown, 1967). These have internal structures indicating winds dominantly from the eastsouth-east (corresponding to an easterly palaeowind). If this wind direction prevailed in the Middle Cambrian then the dominant direction of wind transport would have been towards the sources of terrigenous sediment, rather than away from them. This would have been favourable for the wind transport of carbonate material into areas of siltstone deposition, but not favourable for the wind transport of the terrigenous silt to its site of deposition.

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31

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32