LOWER CAMBRIAN CARBONATE STRATIGRAPHY AND SEDIMENTOLOGY, OLD WIRREALPA SPRING, FLINDERS RANGES, SOUTH AUSTRALIA.

(VOLUME 1)

BY

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This thesis contains no material which has been accepted for the award of any other degree or diploma in any University, nor to the best of my knowledge and belief, does it contain any material previously published or written by any other person except where due reference and acknowledgement is made in the text.

P.G. Haslett

ABSTRACT

The early Lower Cambrian carbonates of the Flinders Ranges, South Australia, are characterized by numerous facies changes. Regional lateral facies changes occur along zones of long-active tectonism within the depositional basin. A study of measured sections throughout the Ranges has shown that the regional carbonate stratigraphy may be described in terms of six major lithological subdivisions. These do not necessarily correspond with established formations, and certain anomolies are apparent in both the mapped distribution of various lithofacies, and in the stratigraphic nomenclature itself. These anomolies are discussed at length and some are accounted for by the introduction of two new formations, the Woodendinna Dolomite and the Wirrapowie Limestone.

More intensive studies at Old Wirrealpa Spring have documented the relationship between abundant facies changes in the Lower Cambrian carbonates there, and the contemporaneous emplacement of a complex structure termed the Wirrealpa Diapir. The latter structure consists of a relatively thick and intact sequence of older Precambrian sediments which are associated with extensive exposures of breccia and megabreccia. Certain breccias are tectonic, but large areas are of sedimentary origin and may underlie or interfinger with nearby Lower Cambrian carbonate sequences.

"Diapiric" material was periodically exposed along a tectonically active zone and lithoclast debris was shed into the Lower Camrian carbonates. This zone of uplift trends NW-SE and separates contemporaneous sequences of markedly different thickness and lithofacies.

To the northeast, thick carbonates of the Black Dog Hill sequence become finer grained and less lithoclast rich away from the uplifted zone. Ooid and lithoclast grainstones and packstones can be observed passing into dark lime mudstones. Columnar stromatolites which are present in the basal beds show morphological variations which can be related to progressive changes in the environment of deposition. Ooids in the grainstones are of two distinct types, and these too reflect lateral changes in the conditions under which they formed.

Lower Cambrian sequences deposited southwest of the zone of uplift (Donkey Bore and Wirrealpa Hill sequences), are much thinner than their equivalents to the northeast. They are generally indicative of open high-energy marine conditions. Ooid and skeletal grainstones are dominant. In the immediate vicinity of the zone of uplift these sequences

contain a number of significant erosional unconformities. Associated with these are well-preserved karst features. The karst includes vertical cave systems which are filled with younger Cambrian debris, flowstones and pisoliths.

Mottled textures, which are widespread in the Lower Cambrian carbonates of the Adelaide "Geosyncline", are well developed at Old Wirrealpa Spring. Detailed investigations, particularly within the Black Dog Hill sequence, have shown that the textures are formed by carbonate dissolution within the unconsolidated sediments due to the movement of reactive interstitial fluids.

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GENERAL INTRODUCTION

PREVIOUS STUDIES

Within the Adelaide "Geosyncline" (Fig. 1), fossils of Cambrian age were first discovered on Yorke Peninsula, in 1878 (Tepper, 1879). Earliest palaeontological studies of these fossils were carried out by Tate (1879), Woodward (1884) and Etheridge (1890). Howchin (1897) reported the first discovery of archaeocyathid remains in the State, from the Sellick Hill-Normanville area south of Adelaide. To the north, in the Flinders Ranges (Fig. 2), further discoveries soon followed. Etheridge (1905) described Cambrian fossils from limestones in the Wirrealpa area, and Taylor (1907; 1910) described the rich archaeocyathid faunas from the Ajax Mine area. Subsequent early work on the Cambrian in the Flinders Ranges was principally carried out by Howchin (1907; 1922; 1925) and Mawson (1925; 1937; 1938; 1939).

It was not until Daily (1956) however, that a systematic biostratigraphic approach was employed in an attempt to subdivide and describe the Cambrian succession in South Australia. Daily was able to recognize twelve distinct faunal assemblages within the Adelaide "Geosyncline", and he proposed a number of new stratigraphic subdivisions from measured sections throughout the depositional basin.

This work established the framework upon which all later stratigraphic studies of the Cambrian in the Flinders Ranges have been based. Dalgarno (1964) added several new names to the stratigraphic terminology of Daily, and by using Daily's established faunal assemblages, illustrated a number of lateral facies changes in the Lower Cambrian units of the Flinders Ranges. Together with Johnson, Dalgarno recognized the importance of syndepositional faulting on the distribution of various facies, and was aware of some of the effects which supposed local diapiric intrusions had on sedimentation (Dalgarno, 1964; Dalgarno and Johnson, 1968).

Regional mapping by the South Australia Department of Mines (Dalgarno and Johnson, 1966; Coats et al., 1973) coupled with exploration for minerals (Johns, 1971; Thomson, 1965) and petroleum (Cooper et al., 1963; Wopfner, 1970), broadened the knowledge of the character and distribution of the Cambrian succession. In addition, there has been continued research by B. Daily and a number of his students at the University of Adelaide, focussing particularly on the Lower Cambrian of the Flinders Ranges.

SUMMARY OF CAMBRIAN GEOLOGY, FLINDERS RANGES

The frequent intertonguing of lithological units in the Cambrian of the Flinders Ranges has resulted in a limited number of formations being present in any one section. The Ten Mile Creek type section of Daily (1956) is one of the most complete available, and it is this section and its lithologies which forms the basis of the stratigraphic subdivision of the Flinders Rangers. Additional formations were proposed by Dalgarno (1964) with further contributions by Mount (1970), Daily (1972a) and Coats et al. (1973). The established formations and their mutual relationships, prior to this study, are given below (Fig. 3).

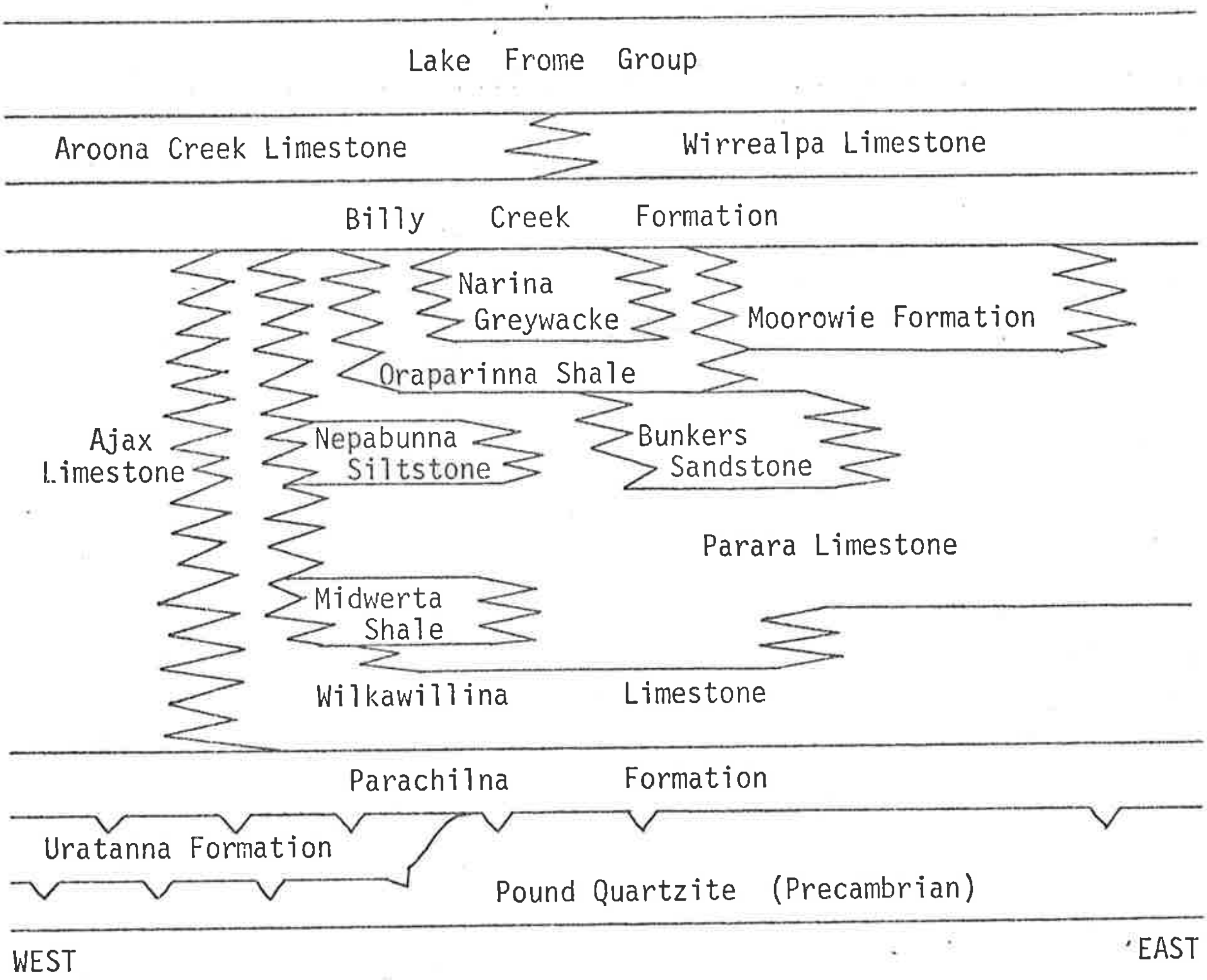


FIGURE 3: Cambrian formation names, Flinders Ranges. (After Coats et al., 1973).

Lower Cambrian formations of the Flinders Ranges, in general, disconformably overlie regressive quartz sandstones of the uppermost Precambrian Pound Quartzite (Daily, 1972b). Daily has recently shown, on the basis of preserved trace fossils, that the sediments of the basal-Cambrian Uratanna Formation are locally developed in erosion channels into the Pound Quartzite (Daily, 1973).

The Uratanna Formation is in turn, unconformably overlain by the transgressive sands and shales of the first widespread Cambrian unit, the Parachilna Formation (Dalgarno, 1962). This formation varies considerably in thickness, and is characterized by impure sandstones rich in burrows of *Diplocraterion* Torell (Dalgarno, 1964). Quartz sands are believed to have been derived in part from areas of exposed Pound Quartzite and cores of diapiric structures during the transgression of early Cambrian epeiric seas (Daily, 1973).

With progressive transgression, thick carbonate sedimentation occurred throughout the subsiding, but generally shallow basinal areas forming the Ajax, Wilkawillina and Parara Limestones. Likewise on the Stuart Shelf (See Fig. 1) very shallow carbonate accumulation gave rise to the Andamooka Limestone (Johns, 1968).

Carbonate sedimentation continued in shallower areas, whilst deeper parts of the basin periodically experienced terrigenous mud and silt deposition as evidenced by the Midwerta Shale, the Nepabunna Siltstone and the Oraparinna Shale (Wopfner, 1970).

In upper Lower Cambrian times a reduction in the rate of basin subsidence occurred, with uplift and erosion of underlying carbonate sequences in some areas (Dalgarno, 1964). Then followed a period of widespread red-bed development of the Billy Creek Formation, with red to brown micaceous siltstones and fine sandstones, many with desiccation mud-cracks and halite casts.

A brief but widespread marine transgression in early Middle Cambrian times gave rise to thin fossiliferous carbonate formations, of the Wirrealpa and Aroona Creek Limestones. Renewed deposition of clastic red-beds followed, resulting in the formation of thick sandstones of the Middle to Upper Cambrian Lake Frome Group. The uppermost formation of the Lake Frome Group, the Grindstone Range Sandstone is believed to represent possible fluvio-deltaic sedimentation (Thomson *et al*., 1976), and may be of Lower Ordovician age. This formation is the last record of deposition within the Adelaide "Geosyncline" prior to the onset of the early Palaeozoic Delamerian Orogeny (Thomson, 1970).

THE PRESENT STUDY

The original aim of this study was to investigate the origin(s) of the so-called "mottled" limestones which are a common feature of the Cambrian rocks of South Australia (Mawson, 1925). It was originally planned to map the distribution of the "mottling" in an area of dark carbonate mudstones, in order to establish critical depositional and diagenetic parameters.

As this work progressed at Old Wirrealpa Spring in the Flinders Ranges, it became clear that the complexities of the carbonates were such that a considerable amount of basic research was needed just to understand the geological setting of the mottled limestones.

Much time was therefore spent in the detailed mapping of the Lower Cambrian carbonates in the Old Wirrealpa Spring area, and in investigating the influence which the Wirrealpa Diapir (Dalgarno and Johnson, 1966), had on their sedimentation and diagenesis.

Although the considerable problem of diapirism itself was avoided where possible, a documentation of the relationship between the so-called diapir and the Cambrian carbonate sediments became a major aspect of this study. The results are presented in PART II. Subsequently it was felt that the significance of the detailed local studies of the carbonates at Old Wirrealpa Spring would be greatly enhanced by presenting them within the framework of the regional Lower Cambrian carbonate stratigraphy of the Flinders Ranges. PART I consists therefore of the results of a reassessment of the Lower Cambrian carbonate stratigraphy of the Flinders Ranges and its relationship to regional basin tectonics.

Having established with some confidence the regional and local geological framework, a return to the more detailed aspects of the Lower Cambrian carbonate was made. Two sedimentological studies are presented in PART III. The first of these topics, a study of the changes in stromatolite morphology with depositional environment, emerged during detailed mapping at Old Wirrealpa Spring; the second is an abbreviated consideration of the original aim, to investigate the origin(s) of the "mottled" limestones.

PART I: LOWER CAMBRIAN CARBONATE STRATIGRAPHY OF THE FLINDERS RANGES.

INTRODUCTION

ESTABLISHED LOWER CAMBRIAN CARBONATE FORMATIONS

Lateral interfingering is particularly evident in the Lower Cambrian carbonates of the Flinders Ranges. The type section of Daily (1956) at Ten Mile Creek conveniently presents a considerable thickness of the two most distinctive and widespread carbonate units, the Wilkawillina Limestone and the Parara Limestone. A further carbonate formation, the Ajax Limestone, is less widespread, being confined to the Mt. Scott Range and certain adjacent areas.

Wilkawillina Limestone

The Wilkawillina Limestone, in its Ten Mile Creek type section, disconformably overlies the Bonney Sandstone Member of the Pound Sandstone, and is extensively dolomitized at its base. In general the unit is massive, pure and pale cream to pink coloured. It consists predominantly of ooid and skeletal grainstones, which may be patchily silicified and recrystallized. An abundant fauna is characteristic of the upper parts, some beds consisting almost entirely of broken skeletal remains of archaeocyathids, and associated brachiopods, hyolithids, and trilobites. Algal remains are common throughout and although some cryptalgalaminates and oncolite horizons are present at the very base, stromatolites are virtually absent. Subaerial desiccation features are not represented in the type section. Daily (1972a) considers the Wilkawillina Limestone to have been deposited on a stable shelf under shallow marine conditions.

Parara Limestone

Flaggy to rubbly, dark to black impure limestone with interbedded dark calcareous shales form the Lower Member of the Parara Limestone in the Flinders Ranges. The Upper Member consists of flaggy and thin bedded dark grey to aphanitic limestones and thin calcareous shales. Although scantily fossiliferous throughout, the Parara Limestone contains trilobites, hyolithids, brachiopods, sponge spicules, conchostracans and rare archaeocyathids (Daily, 1956). Stromatolites, flat pebble conglomerates and desiccation features are absent.

Ajax Limestone

Daily (1956) proposed that the term Ajax Limestone should be used for all carbonates above the Pound Quartzite and beneath the red clastics of the Billy Creek Formation in the Mt. Scott Range area. This comparatively thin carbonate sequence incorporates a number of different lithologies. Daily (1972b) has subsequently distinguished a Lower and Upper Member, and in view of the thickness of this unit, any further subdivision of the Ajax Limestone may prove impractical on a regional scale. It is very important to realize that a large number of lithotypes present in the Ajax Limestone, are present within the Cambrian carbonate formations mapped elsewhere in the Flinders Ranges (Daily, pers. comm.) and that the change in stratigraphic terminology in the Mt. Scott Range area is in large part historical rather than geological.

FAUNAL ASSEMBLAGES OF DAILY (1956)

Daily's work established twelve broad faunal assemblages for the Cambrian of South Australia. These assemblages are based mainly on trilobites and various problematica. The present study restricts itself to those Lower Cambrian carbonate rocks which have developed up to the time of the topmost Faunal Assemblage 2. In the Ten Mile Creek type section, Faunal Assemblages 1 and 2 are confined to the Wilkawillina Limestone, but elsewhere in the basin, the top of Faunal Assemblage 2 seldom corresponds with the top of the Wilkawillina Limestone lithofacies.

Faunal Assemblage 1 consists almost exclusively of various types of archaeocyathids. Sponge spicules and rare brachiopods have also been reported (Daily, 1956). Faunal Assemblage 2 is more varied, with a great abundance of archaeocyathids, numerous brachiopods, including "Nisusia" compta (Tate), hyolithids, sponge spicules, calcareous algae, the tommotiid "Ambonychia" macroptera (Tate), various problematica and fragments of Redlichiacean trilobites. "Micromitra (Paterina)" etheridgei (Tate), an enigmatic phosphatic fossil, is confined to this assemblage. This form had initially been considered to be a brachiopod by Walcott (1912), but more recently its affinities have been compared with the enigmatic form Tannuolina multiflora Fonin and Smirnova (Daily, 1972b). Its presence in considerable numbers, relatively wide environmental distribution and easily recognizable morphology, makes this fossil an extremely useful index fossil. It is for this reason primarily that the arbitrary limitation to this study was placed at the top of Faunal Assemblage 2.

THIS STUDY - AIMS AND METHODS

Early in this investigation of the regional carbonate stratigraphy, it was apparent that some marked misinterpretations of Lower Cambrian lithofacies and formation distributions were present on the published PARACHILNA 1:250,000 map sheet (Dalgarno and Johnson, 1966) and COPLEY 1:250,000 map sheet (Coats et al., 1973) which cover the central and northern Flinders Ranges. Although such inaccuracies are probably unavoidable in the regional mapping of complexly intertonguing formations, it meant that the published geological data could not be confidently used in this study.

Existing formations were also very broadly defined, and it was felt that the lithological variability was such that further subdivision of these formations might be warranted. Accordingly some sixteen sections of the Cambrian carbonate rocks were reinterpreted in terms of six distinctive lithological groupings. These lithofacies were described and their probable environments of deposition interpreted mainly by analogy with intensively studied modern carbonate environments viz. Shark Bay, Bahamas, Persian Gulf etc.

The sixteen sections considered were selected from widely spaced locations in the central and northern Flinders Ranges (See Fig. 4). Six of the sections represent reinterpretations of data from other workers, which is acknowledged on Figure 5. The other ten sections were examined in the field by the writer, and all but one, that at Nantawarrina Bore, re-measured in the field.

Lithologies were described in terms of Dunham's classification of carbonate rocks (Dunham, 1962) which has been used throughout this thesis.

The six regional lithological categories have been termed,

(1) Ooid and skeletal grainstone and packstone lithofacies.
(2) Mudstone and wackestone lithofacies.
(3) Stromatolite/intraclast mudstone lithofacies.
(4) Archaeo/algal boundstone lithofacies.
(5) Mud-crack dolomite lithofacies.
(6) Calcareous shale lithofacies.

The results of this work have been plotted on a panel diagram (Fig. 5). This diagram is a gross representation of the major regional rock relationships and is not an attempt at an interpretation of detailed interrelations. The limitations of such a presentation are very apparent to the writer and bear brief discussion.

The diagram intentionally omits the complex local lithofacies relationships which characterize the Lower Cambrian in the basin of deposition, and for the purpose of this diagram the presence of faulting, folding, possible diapiric intrusion and basement highs has been ignored. This is not to deny their presence or importance to Lower Cambrian sedimentation, but in this attempt to illustrate the broad scale facies relationships in the basin, they are only a complicating influence.

Although the sequences are generally fossiliferous, the palaentological resolution within Faunal Assemblages 1 and 2 is such that correlation between sections is essentially on lithology alone. These correlations have been made over considerable distances, and in some cases have been made across zones from which all Lower Cambrian rocks have been eroded (Fig. 4).

The presence of a considerable number of unconformities, especially in the central Flinders Ranges, is apparent from detailed local mapping (Dalgarno and Johnson, 1966; Haslett, 1969; Pierce, 1969). Such unconformities are often difficult to recognize in section measurement and it is likely that a number of significant time-breaks remain undiscovered within the general interpretation in Fig. 5. A sizeable erosional break occurs at the top of Faunal Assemblage 2 in parts of the central Flinders Ranges, and although this level has been chosen as a datum, it is not necessarily isochronous over the whole of the area covered by this regional interpretation.

REGIONAL CARBONATE LITHOFACIES

OOID AND SKELETAL GRAINSTONE/PACKSTONE LITHOFACIES

Description

This widespread unit corresponds closely in lithology to the major part of the Wilkawillina Limestone in its Ten Mile Creek type section. It contains a range of clastic carbonate rock-types which are characteristically pale coloured.

Ooids and/or skeletal fragments are the major clastic components. In any single section, ooids tend to predominate in the lower parts, the influence of skeletal clasts becoming more significant higher up. In the field, grainstones and packstones are rarely distinguishable, the origin of the interstitial carbonate being indeterminable. Bedding may be massive, with medium scale cross-bedding common throughout.

Sorting in the ooid grainstones is extremely good, with the common cross-bedding sometimes enhanced in weathered outcrop by the presence of minor amounts of well rounded quartz sand grains. The quartz sand component is generally more significant in the basal parts of the unit but is usually of local importance only. Minor amounts of finer terrigenous material may be present, but are rare.

Archaeocyathid remains are the dominant skeletal clasts. Rare individuals are almost intact, but the vast bulk of material is broken into small, often barely recognizable fragments, especially in the more strongly cross-bedded horizons. Sorting of fragments may be moderate to good. Other organisms found include brachiopods, various problematica and less commonly trilobite, and gastropod remains. Phosphatic remains are common. Calcareous algal remains are similarly widespread.

Rare intraformational conglomerates may occur but desiccation mudcracks have not been observed. Small scale laminal fenestrae are present in birdseye limestones, which are widespread but usually thinly developed in the central Flinders. They are frequently pink to cream in colour, and often pelletal or oolitic. Most tend to show a fine somewhat irregular lamination in their finer grained interbeds. Such finer grained mudstone interbeds are not restricted to the birdseye limestones but may occur as a minor lithological component throughout the grainstone/packstone facies.

The grainstone/packstone sequence is also characterized by limestones with large irregular fenestrae filled with stromatactis-type sparry cements. A reddening of some surfaces which may be shown, on palaeontological evidence, to represent depositional breaks has been reported by Daily (1972). Such reddened horizons have been observed by the writer in a number of localities, and are related in some cases to localized silicification.

Irregular masses of secondary dolomite are very frequently developed in the grainstone/packstone unit. Within these zones, dolomitization may be partial or complete, the zones themselves usually being markedly discordant. Dolomitization may be intense enough in some parts to completely obliterate field evidence of the primary sedimentary features. Other diagenetic features include stylolites, which are very common. They are often difficult to distinguish without a close examination of the rock or thin section, since the purity of the carbonate results in very little build up of insoluble residue along the sutured stylolite surface. Thin sections reveal an intense development of microstylolites in skeletal and ooid grainstones where the considerable amount of dissolution may be readily seen.

Environmental Significance

Rocks of the ooid and skeletal grainstone and packstone lithofacies have been previously described as resulting from open shelf carbonate deposition (Daily, 1972a). The writer generally concurs with this interpretation.

The light colour, in the absence of preserved organic carbon or sulphide minerals attests to the good circulation and oxygenation of the depositional environment. The diverse and abundant fauna suggests open marine conditions, probably well within the photic zone.

Energy conditions, although some-what variable, were generally moderate to high. Ooid grainstones, being strongly cross-bedded and devoid of mud, probably record high energy, lower intertidal and shallow subtidal deposition. Skeletal packstones were deposited under slightly less energetic conditions, probably further offshore. The ubiquitous broken fragments and the good sorting of skeletal clasts suggests that in-situ breakage was minimal, and that most fragments have undergone transport prior to eventual deposition.

Thin but widespread birdseye limestones indicate that emergence into at least lower supratidal environments occurred periodically. The absence of desiccation mudcracks, significant intraformational conglomerates or thick dolomite interbeds suggests that extended exposure of unlithified sediment, or prolonged restriction of the depositional environment did not occur.

MUDSTONE/WACKESTONE LITHOFACIES

Description

The mudstones and wackestones of Faunal Assemblages 1 and 2 form a relatively monotonous group which are uniformly dark in colour, fine in grainsize and usually flaggy in field outcrop. Their apparent constancy in field aspect undoubtedly conceals a subtle but distinct variety of depositional and diagenetic characteristics. In this regional study, however, they have been grouped in a single category which is widespread and thickly developed, being as lithologically diverse as the ooid and skeletal grainstones and packstones.

Most of the mudstone/wackestone lithofacies of Faunal Assemblages 1 and 2 show greatest similarity to the Lower Member of the Parara Limestone of the Ten Mile Creek type section. Finely laminated limestone/shale lithologies of the Upper Member of the Parara Limestone (Daily, 1956) of the Ten Mile Creek section are virtually absent from the unit being described.

The ubiquitous dark grey to black colour of the carbonate of the mudstone/wackestone lithofacies is attributed to contained organic carbon and finely dispersed iron sulphides. Fine terrigenous material is also abundant within this unit. A considerable proportion, up to about 30%, of insoluble residue is apparent on dissolution, most of this material being silt-sized quartz grains and clay minerals. Fine to medium grained quartz sands may also be present in certain beds, these normally being of limited lateral distribution. The greatest abundance of terrigenous silt and sand is generally developed in the yougest carbonates of Faunal Assemblage 2. Fine bedding features are characteristically poorly developed in the mudstone/wackestone lithofacies. Exceptions occur in the more terrigenous units where small scale cross-beds are often encountered. The more fossiliferous units also tend to be bedded, with current oriented hyolithids being evident on a number of bedding planes. Shaley interbeds are common in the field, but their exact significance is controversial in that it is within the mudstone/wackestone lithofacies that the most obvious "mottled" limestones of the Lower Cambrian are developed. The origin of the shaley interbeds of the nodular limestones will be discussed at length in PART III. The writer feels that much of this apparently irregular bedding is diagenetic (See PART III, CHAPTER 2).

Pene-contemporaneous slumping may be locally developed, particularly within the wackestone units.

The mudstone/wackestone facies is scantily fossiliferous throughout. Fossils tend to be somewhat fragmented and rich accumulations are confined to distinct horizons. The faunas include trilobites, hyolithids, various brachiopods, tubular organisms, problematica and rare archaeocyathids. Worm trails and bioturbated beds are rarely found.

Stromatolites and desiccation mud-cracks are absent from this lithofacies. Intraclast conglomerates are rare, being confined to the more terrigenous units, which occur in areas of the NE Flinders, near the top of Faunal Assemblage 2.

"Mottling" of probable diagenetic origin, is by far the most conspicuous secondary feature within the mudstone/wackestone lithofacies. Dolomitization and silicification have also occurred. Both appear to have been closely related to the "mottling" process. Dolomitization is never as complete in this facies as it is in the grainstone/packstone facies, the dolomite tending to occur preferentially within the lighter coloured, shaley areas between darker carbonate "nodules" of the mottled limestones. Irregular, discordant zones of complete dolomitization have not been observed in the mudstone/wackestone lithofacies.

Silicification is not particularly common, and tends to be confined to distinct zones which can be traced laterally for considerable distances. As for dolomite, secondary silica is irregularly developed within silty parts of the "mottled" limestones of these zones.

Environmental Significance

This unit is thick, widely distributed and no doubt contains rocks from a number of subtly different yet diverse depositional environments. For this reason any overall environmental interpretations involve considerable generalizations.

The characteristic dark colour suggests that reducing conditions have prevailed within the sediments at the site of deposition. Although slightly deeper conditions than those for deposition of the grainstone/packstone facies may have occurred, the reducing conditions probably indicate greater restriction rather than significantly deeper water deposition for the mudstones (Daily, 1972a). In some instances a slightly greater maximum depth might be favoured since local syndepositional slumps and mud-flow breccias

(See PART II) indicate movement of material downslope away from areas of grainstone/packstone deposition. Relatively rapid accumulation of fine sediment seems probable from the lack of bedding features and meagre evidence of a benthonic fauna or flora.

STROMATOLITE/INTRACLAST MUDSTONE LITHOFACIES

Description

This unit is characterized by dark grey lime-mudstones with green-grey calcareous siltstone interbeds. Outcrop is generally flaggy except for massive interbeds of ooid grainstone, common intraformational conglomerates and thick beds of laterally linked domal stromatolites (Plate 1a). Rare desiccation mud-cracks are also present.

The algal stromatolites bear a spacial relationship in most instances with flat pebble conglomerate beds. The stromatolites are finely laminated, consisting of low laterally linked domes with up to 1.5 m relief. On bedding plane exposure, the domes show little if any preferred orientation, being somewhat squat and equidimensional. The interbedded flat pebble conglomerate beds are commonly strongly lenticular, some developing within narrow steep sided channels. Stromatolites may overlie the conglomerates, or be enclosed by them. More details of this relationship are presented in PART III. Conglomerate clasts appear to have originated by the reworking of thin desiccated mudstone layers, some of which are of cryptalgal origin.

Associated crossbedded ooid grainstone interbeds are developed to varying degrees in different parts of the basin, and are seldom more than 1 m thick. Bedding surfaces are frequently rippled.

The stromatolite intraclast mudstone sequence is, apart from stromatolites, notably depleted in fossils. Several exposures of worm trails on bedding planes and minor instances of bioturbation of bedding laminae are the only evidence of organic activities found by the writer.

Environmental Significance

The stromatolite/intraclast mudstone sequence appears to have been deposited in shallow, sheltered intertidal to lagoonal environments.

The absence of dolomite and relative rarity of desiccation mud-cracks suggest that only limited exposure and restriction prevailed. Tidal action is indicated by steep sided, conglomerate filled channels.

Common intraformational conglomerates, with clasts probably derived from reworked desiccated mud flats, further suggest shallow intertidal deposition (Lucia, 1972).

Energy conditions appear to have been generally low, with a lack of current bedding in the mudstones, and an absence of any current induced, preferred elongation of stromatolite bioherms. Thin cross-bedded grainstone sheets do, however, indicate that brief periods of higher energy conditions penetrated the sheltered mud flats, probably during storm activity.

ARCHAEO/ALGAL BOUNDSTONE LITHOFACIES

Description

Rocks of this unit are usually dark grey to black in colour and extremely rich in archaeocyathid remains. Outcrop may be massive to rubbly with common flaggy to mottled, dark calc-mudstone interbeds. The sequence is usually thinly developed, often occurring as small biohermal masses within the mudstone/wackestone sequence or the grainstone/packstone sequences, particularly in association with skeletal grainstones. Although these bioherms are not uncommon in the Lower Cambrian carbonates of the Flinders Ranges, regionally mappable units of archaeo/algal boundstone are rare.

Within the mapped archaeo/algal boundstone unit itself, dark coloured archaeocyathid/algal bioherms up to several hundred metres long and forty metres high are close packed within similarly dark mudstones and wackestones. Most biocherms are in the order of tens of metres long and show profiles which have a relatively large height to length ratio. Although not always the case, bioherm margins may grade laterally into mudstones and skeletal wackestones, with relatively abrupt upper and lower contacts. Archaeocyathid remains within this unit are characteristically in approximate growth position. These remains are enveloped in irregular dark masses of algal carbonate. In the field these algal masses are fine grained and very dark in colour and can be seen to envelope archaeocyathid tests and to fill or partially fill gaps between the tests. The growths also encrust and bind other clastic material. Under the microscope a crude cellular network is sometimes apparent, although preservation is generally poor. Good _Renalcis_-type remains can be identified.

The archaeocyathids themselves consist of a wide variety of groups with calyxes characteristically elongate and tubular. In cross section the tubular forms are parallel, may be close-spaced, and are interconnected by masses of algal remains. Some debris may occur between tests. The central cavity is commonly filled with sparry calcite, and occasionally dolomite.

Within the archaeo/algal limestones, various other organisms may be common. The most prevalent are the brachiopods Nisusia Sp. and Kutorgina peculiaris (Tate). Numerous other unidentified fragmentary remains may be found.

The effect of diagenesis has been mainly the obliteration of finer textural features by aggrading neomorphism (Folk, 1959). Little evidence of diagenesis is obvious in the field. Secondary cavity filling is ubiquitous; coarse grained white sparry calcite often fills geopetal structures in the central cavity of archaeocyathids.

Environmental Significance

The dark and fetid nature of the limestones of this lithofacies suggests that reducing conditions prevailed, at least within the sediments, at the site of deposition. The profusion of archaeocyathids cloaked in a mantle of algal material are believed to have acted as a baffle to current action and restricted water circulation within the organic framework, resulting in reducing conditions.

The abundant fauna suggests that good oxygenated marine conditions existed above the sediment/water interface, and that growth took place well within the photic zone. Energy levels appear to have been moderate, there being evidence of breakage of archaeocyathid tests, although significant transport of clasts has not occurred. Non-carbonate or other allochthonous debris is essentially absent. Carbonate muds have probably been derived from the disintegration of profuse local algal communities.

More attention is paid to the features of the archaeo/algal lithofacies in PART II, where details of its relationships to adjacent laterally equivalent facies are presented. It appears that this lithofacies records deposition on shallow subtidal offshore mud-banks in warm open marine conditions.

MUD-CRACK DOLOMITE LITHOFACIES

Description

The basal carbonates of this unit are partly or completely dolomitized oolitic and pisolitic limestones, interbedded with very minor green shales. These pass into massive to flaggy yellow weathering dolomites with pronounced desiccation features (Plate 1b). They are associated with low, broadly domed stromatolites and thin cross-bedded, pure quartz sandstones. Intraformational conglomerates, often with dolomite clasts in a quartz sandstone or ooid grainstone matrix, are also common (Plate 1c). Those parts of the sequence which have escaped secondary dolomitization show beautifully preserved primary sedimentary structures. Desiccation mud-cracks, some up to 8 cm deep are common in the dolomitic mudstones. Ripple marks and cross-bedding are present in the ooid grainstones and quartz sandstones. Ooid grainstone beds also commonly show a primary rubbly or cobbled surface, reminiscent of that found in modern environments on areas of subaerially exposed, partially lithified carbonate sands (Plate 2a).

Many sections through the mud-crack dolomite sequence have been strongly affected by secondary dolomitization. This results in the development of a massive dull grey unit which appears, superficially at least, to be lithologically homogeneous. On close examination it has pre-diagenetic lithologies comparable to those already described but perhaps with a greater number of ooid grainstone beds. Some of these grainstones are rich in dispersed quartz sand. Thick, dolomitized algal stromatolite beds and intraformational conglomerates are also common.

Fossil remains, apart from algal stromatolites, are absent from rocks within the mud-crack dolomite sequence.

Environmental Significance

The mud-crack dolomite lithofacies shows numerous features characteristic of deposition on emergent high intertidal and supratidal mud flats. Prevalent desiccation mud-cracks record repeated periods of subaerial exposure, and the highly restricted nature of the environment is suggested by the paucity of fauna and dominance of primary dolomitic mudstones or pene-contemporaneously dolomitized carbonate mudstones. The only organisms capable of tolerating the extremes of restriction and desiccation of the environment were algae, as evidenced by the abundance of stromatolites in the sequence.

Cross-bedded ooid grainstones and quartz sandstones record brief episodes of high energy conditions penetrating the mud flats. These conditions, which probably occurred during periods of storm activity or times of unusually high tides, resulted in the spreading of sheets of coarser clastics from more open marine areas over the exposed mud flats.

CALCAREOUS SHALE LITHOFACIES

Description

A monotonous sequence of green to grey siltstones and calcareous shales, with thin interbedded grey limestones, is developed in the north east Flinders Ranges. These sequences are relatively poorly outcropping and form areas of low topographic relief.

The sequences are poorly fossiliferous the writer not having found any preserved remains in the sections examined.

These shales have been mapped as Midwerta Shale and Nepabunna Siltstone by Coats et al. (1973), and as an unnamed shale unit by Dalgarno and Johnson (1966). For the greater part, the mapped Midwerta Shale lies within the upper part of Faunal Assemblage 2 in the southern areas where interfingering with fossiliferous limestones may be seen. To the north where these shales make up a considerable portion of the column, and are apparently unfossiliferous, the top of Faunal Assemblage 2 is obviously speculative. From the regional facies trends where fossils are present it is clear that a considerable thickness of shales was developed in the north and north-east Flinders Ranges within the span of time considered in this study.

Environmental Significance

The calcareous shale lithofacies appears to be a deeper water facies, and probably formed in a distal basin slope to basinal environment.

DISCUSSION

REGIONAL CARBONATE DEPOSITIONAL HISTORY

The restricted upper intertidal to supratidal carbonates of the mudcrack dolomite lithofacies represent the first widespread carbonate deposition in the Lower Cambrian of the Flinders Ranges. This widespread and distinctive lithofacies is best developed in the north and north-eastern Flinders although indentical facies are found in the basal parts of the Andamooka

Limestone (Johns, 1968) of the Stuart Shelf (See Fig. 1). It is generally conformable, in the Ranges, upon the Parachilna Formation, but to the south in the vicinity of the Ten Mile Creek type section, the mud-crack dolomites thin markedly, and lap onto Upper Precambrian sandstones which occur beneath the regional Cambrian/Precambrian unconformity (Glaessner, 1969, Daily 1972b; 1973; 1974).

Carbonate deposition under widespread open and sheltered shallow subtidal and intertidal conditions followed without break. The deposition of ooid grainstones and initially very minor skeletal grainstones and packstones took place under open, moderate to high energy conditions in the central and western Flinders. These conditions gave way, to the south and north-east, to shallow sheltered intertidal environments in which the stromatolite/intraclast mudstone lithofacies formed. To the north this change in facies occurred abruptly and is readily demonstrable along the line of present day outcrop of the Blinman, Wirrealpa and Frome Diapirs. (See PARACHILNA 1:250,000 map sheet, and Fig. 5). This zone of activity is herein termed the Wirrealpa Hinge Zone. A similar interfingering relationship appears to exist to the south, where grainstones and packstones of the central Flinders pass southward into the dark stromatolite and intraclast mudstones reported by Dalgarno and Johnson (1962), Cooper et al. (1963), and Dalgarno (1964) at Mernmerna and Chace Range in the southern central Flinders Ranges.

Periodic shallowing, with occasional emergence has occurred and is indicated, within the grainstone/packstone sequence, by the development of widespread birdseye limestones. Related unconformities may well have occurred within the sheltered intertidal mud flat sequences too, but reliable evidence of this is difficult to find. Mud-crack dolomite lithofacies may be developed, at least locally, as lateral equivalents to the stromatolite/intraclast mudstones during these cycles of brief emergence of the ooid grainstone/packstone sequences to the south. The details of these relationships will be given below (PART II and PART III).

At this stage, the importance of a regional hinge along the line of present day outcrop of the Blinman, Wirrealpa and Frome Diapirs was firmly established. Areas to the north of this line underwent gradual but persistent subsidence with respect to those to the south. These effects become less marked to the west and along the far western flank of the ranges the lithofacies are apparently relatively consistent from south to north (Daily, pers. comm.).

Thick mudstone and wackestone deposition took place to the north-east on the flanks of what Wopfner (1970) termed the Arrowie Basin. Deeper parts of the basin saw the development of a calcareous shale lithofacies. Elsewhere to the south and west at this time, thick skeletal grainstones and packstones formed in shallow open, moderate to high energy shelf environments. Shoreward, ooid grainstone shoals accumulated under high energy, low intertidal to slightly subtidal conditions. Archaeo/algal boundstones probably formed on shallow offshore mud banks, associated with a proliferation of organic activity, including flourishing algal communities. These communities probably supplied much of the autochthonous carbonate mud to nearby areas of mudstone deposition. Further mud was probably derived from the disintegration of skeletal material in the marginal high energy environments to the south and west.

Periodic uplift of areas to the south of the Wirrealpa Hinge Zone continued, often with substantial local erosion of grainstones and packstones. As will be seen in PART II, these events commonly resulted in the spread of reworked tongues of grainstones and packstones well out into deeper basin margins where they were often associated with lenses and wedges of basinal calcareous shales.

Toward the top of Faunal Assemblage 2 a general shallowing of the depositional basin appears to have occurred. This resulted in a widespread unconformity developed on the skeletal grainstone/packstone lithofacies in the central and southern parts of the Ranges (Daily, 1972a), and the formation of dark shallow water carbonate mudstones immediately north of the Wirrealpa Hinge Zone. These mudstones are notably siliceous and show abundant evidence of periodic emergence. They form a unit within the mudstone/wackestone lithofacies which is widely distributed in the north-east and which persists well above the top of Daily's Faunal Assemblage 2.

STRATIGRAPHIC NOMENCLATURE

Comments on this study

This study of the regional Lower Cambrian carbonate stratigraphy of the Flinders Ranges was undertaken, as indicated above, as a supplement to the more detailed work to follow. It is a brief study, being only of those rocks in Faunal Assemblages 1 and 2, and as stated earlier, the writer is acutely aware of the gross generalization in interpretation involved in the lithological correlation of the measured sections. Despite this, the study has achieved several of the original aims. It has,

(1). Further verified that the carbonate rock units of the Lower Cambrian, do, in detail, show the abundant lateral facies changes ascribed to them by earlier workers (Dalgarno 1964; Dalgarno and Johnson 1966; Daily and Forbes 1969; Wopfner 1970 etc.).

(2). Confirmed the existence and regional importance of a tectonically active zone herein termed the Wirrealpa Hinge Zone and previously referred to by Dalgarno (1964), Dalgarno and Johnson (1966), Daily and Forbes (1969), Haslett (1969).

(3). Demonstrated that within the bounds of practicality it is possible at this time to further subdivide some existing formations into regionally mappable units. Further, that it should be possible, in the light of present-day knowledge, to erect a more precise and lucid framework of stratigraphic nomenclature to cover the Lower Cambrian rocks of the Flinders Ranges. This point, in itself, requires elaboration.

General remarks on stratigraphic nomenclature

The ultimate aim of any stratigraphic scheme must be to provide a concise and unambiguous means for the communication of geological information about the regional rock relations within any particular depositional basin. The Australian Code of Stratigraphic Nomenclature (1964) attempts to formalize the rules by which such aims might be achieved. It is essential, however, to consider the application of these rules in a practical sense.

Whilst it is important, for convenience, that as few as possible formation names are proposed for any given basin, it remains essential that sufficient nomenclature be available to describe the geology on a regional scale, without critical lithological or environmental information being hidden within formations which are too broadly defined.

Ideally too, formations would be best set up after preliminary regional mapping had been attempted. This would guarantee that formations were recognizable lithologically, and regionally mappable. It would also ensure that type sections were selected in the most geologically favourable locations. This is of course, never the case in practice, and the stratigraphic nomenclature is forced to envolve as the scale of regional mapping itself changes and the knowledge of the geology of the particular area increases. This nomenclatural evolution may take place in a number of ways. Older formations may merely be redescribed, or their boundaries redefined, e.g. Ajax Limestone (Daily, 1956). In other instances new names may be proposed for rock types previously unrecognized in the basin, e.g. Moorowie Formation (Mount, 1970). By far the most usual change is that which proposes new names for previously undifferentiated rock types which have been mapped within a pre-existing formation. This may be due to the recongition of previously undiscovered disconformities of time significance, e.g. Uratanna Formation (Daily, 1973), or the recognition of a significantly different lithology indicative of a distinct and regionally important depositional event.

Obviously most nomenclatural evolution results in an increased number of stratigraphic terms. It becomes necessary that stratigraphic schemes remain manageable in a practical sense, and for this reason the introduction of new names is a matter worthy of careful consideration. It is of extreme importance that formations be mappable on a regional scale compatible with the state of geological understanding at that particular time. It is felt that the knowledge of the regional geology of the Lower Cambrian of the Flinders Ranges, at this time, has slightly outpaced the evolution of a convenient stratigraphic terminology particularly in dealing with the carbonate rocks.

The three basic carbonate formations, Ajax, Wilkawillina and Parara Limestones, are inadequate to give a reasonable summary of the carbonate stratigraphy at the mapped regional scale of 1:250,000. Furthermore, the maps at this scale available (COPLEY, PARACHILNA) show considerable inaccuracies with respect to the distribution of even the three above-mentioned formations.

Known inadequacies of the existing regional mapping and regional stratigraphic nomenclature will be discussed below and some suggestions for possible improvement offerred. For the reasons stated above (pp.19 & 20) the writer has resisted any temptation to formally introduce numerous new stratigraphic names at this stage. The only two new formations formally proposed are those which are known to be lithologically distinctive, easily mappable, of widespread distribution and of considerable environmental significance.

Mapped formations

Wilkawillina Limestone

Mapped distribution

PARACHILNA 1:250,000 map sheet (Dalgarno and Johnson, 1966) shows extensive areas of Wilkawillina Limestone throughout, and most corresponds accurately with the ooid and skeletal grainstones and packstones of the Wilkawillina Limestone in the Ten Mile Creek type section. Over most of the area, particularly in northern parts, the mapped unit includes a basal carbonate sequence of the mud-crack dolomite lithofacies. In the very northern-most part of the sheet in the vicinity of Wirrealpa and Mt. Chambers, the mapped Wilkawillina Limestone also includes the stromatolite/intraclast mudstone lithofacies. The same is true for mapped Wilkawillina Limestone to the south, in the Mernmerna and Chace Range areas. The stromatolite/intraclast mudstone lithofacies is not represented in the type section, and has been incorrectly mapped in the above locations.

The COPLEY 1:250,000 map sheet (Coats et al., 1973) shows extensive areas of exposed Wilkawillina Limestone. For the most part this is in gross error. Comparable lithologies to the ooid and skeletal grainstones and packstones of the type section are absent from the area mapped except for the Upper Member of the Ajax Limestone (Daily, 1972b) in the west and minor interbeds of grainstones in the extensive mudstones and wackestones of the NE Flinders. The basal unit of the mapped Wilkawillina Limestone consists of mud-crack dolomite lithofacies and is best differentiated as a separate formation (see below). Upper parts of the mapped Wilkawillina Limestone consist of stromatolite/intraclast mudstone lithofacies and minor mudstone/wackestone lithofacies, neither of which bear any relationship lithologically or depositionally to the type Wilkawillina Limestone. Minor archaeocyathid grainstones and packstones exist south of Angepena (Daily, pers. comm.) but the writer, although being aware of quite common archaeocyathid wackestones, has never observed good archaeocyathid grainstones and packstones in the NE Flinders Ranges.

Proposed subdivisions

The widespread basal mud-crack dolomite lithofacies forms a mappable unit, distinct in both lithology and evironment of deposition. The same may be said for the stromatolite/intraclast mudstone lithofacies which overlies it over large areas of the Flinders Ranges. Accordingly these two units have been formally differentiated from the Wilkawillina Limestone and named the Woodendinna Dolomite and the Wirrapowie Limestone respectively (Haslett, 1975).

Their type sections are located in Wirrapowie Creek and one of its tributaries in the NE Flinders (See Fig. 6). In these sections both formations are well exposed, as are their respective upper and lower boundaries. The type lithologies of the Woodendinna Dolomite and Wirrapowie Limestone are described in Fig. 7, their distribution and environments of deposition having already been described above, being the mud-crack dolomite lithofacies and stromatolite/intraclast mudstone lithofacies respectively (Fig. 5, pp.15 & 13).

Possible future subdivisions

In retrospect, it may have been possible in this study to subdivide the ooid and skeletal grainstone/packstone lithofacies into two units, one dominantly oolitic and the other skeletal. That is to say, it might have been possible to regionally distinguish two such members within the Wilkawillina Limestone of the Flinders Ranges. Throughout, there is abundant interfingering of oolitic and skeletal grainstones, but in general terms one or the other is dominant to the extent that a meaningful picture could be forthcoming upon mapping them separately. The "Oolitic Member" characteristically interfingers with both Woodendinna Dolomite and Wirrapowie Limestone. In the Ten Mile Creek type section oolitic grainstones of the "Oolitic Member" overlie a basal 30 m thick dolomitic unit, and are themselves some 65 m thick. Archaeocyathid remains are present within the ooid grainstones but are <u>not</u> <u>dominant</u>. A lithologically similar unit, but one which is much younger, has been informally named the Bendieuta Member of the Parara Limestone in the Mt. Frome area by Hatcher (1970) and Wigglesworth (1970) at the suggestion of B. Daily (Daily, pers. comm.).

The "Oolitic Member" of the Wilkawillina Limestone usually contains birdseye limestones. Although distinctive in appearance and probable depositional environment, they do not constitute a mappable unit alone. They are characteristically unfossiliferous and occur at a number of different stratigraphic levels in sections in various parts of the Ranges. Few sections of the "Oolitic Member" of the Wilkawillina Limestone examined by the writer, however, lack at least thinly developed birdseye limestones.

The suggested "Skeletal Member", a dominantly skeletal grainstone/ packstone unit of the Wilkawillina Limestone, is approximately 235 m thick in the Ten Mile Creek type section. In general, this unit corresponds lithologically with the uppermost parts of the Upper Member of the Ajax Limestone (Daily, 1972b). It contains varying amounts of oolitic material, but ooids are in the minority, the grainstones and packstones being dominantly composed of archaeocyathid fragments. Laterally these commonly interfinger with dark mudstones and wackestones, which are usually mapped as Parara Limestone. No direct lateral interfingering of the "Skeletal Member" of Wilkawillina Limestone and the Woodendinna Dolomite and Wirrapowie Limestone is known to the writer.

Parara Limestone

Mapped distribution

The Parara Limestone is the most widely mapped carbonate unit in the Lower Cambrian of the Flinders Ranges. It has been mapped on both the PARACHILNA and COPLEY 1:250,000 map sheets, being more common on the latter, where in the Arrowie area some 4,000 m of stratigraphic thickness of Parara Limestone has been recorded. Unfortunately very large areas mapped as Parara Limestone are not of this rock type, and the reasons for this are discussed below.

Comments on mapped Parara Limestone

Although the greatest bulk of the carbonate sequences mapped as Parara Limestone are younger than those rocks dealt with directly in this study, certain relevent features are clearly apparent at this stage and invite preliminary discussion. More intense study of rocks above Faunal Assemblage 2 is required to precisely define the problems associated with this most complex unit.

The name Parara Limestone was first proposed by Tepper (1879) for the dark coloured Cambrian limestones exposed near Ardrossan on Yorke Peninsula. These limestones are generally very fossiliferous, with rich faunas containing brachiopods, trilobites, archaeocyathids, gastropods and hyolithids (Daily, 1956). Lithologically most would be defined as good wackestones with occasional mudstones and packstones; some interbedded calcareous shales also occur near the top (Daily, pers. comm.). The sequence is commonly affected by various degrees of mottling.

The name Parara Limestone was extended to the Ten Mile Creek type section of the Flinders Ranges by Daily (1956) on the basis that the limestones "are so similar to the Parara Limestone of the Ardrossan area that without hesitation the term can well be applied to them". Daily (1956) recognized a Lower and Upper Member of the Parara in the Ten Mile Creek type section. The Lower Member, a dark nodular to flaggy limestone, is widespread in the Flinders Ranges, and although it may contain richly fossiliferous horizons, it is generally poorly fossiliferous. It makes up the greater part of the mapped Parara Limestone of the Flinders Ranges, and is a major rock-type of the extremely thick sequences of dark coloured, sparsely fossiliferous limestones of the Arrowie Basin (Wopfner, 1970). Dalgarno and Johnson (1963) also considered that the mottled, shaley, blue-grey limestones of basin areas were of this lithology.

Richly fossiliferous wackestones identical to those of the Parara Limestone of Yorke Peninsula have accumulated under somewhat shallower conditions on the flanks of the Wilkawillina graben, in which the Ten Mile Creek section was measured, and are preserved as relatively thin sequences (Daily, pers. comm.). In the present writer's view these very fossiliferous dark wackestones are of limited distribution in the Lower Cambrian of the Flinders Ranges. It is here argued that to apply the name Parara Limtestone on the basis of these fossiliferous wackestones, to the thick, poorly fossiliferous lime-mudstones of the more basinal areas of the NE Flinders is most misleading. It is suggested that at some future time, a new formation name should be applied to the more basinal lime-mudstones presently mapped as Parara Limestone.

The Upper Member of the Parara Limestone of the Ten Mile Creek type section is a distinctive, finely-laminated, flaggy, black limestone with relatively rare fossiliferous beds, the fauna being apparently of an allochthonous nature (Daily, pers. comm.). This lithotype is not common in the Lower Cambrian of the Flinders Ranges.

Of the dark coloured limestones mapped as Parara Limestone in the Flinders Ranges, at least two other distinctive lithological units are known to the writer. The first is that referred to as the archaeo/algal boundstone lithofacies in this study. Although the limits of distribution were not sufficiently assessed, it appears that this facies may constitute a mappable unit at least in the NE Flinders (See Fig. 5). More detailed work is required, however, since equivalent lithologies are known from other levels in the Lower Cambrian, and have been reported from the Oraparinna Shale (Haslett, 1969) and Parara Limestone (Hatcher, 1970).

At the time of uppermost Faunal Assemblage 2 and later, thick dark siliceous calc-mudstones developed in most parts of the north and north-eastern Flinders Ranges. This unit was recognized and informally described by Cooper et al. (1963), who considered it to be a regressive facies corresponding to a period of great stability in the depositional basin. In the limited areas that the writer has studied this unit in detail, namely at Old Wirrealpa Spring, this would appear to be, in general terms, a reasonable interpretation. The thick and widespread development of these dark siliceous limestones in younger carbonates of the Lower Cambrian would suggest that they might well warrant formation status at some future time.

Ajax Limestone

Distribution

As indicated above, this formation has only been mapped over a very limited area in the north-western Flinders Ranges. Its occurrence is restricted to the Mt. Scott Range, the Ediacara and Ajax Mine areas, and a narrow faulted zone near Beltana (See COPLEY 1:250,000 map sheet).

Discussion

In expanding the term Ajax Limestone to embrace all carbonates above the Pound Quartzite and below a sequence of unnamed clastics in the Mt. Scott Range, Daily (1956) published what is still probably the most detailed description of the lithologies of that formation. These descriptions are generally in agreement with those of Cooper et al. (1963), although these later workers recorded a slightly thicker basal, unfossiliferous dolomitic unit. The total thickness measured by Daily (1956) was 221 m, whilst that of Cooper et al. (1963) totalled 275 m.

On the basis of lithology, Daily (1972b) subdivided the Ajax Limestone informally into a "Lower member" and an "Upper member", the members being 100 m and 120 m thick respectively. Daily (pers. comm. 1976) considers that the "Lower member" is equivalent to the Woodendinna Dolomite, as recently defined by Haslett (1975). According to the published descriptions of Daily (1956; 1972b) and Cooper et al. (1963), the "Upper member" of the Ajax Limestone consists predominantly of archaeocyathid skeletal grainstones and packstones, with patchily developed archaeocyathid biostromal boundstones toward its top (Daily, 1972b). This "Upper member" contains the regional disconformity recognized at the top of Faunal Assemblage 2 by Daily (Daily in Thomson et al., 1976). The "Upper member", although it contains certain distinctive lithologies (Daily, pers. comm., 1976), appears from published descriptions to be closely comparable lithologically with the Wilkawillina Limestone of the Ten Mile Creek section.

In the light of its close lithological affinities with formations mapped elsewhere in the Lower Cambrian of the Flinders Ranges, viz. the Woodendinna Dolomite and the Wilkawillina Limestone, the present writer questions the practicality of retaining the Ajax Limestone as a distinct and separate formation in the Mt. Scott Range area.

LOWER CAMBRIAN TECTONISM

Introduction

Intermittent tectonism occurred throughout the depositional basin during the development of the Lower Cambrian carbonate sequences. Regional facies distributions as discussed above suggest the presence of major, long active hinge zones. The Lower Cambrian carbonates also characteristically show abundant, abrupt local facies changes which have hitherto been ignored in this study.

The association between deposition and contemporaneous faulting is probably best seen in areas of the Central Flinders Ranges. The Ten Mile Creek type section is itself located within a syndepositional graben with concomitant facies changes on its southern flank (Daily, 1956; Dalgarno, 1964). Pierce (1969) has detailed a number of small fault controlled basins in the top of the Wilkawillina Limestone in the vicinity of Balcoracana Creek. These basins contain a contracted sequence deposited at a time of erosion of areas on the basin margins. On the western margin of the Ranges Lower Cambrian faulting has been recorded by Dalgarno (1964) near Brachina Gorge.

By far the most numerous local facies changes occur in relation to regional hinge zones like that of the Wirrealpa Hinge Zone. These zones have long been the focus of tectonic activity. Evidence of this may be seen from the preferred orientation and concentration of present day fault exposures along these lines (Fig. 5). Associated with these zones of deep seated faulting, structures which are generally believed to be diapiric intrusions are commonly found (Dalgarno and Johnson, 1968). The apparent syndepositional intrusion of some of these complex structures in the Lower Cambrian has given rise to a considerable number of local facies in the adjacent carbonate sequences (Dalgarno, 1964; Haslett, 1969; Pierce, 1969; Mount, 1970; Daily, 1972a; Coats et al., 1973 etc.). The following section of this thesis will deal in detail with one example of the local facies development adjacent to such a structure. A very brief introduction to the concept of diapirism in the Flinders Ranges is a necessary antecedent to this.

Diapirism in the Flinders Ranges

In the Flinders Ranges areas of severe brecciation were first reported from near Blinman by Howchin (1907) (See Mount, 1975). Howchin and later workers extended these observations to exposures of similar material which were found to outcrop elsewhere in the Flinders (Howchin, 1916; 1920; 1922; Jack, 1913; Mawson, 1923). These complex features were considered to be tectonic breccias of some sort until the mapping of the WILLOCHRA 1:63,360 map sheet by Webb and Von der Borch (1958) when they were mapped as diapiric intrusions. This initial interpretation was further enlarged upon by Webb (1960). Since that time more than 150 structures have been mapped as diapirs on the regional (1:250,000) map sheets (ORRORROO, PARACHILNA, and COPLEY). The mapped structures range in area from 200 sq. km. (Worumba) down to very small exposures measured in terms of a few hundred square metres.

In the Flinders Ranges, those brecciated zones which are large enough to be considered representative in outcrop show a number of ubiquitous characteristics. These are...

(1). They are topographically subdued, and often covered with thick scrubby vegetation.

(2). Outcrop is characteristically poor.

(3). Geophysical techniques including gravity give no uniform or characteristic response over these areas of brecciation.

(4). The bodies vary greatly in size and shape, although most may be considered to be elongate in plan.

(5). The brecciated areas are invariably associated with faulting in the adjacent sequences. Many are related to zones of persistent and probably deep seated fault activity.

(6). Contacts with adjacent rock types vary greatly, from very sharp to extremely complex.

(7). Breccias are mineralogically composed mostly of carbonates.

(8). Exotic lithologies present within the breccias are extremely diverse. Most can be related lithologically to rocks within the Lower Callanna Beds of the Willouran Series. Carbonate rock correlation in the breccias is extremely tenuous due to diagenesis.

(9). Sorting of fragments in the breccias is extremely poor. Grainsize may range from blocks in the order of kilometres across, down to the finest rock powder.

(10). A layering is often seen in the breccias. It is commonly referred to as a "flow layering" (Coats, 1965; Mount, 1975) and is usually sub-parallel to the host rock contacts. The layering tends to stream around larger clasts. It may also be polyphase in its occurrence, with later layering cutting sharply across earlier layers. Various low temperature metasomatic minerals may lie within the layering.

(11). Diagenetic minerals within the breccias are indicative of low pressures, low temperatures, open system, oxidizing, alkaline, CO_2 rich, aqueous conditions (Mount, 1975).

(12). Basic igneous bodies are very common within the breccia zones and are of at least two broad categories. The first represent volcanics which are lithologically able to be correlated with those of Willouran sequences elsewhere in the Flinders Ranges. The second, coarse-grained dolerites, are intrusives either into "pre-diapiric" Callanna Beds or maybe into the breccia zones themselves. Convincing evidence that these basic rocks intrude adjacent country rock sequences is lacking.

(13). Massive evaporites are not known from either the "diapirs", or the proposed source sequences in outcrop or at the limited depth the structures have been drilled.

(14). Areas containing lithologies characteristic of Lower Callanna sequences have been exposed at the surface on numerous occasions and reworked into contemporaneously developing sedimentary sequences of the Flinders Ranges. The resultant boulder beds may be spatially related, in many instances, with present day exposures of "diapiric" breccia (Dalgarno and Johnson, 1968; Daily and Forbes, 1969; Haslett, 1969; Coats _et al_., 1973).

(15). The exposure of these Callanna-type lithologies in central basin areas of the Flinders Ranges has taken place over a wide period of time (at least Mid-Sturtian to Lower Middle Cambrian). Sometimes a number of periods of such exposure can be related to a single outcropping area of breccia, e.g. Pinda Diapir (See Coats _et al_., 1973). Furthermore, evidence of exposure involving onlapping relationships rather than reworking is available from the Cambrian, e.g. Mt. John Diapir (Daily and Forbes, 1969), the Permian, e.g. Blinman Dome Diapir (Coats, 1963), from the Triassic, e.g. Burr Diapir (Coats, _et al_., 1973, Mount, 1975), Tertiary, e.g. silcretes on Mt. Painter "diapirs" (Murrell, pers. comm.) as well as the abundant Quaternary and Recent onlaps.

Major studies of the breccia bodies have been carried out by Coats (1963; 1964; 1965), Dalgarno and Johnson (1968), Johns (1971) and Mount (1975). These workers all support, in general terms, the earlier interpretation of Webb (1960), namely that the bodies are diapiric intrusions. This hypothesis considers that the brecciated zones represent piercement structures which have formed by flow of the most basal sedimentary sequences of the Adelaide "Geosyncline", the Callanna Beds upward through the thick (10-15 km) overlying younger sedimentary sequences of the basin. These structures are not restricted to anticlinal cores, but are also believed to be injected along faults in the cover sequence. The source rocks, the Callanna Beds, consist predominantly of shallow water sediments, carbonates and shales with less common interbedded volcanics; they are also considered to have contained massive evaporites. These sedimentary sequences are believed to have become brecciated and chaotically mixed during their mobile phase(s) of emplacement to form the diapiric breccias of the present-day exposures. The postulated evaporitic beds of the source sequences are believed by Coats (1965) and Dalgarno and Johnson (1968) to have imparted both the mobility and a positive buoyancy to the intruding breccias; Mount (1975) attributed only the mobility to the presence of saline evaporites, and did not consider the intrusive material to have any marked positive buoyancy.

There exists a certain conformity of opinion among the above workers in regard to the intrusive nature of the "diapirs", the identity of the source beds, and the genesis and prior mobility of the breccia material; their views differ to some degree on the timing and mechanism of "diapir" emplacement. Relatively forceful intrusion of the structures was postulated by Coats (1965) and Dalgarno and Johnson (1968), with a resultant upturning of the intruded sequences at the "diapir" margins, in a manner akin to that of salt dome intrusions. These workers also envisaged that the emplacement had taken place spasmodically over a long period of time during sedimentation within the basin. Mount (1975) related the intrusion of the diapirs to phases of the Delamerian Orogeny, and stated that the intrusion was passive and occurred under conditions of tensional stress in the overlying intruded sequences.

Mount (1975) has clearly illustrated that the word "diapir" is loosely applied in the literature, and that the local concept of "diapirs" and "diapirism", as briefly given above, may not accord either with the original definition of a "diapir", nor necessarily with the generally accepted present-day meaning of the word. He suggested that the "diapirs" of the Adelaide "Geosyncline" be termed "sedimentary salt breccia intrusions". Despite a general concordance of views among the above workers, the origin and nature of the "diapirs" remains a controversial aspect of the local geology. There is a view that the breccia exposures of the Flinders Ranges might be interpreted otherwise than as "diapiric" structures.

It is not the aim of this study to deal with the general problem of "diapirism" in the Flinders Ranges, nor to make an assessment of the nature or mode of emplacement of these brecciated bodies. However, this thesis is concerned with the stratigraphy and sedimentology of the Cambrian carbonates in the vicinity of the northern part of the Wirrealpa Diapir, a body which shows the above-listed characteristics and which plays an intimate part in the geological history of the study area. It has been necessary to make studies of the relationships between the Cambrian sequences and the breccia bodies, and these studies have led to conclusions about the interpretation of the breccias, which are discussed below (pp.73-91).

These conclusions suggest that alternate interpretations to the structure being a "diapiric" intrusion are possible, and for this reason the word "diapir" is used in this thesis to describe exposures within the Adelaide "Geosyncline" which have the above-listed characteristics (p. 28), but its use is not meant to imply any particular genesis for the bodies.

PART II: THE GEOLOGY OF THE LOWER CAMBRIAN CARBONATES, OLD WIRREALPA SPRING.

INTRODUCTION

GENERAL

Old Wirrealpa Spring lies 603 km by road from Adelaide and is 27 km due east of BLINMAN in the central Flinders Ranges (See Fig. 4). Access to the area by two-wheel drive vehicle is somewhat limited due to a moderate to rugged topography, and dry, boulder strewn creek beds. Flooding of these creek beds only occurs during brief but intense rainy periods in the normally hot, arid climate.

The arid conditions, and the sparse cover of natural vegetation result in extremely good outcrop. Topographically subdued areas of "diapir", which are often covered by Quaternary and Recent soils and outwash gravels, are the only exception.

Post-depositional deformation and metamorphism have had a minimal effect on the Cambrian sequences at Old Wirrealpa Spring. The sequences have been folded during the Delamerian orogeny into a series of broad synclines and slightly tighter anticlines with subhorizontal fold axes. These fold axes are commonly curved forming a series of structural basins separated by horizontally plunging anticlines or areas of "diapiric" material (See Fig. 8). Faulting is common and relatively complex. As will become apparent in detailed discussions below, the structural complications at Old Wirrealpa Spring originate more from the extended period over which deformation has taken place, rather than the intensity of the deformation itself.

It was in part, however, the extensive brecciation at Old Wirrealpa Spring which caught the eye of the earliest workers in the area. Howchin (1922) commented on the extraordinary brecciation, and several others made passing reference to the peculiar chaotic nature of the outcrops in part of the area, without becoming involved in explanations of their origin. For most early geologists, the thick sequences of fossiliferous carbonate rocks held the greatest attraction, and much of the early understanding of the Cambrian stratigraphy of the Flinders Ranges came from the Wirrealpa area and the Bunkers Range to the immediate south (Etheridge, 1905;

Howchin, 1907; 1922; Taylor, 1910; Mawson, 1939). Later still, in the mapping of the BLINMAN 1:36,360 and PARACHILNA 1:250,000 geological map sheets (Dalgarno and Johnson, 1966) and in other publications, e.g. Dalgarno, 1964, Dalgarno and Johnson, 1968, Daily and Forbes, 1969, quite a number of aspects of the sequences in the vicinity of Old Wirrealpa Spring proved noteworthy. These included the thickness and completeness of exposed Cambrian sections, their marked regional change in lateral facies, and the remarkable local facies changes which Dalgarno and Johnson (1968) attributed to the syndepositional intrusion of the Wirrealpa Diapir.

Further work by Haslett (1969) and Pierce (1969), in dealing with the stratigraphy of the area in greater detail, illustrated that some of the earlier mapping had been in error, and more importantly, that several complex stratigraphic and sedimentological problems remained unsolved in the Lower Cambrian sequences at Old Wirrealpa Spring.

THIS STUDY

Detailied work was carried out in the vicinity of Old Wirrealpa Spring in an effort to elucidate the geology of the Lower Cambrian carbonate sequences of Faunal Assemblages 1 and 2 (Daily, 1956) and their relationship to areas previously mapped as the Wirrealpa Diapir (Dalgarno and Johnson, 1966).

Field work

As acknowledged above, a base map on a scale of 1:10,000 was prepared with the assistance of the School of Surveying, SAIT. Since topographic contours over the area were unavailable, form lines were surveyed and plotted on aerial photographic enlargements at a scale of 1:2,500 and subsequently transferred to the base map enlarged to that scale. Completed maps were then reduced to a final scale of 1:5,000. The exceptionally good outcrop of the Cambrian sequences has enabled geological boundaries to be readily traced in the field and later photo-interpretation has been minimal in the preparation of the maps.

Considerable parts of the Donkey Bore sequence (See Fig. 9) and the "diapir" were found to be geologically so intricate that they could easily warrant mapping at a more detailed scale. Time did not permit this, and it is felt that the resultant maps of these areas, although presenting an accurate record of the geology at the mapped scale, still only show a gross simplification of the exposed rock relationships.

Laboratory methods

Over two hundred stained thin sections of the Lower Cambrian carbonates have been examined. Many of these (50) have been large in size, up to 20 cm x 10 cm. This work has been further augmented by the scrutiny of numerous etched and stained rock slabs and acetate peels.

No detailed petrology has been done on rocks from the diapir due to limitations in available time.

Ooids and pisolites have been investigated using a Siemens 370 scanning electron microscope and elemental determinations carried out with the attached multi-channel spectral analyser.

Organic carbon determinations were done on the insoluble residues of acid digestion using a Leco Gravimetric Carbon Determinator.

Presentation

Basic geological information is presented on three adjoining 1:5,000 map sheets (Fig. 10) which are numbered sheets 1, 2 and 3 from west to east (See Fig. 9). The mapped area is covered by an arbitrary grid system, which is used in the text to make reference to specific localities. A location written 2-H9 refers to a point on map sheet 2 with vertical co-ordinate H and horizontal coordinate 9.

The map legend (Fig. 11) and symbol sheet (Fig. 12) are meant for convenience to be used for all three sheets of Figure 10, and present a symmary of the general characteristics of each mapped unit.

The Cambrian of Faunal Assemblages 1 and 2 in the Old Wirrealpa Spring area occurs as three geographically and geologically distinct sequences which have been termed the Black Dog Hill sequence, the Donkey Bore sequence and the Wirrealpa Hill sequence (See Fig. 9). At the present erosion surface the sequences are separated by areas of complex brecciation usually termed the Wirrealpa Diapir. In this thesis, a detailed discussion of each of these four components of the local geology will be presented separately, followed by an overall account of the geological history of the Wirrealpa Spring area.

SEDIMENTOLOGY AND STRATIGRAPHY

BLACK DOG HILL SEQUENCE

Introduction

This sequence, which lies directly north of the Wirrealpa Diapir, strikes approximately east-west and dips gently northward. It is the thickest of the three exposed Cambrian carbonate sequences and shows numerous well exposed lateral facies changes.

In order to facilitate a description of the sequence, it has been subdivided into 6 sedimentary megacycles (Fig. 13). Each megacycle has points of similarity and differences with those above and below. They are numbered I-VI from the oldest to youngest. Individual megacycles are found to have laterally juxtaposed "diapir" outcropping to their west.

Geology

Megacycle I

The oldest outcrops of the Lower Cambrian form the base of this sedimentary megacycle in the Black Dog Hill sequence. The precise nature of the basal contact with "diapiric" rocks is never adequately exposed and remains somewhat problematic. Shales (Dls) and sandy dolomites (Dtd) of the "diapir" are often intensely deformed adjacent to the lowest exposed Cambrian. There is a total absence of reworked "diapiric" material in the basal exposed Cambrian carbonates whilst carbonates to the east of Map Sheet 3 (See BLINMAN 1:63,360 map sheet) overlie thin Parachilna Formation and uppermost Precambrian Pound Quartzite. To the west at 2-F6.5 a large, highly deformed outcrop of Pound Quartzite is exposed abutting the basal lithologies of megacycle I. For the above reasons, a faulted contact against diapiric material is presently favoured. Sedimentary megacycle I may be considered to have been deposited upon an older clastic sedimentary sequence probably following an erosional break. This is particularly evident in the west where Parachilna Formation is completely absent, i.e. at 2-F6.5.

The upper boundary of megacycle I is selected at a thin but laterally persistent stromatolite bed which outcrops from 2-E7 to 3-B13.

The lowermost outcropping carbonates are grey-green calcareous mudstones with minor interbedded flat-pebble conglomerates. To the west these give way to ooid grainstones which become progressively more deformed and secondarily dolomitized as the Pound Quartzite body is approached at 2-F6.5. At stated above, non-carbonate clasts are absent from these basal beds.

Some 6 m stratigraphically above the first outcrops of Cambrian, the first of a series of coarse non-carbonate detrital beds occurs (Plate 2b). This bed thins rapidly to the east into calcareous mudstones and thin dolomitic mudstones, some of which may show irregular thinly interbedded quartz sandstone lenses. This initial appearance of coarser clastics to the west, passing laterally into fine calcareous mudstones eastward, anticipates a persistent sedimentological situation found throughout the rest of the overlying Black Dog Hill sequence.

The entire eastern part of the sequence in megacycle I is dominated by flaggy dark coloured calcareous mudstones (Plate 2c). The sequence is identical to that of the Wirrapowie Limestone described in PART I. The mudstones contain an appreciable fine insoluble residue (approximately 20%), and are for the most part cryptalgal in origin. Desiccation mud-cracks, although generally rare, do occur and indicate a very shallow, sometimes emergent depositional environment. Worm trails are also infrequently found as are wedge-shaped gypsum crystal casts. These further suggest a very shallow depositional environment, probably with intermittent restriction and hypersalinity associated with intense evaporation (Kinsman, 1966; Evans _et al_., 1969).

Numerous thin intraformational conglomerates are interbedded within the mudstone sequence. These are almost invariably associated with stromatolites. Both conglomerates and stromatolites tend to be laterally discontinuous, being broad thin lenticular bodies within the carbonate mudstone. They are considered indicative of shallow sheltered intertidal deposition (Lucia, 1972). Thickest build-up of flat-pebble conglomerates has occurred on what appear to have been slight depressions on a broad sheltered intertidal mud flat. Pebbles are mainly derived from nearby more elevated areas which, being subject to greater periods of exposure and desiccation, have provided mud-clasts to adjacent, lower areas during tidal water movements or during periods of storm activity.

Thicker parts of the intraformational conglomerate beds are commonly cut by steep-sided tidal channels. Channel margins are encrusted by algal stromatolites, with coarse conglomerates occupying the channel floor. No consistent imbrication of clasts has been observed within these channels.

Thin cross-bedded ooid grainstones and packstones are also interbedded with the calcareous mudstones to the east. They contain both dark and light coloured ooids, and occasionally are rich in dolomitic mudstone clasts. The grainstone beds thicken markedly to the west, as one approaches Wirrealpa Creek (2-E9), and there is a concomitant decrease in the proportion of dark coloured ooids in that direction in any individual bed. This is particularly true in the lower parts of megacycle I. The significance of the colour of the ooids will be discussed below, but the distribution of the two types in megacycle I may be seen in Fig. 14.

On Black Dog Hill itself, west of Wirrealpa Creek, grainstone beds become very abundant and thicken westward into massive units, with a corresponding thinning of interbedded mudstones. The ooid grainstone interbeds show medium-scale ripple marks on their upper surfaces (Plate 3a), indicative of a mobile mass being washed in a general, eastward direction into a dominantly mudstone environment. This is believed to have occurred during periodic penetration of higher energy conditions onto the eastward sheltered mud flat environments. Little difference in relative water depths is envisaged. Indications are that ooid grainstone sheets were deposited under shallow, sometimes emergent conditions. A curious rubbly surface is apparent on bed tops of some grainstones and is reminiscent of that seen on shallow recemented beachrock cobbles in some modern carbonate environments.

A marked increase in non-carbonate detritus is associated with the westward increase in grainstones in the sequence on Black Dog Hill. Quartz sands become common in the ooid grainstones and this non-carbonate component becomes coarser, more angular, more abundant and lithologically more diverse to the west. Quartz-sand grainstones (Plate 3b) pass laterally into pebble grainstones (Plate 3c) to massive poorly bedded boulder lithoclast grainstones (Plate 4a).

Stromatolite beds (Plate 4b) are similarly well developed in the western parts of megacycle I outcrop, as they are in eastern areas. The characteristics and significance of the stromatolites are dealt with in detail in PART III. At this point it is important to indicate that the stromatolites show characteristic changes from west to east with change of environment. One such change is that bioherms in the west show stronger and more rigid directional orientation than those to the east, confirming other evidence that energy conditions were higher, and current directions less random. These factors will be dealt with in detail below (PART III).

Sediments in megacycle I on Black Dog Hill, particularly those in the lower part, show a marked vertical cyclicity which is summarized on Fig. 14. Each cycle begins with a significant influx of lithoclast debris, composed of lithologies common in areas of presently exposed "diapir" to the immediate west. Sorting in these lithoclast beds is characteristically poor but improves laterally to the east, as overall grainsize decreases. Within the vertical cycle, lithoclasts decrease in grainsize and abundance upward, until grainstones are dominantly composed of cross-bedded, well sorted ooids.

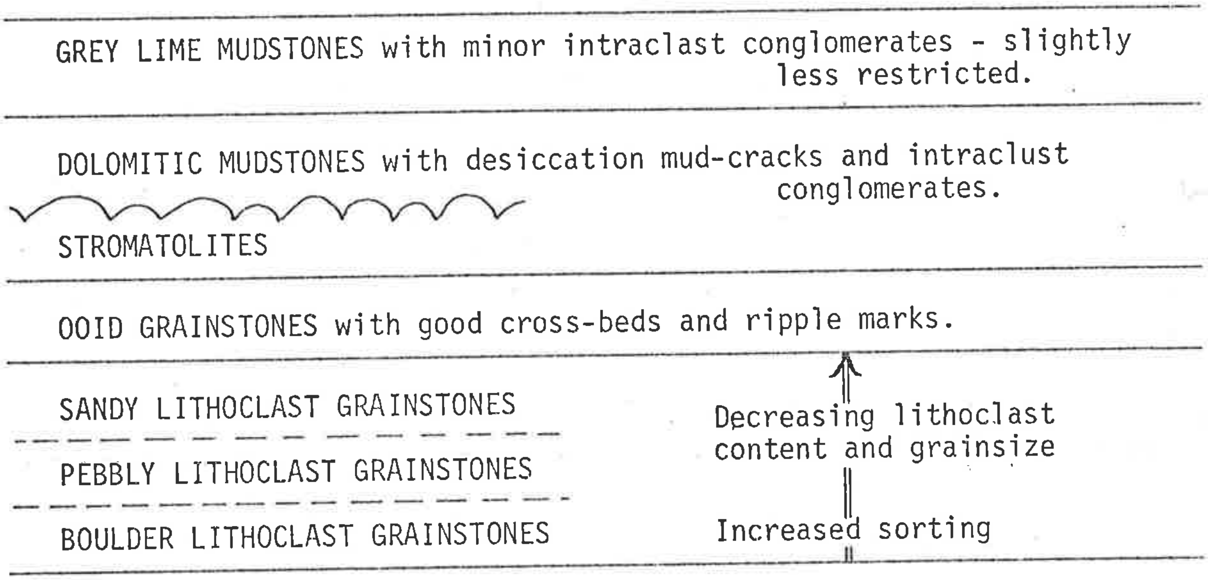


FIGURE 14: Idealized sedimentary cycle from the western parts of megacycle I, Black Dog Hill sequence.

The ooid grainstones are often overlain by biostromes of digitate stromatolites. To the west stromatolites are characteristically associated with progressively coarser and more lithoclast rich grainstones. Both stromatolite beds and grainstones may be cut by narrow pebble filled tidal channels (Plate 4c). Directly above the stromatolites, fine-grained yellow dolomitic mudstones commonly occur. These mudstones are associated with intraformational conglomerates, thin quartz sandstones and abundant desiccation mud-cracks. Thin calcareous mudstones, similar to those to the east, usually overlie the dolomitic mudstones and represent a return to more open, but still sheltered shallow marine conditions. Thick coarse lithoclast grainstones form the basal unit of the succeeding sedimentary cycle.

It is not known whether each cycle is instigated by local tectonic uplift of a suitable source or the removal of an energy barrier to allow the distribution of available nearby source material or both. The writer tends to favour the former possibility for reasons which will become evident below. In any case relatively high energy conditions were required to rework material from a source composed of an heterogeneous assortment of lithologies into nearby Cambrian seas. High energy conditions were dissipated both laterally to the east over shallow sheltered mud flats, and vertically in time, giving rise in the vertical cycle to progressively finer sediments and increased algal colonization. Stabilization of detrital material by algae growth resulted in the formation of the extensive stromatolite beds. Stabilization was no doubt also aided, in time, by slope equilibration with respect to the source, the eventual gravitational stability giving broad low energy flats on which earlier stromatolite growth changed to restricted supratidal dolomite formation. Subsequently, slow subsidence with a corresponding encroachment of fresher marine waters is indicated in the vertical sedimentary cycle by the presence of calcareous mudstones succeeding dolomitic mudstone deposition. These mudstones, and probably in many cases some of the underlying sequences as well, were frequently reworked as intraclast conglomerates at the initiation of the high energy conditions in the next sedimentary cycle.

About ten such cycles appear to have occurred in the lower part of sedimentary megacycle I. Many, however, are not complete in all details due in all probability to either erosion, or the non-completion of each cycle before the onset of the next, or both. Sediments in the upper part of megacycle I characteristically indicate a less energetic depositional environment with fewer, smaller, available lithoclasts. Ooid grainstones with black ooids are dominant, and these units are interbedded with thick biostromal stromatolites.

The sedimentary cycles of the underlying sequence are not present, and uppermost grainstones and stromatolites are laterally more persistent.

Conditions would appear to have been far more stable during the deposition of the upper beds in megacycle I. Energy conditions, whilst remaining appreciable in the west, would appear to have been less extreme, and a nearby lithologically heterogeneous source with high relief would seem to have been less likely.

Whilst dealing with sediments in megacycle I it is necessary to make two slight digressions before continuing with a description of the Black Dog Hill sequence. The dirst digression is a discussion of the possible significance of the two different coloured ooids found in grainstones of megacycle I. A second divergence involves preliminary observations on the contact of the sedimentary megacycle I beds with rocks previously mapped as "diapir" to their immediate west.

Significance of ooid colour

Grainstones composed of black ooids and those of white ooids are for the most part distinct from one another at Old Wirrealpa Spring. Black ooid grainstones appear abruptly in the sequence at a level which corresponds approximately to a marked decrease in lithoclast debris and a lowering of energy conditions (See Fig. 15). The only appreciable intermixing of ooid types occurs in the distal tails of white ooid grainstone wedges into the eastern mudstone sequence. In these, dark ooids become more abundant to the east, and composite ooids are common. Composite ooids may have black coatings on white nuclei or vice versa, the latter probably being the more common.

The distal tails of the white ooid grainstones should strictly be termed packstones and wackestones rather than grainstones sensu stricto, since carbonate mud is common and may be dominant in the most easterly out-crops. Similarly upon thin section examination it has become clear that black ooid grainstones of Fig. 15 are in large part packstones with minor wackestones.

The internal structures of the two ooid types are distinctive in thin section. White ooids are composed of an interlocking mosaic of micrite, and a well developed concentric structure and with little or no indication of a radial structure (Plate 5a). The concentric lamination consists of thin zones of darker very fine micritic material. Quartz sand, pellets and rare unidentified skeletal fragments form the ooid nuclei. Under the microscope, the ooids are greyish-white in colour and relatively translucent.

In contrast, the black ooids are yellow to honey-brown in thin section and consist of elongate calcite crystals arranged radially. The radial crystals may be grouped in "bundles". A fine concentric structure is usually developed but the radial microfabric is dominant.

Both ooid types are of similar size, ranging from .75 mm up to 1.5 mm, by far the greatest number being approximately 1 mm in diameter. Neither type shows an extinction cross under crossed polars. The two types are also indentical with respect to their mineralogy, both being composed of low Mg-calcite. Qualitative analysis using a multi-channel analyser on a scanning electron microscope indicates that both ooid types contain only calcium and oxygen. Carbon was not determinable due to limitations in the counter window aperture. Other elemental components expected, e.g. strontium, magnesium, manganese, iron, sulphur etc. were carefully searched for, but were not present, even in trace amount, in either ooid type.

The white ooids, in having a cortex of concentrically lamellar, cryptocrystalline carbonate, are similar in texture to those found in Recent marine environments (Newell et al., 1960; Bathurst, 1975). Original aragonitic mineralogy no longer persists in the Cambrian ooids, if in fact such a mineralogical analogy with present-day environments is valid (See Bathurst, 1975 pp.82 or more particularly Sandberg, 1975). Calcite crystallographic axes within the Cambrian ooids do not appear to show any preferred orientation, in contrast to that reported for Recent marine ooids (Illing, 1954; Bathurst, 1975).

The black ooids show a marked similarity to those reported from Great Salt Lake, Utah, by Eardly (1938). They differ from them, however, in their colour (The Great Salt Lake ooids are white in colour) and the Cambrian ooids lack any indication of clay mineral inclusions. Despite the very close textural similarities, Great Salt Lake ooids are of mixed calcite-aragonite composition (Bathurst, 1975) whilst at Old Wirrealpa the ooids are now uniformly of low Mg-calcite. Very similar structures have recently been recorded as relic magnesian calcite ooids from the Amazon Shelf (Milliman and Barretto, 1975). Likewise very small ooids of analogous microstructure, and also composed of high Mg-calcite have been recorded by Marshall and Davies (1975) from the Great Barrier Reef. D'Argenio et al. (1975) comments on the origins of radial-fibrous ooids found off the Bahamas, and compares them both to the ooids of Great Salt Lake, and to those within Apenninic Limestones of Italy.

Within ancient carbonates, structures very similar to the black ooids have been described by Korde (1954; in Johnson, 1966 pp.55) as Cambrian algal remains, which he assigned to the genus Poecilophycus. Shearman et al. (1970) also records radial fibrous ooids from certain Jurassic limestones where he considers the radial-fibrous pattern to be diagenetic and superimposed upon a primary concentric structure. Bathurst (1975 pp.83) implies that this radial elongation of calcite in ancient "golden-brown" ooid coats is secondary. The colour he attributes to "contained organic substances". Simone (1974; in D'Argenio et al., 1975) considers the radial fibrous texture to be primary.

Mineralogically, the black ooids at Old Wirrealpa are exclusively composed of low Mg-calcite. This contrasts with those of Marshall and Davies (1975) and Milliman and Barretto (1975) both of whom report high Mg-calcite compositions of modern relic ooids. The black colouration is attributed by Milliman and Barretto to the presence of iron sulphides. Davies (1970) also suggests that iron sulphides are responsible for black pigmentation in ooids and grains from anaerobic seagrass environments in Shark Bay W.A. Black pigments in grains from the Great Barrier Reef are reportedly due to iron and manganese sulphides (Maiklem, 1967).

Analyses of the black ooids from the Cambrian at Old Wirrealpa Spring do not, as stated above, show any trace of iron, manganese, magnesium or sulphur, and indeed have a detectable elemental composition of calcium and oxygen only. It seems likely therefore that organic carbon may be the pigmenting agent. A technique to separate and quantitatively analyse the black ooids has not been available to the writer but whole rock uncombined carbon analyses of samples of ooid grainstones containing on the one hand only black ooids, and on the other only white ooids was carried out. These analyses revealed that the former contained approximately double the amount of carbon of the latter (.02% for black ooid grainstones, .01% for white ooid grainstone).

As pointed out above, in the past it has been considered reasonable to assume that ancient ooids had an original aragonitic mineralogy which has since been diagenetically altered (e.g. Shearman et al., 1970; Bathurst, 1975). A very recent paper by Sandberg (1975) casts doubts on the validity of this argument. At Old Wirrealpa Spring the precise effect of diagenesis upon either the original ooid mineralogy or microstructure is not clear. Definite and demonstrable differences in the distribtuion, lithological associations, and microstructure of the black and white ooid-types are present however. In view of the close association of the ooid types in some beds, and their clearcut composite nature in many places, it is felt that despite possible diagenetic alteration of primary structures, the microstructure of the Cambrian ooids reflects a real and significant difference in origin for the two types of ooid.

The light coloured ooids which have a concentrically laminated micrite cortex, are believed to have formed under open, high energy marine conditions. They are abundant throughout the Cambrian of the Flinders Ranges in well-sorted cross-bedded grainstones, often associated with rocks containing good diverse marine faunas.

The dark ooids are far less common and tend to be associated with lower energy conditions, and dark carbonate mudstones, wackestones and packstones. Conditions are certainly more sheltered and possibly somewhat restricted in sediments closely associated with the black ooids. It is felt, however, that reduced turbulence in the environment in which they have formed is of more significance than any restriction or hypersalinity. Ooids from energetic but hypersaline modern environments (e.g. eastern Hamelin Pool, Shark Bay W.A.) are not characterized by either dark colour or radial-fibrous structure.

The role of algae in the development of the black ooids cannot be confidently assessed, but algal limestones are much more closely associated with the dark ooid limestones than the white ooid grainstones. The algae may simply limit the movement of ooids during their growth. The details of the ooid/algal association have not been adequately researched in this study.

In summary, the two distinct ooid types within the Cambrian at Old Wirrealpa Spring are believed to reflect differences in their environment of formation. Pale, concentrically laminated micritic ooids are indicative of open high energy environments and possibly are broadly analogous with the modern marine ooids of Newell _et al_. (1960). The black ooids are believed to have formed in a more sheltered environment with or without enhanced salinities. They are most similar to modern ooids from less turbulent, shallow hypersaline lagoons, e.g. Great Salt Lake. Their microstructure is considered to reflect the limited turbulence of the depositional environment rather than elevated salinities. The black colour is due to contained, finely dispersed organic carbon, although precise quantitative verification of this has not yet been achieved.

In the light of the recent work of Sandberg (1975) it is interesting to speculate that the microstructure of the light coloured ooids might indicate an original aragonite mineralogy, in contrast to an original calcitic composition for the black, radial-fibrous Cambrian ooids. Likewise, an extremely interesting comparison may be made between the two ooid types described above, and "calcrete" ooids and cave pearls of Cambrian age, which occur in the Donkey Bore sequence to be described below. These ooids and pisolites of subaerial or vadose origin show a strong similarity in microstructure with the dark ooids of the Black Dog Hill sequence. All three Cambrian ooid-types are at present mineralogically indistinguishable.

Sedimentary megabreccia or diapir?

In mapping the western limits of the Cambrian sedimentary rocks in megacycle I certain fundamental difficulties become apparent. Contacts with the area previously mapped as diapir (Dalgarno, 1964; Dalgarno and Johnson, 1966) were found to be extremely complex and gradational, in contrast to the "knife-sharp" contacts ascribed to the diapirs elsewhere, e.g. Arkaba (Mount, 1975), Thompson Gap (Daily, pers. comm., 1976). This problem will be discussed at length below (See p. 73) but since it relates to the following descriptions of the Lower Cambrian sequences, some preliminary observations are necessary at this point.

As indicated above, lithoclast grainstones in sedimentary megacycle I become coarser grained, more poorly sorted and richer in angular exotic clasts as one approaches the "diapir" contact to the west. As sorting becomes poor, secondary calcareous cement becomes volumetrically less abundant, and the grainstones and packstones become correspondingly less well outcropping. Outcrops eventually degenerate into areas of low rubbly matrix material in which sit large to very large exotic, disoriented blocks of lithologies commonly ascribed to areas of diapir (Plate 5b). Low-down in megacycle I these blocks are principly dolerites and sandstones, with yellow secondary dolomites being more abundant further up the sequence. To the west, in mapping these areas of poorer outcrop, it was difficult to be confident that the rocks being mapped were not, in fact, "diapir". Well exposed creek sections, however, confirmed that the lithologies constituted a good clastic breccia of sedimentary origin. A strong superficial similarity existed, however, between the sedimentary breccia and rocks termed "diapiric" breccia elsewhere in the Adelaide "Geosyncline".

As exotic boulders increased in size still further to the west, sedimentary megabreccias became essentially indistinguishable from what in the past might have been considered good diapir outcrop. Despite the fact that the area in question (2-E/F6.5) is stratigraphically underlain by unequivocal Cambrian carbonate sequence, there remained the possibility that the megabreccia lenses represented "diapiric" apophyses, "squirted" laterally from the west into an older Cambrian carbonate sequence of megacycle I. Fortunately it was found that numerous larger boulders of the megabreccia, some up to 4 m in diameter, have their upper surfaces encrusted by algal stromatolites (Plate 5c). These must have grown whilst the boulders were exposed in the Cambrian sedimentary environment, and argue against these megabreccias being formed by diapiric intrusion into a pre-existing country-rock sequence.

Whilst saving a major discussion of the "diapir" contacts until later, it is important that at least two critical aspects of the above brief example be emphasized at this stage to be borne in mind in later discussions. Firstly, "diapir"/Cambrian sequence contacts are not necessarily "knife-sharp" and simple, and secondly, rocks which might hitherto have been readily accepted as being of diapiric origin may in fact be very difficult to distinguish from sedimentary megabreccias of Cambrian age.

Megacycle II

The stable environmental conditions evident in the uppermost part of sedimentary megacycle I have continued into the basal parts of the succeeding cycle. Depositional slopes would appear to have been low, with ooid grainstones deposited in the west upon areas of peneplaned breccia material, previously mapped as diapir. Conclusive evidence of onlap is provided by lenticular ooid grainstone beds within depressions in underlying breccias (Plate 6a). The basal ooid grainstones in the western parts of the megacycle pass laterally into flaggy wackestones to the east, and these in turn, gradually give way to calcareous mudstones (3-C11).

The first preserved body fossils of the sequence occur in these basal beds of megacycle II. They consist of current-oriented accumulations of hyolithids which occur in large numbers on some wackestone bedding planes (Plate 6b). Minor archaeocyathids, and scattered unidentifiable fragments of skeletal remains are also present. Basal mudstones may also show rare worm trails. Stromatolites are absent from this part of the Black Dog Hill sequence.

Early in the depositional history of this sedimentary megacycle, mild movements on a fault at 2-E6 caused small scale facies changes with no related influx of lithoclast material. Later, however, sedimentation within megacycle II became dominated by a major tectonic event(s) to the immediate west, which appear to have been broadly similar to that which gave rise to the significant lateral facies changes evident in megacycle I.

Thick boulder-lithoclast grainstones are developed adjacent to poorly outcropping megabreccias at the western extremity of outcrop of sedimentary megacycle II. Boulders are dominantly composed of dolerite, with less common sandstone and rare dolomite boulders. The boulders are characteristically very well rounded (Plate 6c) even in the west. The coarser conglomerates have a clean carbonate matrix, and poorly developed stratification. Lenses showing crude inverse to normal grading may be found, and these suggest deposition on relatively steep gradients, proximal to a source area (Walker, 1975). The abundance of dolerite and the unusually good rounding of boulders suggests that a suitable source may have been composed of uplifted "diapiric" megabreccias and conglomerates previously occurring up dip and to the west of the exposed sequence.

The boulder lithoclast grainstones are interpreted as having been deposited under shallow subtidal to intertidal conditions adjacent to an active high angle fault scarp. The more lenticular units represent "feeder" channels for the dispersal of course clastics from an uplifted probably poorly consolidated megabreccia source into deeper parts of the Cambrian depositional environment. Marginal to these channels discontinuous bodies of digitate stromatolites are found.

Few dolerite clasts smaller than fist-size are found in the sequence. This size must have constituted a critical size limit with respect to mechanical and/or chemical disintegration in the sedimentary environment. Directly east of the boulder grainstones, the pebbles of the lithoclast grainstones are dominantly sandstones. Apart from an obvious decrease in lithoclast grainsize, the lateral equivalents to the east show good sorting and a well developed planar and in places medium-scale cross-stratification. Finer carbonate and non-carbonate material would appear to have been winnowed away into deeper areas by the relatively high energy conditions of the immediate depositional environment.

Sandy lithoclast grainstones pass laterally into ooid grainstones to the east (2-E7.5). Interbedded within the ooid grainstones are minor pisolitic and lithoclast beds, and significant birdseye limestones. The grainstones in this locality are believed to have constituted an offshore ooid shoal which limited, at least in the plane of present exposure, the penetration of lithoclast material into slightly deeper areas to the east. These offshore ooid banks were periodically emergent, as evidenced by the formation of birdseye limestones. Ooids are exclusively light-coloured.

Eastwards there is an extensive lateral development of wackestones and mudstones, deposited under what are believed to have been slightly deeper environmental conditions. At the eastern extremity of the mapped area (3-B13) there are indications that a shallowing or at least a periodic change to higher energy conditions occurred, since lenses of ooid grainstone have penetrated areas of wackestone and mudstone deposition from that direction.

Topmost sediments in megacycle II indicate a return to local tectonic stability. Exotic clast influxes cease, probably in response to the topographic degradation of nearby source rocks. The accumulation of ooid grainstones continued in areas which previously had seen the deposition of lithoclast grainstones. Conditions of carbonate sedimentation under stable gentle subsidence persisted into the basal part of megacycle III.

Megacycle III

Megacycle III shows a similar spacial distribution of sedimentary facies to that of the previous megacycle. After initial tectonic quiescence, local uplift has given rise to thick boulder, pebble and quartz-sand lithoclast grainstones adjacent to mainly doleritic outcrop at the western end of the sequence. As for megacycle II but in contrast to megacycle I, thick wackestones developed in slightly deeper, probably subtidal areas east of well exposed, intertidal ooid grainstones.

In contrast to megacycle II where postulated offshore shoals consisted of ooid grainstones, megacycle III contains a series of archaeocyathid/algal boundstone units, which are believed to have developed as offshore mud banks (2-E7). These boundstones are interbedded with wackestones and laterally interfinger with these rock types to the west. The archaeo/algal boundstones are laterally persistent, and this is thought to indicate low bottom slopes for the exposed present day section. That is, the present erosion profile at this level on sheets 2 and 3 is approximately parallel to the Cambrian palaeo-shoreline.

Within the boundstones, individual archaeocyathids are elongate, conical, and are oriented in their vertical growth positions (Plate 7a).

Dark cumulate areas of algal material along with exothecal growths bind individuals together. The preservation of fine textures is generally poor, but recognizable algal remains consist solely of Renalcis sp. Such an algal/archaeocyathid association has been reported previously by a number of Russian workers, e.g. Zelenov (1957); Zhuravleva (1960; in Hill, 1972), Rozanov (pers. comm., 1975). No trace of associated Epiphyton has been seen, Epiphyton being considered by the above workers to indicate growth of archaeocyathids in deeper water (50-100 m).

Archaeo/algal boundstone growth seems to relate to periods of relative tectonic stability. When sediment supply rates might be expected to have been high, during tectonic activity to the west, wackestone deposition was dominant. This is further reflected in the lower insoluble residue of the archaeo/algal boundstones and interbedded wackestones (approx. 4.0% and 7.8% respectively).

This content of terrigenous matter (i.e. 4 wt%) is well below that at which Zhuravleva (1960) found that archaeocyathid bioherms flourished best (i.e. 19-34%). Similarly it is difficult, in view of the nearby, laterally equivalent upper intertidal facies, to attribute a depth of even 30 m to their environment of development. This depth (30 m) is considered by the above worker to be that for optimum growth of archaeocyathid bioherms (Zhuravleva, op cit.).

Apart from Renalcis, a relatively rich fauna associated with the archaeocyathid bioherms is dominated by the brachiopod, Kutorgina sp. but also contains Nisusia, numerous hyolithids and various problematica. An interesting and possibly significant feature pertaining to the soft parts of the archaeocyathids themselves, is that the central cavities of even the upright archaeocyathid tests are seldom filled with an internal sediment. Rather, the central cavities are characteristically spar filled, sometimes with small amounts of internal sediment forming geopetal structures.

Toward the top of megacycle III the supply of lithoclast debris from the west was limited. Thick ooid and intraclast grainstones pass rapidly into wackestones and mudstones eastward. Very limited offshore bank development occurred, there bing only one small grainstone body, possibly of this origin, at 2-D/E7. The abruptness of facies changes suggests that carbonate sediment supply at this level was rapid, and that bottom slopes may have been significant for the first time in the deposition of the sequence under discussion. Shallow deposition areas to the west passed to deeper basin margins down dip and to the east.

Megacycle IV

The general depositional arrangement described above persisted into megacycle IV. Ooid grainstones to the far west overlie older megabreccias, the grainstones themselves showing evidence of periodic exposure, in the form of reddened laminated zones, minor thin cobbled and intraclast beds and common large fenestral structures which suggest dissolution, probably within the phreatic zone, well after initial lithification. Only minor lithoclast units are present in this lowermost part of sedimentary megacycle IV.

Continued stability and somewhat deeper conditions resulted in the deposition of carbonate mudstones well west of areas previously covered by lithoclast grainstones. These mudstones are characteristically affected by a diagenetic mottling (See PART III) and show no evidence of very shallow deposition or subaerial exposure. As sedimentation progressed archaeo/algal boundstones developed as offshore mud banks in stable, subtidal areas (e.g. 2-D/E6). These boundstones lens out gradually to the east passing into unfossiliferous mudstones, possibly of deeper water origin (Up to 100 m).

In megacycle IV, the onset of local tectonic instability becomes apparent in a similar manner to equivalent episodic events described below for older megacycles. Lithoclast pebbles are shed from the west into the depositional environment and form grainstone lenses which thin eastward. The average grainsize and thickness of these lenses is in this case, however, slightly less than for the pre-existing megacycles. (The apparent thickness of lithoclast grainstones at 1-E4 is primarily a consequence of topography). The lithoclast enriched units also contain, for the first time in this sequence, pebbles of reworked Cambrian archaeocyathid limestones.

As the lithoclast grainstones lens eastward into deeper basin margins, the actual interfingering with calcareous mudstones takes place in a slightly different manner than for previous megacycles. An apparently greater bottom slope has resulted, in this case, in the transport of coarser material into low energy subtidal areas by slumping and relatively small scale gravity sliding. The clastic wedges penetrate considerable distances into the mudstone sequence, as thin unstratified units with sharp basal and fairly sharp upper contacts. They continue even further east than can be illustrated on a map at the scale presented, and may be found as thin (20 cm) beds at least as far east as 2-C/D8. They are characteristically poorly sorted, in contrast to the extremities of lithoclast grainstones in the older cycles, where grainstone tails tend to be increasingly well sorted eastward. The calcareous mudstones in this part of the sequence may thus have been deposited below the effective wave base. The grainstones of sedimentary megacycle IV contain the last exotic lithoclasts in any substantial quantity, in the Black Dog Hill sequence. Older "diapir" type source rocks are apparently not exposed in the immediate vicinity after the end of sedimentary megacycle IV.

Megacycle V

Dark, poorly fossiliferous, calcareous mudstones dominate the sequence preserved in megacycle V. The mudstones are monotonous in character, with only a diagenetically induced mottling to provide any relief from the lithological uniformity (See PART III). Faunal remains are sparse, occurring in thin bands of highly fragmented hyolithids, trilobites, brachiopods and numerous unidentified forms. Intraformational conglomerates, stromatolites or any desiccation features are totally absent, supporting a projected subtidal shelf-edge to basin slope depositional environment for the mudstones.

The mudstone sequence persists across the entire area of outcrop of the Black Dog Hill sequence, except for the presence of minor wackestones at the western limits. Toward the top of megacycle V a more extensive wackestone wedge occurs adjacent to areas of outcropping "diapir". At 1-D2.5 skeletal grainstones, composed dominantly of archaeocyathid fragments may be found lateral to and westward of the wackestones. Within the nearby wackestones various slump features indicate a general movement of sediment downslope to the east and north-east away from present areas of exposed "diapir".

At least one extensive mudstone megabreccia outcrops in the upper parts of megacycle V. This bed has resulted from the slumping and gravity sliding of unconsolidated and semi-consolidated mudstones and wackestones from shallower areas toward deeper basinal areas down dip and to the east. The bed is thicker to the east and tails off westward, and will be discussed in more detail in PART III, CHAPTER 2. (See p. 113)

Fossils remain rare in the mudstones, but several specimens of Micromitra, which characterized Faunal Assemblage 2, have been found within 20 m stratigraphically from the top of the mudstone sequence in megacycle V (2-C7).

Megacycle V concludes with an enormous influx of skeletal clasts and grainstone fragments into these areas previously experiencing mudstone deposition. This resulted in the extensive development of a thick, skeletal grainstone wedge which thins gradually east and northward, where it interfingers with basinal calcareous shales (This occurs well north of the detailed map area - See PARACHILNA and COPLEY 1:250,000 map sheets).

The skeletal grainstones are massive and commonly cross-bedded toward the top. Secondary dolomite rhombs, authigenic quartz needles and stylolites are present throughout. Archaeocyathid skeletal remains are typically extremely fragmented and form a poorly to moderately sorted skeletal "hash". The grainstones are rich in the remains of Faunal Assemblage 2, including hyolithids, phosphatic brachiopods, problematica, and the index fossil "Micromitra" etheridgei. Most of the components within the grainstones appear to have been reworked under high energy conditions from nearby Cambrian sequences, probably exposed to the south.

The topmost surface of the skeletal grainstone unit in this megacycle appears to represent a substantial erosional unconformity, particularly in western, or more strictly, southern exposures. The upper surface is irregular and usually has a reddened, laminated carbonate crust developed at intervals upon it. Depressions in the surface are commonly filled by lenticular clastic limestones of the basal megacycle VI. Similar unconformities are developed at intervals within the skeletal grainstones as outcrops approach areas of presently exposed "diapir" to the south. The grainstone unit also thins marginally in this direction and contains an interbed of dark, fetid, finely laminated limestone (1-C2). The precise significance of this unit is not understood, but it may represent deposition in a shallow, sheltered and highly restricted basin on a subaerially exposed unconformity surface upon underlying skeletal grainstones. A similar depositional environment is envisaged for lenses of most unusual stromatolites on the topmost unconformity surface at 1-D2. These stromatolite bioherms and lenticular biostromes occupy a small (50-60 m) depression in the unconformity surface, and are notable for their considerable enrichment in hematite. The columnar stromatolites are deep red in colour, in a skeletal carbonate rock which, in the intercolumn cavities, is pale grey to creamish white in colour. The iron enrichment is confined to the lamellae within the stomatolite columns. In all other respects the digitate stromatolites appear quite normal in the field (Plate 7b). Similar structures have been reported by Playford et al. (1969) from the Devonian of Western Australia.

A suspicion that the structures might be inorganic in origin arises from the extreme regularity of the laminae in thin section. This suspicion is reinforced by the occurrence of very similar laminated hematitic surfaces found elsewhere in associaton with subaerially exposed carbonate rocks (See a discussion of the Donkey Bore sequence given below). Otherwise the gross characteristics of the bioherms are so convincingly those of digitate algal stromatolites both in the field and under the microscope, that any suggestion that they are of purely inorganic origin must be seriously questioned. On the other hand, their similarity with other laminated, reddened surfaces must suggest either some sort of algal fixing or iron in those surfaces, or some quite remarkable convergence of physical features between two different environmental processes.

The skeletal grainstones of megacycle V are in places secondarily dolomitized adjacent to areas of exposed "diapir". This dolomitization is markedly discordant, and results in the wholesale obliteration of sedimentary features in irregular zones within the grainstones.

Megacycle VI

Rocks of this sedimentary megacycle disconformably overlie those of megacycle V and are significantly different than older megacycles described above in that they lack evidence of major changes in depositional environment from west to east. Apart from minor complex changes in the extreme south-western exposures (1-D2), a uniformity of conditions appears to have persisted laterally, under relatively stable tectonic conditions. There occurred, however, a number of distinct but small-scale vertical sedimentary cycles within this part of the Black Dog Hill sequence (See Fig. 16 below and Plate 7c).

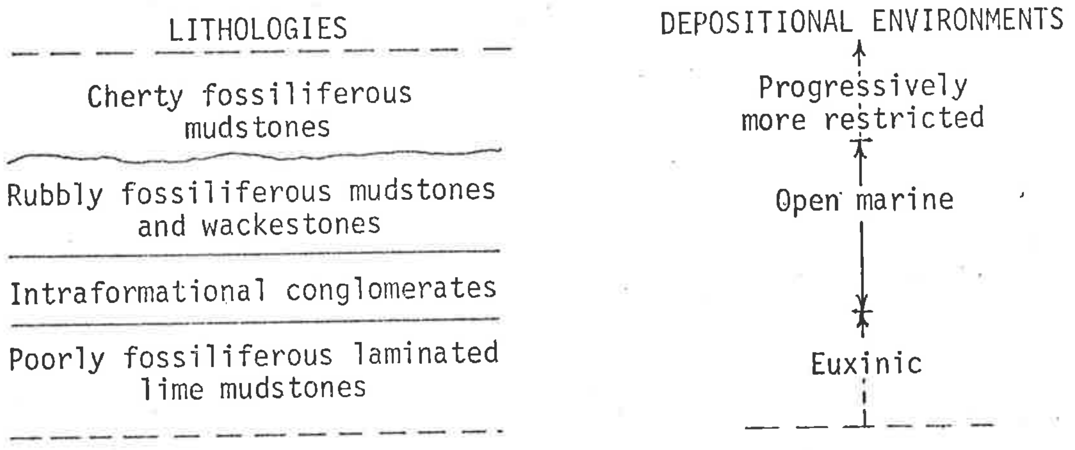


FIGURE 16: Generalized sedimentary cycle from megacycle VI.

Dark coloured, poorly fossiliferous flaggy mudstones are the most abundant lithology in megacycle VI. These lime-mudstones may show a fine bedding lamination. They are overlain, sometimes unconformably, by intraformational conglomerates, composed of reworked fragments of the underlying mudstones. The conglomerates are poorly fossiliferous and are probably of very shallow water origin. Rubbly dark fossiliferous mudstones and wackestones occur above the intraformational conglomerate units. These fossiliferous limestones show a diverse, sometimes extensively silicified, marine fauna. Trilobites, hyolithids, brachiopods, gastropods, small archaeocyathids and various problematica are represented. Rare interbedded layered calcareous mudstones are also fossiliferous but less notably enriched. Such layered fossiliferous mudstones overlie a characteristically irregular surface on topmost rubbly fossiliferous mudstones in the vertical sequence. These mudstones of each minor vertical cycle become progressively more regularly bedded, richer in interbedded pale chert horizons and less fossiliferous until toward the top of each cycle, they pass into the massive, poorly fossiliferous, lime-mudstones described at the cycle base.

At the extreme southwestern exposures of megacycle VI the only demonstrable lateral facies changes in this part of the Black Dog Hill sequence are present. The vertical cycles described above become progressively dominated by the intraclast conglomerate and rubbly fossiliferous limestone, as outcrop is traced toward the "diapir". In the lower part of the megacycle the dark mudstones and wackestones pass abruptly into skeletal grainstones with an abundance of archaeocyathids. These grainstones appear to contain abundant erosional breaks and southwestward are shattered by numerous fractures which are filled with secondary pink to pale grey laminated calcite. The entire zone appears to have been subject to a number of periods of intense shearing, possibly beginning during or soon after deposition and continuing at various times after lithification. The whole zone has been affected by secondary calcitization identical to that to be described below for the Donkey Bore sequence, and attributed to processes within the Cambrian vadose and phreatic zones. Most tectonic activity affecting this part of megacycle VI appears to have ended before topmost Faunal Assemblage 2 times, there being comparatively minor evidence of such activity in the younger rocks.

In the upper parts of megacycle VI, an archaeo/algal boundstone bioherm developed on grainstones adjacent to the diapir. Intraclast conglomerates occur laterally to the north and east of the bioherm, with conglomerates tonguing out into individual cycles of sedimentation as described above. The uppermost contact of the bioherm and overlying dark mudstones of megacycle VI is problematical. The sediments fold around the bioherm top, in a manner which is, for the most part, suggestive of post-depositional compaction. Whether the bioherm shape is depositional or erosional is not certain but there is a suggestion that the latter may be the case, since similar bodies elsewhere in the area are almost certainly erosional remnants of earlier, much more extensive, boundstone units, e.g. at 1-D.5 in the Donkey Bore sequence.

Sediments of megacycle VI are considered, in their greater part, to have been deposited under generally restricted marine conditions. Except in the immediate vicinity of the "diapir" the environment was one of relative tectonic stability. Times of low sediment supply saw the deposition of laminated lime-mudstones and periodic chert formation under conditions of low organic activity. More open, probably shallower, marine environments, with a diverse fauna and greater rate of sediment supply, were initially recorded by influxes of intraclast conglomerates. The succeeding rubbly fossiliferous mudstones and wackestones represent open shallow marine deposition over the area, changing back once again, to a more restricted euxinic environment. Those cycles, in a general way, continue well above the top of Faunal Assemblage 2, where this detailed study was arbitrarily terminated.

DONKEY BORE SEQUENCE

Introduction

The Donkey Bore sequence outcrops along the southwestern flank of the Wirrealpa Diapir (Fig. 9) and dips at between 55^0 and 80^0 in a SW direction. The sequence is the thinnest of the three exposed Lower Cambrian carbonate sequences at Old Wirrealpa Spring but is geologically probably the most complex.

The base of the sequence is in all places in contact with rocks previously mapped as "diapir", the relationships along the contact itself being both intricate and variable. The uppermost rocks of Faunal Assemblage 2 in the Donkey Bore sequence are unconformably overlain by younger Cambrian carbonates of distinctively different lithology to the rocks beneath the major erosional hiatus. Within the sequence itself, a number of notable unconformities are also present.

The carbonates of the sequence are exposed as three distinct "pods" along the diapir margin. For descriptive purposes these are designated as Regions A, B, and C (Fig. 17). Region C contains the most extensive outcrops and the fullest sequence. Stratigraphically below the Cambrian carbonates of Regions A and B, and interfingering with those of Region C, is a sequence of layered breccias (D1b) which are of controversial origin, and will be discussed separately.

Geology of the Donkey Bore sequence

The oldest sediments exposed within the sequence occur in Region C (2-G/H8). They consist of interbedded calcareous and dolomitic mudstones, mostly with a fine regular lamination but many show local bedding disruptions. Patches and horizons of silicification are common. Pisolitic (oncolitic ?) dolomites occur as massive interbeds and pass upward into a more regularly bedded sequence of mud-cracked/dolomitic mudstones, thin lenticular quartz sandstones, and minor intraformational conglomerates typical of the Woodendinna Dolomite which this basal part of the sequence represents. In Region C, south of Old Wirrealpa Spring, this part of the sequence is thinner and more disrupted, as well as being less well outcropping.

The dolomitic mudstone basal sequence north of Old Wirrealpa Spring in Region C becomes progressively richer in quartz sand upward, until thin conglomerate interbeds appear. Pebbles are angular and mainly composed of quartz sandstones, there being no pebbles of dolerite present in the lowermost conglomerate and breccia beds. A channel 100 m long is incised some 10 m into this unit, and is filled with close packed, poorly sorted intraclasts, predominantly of flaggy calcareous grey mudstones and some silicified limestones and minor sandstones (Plate 8a). The pebbles lack any imbrication and the breccia is devoid of bedding. A proximal slump origin is suggested for this unit.

Immediately above the described dolomitic and conglomeratic basal units, initial massive lithoclast grainstone deposition is evidenced. The lithoclasts are similar in size and lithologies to those described from megacycle I in the Black Dog Hill sequence. Grainsize decreases and sorting improves to the south, as does the rounding of individual clasts. Thin interbedded sandstones are present in the lithoclast grainstones some being traceable over 200 m despite a maximum thickness of 2 m. In the south the lithoclast grainstones may pass vertically into white-ooid grainstones across a somewhat irregular contact (Plate 9a). To the immediate north of this, however, (2-G7.5) both are laterally equivalent to a southward thinning wedge of breccia which is of problematic origin and is referred to loosely as "layered diapiric breccia" (Dlb). This lithology deserves separate description and consideration in view of its similarity to material usually described as being of true diapiric origin.

Layered diapiric breccia

The first notable attribute of this rock type, in the field, is its tendency to outcrop very poorly, except where it has been secondarily silicified. This is no doubt responsible for at least part of the problem in assessing its precise origin. The layered breccia occurs, as stated above, as a southward thinning wedge in Region C and, despite poor outcrop, would appear to pass laterally to the south into lithoclast grainstones and to some extent ooid grainstones. Elsewhere it appears to form the poorly outcropping basement to carbonate deposition along the entire length of the Donkey Bore sequence, having its poorest development in the far north-west and being thickest and most strongly outcropping on an elongate hill between Region B and Region C (1-F4.5 to 2-F/G6).

In this region it may be found overlying, with apparent unconformity, a highly folded sequence of dolomites (Dtd) which are part of a sequence of rocks which is indubitably the oldest exposed in the area, and which will be described below (See descriptions of Diapir). The basal breccia, in many respects is quite similar to the poorly outcropping breccias briefly alluded to in a prior discussion of megacycle I (See p. 35). They are, however, far better bedded in their basal parts, having steep southwesterly dips and striking in all instances parallel to the overlying younger Cambrian carbonate rocks. Basal breccias appear to have been intruded by dykes of dolerite (2-E5.5) some time after their deposition, but precise field relationships are indeterminate due to the paucity of good outcrop. Thin sections of the unit were not examined.

During this initial layered breccia deposition, doleritic rocks must certainly have been exposed nearby, as the breccias are rich in both dolerite boulders, and often well rounded, massive hematite boulders with which the presently outcropping dolerites are most intimately related. Other pebbles include recrystallized yellow dolomites, sandstones and pink to green shales. Sorting is usually moderate to poor (Plate 8b), but clasts of extreme dimensions (i.e. greater than 1-2 m) have not been seen. What appeared in initial mapping to be massive "rafts" in the breccia were found on closer examination to be highly silicified masses of boldly outcropping breccia.

At a distinct level in the sequence of layered breccias being described dolerite and hematite boulders abruptly disappear, and bedding becomes poorly defined. Copious quantities of randomly oriented calcareous shale pebbles make up the bulk of the clasts in the breccia. The matrix in general is weakly resistent to weathering and outcrop is very poor. One important feature of these breccias is that thin, highly altered interbedded dolomite units may rarely be found. These give an indication of bedding orientation and in all cases are concordant in both strike and dip with nearby overlying Cambrian carbonates. This concordance of orientation is also apparent in all instances where outcrop is sufficient to delineate a layering within the breccias themselves.

The contact of the layered breccias with the overlying Cambrian carbonates is seldom well exposed and characteristically difficult to interpret. There are several reasons for this, apart from the inferior nature of the breccia outcrop itself. As may be seen for much of the sequence, particularly in the western part of Region C (2-G7), minor faults have displaced the boundary in many places making it difficult to trace laterally. Later subaerial diagenesis of the younger Cambrian sequence has also complicated the essentially conglomerate/carbonate sequence contact in a complex manner, which will be considered below in a discussion of the features of local Cambrian palaeokarst development. It is possible, on the other hand, to clearly see a boundary between layered "diapiric" breccia and well layered lithoclast grainstones in a number of localities. In these instances the boundary is invariably gradational (Plate 8c) there being a vertical increase in the degree of sorting of clasts, and a concomitant increase in the amount of clear sparry calcite cement. Clasts become better rounded, generally slightly smaller, and consist of a greater proportion of the more physically and chemically stable lithologies, e.g. sandstones, suggesting an increasing degree of transport upward.

In general terms, the layered diapiric breccia (D1b) may be considered to be a polymictic sedimentary breccia and conglomerate unit. Deposition has occurred in the near vicinity of a large, polymictic source including basic intrusives. Transport appears to have been minimal, especially in the central parts of the unit. These sediments bear strong similarities to those of an in situ or slightly reworked regolith. Depositional energy conditions have been very low, increasing upward probably as very shallow supratidal to subaerial environments were inundated and influenced by intertidal conditions.

Geology of the Donkey Bore sequence cont-

Pebbly lithoclast grainstone deposition took place above the layered diapiric breccia in Regions A and C, although a limited amount of boulder conglomerate deposition occurred in both areas. Lenses of boulder grainstones, rich in dolerites, thin to the north-west and south respectively in Regions A and C. They are relatively poorly sorted and bedding is absent. Boulders are moderately well rounded. At 2-H8 the boulder beds are thickest in depressions in underlying ooid grainstones (Plate 9a) and may contain blocks of lithified ooid grainstone of local derivation suggesting that at this time, local lithification and exposure of the immediately underlying lithologies had occurred.

During the deposition of the lithoclast grainstones in Regions A and C, Region B and the southernmost part of Region C appear to have been emergent. The pebbly lithoclast grainstones are almost completely absent from Region B whilst in the extremely complex southern parts of Region C, lithoclast pebbles are relatively rare. Indeed, south of Old Wirrealpa Spring in Region C, the sedimentary sequence records frequent periods of emergence and erosion and contains numerous local unconformities. Periods of mudstone, minor wackestone and birdseye limestone deposition are recorded in the southernmost outcrops. The genesis of these units is difficult to assess, but many of the mudstones are pinkish in colour and although stratiform, are similar in many respects to mudstones within discordant palaeokarst features to be described below. They appear to have been deposited adjacent to areas of exposed carbonates in an upper supratidal to subaerial environment. Unlike many other similar instances at Old Wirrealpa, the emergent lithologies would appear to have been older Cambrian carbonates, since, as stated above, lithoclasts of diapiric origin are rare. A record of the older Cambrian sequences is absent southward, and at the southernmost extremity of sheet 2, younger Cambrian carbonates lie directly upon exposures of shattered Pound Quartzite (Ꝑwp).

Immediately south of Old Wirrealpa Spring itself in Region C, a number of very small lenticular stromatolite and mudstone bodies record repeated exposure and shallow water deposition in this locality. Pebbly lithoclast grainstones have small depressions in their uppermost surfaces encrusted with thin, poorly preserved digitate stromatolites. These are in turn overlain by fine calcareous and occasionally dolomitic mudstones prior to the onset of further pebbly lithoclast grainstone deposition. The circular area of nonoutcrop in the centre of this part of Region C is believed to be a recent soil-filled solution collapse structure which does not appear to be strongly related to the Cambrian lithofacies. As mentioned above, (p. 33) the map presented of Region C, south of Old Wirrealpa Spring, is inadequate to precisely illustrate every feature of this most complex area of outcrop.

Sediments within the Donkey Bore sequence become progressively finer grained and less enriched in lithoclast debris with time. In all regions where the sequence is still adequately preserved, (Particularly Region A and Region C at 2-G8) pebble lithoclast grainstones pass into sandy lithoclast grainstones which may be slightly fossiliferous, and show good sorting and planar bedding. Broken archaeocyathid and brachiopod fragments are intermixed with well rounded quartz sand grains. The planar bedding suggests deposition under shallow water conditions in the lower part of the upper flow regime (Simons and Richardson, 1961).

As lithoclasts disappeared, deposition of clean light coloured fossil grainstones dominated the whole of the Donkey Bore sequence. Archaeocyathid fragments are the main biogenic components of the massive to flaggy, bedded limestones (Plate 9b and 9c). In the field the limestones are coarse grained and crystalline. They may contain sizeable limonite pseudomorphs of iron sulphide pyritohedra, particularly in Region C. The uppermost parts of the preserved skeletal grainstone units, particularly in Region A, are characterized by large laminal fenestrae. These elongate but irregular voids become more common upwards in Region A in the proximity of a substantial erosional unconformity surface which occurs at the top of Faunal Assemblage 2 limestones. Faunal Assemblage 2 itself is usually only present in the top few metres of outcrop beneath the unconformity, and in many instances is completely absent. The fenestrae are filled with colloform layers of sparry calcite. Less commonly they may be floored with pink calcareous silt, or fine fragmented skeletal debris. The voids are related to subaerial dissolution during exposure of the lithified skeletal sequences. Also related to emergence is the development of major palaeokarst features over the entire Donkey Bore sequence.

Cambrian karst features of the Donkey Bore sequence

Physical characteristics

The carbonate sequence described above is penetrated by numerous, discordant, dykelike masses (Plate 10a) of vertically layered limestones, which are believed to have formed during extensive karstification of the exposed sequence in Lower Cambrian times. They appear to be the deeper remnants of a large vertical cave system which existed beneath the exposed Cambrian landscape. These elongate narrow bodies in all cases terminate upwards at the major erosional unconformity in topmost Faunal Assemblage 2 times, never penetrating the overlying younger carbonates. The dykes themselves contain abundant preserved fossils of Faunal Assemblage 2, indicating the age of the cave fills to be significantly younger than the country rock sequences they penetrate.

It is interesting to note that the material within the karst "dykes" was apparently more susceptible to erosion than adjacent, flat-lying country rock sequences, since dyke tops occur as pronounced depressions on the unconformity. Within these hollows, lenses of younger Cambrian carbonate conglomerates may occur. In other places subsequent compaction has caused a down-folding of younger flaggy carbonates into these depressions, forming small synclines or basins on the unconformity surface. These downfolds may be seen right along the unconformity, with a particularly good example being at 2-G/H8 where a small syncline of younger carbonates is perched, unconformably atop a dyke, and completely separated from equivalent rocks outcropping slightly to the west.

In plan, the dyke-like karst features are linear, and their distribution appears to have been controlled by joint sets, in a similar way to that commonly seen in modern vertical cave systems (Sweeting, 1972). At Old Wirrealpa Spring there are at least two recognizable sets of dyke-like bodies. Both sets have similar characteristics but one set shows a consistent cross-cutting relationship with respect to the other, quite unlike what might be expected for a simple set of conjugate joints which have undergone penecontemporaneous dissolution. The development of one dyke set clearly predated the development of the other. The older set in Regions A and C would appear to have been oriented almost east/west or slightly north-east/south-west. The younger set, although not well developed in Region A, is oriented north/south to slightly north-west/south-east. The orientation of the bodies in Region B is difficult to determine because of the thin penetrated sequence and subdued present-day topography.

In all cases the karst bodies are oriented perpendicular to the bedding in the country-rock limestones. Contacts are characteristically sharp, but may be difficult to recognize in the field in those situations where lithological contrasts between host and dyke are subtle. The dykes commonly show a downward bifurcation (Plate 10b). Small sub-vertical aphohyses are frequent, and relatively minor sill-like extensions parallel to bedding may occur in the basal part of the dykes. These smaller extensions and apophyses show a pronounced parallelism of their sides as they terminate into spar-filled calcite veins.

The lowermost extremities of the karst-dykes are difficult to assess, partly because of modern-day scree beneath the carbonate hills and because of the characteristically poor outcrop of the layered diapiric breccias (D1b) which are always present at the base of the dykes. In many instances, minor, later dextral fault displacements along the dykes has further complicated the relations (See 2-G7.5). Despite these difficulties, certain details are clearly evident. The bodies penetrate the basal pebbly and sandy lithoclast grainstones, and do not show any significant tapering of their cross section with depth. The dykes become difficult to trace on reaching the boulder lithoclast grainstones where, in many cases, very little carbonate remains between the massive rounded boulders. The dykes as such do not penetrate the layered diapiric breccia unit, and at 2-G8, cut neither the layered diapiric breccia nor the underlying older carbonate sequence. Upon reaching the boulder lithoclast grainstones and layered diapiric breccias, the dykes appear to gradually degenerate into an anastomosing network of spar filled calcite veins, with any larger bodies having a tendency to be horizontal, or stratiform rather than cross-cutting.

Carbonates within the dyke bodies show an irregular vertical layering (Plate 11a). They are commonly pink to grey in colour and many have a subtle variegated or blotchy appearance in outcrop. Carbonate fragments with indistinct boundaries float.within a matrix of pink, clayey micrite, or are bound by vaguely laminated pale calcite cements. Very often the secondary calcite cement consists of fine elongate crystals growing perpendicular to the cavity walls, and having very regular but undulose lamination remarkably similar in field appearance to that found in modern subaerial flowstones. The lamination in these carbonates conforms closely to the margins of the dykes but identical lithologies can also be found as disoriented clasts within patches of "reworked" carbonate breccia fills. Volumetrically much of the fill is of carbonate mud which may be variously contaminated with dispersed fine terrigenous material, mainly quartz silt, clay minerals and iron oxides, the latter imparting a pink to red stain to rocks.

Vertically elongate lenses of fossiliferous sediment are also present within the dykes. No horizontal layering has been observed in these lenses. Although the fossils are greatly fragmented, the lenses are dominated by achaeocyathid remains, as well as very abundant phosphatic brachiopods and tommatids. Micromitra sp. is well represented. The considerable abundance of phosphatic organic remains in some places is attributed to their relative insolubility during reworking of the sedimentary sequences in the subaerial environment.

In general the detrital fill in the dykes or caves is relatively fine grained, and it is rare that individual fragments exceed 20-30 cm in diameter. This is particularly true for dykes of the older set, especially in their lower parts. The cavities appear to have formed gradually by dissolution and at no time had large unrestricted entrances from above nor were they appreciably extended in size by internal collapse - rather they had smooth stable margins.

A most notable exception to this is present in the younger dyke set of Region C (2-H8). Here, in its southern part, a number of individual dyke-like bodies come together to form a massive body of somewhat indeterminate shape. The body's eastern margin is sharp and dips east almost at right angles to the bedding in the westward dipping country rock carbonate sequence. The western margin is obscured by outcropping younger Cambrian carbonates above the regional erosional unconformity at topmost Faunal Assemblage 2. This body is unique to the area in that it is filled by numerous blocks of Cambrian carbonates which range in size from pebbles to house-sized boulders. The numerous larger boulders are completely disoriented and, as for the smaller ones, float in an irregular mass of layered calcite cements and impure cabonate muds (Plate 11b), similar to those found in other dykes and described above. The largest exposed boulder is some 120 m across and contains at least 50 m of younger stratigraphic sequence. An equivalent sequence is no longer exposed in the Donkey Bore sequence, having been completely removed by erosion. Other small blocks of distinctive lithology may be seen adjacent to their source on the dyke margin (e.g. at 2-I8, Plate 11c). The displacement of such blocks is downward in all cases.

This dyke is significant in several respects. The size of the younger boulder fill might suggest that, unlike the other dykes, this one must have had a considerable surface gape to admit such large boulders to a lower level. There being some doubt about the shape of the body, however, it may be that it represents part of a large subaerial talus wedge, with boulders disoriented by gravity slumping from an exposed cliff-line to the immediate east. On available evidence it is not possible to positively confirm either possibility. It is interesting to note, however, that at some time just prior to the formation of this dyke there was a minimum of 120-130 m of stratigraphic thickness of carbonate rocks above the base of the older dyke set in Region C. Thus the remnants of the older set must represent, even by modern standards, the lowermost part of a very deep network of vertical caves. In contrast, the younger, boulder-filled dyke may preserve the uppermost part of a similar but slightly younger vertical cave system. The relation of the above to the depth of the vadose zone in Lower Cambrian times will be dealt with below.

The karst-dyke bodies in Region C characteristically contain pockets of well developed pisoliths. There are at least two distinct types of pisolith present. The first and minor group of pisoliths occur only within the younger dyke-set. These are stained red and contain finely disseminated iron oxides. They occur along with pink carbonate mudstones as patches of ill-sorted cavity fill (Plate 12a). There is no apparent bedding within the deposits, and individual pisoliths vary greatly in size and shape (Plate 12b). Lamination is usually fine and well developed. Radial structures are poorly formed, and there are a variety of different nuclei present in any group of pisoliths. Carbonate rock fragments and phosphatic fossils form the most common nuclei. The red layering successively reproduces irregularities in the original nucleus of individual pisoliths. The laminations do not show mutual growth interference between pisoliths which are juxtaposed, as do those reported from the Capitan Reef (Dunham, 1969b). This suggests that they have evolved elsewhere, probably as nodules in a primitive soil, and have been reworked down into underlying solution cracks, probably by ground water flow through the vadose zone. Little to no further growth has taken place in situ.

The second type of pisolith are distinctively different. They are not enriched in iron oxides, and are pale grey to white in colour. They are very regularly laminated and show a well developed radial arrangement of elongate calcite crystals about their nuclei (Plate 12c). Their appearance is remarkably similar to that of modern cave pearls (Dunham, 1969b; Donahue, 1965; 1969; Mackin and Coombs, 1945). The pisoliths occur in pockets particularly within the lower parts of the older dyke set of Region C. They range in size from about 2 mm up to 4 cm, although most are between 5 mm and

2 cm in diameter. Most have quartz sand grains or small phosphatic fossil fragments as nuclei (Plate 14a). Some have developed around rounded clasts of pink calcareous mudstones.

Although examples of this type of pisolith may occur within pink silts and calcareous muds, the best developed pisoliths occur in rocks which are almost totally devoid of fine carbonate or non-carbonate detritus. This suggests that they have developed under high energy conditons, probably within narrow cavities in the vertical cave system through which considerable volumes of carbonate charged waters are periodically funnelled as they pass through the vadose zone. The extreme regularity of the laminae of cave pearls is usually attributed to continual aggitation during growth (Donahue, 1969). Those Cambrian pisoliths which show the best developed concentric laminae and radial structure occur in a curious close-packed pisolitic rock (Plate 13a). These appear to have grown, unconfined, for a considerable time before they have settled into a fixed, close-packed arrangement. It is not known whether the sudden confinement has been due to a falling off of the rate of water flow through the cavity, with concomitant reduction of turbulence or whether it is due simply to the physical limitation on movement due to the increase in volume of the pisoliths within a cavity of fixed size. Whatever the reason, it may be seen that the regular precipitation of carbonate continued at the pisolith surface even after they became fixed in position. Growth constraints, however, resulted in the regular additions filling the interstitial cavities rather than forming even, spherical coatings on individual pisoliths (See Plate 13b). The nature of the laminations and the microstructure of the crystalline calcite is identical in both situations confirming that the regularity of the fine laminations is a growth phenomenon rather than some form of abrasive effect. Mineralogically there is no variation across the pisoliths and into their interstitial cement, as they are initially composed of low Mg-calcite. Small amounts of dolomite occur in some thin laminae. Continued interstitial cement growth, under a situation of mutual growth restraints, has resulted in the pisoliths having their unusual polyhedral shape (Plate 13c).

The absence of meniscus cement (Dunham,1971) and extreme rarity of microstactites from the close packed pisoliths suggests that the regular cement has formed whilst the pisoliths were completely submerged. That is, although they are formed within the vadose zone, they are confined to rimstone dams or pools which rarely dried out completely. These dams or pools in a vertical cave system must have taken the form of deep, elongate pockets in the cave walls, possibly developed beneath subsurface waterfalls (See Sweeting, 1972 pp.168).

Other autochthonous cave deposits are notably rare, and such features as stalactites and stalagmites have not been observed in the vertical karst-dykes of the Donkey Bore sequence. Cambrian flowstones, however, are very common (Plate 14b) and appear to have formed by the precipitation of regular carbonate layers from sheets of super-saturated vadose waters which have passed downward across the joint surfaces.

Possible significance of Cambrian karst features

Introduction

Despite a recent increased interest in carbonate from subaerial environments, there are still very few works which deal with ancient surficial deposits, partly because, for good geological reasons, these deposits are seldom preserved, and partly because they have until now remained unrecognized in many ancient sequences. Dunham (1969a; 1969b) described most vividly the evidence for subaerial exposure of sediments of the Capitan Reef in the Permian of West Texas. Various others have described Holocene and Pleistocene subaerial features from exposed coral atolls (Matthews, 1968; James, 1972) and more recently from even more ancient sequences, including Carboniferous palaeokarst (Walken, 1974; Walls et al., 1975) and Precambrian palaeosols (Kalliokoski, 1975).

Any interpretation of ancient subaerial carbonate must still rely almost solely upon the limited research into such environments in the present day. Much of the basic descriptive work has been carried out by geomorphologists and speleologists, with as-yet few critical contributions from sedimentologists, or hydrologists. Thus even the most guarded inerpretations of the significance of the exposed Cambrian features may be questionable. It seems inescapable that the Cambrian features described from the Donkey Bore sequence be considered a form of palaeokarst, and as such, pose a number of broad palaeogeomorphological, tectonic, climatic and diagenetic implications on the geological history of the Old Wirrealpa Spring area.

Palaeogeomorphology and Tectonics

Field realtionships have established with little doubt that the Cambrian structures are broadly analogous to the deeper parts of modern vertical cave systems as defined by Sweeting (1972). Sweeting is quick to point out, however, that although vertical cave systems are widespread today in areas of deep karst development (e.g. Dinaric area of Croatia), they "are less accessible and less well known" than other cave systems. They tend to be confined to the vadose zone, and form in areas with extremely deep water tables. According to Sweeting, strong jointing and a rapid rejuvenation of underground drainage are important factors in the development of vertical cave systems. Dissolution along the joints, primarily by the downward flow of CO_2^- charged meteoric waters through the vadose zone, is responsible for the formation of modern vertical caves. Steep-sided valleys or fault escarpments are favourable topographic sites for such features.

The Donkey Bore sequence might thus be expected to have occupied an area of considerable topographic elevation above nearby surrounding areas during the formation of the palaeokarst. As stated above (p. 63) at one stage an absolute minimum of some 120-130 m of stratigraphic sequence was exposed above the base of the karst development. Since the more normal horizontal cave systems of the phreatic zone have not been recognized at the base of the karst, the Lower Cambrian water table may have been even further below the exposed topographic surface. Normal marine limestones of the Black Dog Hill sequence outcrop at the present day only some 300-400 metres laterally from palaeokarst of the Donkey Bore sequence. In the absence of equivalent evidence of major subaerial exposure of the Black Dog Hill sequence and assuming that the vadose/phreatic zone contact approaches mean sea level (See Dunham, 1969a, pp. 162), the topographic relief of the Donkey Bore sequence above the adjacent marine areas to the north-west must have indeed been considerable. A steep topographic relief of several hundred metres across a narrow, north-west trending zone separating the sites of deposition of the two sequences seems to have prevailed.

Although obviously not a static or permanent feature of the Lower Cambrian landscape, the influence of such an appreciable escarpment may be seen at various times throughout the deposition of the carbonate rocks of the Old Wirrealpa Spring area. Subaerial exposure or erosion along the topographic high has been significant, even in terms of geological time, and must surely indicate a narrow zone of considerable Lower Cambrian tectonics. Movements appear to have repeatedly resulted in an upthrust of the south-western block with respect to the north-eastern block.

Palaeoclimate

Modern-day karst may develop in a variety of different climatic zones (Sweeting, 1972). The documentation of the precise effects of different climatic variables is still relatively poor, but a general understanding of the karstification process itself has been known for some time. In the most simplistic terms, dissolution in karst terrains takes place by the action of CO_2^- charged meteoric waters on host limestones. Rainwater, upon passing through plant and soil zones, may have CO_2 contents enhanced in the order of 25 to 90 times that of surface waters (Sweeting, 1972). These downward percolating waters of low pH rapidly dissolve carbonate and become saturated with respect to the particular carbonate polymorph present. Most recent marine carbonates contain more than one carbonate polymorph, and the groundwaters may become saturated with respect to the least soluble polymorph, whilst still dissolving the more soluble one (usually aragonite). Precipitation may occur upon evaporation, or on CO_2 loss or both.

The chemistry of the dissolution/precipitation process in natural carbonate environments is complex and not well understood. A clear discussion of the factors involved has been given by Dunham (1969a, pp.161-163) and Bathurst (1975). The details of the chemical processes are obviously not revealed in limestones of Cambrian age, but certain broad aspects of the karstification process, by analogy with modern environments, are forthcoming.

First, the most likely agent of dissolution was rainwater charged with atmospheric CO_2. Deposition in nearby marine areas at the time was almost exclusively of carbonate rocks, so these marine waters would have been too highly saturated with carbonates to actively dissolve the marine carbonates of the Donkey Bore sequence.

It is unlikely that the concentration of dissolved CO_2 in Cambrian meteoric waters was as much enhanced as that in modern karst areas, since no land plants and only primitive soils, the prime souce of modern vadose-water CO_2, existed in Cambrian times (Yaalon, 1963). On the other hand Kalliokoski (1975) considers that soils resembling a modern type, but highly oxidizing, have been present for some 1,000 million years. The oxidization of various sulphides in those soils may well have given rise to acidic ground waters in a manner similar to that indicated by Dunham (1969a) for the Permian of West Texas.

Even given the large time spans probably available to the karstification process in the Cambrian of the Donkey Bore sequence, very large volumes of carbonate have been dissolved away. It is apparent that immense volumes of water must have percolated downwards through the exposed rock mass above the watertable, especially if the Cambrian vadose waters had reduced dissolution abilities. It is thus not unreasonable to consider that the rainfall at the time was high. In modern karst areas where narrow vertical cave systems and flowstone deposits dominate, it has been found that the rapid dissolution which accompanies intense rainfall is often balanced by the similarly intense precipitation of flowstones which follows the evaporation of the saturated vadose waters. This type of karst is characteristic of hot semi-arid climates influenced by seasonal monsoonal rains which are followed by hot, exceedingly dry periods. Rates of solution in these modern environments are similarly reduced due to lower densities of surface vegetation compared with tropical areas.

Thus, without labouring the analogy to extremes, it seems likely that the climate of the area during the Lower Cambrian was hot and semi-arid, with periodic heavy rainfall followed by times of intense evaporation. This concurs with King (1961) who considered that Gondwanaland at this time experienced a predominantly dry or strongly seasonal climate.

Diagenesis

The recognition of palaeokarst features in the Donkey Bore sequence negates the possibility that the major unconformity at the top of Faunal Assemblage 2, at least in this area, is of submarine origin. Clearly, subaerial exposure and erosion of the sequence has taken place. Thus any future detailed studies of the diagenetic features of the Cambrian sequences must take into account the possibility of subaerial exposure, and its related complex and diverse effects, just as studies of depositional environments must consider subaerial talus, gravity slides and fluvial transport of material.

One other consequence of the recognition of Lower Cambrian karstification must have even more far-reaching significance. This must involve a realization that very large volumes of vadose and phreatic waters, variously saturated or super-saturated, possibly with respect to several different solid carbonate phases, have locally flowed downward into older carbonate and non-carbonate sequences. The diagenetic effects of these solutions as they traverse a hydrological gradient through the more permeable units beneath the karst land-surface must indeed be complex. At Old Wirrealpa Spring, these carbonate-charged solutions have flowed downward into the horizon termed "layered diapiric breccia", which has been discussed in detail above. The underlying brecciated carbonate masses previously considered diapiric (Dalgarno and Johnson, 1966), must have been greatly altered diagenetically by the movement of such solutions. The zone of tectonic fracturing associated with the escarpment development discussed above, must also have provided an avenue of permeability in the hydrological history of these solutions once they had passed beneath the Cambrian of the Donkey Bore sequence.

No petrographic studies of material of the "diapir" have been carried out here, and an account of the precise effects of Cambrian groundwater diagenesis cannot be given. It must be left until a description of the "diapir" itself, to surmise just what complex and varied effects these carbonate-enriched groundwaters may have wrought upon underlying breccias.

WIRREALPA HILL SEQUENCE

Introduction

This sequence is sedimentologically by far the simplest of the three Lower Cambrian sequences exposed at Old Wirrealpa Spring. Its simplicity reflects its deposition upon a widespread, relatively stable, shallow, carbonate shelf.

The sequence is relatively well exposed and is folded around the faulted and steeply westward plunging nose of the Mt Lyall Anticline (See Fig. 9). The Lower Cambrian carbonate rocks have been mapped in detail for some 8 km east of the limit of map sheet 3, but do not show significant facies changes past the edge of this map sheet. The western, or more strictly, northern limit of the exposed sequence is covered by Quarternary alluvium adjacent to the central block of the Wirrealpa Diapir (3-G10.5).

Geology

The Lower Cambrian carbonates of the Wirrealpa Hill sequence lie with apparent conformity upon thin, poorly exposed clayey sandstones of the Parachilna Formation. This formation, in turn, overlies Pound Quartzite, probably disconformably. The Pound Quartzite of the southern limb of the Mt Lyall Anticline (Fig. 8) is dramatically thinned with respect to that of the northern limb.

Carbonate sedimentation was initiated by the deposition of thin dolomitic mudstones and interbedded thin quartz sandstones, intraformational conglomerates and stromatolites. Minor grey calcareous mudstones are also apparent. The lithologies are typical of those of the Woodendinna Dolomite as discussed above, and deposition would appear to have occurred on very shallow upper intertidal to restricted supratidal mud flats. Significant lateral facies changes are not observable in this unit and an apparent thickening across a fault (3-H13) is just a result of a shallower bedding dip on its eastern side. Exotic lithoclasts are not present within these basal dolomitic beds of the Wirrealpa Hill sequence.

Thick ooid and lithoclast grainstones occur between the basal dolomites and a widespread birdseye limestone marker bed (See Fig. 10, sheet 3). These grainstones are notable in that they may be extensively dolomitized, and at times primary depositional features are difficult to determine in the field. The ooid grainstones are invariably well-sorted, and may have massive well-sorted pisolitic interbeds. Although medium to small scale cross-bedding is present, planar bedding indicative of the lower part of the upper flow regime is dominant. Rippled bedding planes are rare.

The lithoclast grainstones show similar bedding characteristics to those of the interbedded ooid grainstones. A number of the lithoclast grainstone beds are very rich in exotic non-carbonate clasts, and are lithologically identical with their equivalents of the Black Dog Hill and Donkey Bore sequences. Most lithoclast grainstones of this sequence are, however, far less rich in exotic clasts and/or quartz sand. In fact many units mapped in this sequence as ooid grainstones contain scattered, rounded lithoclasts and minor amounts of quartz sand, whilst most lithoclast grainstones are only just rich enough in non-carbonate clasts to warrant their mapping as such. This dispersion or dilution of clasts is believed to reflect a more distant source than that applying to the other two equivalent sequences discussed above.

Lenticular stromatolite beds occur throughout this grainstone sequence, although secondary dolomitization may make them difficult to recognize. Most stromatolite beds are thin and poorly developed in comparison with those of Black Dog Hill. An apparent thickening of stromatolite beds to the east of a fault at 3-H13, is mainly due to shallower dips, but there is a suggestion that this fault has had limited movement even during deposition. Calcareous mudstones are exposed east of this fault yet are absent to the immediate west. This might indicate that movements have enabled mud accumulation in a slightly deeper, more protected environment. There are also an increased number of lithoclast grainstone beds to the east of the fault. If syndepositional movement has in fact occurred, and this remains uncertain due to low dips and unusually poor outcrop, then such movements were relatively short-lived and did not influence sedimentation higher up in the grainstone unit. A slight post-depositional reactivation is certainly evident along the fault.

Within the grainstone unit several distinct silicified horizons occur. These are often but not always pisolitic rather than oolitic beds. The massive white silicified beds are up to 2 m thick and are strongly outcropping. At least one silicified grainstone horizon is traceable from the northernmost outcrops of the Wirrealpa Hill sequence around at least to the fault at 3-H13. The significance of these distinct, concordant and laterally persistent zones of secondary silicification is not clear. It is tentatively suggested that they may be related to periods of brief emergence of the shallow marine carbonates. Similar silicification of ancient sequences has been reported by a number of workers including Hsia (1969) and Walls et al. (1975).

The ooid and lithoclast grainstones of this part of the Wirrealpa Hill sequence, like their equivalents on the Black Dog Hill, are notably depleted in body fossils. Some 30 m stratigraphically below the birdseye limestone marker bed, fragmental archaeocyathid remains begin to appear, and such fragments become increasingly more abundant in the ooid grainstones toward the top of the unit.

Deposition of the ooid and lithoclast grainstone unit appears to have generally occurred on a shallow intertidal to subtidal environment under relatively high energy open marine conditions. Lithoclast fragments have been derived from a relatively distant source, compared with their lithological equivalents in the adjacent two Lower Cambrian sequences. The clasts are better rounded, generally fewer in number, and of smaller overall size. Algal colonization of mobile ooid shoals during times when bottom currents and ooid supply were on the wane, allowed the formation of the widespread algal stromatolite beds. As tentatively suggested above, silicified horizons may be related to brief periods of subaerial exposure of the widespread ooid buildups, and could represent brief depositional hiatuses.

A more prolonged period of supratidal exposure and intermittent carbonate deposition is recorded by the overlying widespread development of a birdseye limestone unit. This distinctive, pale cream to pink coloured unit contains very abundant cement filled laminal fenestrae (Plate 14c), each individual fenestrule being up to 3 cm in length and being greatly flattened parallel to bedding. The birdseye limestones tend to be pelletal and many beds contain rounded lithoclast granules. Thin, finely laminated calcareous mudstones are common interbeds. These may show delicate microstylolitization along individual laminae.

Above the birdseye limestones, the sequence is dominated by skeletal grainstone deposition. The copious supply of archaeocyathid remains has resulted in extensive skeletal buildups under generally open marine conditions. Several thin, pale grey calcareous mudstone beds outcrop within the grainstones, but most of those present in the northernmost exposure lens out laterally as the sequence is traced eastwards. The same is true for a number of pebble lithoclast grainstones which occur as south and eastward thinning wedges in the skeletal grainstones and packstones.

Skeletal grainstones are invariably pale grey to honey-coloured, clean and crystalline in outcrop. Some are affected by a secondary mottling, which results in irregular zones of dolomite occurring in the massive limestones. Wholesale secondary dolomitization is not present in the mapped area, although sparry dolomite cement in conical archaeocyathid tests gives certain bands a curious weathering effect in the field. On first glance at the outcrop it appeared that all archaeocyathids were preferentially oriented with the apex of their cones pointing upward. Closer examination revealed that although orientation is really random it is only the overturned tests which preserved an internal cavity rimmed by sparry dolomite cement. On weathering the greater resistance of the dolomite in these tests caused them to stand out in outcrop.

The massive crystalline nature of the grainstones reveals few sedimentary features in outcrop, although medium scale cross-bedding may be seen on rare occasions. It must be stressed that interbedded packstones are common within the skeletal grainstones. These cannot be confidently distinguished in the field and are mapped as grainstones.

Various brachiopods and problematica which characterize Daily's Faunal Assemblage 2 are present in the uppermost parts of the exposed skeletal grainstones. *Micromitra etheridgei* is usually present at least within 10 m stratigraphically of the regional unconformity at top of Faunal Assemblage 2. In the Wirrealpa Hill sequence, litho directly above the unconformity are almost identical with those bel The unconformity is only recognisable on palaeontological grounds, although it may be marked by a thin development of laminated carbonate which is enriched in iron oxides and bright red to pink in colour. It is indeed a curious coincidence that the contact between the Wirrealpa Hill sequence and the diapir/soil cover to its immediate west, should occur almost precisely along this plane of regional unconformity. The paraconformable nature of the unconformity in the eastern parts of the sequence indicates that little tilting or folding of the underlying carbonates occurred prior to the succeeding transgression and renewed skeletal grainstone deposition.

WIRREALPA DIAPIR

Introduction

As already noted (p. 31) this study of the Wirrealpa Diapir has been undertaken as an adjunct to detailed work on the host-rock sequences, the Lower Cambrian carbonates, for which the Wirrealpa Diapir appears to have acted as a source of non-carbonate detritus, and as a positive element in the palaeotopography. The evidence gathered on the relationship between the Cambrian sequences and the "diapir" also places constraints upon the timing and mechanism of emplacement of the latter body itself.

The Wirrealpa Diapir was mapped at the same scale as the three Cambrian sequences which abutt it, and which have already been described. The "diapir" area is topographically depressed and outcrop is considerably worse than that in the Cambrian. This is reflected in the substantial areas of soil and outwash cover apparent on map sheets 1, 2 and 3, (Fig. 10) and in the rarity of well-preserved outcrops in the Cambrian/"diapir" boundary. It is important to stress here that the unshaded areas of the geological map (Fig. 10) indicate only that there is no outcrop, and do not represent an interpreted margin of the "diapir". In most cases the actual margin is probably close to the unshaded edge, but in many cases substantial subcrop areas within the unshaded zones are probably Cambrian. Similarly, certain problematic lithological units in outcrop have been left uncoloured on the map, but as will be seen in the discussion to follow, are finally interpreted, on the bases of available evidence, to be Cambrian sediments. In brief then, the coloured areas of Fig. 10 represent indisputable Cambrian sedimentary sequences. The uncoloured outcrops are either "diapiric" material, or outcrops of contentious origin, about which detailed discussions are undertaken below.

The "diapir" has been studied in the field only and in the absence of any thin section work on the "diapir" rocks, the lithological subdivisions are necessarily very broad. Time did not permit detailed petrological work, although such work would no doubt be an essential part of any future study. General lithological descriptions are given on the Map Legend (Fig. 11).

The "diapir" exposures may be subdivided into three geologically and/or geographically distinct areas. These are the Central Block, the Northwest Limb and the Southern Megabreccia areas (See Fig. 18). Following a brief discussion of the structural setting of the "diapir", these three areas will be described independently.

Structural setting

The Wirrealpa Diapir and its relationship to the local structures in the host-sequences is shown in Fig. 19. Folds in the area are characteristically open with curved fold axes commonly giving rise to a series of broad structural basins and somewhat tighter anticlines with horizontal to sub-horizontal fold axes (See Fig. 8).

The most recent, post-Delamerian, faulting in the area takes the form of SW-NE oriented sinistral faults. The first of these, which cuts the Black Dog Hill sequence on map sheet 3 (Fig. 10), has a horizontal displacement of some 50-60 m. The second such fault is much larger and more difficult to precisely locate. It represents a narrow zone of discontinuity in the local geology and separates the Central Block from the Wirrealpa Hill sequence and the Central Block from the Southern Megabreccia (See Figs. 18 and 19). Regionally the fault passes to the north across an area of poor outcrop in the Cambrian (eastern edge of map sheet 3 and beyond), thence at a low angle across the strike of the

Cambrian carbonates, possibly to connect with a major sinistral displacement of the Cambrian-Precambrian boundary at the southern edge of the Jubilee Range near Wirrapowie Creek (See PARACHILNA and COPLEY 1:250,000 map sheets and Fig. 8). A lateral displacement of some 2,000 m is indicated on the above published sheets. This accords very closely with the expected displacement at Old Wirrealpa Spring itself, as judged from the local geology. Clearly from both Fig. 19 and the PARACHILNA 1:250,000 map sheet, the axis of the westward plunging Mt Lyall Anticline (Fig. 8) trends directly into the axis of the Donkey Bore syncline (Fig. 8). The reversal of sinistral displacement of 2,000 m along the proposed fault plane would align the anticlinal axis with a westward plunging anticline in younger Cambrian carbonates south of the area mapped in Fig. 10 (map sheet 2). This anticline has not been correctly mapped on the published map sheets, despite being very evident in both the field, and on aerial photographs (See Survey 952, plates 16 and 17). The anticline has been mapped by Pierce (1969) although his map does contain minor inaccuracies. Finally the proposed displacement would bring the carbonate sediments of the Wirrealpa Hill sequence into closer proximity with those of the Donkey Bore sequence, with which they have closest affinities.

Post-Delamerian faulting has also occurred as dextral displacements along the Northwest Limb of the Wirrealpa Diapir. Complex and inadequate outcrop make the tracing of the actual fault line impossible within the Northwest Limb itself. Although only a single, almost strike-slip fault, can be seen emerging into the Cambrian sequences near the north-west tip of the limb, it is very likely that a number of dextral fault splinters exist. The south-eastern extensions consist of a number of smaller dextral faults cutting the Donkey Bore sequence in the vicinity of 2-G7. No other displacements can be seen in the Donkey Bore sequence, but this is not unexpected since the trend of the fault in younger carbonates (say at 1-F4) would be essentially parallel to the strike of these lithologically uniform, flaggy outcropping sequences.

As may be seen on Fig. 19, the Black Dog Hill sequence and Donkey Bore sequence generally dip away from areas of outcrop of "diapiric" material. Despite later faulting, the anticlinal structure so formed clearly shows a major thinning of its south-western limb with respect to that of the north-eastern limb (Black Dog Hill sequence). The axis of this anticlinal structure is essentially horizontal and trends almost north-south.

The Northwest Limb of the Wirrealpa Diapir is not parallel to this anticlinal axis, and does not form a core to the structure. In a regional sense this relationship is the equivalent of that which exists on the north-west, or Enorama, limb of the Oraparinna Diapir (See PARACHILNA 1:250,000 map sheet), where this "diapir" is located oblique to the regional N-S anticlinal axis.

At Old Wirrealpa Spring the changes in thickness and facies of the Cambrian carbonate strictly occurs across the line of exposure of the "diapir", rather than across the anticlinal axis.

The details of the contact relationships between the "diapir" and the Cambrain host-sequences have been briefly referred to above in the descriptions of the Cambrian sequences, but these relationships will be further elaborated upon below as each of the three sub-areas of the "diapir" are described.

Central Block

Outcrops in the Central Block belong to a thick, relatively unbrecciated, sequence of sedimentary rocks. The sequence is folded into a major steeply northward-plunging syncline (See map sheet 2, Fig. 10). Moderate outcrop with good facings has allowed a detailed stratigraphic section some 1,500 m thick to be measured. This sequence is presented on the Map Legend (Fig. 11), and is the thickest conformable sequence recorded from the "diapirs" in the Flinders Ranges.

The Central Block is notably devoid of significant tectonic disruption. The only irregularities in bedding within the block, usually in outcrops of Dws, consist of syndepositional slumps, conglomerates and early diagenetic collapse features. "Diapiric" breccia is absent from the area. The only igneous rocks occur in a very small doleritic body sandwiched between the Central Block and the Donkey Bore sequence at 2-G8. There is no indication of massive evaporites in the sequence. Halite casts do occur in cross-bedded sandstones near the base of this thin unit (Dcb).

Contacts between the host-rock sequences and the Central Block, where they are observable, are characteristically sharp. This applies particularly to contacts with the Donkey Bore sequence at 2-G/H8 where a parallel contact between south-west dipping Cambrian dolomitic siltstones and overturned impure sandstones (Dws) may be seen across a few tens of centimeters. There is no indication that the Cambrian carbonates were deposited unconformably upon rocks of the Central Block, although outcrop is not sufficiently good to confirm a tectonic contact.

The northern boundary of the Central Block is also poorly exposed, but the sediments of the Central Block at that location appear to be considerably disrupted. Once again there is no indication that the Cambrian unconformably overlies the "diapiric" lithologies. To the east of the mapped areas the basal Cambrian carbonates overlie the Parachilna Formation and the Pound Quartzite. At 2-F6, despite local overturning of the sequence, the basal Cambrian carbonates appear to have developed directly upon the Pound Quartzite. On this evidence, tenuous as it is, a faulted contact is favoured for the northern margin of the Central Block.

The contact between the Central Block and the Wirrealpa Hill sequence is never exposed, but occurs along the postulated sinistral fault referred to above (p. 74).

Age of the Central Block sequence

The steeply plunging axes of the Central Block contrast markedly with the characteristic shallow plunges of the Delamerian folds in the area. This suggests that the Central Block has undergone deformation of some sort prior to the folding of the adjacent younger Precambrian and Cambrian sequences. An older Precambrian origin for the Central Block sequence seems most likely. It also seems likely that a lithological correlation of the sequence with older Precambrian sequences some 65 km north, at Mt Painter, might be possible.

The stratigraphy of these units at Mt Painter has been described by Thomson and Coats (1964), Thomson (1966), and Coats and Blissett (1971). Further clarification has recently been made by Murrell and Coats (*in press*). Unfortunately the Central Block sequence cannot, with any certainty, be matched lithologically with the described sequence. Some individual lithological units may be matched, however. Among these is a thin sandstone at the base (Dcb) which is lithologically akin to the thick Humanity Seat Formation at Mt Painter. The *overall* similarity of the Central Block sequence with older Precambrian rocks at Mt Painter and in the Willouran Ranges has, however, been verified in the field by both B. Murrell and R. Coats. The sequence is quite dissimilar to the younger Precambrian sequences exposed in the Flinders Ranges.

Time did not permit the writer to personally examine older Precambrian sequences elsewhere, although a brief comparison with the Arkaba Hill Beds (Mount, 1975) and the River Broughton Beds (Preiss, 1974) was made. The former showed a general lithological similarity, but the sequences could only be roughly matched if the described Arkaba Hill sequence is inverted. There is no apparent lithological correlation with beds of the River Broughton Group.

The Central Block sequence is notable in that it does not contain any sign of the thick interbedded volcanics which are characteristic of older Precambrian sequences elsewhere in the Adelaide "Geosyncline". Although it shows common shallow water features, such as halite casts and desiccation mud-cracks, there is no evidence in the sequence that massive evaporites are present or have ever been present.

Northwest Limb

The Northwest Limb forms an elongate brecciated zone which outcrops along the line of massive lateral facies changes in the Lower Cambrian, and separates the Black Dog Hill and Donkey Bore sequences (See Fig. 9). This limb of the Wirrealpa Diapir may be subdivided into three relatively distinct areas marked I, II and III on Figure 20.

Area I contains an essentially conformable but considerably disrupted sequence of rocks which can be lithologically correlated with those of the Central Block. The lithologies represented, Dds and Dtd, appear to be folded into a tight NW-SE trending syncline. Complex smaller scale folds are also apparent. Some of these folds might well have originated as soft-sediment slumps.

The complex synclinal structure of area I is flanked on either side by dolerites. Those on the northern side, in particular, are elongate and aligned in outcrop, and may constitute intrusive bodies. The contacts between these dolerites and their hosts are never exposed.

Area II is a most complex zone of large disoriented blocks which outcrop directly westward of the sedimentary sequences of megacycle I of the Black Dog Hill sequence. The blocks are predominantly composed of highly brecciated, sometimes silicified crystalline dolomites (Dud). As indicated elsewhere this lithological group almost certainly incorporates carbonate rocks of a variety of types. Their present apparent uniformity is believed to reflect a common intense diagenetic history which, in the field, obscures their original identities. Very many of the dolomitic blocks of area II have probably been derived from rocks similar to those of the Central Block, particularly Dtd.

Dolerites are also well represented in the exposed blocks of area II, particularly in the southern parts above the northward dipping beds of the Lower Cambrian. Sandstones and various shale blocks are also present in the area under consideration, but are relatively minor. The "matrix" between the blocks is very poorly outcropping.

Area II of the Northwest Limb is most enigmatic in its relationships with adjacent Lower Cambrian carbonate sequences. As has previously been described (p. 45) the sediments of megacycle II disconformably overlie the breccias of this area. These "diapiric" breccias have certainly been exposed, as a relatively planated surface, at the sediment/water interface prior to the deposition of the carbonates of megacycle II. This relationship negates the possibility that area II represents diapiric breccias which have been intruded laterally into older Lower Cambrian carbonate sequences some time after the deposition of megacycle II sediments.

The presence of large quantities of "diapiric" clasts in the sediments of megacycle I indicates that these older source lithologies were exposed in the area at the time of deposition. If the Black Dog Hill sequence is rotated back to its original horizontal position at that time, the megabreccias of area II of the Northwest Limb are found to overlie the basal carbonates of the Cambrian. The same relationship, "diapir" overlying Cambrian carbonates with apparent conformity, can also be demonstrated on a smaller scale in this area (e.g. at 2-E/F7 as illustrated in Fig. 21). Such relationships suggest that the breccias of area II have not been vertically intruded into their present position, during the Lower Cambrian.

The relationship between area II and laterally equivalent carbonates of megacycle I is no less problematic, as has briefly been indicated above (p. 44). If the sedimentary carbonates of megacycle I are traced laterally westward, the amount and size of non-carbonate lithoclasts increases dramatically toward area II. Sorting and bedding become progressively more poorly developed, and the amount of carbonate cement in the matrix decreases. Outcrop deteriorates as a consequence until, as indicated by the amount of soil cover, it consists mainly of large irregular blocks with the matrix seldom exposed. As has also been indicated above (p. 44) many of these very large blocks exposed near the carbonates of megacycle I have their upper parts encrusted by algal stromatolites. This indicates that at least some of the large blocks of area II have been boulders within a Lower Cambrian sedimentary megabreccia. The very gradational changes in the sedimentological characteristics of the breccias from megacycle I of the Cambrian in the east, to area II of the "diapir" in the west, makes the plotting of a "contact" most difficult, and raises the question of just how much of area II constitutes a sedimentary megabreccia. The nature of the upper and lower contacts with the host rocks described above, further stimulates this question.

Intuitively the greatest objection to the breccias being sedimentary probably rests on the huge size of the individual clasts. In practice, the formation of such a megabreccia would require a suitable nearby source with a considerable topographic relief. Sedimentary megabreccias of a similar type are widely reported in the geological literature. Most are related to the gravity slumping of large blocks on tectonically over-steepened basin margins, e.g. Cook (1960), Kuenen and Carozzi (1953). In the Basin and Range Province of the Appalachians megabreccias have accumulated on the downthrown side of large faults, mainly as landslide debris (See Longwell, 1951). Well described megabreccias from Southern California are polygenetic and occur in regions of low angle thrust faulting. Once again mass movement is initiated by tectonic over-steepening, the movement taking place away from the thrust traces (Kupfner, 1960). A similar mechanism has been proposed by Burns (1963) to explain the formation of megabreccias in the Cambrian of northern Tasmania.

Cook (1960) describes huge blocks of displaced Mississippian limestones, which were originally considered to be remnants of a younger Tertiary thrust sheet. They were later shown to be gravity slump blocks from a nearby range. The blocks may be up to 160 acres in area and 200' thick and rest upon undeformed Tertiary sands and gravels. Hewett (1956) has reported one block 1,000' long and 300' thick from sedimentary megabreccia beds outcropping in parts of California and Nevada. Outcropping blocks at Old Wirrealpa are considerably smaller than these, so size alone should not be considered a valid reason for discounting a sedimentary origin for the megabreccias.

Should the megabreccias of area II be of sedimentary origin, a nearby source of considerable relief would have been necessary. The sedimentology of the laterally equivalent conglomerates of megacycle I suggest that such a source would have been to the immediate west and possibly slightly updip. A comparison of the nature and thickness of the sedimentary sequence preserved in the Black Dog Hill and Donkey Bore sequences at this time, indicates that the area to the immediate west across the Northwest Limb had been the site of considerable uplift and erosion, there being only thin Cambrian sequences present with evidence of older units (e.g. Parachilna Formation, Pound Quartzite) totally absent.

An alternative explanation for the origin of the megabreccias of area II is that they are of diapiric origin. The sequence of events involved in such a genesis must have been initiated by the exposure of a suitable source of exotic lithoclasts to the west during the deposition of the lithoclast grainstones of megacycle I in the Black Dog Hill sequence. Continued deposition of carbonate rocks well above the present top of sedimentary megacycle I might then have occurred, followed by the lateral intrusion of the diapiric material of the megabreccia, probably from the west into, or at least at the level of, the megacycle I sediments. This lateral intrusion must have been such as to leave the underlying carbonate units undisturbed as is presently the case. The size of clasts in the intruding diapiric megabreccia would need to have decreased in size laterally to the east as the Cambrian lithoclast grainstones of megacycle I were intruded. Following this intrusive phase, a major erosional event could have removed younger intruded units to expose the top of megacycle I sediments to the east and the diapiric megabreccia intrusives to the west, prior to the onset of megacycle II sedimentation in the Black Dog Hill sequence. Although the Cambrian sequences of megacycle II, unconformably overlie megabreccia material to the west in present exposures, there is no evidence whatsoever in the Black Dog Hill sequence of a major erosional event between megacycles I and II.

The above sequence of events necessary to explain the established geological relationships of the contacts of area II by a process of diapiric megabreccia intrusion is clearly improbable. Any argument that the facts can be explained by the extrusion of diapiric megabreccias at the surface during the deposition of the carbonate of megacycle I is far more tenable.

Such a process, however, is a sedimentary process, and in the writer's view a sedimentary origin is the only plausible one for the megabreccias of area II of the Northwest Limb.

Area III of the Northwest Limb is characterized by poor outcrop. As has been described in detail in a discussion of the Donkey Bore sequence (p. 56), the ill-sorted breccia unit (Dlb) which underlies the carbonates of that sequence is interpreted as being a probable basal Cambrian regolith formed upon areas of exposed older sedimentary sequences ("diapir"?). These lithologies (i.e. Dlb) are widespread in area III and not confined to its south-western edge beneath the Donkey Bore sequence. In other parts too there is a consistent relationship between the layered breccias (Dlb) and thin interbedded dolomites (Dud), some of which may be quite rich in quartz sand. The outcrops show considerable folding which appears unrelated to Delamerian fold directions, but neither the stratigraphy or the folds are readily traceable from one area of outcrop to the next. The relationships are just too complex and the exposures just a little too inadequate to firmly establish a stratigraphic sequence, although such an accomplishment seemed always imminent during field mapping. More detailed field work, coupled with detailed mineralogical and petrological backup would probably unravel the complications and enable correct relationships between the units to be established.

At 1-D3 the relationship between rocks of the Northwest Limb and the Black Dog Hill sequence is most enigmatic. Beds of megacycle V are almost perpendicular to the layered breccia and dolomites of the "diapir", across an un-exposed contact. Exotic pebbles are totally absent from the Black Dog Hill sequence at this level and it is inconceivable that the two rock types were in contact during the deposition of the carbonates of megacycle V. Upon removing the effects of Delamerian folding, the contact would appear to be approximately vertical. It might indeed represent a more typical "knife-sharp" diapir margin, a feature hitherto unrecognized by the writer at Old Wirrealpa. If this is true, it presents two points worthy of note. Firstly, since there is ample evidence of earlier syndepositional exposure of "diapiric" lithologies, such post-depositional intrusion must mean that the diapirism is multiphase, and thus the diapiric material must be capable of remobilization. Secondly, if the layered breccias are of true diapiric origin, it means that in the field they are lithologically indistinguishable from the layered breccias of sedimentary origin which occur beneath the Donkey Bore sequence of the south-western margin of the Northwest Limb. Finally it must be pointed out that the once vertical contact under discussion at 1-D3 need not necessarily be diapiric, but may in fact represent a faulted contact of older sedimentary layered breccias against downthrown carbonates of megacycle V. Such faulting would need to have occurred some time prior to the close of megacycle V, however, and may in fact be related to the influx of large amounts of detrital material into the nearby upper parts of that megacycle (See p. 51).

Doleritic bodies which outcrop in area III of the Northwest Limb are usually poorly exposed. There is a tendency for them to be aligned parallel to the direction of elongation of the Northwest Limb.

Southern Megabreccia

This portion of the Wirrealpa Diapir lies directly south of the Central Block (Fig. 18) and although it is similar in many respects to both the previously described areas, it has fundamental differences. It contains very large disoriented and closely juxtaposed blocks of sedimentary rocks with a number of large exposures of dolerites and it is possible to directly correlate most of the sedimentary units with lithologies of the Central Block sequence.

Between the blocks, outcrop is typically poor. Several areas of unlayered diapiric breccia are present, but most contacts suggest that this material between the blocks is volumetrically insignificant. At 2-I9.5 a large block of shale which dips almost vertically strikes N-S, abutts a block of undifferentiated dolomites which dip northwards and strike roughly E-W. The contact between the two is very sharp, contains minor gouge, and at the time of mapping could be spanned with a hand. The writer suspects that quite a number of contacts between blocks of the southern megabreccia might be similarly fault-like, although never as well exposed as the example above.

In mapping the Southern Megabreccia it was found that both the structure and stratigraphy of adjacent blocks could be almost concordant, yet it was never possible to satisfactorily map any group or related blocks as a single body. No doubt some real, but as yet intangible relationship exists from block to block, but in this study these relationships could not be adequately resolved. It is important to stress that the anticipated order does not take the form of zoning, a feature of diapirs which must be expected from both real and experimental examples (See Staphansson, 1972).

The dolomitic units (Dud) of the Southern Megabreccia are similar to those elsewhere. They are almost certainly of a number of different origins, having been reduced to a sameness in the field by similar intense deformational and diagenetic histories. The dolomites frequently have thinly interbedded quartz sandstones, and at 3-JII are related to relatively thick undifferentiated green shales.

At 2-I8, highly shattered sandstones of Pound Quartzite lithology, directly overlie a large dolerite body. There are no clasts of dolerite in the sandstone, nor is the sandstone congolomeratic. Highly brecciated but poorly outcropping carbonates occur between the sandstone and the Lower Cambrian sequence to the north. As described above (p. 58) this Cambrian sequence is complex, greatly attenuated, and shows abundant evidence of very shallow deposition and subaerial exposure. The unconformity at the top of Faunal Assemblage 2 in the Lower Cambrian sequence cuts down across poorly exposed breccia material southward, and across the top of the shattered Pound Quartzite. There are no sediments containing faunas of Assemblages 1 or 2 above the Pound, which is paraconformably overlain by younger Cambrian carbonates. Thus the western margin of the Southern Megabreccia consists of poorly exposed contacts with older Cambrian shallow water carbonates in the north, passing southward to a very poorly exposed contact possibly with Cambrian carbonates younger than Faunal Assemblage 2, thence to a highly shattered contact with Pound Quartzite in the most southern part of the mapped area.

The contact between the Southern Megabreccia and the Wirrealpa Hill Sequence is never exposed. This contact is important, however, for at least two reasons. Firstly it is a contact which cannot represent onlap of the Wirrealpa Hill sequence upon "diapiric" material, and would appear to be either intrusive or a faulted contact between the Cambrian and "diapiric" material. The orientation of the contact is uncertain, but its close concordance with folded bedding traces in the Cambrian sequence might suggest a low angle relationship in pre-Delamerian times. In the absence of outcrop this is of course mere conjecture, but it is interesting to note the very close association in the field between the diapir/Cambrian contact and the unconformity in the Cambrian on top of Faunal Assemblage 2. Without exposure or drill-hole information it is not possible to determine whether this is pure coincidence or critical evidence of the nature of the diapir.

The nature of the Southern Megabreccia at Old Wirrealpa Spring is remarkably similar to structures elsewhere termed "chaos" (See Noble, 1941;

Hewett, 1956; Johns and Engel, 1950; Kupfner, 1960; Longwell, 1951; Sears, 1953). A chaos "consists of a mass of large and small blocks of irregular shape, collected together in a state of semi-disorder" (Kupfner, 1960). Chaos differ from megabreccias, with which they are closely related, in that the blocks are larger, more equidimensional, less brecciated, closely packed and have minimal gouge-like matrix. This matrix is non-clastic in contrast with the megabreccia matrix. The chaos of Southern California (e.g. Death Valley, Silurian Hills) and elsewhere (e.g. Tasmania. See Burns, 1963), are intimately related to low angle thrust faults and younger megabreccia wedges. The chaos structures may develop in either the tongue or sole of the thrust, but are best developed in the latter. The structures may contain igneous intrusions related to the thrust movements.

Discussion

Lithology of major blocks

The thick sedimentary sequence of the Central Block does not correlate precisely in terms of lithology with other nearby older Precambrian sequences, although, as discussed above, it bears greater similarity to these sequences than with any sequences within the younger Precambrian or Cambrian. In the light of studies of older Precambrian sequences elsewhere in South Australia (Coats and Blissett, 1971; Preiss, 1973; Mount, 1975; Murrell, in prep.) lateral lithological variability might be expected. Thus the lack of precise lithological correlation does not contradict the widely held view that much of the substance of the Wirrealpa Diapir consists of segments of older Precambrian sedimentary sequences.

Two features of the Central Block sequence are noteworthy. Firstly, thick volcanics with their characteristic amygdaloidal textures which are so common in older Precambrian sequences elsewhere in the Adelaide "Geosyncline", are not present. Similarly, despite shallow water features throughout, the sequence lacks massive evaporites, or any disrupted units which might have indicated the former presence of massive saline evaporites.

Within the Wirrealpa Diapir there are no major blocks which can be lithologically correlated with younger Precambrian or Cambrian formations of the Flinders Ranges. There is no reason to believe that if these were present, they would not be recognizable, particularly blocks of the common sandstone units of the sediment column. This paucity of host rock blocks is unexpected, since the most recent work on the "diapirs" of the Flinders Ranges considers that the diapiric emplacement has occurred by the "quarrying, sculpting and differential scouring" of fracture surfaces in the host sequences by the intruding breccias (Mount, 1975; pp.177).

"Diapiric" breccia

From the fore going descriptions and discussions it must be clear that the genesis of the breccias associated with the "diapir" is difficult to determine. Two large masses of material previously mapped as diapiric breccia and megabreccia by Dalgarno and Johnson (1966) and Haslett (1969), have been reinterpreted in this study and are now considered to be of sedimentary origin (Layered diapiric breccia (Dlb) conformably beneath the Donkey Bore sequence and the megabreccias of area II of the Northwest Limb). These two masses form a very substantial part of the breccia outcrops of the northern part of the Wirrealpa Diapir. The similarity in the field between these sedimentary breccias and certain other breccias, particularly of the Northwest Limb, leads the writer to speculate that there might be very little, if any, diapiric breccia in the area at all. Only more detailed study is likely to resolve this issue.

The megabreccias of the Southern Megabreccia are quite distinct from those of the Northwest Limb, and are believed to be of tectonic origin.

Several factors contribute to the difficult task of assessing the nature and genesis of the breccias at Wirrealpa. The first is the intense and ubiquitous weathering of the outcrops. This extensive weathering is characteristic of the "diapiric" breccias in the Flinders Ranges. At Wirrealpa the nature of the breccias appears to have been further complicated by repeated faulting along the line of the Northwest Limb.

The breccias and megabreccias which have been interpreted in this study as being of sedimentary rather than diapiric origin, are very similar in outcrop to breccias considered to be of diapiric origin elsewhere in the Flinders Ranges, e.g. Blinman Dome Diapir, Oraparinna Diapir, Arkaba Diapir. Mount (1975), in a detailed study of what he called "diapiric metamorphic minerals" in similar breccias from the Arkaba Diapir, considered that the minerals indicated that the breccias had formed under open, oxidative, low pressure,low temperature, aqueous, CO_2-enriched conditions (Mount, 1975; pp.186). Although Mount considered that the breccias were of diapiric origin, the conditions he established could just as easily apply within carbonate breccias formed under surficial conditions by sedimentary processes.

One characteristic of the carbonate breccias of the "diapirs" in the

Flinders Ranges which is believed to indicate that the breccia material has flowed during diapiric emplacement, is a texture termed "flow layering" (Coats, 1965; Fairburn, 1967; Holt, 1970; Mount, 1975). Briefly this texture consists of an irregular undulatory layering in the carbonate breccias formed by gradual variations in the grainsize, composition or colour of the breccias. It occurs on all scales. Elongate or platey clasts tend to be preferentially oriented parallel to the "flow" layers. Larger clasts are enveloped within finer-scale "flow" laminae, giving an impression of bypassing or streamlining. On all apparent scales, clast surfaces which are not penetrated by the "flow" layers accurately but smoothly mould the form of the nearby "flow" laminations, i.e. "flow" lines wrap around impermeable clasts. The density of the laminae tends to intensify adjacent to such clasts, as it does where they are concentrated between two or more larger close-spaced clasts.

At Old Wirrealpa Spring "flow" layered textures may be seen in a number of the breccias of the Northwest Limb. Very similar textures may, however, also be seen in coarse lithoclast wackestones within megacycle IV of the Black Dog Hill sequence. The "flow" layering in these Cambrian rocks is formed during diagenesis and does not relate in any way to the flow of the rock mass itself. The textures are locally termed "mottled" textures and they will be discussed in detail for the Cambrian carbonates in PART III CHAPTER 2 of this thesis (See p. 113). Hitherto the mottled textures have not been reported from coarse lithoclast wackestones like those at Old Wirrealpa, as such rock-types are not common in the Cambrian sequences. Mawson (1925) had noted elsewhere, however, that the mottled textures show flow-like features, and that laminae show "stream lines" around contained clasts.

In the pebbly lithoclast wackestones of megacycle IV diffuse irregular layers form "flow" laminae which "stream" around carbonate and non-carbonate clasts. Non-carbonate pebbles take on a preferred orientation within the rock due to the effects of the mottling process and of compaction (See p.120 and Fig. 33). In extreme cases the mottling in the lithoclast wackestones results in the formation of textures which in the field show all the characteristics of "flow" layering in the "diapiric" breccias.

As will be established below (PART III CHAPTER 2) the formation of this "flow" layering in the Cambrian carbonate breccias takes place during early diagenesis, and appears to be caused by the movement of reactive interstitial fluids through the rock mass. The textures evolve mainly by the solution of carbonate material along avenues of enhanced permeability, and the reprecipitation of dissolved carbonate elsewhere in the rock.

The movement of copious solutions through the "diapiric" breccias of the Flinders Ranges has been widely recognized in relation to their mineralization (Holt, 1970), their geochemistry (Mount, 1975) or simply as an agent to explain the non-appearance of expected evaporites at the surface or in subsurface drilling (Webb, 1960). On the basis of the close similarities which exist between the "flow layering" of the diapiric breccias and certain early diagenetic mottled textures in the Cambrian lithoclast wackestones at Wirrealpa, the writer believes that such textures in the breccias do not <u>necessarily</u> attest to the mass flow of material, but may well represent dissolution features caused by early diagenetic fluid movement within the stationary breccia mass.

Igneous bodies

As stated above, volcanics are not present in the Central Block sequence at Wirrealpa. They are also absent as blocks elsewhere in the Wirrealpa Diapir. The same is not true for coarser grained doleritic rocks, which are common as elongate bodies, aligned plugs or large blocks within the megabreccia areas. The origin of the dolerites remains enigmatic in the absence of reliable subsurface information, since the relatively poor outcrop and complex contact relationships at the surface allow a variation in interpretation.

At Old Wirrealpa, the dolerites do not form a major portion of the outcrop of the diapir, and are subordinate in area to outcrops of dolomite, sandstone and breccia material. For this reason the great preponderance of dolerites in the boulder lithoclast grainstones, particularly of the Black Dog Hill sequence, is somewhat anomolous. The doleritic boulders do not appear to have had enhanced durabilities during reworking since the lateral persistence of dolerite boulders in the grainstone wedge is markedly inferior to that of either dolomites or sandstones. There is no reason to believe that dolerites may have been more common in the source areas for the Lower Cambrian grainstones than they are at the present exposure surface, particularly in the light of the homogeneity of the "diapirs" at different erosion levels in the Flinders Ranges (Mount, 1975). The only explanation which can be offered by the present writer is that the dolerites have occupied sites in the source areas which were very close to the sites of deposition of the boulder lithoclast grainstones in the Lower Cambrian at Old Wirrealpa Spring. That is, the doleritic bodies have been located adjacent to the margin of the uplifted source areas.

Time of emplacement

Much of the evidence for the time of emplacement of the body termed the Wirrealpa Diapir comes from contemporaneous boulder beds in adjacent Cambrian sequences. The boulders consist of distinctive lithologies only present locally within exposed "diapir". Furthermore, the close facies relationships described at length above in a discussion of the Black Dog Hill sequence, confirms that the Wirrealpa Diapir has been the source of the clasts in the Lower Cambrian carbonates. It must be appreciated that such lithoclast units indicate the exposure of older sequences at the surface, and the availability of local erosion and the transport mechanisms for their reworking. Any upward movements of the Wirrealpa Diapir which did not actually break the sediment surface would not have been recorded. Similarly the boulder beds only recorded the exposure of the distinctive source lithologies, and would not necessarily give any indication of the emplacement mechanism which was active. On a smaller scale, individual repetitive lithoclast beds probably record the availability of suitable environmental conditions, e.g. suitable current directions and/or intensitieis, rather than episodic exposures of a source.

Bearing the above in mind, the emplacement of rocks of the Wirrealpa Diapir has clearly not occurred as a single event. As may be seen in the Black Dog Hill sequence, large scale, periodic events are distinct both in time and position, each major recorded cycle appearing to migrate progressively slightly south-westward with time. Earliest local evidence of exposure of older sequences occurs everywhere some few tens of metres stratigraphically above the basal Lower Cambrian carbonates. Periodic exposure is indicated up until megacycle IV in the Black Dog Hill sequence and thus spans a considerable period of Lower Cambrian time. Although later tectonic events are evidenced (e.g. in megacycle V), there is no further indication that "diapiric" material has broken the sediment surface in the immediate vicinity of the mapped area. Exposure of diapiric lithologies does not appear to be related to movements during the Delamerian Orogeny, but has occured well before this tectonic event.

The emplacement of the Wirrealpa Diapir during the time of Faunal Assemblages 1 and 2 of Daily (1956) at Old Wirrealpa Spring, is further supported by significant changes in thickness and facies of the carbonates formed there at that time. A considerable asymmetry in both thickness and facies occurs in sediments which contain evidence of contemporaneous exposure of "diapiric" material at the surface. This asymmetry is exposed across the present-day outcrop of the Northwest Limb, and there is abundant evidence that areas to the south-west of this limb have undergone repeated uplift with respect to those to the north-east during the time of exposure of "diapiric" material in the Lower Cambrian.

Wirrealpa Diapir - a summary

The Wirrealpa Diapir possesses most of the features which characterize the complex breccia bodies of the Flinders Ranges, and which are locally termed "diapirs". The word "diapir" in this study is applied to such bodies in a nonqenetic sense.

Location

The Wirrealpa Diapir does not occupy the core of a regional anticline.

Its Northwest Limb parallels a zone of prolonged tectonism in the early Lower Cambrian, which is reflected by changes in thickness and distribution of various carbonate lithofacies across the "diapir".

Contact relationships

The contacts between the Wirrealpa Diapir and adjacent Cambrian sequences are very variable. Outcrop of the contacts is poor, but some contacts are very sharp. The Central Block in particular would appear to be fault bounded.

The Cambrian sequences may dip away from the contact (Donkey Bore sequence), dip toward the contact (Wirrealpa Hill sequence) or may, at least in part, strike laterally into the contact (Black Dog Hill sequence).

Contacts between the breccias and megabreccias of the "diapir" and the Cambrian carbonates are most enigmatic. Breccias previously mapped as diapiric may

(1) Interfinger with Cambrian sequences (Region C, Donkey Bore sequence; megacycle I, Black Dog Hill sequence).

(2) Be unconformably overlain by Cambrian material (Megacycle II, Black Dog Hill sequence).

(3) Be conformly overlain by Cambrian material (Donkey Bore sequence).

(4) Overlie, with apparent conformity, parts of the lower-most Cambrian carbonate units (Megacycle I, Black Dog Hill sequence).

(5) Be faulted against the Lower Cambrian
   a. At a high angle (Megacycle IV, Black Dog Hill sequence).
   b. Possibly at a low angle (Wirrealpa Hill sequence).

Composition of the "diapir"

A thick, relatively unbrecciated sedimentary sequence, having closest affinities with older Precambrian sequences mapped elsewhere, occupies the main central portion of the "diapir" at Old Wirrealpa Spring. No massive evaporites are present, nor is there direct evidence to suggest that they have ever been present in the rock units of the Wirrealpa Diapir at Old Wirrealpa Spring.

Blocks of younger Precambrian or Cambrian material are not represented in the "diapir".

There is no evidence of zoning or of gravity segregation in the blocks of the "diapir".

Volcanics are absent, but coarse basics (dolerites) are relatively common. They are poorly exposed, particularly their contacts, but a general alignment and elongation of bodies parallel to the Northwest Limb suggests that some at least might be intrusive into their present position.

Certain megabreccias, particularly those south of the Central Block, are almost certainly tectonic and show similarities to exposures elsewhere termed chaos.

A very large proportion of the breccias and megabreccias previously considered diapiric are of Cambrian age and of sedimentary origin. Such an origin does not contravene the conditions postulated by Mount (1975) under which "diapiric" breccias elsewhere have developed.

The so-called "flow" layering in such breccias is not necessarily indisputable evidence of a diapiric origin, but may be interpreted as an early diagenetic solution texture caused by the flow of reactive interstitial fluids within the stationary breccia mass.

Time of emplacement

In the Old Wirrealpa Spring area the Wirrealpa Diapir has been emplaced during the deposition of sequences containing Faunal Assemblages 1 and 2 of Daily (1956).

The emplacement has been somewhat episodic during that early Cambrian time, but had clearly terminated well before the onset of the Delamerian orogeny.

Mode of emplacement

The Wirrealpa Diapir certainly contains sequences with older Precambrian affinities in close association with much younger (Cambrian) units. These older sequences might be considered to have originated from much lower in the sedimentary rock pile.

There is little evidence to confirm, that they have "flowed" upward into their present position by some sort of diapiric emplacement mechanism.

Their emplacement has been accompanied by long-active tectonism. Tectonic megabreccias do occur. There have been repeated uplifts of south-western areas with respect to north-eastern areas across the zone of "diapir" emplacement, as evidenced by the thickness and lithofacies in the Lower Cambrian.

In conclusion, there is little evidence in the Wirrealpa Diapir at Old Wirrealpa Spring to support a diapiric origin for the structure as proposed by Webb (1960). However, the limited nature of this study, at this stage precludes the tendering of a satisfactory alternative emplacement mechanism.

LOWER CAMBRIAN DEPOSITIONAL HISTORY

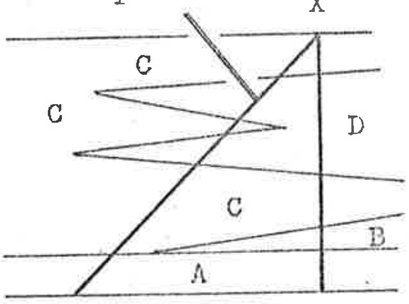
POST-DEPOSITIONAL TECTONICS

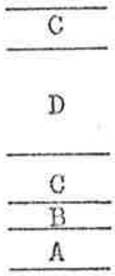
In order to establish the relative positions in Lower Cambrian times, of the three described carbonate sequences at Old Wirrealpa Spring, the effects of the Delamerian folding and post-Delamerian faulting must be accounted for. In such a complex area, with no subsurface information, the removal of these effects of tectonism is fraught with difficulties. Reliable information is virtually limited to the Cambrian sequences themselves in their present plane of outcrop, and allowances made for fault movements and folding are necessarily somewhat speculative.

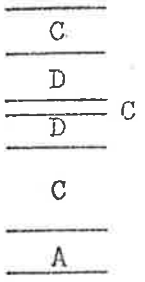
Clearly the latest faulting in the area has occurred as sinistral displacements along NE-SW trending faults. Two such faults of significant displacement are present in the mapped area. These are discussed on p. and their effects can be removed by reversing the proposed displacements on each. The same may be done for the dextral fault displacements which have occurred along the Northwest Limb of the Wirrealpa Diapir in post-Delamerian times.

The unfolding of the Cambrian sequences about the Delamerian fold axes results in the three exposed sequences being located in relation to each other as shown in Fig. 22. The figure was constructed by extrapolating true thicknesses of the exposed sequences into imaginary pre-Delamerian vertical sections. The unconformity at the top of Faunal Assemblage 2 is used as a datum.

The approximations in the above procedures are obvious but are the best available at the present time. Clearly the vertical sections themselves do not precisely represent true geological sections prior to Delamerian folding. The present erosion plane nowhere approaches a plane perpendicular to the bedding of the sequence, thus each section must show a lateral displacement of the original superposed lithofacies, the error involved increasing as the angle of the average present erosion plane approaches that of the dip of the sequence (see below).


Present exposure plane.


True section at X.


Apparent section at X.

HISTORY OF LOWER CAMBRIAN SEDIMENTATION

This interpretation of the depositional history will be given in terms of a series of palaeoenvironmental reconstructions (Figs. 23 to 31). The solid lines on each diagram indicate the projected line of each of the exposed Cambrian sections as seen on Figure 22.

In late Precambrian times the Old Wirrealpa Spring area had already experienced periods of local tectonic instability. The Pound Quartzite sequences are markedly atypical of their equivalents elsewhere in the Southern and Central Flinders Ranges (Ford, pers.comm.). Certain lateral facies and thickness changes are apparent across the present-day Mt Lyall Anticline, (See Fig. 8) the entire sequence on the southern limb being greatly attenuated with respect to the equivalent sequence on the northern limb. The published geological maps (e.g. BLINMAN 1:63,360 map sheet) are in considerable error in the location of faults and lithological units in the area, and despite a broad stratigraphic study of the area by Haslett (1969), the exposures of Pound Quartzite in the Mt Lyall Anticline have not been adequately researched and remain poorly understood. In general terms, however, it is clear that areas to the south and SW have undergone uplift with respect to corresponding areas to the north in late Precambrian times. There is no report of exotic clasts of "diapiric" lithologies being present in the sandstones of the Pound Quartzite, although thin pebbly units do exist.

Small remnant outcrops of Pound Quartzite beneath Cambrian carbonates of the Black Dog Hill and Donkey Bore sequences testify to this unit having been deposited in areas to the south and west of Old Wirrealpa Spring. It would appear to have undergone erosion in these areas, possibly prior to its lithification. Quartz sands were probably reworked into the Parachilna Formation in the basal Cambrian. The Parachilna Formation itself is not developed above the remnant exposures of Pound Quartzite which are overlain directly by Cambrian carbonates. In the Mt Lyall Anticline a thinly developed Parachilna Formation on the south limb contrasts with a thick development of the unit in eastern parts of the northern limb. This indicates that the earlier tectonic instability of the area persisted into lowermost Cambrian times.

Initial carbonate deposition in the Lower Cambrian consisted of widespread shallow to very shallow dolomite mudstones with abundant thin interbedded quartz sandstones (Fig. 23). The well-sorted and well-rounded nature of the quartz sand grains indicates that they probably originated by the reworking of exposed sands of the Pound Quartzite and Parachilna Formation. Broad, restricted, and periodically-exposed dolomite mudflats were widespread. Shallow channels and depressions in the flats saw the deposition of dolomitic intraclasts in thin flat-pebble conglomerate beds. Algal stromatolites and algal-laminated muds occurred throughout, and grey to black lime muds and interbedded intraformational conglomerates and stromatolites formed in slightly deeper less restricted areas, probably to the north and west. In places, continued exposure of the sands of the Pound Quartzite and Parachilna Formation saw a great reduction in the thickness of these units, the sands being dispersed over shallower upper intertidal and supratidal areas by spring tides and storm activity.

The first of a series of major uplifts in the Old Wirrealpa Spring area in Lower Cambrian times is recorded by the megabreccias of megacycle I in the Black Dog Hill sequence and by the first influx of exotic lithoclasts into the Wirrealpa Hill and Donkey Bore sequences. The uplift exposed older Precambrian sedimentary sequences for the first time in the Lower Cambrian seas, the prominant uplift scarp being aligned along the present Northwest Limb of the Wirrealpa Diapir (Fig. 24). The size of megabreccia boulders suggests that the uplift was initially very appreciable, and in the light of the shallow nature of the Cambrian carbonate deposition, is interpreted as having exposed older sequences subaerially in Lower Cambrian times. Except along the immediate uplifted zone, shallow water carbonate deposition persisted elsewhere.

To the north of the escarpment, a lithoclast megabreccia wedge passed laterally into generally sheltered intertidal carbonate mudflats. Certain areas which lacked the physical protection of the subaerially exposed escarpment saw grainstone deposition. Sheltered areas also experienced intermittent ooid and lithoclast grainstone deposition during times of storm activity. Stromatolites and intraclast conglomerates formed on the sheltered mudflats in slightly depressed areas, in tidal channels and on channel margins.

To the south and SE, thick ooid grainstones were deposited on stable higher energy areas. Exposed older Precambrian sequences were rapidly eroded along their southern margins and large talus deposits did not survive. Pebbles of the more resistant lithologies were rounded and reworked by wave and tidal action into cobble beach deposits and further dispersed southward over the shallow carbonate platform. Great mobile bodies of ooids traversed the platform whilst lower energy areas with less mobile substrate were periodically colonized by algae, resulting in the growth of widespread algal stromatolites which are preserved in the Wirrealpa Hill sequence.

Deposition kept pace with subsidence, even on the NE block, and shallow carbonate depositional environments were generally maintained. Areas of older Precambrian material which were the source of non-carbonate debris were gradually planated by erosion to form large, lithologically variable areas with low, possibly subaerial relief (Fig. 25). These broad areas continued to act as barriers to the penetration of high energy conditions onto sheltered tidal flats to the north, and stromatolite growth flourished adjacent to and upon older talus deposits. Conditions to the SW remained essentially the same, with a high energy carbonate platform experiencing ooid and lithoclast grainstone deposition, with relatively minor stromatolite growth. Periodic storms washed ooids and lithoclasts across the low barrier to the north, forming thin, clastic, sheet deposits upon the sheltered tidal mud-flats.

Upon the planated barrier itself a primitive regolith probably developed. Very little movement of sediment occurred and dolomite and minor shale formation possibly took place within shallow ephemeral lagoons on the flat barrier surface.

Apart from algal growth and minor worm activity in areas of lime mud deposition, evidence indicates that bioactivity at this time was very low over the entire range of sedimentary environments.

With the progression of time and continued stability, thin Cambrian ooid grainstones and minor lime mudstones transgressed over the barrier from the SE and north respectively.

A period of renewed tectonic activity followed, resulting in the uplift once again of areas to the SW with respect to those to the NE. The activity took place predominantly along the same NW-SE trend, but probably slightly more to the SW. The event was far less intense than its predecessor, and the lesser relative movements resulted in much lower slope changes at the surface along the line of the NW trending zone, and megabreccias did not form on the same large scale as those of the previous cycle of tectonic activity.

In the Black Dog Hill sequence, preserved evidence in megacycle II indicates that large, often well rounded boulders of non-carbonate material were shed, probably along tidal feeder channels, from the SW into slightly deeper carbonate environments to the NE. Erosion of the older regolith on the SW block was not particularly intense since thick sequences are preserved in the Donkey Bore sequence as crudely layered breccia (D1b).

At this stage the rate of subsidence to the NE began to outpace the rate of sediment accumulation in that area. This resulted in environments to the NE becoming gradually deeper, with appreciable bottom-slopes being developed in that direction for the first time. This would have resulted in the gradual reversal of the tidal drainage direction and the occurrence of a wackestone lithofacies between the grainstones and mudstones in the Black Dog Hill sequence. Previously, coarser sediments had only accumulated on the mud-flats to the NE during essentially single events e.g. storms, periods of spring tides. This is reflected in the nature of the lateral facies changes in megacycle I of the Black Dog Hill sequence (see above). The slight deepening to the NE, however, resulted in coarser material being slowly and continually shed downslope to intermix with autochthonous carbonate muds and form extensive areas of wackestone deposition for the first time in that area.

This changed palaeogeomorphology also allowed the accumulation of thin ooid grainstone banks slightly offshore, on the gentle NE sloping generally muddy bottoms (Fig. 26). The banks were only thinly developed due to shallow conditions and the limited amount of available wave energy generated in these shallow and essentially still-protected NE areas. The ooid banks experienced repeated periods of supratidal exposure which probably corresponded with a regional regressive phase as recorded in the Wirrealpa Hill sequence by thick and widespread birdseye limestones. Areas of the Donkey Bore sequence must also have undergone this periodic exposure but the events are not clearly recorded in the lithoclast conglomerates which were being deposited in that area at the time.

There followed a brief period of stability which saw very limited deposition in the region. It was at about this level, however, that archaeocyathids made their first appearance. Thin archaeo/algal boundstones developed slightly offshore to the north-east of the once-active zone whilst archaeocyathid fragments began to be a significant component of grainstone bodies to the SW in high energy shallow marine environments (recorded as archaeocyathid and ooid grainstones above the birdseye limestones of the Wirrealpa Hill sequence). Limited deposition of lithoclast grainstones still persisted in the region of the previously active zone.

The next episode of major tectonism, as recorded in sediments of megacycle III in the Black Dog Hill sequence, was essentially similar to the previous one, except that once again the main zone of movement was slightly further to the SW. The movements again accelerated the deepening of areas to the NE since carbonate sedimentation rates generally lagged slightly behind the rate of subsidence in that area (Fig. 27). Slightly offshore, archaeo/algal boundstones formed mudbanks which were periodically inundated by rapidly deposited wackestones, probably shed northward in response to increased rates of uplift to the immediate SW and concomitant periodically increased bottom slopes. Conditions to the NW remained essentially sheltered but unrestricted, with thick accumulations of lime mudstones.

On the SW block, shallow, energetic open marine environments experienced predominantly grainstone depositon, with very minor areas of fine lime-mud build-up. Grainstones were increasingly composed of archaeocyathid fragments, with ooids and minor lithoclasts as subordinate but still important constituents.

Sediments of topmost megacycle III and basal megacycle IV of the Black Dog Hill sequence were deposited during times of considerable bottom gradients from the active zone basinwards to the NE. Grainstones, still predominantly oolitic and deposited under high energy conditions, prograded across the planated surfaces which had been uplifted during the immediately precedent tectonic event. Exposure of these areas occasionally occurred, as evidenced in the basal part of megacycle IV of the Black Dog Hill sequence. There, Cambrian carbonates have minor reddened, laminate horizons and abundant large dissolution fenestrae. Thick wackestones passed rapidly into deeper water mudstones to the North, and at this stage, archaeocyathid-algal build-ups did not occur (Fig. 28).

The next event followed the general theme of earlier ones, with relative uplift of a SW block with respect to a NE block. The resultant differences in depth of the two environments was relatively slight, since again deposition managed to keep pace with subsidence. The distribution of various lithofacies was fundamentally the same as that for the previous cycle (See Fig. 27). Lithoclast debris, however, was reworked into the Cambrian sequence for the last time in this particular area, and it appears that the tectonic events to follow never exposed older non-carbonate source material at the sediment surface again. The lithoclast grainstones shed to the NW at this time were also the first to show any substantial content of reworked Cambrian archaeocyathid grainstone pebbles. The lithoclast beds were initially confined to areas immediately adjacent to the zone of uplift, partly due perhaps to the relatively limited volumes of source material available, and partly due to the effect which offshore archaeo/algal mudbanks had in limiting the movement of clastic debris basinward across gentle bottom slopes.

As uplift continued bottom slopes increased and wackestones swamped the growth of offshore boundstones. As appreciable depositional slopes became established, lithoclast grainstones were spread basinwards by the periodic gravity slumping of material in a north-easterly direction. These lithoclast wedges tailed off into thick poorly fossiliferous lime mudstone deposits. In these environments of sheltered mudstone deposition, bottom circulation was poor and reducing conditions prevailed.

At this time the uplifted energy barrier along the active tectonic zone must have been low but relatively continuous, since there is little to no sand-size carbonate detritus shed northward across it from the more southerly areas of ooid and skeletal grainstone deposition.

During the succeeding periods of tectonic quiescence the distribution of carbonate lithofacies in the area appears to have been relatively simple, probably once again similar to the simple picture presented in Fig. 28. Much of the evidence for the lithofacies distribution at this time, particularly in the Donkey Bore sequence, has been removed by later uplift and erosion. Rock types deposited in the Black Dog Hill and Wirrealpa Hill sequence at this time indicate that lime mudstone and skeletal grainstone desposition took place in the northern and southern areas respectively. Wackestones presumably occupied a broad zone covering the gentle break-of-slope between the two depositional extremes.

The next major uplift had a considerable effect on the thick grainstone sequences which had accumulated on the southern margins of the zone of activity at Old Wirrealpa Spring. Renewed movements lifted these rock-types into the vadose zone resulting in considerable erosion, and the development of the first generation of karst features which were to be preserved in the Donkey Bore sequence (Fig. 29). The acutely depressed water-table on the southern or uplifted block, as discussed above (see p. 66), attests to local relief having been considerable at this time. Major erosion also appears to have been localized between the southern limit of the Donkey Bore sequence and the interpreted position of the Wirrealpa Hill sequence. There sediment cover was stripped to about the level of the underlying Pound Quartzite. To the immediate south, shallow, flat-lying areas of lithified skeletal grainstones were swept clear of unlithified sediment by wave and current action. Although the resultant paraconformity within the Wirrealpa Hill sequence is not clearly revealed, such a feature might well relate to zones of silification found within that sequence. To the north thick lime mudstones and wackestones formed, with minor grainstones being deposited adjacent to the uplifted zone.

As tectonic stability returned, uplifted areas were gradually planated, and any cavities within the karst fissures not closed off by one sort of subaerial carbonate cement or other, gradually filled with marine skeletal debris. Continued submarine erosion occurred along elevated zones until widespread skeletal grainstone deposition once more took place. Despite little remaining evidence, it is believed that a regional marine transgression at this time might well have been responsible for the build up of thick unlithified skeletal accumulations along the zone of earlier activity and to the immediate south. Evidence of this phase of very rapid sediment accumulation comes firstly from the occurrence, for the first time, of sizeable slumps of wackestones and mudstones northward into deeper areas. Secondly, during the further uplift which was soon to follow, enormous amounts of reworked skeletal debris was shed to the north, swamping wackestones and mudstones on the basin margin and penetrating deep into the basin proper. Within these skeletal grainstones there is a pronounced paucity of reworked clasts of archaeocyathid grainstones, suggesting that the source material, although in great volume, was essentially unlithified.

These movements, referred to above, once again elevated remnants of the previously exposed Cambrian landsurface into the subaerial environment, and karstification began afresh (Fig. 30). Again, deposition to the south at this time was very limited, where conditions of mild erosion/non-deposition persisted until the end of Faunal Assemblage 2 times. Gradual erosion of the more uplifted areas resulted in their eventual planation, with essentially only the roots of the karst features being preserved in the Donkey Bore sequence. In places this period of widespread erosion, possibly related to a regional marine regression, resulted in the entire Lower Cambrian carbonate sequence being stripped from the older breccias along the tectonically active zone. Evidence of exposure and erosion at this time stretches well north upon the grainstones of the Black Dog Hill sequence.

When sedimentation resumed to the immediate north of the active zone, it took the form of lenticular intraformational conglomerate beds deposited within shallow depressions on the older unconformity surface. Thereafter, the alternating cycles of open shallow marine sedimentation and very shallow restricted mudstone deposition, as evidenced in megacycle IV, persisted on the shallow relatively stable areas to the north until the close of Faunal Assemblage 2 times (Fig. 31). There is some suggestion, particularly from evidence in Region A of the Donkey Bore sequence, that archaeo-algal boundstones may have periodically formed along the active zone to the south at about this time. These boundstone bodies were, however, affected by the repeated erosional episodes which characterize the southern areas, and only minor erosional remnants may be found beneath the Faunal Assemblage 2 unconformity. Well south of the active zone, stable flat-lying areas or lithified grainstones maintained their position at about mean sea level and sediment accumulation was minimal.

Sedimentation immediately above the sequences of Faunal Assemblage 2 age at Old Wirrealpa does not reflect movement along the previously active NW-SE trending zone of earlier times. Dark grey mudstone deposition persisted above older sequences of the Black Dog Hill and Donkey Bore sequences, whilst renewed open marine grainstone deposition took place south of an east-west trending zone between the interpreted pre-Delamerian location of the Donkey Bore and Wirrealpa Hill sequences (See Fig. 22).

PART III: ASPECTS OF THE CARBONATE SEDIMENTOLOGY AT OLD WIRREALPA SPRING.

CHAPTER 1

STROMATOLITE MORPHOLOGY AS IT RELATES TO DEPOSITIONAL ENVIRONMENT

INTRODUCTION

During the mapping of the carbonate sequences of megacycle I on Black Dog Hill, it was apparent that certain systematic changes occurred in the stromatolite morphology from west to east, within any single stromatolite bed. The description and interpretation of these changes was the subject of a paper prepared during this study (Haslett, 1976). For completeness, the paper has been adapted for inclusion in this thesis, along with the other facets of the geology at Old Wirrealpa Spring which have been the subject of this investigation.

The sedimentary sequence of megacycle I and its depositional significance has been described in full above, and will not be repeated here.

In studying the stromatolites in particular, selected samples were cut into three mutually perpendicular slabs, acid-etched and stained with alizarin red S for laboratory study. Large thin sections of selected specimens were also examined. Preservation of features is generally good, but certain microscopic features have been obscured by diagenesis. No attempt has been made to apply a rigorous classification to the stromatolites studied. Instead, the structures have been described in general terms, chiefly following the orderly scheme of Hofmann (1969).

STROMATOLITE DESCRIPTIONS

Thickness and macrostructure

The thickest units of columnar stromatolites occur within the western grainstone sequence, where stromatolitic beds are up to 10m thick. Most, however, have a maximum thickness in the order of 1-1.5 m and show gradual thinning to the east, where the underlying grainstone lenses thin into calcareous mudstones.

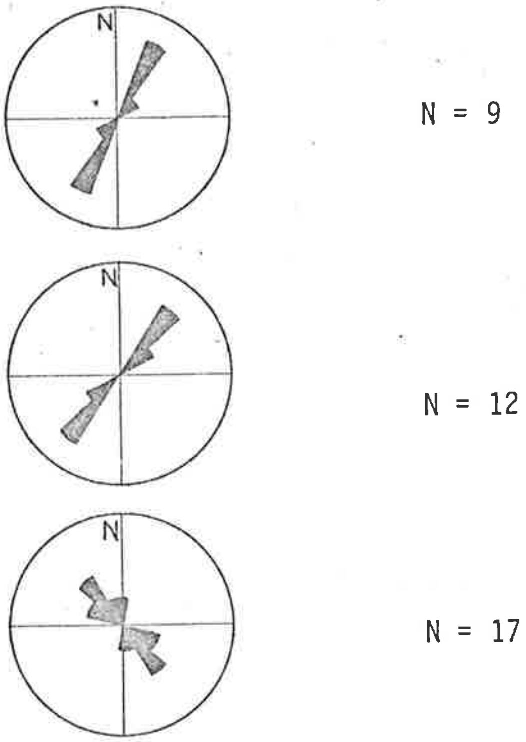
Stromatolite beds to the west generally have planar basal contacts with underlying grainstones. Stromatolite biostromes with relief of up to 25 cm (Plate 4b) occur adjacent to the diapir, and these pass gradually into tabular stromatolite beds to the east. There is a corresponding change within the bed from radiating to erect columns. In those cases where stromatolites develop on rippled ooid grainstone surfaces, stromatolite elongation is perpendicular to the ripple crest, indicating common current directions for both structures (See Fig. 32).

Beds of columnar stromatolites within the mudstone sequence are more lenticular and thinner than their counterparts to the west. Maximum thickness of the beds does not exceed 2 m, and the relief of constituent domed stromatolites is less than 10 cm. Columnar stromatolites are invariably associated with flat-pebble conglomerate beds, and the maximum thickness of stromatolites appears to occur where conglomerate lenses thicken. In many places both stromatolites and flat-pebble conglomerates are cut by channels. The columnar stromatolites may be seen to pass laterally into dome-shaped stromatolites and algal laminates.

Current directions

A scarcity of bedding-plane exposures limits the number of measurements of stromatolite elongation that can be taken. A plot of the readings that have been obtained, however, shows good agreement within particular beds (Fig. 32). Current directions measured from stromatolites in the western part of the sequence, also show good agreement with those measured from ripple marks in associated grainstones. Stromatolites in the eastern part of the sequence do not show such marked elongation, and give a wider spread of current directions.

Some biohermal stromatolite beds in the eastern sequence show weak asymmetric growth, similar to that reported by Hoffman (1967). The asymmetry indicates a supply of carbonate mud from the northwest.



Measured from

a. Stromatolite bioherm elongation in open tidal flat.

b. Current ripples open tidal flat.

c. Stromatolite bioherm elongation in restricted tidal flat.

FIGURE 32: Current direction measurements, megacycle I, Black Dog Hill sequence.

Lateral changes in stromatolites

In mapping the nature and distribution of stromatolites in the sequence, all beds were traced laterally and their characteristics noted. More detailed work was concentrated on two beds in the lower, more markedly cyclic part of the sequence. The two beds were selected for their good exposure and the apparent wide range of sedimentary environments which are laterally represented. Details of differences in stromatolite morphology from west to east can be most easily described with reference to representative samples A-K as marked on the diagrammatic cross-section (Fig. 15). Some very large allochthonous boulders derived from the diapir form sites for growth of columnar stromatolites (A). These boulders, which presumably remained immobile after initial deposition, have their top-most parts encrusted by stromatolites in layers up to 20 cm thick. The stromatolites are slender, erect, cylindrical, close-spaced and about 5 mm in diameter. Rare branching is dendroid to anastomosed (Hofmann, 1969). Laminae tend to be diffuse, slightly wavy and convex, with low relief. Wall structure is poorly developed. Intercolumnar sediment is up to 2 mm in grain size, but most sediment within the columns is less than 0.3 mm.

Stromatolites are not generally well developed within the coarse lithoclast grainstones between points A and B; however, minor crusts cap some boulders, and detached thumb-sized columns also occur.

At point B, stromatolite beds become well developed. The stromatolite columns tend to be radiate and constringed, with ragged margins. Anastomosing of columns is common, although furcate branching also occurs. The average diameter of individual columns is about 5 mm and most columns tend to be short. Thin-section examination reveals diffuse to lumpy laminations, with a moderate to low degree of inheritance. Some laminae are wavy and convex with a very slight tendency to lap over column margins. Microstylolitization has removed many column edges. Intercolumnar lithoclasts are up to 2 cm in size, whereas material within the column is usually less than 2 mm in grain size.

Stromatolites of the type which occur at B have a very notable feature about their microstructure. Within columns, generally at the same level from column to column, irregular patches of micrite and pseudospar occur. Rare cellular structures similar to Renalcis (Johnson, 1966, p.25) may also be found (Plate 15a). Other globular, branched areas of pseudospar are also apparent within the columns (Plate 15b). Branching of these areas is invariably divergent upwards. Although preservation is far from perfect, it appears that algal species capable of carbonate precipitation have at times played a part in the development of these stromatolites.

Some distance farther east (C), lithoclasts seldom exceed 1 cm in diameter. Stromatolites are similar to those described above, being short, highly constringed columns with common anastomosing and dendroid branching. Laminations are extremely irregular and bulbous, with low inheritance.

Stromatolites at point D are associated with well-sorted grainstones which only rarely contain large lithoclasts. The erect cylindrical columns, some strongly constringed, may be up to 1.5 cm in diameter. The columns are close-spaced, with anastomosed to umbellate branching. Wall structures are strongly developed and commonly show intense black pigmentation (Plate 16a). The diffuse to lumpy laminations show high relief. A basic difference appears to exist between the irregular but relatively continuous laminae in the central parts of the columns, and the clotted irregular fabric of the pigmented areas. The pigmented areas sometimes form laminae but are mainly concentrated along column walls

(Plate 16a).

As the stromatolite beds thin to the east, and associated grainstones lens out into mudstones and flat-pebble conglomerates, the stromatolite columns generally become broader in cross-section (E). Branching of the erect to decumbent columns is usually umbellate. Laminations show diffuse to clotted textures with low to moderate inheritance. As seen in profile, the laminae are convex to penecinct with moderate to high relief. Large flat mudstone pebbles which appear within the stromatolite beds often cap columns and appear to have prevented continued growth. They subsequently became colonized and acted as a base for new columns. The columnar stromatolite beds are in general overlain by irregular stratiform stromatolites.

At point F, squat columnar stromatolites are closely associated with flat-pebble conglomerates within the mudstone sequence (Plate 16b). Columns are 2-5 cm in breadth, and are cylindrical to turbinate, with furcate branching. The erect columns show distinct, even laminations which are convex and have low relief. Partial linking of the close-spaced columns occurs locally. Several thick irregular layers contrast with the more normal thin, regular and strongly inherited laminations. The irregular layers are readily traceable from one column to the next. Stromatolites at G are dominantly stratiform, but show a strong similarity to the broad columnar forms with respect to their laminations. The porous, irregular layers are thick, and loaf-shaped. The high degree of inheritance in overlying regular laminations means that many irregularities are reproduced with subsequent stromatolite growth. Some irregularities soon disappear, but some are enhanced by further growth, and furcate branching may result.

To the east, cryptalgalaminates, and nodular stromatolites occur. Columnar stromatolites are associated with flat-pebble conglomerate beds, particularly in areas where the conglomerate beds are thickened. Some columnar stromatolites which have grown on flat-pebble conglomerates have fine carbonate mudstone between and above the columns (H). These stromatolites are upright and slender, with diffuse laminations but well-developed, highly pigmented wall structures (Plate 17a). Large irregular spar- and sediment-filled cavities are generally found within the columns. The cavities show radial shrinkage cracks and probably formed during periods of subaerial exposure. Another type of columnar stromatolite forms low, discrete bioherms (K). Digitate branching of the close-spaced cylindrical columns is common. Laminae are convex, regular to wavy, and have low relief. Walls are not well developed. Intercolumnar sediment consists of carbonate mud, and of carbonate intraclasts up to 5 mm in length. Columns usually coalesce at the tops of the bioherms and pass into algal laminates.

Many columnar stromatolites associated with the thickest parts of flat-pebble conglomerate beds (I) have grown from oncolites which have finally come to rest (Plate 17b). Broad columnar stromatolites, upon umbellate or furcate branching, form numerous smaller constringed columns. The branching typically occurs at particular levels throughout the stromatolite. Laminae may be planar or low-relief convex, and are markedly down-curved on column margins. Most laminations are regular and somewhat diffuse, but thick irregular clotted layers with considerably higher relief and lower inheritance than the more normal laminations occur at certain levels. These irregular layers are similar to those described above (F and G) and are traceable from one column to the next. Textures of the irregular layers are fairly well preserved, and are somewhat similar to those found in Madiganites mawsoni, and described by Walter (1972) as vermiform microstructure.

Stromatolites which grow on the edges of steep-sided channels which intersect flat-pebble conglomerate beds (J), have formed adjacent to, but at a topographically lower level than, those just described (I). They consist of cylindrical to turbinate close-spaced columns which show digitate branching and distinct convex to geniculate laminations (Plate 18a). The regular laminae have a moderate to high relief and generally show a moderate degree of inheritance. Lenticular bands with an irregular clotted structure also occur within these stromatolites. They tend to have higher relief than normal regular laminae and cause irregularities in the column structure. The irregular layers correspond in adjacent columns, and commonly occur at levels of column branching.

DISCUSSION

Workers on recent stromatolites (Logan, 1961; Monty, 1965; 1967; Gebelein, 1969) have recognised that the characteristics of a particular stromatolite are moulded by complex interrelationships between physical, chemical and biological aspects of the environment in which it forms. Recent stromatolites have been shown to form by the binding, trapping or precipitation of sediment, mainly by communities of blue-green algae. It is only recently that the biological complexity and environmental sensitivity of such algal communities has been really appreciated (Carr and Whitton, 1973). There still exists, however, a polarization of views on whether the major factors that determine stromatolite morphology are biological (Cloud and Semikhatov, 1969; Walter, 1972) or physico-chemical (Logan et al., 1964; Hofmann, 1969). The contentious points, which bear on the validity of stromatolite biostratigraphy, have been summarized by several different workers (Hofmann, 1969; Cloud and Semikhatov, 1969; Walter, 1972), and will not be repeated here.

At Old Wirrealpa, stromatolite morphology appears to be related to lithofacies distribution. Most variation in form occurs laterally, with little or no vertical change within equivalent lithofacies. Precise correlation between stromatolite morphology and lateral changes in physical, chemical or biological factors is difficult to make in ancient sequences. At Old Wirrealpa no preserved organic matter has been found, chemical factors such as pH and salinity are indeterminable, and even physical factors are difficult to assess, due to outcrop limitations and diagenesis. Despite these difficulties, it is possible to make some tentative environmental analogies with modern stromatolites.

Growth mechanisms

Algal stromatolites at Old Wirrealpa appear to have grown predominantly by the trapping and binding of sediment. This is most obvious in the western sequence where large amounts of non-carbonate sand and silt occur as layers within stromatolite columns. The ability of algae to trap and bind sediment in modern environments has been found to depend on factors such as current velocity, sediment size and supply rate, and the species of algae involved (Gebelein, 1969). Stromatolites do not occur in the bottom of channels at Old Wirrealpa, where energy levels and abrasive action must have been high. Columnar stromatolites which encrust large boulders in the western sequence appear to have formed under high-energy conditions but would, because of their elevation, have been less subject to abrasion.

Carbonate precipitation appears to have contributed minor amounts to stromatolite growth, and although evidence is scarce, much of the carbonate precipitation appears to have taken place under algal influence. Clotted, highly pigmented and cellular structures of possible organic origin have been observed within columnar stromatolites associated with clastic grainstones (see p. 105 and Plates 15a and 15b). Such bands of apparent precipitation may be traced from column to column at approximately equivalent levels. Although best developed on column margins, some bands may be traced from within columns, down margins and as bridges across to adjacent columns. The thickening of these pigmented bands on the vertical column margins in contrast to the more normal laminations, which are thickest on column tops, suggests that dominant growth was by precipitation. An almost total absence of non-carbonate detritus from within these bands, even in the western sequence, indicates that their development was associated with low current velocities and low sediment-supply rates. It may be that such layers are ancient analogues of calcified layers found in Recent algal mats, correlated by Monty (1967) with periods of emergence.

Similarly, the irregular sparry layers described from well-laminated columnar stromatolites within the mudstone sequence (p. 106) may also be the result of carbonate precipitation. Most of these once very porous bands occurred on column tops (See Plate 18a), but some form continuous dome-shaped layers in stratiform and nodular algal limestones. The greatest thickness and frequency of these layers seems to occur in columnar stromatolites from slightly more elevated parts of the tidal flat (compare samples I and J, Plates 17b and 18a). These layers may represent growth of different algal species, or a reaction of certain species to a period of subaerial exposure.

Effects of sediment grain size

Despite the ill-sorted nature of sediment supplied to stromatolites in the western part of the sequence at Old Wirrealpa, trapped and bound material within the columns is restricted to sand- and mud-sized grains. Detrital material caught between columns commonly contains larger well-rounded pebbles. Persistent agitation in this environment probably caused such pebbles to be dumped on growing algal mats at various times, terminating growth in these positions. The size of such pebbles, however, would have reduced their chances of being bound, and further agitation could have removed them and allowed renewed growth upon columns. Such a mechanism probably played an important role in the development of irregular laminations and to some extent may have influenced column branching in this part of the sequence (See p. 112).

Columnar stromatolites to the east are composed of very fine calcareous muds, with minor fine quartz sand and silt. Sediment between columns is usually of equivalent grain size, but may consist of intraclast chips, coarser quartz sand and occasional larger flat conglomerate pebbles which were trapped edgewise between columns. The periodic incursion of high-energy conditions into these sheltered environments, probably during storms, has resulted in local accumulation of flat-pebble conglomerates upon the stromatolite beds. Unlike their grain-size equivalents to the west, these pebbles appear to have been seldom shifted after initial deposition. Their flattened shape and the relatively rare incursion of high-energy conditions into this environment probably account for this. Depending on the thickness of the flat-pebble conglomerate beds, columnar stromatolite growth may have been effectively stopped.

The selective trapping and binding of finer sediment fractions by algae, as illustrated by these Cambrian stromatolites, has been reported in studies of Recent environments (e.g. Black, 1933; Gebelein, 1969). The greater range of grain sizes within columns in the western part of the sequence at Old Wirrealpa, compared with that to the east, probably reflects to some degree the greater range available in the west, due to a poorly sorted supply. The possibility that this wider range of grain size might be contributed to by differences in the nature of algal communities living in the two environments cannot be discounted.

Stromatolite laminae

As a general rule, stromatolite laminae in the carbonate mudstone lithofacies show far greater regularity than those associated with grainstones in the western sequence. Columnar stromatolites within the mudstones have finer laminae of more uniform thickness and with a greater degree of inheritance than those to the west. Cryptalgalaminates and domed stromatolites have even finer and more uniform laminations than columnar varieties. As has been reported by Gebelien (1969) for some stromatolites of Bermuda, high degrees of lamina regularity may be related to areas of lower rates of sediment supply. As discussed above, other factors such as the degree of sorting of supplied sediment, and the nature of the actual algae, may also influence the regularity of the laminations. Stromatolites within the mudstone sequence commonly show down-folding of laminae at column margins to form walls. Such walls are usually best developed where inter-columnar sediment is fine grained. Broad, squat columnar types have better-developed walls than the slender columnar varieties.

The irregular nature of laminations within stromatolites in the western part of the sequence may be partly due to large pebbles temporarily preventing growth (See above, p. 109), but erosion may also play a part in this irregularity. The thickness of individual laminae varies markedly from one lamina to another, and within a single lamina there may be pronounced thickness variation. Wall structures such as described above are rare, the column margins usually being ragged. An exception occurs, however, in that some column peripheries have clotted and highly pigmented margins of what is interpreted to have been organically precipitated carbonate. These margins differ from the dominantly laminated central portion of the column, and are probably best described as mantles (Raaben, 1964: see Hofmann, 1969, p. 18).

Distribution of columnar stromatolites

All stromatolites within the grainstone sequence at Old Wirrealpa are columnar. Columnar stromatolites in the mudstone sequence only occur in close association with flat-pebble conglomerate beds, which appear to have accumulated in areas which were slight topographic depressions on the sheltered tidal flats.

The growth of columns and domes in present-day stromatolites is due, fundamentally to enhanced stromatolite growth in certain parts of a mat and/or limited growth in adjacent parts. Substrate irregularities are believed to initiate column growth in certain instances (Logan, 1961; Walter, 1972). Continued column development may take place due to the restriction of active mat growth to column tops and sides, and the retardation of growth between columns by such factors as excessive wetting, mechanical erosion, and very heavy sedimentation (Logan et al., 1964). Monty (1967) suggests that initiation and growth of columns may be related to the growth of certain distinct algal species. In areas with high rates of sediment supply Gebelien (1969) has reported nodular, rather than flat laminar, stromatolite growth.

Cambrian columnar stromatolites at Old Wirrealpa do not necessarily form on very irregular substrates, and some conglomerate beds are overlain by only slightly domed forms. The columnar stromatolites appear to have grown most prolifically in areas where sediment of suitable size for algal trapping and binding was supplied at a high rate, mainly as a consequence of topographic position on the very shallow tidal flats. Judging by the greater frequency of desiccation mud-cracks in those parts of the sequence in which flat-laminated and domed stromatolites are found, these stromatolites appear to have formed in even shallower areas, where sediment-supply rates might be expected to have been very low. Thus, sedimentation rate may well have been an important contributing factor in the distribution of columnar stromatolites within the Cambrian sequence.

Branching

Much of the above discussion of columnar-stromatolite distribution is also relevant to stromatolite branching. All of the columnar stromatolites show branching of one type or another. Stromatolites from within the western or grainstone sequence usually exhibit markedly divergent types of branching. This branching tends to occur at irregular intervals during column development. Growth constraint (Hofmann, 1969) caused by pebbles resting on active algal mats was probably the most common cause of initial branching of stromatolites in the western grainstone sequence. However, the low inheritance of laminae in these stromatolites means that there is a fairly small chance that any single growth constraint will give rise to branching, without the largely fortuitous intervention of other environmental factors. In most instances constraints in lamina growth are "evened out" by succeeding laminae.

In contrast the branching of columnar stromatolites in the mudstone sequence is mostly parallel to slightly divergent. Columns within a particular bed commonly branch at about the same level, and their structure, to use the term of Walter (1972), appears to "anticipate" branching. The regularity and high inheritance shown by column laminae means that any irregularities in the structure are reproduced for a considerable time by successive laminar accretions. These variations are frequently enhanced by other environmental factors, such as erosion or preferential deposition in hollows, and distinct branches result. Irregular bands of probable precipitative origin may provide the necessary irregularity within stromatolite columns to enable this sort of branching to begin (see Plate 18a).

SUMMARY AND CONCLUSIONS

Lower Cambrian algal stromatolites at Old Wirrealpa Spring formed in open to protected intertidal environments. The nature, sorting and rate of supply of sediment to the growing stromatolites varied markedly from one environment to the next. Stromatolite growth took place predominantly by binding and trapping of the finer sediment fractions, although minor distinct intervals of carbonate precipitation also occurred. These intervals commonly show an irregular black pigmentation and contain poorly preserved cellular structures.

Columnar stromatolites formed where rates of supply of finer sediment were relatively high. Cryptalgalaminates and domed stromatolites developed in upper intertidal areas where sediment supply was lower.

Columnar stromatolites which grew on open tidal flats show irregular laminae and poorly developed wall structures. The slender, commonly constringed columns branch at irregular intervals, and the branches tend to be divergent.

Columnar stromatolites from sheltered tidal flat environments are usually regularly laminated, with individual laminae showing high inheritance. Wall structures are commonly developed by laminal downfolding on column margins. The columns, most of which are closely spaced, have parallel branching which often occurs at distinct levels within the stromatolite.

PART III : CHAPTER 2

MOTTLED TEXTURES IN LOWER CAMBRIAN CARBONATES OF SOUTH AUSTRALIA

INTRODUCTION

Certain of the Lower Cambrian limestones of South Australia, particularly the dark coloured lime-mudstones, exhibit a curious texture, locally referred to as mottling. The feature is most conspicuous within the mapped Parara Limestone of the Flinders Ranges, and the Sellick Hill Formation and parts of the Fork Tree Limestone south of Adelaide (Daily, 1963; 1972). Howchin (1925) described some of these limestones from south of Adelaide as being "disfigured by the presence of thin streaks of arenaceous material". Mawson (1925) referred to the mottled limestones as being "a mixture of purer limestone nodules in a silt base" where the "limestone fragments are rather angular and bedded in silt which shows stream lines around them".

Apart from these initial observations and a brief comparison of the local material with similar lithologies in the MacDonnell Ranges (Mawson and Madigan, 1930), little further work was carried out in South Australia on the systematic description of the widespread mottled limestones. The origin of the mottled textures has remained enigmatic, although Mawson (1925), and Mawson and Madigan (1930) had guardedly suggested that algae may have played a part in their formation.

In this study, work has mainly been carried out on the Cambrian carbonates at Old Wirrealpa Spring. Further studies have been made of material from Yorke Peninsula, Fleurieu Peninsula and various parts of the Flinders Ranges. Certain aspects of this work, particularly those relating to the chemistry of the mottled limestones, are still in the preliminary stages, and as indicated below, must be treated with caution. Further more detailed work is planned or is in progress.

CHARACTERISTICS OF THE MOTTLED LIMESTONES

Preliminary descriptions

In the most general terms, the rock textures under discussion consist of dark-coloured carbonate-enriched zones, intricately associated with lighter coloured zones which are relatively deficient in carbonate. The relative proportions of the two zones may vary considerably, as may the shape and spatial distribution of the related zones. In outcrop a gradation exists from rocks which show a regular distribution of dark and light coloured areas, to rocks in which the two show an extremely jumbled irregular association.

The features are most conspicuous in the dark-coloured impure lime-mudstones of the Lower Cambrian, and it is for these lithologies that initial descriptions of the textural relationships will be made.

In sections perpendicular to the bedding, the textures may be arbitrarily subdivided into three distinct types, each intergrading with the other laterally and vertically, both on the scale of individual outcrops, and regionally.

The first and simplest group has been termed ribbon limestones (Plate 18b). They consist of rather uniformly interbedded carbonate-rich and carbonate-poor zones, the vertical contact between the two being characteristically gradational. The darker beds consist of impure black micritic limestones which are commonly finely layered, although some are not. They are characteristically poorly fossiliferous. Their diffuse upper and lower boundaries with the lighter coloured areas are parallel to any internal layering which might exist in the darker beds. Insoluble residues consist of fine quartz silt and clay minerals. Across the boundaries into lighter coloured zones there is a gradual decrease in the amount of carbonate and a concomitant increase in the proportion of fine silt and clay. This is reflected in the increased durability of these zones on being subjected to weathering, where rainwater tends to etch away the carbonate-rich bands, leaving the clay-rich horizons in positive relief. The clayey zones show a fine, sometimes undulatory lamination.

The second textural group are termed nodular limestones. They are fundamentally similar to the ribbon limestones except that the continuity of the carbonate-enriched zones is interrupted by the spread of the lighter carbonate-deficient zones either upward, downward, or both, to form broader irregular zones of clay-rich material (Plate 19a). These breaches of the carbonate horizons may occur as broad gaps or as narrow sutured or jagged penetrations of the layers by clayey material. The overall texture is correspondingly much more irregular than that of the ribbon limestones, with carbonate nodules of widely variable shapes, but still generally elongate parallel to original bedding such that, in the field, the regional strike and dip is still readily recognisable. Within the carbonate-enriched nodules themselves, primary bedding is very rarely seen, but where present, is always parallel to the elongation direction of the nodules. The clayey zones characteristically contain irregular laminations. The laminations tend to fold into hollows in the nodules and both upward and downward into breaches in the carbonate bands. In some cases the fine clayey laminae may pass directly into carbonate-enriched areas where they, the clay layers, usually diverge and dissipate into the nodules (Plate 19b).

The third textural group, the mottled limestones themselves, represent even greater irregularity with respect to the relationship between areas of carbonate- and clay-rich material. Such is the resultant effect that little to no trace of any original bedding features, which may have been present, ever remain. In the field, outcrops consist of massive chaotic areas of irregular, carbonate-enriched black nodules, "floating" within a lighter clayey matrix. There is little to no indication of the regional strike and dip preserved (Plates 19c and 20a). The limestone nodules are composed of impure micrite, are generally unfossiliferous and seldom show any internal layering. In those rare cases where layering may be seen, it is always oriented parallel to the expected regional dip and strike. As for the nodular limestones, the lighter clay-rich zones in the mottled limestones are finely but irregularly laminated, are folded into depressions in the nodules and generally "stream" around the carbonate-enriched zones, except where they may pass directly into these zones. Where nodules are closely juxtaposed, or where narrow breaks occur in nodules, the laminae converge into the gap where the intensity of the clay enrichment is further increased (See Plate 20b).

As mentioned above, the three textural types which are briefly described, may grade both laterally and vertically into one another. The vertical intergradations in particular may be seen in individual outcrops (Figs. 20c, 21a, 21b).

Regional distribution

Limestones with mottled textures are common in most Cambrian carbonate sequences in the Adelaide "Geosyncline". As will be seen below, the textures are developed in a range of carbonate rock-types. The textures are recognisable in exposures which have undergone considerable folding and metamorphism e.g. those of Fleurieu Peninsula south of Adelaide, as well as being well exhibited in flat lying, unmetamorphosed Cambrian platform deposits of Yorke Peninsula. Thick mottled limestone sequences are extremely well exposed over large areas of the unmetamorphosed and mildly deformed Lower Cambrian outcrops in the Flinders Ranges. All three textural types, ribbon, nodular and mottled limestones are well represented throughout.

Local distribution of textural types at Old Wirrealpa Spring

Within megacycles IV and V of the Black Dog Hill sequence, all three textural types are present within a single lithological unit of dark coloured impure lime mudstones. In the field these mudstones appear to be essentially of identical lithology, despite a strong variability in the distribution of the three types of mottled textures described above. On the basis of the preserved evidence there would not appear to be any substantial change in depositional environment which might be sufficient to explain the textural changes seen.

Clearly there is evidence in this sequence that major west-to-east facies changes have occurred (See PART II above), and it is not unreasonable to postulate that less obvious environmental changes might have occurred across the area even within zones of uniform mudstone desposition. That is to say, the mottled textures might reflect environmental changes which were so subtle, within mudstones, that other sedimentological evidence of these variations is not preserved e.g. temperature, salinity. If this were so, however, it might be expected that these changes would have mirrored the predictable major regional environmental changes from west to east, and there might therefore be a consistent change in textural type in that direction.

Accordingly, the detailed distribution of the three mottled types was mapped exclusively within the apparently homogeneous mudstone sequence (Fig. 33). Any orderly changes in the distribution, which might have been anticipated had unknown factors in the primary depositional environment been the major control on the mottling, were not forthcoming. There is no apparent regularity to the textural changes either from west to east, or vertically within the mudstone sequence.

Organic influences

Mawson (1925), in considering the origin of the Cambrian mottled limestones, suggested that their "genesis can perhaps best be explained by assuming the cooperation of calcareous algal growths". Some more recent workers have also proposed a possible algal origin for the mottling e.g. Daily (1972a). In view of the well-established susceptibility of the form of algal communities to subtle changes in environment (See Carr and Witton, 1973) such suggestions bear close scrutiny.

Had such algal activity been responsible for the development of the mottled textures, some trace at least of the original algal structures might be expected. Relatively good remains of Renalcis sp. are found within this sequence, (See p. 105) in rock types which appear to have formed under high energy, oxidative conditions. The fine dense mudstones of megacycles IV and V might thus be expected to reveal at least some trace of cellular algal remains. These mottled lithologies have been thoroughly searched in this study without success, and the present writer must agree with the earlier work of Mawson (op.cit.) who remarked that "so indefinite and wanting in cell structure are these features that geologists have hesitated to regard them as of organic origin"; Mawson further added that "there is no positive evidence of the structures being organic".

Effect of grainsize

Despite the mottling being particularly well developed, or more conspicuously developed in the mudstone lithofacies of the Cambrian, it is by no means confined to such lithologies. The texture is very widespread over the whole range of sedimentary grainsizes, up to at least that found in coarse pebbly lithoclast and skeletal grainstones and packstones at the western extremity of the Black Dog Hill sequence in megacycles IV and V (See PART II above). Wackestones, packstones and much less commonly, impure carbonate grainstones, may all show well developed mottling.

As the grainsize in the above sequences increases gradually westward, there is not necessarily any concomitant change in the type of mottling developed. That is, the type of mottling appears to be essentially independent of the average grainsize of the carbonate sediment in which it is developed. There does, however, seem to be a relationship between the degree of development of the mottled textures, and the sorting of the rock. This will be dealt with below (See p.119).

One very critical relationship exists between the mottled textures and the grainsize of the rock in which it is developed. In all cases observed by the writer, the range of non-carbonate clast grainsizes which may be observed within the carbonate-enriched zones is the same as that observed within the carbonate-deficient zones of that rock. The writer has never, for example, observed non-carbonate lithoclasts within the carbonate-enriched zones, of any size which was not present, in greater concentration, in the carbonate-deficient matrix of that rock. Such relationships are most easily observed in the ill-sorted lithoclast conglomerates of megacycle IV, at the western limit of the Black Dog Hill sequence. On weathering, the concentration of coarse non-carbonate detritus within the matrix, gives these mottled rocks a strong honey-combed appearance in the field (See Plate 22a). More detailed characteristics of the layering of these mottled conglomeratic units will be given below (p. 120).

Whilst on the subject of grainsize as it relates to the mottled textures, it is important to point out that in coarser grained units, it is not unusual to find large fragments of archaeocyathids within the carbonate-enriched zones of the mottled textures. Neither large nor small fragments of archaeocyathids have ever been observed, by the writer, within the carbonate-deficient matrix of such rocks.

Sorting

As a general rule, mottled textures tend to be preferentially developed in the more poorly sorted rock-types. Mottling is prevalent in lime wackestones and packstones, but is seldom seen in well-sorted grainstones. Even where the grainstones contain appreciable amounts of well-sorted lithoclast debris, mottling is only poorly developed, if at all. Those packstones and wackestones which have conspicuous mottling, have predominantly fine-grained micritic carbonate within their nodules. Their overall range of grainsizes argues against any depositional environment in which high energy conditions have prevailed.

Bedding features

Bedding is characteristically poorly developed within the carbonate-enriched zones of mottled limestones, although ribbon limestone types may exhibit a fine regular layering in those zones. Generally the zones are massive, homogeneous and poorly sorted. Although the mottled limestones are usually poorly fossiliferous, some carbonate-enriched zones do show narrow bands of fine fossil fragments. Evidence of burrowing, boring or bioturbation of bedding has not been recognised by the writer within any of the limestones which commonly show mottled textures.

The carbonate-deficient zones, or matrix, are also usually poorly sorted, but very commonly show a well developed, irregular lamination. The lamination consists of thin concentrations of clay minerals, quartz silt, and common associated fine iron oxides. As noted by Mawson (1925) the matrix laminations tend to "stream" around carbonate nodules. The laminations are folded into depressions in both the upper and lower boundaries of the nodules (See Plate 22b), and they may pass directly into the nodules in some circumstances. In the nodular-type texture this penetration of fine clayey laminae into the carbonate zones tends to occur laterally, whilst in mottled-type textures the penetration may be in any direction. The clay stringers, as stated above, may diverge and dissipate within the nodules, but very commonly, especially where narrow "breaks" occur in the carbonate-enriched zones, the fine clayey laminae converge and form a dense irregular clayey seam (Plate 22c). The individual clayey laminations which contribute to such seams, are in thin section found to be microstylolitic (Plates 23a and b). The thicker laminate seams represent sets of close-spaced microstylolites each containing fine clays, quartz silt and, very commonly, iron-oxides (Plates 23c and 24a). Comparable features showing the same tendency to concentrate and diverge (Plates 24b and 24c) have been described by Roehl (1967) and Mossop (1972) as "horse-tail" stylolites.

The microstylolitic nature of the laminations in the carbonate-deficient zones is supported by the total absence of any recognisable primary bedding features within these zones e.g. micro-ripples, cross-beds etc. There is no indication of small scale cut and fill structures, nor is there evidence of lenticular beds which might have formed in depressions in the tops of carbonate nodules, had these been exposed at the sediment/water interface during any brief depositional hiatuses. It is confidently suggested that the laminations presently seen in the carbonate-deficient zones of the mottled textures are unlikely to represent original bedding in this clayey material, but are in fact horse-tail stylolites.

One further important aspect of the layering of the carbonate-enriched and carbonate-deficient zones is forthcoming on a close study of mottled textures in coarse, ill-sorted lithoclast wackestones of megacycle IV (See Plates 25a & b). Within the carbonate-enriched zones, bedding is absent, and measurements of the long-axes of lithoclast pebbles, in a plane perpendicular to expected bedding, reveals an almost random orientation of these clasts with only a slight tendency for the long-axes to be parallel to expected bedding (See Fig. 33). In contrast, the result of measuring the equivalent features in the carbonate-deficient matrix shows a strong preferred orientation of the pebble long-axes parallel to the general bedding and thus also parallel to the layering of the matrix zones (Fig. 33).

Where lithoclast pebbles occur within the matrix, the clayey laminations tend to stream past the pebbles, and in no instances have the clayey seams been observed passing into the larger lithoclasts, as they can do into the carbonate nodules.

Composition of mottled limestones

As indicated already in prior descriptions, mottled textures are found in a wide variety of the Lower Cambrian carbonate rock-types. The texture is not developed in non-carbonates and cannot be seen in very pure carbonate rocks; that is carbonates with low insoluble residues. Acid digestion of mottled limestones from Old Wirrealpa Spring has shown that all are relatively impure. Mottled lime mudstones have insoluble residues in the range of 5-20% (12 samples), wackestones 9-20% (8 samples), sandy lithoclast grainstones and packstones 12-30% (5 samples) and pebbly lithoclast grainstones and packstones 14-40% (4 samples). Insoluble residues for ooid grainstones may range up to 5% (6 samples), skeletal grainstones up to 1% (3 samples), with neither of the latter rock-types showing any apparent development of mottled textures.

For the above analyses, the range of insoluble residues found must in large part be attributed to the varying proportions of carbonate- and clay-rich zones in the whole rock. Clearly those rocks with the greater proportion of clay-rich zones showed greater values for the insoluble residue overall.

In those samples of mottled lime-mudstone where it was possible to separate carbonate zones and clay-rich zones (6 samples), insoluble residues averaged 11.5% and 32% respectively.

Whole rock analyses for the amount of insoluble residue in the three different textural types in the mudstones at Old Wirrealpa Spring showed averages of 6.6% for ribbon limestones, 12.3% for nodular limestones and 7.9% for mottled limestones. This result too tends to be less meaningful in that, although specimens were selected which had about the same relative proportions of calcareous and clayey zones, the sample selection was not strictly quantitative.

In all three textural types in the lime mudstones, the clay minerals, as determined by X-ray diffraction, were illite and less commonly, minor chlorite. No expansion of the clay mineral crystal structures were observed with glycol (See Carroll, 1970). Identical results were forthcoming whether dilute HCl or dilute acetic acid was used in the insoluble residue preparation.

Analyses for organic carbon were carried out on a number of the insoluble residues of local carbonate rocks. Light coloured ooid and skeletal grainstones, which were not mottled, revealed no detectable organic carbon. Values from dark coloured calcareous mudstones and wackestones, which did show mottling, were in the range .05% to .13%. For those few samples in which it was possible to separate carbonate-enriched and clay-enriched zones for analysis, the carbonate zones showed an average uncombined carbon value of double that in the clay-enriched zones (.08% and .04% respectively).

The preliminary results given above undoubtedly require further confirmation by a greater number of more vigorous analyses. Petrographic assessments of the composition of the mottled limestones are, however, in general agreement with the initial analytical results presented here.

Pyrite is a common constituent of the dark coloured, carbonate-enriched zones of the mottled limestones. Authigenic fine- to medium-grained crystals may be seen in thin section, whilst fresh cubes sometimes are found in broken samples in outcrop. By contrast, the carbonate-deficient zones contain abundant iron oxides which are concentrated along the "flow" laminae or horse-tail stylolites in the matrix.

Some mottled mudstones and wackestones also exhibit considerable silicification in certain zones. At Old Wirrealpa Spring, early diagenetic cherts appear spasmodically in particular horizons of the mottled mudstones, and a notably silicified band in the mottleds of the Black Dog Hill sequence is marked on Fig. 31. In thin section incipient silicification takes the form of elongate doubly-terminated quartz crystal overgrowths on detrital quartz grains present in the carbonate-enriched zones.

In the mottled rocks, the carbonate mineral is dominantly calcite, although some specimens have minor euhedral dolomite scattered in the nodules and somewhat more concentrated within the matrix zones. As has previously been pointed out by Daily (1972a), ferroan-calcite and to a lesser extent ferroan-dolomite are very common in the dark mottled limestones of the Lower Cabrian. In all cases observed by the writer, the composition of the carbonate mineral(s) of the nodules corresponds to that of the carbonate mineral(s) in the matrix, i.e. if non-ferroan calcite is in the nodules, then non-ferroan calcite is in the matrix. Ferroan-dolomites are almost exclusively confined to very late stage cements.

Within the carbonate-enriched zones it is not clear what proportion of the micrite present represents primary carbonate mud, and what proportion has originated as a fine-grained secondary cement.

Time of formation of mottled textures

Within the lime mudstones and wackestones of megacycle V of the Black Dog Hill sequence, there is abundant evidence that soft sediment slumping has occurred from west to east, some time soon after initial deposition (Plate 26a). These slump folds invariably show well developed nodular to mottled textures actually folded around them, along with bands of incipient chert development. Thus both the mottling and silicification processes appear to have started during the earliest stages of diagenesis. Furthermore, a close examination of the axial zones of such slump folds indicates that the irregular clay seams or horse-tail stylolites which had formed the initial nodular and mottled textures subsequently began to develop roughly parallel to the axial plane of the slump, or parallel to the original bedding direction (See Plate 26b). This indicates that the mottling process has continued within the probably still incompletely lithified sediments after the slumping process has occurred.

At about this same level in megacycle V, certain relatively minor units are found which appear to record the transfer of partially consolidated carbonate material by gravity slumping and mudflows into the depositional basin, presumably from west to east. The resultant units are distinctive, despite the fact that clasts are essentially autocthonous and composed of dark lime mudstones and portions of dislocated silicified mudstones (Plate 26c). Slump-type folds are clearly exposed and where bedding may be seen in the clasts, it appears to have random orientations. This is in marked contrast to the interbedded mudstones with mottled textures, from which mudflow units may be confidently distinguished in the field. A pertinent property of these mudflow units is that they may contain large intact blocks of lime mudstone (Plate 27a). These blocks characteristically exhibit mottled textures which are in strong contrast to those of the matrix material. The blocks generally have a nodular texture which appears to have developed before their incorporation into the mudflow unit. The margins of the blocks tend to be indistinct and nodules at their edges are commonly plastically deformed but not broken, indicating that the block was only partially consolidated at the time of transport and not strongly lithified, even in its carbonate-enriched zones. The gradational nature of the block margins is further enhanced by the penetration of large horse-tail stylolites from the surrounding mudflow breccia into the block itself. This further suggests that the mottling process continued in both the blocks, and the main mass of the mudflow units after they had come to rest. The resultant textures, however, remain clearly distinguishable from those formed in the adjacent mudstones which have remained undisturbed.

Early diagenetic chert nodules

As mentioned above, early diagenetic silicification has occurred in many places within the mottled mudstones, and appears as irregular chert nodules and cherty zones, which may be found folded by soft sediment slumping. The chert occurs as very irregular elongate nodules forming discontinuous bands parallel to the regional bedding. In some intensely mottled limestones the chert nodules appear to have had a curious influence upon the development of the mottled textures (Plate 27b). Despite their occurrence within units showing the most extreme form of mottling, the texture of the limestones immediately adjacent to the nodules is commonly of the nodular to ribbon type; that is, in direct contrast to the intense mottled texture of the enclosing rock. Between the chert nodules, vertical sections may be uniformly mottled, the nodular and ribbon textures being confined to areas above, and below the chert nodules. Thus in the field, the early diagenetic cherts appear to have at least partially shielded the nearby mudstones from the more extreme effects of the mottling process. The other obvious alternative of course, is that chert development has only occurred in those patches which have escaped the most intense effects of the mottling. The latter seems less likely since authigenic quartz is relatively widespread in all three mottled types, and dense chert is, if anything, less common in the thicker ribbon limestone units in comparison to the mottled-type limestones.

Mottling and sediment lithification

Slump folds in the mottled sequences clearly illustrate that the carbonate-enriched nodules deformed plastically, even after a considerable degree of mottling has occurred. There is no evidence in these folds, of brittle fracture of the carbonate-enriched zones, and it is suggested that lithification was only minor, even though reworked blocks in the mudflow units attest to the considerable cohesion of these nodular sediments. Even at this early diagenetic stage, the carbonate nodules appear to have acted in a more rigid manner than the interbedded carbonate-deficient zones, since the lamination in these zones shows clear folds into any irregularities in adjacent nodule surfaces. The relative rheidity of the carbonate-enriched and carbonate-deficient zones was such that the latter showed the greatest tendency to flow due to compaction even under conditions of minimal burial. The mobility of the clay-rich matrix material may have been related to considerable quantities of interstitial water within what were probably "spongy", uncompacted seams.

Lithification might be expected to have been associated with the gradual dewatering of the matrix material due to compaction, and the precipitation of further carbonate cements within the carbonate-enriched nodules during later stages of diagenesis. The onset of lithification might thus be expected to result in the reduction of mobility of the matrix, and the appearance of fracture rather than flow features in the carbonate nodules.

At Old Wirrealpa Spring, the carbonate nodules in a large number of the mottled limestones show V-shaped cracks or fractures which gape at the nodule/matrix contact and penetrate into the nodule. These cracks may be numerous or rare in any single sample, but always penetrate only the carbonate-enriched zones, the penetrations being from any direction i.e. they do not preferentially penetrate, say, the tops of the nodules or the bottoms. The cracks appear to indicate that substantial lithification had occurred, and that the nodules have reacted in a brittle manner to some applied stress, possibly from the overburden. For this to occur, one might expect that the matrix material too must have lost its mobility at this stage, probably due to compaction and dewatering. This indeed appears to have been the case, since the cracks are always filled with coarse secondary carbonate cements, never being penetrated any appreciable distance by the enclosing clayey matrix (See Plate 28a). The common slight penetration of the matrix into the gaping mouths of the cracks attests to there having been the tendency for such movement to have occurred prior to the filling of the cavity by cement. The mobility of the matrix must clearly have been greatly reduced at this stage. The development of the microstylolitic lamination in the matrix and the mobility of that matrix material (as evidenced by the folding of that lamination) are obviously fundamental to the production of the mottled textures i.e. to the mottling process itself. Essentially then, the mottling process has ceased prior to the lithification of the rock.

SUMMARY OF CHARACTERISTICS OF MOTTLED LIMESTONES

(1) The mottled textures consist essentially of carbonate-enriched and carbonate-deficient zones within the rock.

(2) The mottled limestones may be differentiated into three basic types, which in order of increasing irregularity of the textures are termed ribbon limestones, nodular limestones, and mottled limestones.

(3) The above three types grade both laterally and vertically into each other, their lateral distribution being difficult to relate at Old Wirrealpa Spring, to any particular factor(s) of the primary depositional environment.

(4) The mottled limestones show no trace of cellular structures or stromatolitic layering which might indicate that they are of algal origin.

(5) Mottled textures are evident in limestones of a variety of grainsizes. Most mottled limestones are poorly sorted. In all cases the composition and grainsize of the material in the carbonate-deficient zones is the same as that of the non-carbonate detritus within the carbonate-enriched zones.

(6) Most mottled limestones have poorly developed bedding. Where this feature may be seen in individual carbonate-enriched zones, the bedding is consistently oriented parallel to the regional strike and dip.

(7) The poor sorting, general lack of bedding features and lack of evidence of an active infauna, suggests that mottling is favoured in rocks which were rapidly accumulated under low energy conditions. Reducing conditions might well have been widespread within such sediments. Coarser mottled lithoclast wackestones, at least, appear to have been transported into slightly deeper depositional environments by gravity sliding along low bottom slopes.

(8) The fine layering within the carbonate-deficient zones consists of accumulations of fine insoluble materials e.g. clays, silts and iron oxides, along microstylolites. These microstylolites form irregular networks which are apparently identical to the "horse-tail" stylolites of Roehl (1967). The horse-tail stylolites may be found penetrating the carbonate-enriched nodules.

(9) Within the mottled lithoclast wackestones, large non-carbonate pebbles may span the carbonate-rich carbonate-deficient zone boundaries. The large pebbles located within the carbonate-enriched zones tend to have rather randomly oriented long-axes in sections perpendicular to

the bedding. Equivalent pebbles in the matrix zones show strong preferred long-axial orientation parallel to the regional strike and dip.

(10) Mottling appears to be preferentially developed in limestones with high insoluble residues, although well sorted, cross-bedded grainstones with appreciable quartz sand residues, seldom show mottling.

(11) Within mottled dark mudstones and wackestones, organic carbon and iron sulphides are commonly found. Carbonate-deficient matrix zones are richer in iron oxides and appear to contain appreciably less organic carbon than related carbonate-enriched zones.

(12) The carbonate minerals of the mottled limestones may be calcite or ferroan-calcite with minor dolomite and ferroan-dolomite, the latter occurring as very late diagenetic sparry cements. No significant compositional variations exist between the carbonate minerals of the nodules and those of the carbonate-deficient zones.

(13) The carbonate nodules are invariably very irregular in shape, and no zoning or accretion nuclei have been observed.

(14) There is no evidence of bioturbation in either the carbonate-enriched or carbonate-deficient zones. Calcareous fossil fragments, particularly archaeocyathid remains, are found within the carbonate nodules, but never in the matrix. Fossil fragments have not been seen transgressing the nodule/matrix boundaries, but are commonly truncated at these boundaries.

(15) The mottled textures have mainly formed during early diagenesis since

(a) The textures are folded by slump folds, and soft but cohesive nodular limestone blocks may be incorporated within mudflow units.

(b) The textures appear to predate the dewatering of the matrix and lithification of the nodules.

(16) The mottling is approximately contemporaneous with local widespread silicification within the limestones at Old Wirrealpa Spring.

BRIEF REVIEW OF "MOTTLED" LIMESTONES REPORTED ELSEWHERE

Mottled textures similar to those described above from the Lower Cambrian of South Australia have been widely reported elsewhere in the geological literature. An excellent review of mottling in a number of limestone formations of the U.S.A. has been given by Osmond (1956). The mottling there has mainly been described from Palaeozoic formations, some of which are tabulated below.

Simonson Dolomite	Mid. Devonian	Nolan (1935)
Nevada Formation	Mid. Devonian	Sharp (1942)
Hidden Valley Dolomite	Silurian & L. Devonian	McAllister (1952)
Interlake Formation	Silurian	Roehl (1967)
Platteville Limestone	Mid. Ordovician	Griffen (1942)
Stony Mountain Formation	Ordovician	Roehl (1967)
Maurice Formation	Late Cambrian	Brown (1959)
Goodsprings Formation	Mid. Cambrian	Hewett (1931)
Muav Dolomite	Cambrian	McKee (1945)

Matter (1967) described what he called "lumpy" limestones from within the New Market Limestone (Ordovician) of Western Maryland, whilst Braun and Friedman (1969) discussed mottled textures from within their "Facies 2" and "Facies 7" of the Tribes Hill Formation of the Mohawk Valley. They attributed the features to "pseudoripples" due to "undulating stromatolite structures", and burrow fills, respectively. Swett and Smit (1972) reported mottled limestones associated with dolomitization and silicification in the Cambro-Ordovician carbonates of Newfoundland and Central Eastern Greenland. They compared these with the mottled limestones of the Durness Formation of the same age from Scotland.

In Canada, McCrossan (1958) has described somewhat similarly textured limestones from the Upper Devonian and attributed the textures to a process of sedimentary boundinage. Mossop (1972) reported mottling from the Redwater Reef of Alberta (Devonian) and considered that late diagenetic pressure solution was responsible for their formation. Hopkins (1972) has studied the carbonate slope sediments associated with the Devonian Ancient Wall and Miotte carbonate complexes in Alberta. He described many examples of mottled textures from the Mt. Hawk and Perdrix Formations and attributed their formation to preferential cementation, and to some extent, reworking of lithified clasts. Mottled textures in carbonates from the Belcher Islands, Canada, are figured by Moore (1918, Fig. 15) and interpreted as being of algal origin.

In Europe, mottled limtestones which, at least in part, have analogous textures to those of the local limestones have been described in detail from the Lower Palaeozoic of the Oslo region by Björlykke (1973).

He considered that the texture of these limestones has generally evolved by the incomplete dissolution of beds of marly sediments on the ocean floor. Henningsmoen (1974), however, favoured an early diagenetic segregation process for the formation of the mottled and nodular textures in the limestones of Norway. He considered that the carbonate-enriched zones were essentially concretions which formed in clay-rich lime muds. After the consolidation of the concretions he envisaged that limited carbonate dissolution took place within the uncompacted clayey interstices, which may have had up to 80-90% porosity (Engelhardt, 1973; in Henningsmoen, 1974). Both Björlykke and Henningsmoen considered that the carbonate-enriched nodules were essentially undisturbed, and had developed in situ.

Elsewhere in Europe and Northern Africa textures referred to as "griotte" in Devonian and Carboniferous limestones show close similarities to the local Cambrian mottled limestones (see Jenkyns, 1974; Tucker 1975; Bandel 1975). The most wide-held hypothesis concerning the origin of "griotte" textures is that of Grundel and Rosler (1963; in Jenkyns, 1974). These workers proposed that organic decay under anaerobic conditions had resulted in carbonate solution by upward migrating pore fluids, from which the carbonate was reprecipitated on reaching the oxidation zone.

Probably the most studied analogue of the local mottled textures is present in the Knollenkalk and Rosso Ammonitico of the Mediterranean Alpine Jurassic (Hallam, 1967; Garrison and Fischer, 1969; Jenkyns, 1974). Such mottled textures characterize the limestones of much of the "Tethyan Belt" as far east as Indonesia. The plates and detailed descriptions presented by Jenkyns (1974) leave little doubt that the textures are identical to those in the Cambrian of South Australia. Obvious differences exist in the pervasive pink colouration of the former units and their richly fossiliferous nature, as compared with the local material.

Despite intensive study, the origin of the textures of the Rosso Ammonitico and its equivalent units is still the subject of considerable controversy. Hallam (1967) attributed the texture to a diagenetic segregation of material within a more or less uniform marly sediment, to form carbonate-rich nodules and a non-carbonate mudstone matrix. The process is similar to that which he proposed for the rhythmic nodular limestones of the English Lias (Hallam, 1964). Garrison and Fischer (1969) refuted any suggestion that the limestone nodules are concretionary, and favoured them being "discrete, clast-like remnants of former beds". They added that the nodules are strictly not "clasts", have never been moved by current action, and lithologically are always indicative of quiet water deposition. Garrison and Fischer (1969) favour the widely held interpretation of Hollmann (1962; 1964) that the nodules are solution relics of marly carbonate beds, formed at depth on the sea floors, and subsequently partially destroyed at the sediment/water interface by a process termed subsolution. There is widespread evidence that solution was an important factor in the formation process in the form of numerous incomplete, partially dissolved ammonite and crinoid remains (See Hollman, 1964, Fig. 4, Plates 7, 8). As for the local examples, slumping of unlithified and partly lithified material has occurred.

Jenkyns (1974), in a summary of the features of the Ammonitico Rosso of the Alpine-Mediterranean, lists a number of points about the characteristics of the mottled limestones which are critical to their origin. Disregarding those points pertaining to the contained fossils, the local features accord closely to those he attributes to the Jurassic limestones of the Tethys. On the basis of these characteristics, Jenkyns (op.cit.) challenges the sea floor solution hypothesis of Hollmann (1962; 1964) on the grounds that firstly, the required very deep water environment necessary for subsolution to occur (2000-3000 m), is far from established for the Rosso Ammonitico, especially in view of inter-bedded well-developed algal stromatolites (Sturani, 1971). Secondly, Jenkyns reasons that if solution of carbonate at the sediment/water interface had been of fundamental importance, it would have been unlikely that the aragonitic tests of ammonites would have persisted into the burial stage to form the ubiquitous ammonite moulds of the unit. Jenkyns (1974) concluded that the detailed observations on nodular limestones are completely incompatible with a concept of a solution rubble at the sediment/water interface.

As an alternative hypothesis, Jenkyns (1974) supported a process involving early diagenetic segregation within the unconsolidated sediment. He stated that "it is difficult to avoid the impression that some kind of solution process has taken place" and even questioned whether "the marly interstices simply represent zones in which calcium carbonate was not precipitated, or from which it was actually withdrawn?". He eventually suggested that the mottled texture formed by localized calcification, although he admitted this "segregation theory" also suffers from the lack of a well documented mechanism. He anticipated that an original homogeneous mixture of clays, aragonite mud and calcareous nannofossils underwent dissolution of the aragonite and fine grained calcite from within the muds. The carbonate in solution was later reprecipitated at a higher level in the sediment pile as the less soluble high-Mg calcite polymorph.

Jurgen (1969; in Jenkyns, 1974) considered that all of the interstices in the Rosso Ammonitico were formed by late diagenetic pressure solution. Jenkyns (1974) argued that the postulated initial homogeneity of the sediment, had not some other process formed the nodules, would have resulted in the role of pressure solution being only minor.

In Australia, Ordovician limestones of the Bungonia area, N.S.W., show textures similar to those of the local Cambrian limestones (P. Moore, pers. comm. 1976). B.W. Logan and V. Seminouk at the University of W.A. are also presently studying similar textures in Devonian limestones from the Canning Basin, W.A.

DISCUSSION

The mottled textures in the local Lower Cambrian limestones do not appear unique in the geological record. Similar features in limestones, from the above review, are obviously widespread both in time and location. It is unlikely that the local mottled limestones are identical with the above examples in all respects, or that any single proposed mechanism of formation is likely to apply in all cases. Certain suggested modes of formation of mottled limestones are clearly not able to be applied to the local examples, whilst others merit closer examination.

Sedimentary boudinage

As detailed above, the carbonate-deficient, clayey interbeds have a well developed lamination which folds into depressions in carbonate nodules, and up and down into gaps between nodules. Somewhat similar effects have been attributed by McCrossan (1958) and Wobber (1967) to the interpenetration of water-logged clayey primary sedimentary layers into more brittle limestone interbeds by flow under the influence of overburden pressures - in short a process of sedimentary boudinage. A similar process has been suggested as a possible origin for certain local mottled textures at Sellick Hill, south of Adelaide (Daily, pers.comm. 1971).

Quite clearly, the evidence presented above on the relationship between mottling and slump folding tends to mitigate against such an hypothesis. The characteristics of the mottled limestones at Old Wirrealpa Spring suggest that overburden pressure has had only a minor effect on the mottling, and that the greater part of the mottling process had essentially finished before burial effects came into play.

Had later diagenetic boudinage been the fundamental force in the mottling process, those units with the most intense mottled textures must be interpreted as those which have undergone the greatest and most inhomogeneous compaction or disruption due to burial. Within thick (up to 100 m true thickness) intensely mottled units in the Black Dog Hill sequence it is possible to find a single thin band, or group of thin beds of ribbon limestone which is continuous, undeformed and still parallel to the expected regional bedding (Plate 27c). Had the mottling formed at some depth i.e. under considerable overburden pressure, it is difficult to account for the lack of disruption of the interbedded thin ribbon limestones.

It is true that McCrossan (op.cit.) did not visualize great burial depths or total lithification of the sediments during sedimentary boudinaging. He has reported V-shaped cracks from carbonate nodules which, like the local examples, are filled with coarse sparry cements and not matrix material. McCrossan believed that these cracks originated due to tension as the nodules were flattened by overburden pressure. As Hopkins (1972) has pointed out, McCrossan has not indicated why these cracks have not filled with the surrounding fluid muds in which the sedimentary boudinage process is supposed to have taken place.

Clastics, olisthostromes

There are certain superficial similarities between the local mottled limestones and submarine mudflow deposits or olisthostromes. Olisthostromes consist of an argillaceous matrix in which angular fragments, often carbonate, are chaotically distributed (Gorler and Reutter, 1968). These bodies contain no trace of a depositional stratification.

The local mottled textures do not appear to be of this origin. Except in rare and easily distinguishable cases where nodules and mottled blocks have been reworked by mud-flows, there is no evidence that the carbonate-enriched nodules have been moved subsequent to their formation. Where primary bedding may be seen, which in the true mottled-type textures is admittedly seldom, the bedding in the nodules is never rotated more than a few degrees at the most from the expected regional strike and dip. At Old Wirrealpa Spring, evidence suggests that the mottling process had occurred both before, and to some degree after, soft sediment movements had taken place.

It is also clearly unlikely that the local features have formed by "sediment unmixing" during downslope sliding as postulated for other mottled limestones by Jurgen (1969; in Tucker, 1973).

Mudflow processes have, however, probably been important agents in the deposition of the primary sediments at Old Wirrealpa Spring, upon which an early diagenetic mottling process has then become active. The nature of the mottled sediments, as presented above, suggests rapid deposition of poorly sorted carbonate sediments, clay minerals, various sized lithoclast debris, fine organic remains and probably dispersed iron oxides. The lack of bedding features indicates that reworking was rare, and that the depositional environment was one of low bottom activity. Reducing conditions would have prevailed within the sediments and interstitial fluids, if not initially anoxic, would soon have become so by the oxidation of at least some of the contained organic material.

A submarine mudflow origin is very likely for the distinctive mottled, pebbly, lithoclast wackestones of megacycle IV in the Black Dog Hill sequence (See p. 120 and Plates 25a and 25b). These ill-sorted, coarse-grained, lithoclast-enriched carbonates are particularly instructive as to the mechanism of the mottle formation. As pointed out by Dott (1963) the transport of the original sediment into the low energy depositional environment by mudflow would involve a flow mechanism intermediate between the plastic flow of a slump, and the viscous fluid of a turbidity current. A limited amount of pebble long-axis alignment would be expected parallel to bedding in the muddy matrix. As can be seen in Fig. 33, the local example does show a limited alignment of long axes in this direction in the carbonate-enriched zones of the later mottled textures. The carbonate-enriched zones still retain a mud-supported fabric which must have been present during original deposition. These zones retain an elongation parallel to the regional dip and strike and do not appear to have moved within the matrix material. In contrast, the present matrix or carbonate-deficient zones show a very strong alignment of pebble long-axes (Fig. 33). These zones no longer have a mud-supported fabric, but appear grain-supported. It seems that the matrix zones must represent material which, once similar to that of the carbonate-enriched zones, has suffered a loss of carbonate from between the inert, non-carbonate clasts, resulting in the formation of a secondary grain-supported fabric, and an overall rotation of pebble long-axes toward a plane perpendicular to the direction of maximum subsequent compaction. The mottling process would seem therefore to have involved differential carbonate solution within the sediment after initial deposition.

Organic influences

Certain mottled limestones elsewhere have had their textures attributed, at least in part, to the activities of organisms e.g. Liassic limestones of South Wales (Wobber, 1967). Fürsich (1972) implicated the trace fossil Thalassinoides in the formation of nodular textures in the Corallian Beds of Southern England. He figured textures not unlike the local examples, and illustrates a progression from carbonates in which the fossils are quite recognisable, to an eventual mottled texture in which the prior influence of the organic activity was obscured. In the local Lower Cambrian structures there is no evidence that the life activities of organisms have played a role in the mottled limestone formation.

As indicated above, the involvement of algae in mottled limestone formation, either as sediment binders etc. or as skeletal contributers, is intuitively attractive. However, neither this study, nor any earlier work, has been able to substantiate the direct involvement of algae in the local process.

Preliminary analyses do suggest that local limestones which show mottling have enhanced contents of organic carbon, particularly within their carbonate-enriched zones. Preserved organic matter within carbonate sediments elsewhere has been implicated in the formation of mottled limestones by carbonate dissolution (Grundel and Rosler, 1963 in Jenkyns 1975). Sass (pers. comm. 1973) has also pointed out that the oxidation of contained organic matter may be a powerful dissolution agent in carbonate rocks. Any such dissolution process, on a large scale, cannot rely simply upon diffusion and local cementation to remove the dissolved carbonate, but must involve the movement of pore fluids and thus a considerable permeability. The importance of permeability to the formation, by solution, of clayey layers in Oligocene calcarenites has been stressed by Barrett (1964).

In the local examples of mottled limestones, permeability does not seem to be the only prerequisite for mottling to form by solution. Well sorted ooid and quartz sand lithoclast grainstones, which must be expected to have had high initial permeabilities, do not necessarily show significant solution features or mottling. It would thus appear that the composition of the initial sediments and/or that of the moving interstitial pore fluids must have had a most important influence on any dissolution processes. It is here suggested that an abundance of preserved organic matter within the sediment pile was an important factor in the formation of the mottled textures.

Subsolution

The subsolution mechanism proposed by Hollmann (1962; 1964) for the formation of carbonate nodules in a marly matrix, visualized that the nodules were solution remnants of continuous carbonate beds which had formed in very deep-water environments (2000-3000 m). The solution is considered to have taken place due to gentle, cold, bottom currents dissolving the carbonate at the sediment/water interface. The clayey insoluble residues remained essentially in situ as a marly matrix. This mechanism is unlikely for the local mottled limestones for a number of reasons. Firstly, such extreme water depths are most unlikely, especially in view of the nearby certain shallow-water facies at Old Wirrealpa Spring. There is also evidence of micro-unconformities or diastems which, by the subsolution theory must occur at every level of nodule formation in the sequence. There are no small scale cut-and-fill structures or lenticular coarser grained lenses for example in depressions in the nodule tops. Finally the subsolution theory presupposed very low sedimentation rates to allow time for the bottom solution of the carbonates to take place under the influence of sluggish bottom currents. Local mottled limestones for the most part appear to have deposited rapidly, with the probable exception of the ribbon-type limestones, for which much lower sedimentation rates are envisaged.

Concretionary origin

Henningsmoen (1974) proposed that the carbonate-enriched zones of some limestones, which at least in part appear similar to local material, have formed by concretion. He envisaged that the precipitation of regular layers of carbonate about some sort of nucleus had occurred prior to, and to some extent, during compaction. The local mottled limestone nodules, however, are more irregular in shape i.e. seldom spheroidal, show no concentric layering of any description, and do not contain any structures which might be interpreted as having formed a nucleus about which concretion has taken place.

One further point which tends to discount early diagenetic concretion formation in marly sediments as the origin of the carbonate nodules is that carbonate skeletal debris is relatively common in the carbonate-enriched zones of certain mottled limestones. In these cases, however, the writer has never observed calcareous skeletal debris in the matrix, suggesting that the matrix has been a site of carbonate dissolution, and that the fragments have been removed in solution. The same is true for larger fossils which abutt the nodule/matrix contacts. The writer has never observed the fossils penetrating into the matrix, but they are sharply cut off at the contact, usually by microstylolitic laminae (See Plate 28b). B. Daily has noted instances where larger fossils do cross the nodule/matrix boundary, and in these cases, that portion of the fossil which lies within the matrix is totally leached and compacted (B. Daily, pers. comm. 1976).

Pressure solution effects

At the present time stylolites are generally considered to have been formed by pressure solution as advocated by Stockdale (1922), and there remain few adherents to the "contraction-pressure" theory of Shaub (1939). There is, however, a diversity of opinion on the precise definition of a stylolite (e.g. Bathurst, 1975 c.f. Trurnit, 1969) and the stage of diagenesis at which stylolitization has occurred (e.g. Dunnington, 1954; 1967, c.f. Park and Schot, 1968a). There are some workers too, who question the role of pressure in the solution of carbonate along a stylolite seam (See Prokopovitch, 1952). Since stylolite features are ubiquitous to the mottled limestones of South Australia, both on macro- and microscopic scales, it is necessary that a consideration of the definitions and genesis of stylolites be examined prior to any assessment of their role in the formation of the mottled textures.

Park and Schot (1968b) considered that styoloites are irregular planes of disconformity along which two rock units are interlocked or mutually interpenetrating. The planes are of solution origin and are commonly characterized by accumulations of insoluble residue. Bathurst (1975) includes a genetic connotation in his definition, namely that stylolites are of pressure solution origin. Stylolite planes are generally very irregular (Park and Schot, 1968b) but recent work by Trurnit (1969) has clearly indicated that pressure solution contacts can take a variety of forms, including being planar.

Controversy still exists concerning the diagenetic stage at which stylolites form in carbonate rocks. Most workers agree that very late diagenetic pressure solution may occur in relation to tectonism, with stylolite planes forming perpendicular to the direction of maximum stress (Park and Schot, 1968a; Bathurst, 1975). Park and Schot (1968b), however, favour the great majority of stylolitization occurring by pressure solution prior to substantial cementation within the rock. Bathurst (1975) favoured their formation post early cementation and continuing until complete cementation occurred. Dunnington (1967) considered stylolitization to be a post induration phenomenon.

Clearly such controversy still exists as to the characteristics, genesis, and timing of stylolitization that the recognition of such features in the local mottled limestones, and their interpretation, must be undertaken with considerable care, and be assessed on its own merits.

As indicated above, the layering in the carbonate-deficient, or clayey zones of the mottled limestones commonly takes the form of "horse-tail" stylolites as described by Roehl (1967) and later by Mossop (1972). The "horse-tail" stylolites usually consist of bands or sets of close-spaced microstylolites which are delineated by accumulations of fine grained insoluble residues. These sets of microstylolites are usually most irregular in their arrangement, and commonly converge into dense narrow clay-rich zones. If these narrow zones persist for any distance, which they often do, they may show the characteristic sutured stylolitic form.

According to Roehl (pers. comm. 1974) horse-tail stylolites formed under minimal overburden pressure, and conditions of minimal pressure solution. He considered that other factors, such as lateral fluid transfer, were more important than regionally uniform overburden pressures in the genesis of horse-tail stylolites, and that their genesis was at shallow depth, maybe even subaerial. Mossop, on the other hand, believed that the horse-tail stylolites of the Redwater Complex are certainly late diagenetic in origin and have formed under at least several thousand feet of overburden (Mossop, 1972). He considered that they have formed by pressure solution under conditions of regional overburden stress. The tendency of this particular variety of microstylolite to converge into "horse-tails" under conditions of uniform overburden pressure is explained by Mossop as resulting from the convergence, due to solution, of two relatively insoluble bodies/grains within the rock. He believed the result of such convergence would be that "the stress indicitracies in the vicinity of the two approaching grains would be such as to favour the development of a three dimensional fan of microstylolites (i.e. a horse-tail), dispersing the accumulated strain over a considerable volume of the laterally equivalent matrix material " (Mossop, pers. comm. 1974). At Old Wirrealpa Spring the writer has never observed any differences in the fabric or composition of the carbonate on either side of the "foci" of the horse-tail stylolites which might support the above hypothesis of Mossop. In fact, if the local horse-tail stylolites are indeed analogous to those described by Mossop (1972), the local evidence suggests that they might well have formed prior to any substantial lithification, and that any accumulated strain could have been dispersed by the flow of the unconsolidated material.

It seems inescapable that the clayey laminations in the local mottled limestones are horse-tail stylolites and of solution origin. It remains to consider the influence which overburden pressure may have had upon this dissolution process.

As discussed above (p. 123) the microstylolitic laminations present in the carbonate depleted zones of the mottled limestones were formed during the very early stages of diagenesis. Clearly then, large amounts of carbonate dissolution must have occurred at this early stage, with most of the dissolved carbonate being reprecipitated nearby as early diagenetic cements. Taking into consideration the fine grained and ill-sorted nature of the primary sediment, it is unlikely that all of the enormous quantities of dissolved material could be accommodated as cement by ionic diffusion into nearby carbonate-enriched nodules. Such massive redistribution of carbonate material must surely require pore fluid movement rather than just ionic diffusion (See Weyl, 1968).

The problems involved in the mechanics of redistribution of carbonate material during pressure solution have been dealt with by Bathurst (1975). He considered that before complete cementation, dissolved material may have proceeded from the dissolution surface(s) parallel to the linear stress axis (gravity field) to be precipitated as cement in nearby interstitial pores. With continued dissolution this avenue of escape would have become increasingly restricted by cementation, and an alternative route of solute movement along the stylolite contact itself would have become necessary. As Bathurst (1975) indicated, this latter route "between the opposed surfaces (of the stylolite) hardly seems a broad and generous highway for the transport of such large volumes of solute".

In the case of the very substantial buildups in the horse-tail stylolites of the mottled limestones it <u>must</u> be postulated that extremely large amounts of carbonate have been dissolved and removed. Apart from that which has provided cement to nearby nodules, much must have been removed from the immediate vicinity by fluid movement possibly along the clayey seams. As indicated by Jenkyns (1974), upon compaction these seams would be most unlikely to provide conduits for fluid movement. It must therefore be considered likely that the clayey zones remained "spongy", water saturated and essentially uncompacted during the formation of the horse-tail stylolites, suggesting that no substantial overburden pressure was involved. Evidence of the ability of the matrix to "flow" during early diagenesis, as detailed above, further confirms that the microstylolitic zones remained engorged with interstitial fluids during early diagenesis.

The above considerations suggest that the horse-tail stylolites have formed during early diagenesis, but it appears that there has been minimal pressure involved in their formation. The writer feels that the stylolitic zones were in fact zones of permeability, and that any solution which has taken place has been chemical rather than pressure solution. As mentioned above, a similar mechanism, with its emphasis on permeability, has been proposed by Barratt (1964) for stylolitic clay seams in Oligocene calcarenites in New Zealand.

Although the fundamental mottled textures have formed in response to early diagenetic horse-tail stylolite development, late diagenetic overprinting of the mottled textures by pressure solution has taken place in some localities in South Australia. The mottled limestones from south of Adelaide in particular, show intense folding and metamorphism. In these, the early diagenetic mottled textures are greatly changed by numerous pressure solution contacts, which have strong, preferentially-oriented stylolite planes and a marked alignment of the crests and troughs of the stylolites themselves.

SUMMARY OF PROPOSED ORIGIN FOR THE MOTTLED TEXTURES

Mottled textures in the local Lower Cambrian limestones are believed to have formed by the very early diagenetic dissolution of carbonate minerals along irregular zones within partially-lithified, uncompacted impure carbonate sediments. Solution by moving pore fluids of relatively low pH is believed to have resulted in the formation of bands of horse-tail stylolites containing accumulated insoluble residues. Dissolved carbonate was reprecipitated locally as cement in nearby less permeable nodules, or carried out of the sediment altogether, presumably passing laterally and upwards into overlying marine environments.

The incorporation of large quantities of unoxidized organic matter into the sediment, as well as limited and patchily developed early diagenetic cementation appears to have favoured the formation of the most intense mottled-type textures. Iron-rich sediments may also have been particularly susceptible to the mottling process.

The chemical process tentatively favoured for the dissolution mechanism within the sediments is that proposed by Gardner (1973), entailing sulphate-reduction in anoxic pore fluids. The first stage of this process involves the localized precipitation of calcium carbonate and pyrite within the sediment. Upon the consumption of the reducable iron oxides of the system, the pH of the pore fluids drops significantly and carbonate dissolution takes place along with the oxidation of contained organic carbon. The dissolution process, according to Gardner (op.cit.) continues until all carbonate is removed. In nature the limited supply of preserved organic matter, or the availability of sulphate ions which are supplied either by diffusion from overlying marine waters or by pore water movement, are likely to have prohibited the ultimate dissolution of all carbonate minerals. In any case the process would have terminated due to advancing cementation and compaction of the rock and the concomitant reduction of permeability and thus the flow of reactive pore fluids within it.

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