THE UNIVERSITY OF ADELAIDE

STRATIGRAPHIC INVESTIGATIONS OF TERTIARY SEQUENCES, WESTERN MURRAY BASIN, SOUTH AUSTRALIA.

S.D. Giles

Honours Thesis
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STRATIGRAPHIC INVESTIGATIONS OF TERTIARY SEQUENCES, WESTERN MURRAY BASIN, SOUTH AUSTRALIA.

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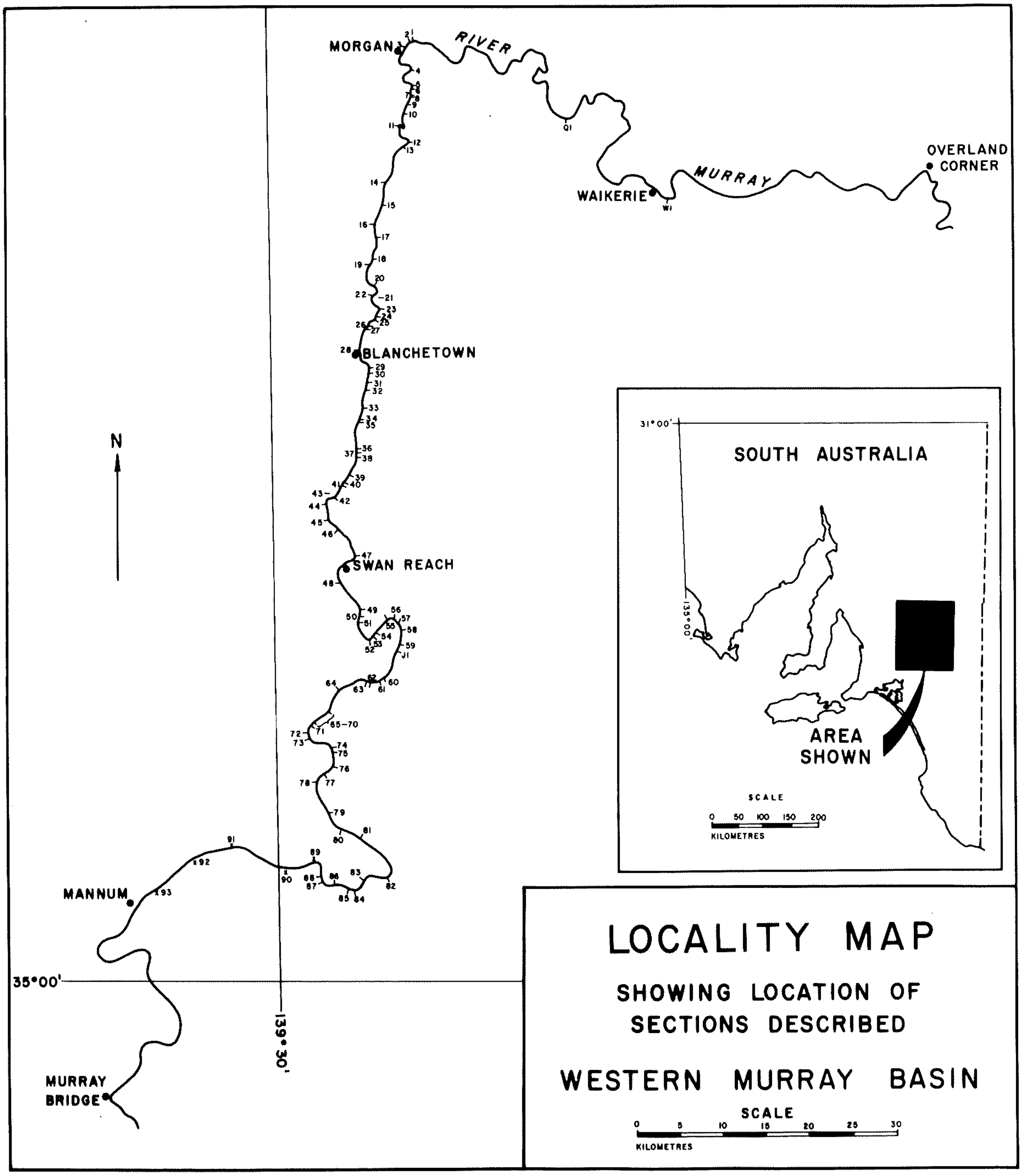
1972.



MORGAN
RIVER
MURRAY
WAIKERIE
OVERLAND CORNER
BLANCHETOWN
SWAN REACH
MANNUM
MURRAY BRIDGE
N
35°00'
139°30'
31°00'
135°00'
SOUTH AUSTRALIA
AREA SHOWN
SCALE
0 50 100 150 200
KILOMETRES
LOCALITY MAP
SHOWING LOCATION OF SECTIONS DESCRIBED
WESTERN MURRAY BASIN
SCALE
0 5 10 15 20 25 30
KILOMETRES

CONTENTS

STRATIGRAPHIC INVESTIGATIONS OF TERTIARY SEQUENCES, WESTERN MURRAY BASIN, SOUTH AUSTRALIA.

A B S T R A C T

In an attempt to improve the understanding of the biostratigraphy, sedimentology and palaeoecology of Tertiary sequences in the western Murray Basin, sections are described from cliff outcrop surrounding the lower River Murray. The relation of the upper boundary of Finniss Clay (Miocene) at its stratotype, to the overlying Morgan Limestone (Miocene), examined with respect to other occurrences in the basin, is questioned. The significance of the Batesfordian Stage, as known in the Murray Basin, is examined biostratigraphically. The Cadell Marl is reinterpreted as a shallow water deposit, and a cross-bedded member of the Morgan Limestone, representing tidal sediments, is described for the first time. Certain sedimentary cycles inferred from Tertiary strata are correlated with the Otway Basin.

a poor abstract

INTRODUCTION

The aims of this study were to elucidate the Middle and Upper Tertiary strata exposed in the cliffs bounding the River Murray from Morgan to Mannum. For this purpose, construction of a continuous lithological chart was attempted, despite poor outcrop in some places; the correlation of 86 sections of Miocene and Pliocene calcareous sediments by means of individual beds was enhanced by 19 sections measured and examined in precise detail; 4 sections were extensively collected, and palaeontological and sedimentological studies were carried out on these sequences (Appendix II). Following laboratory examination and statistical analysis, it was attempted to deduce the environment of deposition of each unit.

The Cretaceous and Tertiary geology of the southeastern Australian Otway Basin has been divided into sedimentary cycles by Bock and Glenie (1965); certain similarities in the Murray Basin strata led the author to postulate the applicability of these cycles to this area, and research into the sediments, and the relevant literature was undertaken.

Investigational history

The first records of fossiliferous rocks in the Murray Basin were those of Sturt (1833), with drawings of shells from the cliffs. Apart from isolated private wells sunk for petroleum exploration as early as 1902, the emphasis remained with palaeontological aspects of the strata, despite some quite detailed studies being undertaken (Tate, 1885; Howchin, 1929; Crespin, 1944), until the late 1940's, when the stratigraphic aspects of the rocks were considered important (Dolling, 1949; Barnes, 1951). Following these investigations, acceptance of the use of biostratigraphy based on foraminifera enabled elucidation of the lithostratigraphy (e.g. Glaessner, 1951) - most of the biostratigraphy which led to reports on the geology of the Murray Basin (Spence, 1958; O'Driscoll, 1960; Ludbrook, 1961)was conducted by Ludbrook (1957, 1958); further papers on the area by Ludbrook (1962, 1967, 1969) have been based on revision of her major work (Ludbrook, 1961, op. cit.). Most of the studies in the Murray Basin since then have been under the auspices of the South Australian Department of Mines (Lindsay, 1965, 1966, 1968; Lindsay and Bonnett, 1971; Firman, 1972; Thornton, 1972); the few exceptions have been basically palaeontological (Jenkins, 1966, 1972; Philip and Foster, 1971).

Acknowledgements

I would like to thank Mr. R.J.F. Jenkins, who suggested and supervised this project; also, Drs. B. McGowran and V.A. Gostin, for helpful discussions during the year. Mr. J.M. Lindsay, of the Palaeontology Section, South Australian Geological Survey, supervised me while employed with the survey on projects relating to the Murray Basin; he also introduced me to micropalaeontology and provided invaluable advice and encouragement. I would especially like to thank my wife, Gail, who persisted with much of the draughting, and gave physical and moral support during the past two years.

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LOCALITY MAP

Showing basement outcrop surrounding the

MURRAY BASIN

Scale

0 100 200 300 400 Km.

FIG. 1

gg

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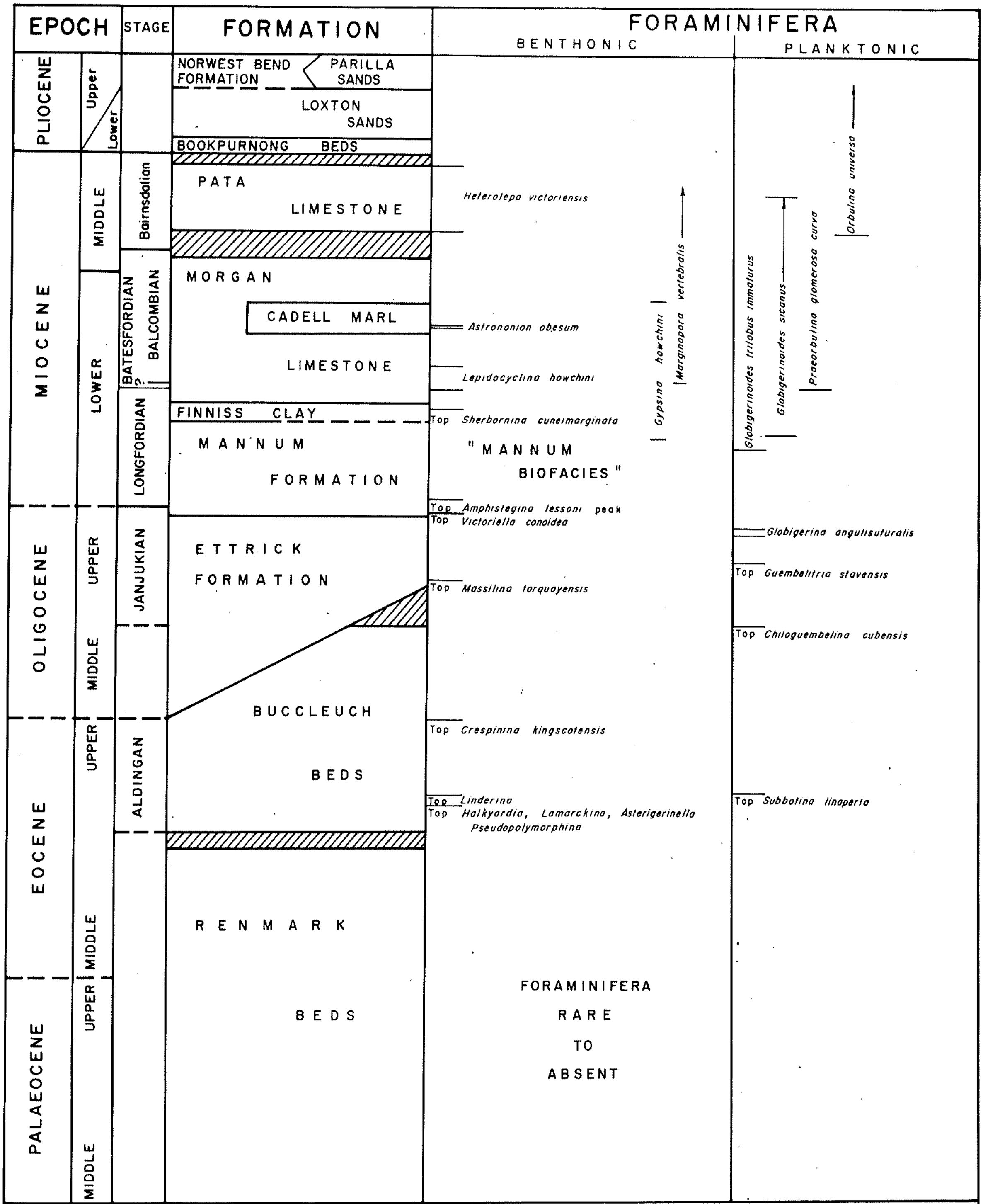
GEOLOGICAL PERSPECTIVE

I. BASEMENT

The Murray Basin is a roughly circular area of Tertiary sedimentation (Ludbrook, 1961) occupying 300,000 km^2, of which the southwest quadrant is mainly marine deposits (Brown, Campbell, and Crook, 1968). It is bounded on the west and north by the Proterozoic-Cambrian Adelaide Geosyncline (Mt. Lofty-Olary arc), and on the east and southeast by Lower Palaeozoic strata of the Tasman Geosyncline, outcropping as the Great Dividing Range and Snowy Mountains respectively (Fig. 1). Patchy outcrop of Cambrian metasediments and Ordovician granites on the southwest indicates the surface expression of the Padthaway Ridge, which, during the Tertiary, formed a line archipelago acting as a fluctuating barrier to the southern ocean and the Otway Basin (Ludbrook, 1961).

Metamorphic basement is low-grade Lower Palaeozoic greywacke, schists, and shales of Kanmantoo Group (?Cambrian) in the west, and Cambro-Ordovician metasediments in the east, which crop out on the edge of the basin. This surface dips towards the tri-State corner, where it reaches a maximum depth of 3500m. This, the Renmark Trough, trends northeast, parallel to other lesser troughs in the area; it contains up to 1500m. of non-marine clastics, of possible Devonian age. These sediments were unconformably overlain by 900m. of marine Lower Permian glacigenes; boulder clays are also reported from the southwestern corner of the basin. Influence from the Great Artesian Basin during the Albian (Lower Cretaceous) led to marginal and restricted marine fine clastics up to 600m. thick being deposited in the Renmark Trough area, and in Victoria.



MICROPALAEONTOLOGY & LITHOSTRATIGRAPHY
WITHIN THE MURRAY BASIN
SOUTH AUSTRALIA

after LUDBROOK, 1957 – 69
LINDSAY & BONNETT, 1971

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FIG. 2

Although these sediments must be considered basement with respect to the Tertiary basin, as they represent completely separate periods and modes of deposition, those units younger than Lower Palaeozoic, especially the Permian, are areas of interest for petroleum exploration, and are therefore above metabasement (Thornton, 1972).

The upper surface of the Lower Cretaceous sediments was eroded to form valleys with a drainage pattern towards the Renmark Trough (Lawrence, 1966; Thornton, 1972); it was on this surface that the widespread earliest Tertiary sediments were unconformably deposited.

II. TERTIARY

All epochs of the Tertiary period are represented by discontinuous sedimentation in the Murray Basin (Ludbrook, 1961). The oldest deposits are non-marine; the increasing marine influence reached a peak in the Oligocene, and regressed in the later Miocene. A latest Miocene-earliest Pliocene transgression was followed by retreat in the Upper Pliocene. Foraminifera are the most widely applicable tools for Tertiary marine correlation, and have been used extensively in the Murray Basin (see Fig. 2).

Renmark Beds

who called them Renmark Beds?

Defined by Sprigg and Boutakoff (1953) as the Knight Group in the Gambier Embayment, Harris (1966) redefined the formation within the Murray Basin, and dated it as Middle Palaeocene to Middle Eocene at Waikerie (Lindsay and Bennett, 1971). They are represented by widespread non-marine carbonaceous clastics, pyritic clays, silts and sands, overlain by fluviatile to paludal pyritic and micaceous siltstones and sandstones, with frequent Eocene lignites developed on bedrock highs (McGarry, 1953). The upper part of this unit has marine and shelly beds representing brief ingressions from the south; most of the Renmark Beds contain only non-marine fossils, such as fossil spores and pollen.

Buccleuch Beds

The Buccleuch Beds were defined by Ludbrook (1957) from subsurface in the Coonalpyn Township Bore; they are not known to outcrop. Their limited previously-known extent was increased by Lindsay and Bonnett (1971) who described the diachroneity of bed B at Waikerie.

The basal 45m. (bed A) varies from marl and limestone to clastic, but is generally glauconitic, fossiliferous and transgressive upwards (Ludbrook, 1961; Lindsay and Bonnett, 1971). The pan-tropical benthonic foraminifera Linderina and Halkyardia suggest a climatic optimum for this unit - its Upper Eocene age is indicated by the local extinctions of Asterigerinella adelaidensis, Lamarckina airensis, and Pseudopolymorphina sp..

Bed B, a regressive marginal to nonmarine unit, is notable because the thin (7.5m.) limestones and carbonaceous sands at the type section, which are of Upper Eocene age ("top" Porosorotalia crassimura, Lamarckina glencoensis) increase in thickness (to 63m.) and age range (Upper Eocene to middle Oligocene - Chiloquembelina cubensis extinction) of the pyritic sands, carbonaceous clays and shelly sands attributed to bed B at Waikerie. The top of bed B is thus markedly diachronous within the Murray Basin (Lindsay and Bonnett, 1971).

Bed C at Waikerie is missing; the top of bed B is cemented, and represents a disconformity. At its stratotype, this unit is a limonitic, carbonaceous clay, 0.6 m. thick.

Ettrick Formation

The Ettrick Marls (Ludbrook, 1957) were renamed the Ettrick Formation (Ludbrook, 1961) to encompass more completely the lithology of the unit. The subsurface type section at Launer's No. 2 Bore, Hd. Ettrick, was selected before the earliest outcrop of Tertiary strata in the Murray Basin was recognized just south of Tailem Bend, as a low shelf in the River Murray valley; this outcrop, which represents the top of the formation, is a leached, white limestone, with occasional chert nodules. At the type section, the lower part is a greenish-grey, clayey, glauconitic and limonitic marl; this can be recognized at Waikerie as a 7.5m. "glauconitic clay unit" (Lindsay and Bonnett, 1971), and in Victoria as the Yanac Member (Lawrence, 1966). The good microfauna at the type section is replaced by a restricted marine assemblage in the lower unit at Waikerie. The upper portion at the type section is a lighter-coloured marl with Massilina torquayensis (which suggests an Upper Oligocene age); at Waikerie, the more open marine "glauconitic marl unit" (30m.) contains the key planktonic foraminifera Globigerina angulisuturalis (Lindsay and Bonnett, 1971) indicating a marine incursion in the late Oligocene. The equivalent unit in Victoria, the Netherby Marl, is dated Janjukian (Lawrence, 1966) and grades easterly into the restricted marine, pyritic, Geera Clay.

Mannum Formation

Ludbrook (1961) defined this unit as the oldest member of the Murray Group (Tate's (1885) Middle Murravian Series).

It represents deposition in a stable basin after transgression, and is widespread, overlying bedrock in the west (Ludbrook, 1961), and forming the lower portion of the Duddo Limestone, Winnambool Formation, and nonmarine Wunghu Group in the far east of the Murray Basin, in Victoria (Lawrence, 1966). The formation forms a later part of this thesis, so will not be discussed further in this section.

Finniss Clay

This blue-grey marine clay is an anomalous unit best developed near the western margin of the basin. Its genetic position in relation to the shelf limestones is unsure. It will be discussed in greater detail later in the text.

Morgan Limestone

The description of a new member of Morgan Limestone in this thesis has enabled clarification of the palaeogeography of the Murray Basin at this time; the widespread nature of the Morgan Limestone is noted by Lawrence (1966), who admits the obvious similarity between the Cadell Marl and a glauconitic marl 10m. to 22m. below the top of the Duddo Limestone, in Victoria.

Pata Limestone

This unit is defined subsurface in Drainage Shaft No. 18, Loxton (Ludbrook, 1961), but outcrop of this Bairnsdalian (Middle Miocene) limestone has since been recognized by Lindsay (1965) at Sunlands Pumping Station, near Waikerie. It is a yellow shelf limestone, similar to the rest of the Murray Group limestones, but abundantly ditrupal. Characteristic and, within the Murray Basin, defining microfossils are *Heterolepa victoriensis* and *Orbulina universa*. The Pata Limestone represents deposition in deeper parts of the basin during a partial transgression, following post-Morgan emergence.

Bookpurnong Beds

The thin, but extremely persistent Bookpurnong Beds are confined to the eastern part of the basin by a partial transgression, bringing shallow seas to cover the Miocene deposits in the latest Miocene or, more likely, earliest Pliocene. The 2.5m. of finely clastic micaceous and carbonaceous marls, defined at Great Pyap Bend, near Loxton (Ludbrook, 1961), but first described by Howchin (1929), contain an abundant micro- and megafauna, especially bivalves. Subsurface, the unit may exceed 20m.

Loxton Sands

Overlying the Bookpurnong Beds at their stratotype are the Loxton Sands, angular, micaceous, ferruginous, quartz sands, often calcareous and fossiliferous, and up to 60m. thick. They are regarded as Lower Pliocene in age, and extend into Victoria, where the equivalent Diapur Sandstone forms northwesterly trending ridges thought to be dunes formed after retreat of the lake responsible for the deposition of the nonmarine upper portion of the Loxton Sands (Lawrence, 1966).

Norwest Bend Formation

The Norwest Bend Formation, although defined at Nor'west Bend Station (Tate, 1885) does not occur typically at any one locality. As demonstrated later in the text, the concept of a type section for this formation of variables (yet a mappable unit) is difficult to support.

Parilla Sands

Basally of Upper Pliocene age, and marine origin, these fine, clayey sands are generally nonmarine, and of a great enough time differential to overlie the Norwest Bend Formation at Ramco Quarry ("Ramco Stone") with an erosional unconformity.

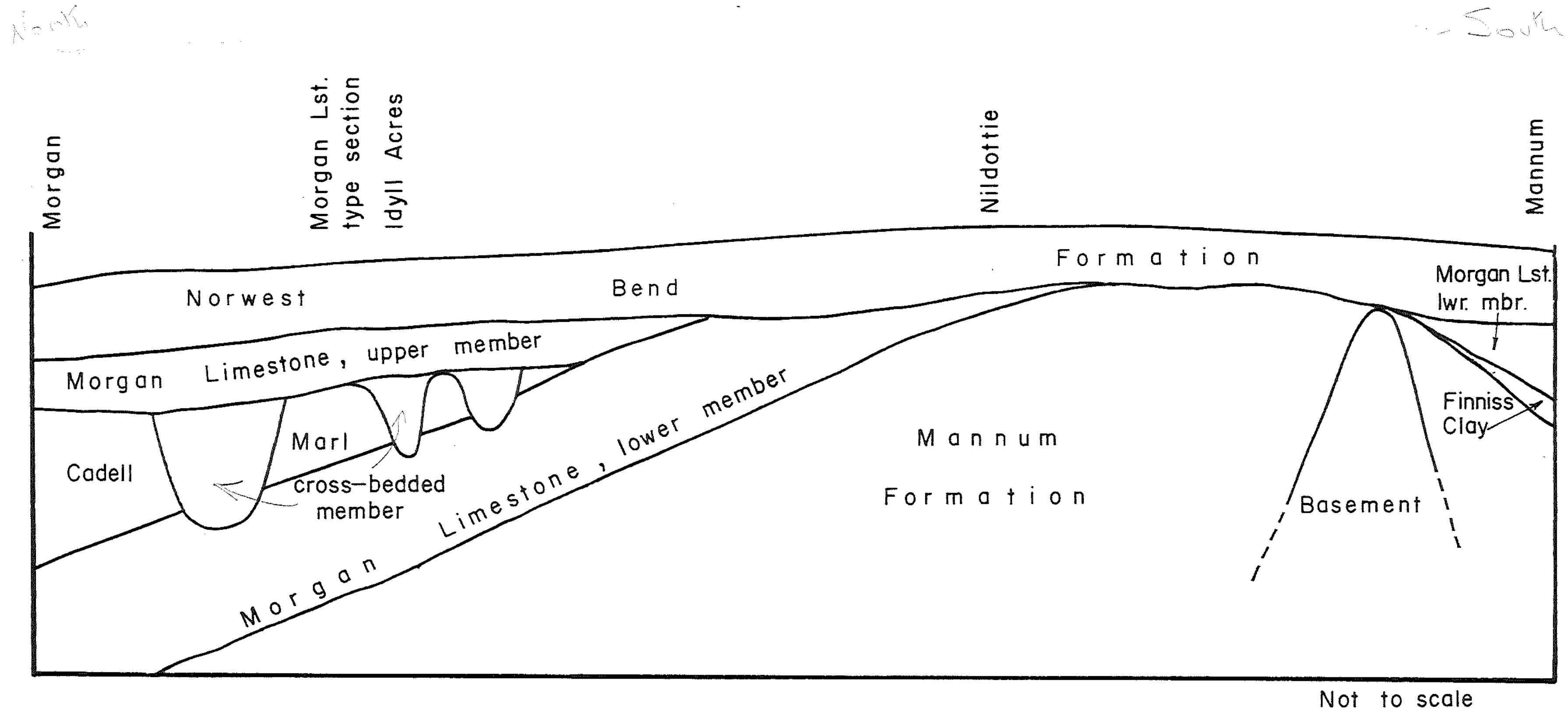
Pleistocene to Recent units

Thin surficial deposits of lacustrine and fluviatile origin cover most of the older strata in the Murray Basin. For a comprehensive description, Firman (1972) should be consulted.

FIG. 3

LITHOSTRATIGRAPHIC ANALYSIS OF TERTIARY SECTIONS IN THE RIVER MURRAY CLIFFS

MORGAN TO MANNUM, S.A. with biostratigraphic datums



INTERPRETATIVE GEOLOGICAL SECTION

RIVER MURRAY CLIFFS, MORGAN TO MANNUM, S.A.

S.D. Giles 1972

FIG. 3a

STRATIGRAPHY

Apart from the Finniss Clay, the Miocene strata exposed in the river cliffs are all interpreted as marine shelf carbonates with differing environmental affinities; Pliocene sedimentation is representative of a separate pattern of calcareous clastic deposition. Broad structural movements, both before and after Pliocene times has led to variation in formation outcrop extent, so that, in some areas, Mannum Formation forms the whole mid-Tertiary portion of the cliff, while at other localities, the overlying Morgan Limestone is continuous to below river level. In an attempt to elucidate the lithostratigraphy for future studies along the lower reaches of the river, a continuous chart, showing correlation of beds and boundaries was constructed (Fig. 3). This is supported by 18 precisely detailed sections (Figs. 4-7; Appendix I). Biostratigraphic events, where they can be inferred, have been placed on the sketch sections (Fig. 3) as extrapolations. A simplified, interpretative version of Fig. 3 is included in the text (Fig. 3a).

Although no detailed lithocorrelation has been carried out for the upper reaches of the River Murray, personal observations indicate that similar structural fluctuations occur in this area, until the disappearance of virtually all Miocene outcrop east of Overland Corner. The Oligocene Ettrick Formation, the oldest Tertiary rocks exposed in the Murray Basin proper are found as a low shelf just south of Tailem Bend. Basement outcrops in the area studied as granite (section 93, Frontispiece), migmatitic gneisses, and dark metasediments of the Kanmantoo Group (sections 91 and 89, respectively), all overlain by Mannum Formation limestones.

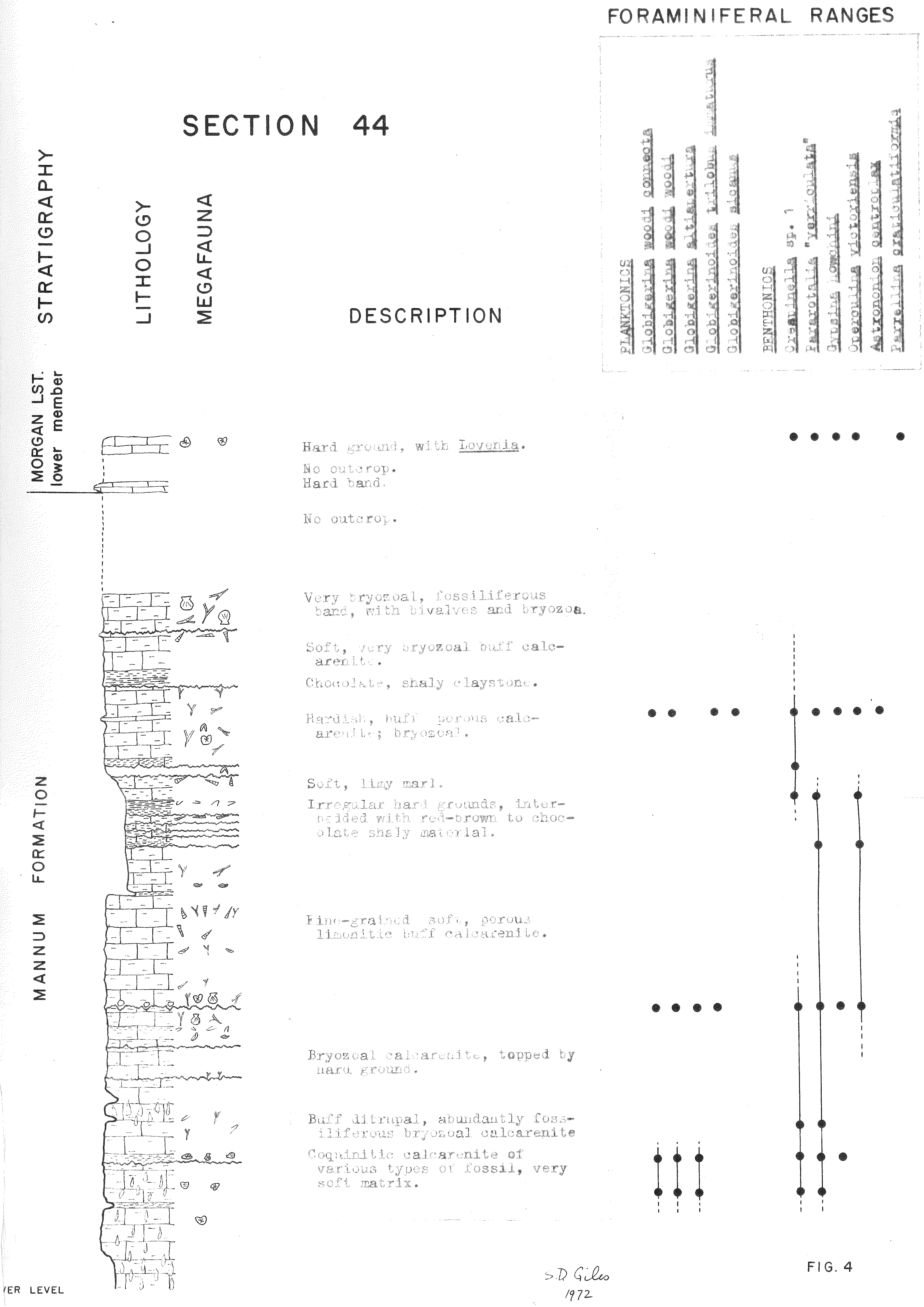
I. MANNUM FORMATION

Previous Work

The Mannum Formation was first described by Ludbrook (1961) at Mannum Pumping Station, where she recognised two units. The lower member was described as yellow to brown, limonitic, fossiliferous sandstone, with common fragments of the irregular echinoid Lovenia forbesi, and is in excess of 8m. thick, the lower boundary not being exposed here. The upper member (11.3m.) is less banded, and more clayey, weathering to form Tate's (1885) 'raggy limestone'; the abundance of Lovenia in this member caused it to be classified, in places, as a coquinite; this distinctive fossil typifies the formation away from the stratotype.

Foraminifera described from the type section (Ludbrook, 1961) include Sherbornina atkinsoni, which does not occur above the lower member, and S. cuneimarginata, restricted to the upper member. Other characteristic benthonic microfossils, such as Astrononion centroplax and Cibicedes vortex are not known from sequences younger than the Longfordian Stage (Carter, 1964), and it is therefore concluded that this formation lies mostly within the Longfordian. However, although Ludbrook (1961) does not place the base of the formation below the base of the Miocene, Lindsay and Bonnett (1971) record the top of Victoriella conoidea just above the lowest Mannum Formation; Carter (1964) records the top of V. conoidea as marking the top of the Janjukian Stage (upper Oligocene). The author does not intend to imply non-isochroneity of the lower boundary from this information - merely that the earlier work was exploratory and not as complete as the later study.

Five planktonic zones of Ludbrook and Lindsay (1969)



SECTION 44
STRATIGRAPHY
LITHOLOGY
MEGAFAUNA
DESCRIPTION
FORAMINIFERAL RANGES
PLANKTONICS
Globigerina woodi connecta
Globigerina woodi woodi
Globigerina altiapertura
Globigerinoides trilobus immaturus
Globigerinoides sicanus
BENTHONICS
Crespinella sp. 1
Pararotalia "verriculata"
Gypsina howchini
Operculina victoriensis
Astrononion centroplax
Parrellina crassicuatiformis
MORGAN LST. lower member
MANNUM FORMATION
Hard ground, with Lovenia.
No outcrop.
Hard band.
No outcrop.
Very bryozoal, fossiliferous band, with bivalves and bryozoa.
Soft, very bryozoal buff calcarenite.
Chocolate, shaly claystone.
Hardish, buff porous calcarenite; bryozoal.
Soft, limy marl.
Irregular hard grounds, interbedded with red-brown to chocolate shaly material.
Fine-grained soft, porous limonitic buff calcarenite.
Bryozoal calcarenite, topped by hard ground.
Buff ditrupal, abundantly fossiliferous bryozoal calcarenite
Coquinitic calcarenite of various types of fossil, very soft matrix.
VER LEVEL
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FIG. 4

(the upper part of the *Globigerina euapertura* Zone, *Globoquadrina dehiscens* Zone, *Globigerina woodi* s.l. Zone, *Globigerinoides trilobus* Zone, and the lower part of *G. sicanus* Zone) are recognised, and allow correlation to the rest of south-eastern Australia, and thence regionally; by this means, biostratigraphy assists in chronostratigraphy. Jenkins (1972) has measured a section through the Mannum Formation at Nildottie, 40 km. north-west of Mannum, and on the basis of the correlation of planktonic foraminifera with an absolute time scale (Berggrenn, 1969), concludes that deposition of the Mannum Formation there was slow (1cm./1000yr.), being continually interrupted by diastems inferred from outcrop.

Lithology

Within the area studied, the Mannum Formation is a medium to coarse-grained, cemented, skeletal calcarenite, with apparent current winnowing, inferred from the general lack of fine-grained material. However, some beds obviously represent lower energy conditions, as soft, finer-grained marl was deposited (e.g. section J1, Appendix 1). The overall lithology of the formation is a carbonate, with a small fraction of fine to medium-grained terrigenous material, and occasional bands of calcareous clay (e.g. Fig. 4).

Palaeontology

The microfauna of the Mannum Formation is sparse and recrystallized, and biostratigraphy on the basis of planktonic foraminifera is difficult. The term "Mannum biofacies" used by Lindsay and Bonnett (1971) to described the monotonous nature of the benthonic forms is supported by this study. On the basis of the dominantly calcareous microfauna, biostratigraphic resolution was not possible beyond formational level, (Fig. 4).

Hard grounds

Some beds in this unit are continuous over distances up to 10km. (see Fig. 3, in the vicinity of sections 50 to J1), but others become lost over a matter of metres. Less continuous beds are generally observed because of their cementation; the hypothetical formation of these hard grounds has been described in some detail by Jenkins (1972), using evidence by Shinn (1969) and others. The hard grounds represent submarine lithification and subsequent erosion during periods of low sedimentation. Lithification occurs in porous sediments 0.1 to 1.5m. below the water interface, and biogenic activity by infauna (possibly worms, echinoids, crustaceans, etc.) is preserved as trace fossils; body fossils, mainly as moulds of the high-spire gastropod Turritella murrayana, occur abundantly as clusters, distinguishing these "still-stands" from more continuous sedimentation. Cyclic deposition of this degree appears restricted to the Mannum Formation within the outcrop examined; lesser developments of these beds produces the intercalated hard and soft calcarenite of the Morgan Limestone, and flaggy banding as described later.

During erosional episodes associated with hard ground formation, large (5 to 20cm.) blocks of burrowed, cemented material were stripped from the substrate and incorporated in the calcarenitic matrix forming the less cemented interbed (Plate 2,b). As hard grounds were often produced with their erosional surfaces less than .3m. apart, phreatic solutions cemented a particular stratum several times before decreasing permeability prevented further hardening. Therefore, the interbeds are often no more susceptible to weathering than the hard grounds themselves, and banding is not observed in the cliffs formed from these strata (Plate 2,c).

Due to the particular conditions for submarine lithification (see Shinn, 1969), the degree to which a contemporaneous surface was cemented fluctuated greatly; the lateral extent of hard grounds, in outcrop is therefore very variable, and it is found that, whereas some may range throughout all suitable outcrop (e.g. the Mannum-Morgan boundary, described later), many can only be traced for a few tens of metres before they become indistinguishable from the surrounding sediment.

Environment

The sediments of the Mannum Formation can be interpreted as resulting from a marine shelf carbonate deposit, with a general current flow sufficient to remove the finer fraction, but not great enough to incorporate coarse-grained terrigenous clastics, or produce obvious current bedding. From studies of the fossil decapod crustacea, Jenkins (1972) concludes a depositional depth between 50 and 110m., which is consistent with the sedimentological data. In the same study, he suggested palaeotemperature gradually increased through the formation. Hornibrook (1967) suggests that a peak in abundance of the benthonic foraminifera *Amphistegina lessoni* represents a climatic optimum; Lindsay and Bonnett (1971) record such a peak (Fig. 2), and infer a "high" in the lower Longfordian.

temperature

II. FINNISS CLAY

Overlying the Mannum Formation at Mannum Pumping Station is the stratotype for the Finniss Clay, 4.6m. of blue-grey marine clay; a poorly preserved microfauna, dominated by *Amphistegina lessoni* and *Operculina victoriensis*, is present mainly as limonitic internal moulds (Ludbrook, 1961). Occurrences within 10 km. of this locality are known to have typical Finniss Clay, but, elsewhere in the basin, equivalent stratigraphic positions are represented by a "grey finely shelly marl" (Lindsay and Bonnett, 1971) or as a thin, softer calcarenite underlying three hard grounds, which Jenkins (1972) used as the marker for the Mannum-Morgan boundary (section J1, appendix I). On the basis of benthonic foraminifera (e.g. *Sherbornina cumeimarginata* from bores at Waikerie. (Lindsay and Bonnett, op. cit.), *Astrononion centroplax* and *Planorbulinella plana* from strata above it (Lindsay, 1968)), the Finniss Clay is placed in the upper part of the Longfordian Stage.

At excavations for the duplication of the Morgan Pumping Station, Lindsay (1968) discovered that, while at the type section, Finniss Clay overlies the Mannum Formation with an erosional disconformity (Ludbrook, 1961, supported by personal observation) typical Finniss Clay is contained in cavities within the top of the Mannum Formation at this site.

Although megafauna appear to be absent from the formation, Lindsay (op. cit.) records common fish fragments from Finniss Clay at Morgan. Microfauna, while sparse at the sections where the major lithology is a clay, becomes large as the unit increases in carbonate content. Lithologies pertaining to type Finniss Clay are known only from outcrop near the western margin of the basin; towards deeper areas within the basin, equivalent units become marly and shelly. The interpretation placed on this evidence is that a fine-grained clastic was introduced (possibly from the west), and the large bulk of it was deposited as typical Finniss Clay; greater distance from the terrestial source decreased the influence on the sediments, and more calcareous deposits were laid down.

III. MORGAN LIMESTONE

Previous work

Ludbrook (1961) selected a section measured by Tate (1885) "4 miles downstream from Morgan" (on Section C, Hd. Cadell) as the type section for the Morgan Limestone and Cadell Marl lens, because this section is the type locality for many of Tate's molluscan species (Ludbrook, op.cit., p.53). She informally divided the formation into three members (lower (13.3m.) and upper (7.8m.) members of Morgan Limestone, and Cadell Marl lens (6.4m.)) at this locality; in this thesis a fourth member is recognised and described for the first time - this new member fits stratigraphically between the Cadell Marl and the upper member of the Morgan Limestone.

(a) lower member

Boundary conditions

In most areas of outcrop on the river cliffs south of Morgan, Finniss Clay is not present as an obvious lithological marker between the Mannum Formation and the Morgan Limestone; however, a number of well-developed conspicuous hard grounds at approximately the correct stratigraphic level have been used firstly by Jenkins (1972) and in this study, as denoting the boundary (Fig. 3). At Mannum, the Finniss Clay is interbedded with calcarenites for 2.7m. of its 4.6m. type thickness (Ludbrook, 1961), but examination of these bands by the author did not reveal any evidence which would enable their classification as hard grounds; the relationship between these beds and the marker described above remains unexplained.

The benthonic foraminifera *Lepidocyclina howchini* has long been thought to be an accurate biostratigraphic marker (Glaessner, 1951; Ludbrook, 1961; Wade, 1964, and others); within the Murray Basin, the base of the zone is generally thought to occur 4.5m. to 5.5m. above the base of the formation (Lindsay, 1968; Lindsay and Bonnett, 1971; Jenkins, 1972), whereas, at Mannum Pumping Station, J.M. Lindsay (pers. comm.) has made a recent recording 2.5m. above the top of Finniss Clay, as defined by Ludbrook (1961); this is anomalously low, and perhaps the first calcarenite band encountered up-section should mark the base of Morgan Limestone, thus making the Lepidocyclina horizon commence 5.2m. above the lowest Morgan Limestone at Mannum.

Lithology

The lower member extends in outcrop from Overland Corner more or less continuously to south of Nildottie (Fig. 3), and then again from Mannum, southwards; the typical lithology is "a fairly uniform soft bryozoal limestone.........becoming banded in the upper [9 metres] " (Ludbrook, 1961). This lithology is not only uniform vertically, as at the type section, but also laterally - the major variations are in the slight faunal changes, and in the cementation; this latter can be noticed by the hard nature of Lepidocyclina limestone from south of Mannum, compared with the friability of similarly fossiliferous material from Blanchetown. Studies on Morgan Limestone from the stratotype (section 7, Fig. 5) and Morgan Pumping Station (section 2, Fig. 6) have shown it to be basically as previously described. Skeletal carbonate, ranging in size from rare, large (10cm.) bryozoa (Cellepora) in life position, to a small proportion of clay-silt size particles, is responsible for about 80% of the rock, the majority of the remainder being medium quartz sand to clay, with common glauconitized faecal pellets.

FIG. 5

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Palaeontology

Whereas the Mannum Formation is typified by echinoid remains, the lower member of the Morgan Limestone can be distinguished by its highly bryozoal nature; large dendroid colonies of *Cellepora gambierensis*, and other monticular forms, are common. Echinoids are frequent, but not common, and *Lovenia* does not constitute the majority of this group. Nautiloids (mainly *Eutrephoceras*) are occasionally present, especially at the *Lepidocyclina* horizon.

Many local extinctions of benthonic foraminifera occur low in this member, including *Astrononion centroplax*, *Planorbulinella plana* and *Crespinella* sp. 1; also, the base of a temporary absence of *Pararotalia* "*verriculata*", which extraordinarily makes a brief reappearance high in the Cadell Marl (Figs. 5, 6), although this may not always occur (Lindsay and Bonnett, 1971, and Fig. 7). Slightly above this cluster of "tops", the base of the *Lepidocyclina* horizon is noted.

At Batesford New Quarry, Carter (1964) records *Lepidocyclina howchini* in association with *Cycloclypeus victoriensis*. Apart from a single unsubstantiated report (Crespin, 1944), *Cycloclypeus* has not been found east of the Otway Basin, but *Lepidocyclina* is found as far east as St. Vincent Basin (Fig. 2)(Glaessner, 1951; Wade, 1964; Lindsay, 1969, 1970). The report of *Cycloclypeus* from the Murray Basin was from a collection by F.A. Cudmore, "4 miles [6.4 km.] downstream from Morgan" (Crespin, 1944); the description of the lithology and microfauna suggest lower member of Morgan Limestone, but *Lepidocyclina* was not recorded. Examination of the type section by the author, and J.M. Lindsay, South Australian Geological Survey, revealed *Lepidocyclina* 1.5m. above normal river level (Fig. 5), although earlier attempts do not record

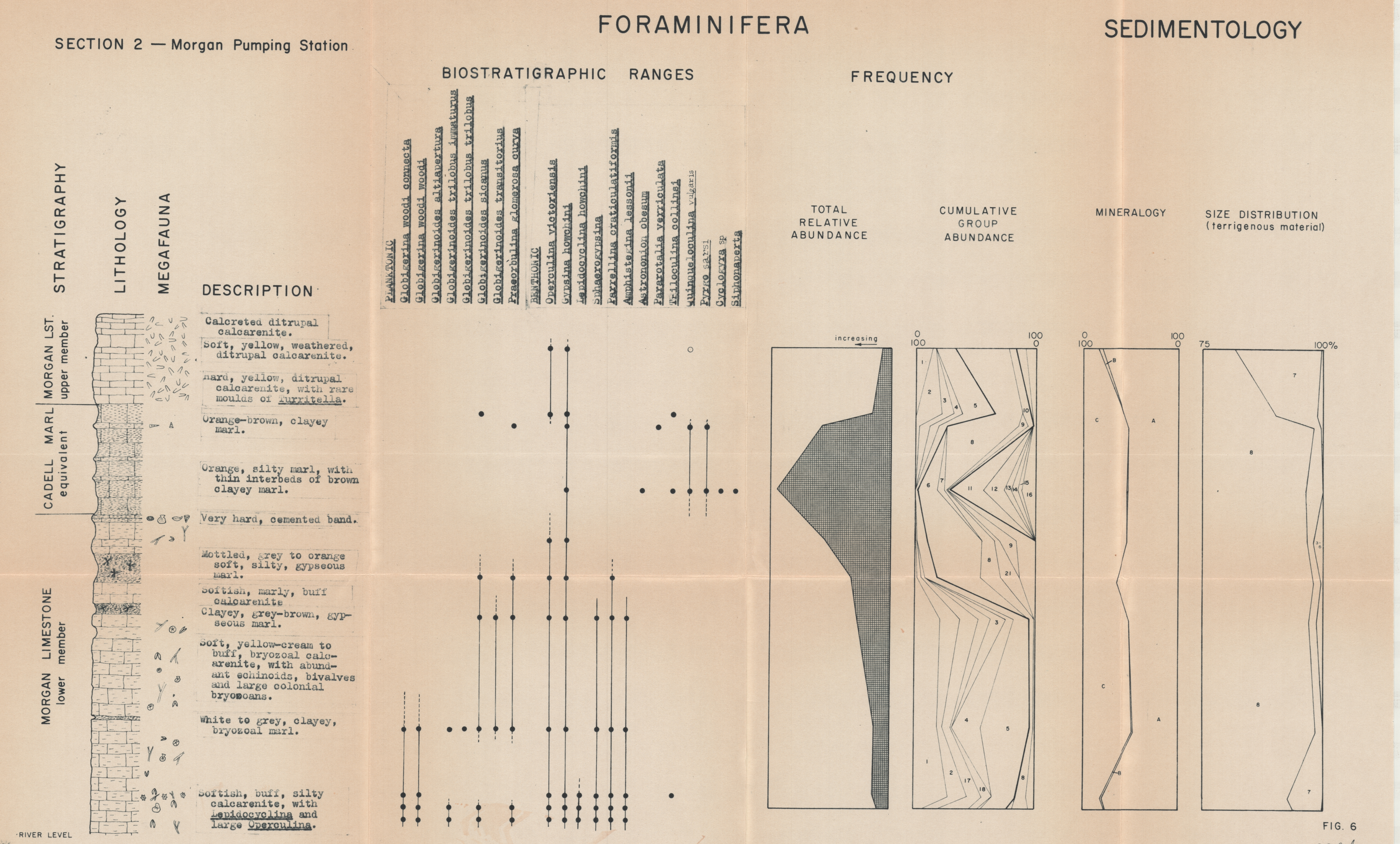

FIG. 6

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it (e.g. Ludbrook, 1961). This horizon appears to be widespread throughout the basin (Ludbrook, 1957, 1961, 1962, 1969; Lindsay, 1968; Lindsay and Bonnett, 1971; this paper, Figs. 5, 6, 7, and Appendix I); above the top of this zone, the microfauna remains fairly constant, dominated by large, calcareous, benthonic foraminifera such as Parrellina craticulatiformis (which is restricted to the lower member of Morgan Limestone), Operculina victoriensis, Amphistegina lessoni and Gypsina howchini.

Environment

The environment interpreted from this data is a fairly low energy area of deposition, generally neritic, with a few pulses of transgression, where terrigenous material and grainsize decreases, and the proportion of planktonic microfossils increases. The calcareous-dominated foraminiferal assemblage indicates fairly open-marine conditions (for the Murray Basin); a high frequency of Operculina and Amphistegina imply warm, shallow conditions, which are supported by the presence of the large pan-tropical Lepidocyclina.

The Batesfordian Stage

Carter (1958) defines the Batesfordian Stage at Batesford New Quarry in Victoria by the presence of Lepidocyclina howchini and Cycloclypeus victoriensis. Studies on the Lepidocyclina zone in the St. Vincent Basin have generally shown it to be within the Globigerinoides sicanus Zone (Lindsay, 1969, 1970). The lower Member of Morgan Limestone was previously thought to be within the G. sicanus Zone, and the Batesfordian (Ludbrook, 1961; Lindsay and Bonnett, 1971), until the next evolutionary member of the Orbulina bioseries of Blow (1956), Praeorbulina glomerosa curva, was found; its presence signifies the beginning of the

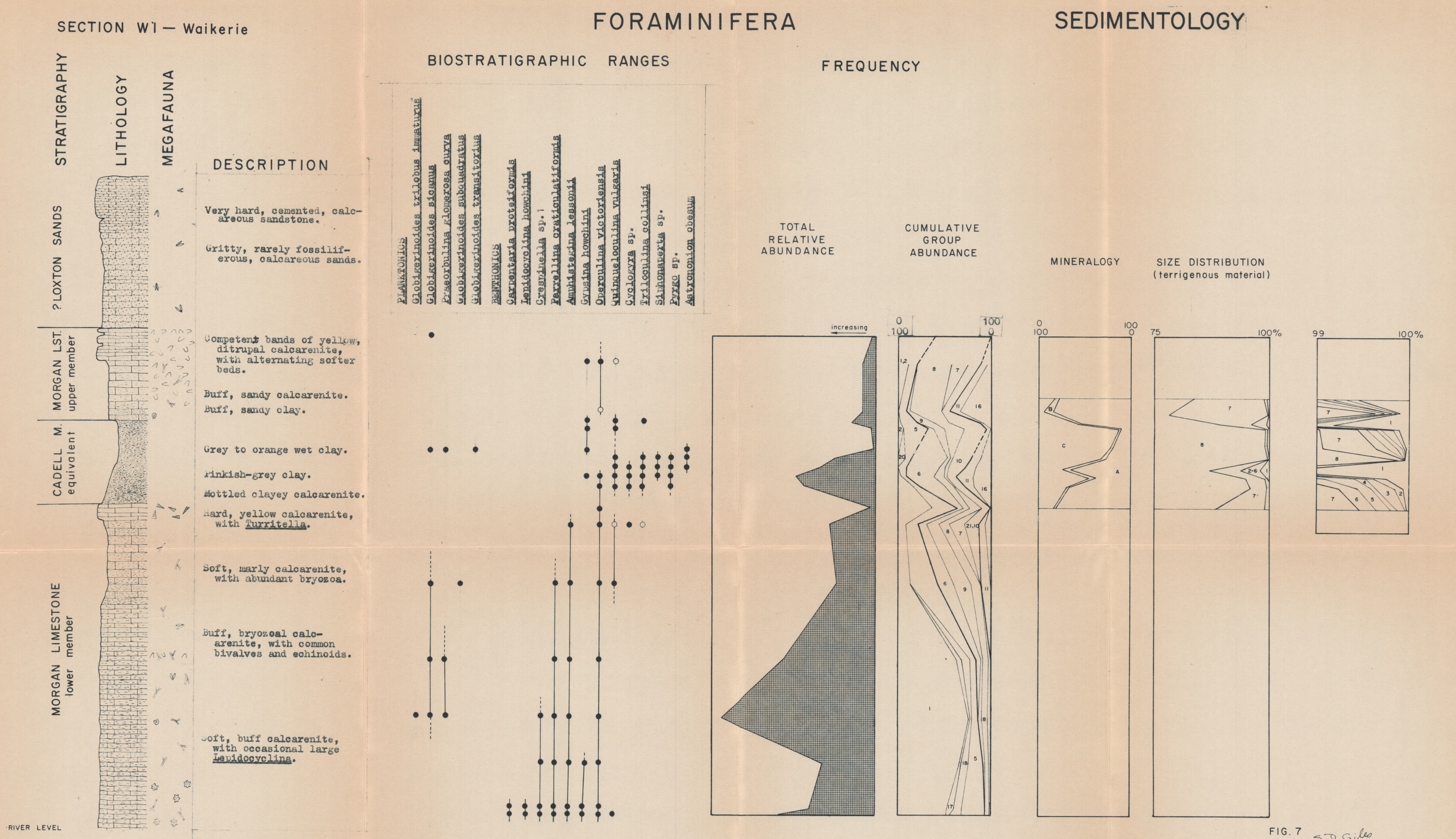

FIG. 7

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Balcombian Stage (Carter, 1958). Recent studies have shown _P. glomerosa curva_, and _Globigerinoides transitorius_ to range down at least into part of the _Lepidocyclina_ horizon, thus either reducing the thickness of strata deposited during the Batesfordian Stage to a minimum, or showing a relative diachroneity of the _Lepidocyclina_ Zone into the Murray Basin. However, R.J. Foster (pers. comm.) during his work on Tertiary echinoids states that he can discover no evidence for the Batesfordian Stage on the basis of Tertiary echinoids.

(b) Cadell Marl

Introduction and boundary conditions

Sediments attributed to the Cadell Marl and its equivalents crop out for only a few kilometres to the south of the type section, but are extensively developed in cliffs to the east as far as Long Cliff (13km. east of Waikerie); where examined in detail (Figs. 5, 6, 7), these sediments are found to overlie a harder band of calcarenite, occasionally (Fig. 6) extremely cemented. However, there is no evidence of erosion on these beds. Lithology and microfauna of the Cadell Marl is consistent throughout, and, despite the type section being the only locality where original shell material is preserved, suitable outcrop (e.g. section 2) displays moulds of the characteristic molluscan megafauna (for a comprehensive list, see Tate, 1885).

Lithology

The lithology at the type section is a grey to orange, friable, fine-grained, mottled marl, with blue-grey clayey interbeds. Here, beds of gastropods and bivalves (mainly _Turritella murrayana_) form a significant proportion of the rock. The mottling is caused by burrows of 1cm. to 5cm.-size organisms, and the chemical (?oxidizing) effects they had; this size burrow is dominant over the .1cm. to 1cm. burrows common in the hard grounds of the Mannum Formation. Clastic material comprises 40% to 60%, and is medium sand to clay with rare glauconite; this is generally the lithology at other occurrences (Lindsay, 1965; Lindsay and Bonnett, 1971; this paper, Fig. 6), but at section W1 near Waikerie (Fig. 7), a coarse-grained fraction of clastic material is present within a typical fine-grained matrix, intercalated with beds where the carbonate content decreases to 15%. This granule-size sub-rounded quartz is very severely restricted to this locality; studies within 3km have failed to record such anomalies (Lindsay, 1965, 1966; Lindsay and Bonnett, 1971).

Palaeontology

The microfauna of the Cadell Marl is diverse, dominated by a miliolid-arenaceous assemblage of foraminifera; calcareous forms, especially planktonics, are rare. Dominating the miliolid fauna are Quinqueloculina vulgaris, Triloculina collinsi, and frequent Pyrgo sarsi and Cyclogyra sp.; the arenaceous foraminifera display an interesting change - the lower portion of the sequence is dominated by the triserial Tritaxia sp., while higher in the section, and continuing into the upper member (Morgan Limestone), the majority is formed by biserial Dorothia spp.; although the reason for this microfaunal crossover is not known, it is widespread within the Marl (Figs. 5, 6, 7). Other agglutinated forms include Textularia sp., Clavulinoides sp., and Cylindroclavulina sp. This assemblage is not, at present, known to be biostratigraphically significant; this property is retained by the calcareous types, especially the planktonics.

An important microfossil so far not recorded from the Murray Basin, despite extensive examination, is the alveonolid Flosculinella bontangensis, which is thought to have penetrated from the west, and has been found as far east as the St. Vincent Basin (Lindsay, 1969), at a level stratigraphically correlable with the upper part of the Cadell Marl. This large foraminifera supposedly represents a climatic optimum of the same order as that shown in the lower member of Morgan Limestone by Lepidocyclina. Most of the other fauna examined from this unit is whole and fragmentary bryozoa, but sponge spicules, often present as complete tetraxons, are significant.

Biostratigraphy

The Cadell Marl lies wholly within the Praeorbulina glomerosa curva Zone of Ludbrook and Lindsay (1969), and later forms of the Orbulina bioseries are not known until the Bairnsdalian Pata Limestone, where Orbulina universa is found (Fig. 2). Thus, on superficial examination, this sequence (up to 35m. thick) is entirely Balcombian (Carter, 1964). D.J. Taylor (pers. comm.) notes that the P. glomerosa curva Zone in open-sea regimes (e.g. off-shore Bass Basin) is only a matter of a few metres thick; his interpretation is that planktonic foraminifera were restricted from entering the Murray Basin for a significant period; hence, pelagic foraminifera may not have isochronous datums between the Murray Basin and the rest of south-eastern Australia at this time, and correlated chronostratigraphy may be somewhat inaccurate here.

One calcareous foraminifera which appears reliable and biostratigraphically significant is the benthonic Astrononion obesum. This forms a thin zone about 2m. above the base of the Cadell Marl (Figs. 5, 6, 7), and occurs at a similar stratigraphic position in the Fyansford Clay, overlying the Batesford Limestone in Victoria (Carter, 1964), where it is considered to be of definite Balcombian age.

Environment

The Cadell Marl is a fine-grained carbonate deposit, with little evidence of bedding, representing a period of quiet sedimentation. This has been interpreted as representative of "deeper marine deposition, hence a further transgressive pulse" (Lindsay and Bonnett, 1971). However, apart from the obvious lithological evidence, no support has been found for this hypothesis. Deeper conditions generally lead to an increase in the proportion of planktonic foraminifera (Taylor, 1965, 1971), which is not seen; in fact, the domination of the microfauna by benthonic foraminifera infers a shallow environment. Despite the rarity of pelagics, the singular presence indicates normal salinity, as they are very susceptible to osmotic pressures. This suggestion of shallow deposition is supported by the frequency of Cyclogyra sp., which lives as an encrusting foraminifer on seagrass, the latter occupying the upper photic zone (top 20m.). The non-calcareous assemblage is indicative of a restricted area of deposition, and the presence of complete tetraxons and unabraided delicate fossils (e.g. bryozoa) implies quiet conditions.

It is postulated, therefore, that the depositional environment during Cadell Marl times was that of a restricted basin, and the restriction was caused by the emergence of the Padthaway Ridge at this time; the barrier prevented the influx of planktonic microfauna, including later evolutionary members of the Orbulina bioseries. The basin was shallow, and had good circulation; benthonic biogenic activity was intense; evaporation while encouraged by the warm conditions (indicated by Lepidocyclina and, in the St. Vincent Basin, Flosculinella), was hindered by a humid climate, as salinity remained normal. High influx of mainly fine-grained clastics, except at Waikerie where they were granule-sized, supports this climatic theory - widespread fine clastic carbonates were deposited in south-eastern Australia at this time (e.g. Balcombe Clay, Fyansford Clay, Munno Para Clay). The granules in the marl at section W1 may represent close proximity to the outflow of a river - the lateral restriction of this facies implies some sort of channel.

A model proposed is that of the present Gulf St. Vincent (Fig. 1), only larger and probably shallower. The Gulf today is a depositional area for mainly skeletal calcarenites, with lower terrigenous content (Cooper, 1960; C. Waters, pers. comm.) - an increase in precipitation would increase the clastic ratio and hence the similarity.

(c) cross-bedded member

Introduction

In a stratigraphic position above the Cadell Marl, but ? generally exclusive of it, is a facies of Morgan Limestone not previously described. It is a coarse quartzose skeletal calcirudite, with strong current-bedding, patchily developed over a wide area on this section of the river (section 5, and northwards; section 10; sections 13, 14); it is typically developed at Idyll Acres (section 10), where the erosional contact with the marly lower member of Morgan Limestone, and the conformable contact with the overlying, blocky, upper member can be observed (Plate 1,a). The lower contact dips 30° towards 240°, and is heavily stained with iron-rich minerals. Cross-bedding is diagnostic of the unit - here, cross-beds are inclined 15° in a northerly (000°) direction. The unit ranges from nothing to more than 13m. in thickness at the type section.

Lithology

Coarse sand to coarse granules of sub-rounded quartz, which comprise 50% of the rock, show poor graded bedding. Small and fragmentary bivalves, and the voids left by leaching of their shells, are responsible for a further 40%; these show the bedding by changes in concentration, and generally lie convex-up (Plate 1,c). Cross-beds shown by this lithological variation range in dip between 5^o and 30^o; current directions are both northerly (000^o) and southerly (185^o) (Plate 1,b).

Incomplete filling of voids formed beneath current-bedded bivalves provides further geopetal evidence.

Palaeontology

Remnant biogenic detritus consists of fragments of oysters, bryozoa, and echinoids, particularly *Monostychia*. R.J. Foster (pers. comm.) has described *Echinocyamus* in association with the large pan-tropical benthonic foraminifera *Marginopora vertebralis* from this unit at the type section. The lithology of this formation does not allow normal microfaunal examination; a single specimen (mould) of *Quinque loculina* sp. was noted on a polished surface.

Environment

The depositional environment of this unit is obviously extremely high energy; the angled erosional contact and its limited (although recurrent) lateral extent suggests a channel deposit. The total reversal of current directions in alternate beds implies a regular change, which can be attributed to tidal movement. The mature, but bimodal, sediments (quartz grains, and shell fragments) indicate a source such as coarse ~~ortho~~quartzarenite, or, more likely, little terrigenous input at all. Movement of coarse-grained, mature sediments is readily achieved by tidal channels on recent beach flats, such as those at Pt. Gawler, 30km. north of Adelaide. It is suggested that, at cross-bedded member times, the western edge of the Murray Basin represented the littoral or uppermost sub-littoral zone.

(d) upper member

Lateral extent

The upper member of Morgan Limestone, defined on Section C, Hd. Cadell, extends in outcrop south to section 26 (north of Blanchetown), and east to 7km. east of Waikerie; other areas of deposition have been scoured by Pliocene erosion, resulting in a slightly angular unconformity between the lower (Morgan) strata and the Pliocene deposits.

Lithology and palaeontology

At the type section, the upper member is "a hard yellow limestone with Cellepora" (Ludbrook, 1961); her brief description is elaborated by Jenkins (1966), who gives some description of the megafauna, which includes Turritella, Ostrea, large brachiopods, and calcareous algae, contained in the quartzose calcarenite matrix. Thin beds of stiff, brown clay are intercalated with softer calcarenite bands, but this gives way to hard, coarse calcarenite higher in the section (Figs. 5, 6, 7). The unit weathers to readily distinguishable flaggy bands, differentiating it from the underlying formations; its beds often show scour and fill structures, filled with coarse (1cm.) shell fragments.

The sparse microfauna is dominated by calcareous and arenaceous foraminifera; planktonics are not well preserved in this coarse sediment, but, from a clay band at the type section, rare specimens were obtained, the most significant of which was an advanced Praeorbulina aff. glomerosa glomerosa. This signifies the unit is contained within the Balcombian Stage as defined by Carter (1958).

Environment

The coarse nature of this member suggests a high energy environment, as do the scours common in the upper part of the unit. The megafossils described here, especially the calcareous algae Lithothamnion, imply shallow deposition, down to 30m. (Johnson, 1961), which is consistent with the sedimentological data. Jenkins (1972) believes that the upper member is representative of sub-tidal deposition, followed by emergence; observations made during this study support the depositional environment, but do not show any evidence for emergence.

Following deposition of the upper member of Morgan Limestone, a period of non-sedimentation occurred until a partial transgression during the Bairnsdalian (Middle Miocene) which resulted in the Pata Limestone.

IV. NORWEST BEND FORMATION

Previous work

The type section of the Norwest Bend Formation was described by Tate (1885) on Nor'west Bend Station, but examination of this stratotype, and other occurrences of the unit, have shown that the formation is complicated by facies changes. Ludbrook (1961) notes that they overlie the Loxton Sands, and occur only at the western margin of the basin.

Lithology and palaeontology

Although thick banks of oysters (*Ostrea sturtiana*) form a major part of the unit, lithologies vary from a fine, shelly, quartz sand at Tailem Bend to a coarse, angular gravel at Mannum Pumping Station; 5km. south of Mannum, a fossiliferous, highly immature, coarse, feldspathic litharenite overlies Morgan Limestone - these last two facies, attributable to the Norwest Bend Formation, are probably derived from the nearby Palmer Granites.

Some facies developed show rapid vertical changes - at a locality near section 78, the Norwest Bend Formation lies unconformably on an eroded hard ground of the Mannum Formation. Basally, it is a grey, gypseous marl, but one metre above the base, large (15cm.), old (many layered) oysters occur rarely within this matrix; over the next metre, the oysters become smaller (8-10cm.), and more frequent, and for the top .3m. they form a compact oyster bed. Above this, they rapidly become fragmented, the rock becoming a coarse, lithic, skeletal calcirudite, with small (1cm.) pieces of shell, and a coarse, ferruginous matrix. This facies becomes cross-bedded, and continues to the top of the section, about 10m. In this sequence, the environment changed progressively from quiet, deeper water conditions to a very shallow, high energy, sub-tidal situation.

At Qualco (section Q1), the Norwest Bend Formation begins as a coarse, clayey, quartz sand, followed by rapid colonization by oysters - the megafauna, however, had to attach to a firm substrate, and oysters tended to grow one on top of the other, resulting in a columnar growth pattern (Plate 2,a), surrounded by clayey sand.

Foraminifera from the Norwest Bend Formation are common, but non-diagnostic, apart from signifying a Pliocene age;

planktonics are absent. Ludbrook (1959) describes the molluscan fauna as being typically Pliocene.

Environment

The Norwest Bend Formation shows rapid and local changes in facies; bore data from areas surrounding the River Murray have shown it to be very limited in lateral distribution away from the present river course. On the evidence of the sediments and the palaeontology, especially Ostrea and the frequent Lithothamnion, the writer agrees with the interpretation of Ludbrook (1961) and others, who suggest that it represents an estuarine deposit.

CONCLUSIONS

Of the strata examined during the study, the Mannum Formation was deposited under the deepest and most temperate conditions. The medium energy environment was sufficient to winnow fine-grained material, but not enough to cause current-bedding; although the ratio of planktonic foraminifera is not high, sediments and other faunas imply an outer neritic environment of deposition for this unit. Marginal influence of a terrigenous sediment is shown by the localized Finniss Clay - its appearance represents an ~~endemic~~ local break in the general pattern of limestone deposition. Large foraminifera, including *Lepidocyclina*, contained in the soft, marly sediments and harder, more clastic interbeds of the lower member of Morgan Limestone suggest a warm, shallow, inner-shelf environment. These, too, were the depositional conditions for the Cadell Marl, except uplift of the Padthaway Ridge prevented open-sea conditions from reaching the Murray Basin; higher influx of terrigenous material was caused by an increase in precipitation, a climatic change producing contemporaneous marls throughout southeastern Australia. The general pattern of shallowing came to a climax in the cross-bedded member, which represents emergence, and littoral or uppermost sub-littoral tidal channel deposits. Slight subsidence led to the deposition of the upper member of Morgan Limestone under sub-littoral to inner neritic conditions, showing very shallow water structures near its upper boundary. A period of non-deposition of 10 million years (Middle Miocene to Upper Pliocene) ended with erosion of pre-existing rocks, and deposition of the variable Norwest Bend Formation in estuarine conditions. Post-Pliocene emergence resulted in the deposition of thin fluviatile and lacustrine limestones and clays (Firman, 1972).

Correlation of the Murray Basin Tertiary sequences with Bock and Glenie's (1965) cycles in the Otway Basin can be made following this study and a review of the literature involved. The nonmarine to paralic sequences of the Upper Cretaceous (Cycle 1) are missing. Cycle 2, the Palaeocene-Eocene nonmarine deposits with short-lived marine ingressions, is represented by the Renmark Bed and the Buccleuch Beds at their type section; the Buccleuch Beds at Waikerie, overlain by the marly lower part of the Ettrick Formation indicates Cycle 3, the major Eocene and Oligocene transgressions under marginal conditions. The upper Ettrick Formation, and the Miocene limestones indicate the presence of Cycle 4 equivalents, the shelf carbonates and marls; however, the Batesfordian - Balcombian transgression described by Bock and Glenie does not influence the Murray Basin - this period was one of shallowing, here. The major Port Campbell Limestone-producing Bairnsdalian transgression effects only a partial submergence ofthe Murray Basin, with the deposition of the Pata Limestone.

During the later part of the Miocene (post-Batesfordian), tectonic upwarping of the continental crust had a greater influence on the depositional environment of the Murray Basin than did the regional transgressions (possibly tectono-eustatic - McGowran, 1971) noted elsewhere in southeastern Australia.

The overlying Pliocene beds (Bookpurnong Beds, Loxton Sands, Norwest Bend Formation) are representative of a brief transgression; although the upper part of Cycle 4 is noted as a regression in the Otway Basin, the similar lithology of the Victorian Moorabool Viaduct Formation, and a correlable earlier break in sedimentation, suggest these units are indicative of the same general phase of geological evolution. There is also some justification for the Pliocene clastic-carbonate deposits in southeastern Australia being dissimilar enough to be assigned to a separate cycle.

The suggestion of restriction of planktonic foraminifera from entering the Murray Basin during the later Balcombian necessitates the careful examination of reliability of all planktonic zones in intracratonic basins. Although no further examples are known in this area, closer examination may bring some to light; isochroneity can be assumed in the case of Lepidocyclina, as it represented a short-lived climatic optimum.

The problem of the Batesfordian Stage is not one to be resolved easily - Praeorbulina glomerosa curva may exist in association with Lepidocyclina at Batesford, but it has not yet been found; alternatively, the upper part of the Batesford Limestone may represent a very short period of very rapid deposition (Foster, 1970); planktonic exclusion does not seem likely for this area. The fact that isolated pockets of Lepidocyclina may have continued to exist in the Murray Basin later than their extinction at Batesford does not concern us, as it is only the interval between the incoming of Lepidocyclina and P. glomerosa curva which is attributed to the Batesfordian (Carter, 1958).

Although this study is incomplete in many ways, it is hoped that the data and hypotheses presented in this thesis will aid workers who decide to make further examinations of the Tertiary strata of the Murray Basin.

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PLATE 1

(a) Type section, cross-bedded member of Morgan Limestone. Photograph shows lower (erosional) and upper (conformable) contacts to lower and upper members of Morgan Limestone. Section 10, Idyll Acres.

(b) Section 13, cross-bedded member of Morgan Limestone. Photograph shows clearly defined cross-bedding in cliff emphasised by weathering.

(c) Cross-bedded member of Morgan Limestone, cut section. Photograph shows cross-bedding, and geopetal structures caused by bivalves. The section was ground, and stained with weak Alyzarin Red S, and photographed under artificial white light, using a green filter. The photograph has been slightly retouched to emphasise bedding.

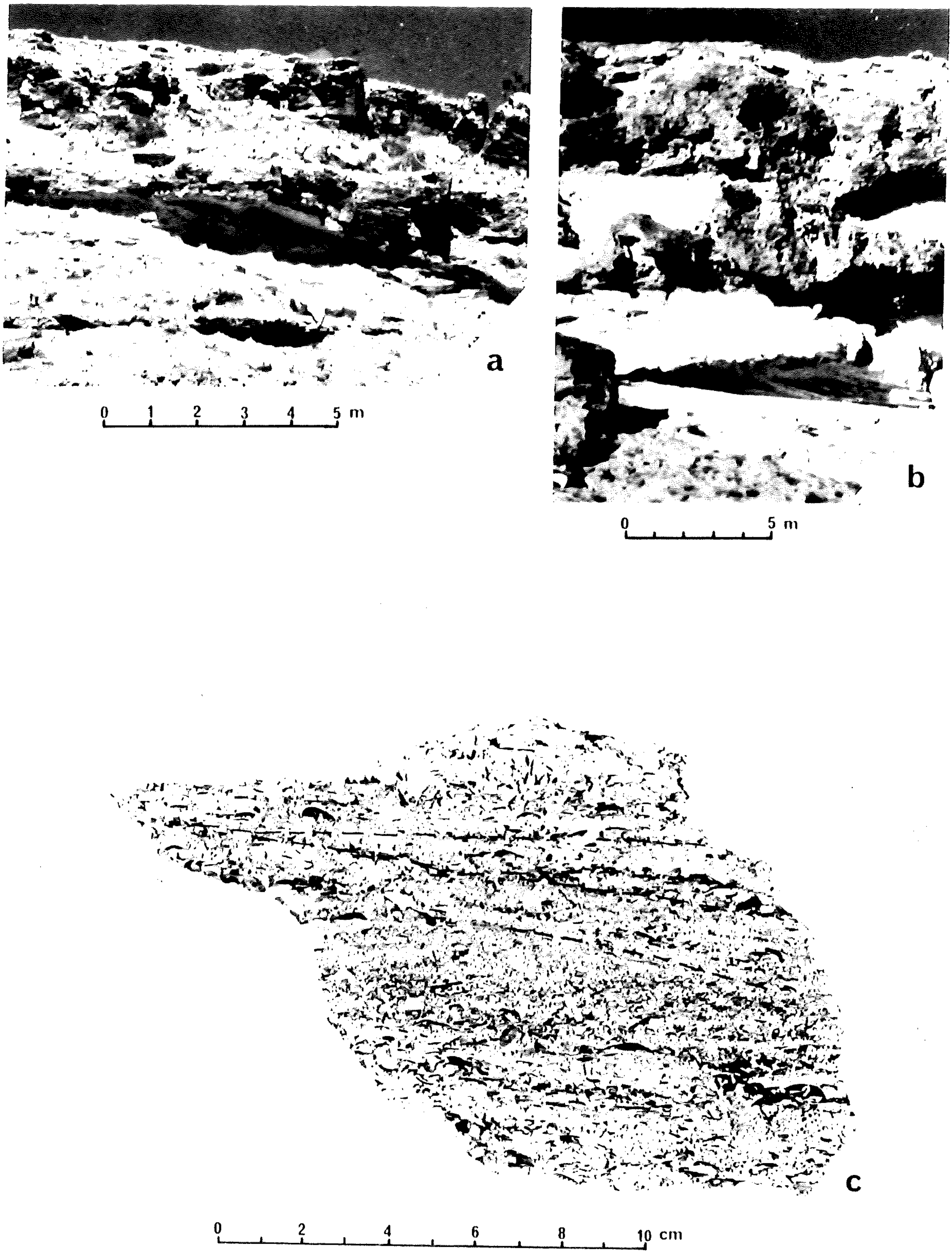


PLATE 1

PLATE 2

(a) Section Q1, Norwest Bend Formation. Photograph shows columnar development of oysters in clayey sand.

(b) Section 71, Mannum Formation. Photograph shows hard ground, with irregular and erosional upper surface.

(c) Section 71, Mannum Formation. Photograph shows cyclic nature of hard grounds.

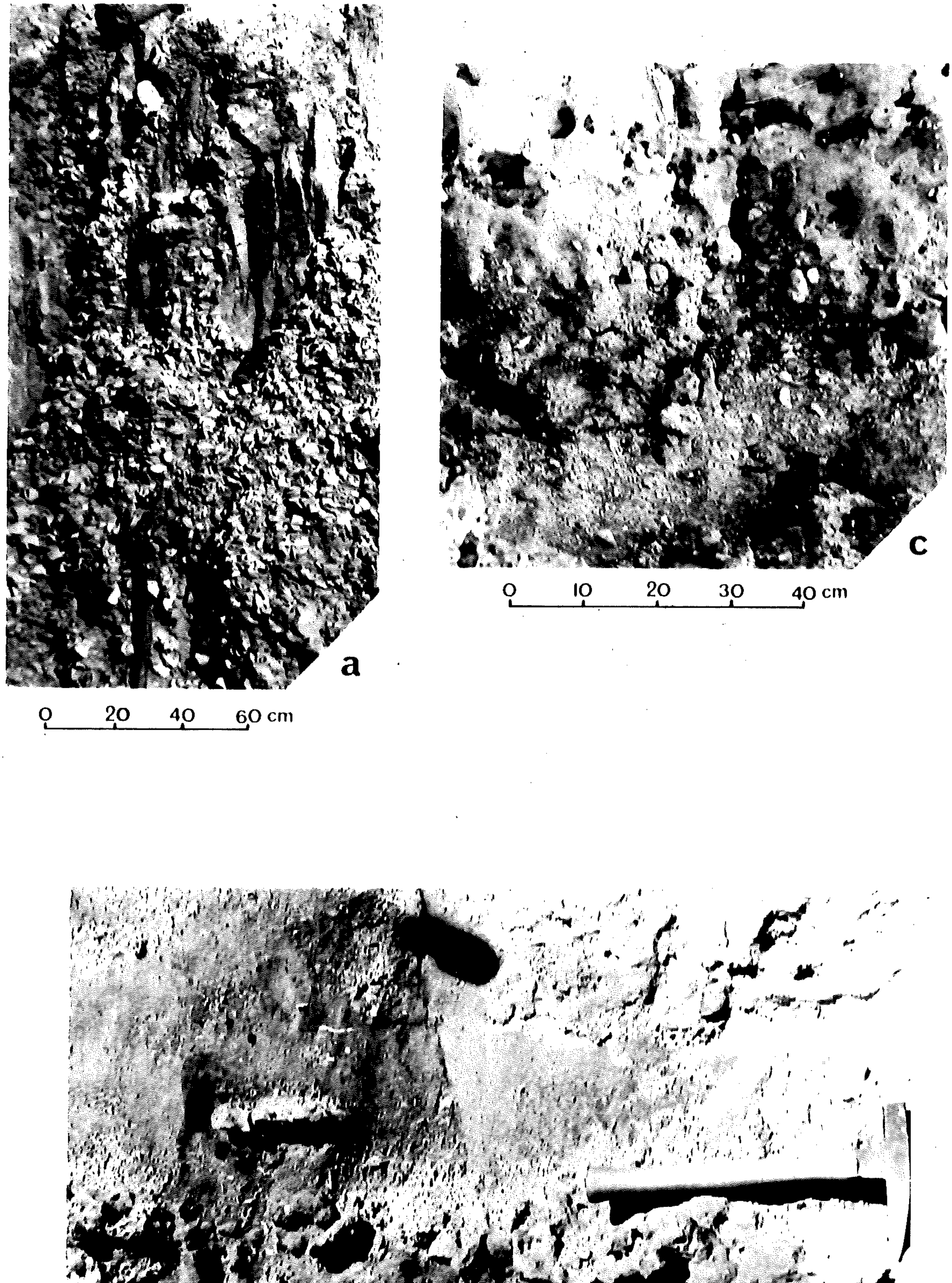


PLATE 2

APPENDIX I - MEASURED SECTIONS

Sections are in back pocket.

REFERENCE

TO MEASURED SECTIONS

LITHOLOGY

- Soft calcarenite
- Hard calcarenite
- Slightly marly calcarenite
- Fine-grained calc-arenite, or marl
- Coarse Quartzose calcarenite or calc-sandstone Fine
- Gypsified calcarenite
- Biocalcirudite
- 'Raggy limestone' (Tate, 1885)
- Hard ground
- Sandstone
- Cross-bedded sandstone
- Clay

MEGAFAUNA

- Bioturbation
- *Ditrupa*, & other worm tubes
- Foraminifera (large)
- *Lepidocyclina*
- Bryozoa
- Colonial bryozoa (*Cellepora*) *in situ*
- Brachiopods (small)
- Brachiopods (large)
- Irregular echinoids, mainly *Lovenia*
- Regular echinoids
- Solitary corals (*Placotrochus*)
- Gastropods, mainly *Turritella*
- *Chlamys*
- *Spondylus*
- Oysters, mainly *Ostrea*
- Bivalves, other than *Ostrea*, *Spondylus*, & *Chlamys*
- Calcareous algae
- Ostracodes (Bungunnia Limestone)

Line on left of column represents outcrop pattern in cliff or slopes.

Scale : 1 : 100 (1cm. = 1m.)

S.D. Giles, 1972

APPENDIX II - METHODS

APPENDIX II - METHODS

I. FIELD EXAMINATION

(a) Measured sections (Figs. 3, 4, 5, 6, 7, and Appendix I).

These sections were measured using a 2m. Jacob staff, and levelled sight attachment. Accuracy on cliff sections, where slopes averaged more than 45°, was greater than 95%. On lesser slopes, where sighted distances were in excess of 20m., accuracy ranged between 90% and 95%.

(b) Sketch sections (Fig. 3)

These were estimated in total height, using nearby measured sections, and contours on "South Australia 1:31680 Topographic Series, First Edition" (Lands Department) maps; accuracy of estimation of overall cliff height was 90%. Bed and boundary subdivisions within the cliff were estimated by means of ratios, both of total cliff, and with respect to a 2m. staff placed near the base of the cliff; accuracy of this section ranged down to 70%.

(c) Collection of samples

Samples were collected at accurately located intervals in sections, to examine later, for determination of biostratigraphic horizons and palaeoecology. The outer 10cm. of rock was cleared from the face to be collected, and, using a chisel, sediment from a hole generally about 10cm. x 10cm. x 10cm. was collected (approximately 500gm.), and labelled with the section number and height above river level. Softer bands were predominant in the collection series, as these sediments tended to disintegrate more readily, for micropalaeontological examination, and often contained a higher proportion of the biostratigraphically-important planktonic foraminifera. To prevent a facies bias, however, coarser and harder bands were also collected.

II. LABORATORY EXAMINATION

(a) Biostratigraphy (Figs. 4, 5, 6, 7)

Approximately 200gm. of rock was crushed in a pestle and mortar to about 1cm. size - grinding was avoided as this tended to break up the microfossils also. The crushed rock was placed in an enamel bowl with about 20gm. sodium carbonate, 1-2cc. detergent and 500cc. water. The mixture was boiled for about an hour - very clayey samples needed less time, but had to be washed two or more times; hard samples had to be recrushed while wet after the first boiling. After disintegration of the sample had been effected, it was washed into a BSS240 mesh seive, and the clay and silt removed by elution with high pressure water through the seive. When free of fine material, the residue was returned to the bowl with a minimum of water, and evaporated to dryness.

Examination of the sample followed by two methods. The first involved examination of all size fractions of the sample, under a binocular microscope, in turn (greater than 1.0mm.; 1.0mm. to 0.5 mm.; 0.5mm. to 0.2mm.; less than 0.2mm.), and removal of specimens of each type of foraminifera present to a grid slide. The second required selection of the fraction less than 0.5mm., which was treated with tetrabromoethane (S.G. 2.89) diluted with acetone to S.G. 2.0; the lighter foraminifera (especially the planktonics) floated to the top of the liquid and were poured off into a filter paper; draining, washing with acetone, and drying allowed examination of a sample containing a high proportion of planktonic foraminifera, which were also placed on the grid slide; examination of the microfossils on the slide enabled diagnosis of a biostratigraphic position for the sample. The species determined and other significant notes pertaining to the sample were recorded on cards which are on file in the Department.

(b) Palaeoecology (Figs. 5, 6, 7)

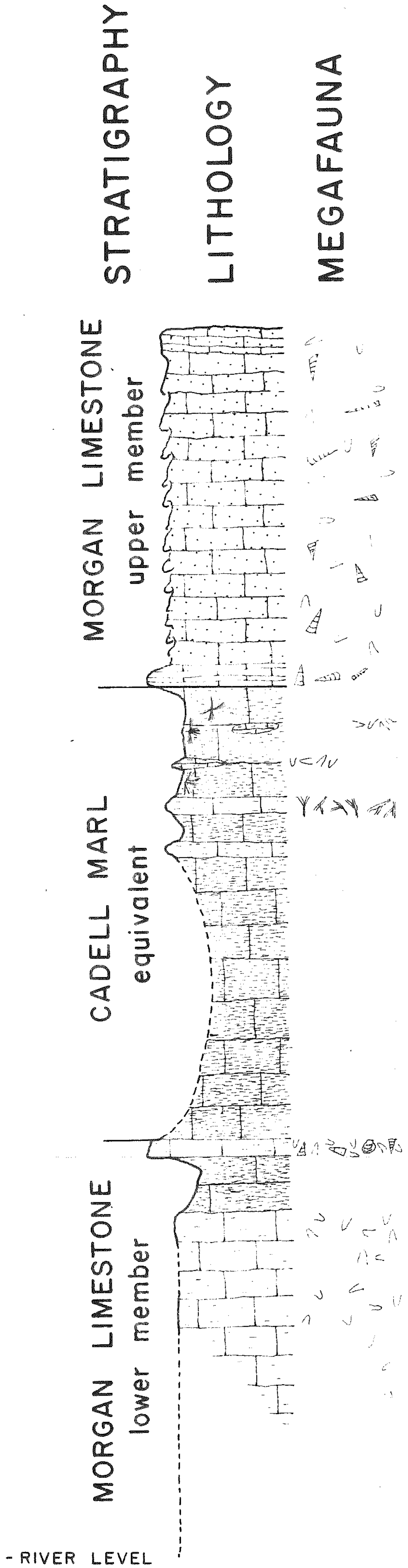
Samples were disintegrated in the same way as that used for biostratigraphy. The fraction between 1.0mm. and 0.5mm. was selected and spread thinly on a 9cm. by 5cm. strew plate; using a binocular microscope at 25x magnification, the foraminifera were classified into genera and larger groups, and the numbers encountered in two trays (approximately 2.5gm.) were recorded on cards which remain on file in the Department. The data was plotted stratigraphically as total count (number of tests per two trays), which gives some indication of foraminiferal abundance, and relative group abundance (group numbers converted to a percentage), which enables objective interpretation of environment. Errors are inherent in the first part of the method, as the number of tests counted depends to some extent on the ease of disintegration of the rest of the rock - more accurate would be the time-consuming method of weighing a piece of sediment, effecting complete breakdown, and counting every foraminifera; even this process would not enable calculation of the living biotic mass, which is a means of measuring metabolic activity. The second part leaves itself open to lesser inaccuracies, such as exclusion of the larger and smaller groups of foraminifera (e.g. the larger Operculina, and the smaller planktonics); the medium fraction covers most of the dominant groups in the sediments examined, as planktonics were a very minor constituent (less than 1%).

(c) Sedimentology (Figs. 5, 6. 7)

About 50gm. dry samples were weighed to within 0.1 gm., crushed to 1cm., and leached with strong hydrochloric acid

(1:1 concentrated commercial grade HCl and water) in Pyrex beakers; the insoluble acid residues were filtered under vacuum and washed with water, dried at 65^{o}C, and reweighed. Removal of the clay and silt fraction by washing through a BSS240 mesh seive, drying the residue and reweighing enabled calculation of the fine fraction. The coarse fraction was seived into seven fractions (greater than 1.0mm.; 1.0mm. to 0.75 mm.; 0.75mm. to 0.50mm.; 0.50mm. to 0.30mm.; 0.30mm. to 0.20mm.; 0.20mm. to 0.15mm.; less than 0.15mm.) which were weighed and examined under a binocular microscope (up to 100x magnification); the descriptions of these sediments enabled their classification into terrigenous (quartz, rock fragments, and clay chips which did not break down) and authigenic (glauconite, limonite). Reassessment of calculated percentages, through two steps, allowed recording and plotting of total carbonate - authigenic - terrigenous sediments and size distribution of terrigenous sediments. Index cards containing numerical evaluation of data pertaining to these examinations remain on file in the Department.

SECTION 6



DESCRIPTION

Calcrete

Burrowed, quartzose calcarenite, with ferruginous moulds of Turritella.

Very hard, flat bed.

Gypsified marl, with occasional harder bands, extensively bioturbated.
Hard, Cellepora Bed.
Marl.
Hard band.

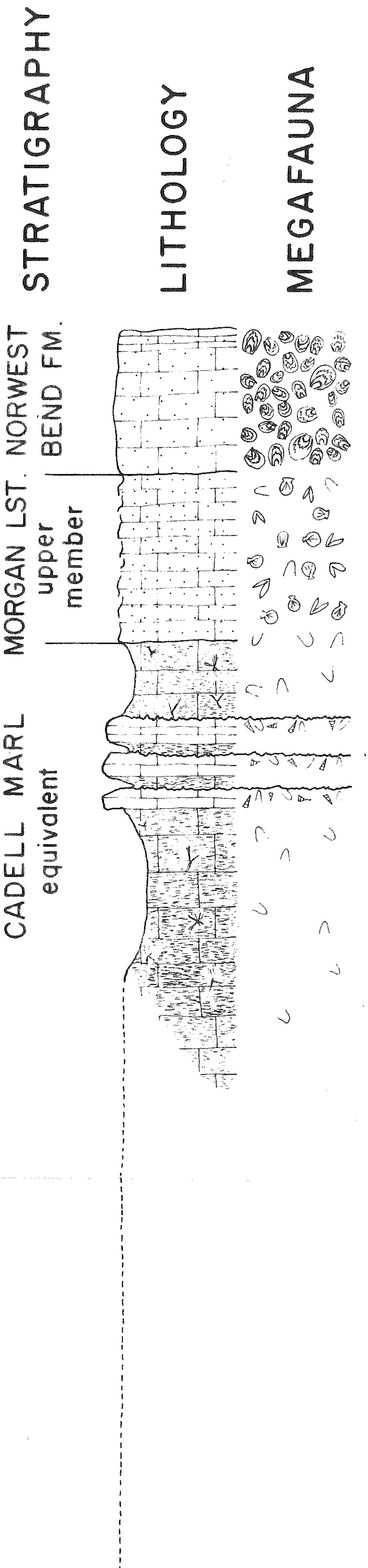
Marl, covered by fallen debris, including material from the same bed.

Extensively burrowed hard band, with Turritella, and rare Ostrea.
Soft grey marl, mottled with orange.
Highly fossiliferous calcarenite.

Soft, white, leached calcarenite.

S.D Giles
1972

SECTION II



DESCRIPTION

Oyster beds, calcreted at top.

Biocalcirudite, composed of bivalves, esp. *Chlamys*. Bioturbation into lower marl is infilled with coarse shell material.

Softish, gypseous marl.

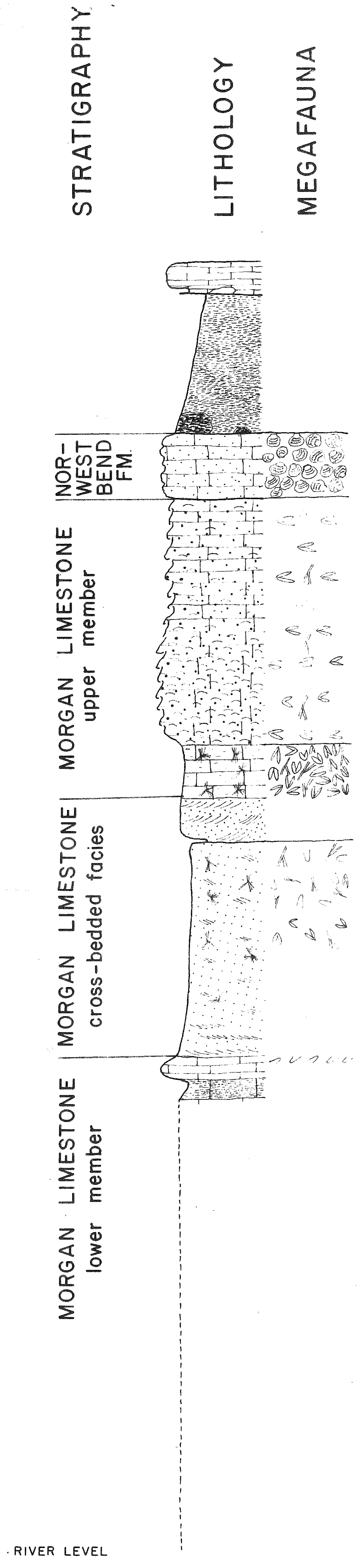
Thin, undercut hard-grounds.

Hard band, with *Turritella*.

Soft, grey, gypsified marl

No outcrop.

SECTION 13



DESCRIPTION

Calcrete.

Blanchetown Clay.

Oyster beds (cemented).

Ferruginous, quartzose, coarse bioclastic rock, mainly bivalves. Well-bedded.

As above, but more fossiliferous.

Leached, and regypsified, bivalvic coquina, shells rarely articulated.

Coarse, cross-bedded sandstone.

Buff to grey, finely bryozoal and ditrupal, gypsiferous, cross-bedded calc-sandstone.

Shells transported, and unrecognisable.

As above.

Asabove, more strongly cross-bedded.

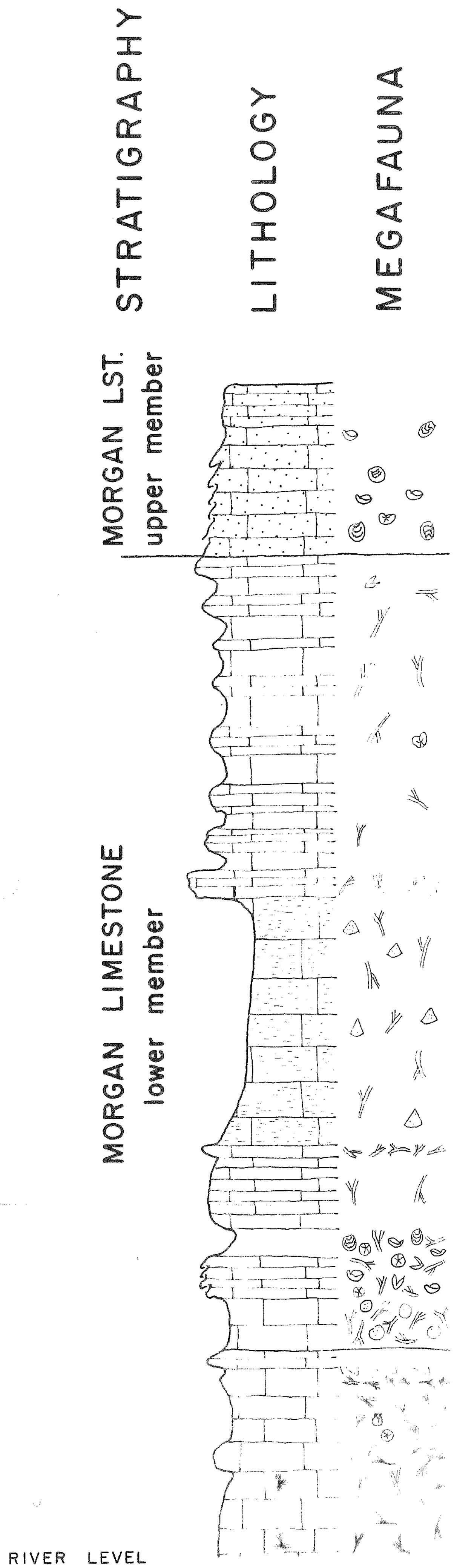
Hard, ditrupal band.

Soft, undercut, buff marl.

No outcrop.

S.D. Giles
1972

SECTION 14



DESCRIPTION

Calcrete.

Coarse, quartzose calcarenite, with large brachiopods and oysters.

Alternating harder and softer bands, mainly bryozoal, but with common echinoids, and large bryozoa in life position.

Strongly cemented, bryozoal band.

Very soft, fine-grained bryozoal calcarenite, with in situ fossils, esp. bryozoa.

Harder, bryozoal band.

Finely, bryozoal, harder band.

Undercut, with common brachiopods.

Fossiliferous hard band.

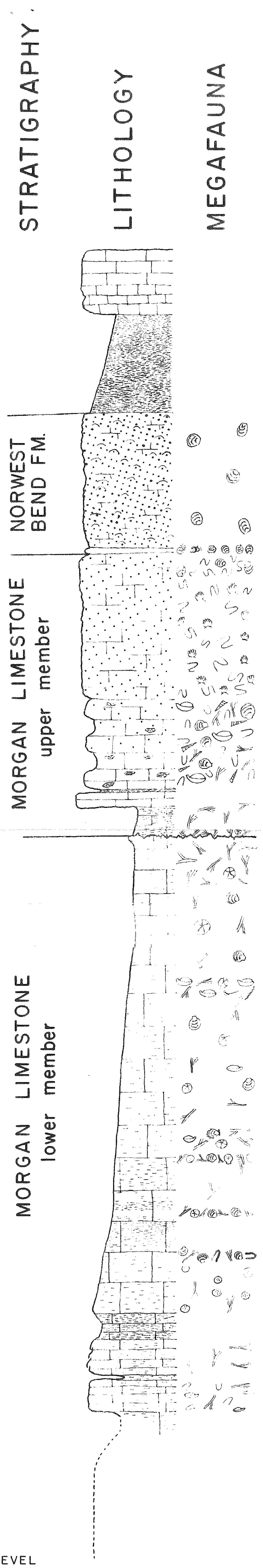
Soft, very bryozoal material, with large *Operculina*.

Very fossiliferous.

Soft, somewhat gypsified. Much *Cellopora*.

S.D. Giles
1972

SECTION 17



DESCRIPTION

Calcrete, with rubbly base.

Blanchetown Clay.

Fragmented oysters, forming large proportion of calc-sandstone, with burrows.

Oyster bed.
Quartzose, bioturbated calc-arenite.

Bioturbated, quartzose calcarenite, coarse quartz 30%, with calcareous algae, Lithothamnion.

Hard band, with clasts of unlithified clay; well-burrowed, Turritella, large brachiopods, oysters, and bryozoans.
Dark brown clay.
Hard band, continuous.
Hard, bryozoal marl.
Hard ground, very fossiliferous upper surface.

Very bryozoal, soft calc-arenite, with Cellepora.

As above, with large brachiopods.

As above, but less fossiliferous, with Ostrea, Cellepora, and echinoids.

Cellepora bed, with large Operculina, and Amphistegina.

Soft grey marly calcarenite.

Abundantly fossiliferous calc-arenite.
Fine bryozoal, foraminiferal calcarenite.

Hard, undercut band.

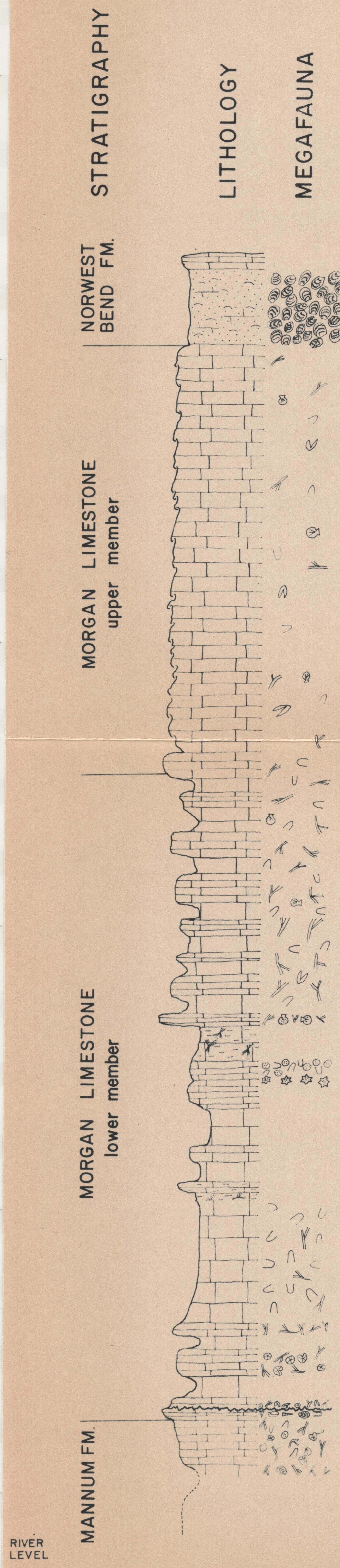
Flaggy, bryozoal calcarenite.

Hard, buff calcarenite.
Soft, undercut bed.

No outcrop.

S.D. Giles
1972

SECTION 18



DESCRIPTION

Calcrete.

Oyster bed.

Hard beds, alternating with softer units, over about one metre cycles - ditrupal, bryozoal, and quartzose.

As above.

Alternating slope-forming and hard beds, strongly ditrupal and bryozoal.

As above.

Hard band, with Cellepora, etc.

Soft, but gypsified band.

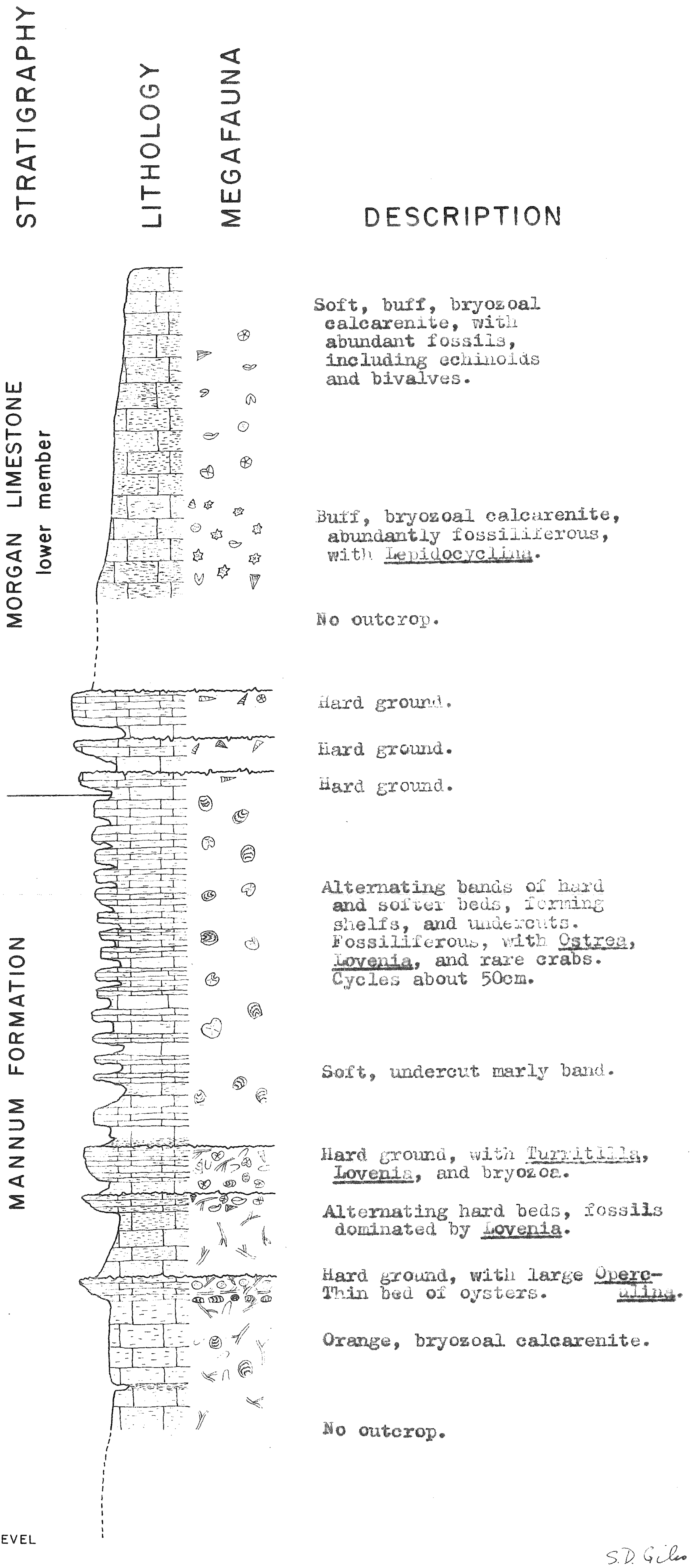
Hard foraminiferal calcarenite, with Lepidocyclina.

Alternating soft and hard beds, becoming harder downwards, and colour changing from buff to orange.

Soft, orange, ditrupal calcarenite.

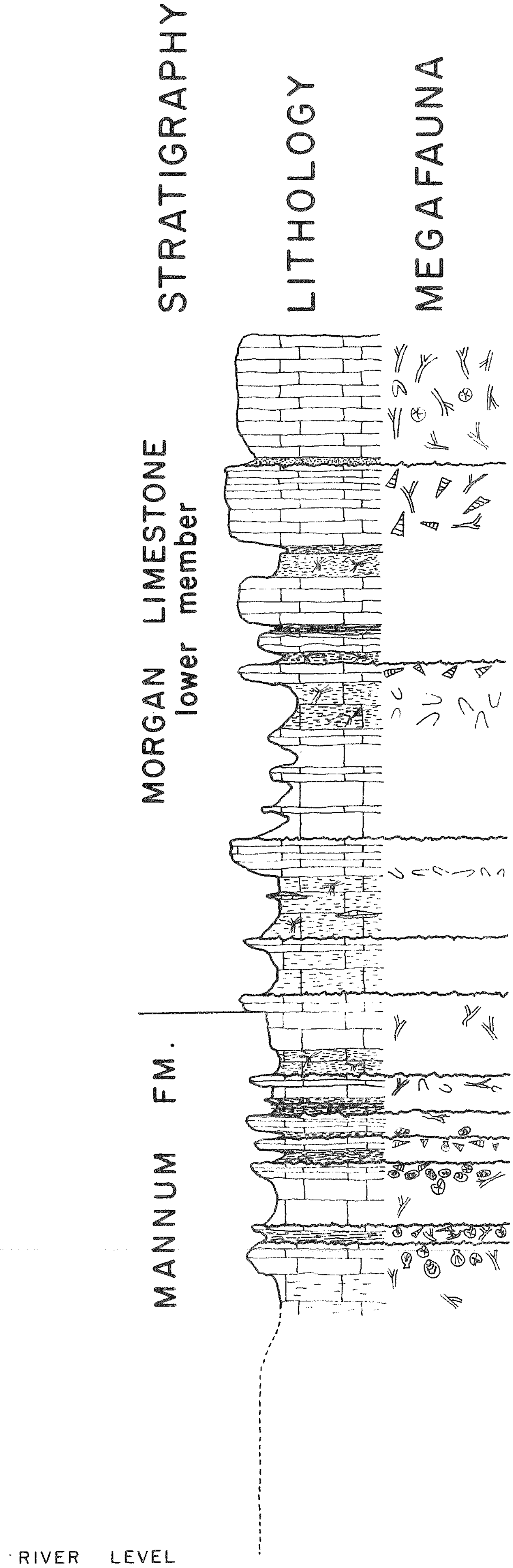
S.D. Giles
1972

SECTION 28



S.D. Giles
1972

SECTION 33



DESCRIPTION

Strongly bryozoal, very fossiliferous hard calcarenite.

Thin, wavy-bedded sandstone.

Thick hard ground, with *Turritella*.

Soft, clayey marl, gypseous lower.

Hard, porous, unfossiliferous calcarenite.

hard ground, with *Turritella*.

Soft, gypseous, bioturbated marl.

Alternating soft and hard (gypseous) bands, within marl.

Hard ground, with sub-horizontal burrows at base.

Gypsified soft band.

Alternate beds of soft, marly calc-arenite, and harder, gypsified marl and calcarenite.

Soft, grey, clayey marl.

Hard ground, completely barren.

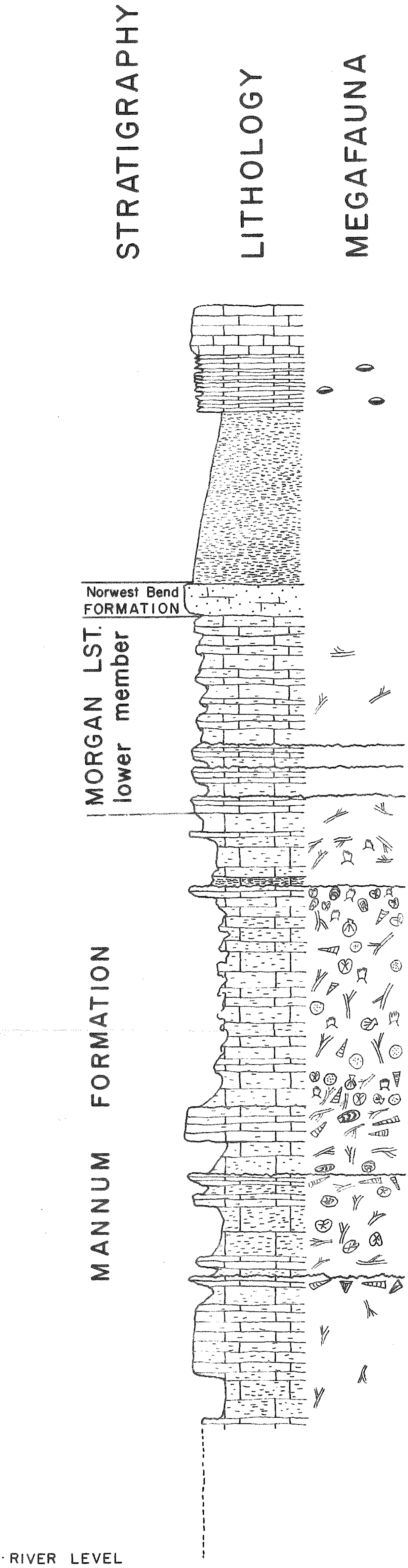
Soft, flaggy, bryozoal calcarenite.

Shaly, undercut bed, with *Lovenia*.

Hard ground, with *Lovenia* and *Ostrea*.

Soft, buff, bryozoal calcarenite.

SECTION 37



DESCRIPTION

Calcrete.

Bungunnia Limestone.

Blanchetown Clay.

Coarse quartzose calc-sandstone.

Bedded, yellow calcarenite.

Hard grounds, alternating with softer, buff calcarenite.

Flaggy, soft, bryozoal calcarenite, with Lithothamnion.

Abundantly fossiliferous, bryozoal, buff calcarenite, with Turritella, Chlamys, Lovenia, large Operculina, and Lithothamnion.

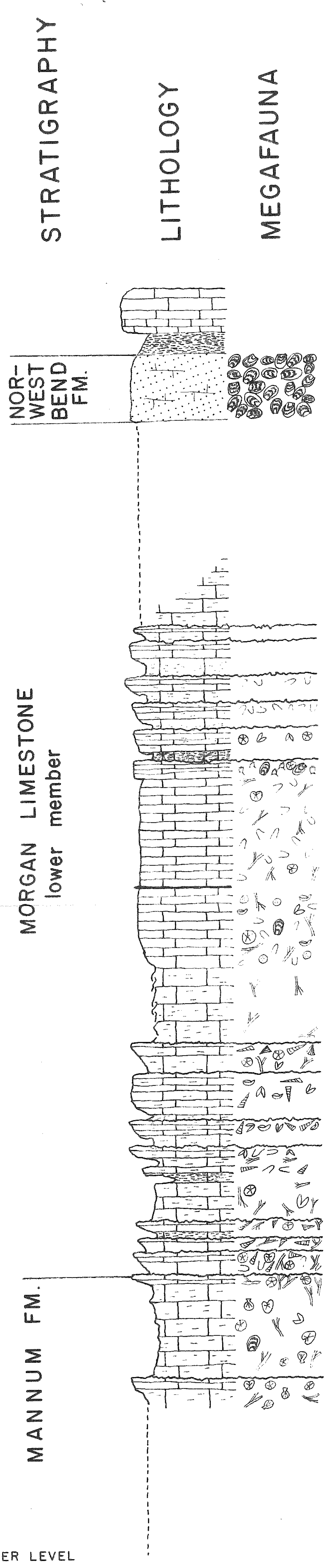
Hard, with Turritella.

Irregular hard ground.

Thick, hard, bryozoal bed of calcarenite.

S. D. Giles
1972

SECTION 41



DESCRIPTION

Calcrete.

Blanchetown Clay.

Abundant oysters, and calcareous sandstone (float).

No outcrop.

Hard bands, interbedded with softer calcarenite. Bivalves and echinoids; extensively burrowed.

Soft, unlithified, gypseous marl.

Very ditrupal, hard, bryozoal calcarenite, with rare *Lovenia*

Hardish, very ditrupal bryozoal and foraminiferal calcarenite.

Soft, buff, flaggy calcarenite.

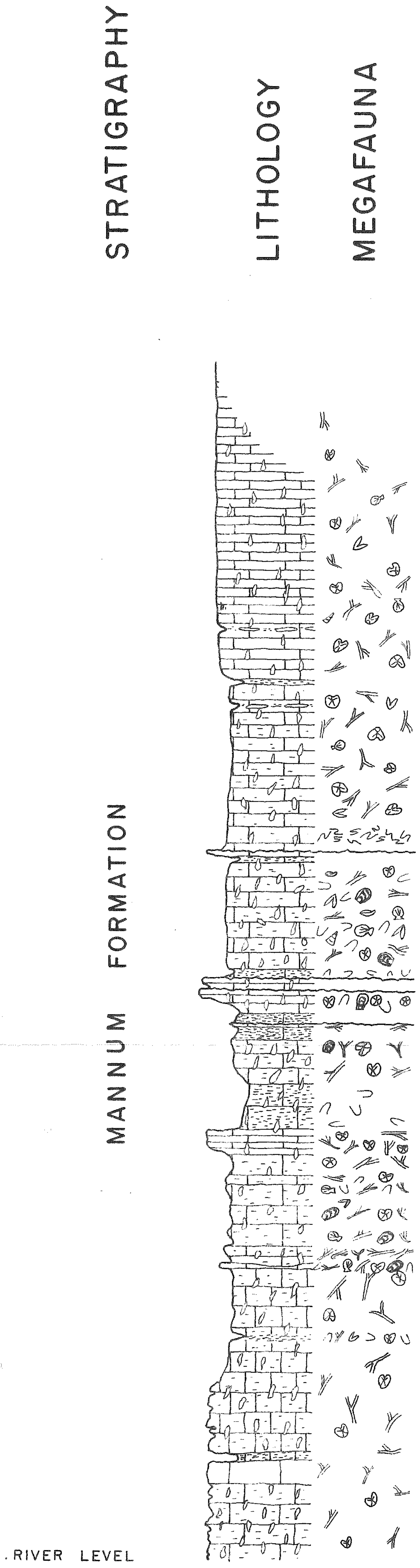
Alternating harder and softer bands, some hard bands becoming hard grounds. Common *Turritella*, brachiopods, rare bivalves and echinoids.

As above, but with rare 5–10cm softer bands, but no faunal change with lithology or hardness. Rare crab claws and *Ostrea*.

Soft, orange, bryozoal calcarenite, with *Cellepora* and *Chlamys*.

No outcrop.

SECTION 65



DESCRIPTION

No access.

'Raggy Limestone' (Tate, 1885) with _Lovenia_ in concentrations. Cemented, buff calcarenite.

Thin, continuous undercut bed.

Leached biocalcirudite, buff to khaki, with _Lovenia_, bivalves and gastropods.

Bioturbated, buff calcarenite.

Very fossiliferous bed, with abundant _Lovenia_.

Soft band with rare to absent megafauna.

Continuous hard band of buff, bryozoal calcarenite.

Soft, buff bryozoal and echinoidal calcarenite, with irregular boundaries.

S.D. Giles
1972

SECTION 71

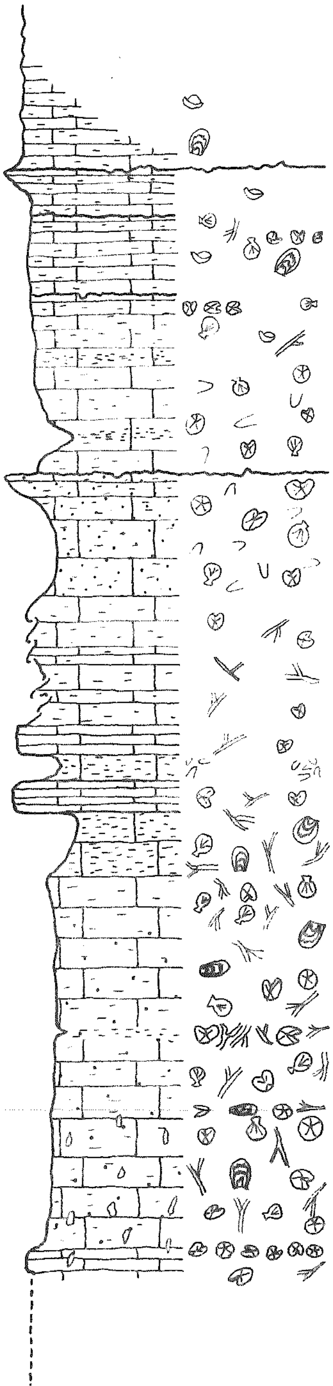
STRATIGRAPHY

LITHOLOGY

MEGAFAUNA

DESCRIPTION

MANNUM FORMATION



No access.

Softish, marly calcarenite, with Lovenia concentrated parallel to bedding.

Buff, marly calcarenite, with softer pockets.

Hard ground.
Soft, sandy material, with pockets of fossiliferous material.

Flaggy, hard and soft irregular bands, over 40-60cm. cycle.

Shelly calcarenite, with abundant Lovenia.

Lovenia and Cellepora very abundant.

Soft, buff-brown calcarenite, rarely quartzose.

No outcrop.

RIVER LEVEL

S.D. Giles
1972

SECTION 83

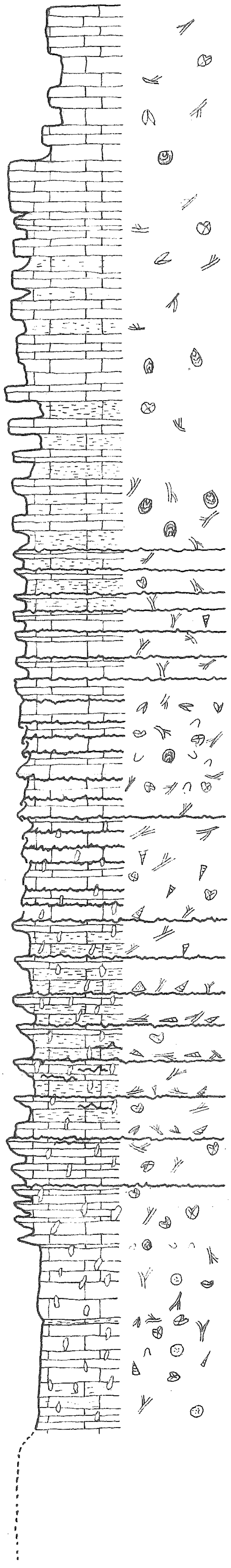
STRATIGRAPHY

LITHOLOGY

MEGAFAUNA

DESCRIPTION

MANNUM FORMATION



Slightly fossiliferous bryozoal calcarenite.

Very fossiliferous calcarenite, with common Ostrea.

Slightly fossiliferous bryozoal calcarenite, with frequent hard grounds.

Flaggy bryozoal calcarenite, formed by closeness of hard grounds. Megafauna not common.

Fauna concentrated in pockets, and hard grounds close, and often lensatic over short distance.

Alternating bands of softer and harder calcarenite; fauna not variable with cementation.

Pockety fossiliferous calcarenite.

Medium soft echinoidal bryozoal calcarenite. Operculina and Turritella rare.

No outcrop.

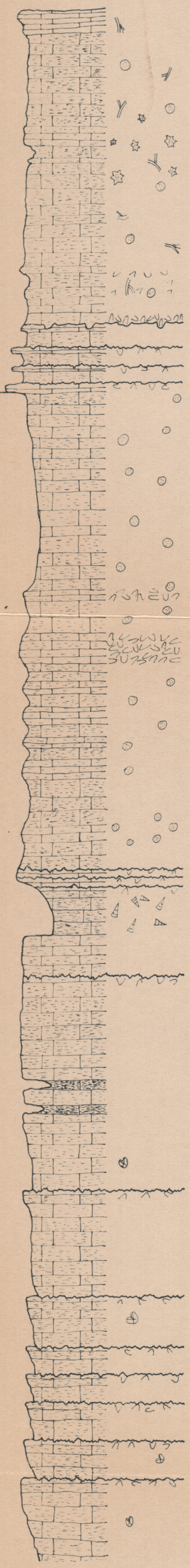
River Level

S.D. Giles
1972

SECTION J1 (between 59 and 60)

After Jenkins, 1972

STRATIGRAPHY | LITHOLOGY | MEGAFAUNA | DESCRIPTION



MORGAN LIMESTONE lower member

Calcrete.

Yellow-brown, fossiliferous calcarenite.

Erosion surface; Ditrupa common above.

Alternating brown, highly indurated calcarenite beds and soft, yellowish calcarenites.

MANNUM FORMATION

Friable, buff coloured, calcarenite.

Calcarenite bed with crowded remains of Ditrupa.

Bedded, buff-reddish-brown, cavernous weathering, fossiliferous calcarenite. Operculina common.

Hard grounds.

Friable, yellowish calcarenite with clusters of moulds of Turritella.

Pale grey marl beds.

Buff-reddish-brown, cavernous weathering, fossiliferous calcarenite. 'Raggy limestone' of Tate (1885).

Buff, cavernous weathering, shelly calcarenite with numerous hard grounds.

RIVER LEVEL

S.D. Giles
1972