# Depositional and Environmental Interpretation of the Meander River Carbonate Sheet, Avondale, Hants County, Nova Scotia

by

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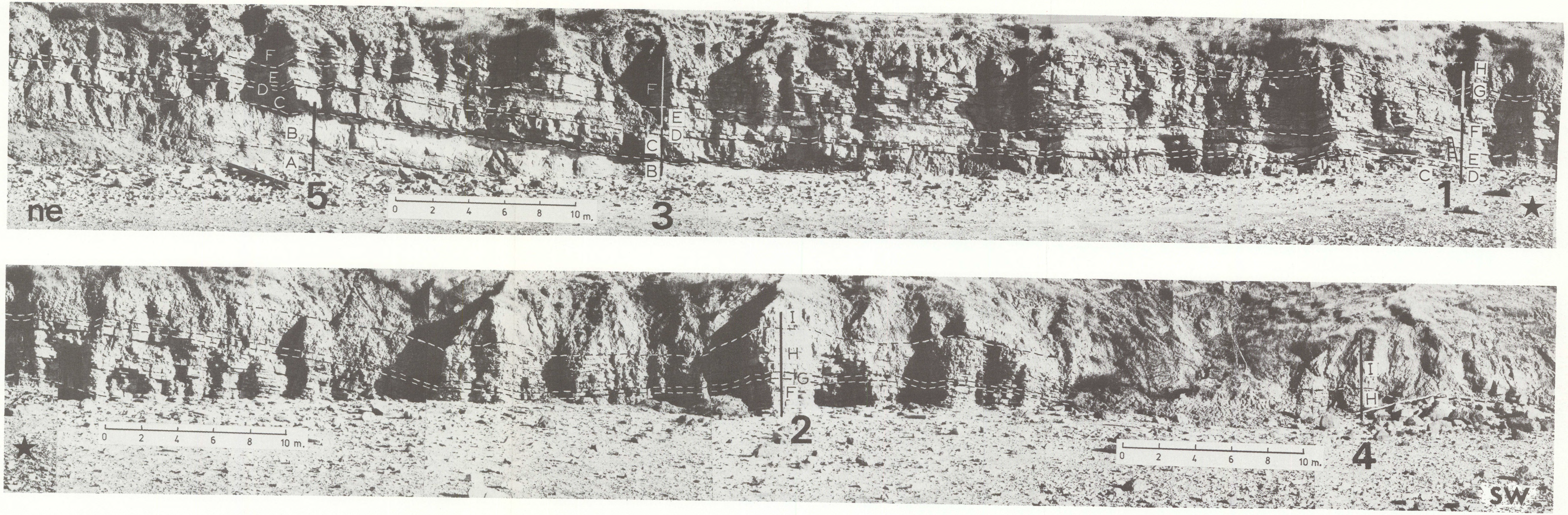


## PANORAMA OF THE MEANDER RIVER CARBONATE SHEET AT AVONDALE, HANTS CO., N.S.

A - red siltstone (Lz. I)
B - Green siltstone (Lz. I)
C - oosparite (Lz. III)
D - transition (C → E)
E - biosparite (Lz. V)
F - flat pelsparite (Lz. VI)
G - algal blister mat (Lz. VII)
H - undulating pelsparite (Lz. VIII)
I - calcrete soil (Lz. IX)
1-5 : stratigraphic sections

Lz. I, (etc.): Lithozones

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ABSTRACT

Detailed investigation of the Lower Carboniferous Meander River carbonate sheet (Limestone 2, Subzone D of the Windsor Group) exposed at Avondale, Hants County, Nova Scotia, reveals a pair of incomplete, asymmetrical, transgressive and regressive cycles.

Lithologies present are (1) ostracodal biosparite; (2) oosparite; (3) biosparite-calcisiltite; (4) flat-lying laminated pelsparite; (5) algal laminated pelsparite; (6) undulating laminated pelsparite; (7) pelsparite breccia and pseudobreccia; (8) sparitic mudstone and grainstone; (9) interbedded red and brown mudstones, siltstones, sandstones and conglomerates; and (1) laminated algal sparite.

Nine major zones were identified and they are (in ascending order): (1) marginal marine marsh; (2) oolitic shoals; (3) shoal lime sands; (4) subtidal to intertidal lagoon; (5) supratidal lagoonal fringe; (6) lagoonal intertidal flats; (7) calcrete soil; (8) alluvial fan mudflows and fluvial deposits and (9) a playa lake. The entire carbonate sequence is bounded above and below by massive red and green fluvial siltstones.

The initial transgression of the carbonate complex is represented by lithozones 1-3. A very rapid regression prevented the deposition of an inversion of lithozones 1-3 over the initial transgressive units, and resulted in the seaward progradation of the nearshore lagoonal facies 4. This is transitional to lithozone 5 which is slightly eroded

and overlain by pelsparites of lithozone 6, representing a second, subdued transgressive pulse. Lithozone 6 probably continues on as a shallowing upwards sequence, but is obscured due to the later formation of a calcrete soil (lithozone 7) on the subaerially exposed sediments of lithozone 6. This soil is preserved by the rapid deposition of fanglomerate sediments of lithozone 8. Lithozone 9 is located within the sediments of lithozone 8.

The probable mechanism which controlled the rise and/or fall of the ancient sea level was basinal faulting and warping. Only very slight changes in bottom slope and/or elevation were required since water depths probably only ranged from 0-4 metres in this area.

ACKNOWLEDGEMENTS

I would like to express my gratitude and deepest thanks to Dr. Paul Schenk of Dalhousie University who provided financial assistance, guidance and was always there when I needed him. Dr. Peter Giles of the Nova Scotia Department of Mines gave up much of his valuable time discussing with me the Windsor Group stratigraphy and kept me thinking. Special thanks goes to those people who assisted me in the arduous task of sample collecting and outcrop measuring: my brother Gary, my cousin Micheal Barter, Blair Parsons, Bernie Kelly and Kevin (Angus) MacKillop. To Stephen Harnish I am most grateful for his assistance in the field, stimulating discussions and invaluable criticisms and advice. I am indebted to Barry Hatt, presently with Amoco Canada Ltd. for suggesting to me the Avondale section as a thesis topic. Also, I acknowledge the helpful advice and assistance I have received from all my fellow students in the Geology Department at Dalhousie.

Also, I wish to express my gratitude to Mr. and Mrs. W. D. Siler, on whose property the carbonate sheet is exposed. Their hospitality and assistance (apple pie, coffee and ladders) made all the difference between enjoying and despising winter field work.

Finally, I would like to thank my parents, Mr. and Mrs. Alfred and Geraldine Brown for providing printing services for the photographic and drafting portions of my thesis and transportation to the study site respectively. Without their help, this thesis would not have been possible.

# CHAPTER 1: INTRODUCTION

# INTRODUCTION

The purpose of this study is to reconstruct the primary depositional environment of the Meander River carbonate sheet at Avondale, Hants County. Cliff exposures along the shoreline of the Avon River present the carbonate-siltstone unit as a flat, tabular, sheet-like mass containing separate, laterally continuous lithozones. Five, equally spaced stratigraphic sections were measured and described in order to provide information on the lateral, as well as vertical changes in each separate lithozone. The outcrop is approximately 170 metres long, averages 5 metres in height and the spacing between the stratigraphic sections is roughly 40 metres.

# CLASSIFICATION USED AND TERMINOLOGIES

Since the purpose of this study is to reconstruct the paleoenvironment of the Avondale carbonate sheet, Folk's (1962) classification (fig. 1a) was used to describe the bulk of the samples, along with the check list provided by Wilson (1975). This classification permits the interpretation of depositional environments by the types of clasts, matrix and cement present, and results in a descriptive lithology name. Embry and Klovan's (1971) amplification of the original Dunham (1962) classification (fig. 1b) was found to be the best for describing the samples from lithozone IX as this classification relies on matrix size and clast relationships within the matrix.

In order to clarify terms used in this work, especially for

| Allochthonous limestones original components not organically bound during deposition | | | | | | Autochthonous limestones original components organically bound during deposition | | |
|---|---|---|---|---|---|---|---|---|
| Less than 10% > 2 mm components | | | | Greater than 10% > 2 mm components | | By organisms which act as baffles | By organisms which encrust and bind | By organisms which build a rigid framework |
| Contains lime mud (< .03 mm) | | | No lime mud | | | | | |
| Mud supported | | Grain supported | | Matrix supported | > 2 mm component supported | | | |
| Less than 10% grains (> .03 mm < 2 mm) | Greater than 10% grains | | | | | | | |
| Mudstone | Wackestone | Packstone | Grainstone | Floatstone | Rudstone | Bafflestone | Bindstone | Framestone |

**Fig. 1a** Amplification of original Dunham (1962) classification of limestones according to depositional texture by Embry and Klovan (1971, Fig.2), courtesy of Canadian Society of Petroleum Geologists

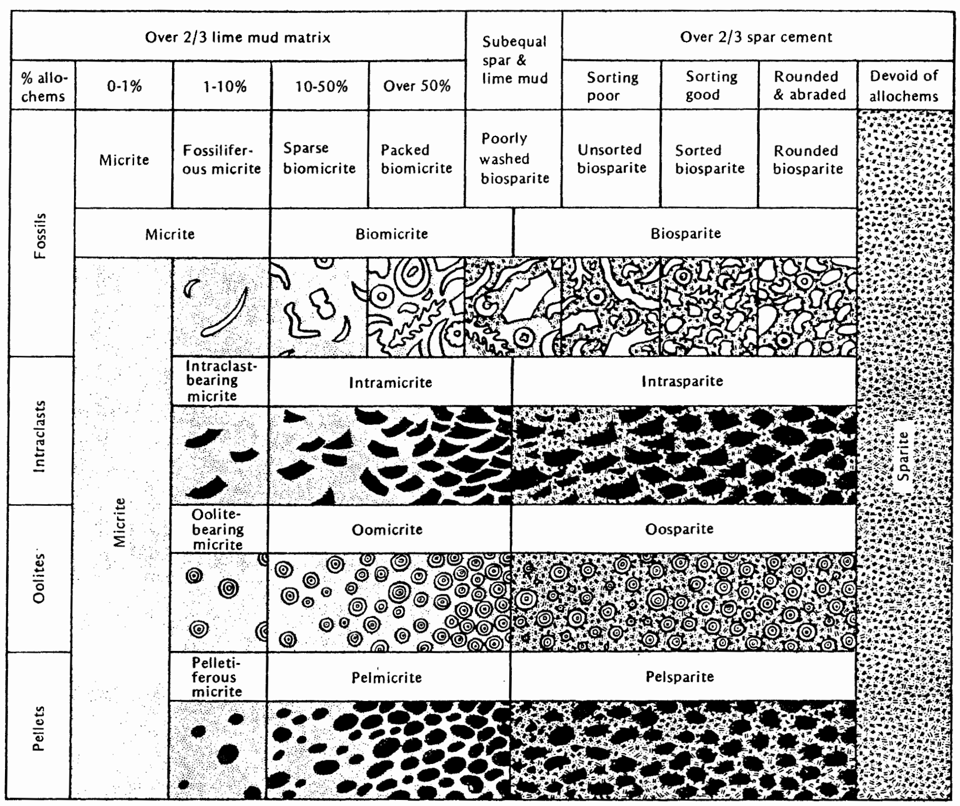



Figure **1b** A classification of limestone rock types **(after Folk, 1962)**

**EXAMPLES OF COMBINATIONS**

**Fossiliferous Intrasparite**
**Oolitic Pelmicrite**
**Pelletiferous Oosparite**
**Intraclastic Biomicrite**

# fig.1

those readers not acquainted with carbonate or sedimentological terminologies, the meanings of each term are given below. (Note: all terminologies are taken from American Geological Institute Glossary of Geology, 1972, unless otherwise stated).

Bed - A subdivision of a stratified sequence of rocks, lower in rank than a member or formation, internally composed of relatively homogenous material exhibiting some degree of lithologic unity, and separated from the rocks above and below by visually or physically more or less well-defined boundary planes; "the smallest rock - stratigraphic unit recognized in classification" American Commission on Stratigraphic Nomenclature (ACSN), 1961, article 8). A bed may be of any thickness, although it commonly varies from several centimeters to a metre.

Buckle cracks - Horizontal cracks resulting from the separation of sediment laminations along the horizontal plane by desiccation through water loss (Reeves, 1976).

Calcarenite - A limestone consisting (more than 50%) of detrital calcite particles of sand size; a consolidated calcareous sand. (Particle size range from 1/16 to 2 mm).

Calcisiltite - A limestone consisting predominantly of detrital calcite particles of silt size; a consolidated calcareous silt. (Particle size range from 1/256 to 1/16 mm).

Calcrete (Caliche) - [Soil] - A term applied broadly in the SW U.S. to an opaque reddish-brown to buff or white calcareous material of secondary accumulation (in place), commonly found in layers on, near, or within the surface of stoney soils of arid and semiarid regions, but also occurring as a subsoil deposit in subhumid climates. It is composed largely of crusts or succession of crusts of soluble calcium salts in additions to impurities such as gravel, sand, silt and clay. It may occur as a soft, thin, extremely porous and friable horizon within the soil, but more commonly it is a thick (several centimeters to a metre or more), impermeable, and strongly indurated layer near the surface or exposed by erosion; the cementing material is essentially calcium carbonate, but may contain magnesium carbonate, silica or gypsum.

Cross-stratification (Cross-bedding) - An interval arrangement of the layers in a stratified rock, characterized by minor beds, or laminae, inclined more or less regularly in straight sloping lines or concave forms at various angles (but less than the angle of repose) to the original depositional surface, or principal bedding plane, or to the dip or contact of the formation. It is produced by swift local changing currents of air or water.

Facies - The sum of all primary lithologic and paleontologic characteristics exhibited by a sedimentary rock and from which its origin and environment of formation may be inferred; the general aspect, nature or appearance of a sedimentary rock produced under or affected by similar conditions; a distinctive group of characteristics that differs from other groups within a stratigraphic unit.

Lithozone - A stratigraphic zone defined a lithology or several variations of that lithology.

Megaripple - A large sand wave or ripple-like feature having a wavelength greater than 1 metre or a ripple height greater than 10 cm, composed of sand and formed in very shallow water in a fluvial, tidal or marine environment. Wavelengths may reach 100 metres and ripple heights of about 1 metre.

Prism crack - A mud crack that develops in regular or irregular polygonal patterns on the surface and that breaks the sediment into prisms standing normal to bedding.

Stratum - A sedimentary bed or layer.

Fenestrae are described throughout this thesis and are defined by Tebbutt et al. (1965) as representing

> "A primary or penecontemporaneous gap in the rock framework, larger than grain-supported interstices. A fenestrae may be completely or partially filled by secondarily introduced sediment or cement. The distinguishing characteristic of fenestrae is that the spaces have no apparent support in the framework of the primary grains forming the sediment."

Logan (1974) describes their formation as:

> "...due mainly to interaction between algal-mat and algal-bound sediment, but dessication, oxidation and lithification are also important."

The reader is refered to Davies (1970), Logan (1974) and for a detailed analysis of fenestral types and their formation, relation to environment, etc. with respect to sediment at Shark Bay, Australia.

Fig. 2. Classification of Fenestral Fabrics

| TYPE | VOID SIZE(mm) | COARSE | MEDIUM | FINE |
|---|---|---|---|---|
| Laminoid | Av. Height | 5 | 1 - 5 | 1 |
| | Av. Length | 10 - 30 | 10 - 30 | 5 - 30 |
| Irregular (Pustular) | Av. Height | 5 | 1 - 5 | 1 |
| | Av. Length | 5 - 10 | 1 - 5 | 1 |
| Tubular | Av. Diameter | 5 | 1 - 5 | 1 |

After Logan (1974)

The classification of the different fenestral fabrics from Logan et al. (1974) is shown on the previous page.

## METHOD OF STUDY

Five stratigraphic sections along the cliff exposure, approximately 40 metres apart were measured, described and sampled. In each section, units with a distinct lithology were sampled at the top, center and bottom, whereas the larger units were sampled at fixed intervals. Samples collected were coded as follows: the first number representing the section number, and the second number the sample number. The location of each sample was noted on graphic logs. Alphabetical suffixes such as A, B, C etc. sometimes follow the sample number. They indicate samples which were taken after the initial sampling of the section was completed. The samples were numbered the same as the nearest sample above or beneath it, but have the added letter designation.

Each sample was then cleaned, cut into slabs perpendicular to layering, with a rock saw, handground with 120, 400 and 600 carborundum grits and polished with tin oxide on a mechanical lap. Thin sections were made only if it was sensed that they would reveal features or textures not observable in polished sections. Microfacies interpretation of each slab and/or thin section was performed with the use of a binocular reflecting microscope or a petrographic microscope (see Appendix I).

All samples were analyzed for their insoluble residue content by dissolving powdered samples in 1→1 HCl and water with subsequent drying and weighing of the residue (see Appendix III). X-ray defraction and microprobe analyses were carried out to identify unknown minerals in some samples.

Following the compilation of all obtainable data, paleoenvironment interpretation of the carbonate-siltstone body was undertaken.

## PHYSIOGRAPHIC SETTING

### Location and Access

The area studied is located on the eastern bank of the Avon River, between the mouths of the Kennettcook and St. Croix Rivers (fig. 3). The community of Avondale is approximately 20 kilometers by road east of the town of Windsor, the shiretown of Hants County. The area is easily accessible from Halifax, via the 101 expressway and good secondary roads. Access to the site is through the property of Mr. and Mrs. W. D. Siler. A farm track, capable of supporting normal vehicles leads to the Avon River shoreline and study site.

### Topography

The Avondale area is characterized by a series of small, undulating hills and shallow, swamp-filled depressions. Along the coast, these hills attain a height of no more than 35 m above sea level, while those about a kilometer or so inland attain a height of

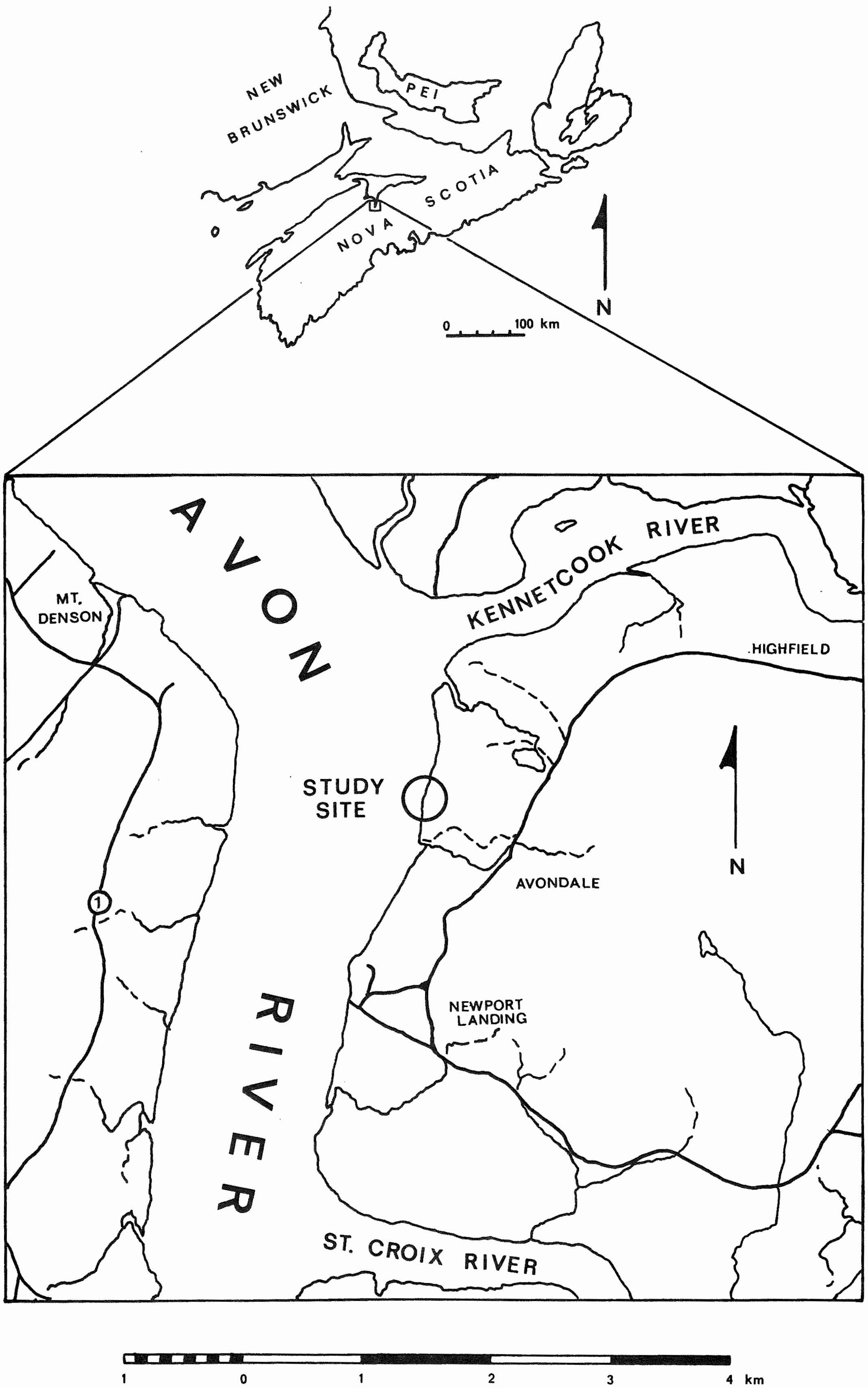

NEW
BRUNSWICK
PEI
NOVA
SCOTIA
N
0
100 km
AVON
RIVER
KENNETCOOK RIVER
MT.
DENSON
HIGHFIELD
STUDY
SITE
AVONDALE
NEWPORT
LANDING
ST. CROIX RIVER
1
1
0
1
2
3
4 km

fig.3

80 m. Small, slow moving streams drain the area. Funnel-shaped sinkholes are common in areas underlain by gypsum. Glacial till of Pleistocene age blankets most of the area, with thicknesses ranging from 0 to 15 m. West of Avondale, rugged highlands up to 200 m elevation dominate the surrounding area. These hills are underlain by resistant Devonian granites and in some areas, Ordovician metasediments. To the north, the terrain is similar to that surrounding Avondale, but is higher and reaches up to 160 m above sea level.

Three large, tidally dominated rivers drain the area: the Avon, Kennettcook and St. Croix Rivers respectively. The latter two drain into the Avon River and hence into Minas Basin about 9 km northwest of Avondale. The banks of these rivers, especially the Avon, have extensive mud flats formed by the very high tidal range of the Minas Basin. The average tidal range at Avondale is approximately 15 m. This, combined with the effects on the water mass of a causeway across the Avon River at Windsor have produced or enlarged extensive sea cliffs, averaging 15 m in height which residents in the study area claim erode about 1 metre per year. Over a four month period, the author observed the destruction of several stratigraphic sections, two of which are presently unrecognizable.

## PREVIOUS WORK

Bell (1929), who first divided the Windsor group into six major subzones, considered the carbonate sheet studied in this work as being equivalent to the lower D subzone Avon Limestone. The Avon Limestone crops out along the same shoreline about one kilometre from the northern end of the Meander River Limestone section, and is similar with respect to thickness and lithologic development. The Meander River Limestone is extensively faulted and blocks of this limestone occur in close proximity to the Avon Limestone.

The Meander River Limestone was first recognized as a separate carbonate body by Crowell (1967). He considered that Bell's unit (n), section 9 (see Bell; 1929, p. 53) was the basal oolite member of the Meander River carbonate, and that his concealed interval, unit (o) contained the remaining overlying carbonate facies. Crowell subdivided the 'D' limestones and distinguished the Meander River $D_2$ limestone from the Avon $D_1$ limestone by fossil content, bed to bed relationships within each lithozone and the prominent breccia which caps the former. He interpreted the Meander River Limestone as a transgressive unit with deep-water carbonates overlying shallower ones. The Avondale carbonate sheet was made the reference section, with the type section located on the Meander River, 15 km southeast of Avondale.

Waring (1967) shared Crowell's conclusions in his slightly more detailed description of the Upper Windsor limestones in the Windsor Area. Moore (1967) also believed the Meander River Limestone was indicative of a transgressive unit. To this date, the author is unaware of any other study which may have been carried out on the carbonate sheet at Avondale.

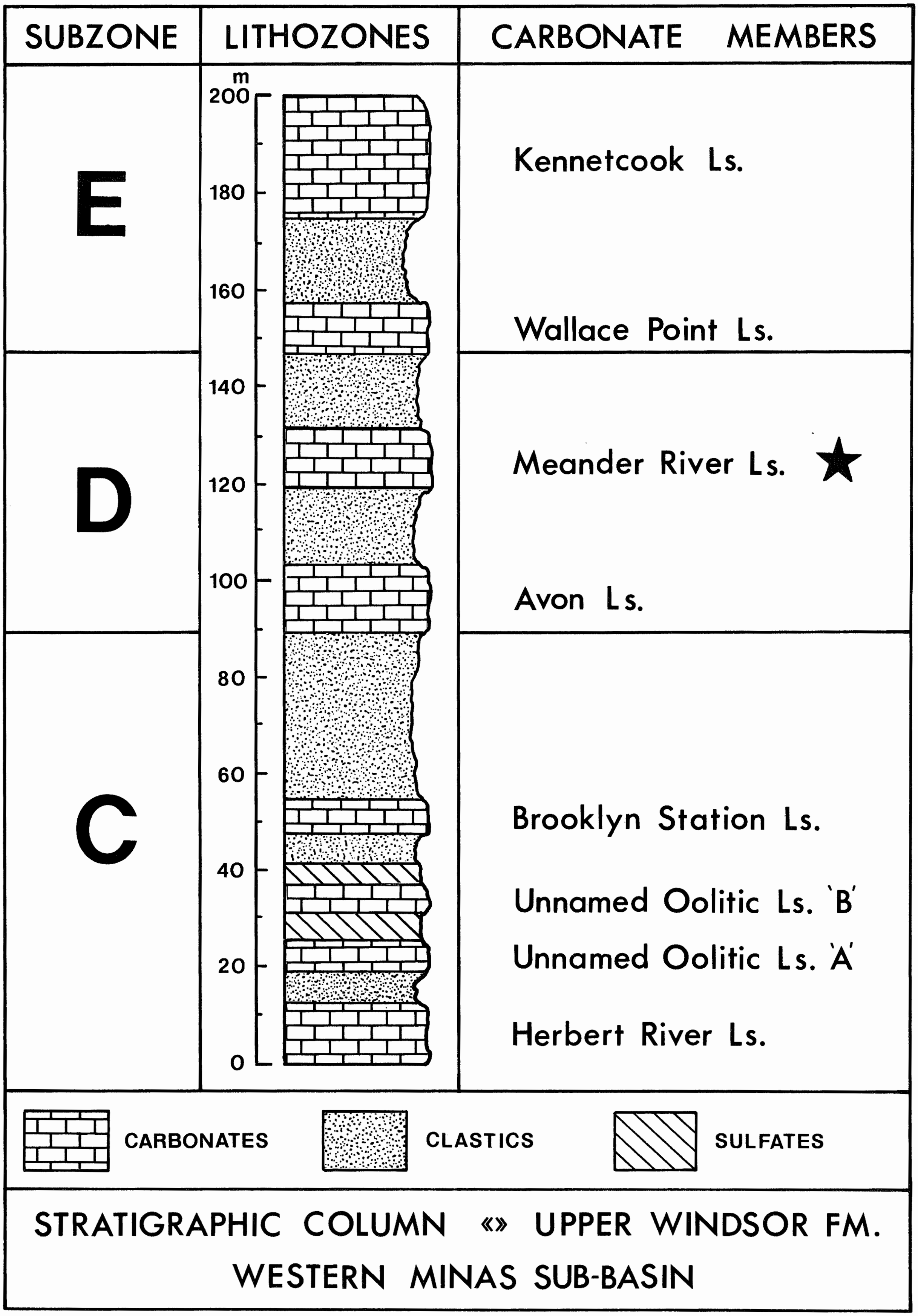
## GEOLOGIC SETTING

At the time of deposition of the Mid-Carboniferous Windsor Group, Nova Scotia was located approximately 10 degrees south latitude of the Carboniferous paleoequator (Irving, 1964). A complex rift-valley system formed during the late Devonian Acadian Orogeny throughout the Atlantic Provinces (Bell 1958; Howie and Cummings 1963). This rift-valley system is known as the Fundy Basin, and within it developed northeast to east trending valleys bounded by horst blocks of basement material. These blocks served as a source for the resulting thick accumulation of red and grey sandstones, shale and conglomerates of the upper Devonian-lower Carboniferous Horton Group. Bell (1929) identified this thick sequence (1 km maximum thickness) as representative of fluvial flood plains with alluvial fans along the flanks of the horst blocks. Minor uplifting of the Horton Group initiated some erosion of the sediments producing local unconformities.

Repeated marine incursions of the graben basins resulted in the formation of the Windsor Group which in some areas lies disconformably upon sediments of the Horton Group. It is about 1 kilometer thick and is characterized by cyclic shallow marine carbonates, evaporites and red siltstones (fig. 2). At least twelve episodes of marine transgressions were recognized in outcrop by Bell (1929) and perhaps 24 by Giles (pers. comm.) and are marked by thin carbonate blankets. The presence of evaporites was considered indicative of a warm, arid climate by Bell (1929).

The lower Windsor subzones, A and B (see Bell 1929, 1958) are characterized by their great areal extent and thickness (especially zubzone B), large volume of evaporites and cyclic sedimentation. The upper Windsor subzones C, D and E represent considerably reduced cyclic marine encroachments covering smaller areas and producing thin carbonate-siltstone (minor evaporite) sheets (Crowell, 1967), (fig. 4).

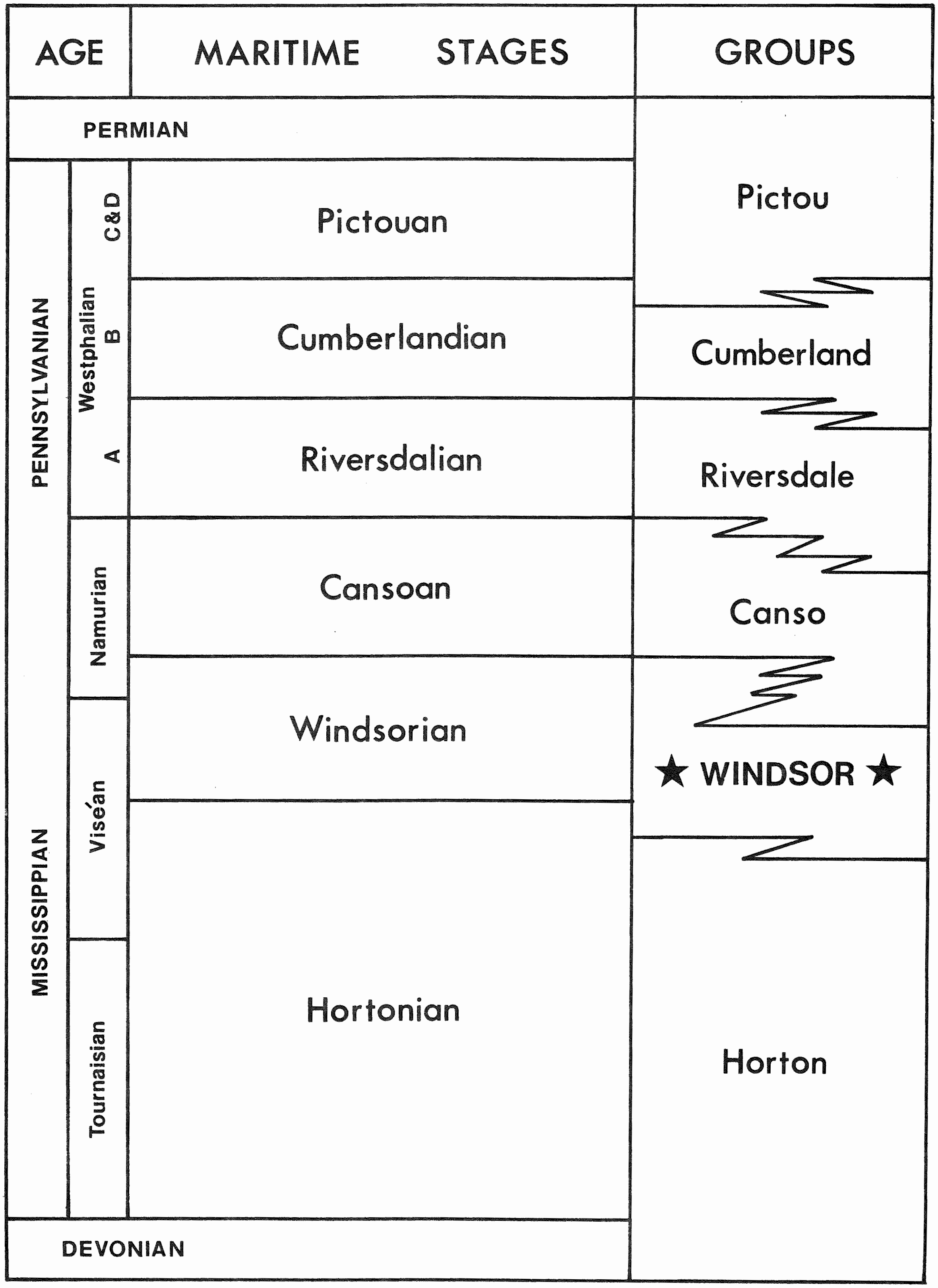
Mamet (1970) assigned a late Viseon-early Namurian (late Meramecian-early Chesterian) age to the Windsor Group on the basis of eleven, short ranging microfauna taxa (fig. 5). This age generally agreed with Bell's (1929) determination of a middle to late Visean age based on macrofauna. There exists, however, a slight age discrepancy between the microfaunal and macrofaunal determinations which so far has eluded explanation. From his study, Mamet concluded that the Windsor Group was deposited over a relatively short time interval, approximately four million years.




( modified from Moore and Ryan, 1976; pg. 5, fig. 1 )

fig.4

# STRATIGRAPHIC CLASSIFICATION OF THE CARBONIFEROUS IN NOVA SCOTIA




(modified from Schenk, 1975; and Howe and Barss, 1975)

fig.5

# CHAPTER 2: LITHOZONE DESCRIPTIONS

# LITHOZONES

The carbonate/clastic sheet at Avondale can be subdivided into twelve distinct lithozones. Each lithozone is characterized by its own unique lithology(s), thickness and colour. The lithozones are described in ascending order. Average thicknesses are given as most lithozones vary in thickness only between 5 and 10 cm about their average, the thinnest lithozone varying by less than 2 cm.

## LITHOZONE I

Thickness: $>10$ m

The medium grained siltstone varies in colour from red to green, being either grey or orange towards the top of the unit. Its thickness is at least 10 metres. The original colour of the entire siltstone unit appears to have been red, as numerous, irregular red mottles occur in the green siltstone. The reason for this colour change is explained in Chapter 3. The lithozone is quite massive and sedimentary structures such as cross-stratification and ripples are poorly displayed. Separating the red and green siltstones is a 50 cm thick bed of soft, black shale and green siltstone, with one continuous shale bed approximately 10 cm in thickness. The shale displays fine laminations interbedded with green siltstone and occasionally green to tan coloured medium grained sand. The sand forms parallel ridges of small (1 cm wavelength) straight-crested current ripples (fig. 6). The ripples are orientated approximately perpendicular to the outcrop face. The upper contact of the siltstone is irregular and undulating, with a thickness variation of 10 cm between peaks and troughs of apparent megaripples. Small, 3-5 mm thick veinlets of selenite gypsum follow the contact within the siltstone. Some selenite veinlets are observed filling fractures in the siltstone to a depth of 50 cm below the contact.

## LITHOZONE II

Thickness: 0.15 m

This lithozone consists of a light to medium brown near-homogenous ostracodal biosparite (samples 3-1, 3-2) which has a wide range thickness, from 10-20 cm (averaging 15 cm). The lower portion of this unit (sample 3-1, fig. 7) is not continuous, but occurs as isolated lenses in the troughs of the undulating upper surface of the siltstone. This portion contains numerous ostracods and a pustular (irregular) fenestral fabric. The upper portion of the lithozone (sample 3-2, fig. 8) is composed of abundant ostracods, ooids and rare shell fragments. Angular oolitic intraclasts are common (fig. 7). Fine black laminations are present within the bottom few millimeters of the lithozone, and also as a shaley film separating the carbonate from the siltstone . A few of these laminations are bounded by laminoid fenestrae indicating that they are possibly remnant blue-green algal mats. The remaining laminations do not have the associated laminoid fenestrae and are considered as shale laminations. Pellets (0.03-0.04 mm) are also common in the upper portion. Laminations within the lower portion of the lithozone are distinct, from 2-10 mm in thickness (fig. 8).

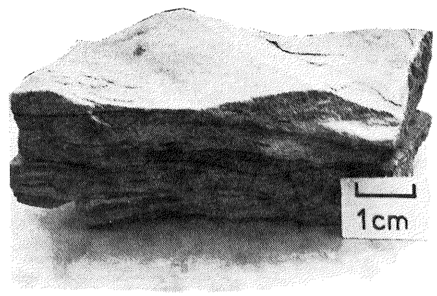



Fig. 6 (Left) Straight-crested current ripples in a sand matrix. Note the fine black shale laminations interbedded within the sand.

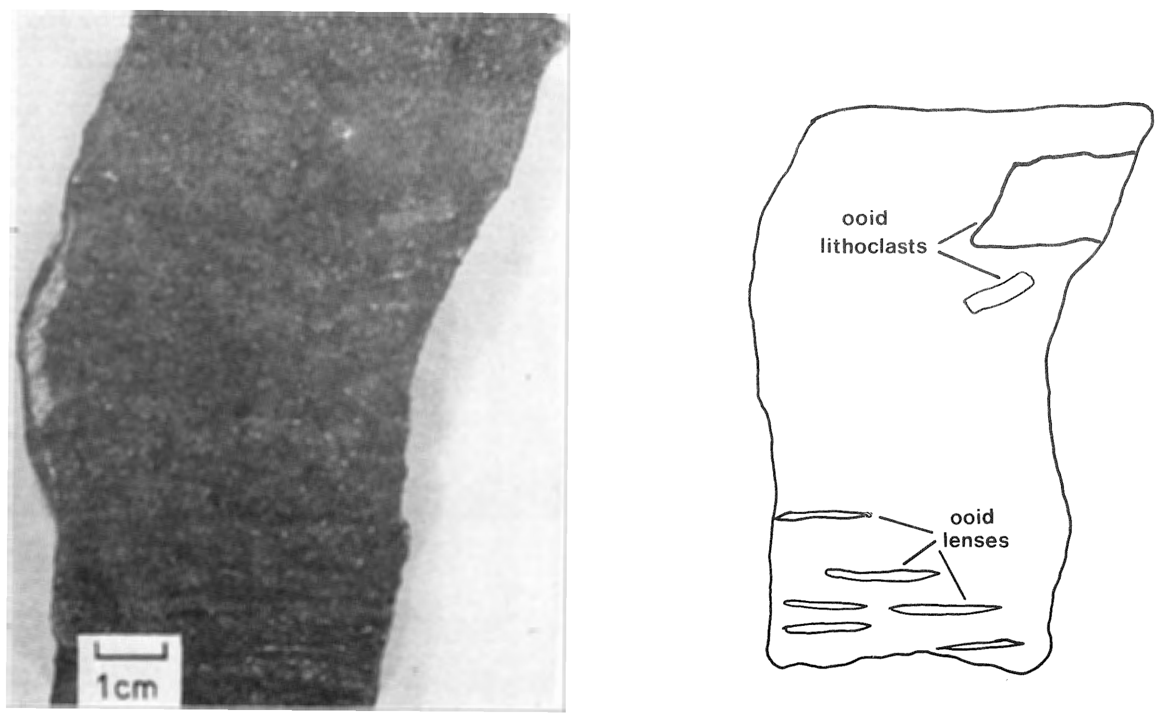



Fig. 7. (Below left) Ostracodal-biosparite (Lithozone II). Note the vaguely laminated ooids and the large ooid lithoclast.

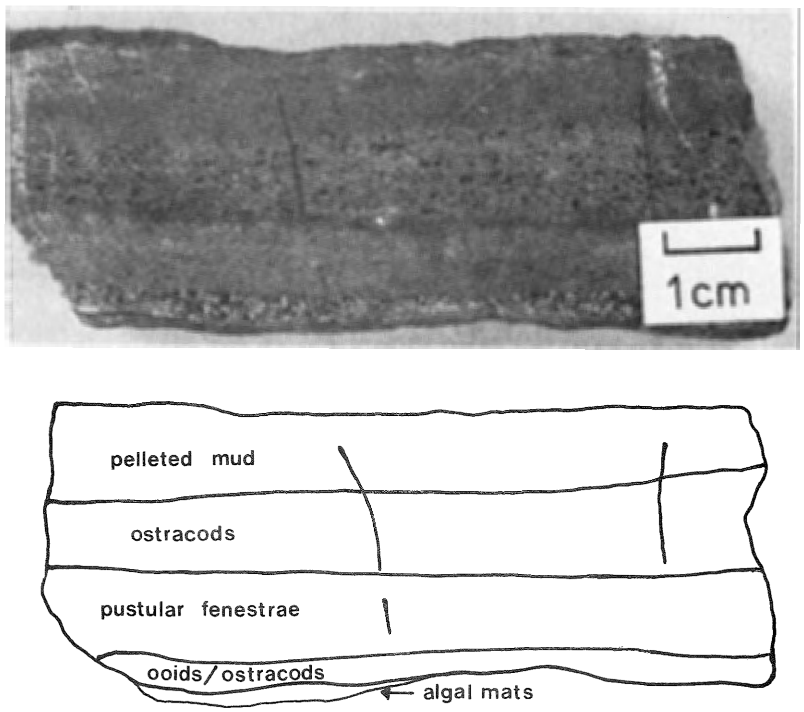



Fig. 8. Laminated basal carbonate with (from bottom to top); algal mats, ooids/ostracods, pustular fenestrae , ostracod-rich layer and a pelleted mud.

## LITHOZONE III

Thickness: 1.1 m

A dark brown oosparite is the dominant lithology in this unit. The oosparite is composed of ooids, minor oolitoids, coated grains, and rare bioclasts. The ooids are generally spherical in shape, with a small number of elongate, oval forms. They range in size from 0.5 mm diameter at the base of the unit to 2.0 mm at the top. They are well-sorted with respect to size, and somewhat by shape. The ooids contain fine concentric or, less commonly, spiral laminations with dark brown centres. Nuclei include, in order of decreasing abundancy, ostracods, forams, shell fragments, spines and quartz grains. Radiating boring algal filaments are very common. Some ooids are mottled light brown possibly due to their recrystalization to microspar. Coated grapestone lumps are occasionally observed, composed of up to four individual ooids which display three episodes or periods of coating. The unit is vaguely laminated with low angle cross-stratification (up to 15°) visible on weathered surfaces (fig. 9). Solution compaction is quite visible in sample 1-1. Close packed ooid layers are bounded above and below by overpacked ooids with suture joints between each adjacent ooid. Pellets and bioclastic debris increases in quantity towards the top of the lithozone. Remnant algal mats are present in moderate amounts at and near the top of the lithozone. Calcisiltite appears near the top as isolated patches and eventually as matrix, with the ooids displaying either open packing, or scattered throughout the calcisiltite (fig. 10). In

Fig. 9. Cross-stratification within oolitic sediments of Lithozone III. Scale is approximately 3 cm wide and the apparent paleocurrent direction is from the NE to the SW (left to right). Photo courtesy of Steve Delahay.

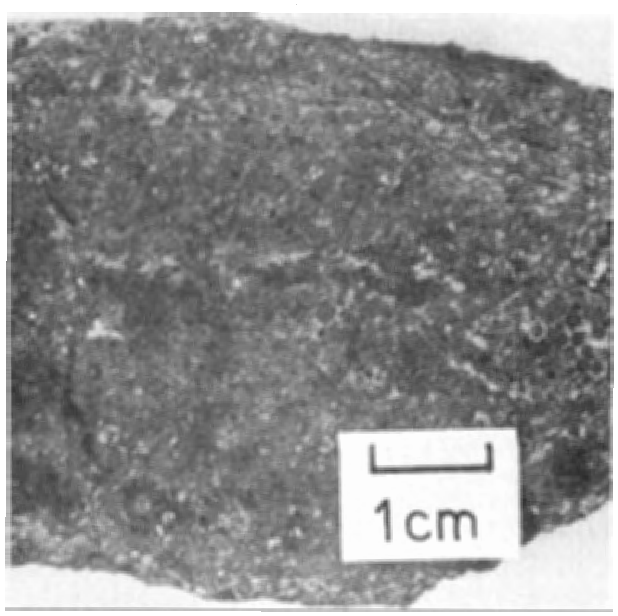



Fig. 10. Large, grey, reduced ooids in a light grey calcisiltite matrix with algal mat remnants (laminoid fenestrae) and bioclastic debris. Sample 1-4, located at the top of Lithozone III.

this zone, the ooids have a grey to black external colour and occur in a 5-8 cm thick layer composed of a carbonate silt matrix.

LITHOZONE IV

Thickness: 0.20 m

This lithozone appears to be transitional between lithozone III and lithozone V. Lithozone IV is medium grey in colour and consists of two strata in which ooids are dominant in the lower, and bioclasts dominate in the upper stratum. Ooid size is highly variable, from 0.3-1.4 mm in diameter. Faunal remains include ostracods, brachiopods, fragments of echinoids and crinoids, foraminiferas, dasycladacean algae and rare gastropods. Small, rounded bithoclasts of calcisiltite are common. Pellets are occasionally seen, protected by overlying shell fragments from alteration during cementation.

The lower half of the unit is a homogenous mass with no preferred orientation of the clasts. In the upper half however, the long axes of all bioclasts are horizontal. The cement consists of a clear, blocky calcite with irregular patches of calcisiltite within. The calcisiltite replaces the blocky calcite as the matrix and cement in the upper half of the lithozone.

LITHOZONE V

Thickness: 1.8 m

This lithozone is characterized by its light grey colour, shaley weathering, and concentration of bioclasts. Three units are present within the lithozone, each approximately equal in thickness.

The lowest unit (samples 1-7, 1-8) contains abundant crinoid and echinoid fragments (plates and spines), brachiopods, pelecypods and dasycladacean algal fragments. The bioclasts occur in patches cemented with calcite spar. As a consequence, they are resistant areas to the soft calcisiltite matrix. The fossils are broken into small rounded fragments between 2 and 6 mm in size. The grain size of these fragments become larger (up to 1 cm) towards the top of this, the lowest unit, and are noticeably less fragmented. Stratification is slightly inclined, with the long axes of most fossils oriented horizontally. Much of the original stratification features have been destroyed by extensive burrowing, apparently while the sediment was still soft. This is inferred by the absence of truncation of shell fragments and the churned appearance of the fossil-rich sediment. The burrows are approximately 1 cm deep. They are either inclined or vertical and are filled with bioclastic debris and/or carbonate sand. Small, equidimensional, light coloured calcisiltite intraclasts are common in samples throughout the lower portion of the lithozone. They increase in size and number towards the unit top (up to 1 $cm^2$). All of the afore-mentioned features of this unit are displayed in fig. 11.

The second unit is a massive calcisiltite with a rough, irregular, horizontal parting. Bioclasts are rare and include only echinoid spines and plates and rare shell fragments. Approximately

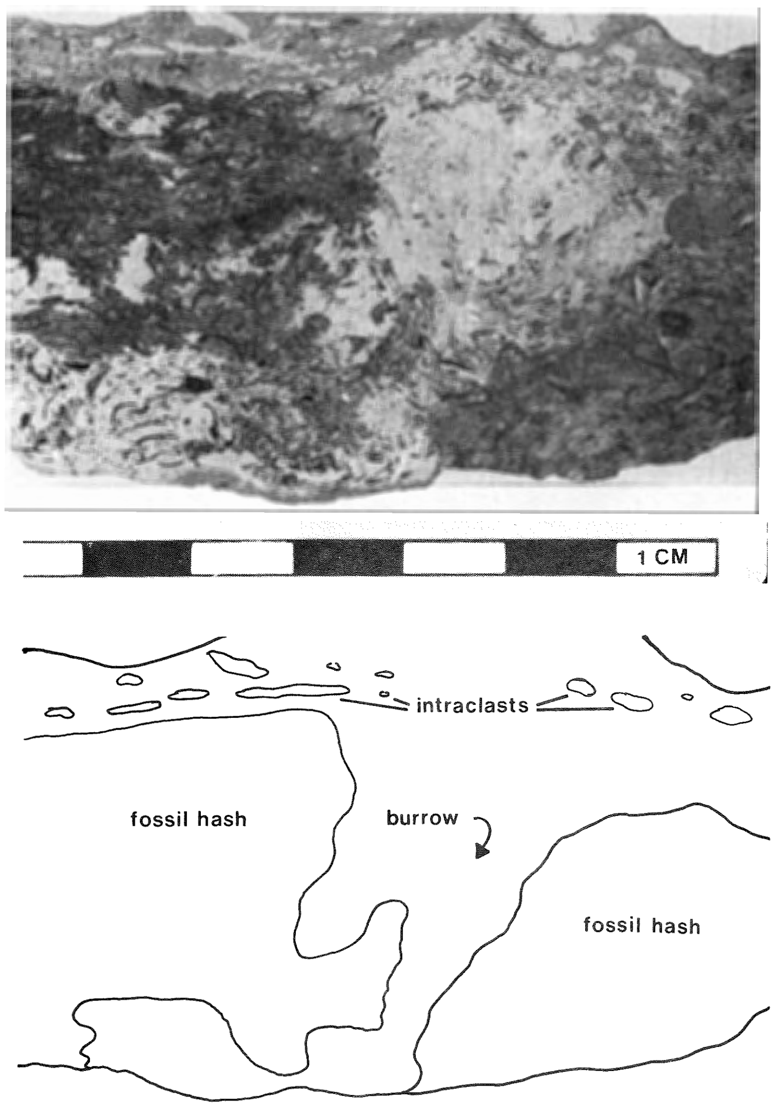



Fig. 11. Fossil-rich calcisiltite with intraclasts and extensive burrowing.

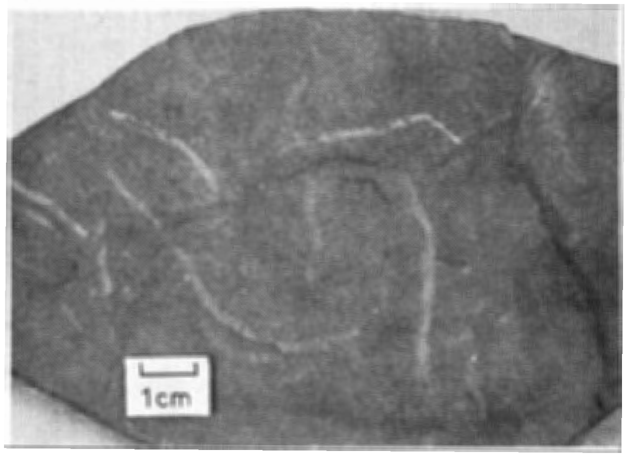



Fig. 12. Spagetti-like horizontal worm tubes in calcisiltite.

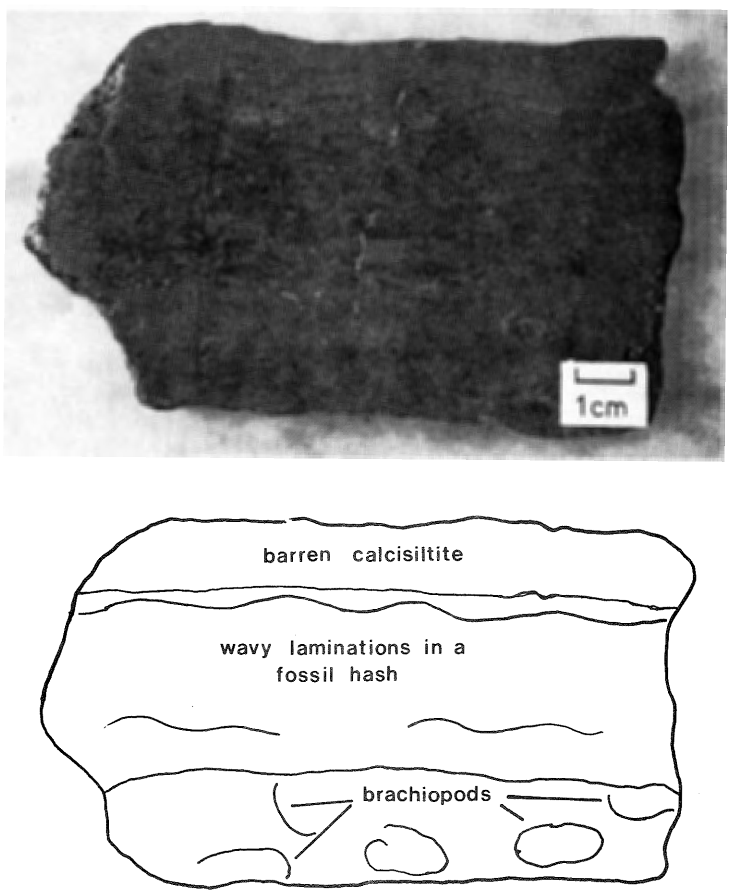



Fig. 13. Fine-grained calcisiltite with bioclast-rich and barren zones. Compare with the fossil shapes and sizes in figure 11.

20% of the shells observed are in unstable positions. Horizontal worm tubes are common, having a spaghetti-like pattern (fig. 12). The carbonate silt is slightly coarser than that of the previous unit, 0.07 mm versus 0.04 mm. Quartz silt is abundant in this middle portion of the lithozone, with values up to approximately 33% by weight.

The last and uppermost unit of this lithozone contains a less diverse fauna than the previously described lower-lying portion of the lithozone. Brachiopods, echinoids, crinoids, dasycladacean algae and occasionally, gastropods, are present. Most bioclasts are well-preserved and are much less fragmented than those in the lowest unit of the lithozone. Brachiopods are noted to have both valves attached. Good sorting of both size and shape of the clasts results in the formation of wavy beds and lenses in the unit. The wavelength and amplitude of ripples in the bioclastic-rich strata are 2.0 cm and 0.5 cm respectively. Within the bioclastic-rich stratum are sharp, erosional contacts with thin (1-3 cm) unstructured and barren, grey calcisiltite sheets that overlie the bioclastic material (fig. 13). Whole brachiopod shells are filled in most cases with light grey calcisiltite.

LITHOZONE VI

Thickness: 2.7 m

The light grey to brown pelsparites characteristic of this lithozone occur as flat, platey, laterally continuous beds from 5-10 cm thick. Thickness of the beds increases towards the top of the lithozone. Separating the individual pelsparite beds are soft, fissile, highly fossiliferous beds of light grey calcisiltite. The thickness of these carbonate silt beds decreases toward the top of the lithozone and range from 5-100 mm (fig. 14). Fossils in this calcisiltite include echinoid fragments, brachiopods, and clam fragments.

The more resistant pelsparites display delicate parallel laminations with occasional low-angle cross-bedding. The matrix is vaguely pelleted in most cases as the original fabric of the sediment has probably been destroyed or altered by later cementation. Better preserved pellets are found under shell fragments which act as umbrella structures. Fossils are rare in this lithology and are composed mostly of brachiopod fragments in unstable positions within the sediment. They are in stable positions only within the top and bottom centimeter of each stratum or bed. Angular intraclasts composed of the matrix material are abundant in some samples (fig. 15). Fine, black laminations are present in this part of the lithozone, with a greater abundance towards the unit top. The presence of laminoid fenestrae surrounding these laminations suggests that they are remnant algal mats (see sample descriptions, Appendix I). These remnants of algal mats are located within the top and bottom centimetre of each pelsparite bed, but rarely in the centre. Small 0.2-0.8 mm gypsum crystals are frequently visible in samples from the upper half of the lithozone. They are well-rounded and appear to have been formed during carbonate sedimentation as they occur in thin,

Fig. 14. Outcrop view of the decreasing thickness of calcisiltite beds (shaley) towards the top of the lithozone. Scale is about 60 cm. long.

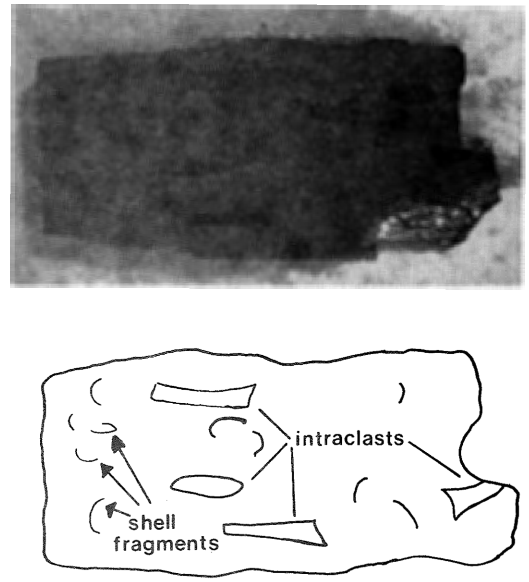



Fig. 15. Pelsparite with angular intraclasts and shell fragments in unstable positions. Sample courtesy of Peter Thomas and Rick Horne.

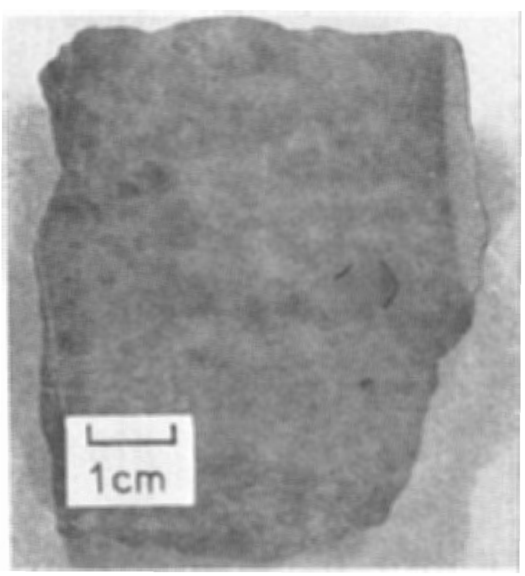



Fig. 16. Brownish-green mottling in pelsparites of Lithozone VI. Note the light-coloured halos around the mottles, and the positions of brachiopod fragments (centre-right).

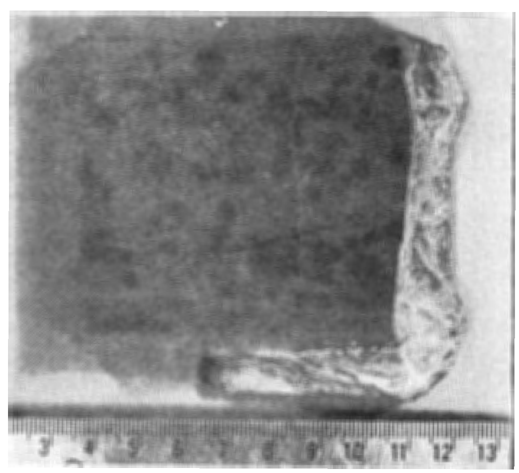


Fig. 17. Brown mottling occuring stratigraphically above that in figure 16. Note the fuzzy nature of the mottles and the absence of fossils.

stratified laminations within the carbonate, and no evidence for the displacement and/or incorporation of carbonate sediment within the crystals is present. Prism cracks are also observed in samples from the top portion of this lithozone. Burrowing is common throughout the lithozone, occurring as small, 1 cm deep, vertical protrusions into the underlying sediments.

The top half to one third of the lithozone displays a greenish, waxy, weathered appearance. This has been designated as the Mottled Zone in Sections 1 and 2 (see Appendix II). On fresh-cut surfaces, flattened to irregularly rounded brownish-green mottles in a tan-green groundmass are visible (fig. 16). The mottles are slightly harder than the groundmass and are associated with fine, dendritic, horizontal cracks following the outline of the mottles, but never cutting through them. The size and relative abundance of the mottles increases upwards in this portion of the lithozone. Fossils within the sediments display no alteration; however, the rock itself has lost its platey appearance and now has an irregular to blocky, fractured appearance.

Mottles found in the upper portion of this zone are fuzzy in nature and do not have the cracks that are usually associated with mottles that underlie this zone (fig. 17).

LITHOZONE VII

Thickness: 0.35 m

This dark brown lithozone has a gradational contact with the underlying pelsparites of lithozone VI, but differs in that the pellets or peloids of this lithozone are very poorly preserved and barely recognizable. Laminoid fenestrae is very common and occurs throughout the unit. The lithozone contains several different sub-units within it.

The lowest portion of the lithozone, approximately 10 cm in thickness, consists of a light yellowish-tan carbonate. It is soft and earthy in texture, and has neither fossils nor sedimentary structures of any kind. It would appear from the above observations that this lower portion of the lithozone represents a leached carbonate.

Overlying this carbonate are sediments with abundant laminoid fenestrae (remnant of algal mats), pustular fenestrae and small (0.5-1.0 mm) solution pits and associated fine, irregular fractures having a blocky pattern. The matrix is very clotted in appearance. This sub-unit is approximately 10 cm thick and is transitional over 1-2 cm into the third overlying sub-unit.

The third and final sub-unit, approximately 15 cm in thickness, is characterized by abundant laminoid fenestrae and large (0.5-2.5 cm diameter), open, lined dogtooth-spar filled or unlined vugs.

The laminoid fenestrae has previously been described and interpreted (see sample descriptions from this lithozone, Appendix I) as being formed by the interaction of the carbonate sediment and algal mats. However, some questions arise as not all of the laminoid fenestrae are well-developed and probably are not the result of sediment-algal mat interactions. The poorly developed fenestrae sometimes contain a black, insoluble residue (fine clay). These fine clay laminations could well form fenestrae if after deposition they became dehydrated and shrank, thus leaving a minute, yet open void space within the more consolidated carbonate sediments. The majority of the laminoid fenestrae however appear to be algal in origin. The reasons for this statement are the fenestrae are larger (up to 1 mm as opposed to a few tenths of a mm), much better developed, and are similar in appearance to those displayed in numerous texts (Davies, 1970; Logan 1974; and Logan et al., 1974). Fossil fragments (sometimes in unstable positions) are occasionally concentrated directly above and overlying the fenestrae. The presence of a sticky, gelatinous algal mat film on the sediment surface would act as an adherent resulting in fossil fragments sticking to it, some in unstable positions. Also, small (1-5 mm long) wisps of algal material are observable in the sediments.

The open vugs present in this lithozone could have formed in several ways.

1. Dissolution of Fossils - This process involves the preferential dissolution of fossil fragments by fresh water charged with $CO_2$. In

this lithozone, nearly all the vugs do not appear to resemble any type of fossil and are much larger than any fossils observed in the entire carbonate sheet. The general lack of fossils in this lithozone (only a few brachiopods) and their small size tends to rule out this method for the production of the vugs.

2. Dissolution of Gypsum - Gypsum is present in this lithozone in two forms: (1) small, rounded to euhedral crystals (fig. 23a) and (2) small hemispherical masses (fig. 19). The small crystals apparently show no signs of dissolution throughout the sediment. The gypsum masses however do. These gypsum hemispheres are always observed to have a brown, lacework pattern or network of carbonate material, filled with a fine-grained crystalline sulfate. This pattern, minus the sulfate is sometimes observed, indicating that solution of gypsum took place. These empty masses are only observed at the top of the lithozone, which apparently has undergone solution (fig. 18). The unaltered sulfate masses are located within the zone containing the dogtooth spar-lined or filled vugs. Vugs containing gypsum (in the above form) and dogtooth together are not observed.

Thus it would seem that two types of vugs existed; those once filled with gypsum and those representing something else. It appears unlikely that dissolution would be preferential and dissolve large gypsum masses adjacent to smaller ones first, and not affect the smaller ones. It should be noted that no gypsum hemispheres greater than 1 cm in diameter have been observed. For the most part, they seem to average approximately 0.5 cm in size.

These gypsum hemispheres are identical to gypsum blisters described by Davies (1970) at Shark Bay, Western Australia. The gypsum blisters form by the growth of sulfate material within the sediments and the lacework or network pattern are possibly algal filaments (Davies, 1970).

3. Organic Decay - This process for the formation of the vugs is supported by the following features observed in samples collected and studied from this lithozone. The vugs formed as a result of the decay of organic matter in the carbonate sediments through subaerial exposure, thus resulting in the production of organic gases. Algal mats at the surface, softened by rain, expanded into blister-like forms from the pressure exerted by the gas below. The vugs in this lithozone are identical to algal gas-blisters described by Davies (1970), Logan *et al*. (1974) and Hoffman (1976) from Shark Bay, Western Australia.

In figures 18-20, the blisters are clearly displayed. They have radiating fractures on the top of the blisters, probably the result of drying of the algal sediment and expansion of previously formed fractures from the initial growth of the blister. They show a hemispherical shape in profile (flattened bottom) and remnant algal mats with associated laminoid fenestrae that form the roofs. Distortion of some blisters by the weight of overlying sediments is also shown in figure 18, as are probable vertical gas-escape cracks into overlying blisters. Lithification of the sediment through sub-

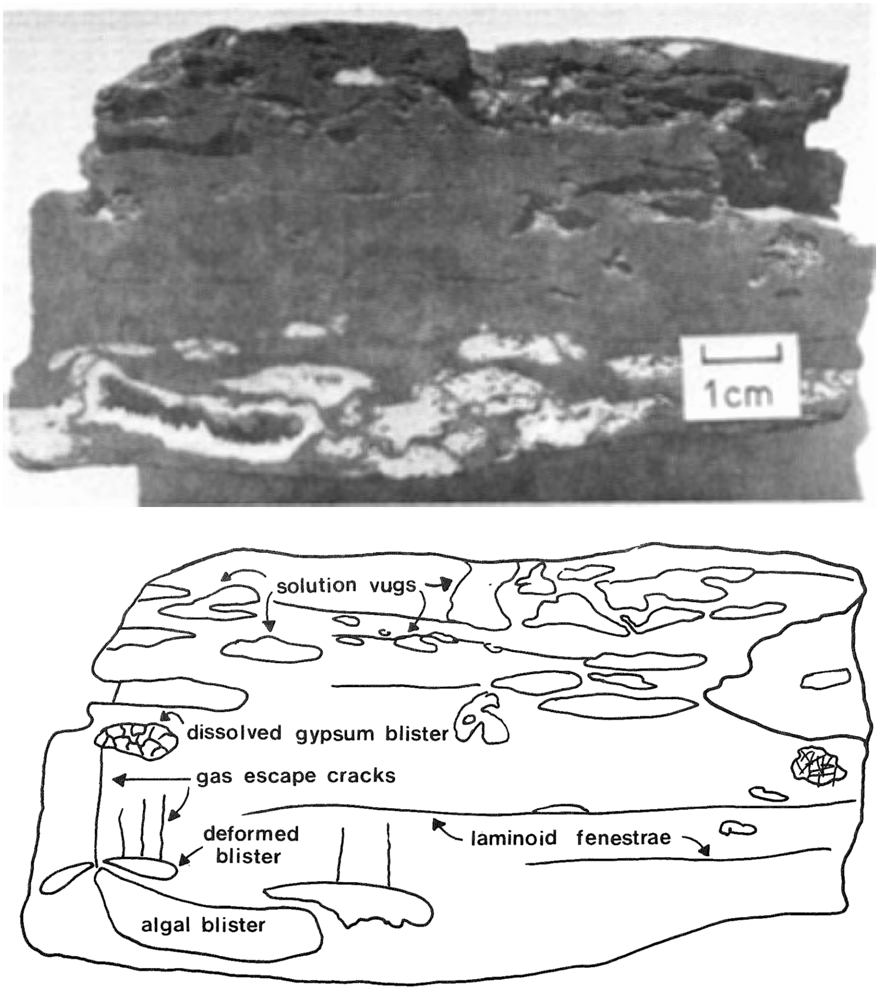



Fig. 18. Side view of algal blisters filled or lined with white dogtooth spar. Note that the upper portion has undergone solution. Laminoid fenestrae are clearly visible, as are vertical gas-escape cracks and deformed blisters.

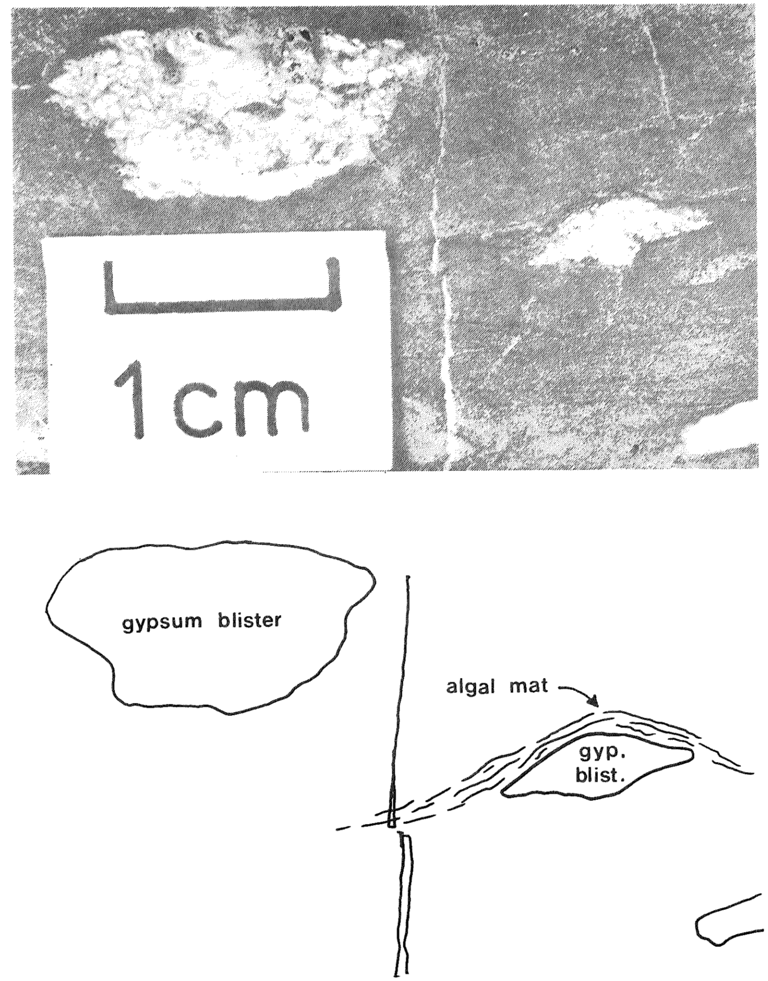



Fig. 19. Gypsum blisters. The gypsum is soft and bladed with a fine mesh or lacework pattern. Algal mats are visible overlying the blister on the right.

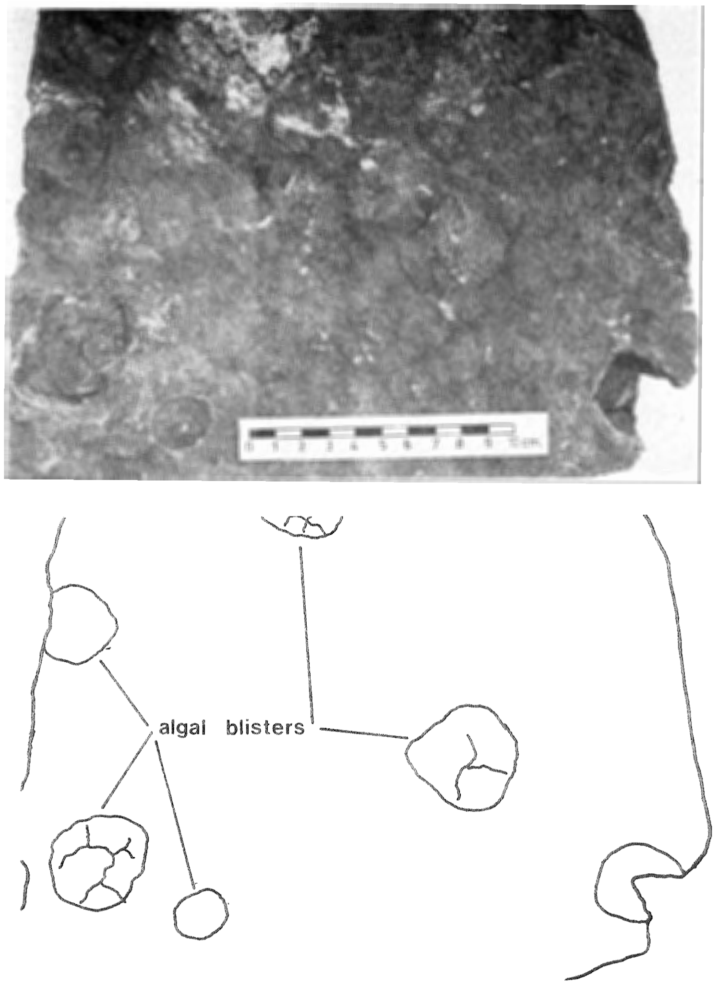



Fig. 20a. Top view of algal blisters with radiating surface cracks. Limonite staining in moderate amounts is present within the blisters.

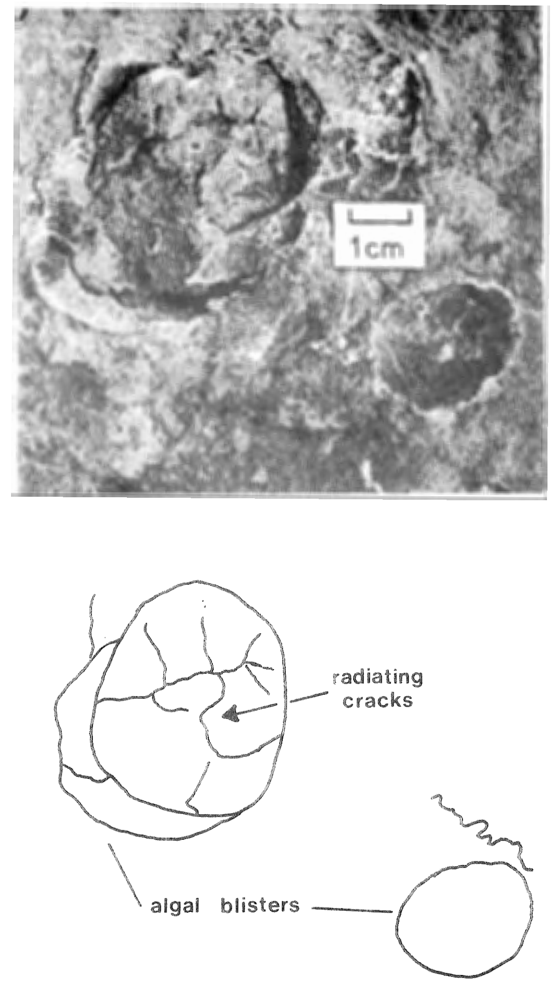



Fig. 20b. Close-up of algal blisters shown in figure 20a (bottom left).

aerial exposure is suggested by the preservation of the delicate blisters themselves, the solution effects at the top of the lithozone (with abundant iron oxide; ie. limonite) and the presence of the leached carbonate within the lithozone (indicating probable subaerial exposure). Considering that these blisters are restricted to the high-intertidal to supratidal environments, induration is likely to have taken place (Davies, 1970; Logan, 1974). The crystalization of the dogtooth spar that lines or fills the blisters took place after induration of the sediment.

In conclusion, the vugs were formed by two processes. The first consisted of the formation of algal gas-blisters via organic decay. Approximately 80% of the vugs formed in this way. The second process, the growth of gypsum blisters, accounts for the remaining 20% of the vugs, actually formed through the secondary process of dissolution of the gypsum blisters. The dissolving of fossil material to produce the vugs is deemed highly unlikely in view of the observable evidence.

Several other features are present in this lithozone. Bioclastic debris and carbonate silt is sometimes observed forming "wind shadows" adjacent to one side of the algal blisters. Peloids of unknown origin (fecal ?) appear to have comprised the matrix before lithification as their vague outlines can sometimes be observed in the sediment. Rounded to euhedral gypsum crystals (see sample descriptions for samples 1-19 and 2-7, Appendix I) are common and associated with the algal-laminated sediment. Large (1 cm long), clear, tabulate solitary gypsum crystals are occasionally present within the algal blisters. They appear to have formed after the crystalization of the dogtooth-spar that lines the blister cavity. Limonite is very common in the lithozone; especially the upper portion which underwent dissolution, as a fracture coating, and irregularly 'dusted' throughout the sediment.

## LITHOZONE VIII

Thickness: 2 m

This lithozone is somewhat similar to the flat, finely laminated pelsparites of lithozone VI, as both have a pelleted matrix and contain delicately laminated sediments. However, this lithozone is characterized by sedimentary structures that are a combination of current and wave ripples which produce interference ripples. The interference ripples occur as rounded mounds with a wavelength and amplitude range of approximately 6 to 12 cm and 2 to 7 cm respectively. Scours and crossbeds are abundant, and many ripples display abrupt pinch-outs. The ripples have a delicately laminated pelleted matrix, usually dark brown in colour. The lithozone is extensively burrowed, including trumpet-shaped burrows reaching up to 5 cm across and at least 3 cm deep (fig. 21).

Prism cracks are also abundant and they usually extend through an entire bed. Each bed is separated by thin (2-5 mm) black to grey calcareous shale or carbonate (fig. 22).

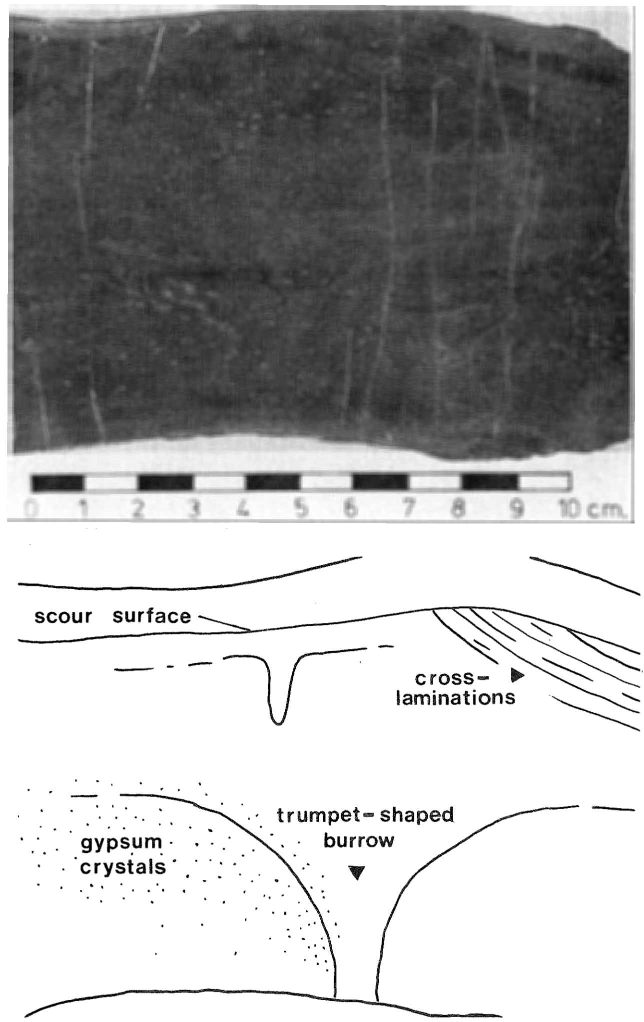



Fig. 21. Pelsparite sample from Lithozone VIII. Note the large trumpet-shaped burrow, cross-laminations, scours and gypsum crystals.

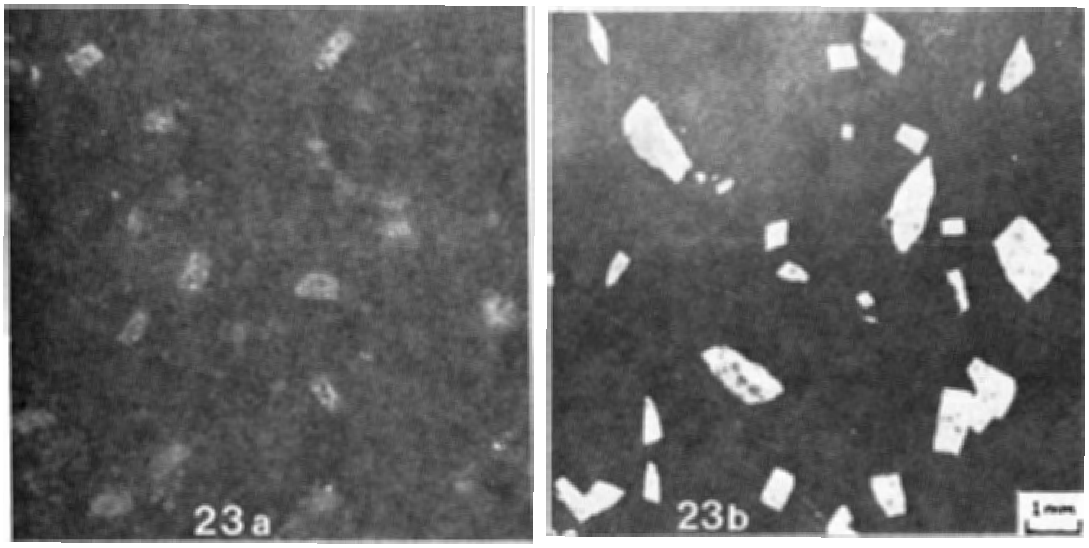

Fig. 22. Outcrop view of Lithozone VIII displaying its undulatory nature and black calcareous shale interbeds.

Gypsum is very common in the form of rounded to euhedral crystals (fig. 23a, b). The crystals are observed in laminations and truncations (rounded) or scattered throughout the matrix in wide bands (euhedral). Series of laminations containing euhedral crystals are often trucated by scours and overlain by barren sediment, or sediments containing rounded gypsum crystals.

Fauna is restricted to brachiopod fragments in a variety of orientations and remnant algal mats which appear within the top and bottom centimeter of each bed. Pellets are very well preserved towards the top of the lithozone, and appear to be slightly larger than those in the lower part of the lithozone.

The undulatory nature of this lithozone tends to be subdued and eventually flattened in the top 30 to 40 cm of the lithozone. Rounded to pear-shaped solution voids with diameters from a few to several tens of mm are common in the upper 60 cm of the unit. Blocky calcite-spar lines the voids (fig. 24). Fractures are common, many of which are filled with clear spar and connect or pass through the voids. Most fractures are vertically orientated and extend to the top of each bed. In this zone, the sediment is massive, with few observable laminations; especially in the top 10-15 cm of the lithozone.

Quartz silt is common in the sediments with a range in values from 4-15%. This residue is seen in the polished slabs as fine, raised grains in continuous 'beds', a few grains thick, following




Figs. 23a & b. Comparison between gypsum crystals present in the sediments of Lithozone VIII (fig. 23a) and those described in Elf-Aquitaine (1975), (fig. 23b). Note the pelleted matrix in figure 23a. Scale is identical for both figures.

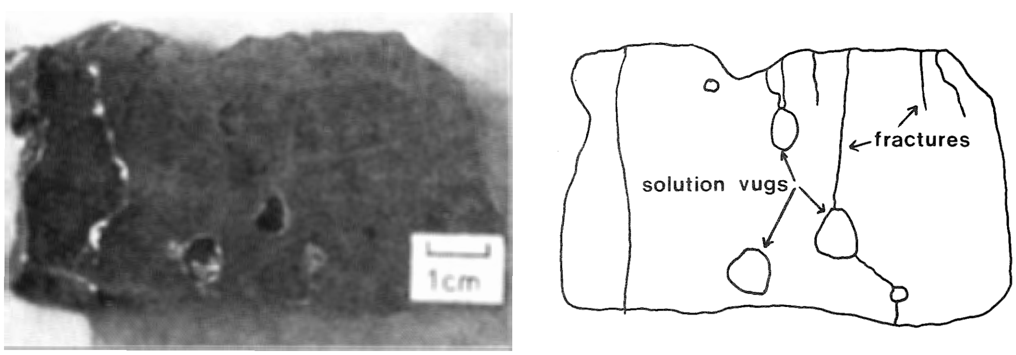



Fig. 24. Vuggy pelsparite located beneath the calcrete pseudobreccia. Note that vertical fractures normally terminate at, or connect solution vugs.

the carbonate laminations, scours, crossbeds and truncated surfaces. The quartz silt is fairly uniform in size; from 0.02-0.06 mm, well rounded and frosted (see Appendix III).

LITHOZONE IX

Thickness: 1.6 m

Lithozone IX can be subdivided into 5 separate units, each with its own unique characteristics. The total lithozone is displayed graphically in Appendix II, Section 4. The units are described below in ascending order and are as follows.

Unit A is approximately 40 cm thick and consists of a dark brown pelsparite breccia and pseudobreccia. The lower half of this unit is brecciated and consists of pelsparite clasts each with a clotted appearance, in a light tan sparite matrix (fig. 25). The clasts are subangular and voids between the clasts are lined with clear, blocky calcite spar. Micrite stringers and rare coatings (fig. 26) are observed in thin section. The micrite coatings are thickest on the bottoms of the clasts, and are thin along the sides and top.

The upper half of the unit consists of a pseudobrecciated pelsparite, similar to the pelsparite in the lower portion of the unit (fig. 27). There are no individual clasts in the pseudobreccia, rather a very vuggy carbonate which when observed in outcrop, appears brecciated. This half is capped by a hard algal crust with remnant laminoid fenestral clearly visible. The solution vugs range from 1 mm to 1 cm in size and are irregular in shape. Fine blocky calcite

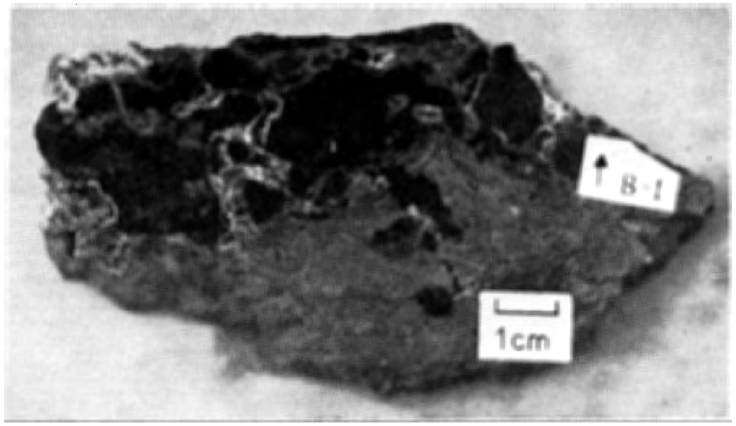



Fig. 25. Dark pelsparite breccia with spar-lined clasts floating in a light brown carbonate matrix.

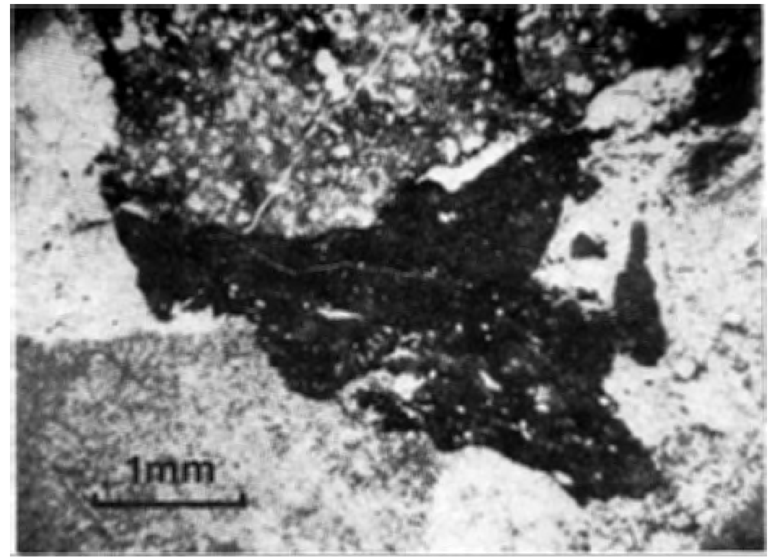



Fig. 26. Micrite coating located on the underside of a breccia clast. Note the vague laminations and thin micrite coating on the left side of the clast.

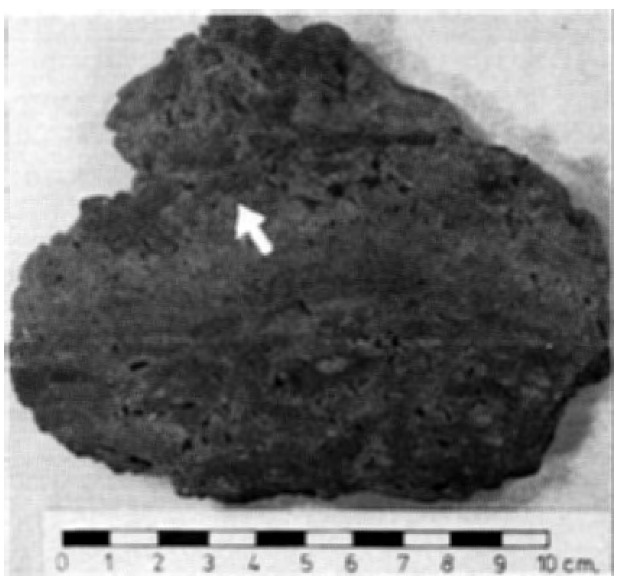



Fig. 27. (Left) Pelsparite pseudobreccia. It has a vuggy, unbrecciated character and continuous laminations which are uninterrupted. Darker pelsparite at the top of the sample appears to exhibit signs of slumpage that may indicate solution of the carbonate before total induration (white arrow).

lines the vugs. Very fine, suture-like cracks connect the vugs. Laminations in hand samples can be followed across the samples and are not disrupted by the vuggy character of the carbonate. Small gypsum crystals are abundant in this portion of Unit A in certain beds or laminations. Limonite is very common throughout the unit in the form of fracture coatings, vug linings and botryoidal masses.

Unit B is 60 cm thick and also consists of a dark brown pelsparite. However, here the pelsparite is extremely brecciated with rotated, 1 $cm^3$ (average) clasts, and calcite-lined voids between each clast (fig. 28). The clasts are subangular to subrounded in shape. Buckle cracks are common. Laminations can be traced across several of the clasts until interupted by brecciation in some cases. Meniscus cementation of the clasts at their contact points is frequently observed. Some areas of the pelsparite in the breccia are not broken into clasts, but rather appear to have 'flowed' or are bent over underlying breccia clasts. This may possibly indicate that the sediment was still somewhat soft during brecciation (fig. 28).

Unit C has a thickness of 40 cm and is composed of a light tan, chalky spar rudstone (fig. 29). It is made up of irregular, unorientated microspar to spar-sized calcite crystals with minute voids between the grains which gives the rock a saccharoidal or sugary texture. The unit is massive with no bedding features and is very soft. The upper quarter of the unit is dark brown in colour and,

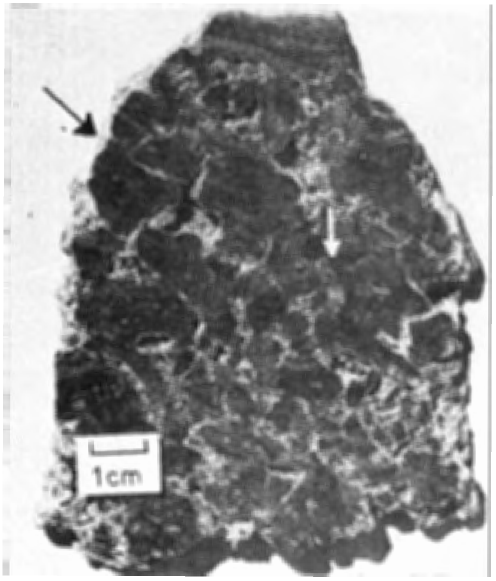
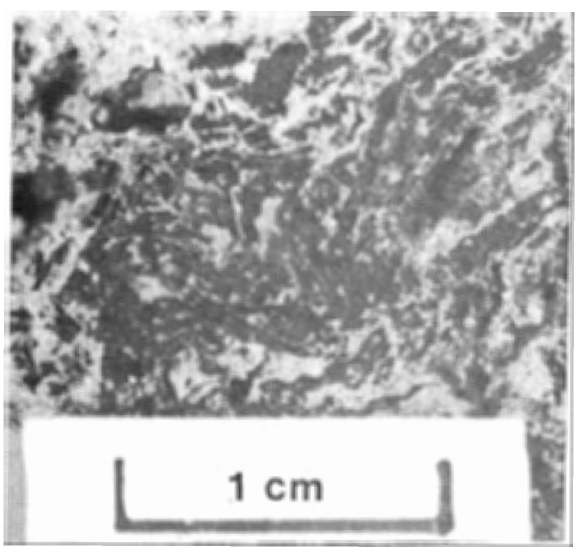




Fig. 28. Pelsparite breccia with buckle cracks (black arrow) and spar-lined vugs. Note that some of the clasts are bent and not broken, possibly indicating brecciation before cementation (white arrow).



Fig. 29. Spar rudstone with dark petroliferous zone at the top. Arrow indicates the location of the roots shown in figure 30.





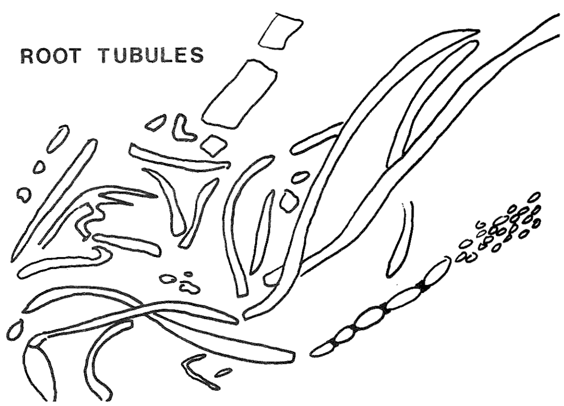




Fig. 30. Root tubules from sample B-4 (figure 29). Note the bending and entwining of the roots over each other.

contains larger void spaces than the lower carbonate. When broken, samples from this portion of the unit emit a strong petroliferous odour. Small (1 cm long and 1-2 mm wide) rod-like structures are common in this portion of the lithozone (fig. 30). They are observed as individuals or, more commonly, as entwined masses surrounded by dark brown ferroan calcite forming small (1 $cm^2$) pseudoclasts. Because of their shape, relationship with the organic-rich zone and total absence of fossils of any kind, these structures are interpreted as being root tubules (fig. 30).

Throughout the unit, fine micrite stringers, limonite stains and small siltstone chips are common.

Unit D is not always present in Lithozone IX. Its maximum thickness is approximately 20 cm. The unit is composed of a laminated spar grainstone (fig. 31). It is more consolidated than the previous unit, with a smaller spar grain size. Thin (6 mm) beds of poorly laminated microspar float in the spar matrix. These beds are broken by regularly spaced prism cracks, producing small, slightly convex (upwards) tablets or saucers. Beds on the upper surface of the unit very well display the saucer-like appearance of the clasts. Limonite is abundant in the form of staining either irregularly orientated or parallel to bedding. In thin section, minute micrite stringers are present, either perpendicular or parallel to bedding.

Scattered throughout the lithozone are thin, hard, finely laminated dark brown microspar beds which make up Unit E (figs. 32).

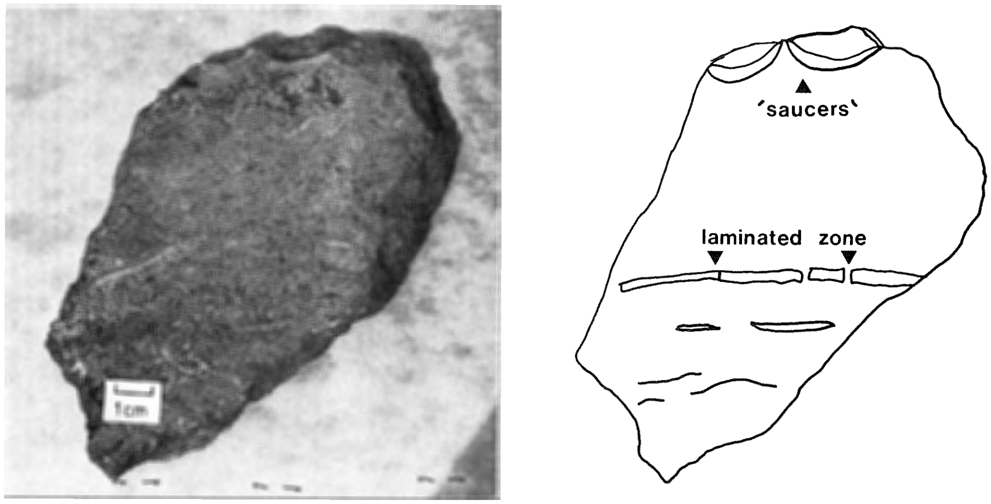



Fig. 31. Spar grainstone showing desiccated laminated zones and saucer-shaped pebbles at the top.

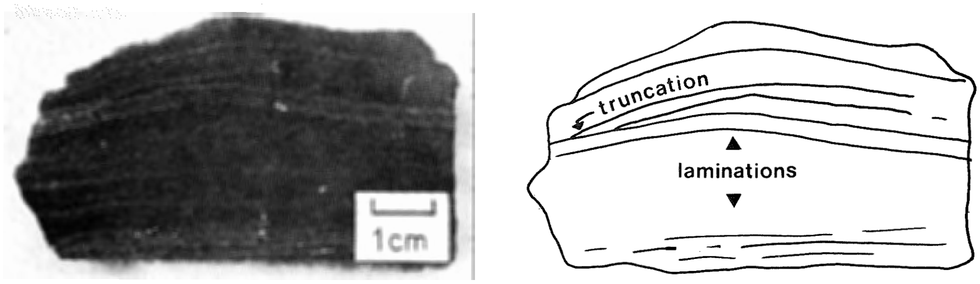



Fig. 32. Close-up of the laminated sparite from the calcrete of Lithozone IX. The truncation of several laminae is visible on the left portion of the sample.

Fig. 33. Surface of a flat-lying laminated zone which has undergone desiccation(?) and solution.

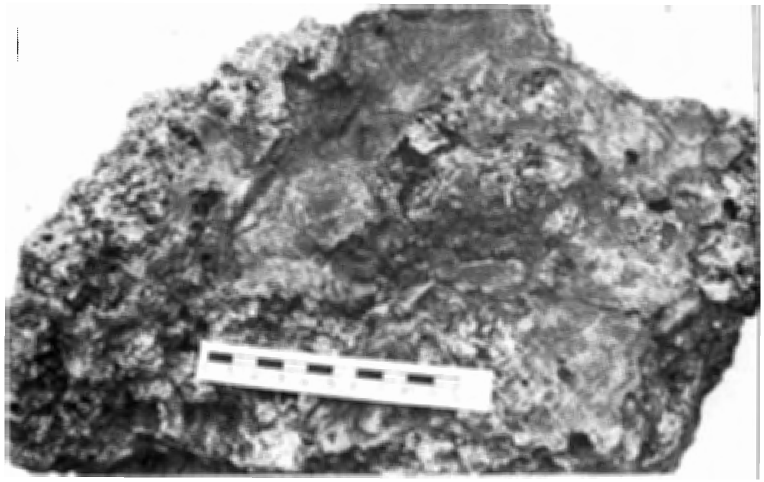
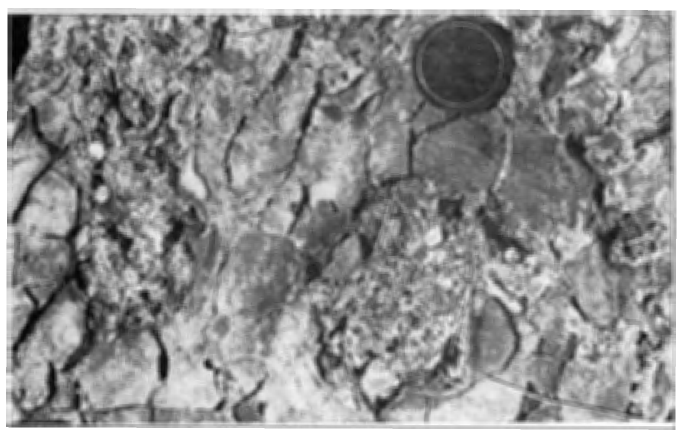


Fig. 34. Laminated sparite draped over a pelsparite breccia. Note that portions of the sparite are missing and the presence of solution pits (right side of sample).



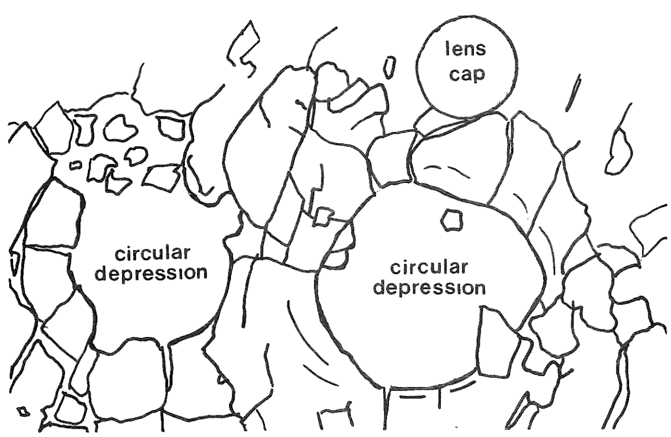



Fig. 35. Depressed circular areas occasionally observed on the top of the laminated zones of the calcrete. Scale is approx. 3 cm. across. Photo courtesy of Steve Delahay.

The microsparite beds contain very fine, tan-coloured laminations that are crinkly and diffused and often pinch-out. In thin section, the laminations appear to be composed of dark brown micrite. The matrix is an even-grained, nodular calcite spar with a clotted appearance. These laminated beds which occur throughout the lithozone are intact or brecciated; apparently by dessication (fig. 33). They usually separate the different units of the lithozone and vary in thickness from 0.5 to 2.0 cm. In some cases, the laminated beds are not flat-lying as normally is the case, but follow the irregular contours of the underlying breccia. They are thinnest at the top and thickest in small depressions within the breccia (fig. 34). Solution pits lined with spar calcite and limonite are common on the upper surfaces of some laminated beds, especially those that are slightly brecciated (fig. 33). When the laminated zone is observed on blocks of pelsparite breccia, depressed, circular areas, approximately 5-15 cm across composed of the laminated carbonate are commonly seen (fig. 35).

## LITHOZONE X

Thickness: $\sim$ 0.7 m

This lithozone consists of poorly consolidated brown, red and green siltstones, mudstones and conglomerates. At Section 4 (western edge of study site), this lithozone can be inspected only by digging into the bank directly above the Lithozone IX. Three units can be seen at this site.

The bottom portion is approximately 35 cm thick and consists of poorly bedded (0.5-2.0 cm) red to brown siltstone and mudstone. The unit is highly calcareous and includes numerous grey-green discoidal silt fragments; 1 mm to 1 cm in size which are sub-rounded to sub-angular in shape.

The center unit is a poorly sorted grey-green conglomerate with red and green mudstone clasts ranging in size from a few millimetres up to 5 cm diameter. The green siltstone matrix is slightly calcareous and softer than the clasts. This unit is approximately 25 cm thick.

The uppermost unit of the lithozone is 8 cm thick and is composed of a slightly calcareous reddish brown to brown vaguely bedded siltstone and fine sandstone.

Three hundred metres to the west of section 4, this lithozone is slightly thicker (approximately 1 m) than that at Section 4. Again, this outcrop can only be observed by excavation of the bank. No separate units could be determined from the outcrop due to its poor preservation. However, several samples were taken which revealed lithologies similar to those described above, but in a better state of preservation.

The sorting of clasts in the conglomerate at this site is much better than at Section 4. Both normal and reversed size-grading occurs. The clasts are sub-rounded to sub-angular in shape and are composed of red, brown, green and grey mudstone or sandstone fragments. The clast size range from 1 mm to several centimeters. Angular quartz pebbles and slate fragments are uncommon. The matrix consists of mud to sand size sediments.

Laminated sediments usually cap the top of conglomeritic beds. The sediments can be unstructured red sandstone beds, red, grey or green siltstone or mudstone beds with fine black clay laminations, or a combination of sediment types.

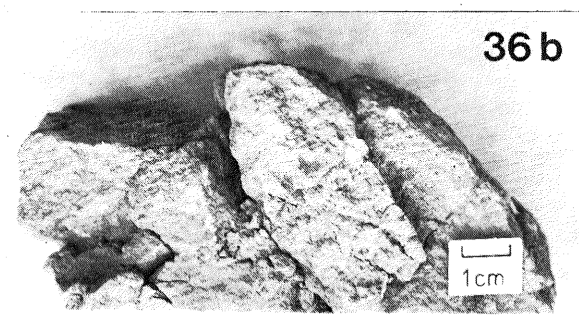
Several sedimentary structures are present in samples from this outcrop. They include ripples (rare), crossbedding in conglomerates (sometimes present) scours and fill (common) and slumps (uncommon).

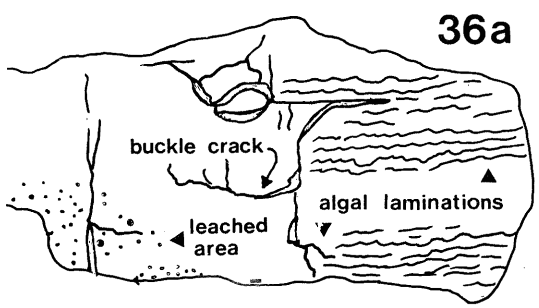
Limonite is common, especially in the conglomeritic sediments as a slight staining at the top of the unit. Muscovite is abundant throughout the different sediments and is also observed within the mudstone clasts.

## LITHOZONE XI

Thickness: 0.06 m

Lithozone XI consists of a thin (average 6 cm) light grey to brown sparite located within poorly sorted red conglomeritic sediments. Black, wispy, laterally continuous structures with well-developed laminoid fenestrae are abundant. They resemble the algal mats described in lithozone VII and are interpreted here as also being algal mats. Cut-and-fill structures are seen in some samples displaying


Figs. 36a, b. View of the algal-sparite from the playa lake facies (Lithozone XI). Figure 36a (above left) is a profile showing the unclear algal-laminations, prism and buckle cracks. Figure 36b (above) is a plan view of the top of the previous figure (fig 36a)( exhibiting the flat-pebble breccia.

disruption of the algal laminated sediment, and subsequent later growth of algal mats over the scour fill. Small rounded calcite grains (birdseyes ?) are abundant throughout the sediments, as are flattened siltstone fragments, angular quartz grains (up to 4 mm size) and rare mica flakes (biotite).

Lithozone XI was also observed in outcrop approximately 300 metres west of the western edge of the study site. Here, it appears brown in colour, is moderately leached and displays large prism (up to 3 cm deep by .6 cm wide) and buckle cracks (fig. 36a). In plane view, the unit has a flat, pebble breccia appearance, this probably being the result of extreme dehydration and subsequent deformation (fig. 36b). A vague, polygonal pattern to the prism cracks can be seen. Flattened red and green siltstone fragments are abundant on the upper and lower surfaces of the breccia clasts. They are about three times the size of those observed in samples from the main outcrop 300 metres to the east.

The silt/sand content of this lithozone is in the vicinity of 30%. Limonite is also present in the form of surface staining.

LITHOZONE XII

Thickness: 3 m +

This lithozone could not be observed in detail because of a thick overburden cover which covers the sediments. The lowest 2 metres are composed of sediments similar to those described in lithozone X (western end). These sediments grade upwards with a green, fine grained siltstone containing fine laminations. Above the green siltstone is a red, massive, unstructured siltstone that is at least 8 metres thick and partially obscured by till.

It must be noted that outcrops of lithozones X-XII are ephemeral in nature, and are usually covered by thick recent mudflows from the till embankment overlying the sediments. Only in late summer to early fall are they observable as the mudflows harden and tides sweep the embankment to expose the soft outcrop.

# CHAPTER 3: DEPOSITIONAL ENVIRONMENTS

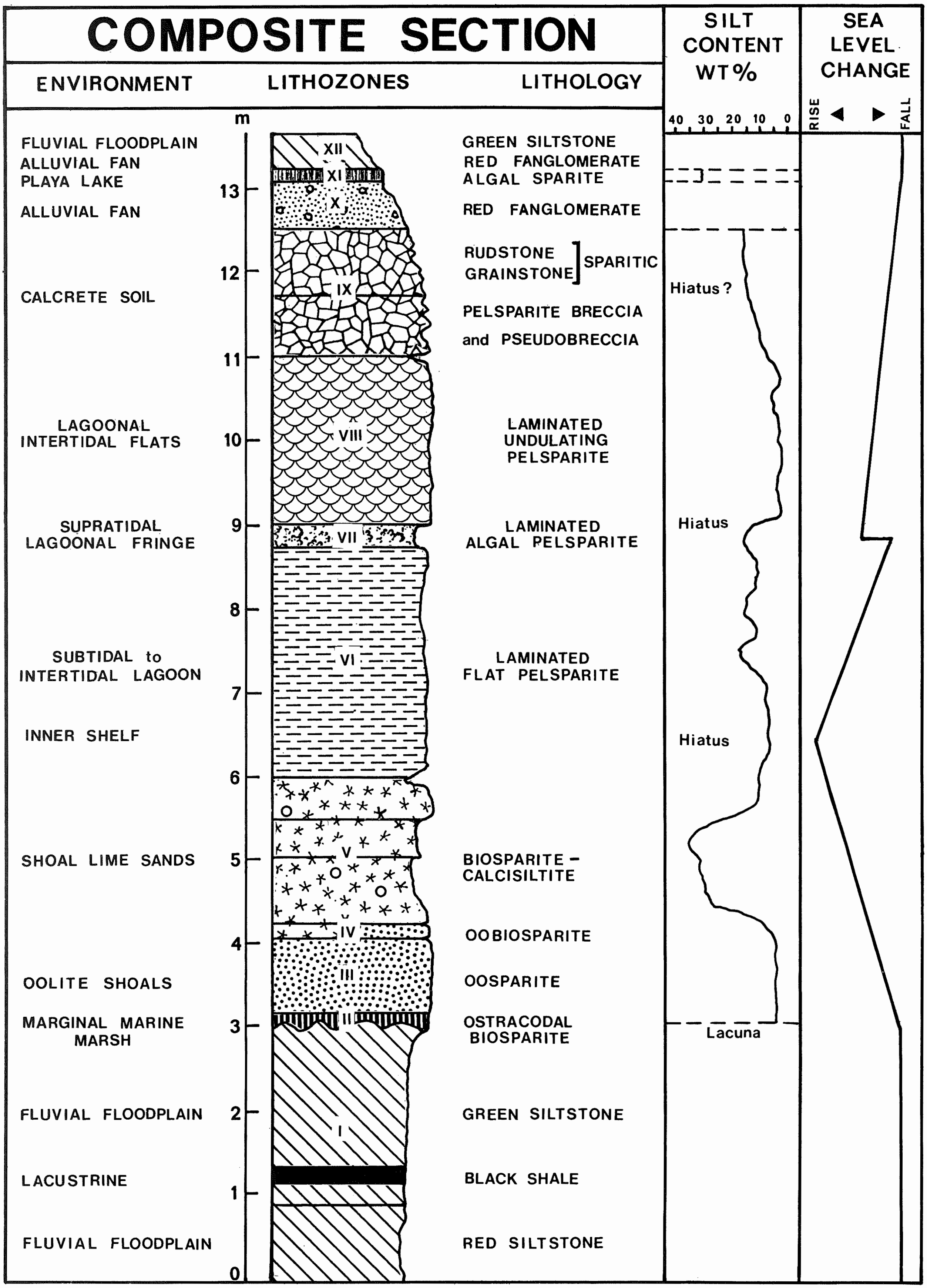

COMPOSITE SECTION
ENVIRONMENT
LITHOZONES
LITHOLOGY
SILT CONTENT WT%
SEA LEVEL CHANGE
m
40 30 20 10 0
RISE
FALL
FLUVIAL FLOODPLAIN
ALLUVIAL FAN
PLAYA LAKE
ALLUVIAL FAN
CALCRETE SOIL
LAGOONAL INTERTIDAL FLATS
SUPRATIDAL LAGOONAL FRINGE
SUBTIDAL to INTERTIDAL LAGOON
INNER SHELF
SHOAL LIME SANDS
OOLITE SHOALS
MARGINAL MARINE MARSH
FLUVIAL FLOODPLAIN
LACUSTRINE
FLUVIAL FLOODPLAIN
13
12
11
10
9
8
7
6
5
4
3
2
1
0
XII
XI
X
IX
VIII
VII
VI
V
IV
III
II
I
GREEN SILTSTONE
RED FANGLOMERATE
ALGAL SPARITE
RED FANGLOMERATE
RUDSTONE
GRAINSTONE
SPARITIC
PELSPARITE BRECCIA
and PSEUDOBRECCIA
LAMINATED UNDULATING PELSPARITE
LAMINATED ALGAL PELSPARITE
LAMINATED FLAT PELSPARITE
BIOSPARITE – CALCISILTITE
OOBIOSPARITE
OOSPARITE
OSTRACODAL BIOSPARITE
GREEN SILTSTONE
BLACK SHALE
RED SILTSTONE
Hiatus ?
Hiatus
Hiatus
Lacuna

fig.37

The depositional environments of the twelve lithozones described previously are discussed in this chapter. The major elements used in interpreting each lithozone are discussed; however, for a more complete and detailed analysis of each lithozone, the reader should refer back the Chapter 2 and ultimately the sample descriptions in Appendix I and their location in Appendix II. A composite section of the entire carbonate sheet and bounding clastics is shown in figure 37.

## LITHOZONE I

### Fluvial Floodplain

The thick siliclastics underlying the carbonate sheet represent sediments typical of a fluvial flood plain complex. The clastics are massive, but poorly preserved sedimentary structures such as ripples, crossbeds and scours are occasionally observed. Within the siltstone is a thin, black shale unit displaying fine laminations within a sand-sized sediment. Straight-crested current ripples are also present. This small sub-unit is interpreted as a lacustrine deposit due to the above features and its position within the fluvial clastics. It also acted as barrier, preventing the reduction of the oxidized, underlying red siltstones. The siltstones above this barrier are green with a red mottling, green, orange, and immediately below the carbonates, dark grey. The siliclastics are highly calcareous adjacent to the carbonates, but over a downward distance of 1 metre decreases, until no reactions with HCl within the siliclastics could be observed.

Earlier workers in the Windsor Group such as Bell (1929), Moore (1967), Schenk (1967, 1969) and others have considered the siliclastics as fluvial in origin.

## LITHOZONE II

### Marginal Marine Marsh

The features which show this lithozone to be a marginal marine marsh are its location or position within the carbonate-clastic unit, restricted and abundant fauna (ostracods and blue-green algal mats) the presence of ooid lithoclasts and the thickness of the lithozone.

The sediments of this lithozone are located within troughs on the upper contact of the underlying siltstone. Ooid lithoclasts from seaward oolite shoals indicate a probable landward direction for the location of this unit. This is further supported by the increase in abundance of ooids towards the top of the unit and the conformable contact with the overlying oolite.

The presence of abundant ostracods is probably the second most important factor in assigning a marine marsh environment to this lithozone. Studies on the diets of living ostracods by Van Morkoven (1962) revealed diverse food sources such as diatoms, bacteria, proterozoans (all environments); organic detritus of higher plants and animals, living pond weed stalks (lacustrine to brackish); and eelgrass or coralline algae (marine environment). Corraline algae is found in the upper portion of the carbonate sheet (lithozones IV and V) but no ostracods. The ostracods are found abundantly in this lithozone above a fluvial siltstone which would probably be rich in detrital remains and living grasses. Therefore it is highly probable that the fossil ostracods had a food source similar to the modern forms and along with the previously mentioned observations represent a brackish-water, marginal marine marsh.

## LITHOZONE III

### Oolite Shoals

An oolitic shoal environment is inferred from the sediments of lithozone III. The ooids present are smallest at the bottom (0.5 mm) and largest at the top (1.4 cm) of the unit indicating deepening water depths (Giles, pers. comm.). The brown colour of the lower ooids is probably due to organic matter contained in the ooid (Bathurst, 1975) whereas the uppermost ooids are grey, indicating a reduction of the organic material (Kendall and Skipwith, 1969). This reduction would occur in an environment where abundant reducing bacteria and other types of organisms feed off abundant decaying organic matter. This environment would be represented by lithozone V, with its abundant fossil remains (Multer, 1977).

The presence of ooids indicates a high-energy environment swept by tidal currents, waves and storms producing a very mobile substrate. On this type of bottom, no large plants or animals (i.e., crinoids) could establish themselves.

In the lithozone, close packed ooid layers (1 cm thick) in a clear spar matrix/cement are bounded above and below by overpacked ooid layers (up to 5 cm thick). The overpacked ooids display suture-like contacts between each ooid, indicative of grain-to-grain pressure solution (Bathurst, 1975). Originally, the now overpacked ooids may have been lightly cemented with aragonite at point contacts and later suffered the effects of pressure-solution due to loading. The close packed ooid layers that bound the overpacked ooids do not display pressure-solution features and therefore must have been cemented adequately enough to withstand the effects of pressure. Cementation probably occurred before burial (shallow-water marine cementation). Supporting evidence for this is the presence of large ooid lithoclasts in the underlying ostracodal-biosparites of lithozone I (see sample description 3-2, Appendix I). This type of cementation is common in oolitic banks of the Bahamas (Ball, 1967).

The process of pressure-solution cannot take place after the precipitation of the second generation of cement (final pore-filling material) displaces the overlying pressure evenly and prevents the movement of the ooids in response to pressure (Bathurst, 1975).

The shape and extent of the ooid environment can only be speculated upon. It may have existed as a belt a kilometer or so wide which stretched across the basin. Tidal channels must have cut across the belt resulting in the formation of bars and splay fingers of oolitic sediments into the adjacent environments.

## LITHOZONE IV

### Transition Zone (III - V)

This lithozone is a transition between the underlying oolitic shoals (lithozone III) and the overlying shoal sands (lithozone V). It consists of two distinct beds with the lowest dominant in ooids and the highest bed abundant in faunal remains. The clasts in both beds are orientated at all angles and well-coated ooids are scattered throughout the calcisiltite matrix. Ball (1967) indicated that these features are indicative of extensively churned sediments by active burrowing organisms.

## LITHOZONE V

### Subtidal Shoal Sands

This lithozone is interpreted as subtidal carbonate sand shoals predominately from sediment size (0.06-0.13 mm), i.e.; silt to fine sand size carbonate grains (calcisilitite to calcarenite). Plumley et al. (1962) showed that sediments of this size range are dominant in the subtidal regime, being swept by tidal currents and waves preventing the deposition of finer sediments. In this moderately agitated environment abundant and diverse fauna are present which are sub-rounded to well-rounded in shape and moderately to well sorted. Plumley also observed that clastic material can be in concentrations up to 50% in these sediments. In figure 37, a high clastic content is shown to be present in the sediments of Avondale, this the author believes the result of the winnowing effect of water currents in the oolitic facies. Quartz fragments are then later deposited in the quieter waters of the adjacent lithozone.

The upper portion of the lithozone is barren with respect to fossil fragments except for rare shell fragments and abundant worm tubes. Plumley et al. (1962) show that this type of assemblage along with a greater siliclastic content and slightly finer carbonate grains (both present in the Avondale sediments) are representative of a still lower-energy environment which is only intermittently agitated and bordering on a very quiet environment which is composed of mud to clay-sized carbonate sediments. An intercalated contact indicates interfingering of the carbonate silt into these finer sediments. This is observed at Avondale and is composed of alternating calcisiltite and pelsparite beds with the former decreasing in thickness and eventually eliminated over a vertical distance of about a metre (fig. 14). This interfingering of coarser sediments into finer ones is probably the result of storms which would have swept the bottom sediments, and with strong tidal currents and waves, effectively move the zone of high energy seaward and thus making it possible to deposit the coarser grained carbonates in deeper water.

## LITHOZONE VI

### Inner Shelf to Subtidal-Intertidal Lagoon

Detailed study of this lithozone showed that not one, but two depositional environments are represented by the single pelsparite lithology.

The inner shelf facies identity was determined by its relationship with the underlying carbonate silts and sands of the sand-shoal environment, low energy sedimentary structures, paucity of fossils (brachiopods only) and low clastic content. Plumley et al. (1962) and Wilson (1975) also indicate these features and relationships as representative of an inner shelf, quiet water environment.

The upper half of this lithozone represents a subtidal to intertidal lagoon environment. This environment appears to overlie the inner shelf facies conformably. However, siliclastic content analysis and a study of the sediments show that this cannot be the case and that a diastem exists within the pelsparites of this lithozone (i.e., clastic content experiences a rapid rise in concentration).

The main reason for interpreting the upper portion of this lithozone as a lagoonal facies is the conformable and gradational relationship with the overlying sediments of lithofacies VII, a supratidal lagoonal fringe (see lithozone VII for details). Other observations include the relatively massive sediments (no laminations), abundance of angular lithoclasts, shell fragments in unstable positions, the increase in siliclastic content, presence and increasing abundance of small gypsum crystals in the sediment (indicating elevated salinities) increasing abundance of algal mats, prism cracks, extensive burrowing and a mottled texture of the upper third of the lagoonal sediments. The angular lithoclasts, shell positions and clastic content indicate a period of high energy agitation of the sediment. This was caused by a regression phase and subsequent reworking of inner shelf sediments by tidal currents and waves now that the water depth above the sediments is reduced. The siliclastic material has a shorter distance to travel to the bottom thus reducing the chances of removing the clastics before they settle into the sediments. This siliclastic content increase is shown in figure 37. Prism cracks and gypsum indicate near-exposure to the surface of the water and elevated salinities respectively.

The mottling of the upper portion of the lithozone is probably an indirect result of the subaerial exposure of sediments of the overlying lithozone VII resulting in a slight diagenetic alteration of portions of the sediment, or the result of burrowing.

The features and structures of these lagoonal sediments and other observations are discussed in detail by Wilson (1975) and to a lesser extent by Milliman (1974). The writer believes that the sediments observed represent an open lagoon environment with the possibility of a few small barriers at the edge of the lithozone. These barriers were probably composed of oolitic sediments. The oolitic environment represents the high energy zone and absorbs the actions of waves and tidal currents. This would result in a low energy zone being formed behind this environment, with quiet water and conditions favourable for the formation of an open lagoon. Due to the shape of the basin (fig. 38), these environments existed several kilometres to the southwest and a later regressive phase subsequently altered the shape and extent of these two lithozones.

# LITHOZONE VII

## Supratidal Lagoonal Fringe

This lithozone is interpreted as a supratidal lagoonal fringe from the distinct features in the sediment caused by the growth of and interaction between blue-green algal mats and the sediments. Algal blisters, laminoid fenestrae, fine pustular fenestrae, minute gypsum crystals and rare restricted fauna all indicate a very high intertidal to supratidal environment as shown by LaPorte (1967), Shinn (1968), Davies (1970), Logan (1974), Logan et al. (1974) and Hoffman (1976) in both recent and ancient sediments. Wilson (1975) and James (1977) also reviewed the characteristics of this environment but in less detail.

Several features such as blisters and pustular fenestrae have been shown to be the result of organic gases from decaying organic matter which seek the surface and evenutally form these features (Shinn, 1968; Davies, 1970; Logan et al., 1974 and Hoffman, 1976). Gypsum crystals are known to be particularly common below algal blister mats (Brown and Woods, 1974) and are also present in upper intertidal sediments. The paucity of faunal remains indicates a harsh, restricted environment with subaerial exposure and elevated salinities (i.e., presence of gypsum). Only a few, thin-walled shell fragments are present. Desiccation features are present, especially on the upper surfaces of the blisters (fig. 20).

Gypsum blisters identical to those described by Davies (1970, p. 193) are present in the Avondale sediments and were observed by Davies to be located in very dry areas of the supratidal zone and especially around the margins of salt pans at Shark Bay.

The subaerial exposure of the sediments results in a rapid induration of the sediments by fine aragonite after drying (Davies, 1970; Logan, 1974). This subaerial exposure, the author believes, resulted in the top few centimeters to be exposed to rainwater which lead to the dissolving of the carbonate, clearly seen in figure 18. Limonite staining is abundant in this zone and may be concentrated from the carbonates after their dissolution.

## LITHOZONE VIII

### Intertidal Flats

Although lithologically identical to lithozone VI, this environment is different with respect to the types of sedimentary structures present, dessication features and other minor characteristics, and represents a high-energy intertidal flat environment. Although little has been written on ancient carbonate examples from this environment (James, 1977), the data available plus information pertaining to modern and ancient low-energy examples was found to be useful in determining the depositional environment of this lithozone.

The interference ripples characteristic of this unit are the result of interfering current and/or wave systems in very shallow water (Schwarz, 1975). Intermittent exposure of the sediment produced fine prism cracks, and very fine laminoid fenestrae (Shinn, 1968). The abundance of laminoid fenestrae in sediments of the low intertidal zone and irregular, pustular fenestrae (birdseyes) in the middle to upper intertidal zone is well documented by Shinn (1968) at Shark Bay, Australia. This relationship of fenestrae to environment probably exists in the sediments of this lithozone as birdseyes are common at the top of the unit and are absent in the lower portion. This is reversed for the laminoid fenestrae. Subaerial exposure of the sediment between floodings probably assisted in the preservation of the abundant, large, open burrows found throughout the unit (Purser, 1975) (fig. 21).

The intermittent exposure of the sediments resulted in the formation of small euhedral gypsum crystals within certain zones or laminae. They formed by the precipitation of sulfates from concentrated pore waters in the sediment, due to elevated salinities from evaporation during subaerial exposure (Kendall and Skipwith, 1969; Schwarz, 1975).

The paucity of fossils, while not diagnostic of a tidal flat environment, when considered with the other observed features indicate a harsh environment with little diversity of life forms. The fossils include only disarticulated brachiopods at all orientations in the sediment.

Quartz silt is observed as fine lines in laminations and along truncated surfaces. The author believes this to be wind-blown clastic material that has settled on subaerially exposed sediments, or, sediments in very shallow water (tens of centimeters) thus allowing the clastic material to settle into the sediments before being removed by wave or current action.

High-energy sedimentary features decrease towards the top of this lithozone. The clasts of the overlying breccia are composed of sediments from this lithozone and also display features indicating a much lower energy environment. A few ostracods are observed within these breccia clasts and the author believes that the very top of this lithozone (located within the breccia) represents a return to a brackish-water, marginal marine marsh, as described in lithozone I. Ostracods are only found in the bottom 50 cm of the carbonate sheet, and within the breccia. Only 50 cm of carbonates remain (calcrete soil, lithozone IX) in the carbonate sheet and is overlain by continental fanglomerate sediments of lithozone X.

## LITHOZONE IX

### Calcrete Soil

A very detailed study of the pseudobreccia, breccia, spar rudstone, spar grainstone and laminated sparites of this lithozone reveal it to be a mature calcrete soil. The characteristics of modern and ancient calcrete soil profiles are described by Bretz and Hornberg (1949), Blank and Tynes (1965), Reeves (1970, 1976), James (1972), Walls et al. (1975), Harrison (1977) and Harrison and Steinen (1978).

In the Avondale calcrete, the determining features are the pseudo-breccia and breccia, laminated sparite zones, laminated saucers, root tubules, coated clasts, buckle cracks, prism cracks, micrite stringers and meniscus cementation. It should be noted that calcretes will display all or only some of the features noted here. To quote Harrison and Steinen (1978):

> ... variability within and interaction between these factors (climate, soil, transmissability, availability of $CaCO_3$, nature of substrate and time) will be the rule rather than the exception, and the resultant complexity will potentially be reflected in the products of near-surface diagenesis. The caliche (calcrete) profiles need not, and, in point of fact, do not resemble each other in outcrop appearance.

The complex nature of this calcrete horizon and its formation is discussed in detail in Chapter 4; Diagenesis.

## LITHOZONE X

### Alluvial Fan Debris Flows

Although this lithozone is rarely well exposed, the author was able to exhume samples from under one metre of till. The samples range from fine mud to a coarse conglomerate which is poorly sorted. The variable clast size, orientation of clasts, mud matrix, interbedded sands and silts, red oxidized color, rough crossbedding, scours and other sedimentary structures are characteristic of debris flows (Bull, 1972). The preservation of the soft mud and siltstone clasts in the conglomerate indicate a nonturbulant transport of the clasts, typical of debris flows (Enos, 1977). Interbedded sand and silt layers are recognized as either the last stage of debris flow sedimentation or later flood events associated with the debris flows (Bull, 1972). Muscovite mica, slate and angular quartz fragments are common in these sediments, indicating a possible source of these fragments from the west, south and southeast, the basin edge being approximately 10 km away (fig. 38). This is further evidence for an alluvial fan complex in a southwards direction from the Avondale area.

These sediments, the author believes, are indicative of debris flows located at the edge of an alluvial fan. Belt (1968), interpretated similar sedimentary sequences in Carboniferous of Atlantic Canada as representative of alluvial fans and associated deposits. The preservation of the terrestrial calcrete soil horizon of lithozone IX is also a strong indication for an alluvial fan origin of the varied sediment types.

## LITHOZONE XI

### Coastal Playa Lake

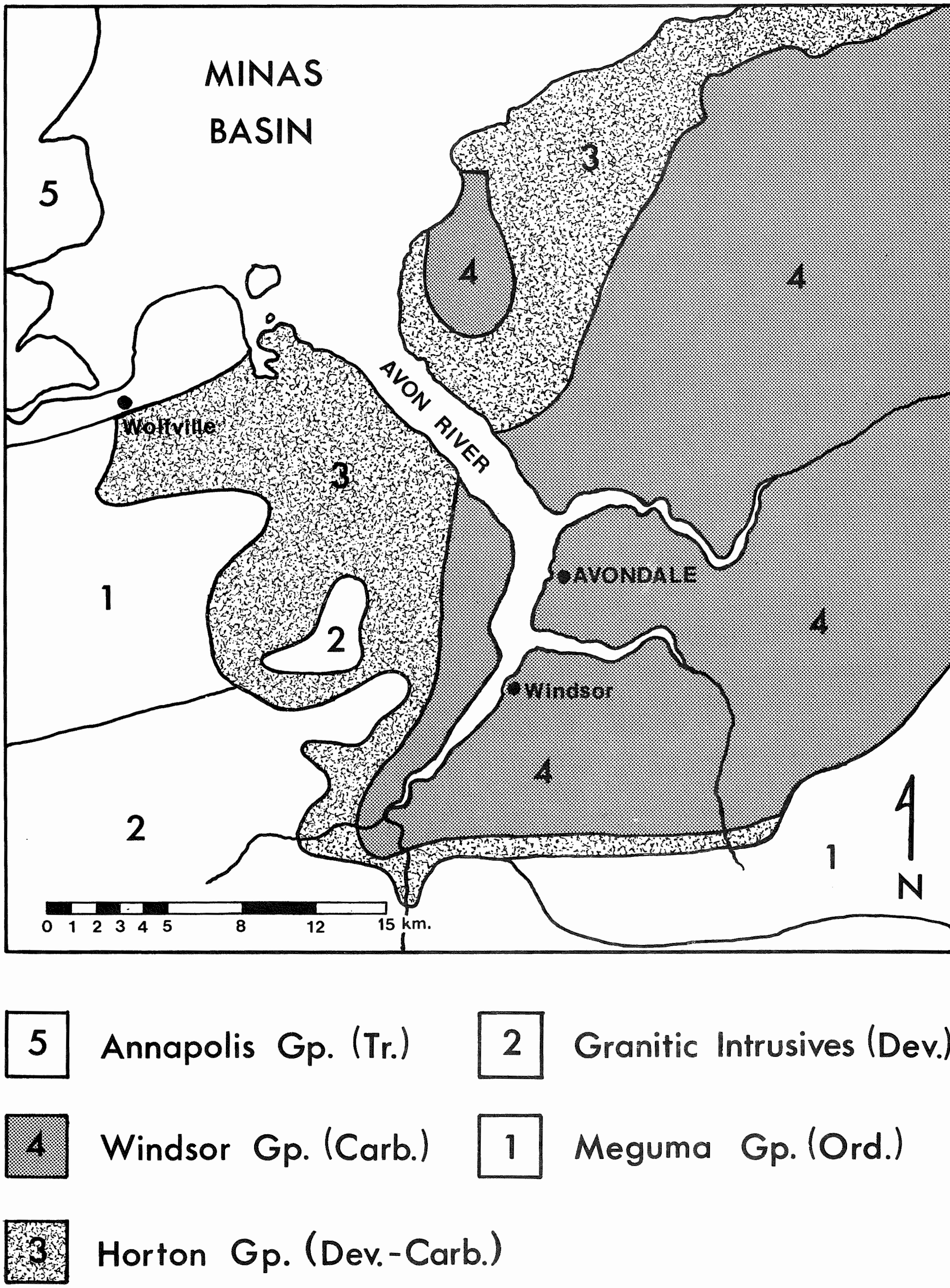
The main reasons for assigning a playa origin to the carbonates of this lithozone are its lack of any faunal remains except blue-green algal mats, extreme dehydration features (buckle and prism cracks), leaching of the dehydrated carbonate, presence of a flat pebble breccia (located only in the southwestern end of the study area) and its thickness (less than 8 cm). This breccia is characteristic of a high supratidal environment with associated stromatolites (Davies, 1970; Logan, 1974 and Read, 1974).

The author believes that these features represent a playa lake facies above or bordering the supratidal zone, that is subjected to occasional flooding by marine waters during storms. The presence of angular quartz, mica and slate fragments is derived from bordering debris flows located at the fringe of an alluvial fan. As this is a diagenetic environment whose sediments are of both marine and adjacent continental origin, the location of this facies within the fanglomerate sediments is possible (Glennie, 1970). This environment is also characterized by evaporitic conditions. The absence of sulfates and evaporites is due to the fact of their high solubility, which would result in their entering solution (i.e., rainwater) and removal by runoff or percolation into the groundwater table (Mabbutt, 1976). Deflation is also another effective method for the removal of the salts and sulfates.

## LITHOZONE XII

### Fluvial Floodplain

This lithozone is identical to lithozone I and is interpreted as representing the same depositional environment.




AREAS UNDERLAIN BY THE WINDSOR GROUP;
WESTERN MINAS SUB-BASIN

fig.38

# CHAPTER 4: DIAGENESIS

## CALCRETE FORMATION

The study of the calcrete horizon of lithozone IX reveals a complex soil profile representing several stages of subaerial diagenesis superimposed upon each other. This is a result of the variability within and interaction between the factors of time, climate, nature of substrate, $CaCO_3$ availability, and soil transmissibility (Harrison and Steinen, 1978). This interplay of variables is reflected in the structures and textures present in the calcrete observed at Avondale. In this chapter, the structures' and textures' mode of formation is discussed and from this an attempt is made to interpret the diagenetic history of the entire soil profile.

A distinctive feature of many calcretes is the presence of a breccia (and pseudobreccia in this case) horizon in the soil profile (Blout and Moore, 1969; Steel, 1974; Walls et al., 1975; Reeves, 1976, and Harrison and Steinen, 1978). The breccia is formed by nontectonic fracturing (desiccation), the action of plant roots and the dissolving action of rainwater. This process takes place on subaerially exposed carbonate sediments, or those under a thin clastic soil cover. The rainwater, when combined with atmospheric $CO_2$ (or $CO_2$ derived from the soil) forms carbonic acid, $H_2CO_3$. This acid attacks the carbonate and calcium will go into solution:

$$CaCO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2$$

The breccias formed are characterized by their shape (angular to sub-rounded, depending on the action of carbonic acid), close fit between adjacent clasts (even if they are slightly rotated), traceability of laminations within the breccia clasts over distance (especially so in the pseudobreccia which is not segmented into individual clasts) and coated grains or clasts. The breccia may be either floating in a carbonate matrix or bound by meniscus cementation at the points of contact between clasts that may result in up to 30% secondary porosity.

The coated clasts and laminated horizons in the profile are formed by the precipitation of the carbonate which is in solution. This occurs when the solution is near the surface and undergoes evaporation, or, at depth where the solution becomes supersaturated with calcium (James, 1972; Reeves, 1976; Harrison, 1977). This latter process is the result of fluctuation between pH and $CO_3$ content which both control the carbonate solubility (Reeves, 1976). An undersaturated solution will take in carbonate which produces $CO_3^{2-}$ ions which in turn increases the solution pH:

$$CaCO_3 + H_2O + CO_2 <-> Ca^{2+} + 2HCO_3^-$$

However, when the solution becomes supersaturated with carbonate, precipitation occurs, $HCO_3^-$ ions disassociate and the pH is reduced.

Coated grains and clasts are uncommon in the calcrete of this section, and for the most part consist of only a small coating on the undersides of clasts within the breccia. The other portions of the clasts appear to have been slightly corroded. The general lack of coated grains is probably due to the fact that the carbonate in solution is deposited at the base (and later at the top) of the breccia in the form of laminated zones.

The laminated zones consist of dark brown, hard calcite microspar with very fine micrite laminations. The laminated zones of most caliches or calcretes consist of very fine micrite (Steel, 1974; Walls _et al_., 1975; Reeves, 1976; Harrison, 1977; Harrison and Steinen, 1978). However, the author believes that the laminated zones in this calcrete probably originally consisted of micrite but have since recrystallized to spar. The dark micrite laminations still present may be original micrite laminations with a high iron content. The laminated carbonate occurs in at least four areas in the profile, possibly more. It exhibits either a vuggy, brecciated character (fig. 33) or a drape-like form over the pelsparite breccia (fig. 34). Both of these types of laminated zone are described by the above writers.

Small vaguely laminated 'saucers', similar in appearance to those described by Bretz and Hornberg (1949) and Reeves (1976) are located at the top of the calcrete profile. It is difficult to explain their formation; however, they may be poorly consolidated examples of the harder laminated zones, or related to them in some way.

The clotted texture of the pelsparite breccia is the result of one or more of the three processes described by Harrison (1977); 1) in situ micritization of the carbonate substrate, 2) continued nucleation of crystals on micrite pellets and 3) cementation of interpellet porosity by additional micrite or very fine crystalline sparry calcite. The author favours the third process as clear, fine spar is present as the cement of the original pelsparite.

Root tubules are abundant in a zone in the upper portion of the calcrete (Unit C) which is very fetid and gives off a petroliferous odour when broken. This fetid zone is probably the remains of a very organic rich portion of the soil which underwent the process of decay. This zone would be a major contributor of the $CO_2$ needed to form carbonic acid when mixed with water. The concentration of $CO_2$ in this zone could be 2-3 times greater than that in the atmosphere (references cited in Harrison, 1977).

Micrite stringers are not common in the calcrete of lithozone IX and are usually less than 1 mm in thickness. They are thought by the author to be small fractures lined with precipitated dark brown micrite.

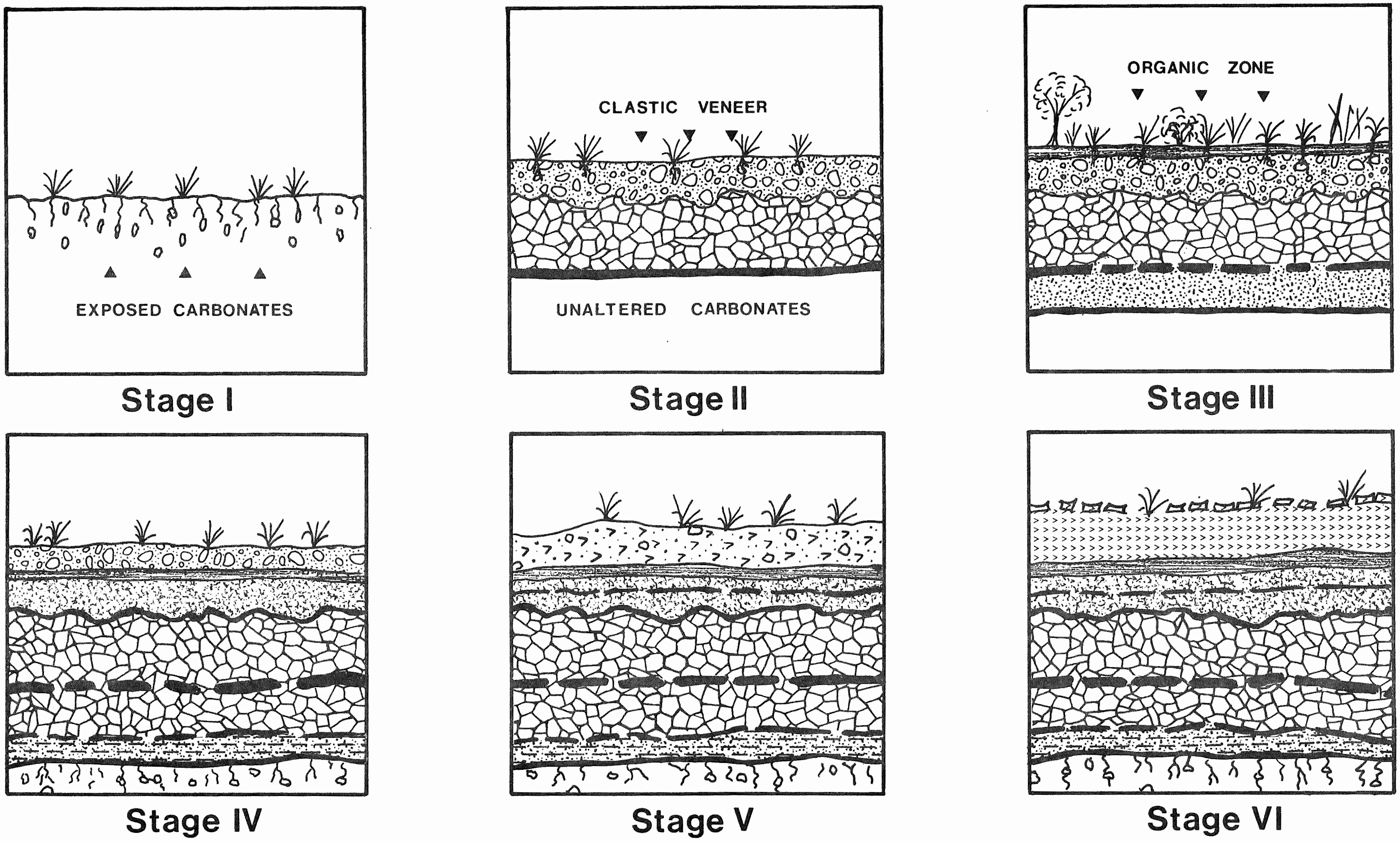
Buckle cracks are the result of separation of sediment laminations along the horizontal plane by dessication through water loss. Their presence in the calcrete breccia proves that at least some of the sediment was displaced by dessication through subaerial exposure (Reeves, 1976) (fig. 28). The same may be said of the abundant prism cracks observed in clasts of the breccia.

The author believes the following account represents a reasonably accurate picture which reveals the sequence and mode of formation of the calcrete and its previously described features. The stages of the calcrete formation are illustrated in figure 39.

A regression of marine waters resulted in the subaerial exposure of high intertidal to supratidal carbonate sediments (Stage 1). Falling rainwater charged with atmospheric $CO_2$ formed carbonic acid which attacked the exposed carbonates and released the carbonate to be incorporated into the solution. The downward percolation of the solution was aided by the formation of fractures and dessication features by plants and sediment shrinkage respectively in the sediments.

Stage 2 follows, with the formation of a breccia after sufficient exposure. The carbonate in solution is precipitated at the bottom of the profile to form a laminated horizon or "plugged" zone, which prevents further downward percolation of water and protects the underlying sediment.

A thin veneer of siliclastic material probably was deposited over the carbonate breccia in Stage 3. Carbonate material also was incorporated into the clastics in the form of a wind-blown dust from subaerially exposed carbonates from an adjacent near-by area, sea spray or was already present in the clastic material (James, 1972).




STAGES OF CALCRETE FORMATION
(Lithology key in Appendix II)
fig.39

Plants and grasses would now have an opportunity to grow in this area. Carbonate-bearing solutions continued to be percolated through the breccia, and at some stage were undersaturated with carbonate, thus attacking the laminated zone and underlying sediments to form a new, lower breccia and laminated horizon. Few breccia clasts were covered with a micritic coating due to the continuing solution of the carbonate by rainwater.

Stage 4 represents a period when the downward degradation of the carbonates is halted. Several laminated zones formed from the fluctuations of conditions favourable for the dessication, solution and reprecipitation of carbonates. Carbonates under the lowest laminated zone contain abundant spar-lined voids and small fractures (fig. 24). Those above this zone are extremely vuggy and fractured; but not into individual clasts, and form the pseudobreccia. A laminated horizon has formed at the top of the breccia, reprecipitated from carbonate material from within the clastic soil veneer. This plugged zone now prevented the further degradation of the breccia and caused carbonate reprecipitation to occur above the breccia, within the interstitial zones between the clastic grains. Organic detritus within the soil contributed large amounts of carbon dioxide to percolating rainwater, thus increasing the production of carbonic acid, which in turn dissolved the carbonate material in the soil and reprecipitated it further below.

The growth of carbonate within the clastic soil resulted in a carbonate grainstone with approximately 30-35% siliclastic material included within. In Stage 5, this process continues above the organic zone. Arid climatic conditions would allow the solution in the soil to rise by capillary action, reach oversaturation and reprecipitate carbonate after the water has evaporated (Reeves, 1976). This action formed the spar rudstone observed at the top of the calcrete profile.

In the last stage, Stage 6, the clastic soil veneer has been removed, probably by deflation. The soft carbonate is now exposed and becomes indurated. Small, cusp-like pebbles or saucers form at the top of the carbonate soil. They have been described by Reeves (1976) and earlier by Bretz and Hornberg (1949) who indicate that they are formed by the solution of the centre of carbonate pebbles by rainwater during infrequent wet periods. The climate was probably still arid as these pebbles are not large, and only slightly cupped. Also, the underlying rudstone and grainstone show little signs of solution. Alluvial fan sediments later covered and preserved the calcrete soil.

Therefore, the calcrete soil was formed by two processes; 1) *in situ* degradation and 2) *pedogenic* action, (including capillary rise) (Reeves, 1976). These processes resulted in the formation of the pseudobreccia and breccia, and the spar grainstone and rudstone respectively. This model for the formation of the calcrete is by no means complete. The scope of this thesis restricted a complete study of this lithozone. Further studies should carefully examine the profile in detail and an examination of the types and history of cementation is deemed vital for a more complete (and correct) understanding of the processes involved in the formation of this very intriguing carbonate.

# CHAPTER 5: CONCLUSIONS

The facies model illustrating the paleoenvironments is graphically portrayed in figure 40.

## PALEOENVIRONMENT

The U-shaped Minas Sub-basin during the late Windsor time (late Viséan - early Namurian) was filled with previously deposited clastics, carbonates and sulfates of lower Windsorian age (middle Viséan). This sub-basin was bounded by Ordovician metasediments of the Meguma Group to the east and west, and by Devonian Intrusives to the south (fig. 38).

At the initiation of carbonate sedimentation of the Meander River Limestone, the sub-basin was covered by fluvial clastics and in some areas, thin deposits of lacustrine muds and sands. A transgression of the shallow, warm Windsorian sea from the northeast (Moore, 1967) permitted the development of oolite shoals, subtidal bioclastic calcarenite shoals and fine, inner shelf, micritic muds. The initial carbonate deposited consisted of a ostracod-rich grainstone occurring within troughs and low areas of the onlapped fluvial clastics. This carbonate with its very restricted fauna represented the marginal marine facies, probably a coastal marsh/brackish-water environment. It eventually developed into a subtidal to intertidal lagoon in the southwest portion of the basin after the cessation of the marine transgression and stabilization of the different depositional environments. Oolitic shoals probably developed barrier bars to the southwest of the Avondale area assisting in the formation of the lagoon.

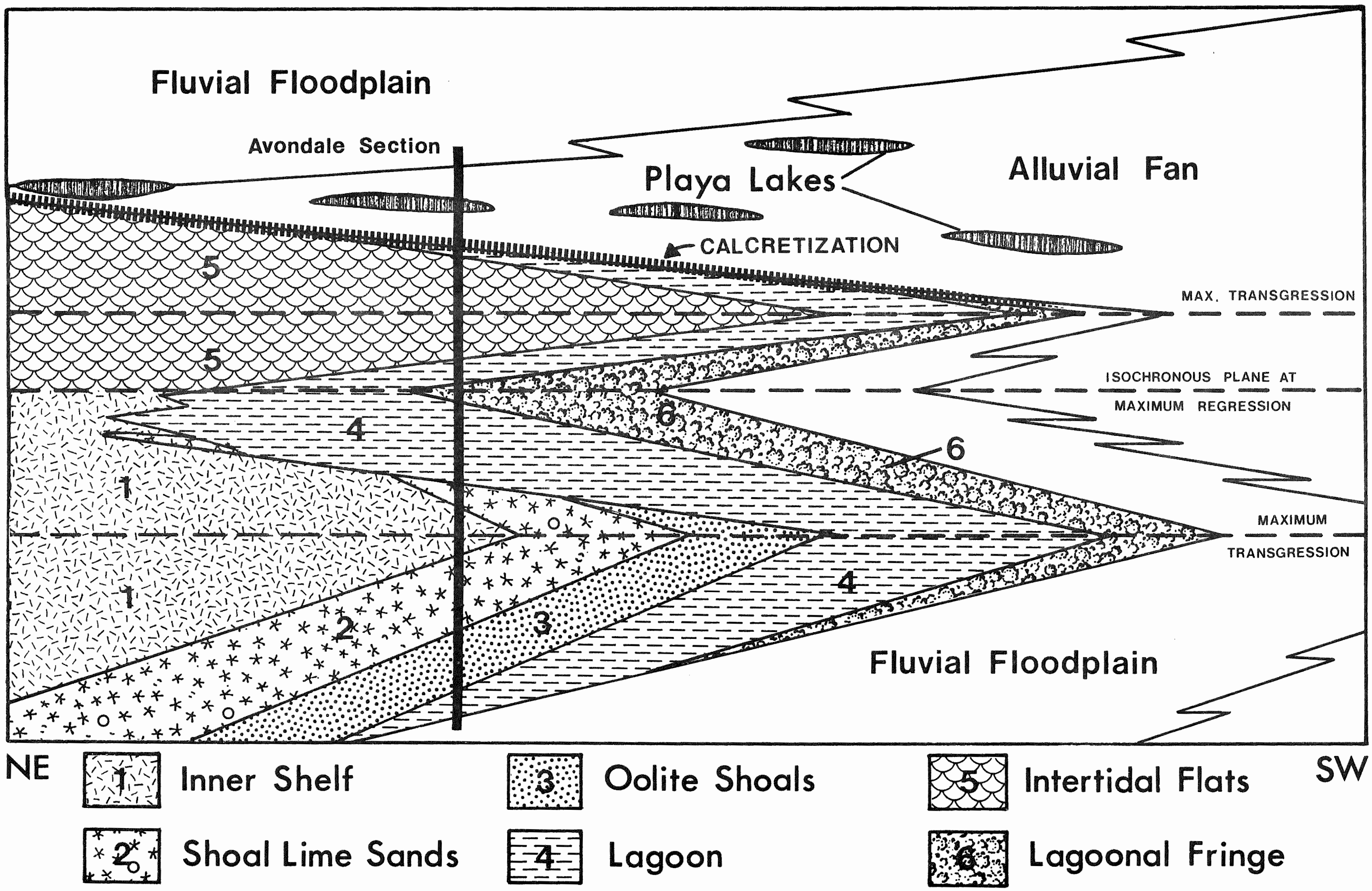
A rapid regression of this shallow sea prevented the deposition of an inversion of the oolitic and bioclastic sediments upon the initial transgressive units in the Avondale area. The thick nearshore lagoonal facies prograded seaward and was deposited on micritic muds of the inner shelf environment. Sediments of the supratidal lagoonal fringe were subaerially exposed and subsequently indurated and eroded.

Before total destruction of the supratidal sediments could occur, a second minor transgression occurred effectively covering and protecting these sediments. A reworking of the inner shelf and lagoonal muds by tidal forces resulted in the formation of a high-energy, intertidal flat facies. Frequent subaerial exposure of this environment produced desiccation features, a paucity of fauna and abundant gypsum crystals that indicate a semi-arid climate probably existed at that time. Eolianitic clastic material was deposited in the sediments as very minute concentrations on the exposed or slightly submerged carbonate sediments.

A slow regression, or shallowing upwards of the carbonates created an open lagoon and marginal marine marsh facies, both adjacent to, and later deposited over the tidal flat facies. An acceleration of the regression caused the carbonate sediments to become subaerially exposed. Exposure to the dissolving action of rainwater, direct heat and plant root action all contributed to the <u>in situ</u> formation of a breccia from the exposed carbonates. This was the first phase of the formation of the calcrete soil horizon. A thin veneer of clastic material covered the breccia and the pedogenic formation of the calcrete continued. Induration of the soft calcrete occurred after its exposure by removal of the overlying clastic veneer or soil by deflation. Fluvial clastics or eolianitic sediments later covered the calcrete, and in small, low depressions of the clastics coastal playa lakes or ponds formed. These ponds may be the remnants of a third, minor transgression, probably only observable in sediments to the northeast. The playas were subjected to periods of flooding by marine waters during storms and were exposed subaerially for long periods, producing a flat-pebble breccia.

This area was then rapidly covered by debris flow sediments from adjacent alluvial fans. The playa deposits occur within these fanglomerate sediments in some parts of the study area. Conceivably, debris flow sediments may have existed before playa formation. The sediments of the debris flow consist of poorly sorted conglomerates and interbedded muds, silts, coarse sands and gravels. Quartz, mica and slate fragments contained in these sediments indicate a source from the surrounding basinal uplands (slate: > Ordovician metasediments, quartz and mica: > Devonian granites) and their angularity suggests a rapid mode of transportation, or one which protected the fragments (i.e. debris flow).

As tectonic stability returned to the basin area, fluvial floodplains were re-established. Siliclastic sediments were again deposited in the basin, eventually levelling it out and awaiting the next marine transgression.




FACIES MODEL, MEANDER RIVER CARBONATE SHEET, AVONDALE AREA

fig.40

# SEDIMENTATION CONTROLS

It is possible that sedimentation in the western Minas Sub-basin was controlled by tectonic forces and gradual, but persistent basin subsidence during Meander River time. Local rejuvination of bounding faults during this time would cause local variations in the slope and/or depth of the basin and the subsequent changes would especially be reflected along the basin edge. The 'trigger' for the initiation of faulting could be basinal subsidence or a reaction to tectonic forces operating on a larger scale in a distant area.

Since the carbonate sediments of the Meander River Limestone represent shallow marine environments (approximately 0-4 metres), only slight changes in the basin slope and/or depth would cause rapid lateral movement of these energy-sensitive environments. The absence of an inversion of the sediments of the initial transgression during the first regression, preservation of an apparently rapidly formed calcrete soil and the presence of alluvial fan sediments indicates that local changes did take place.

Glacial eustatic changes of the sea level may also be a cause for the series of transgressions and regressions observed in the Meander River carbonates. However, due to the small size and restricted study of the Avondale exposure it is really impossible to determine the sedimentation controls and they may only be speculated upon. A detailed study of the siliclastics and carbonates of the entire basin would be needed to determine if tectonism played a major role in controlling sedimentation in the basin. Even a study of this size and scope may yield little data that would determine the causes of the series of transgressions and regressions observed in the western Minas Sub-basin.

## PALEOCLIMATE

Climatic conditions during the deposition of the Meander River carbonates in this area ranged from semi-arid to temperate. The lack of thick supratidal evaporites, primary or syngenetic dolomite and extreme desiccation features negate an arid environment, whereas the abundance of fine gypsum crystals in intertidal carbonates, the presence of algal gas blisters and gypsum blisters and the occurrence of the calcrete soil point to semi-arid conditions. The formation of the calcrete inself is usually only initiated in temperate to semi-arid conditions with infrequent periods of heavy but brief rainfalls and long, dry spells (Bretz and Hornberg, 1949; Reeves, 1970, 1976; James, 1972; Steel, 1974 and Walls et al., 1975). Although several studies cited by Reeves (1976) show that calcretes form over a broad spectrum of climatic conditions, the universal concensus is that their formation is representative of prolonged, near surface aerial exposure and that more indurated calcretes (i.e., like that at Avondale) are indicative of drier climatic conditions (Reeves, 1976).

The presence of roots in the calcrete, along with an organic rich zone may suggest that the climate was not so dry that plants (in abundance ?) could not grow. Shifts from a near-temperate to semi-arid climate, or vice-versa could indeed be possible, but probably impossible to determine in the carbonate section studied.

## RECOMMENDATIONS

The complexity and extent of the calcrete soil profile deserves a detailed examination alone, especially in the western Minas sub-basin. A study of this kind would fulfill the need for more data on ancient calcretes (a call echoed in many papers on this subject) and possibly provide a better understanding of the type of climate in this area during Windsor times. A work of this nature and scope would also assist in further refining the paleotopography and paleogeography of this area.

The fanglomerate sediments (debris flows) should be examined throughout the area to try and determine the paleocurrent direction and sources of the alluvial fans and their relationship to tectonic events in this basin.

It would be ideal if a study of the entire Meander River Carbonate from the Windsor area to the Shubenacadie Basin could be undertaken. Because of its sheet-like extent and little change in thickness, it would offer a fine opportunity to observe the lateral variations of the different lithozones through time or at a point in time, and permit a "tie-in" of the western Minas sub-basin and Shubenacadie basin.

Finally, the author would like to see further studies on a B.Sc. or M.Sc. level on the other sheet-like carbonates of this sub-basin which are typical of the Upper Windsor Group.

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# APPENDIX I

SECTION I

## SAMPLE 1-1A

## OOSPARITE

This sample consists of two major components; ooids and oolitoids, with the former the dominant clast. The ooids are complete and boring algal filaments are prominent. Boundaries between ooids are sharp except for rare microstylolitization. The oosparite is 99% pure, with rare uncoated bioclastic remains. Ooid sizes range between 1.0-1.4 mm and contain nuclei in sizes from 0.05-0.05 mm. The nuclei include foraminifera, ostracods, shell fragments, pellets, spines (phyla unknown) and rare quartz grains. The ooids display little over-packing, and are well sorted with respect to size and shape. This is best seen where vague laminations occur in the sample, with ooids decreasing in size upwards and displaying a more open-packing, which forms the laminations. Grapestone lumps are occasionally present composed of up three ooids or oolitoids. These lumps are well coated and display boring algal filaments. Sparry calcite forms the cement which is clear, blacky and uniform.

## SAMPLE 1-1

## OOSPARITE

Similar to sample 1-1A, this sample is made up of ooids, oolitoids and also, coated grains. Most ooids are complete, with some superficially coated grains; and display concentric growth, some spiral. Ooid size ranges from 1.0-1.5 mm and nuclei from 0.05-0.5 mm. Nuclei are similar to those in sample 1-1A. Laminations and low angle crossbeds are the same as in 1-1A, but are more noticeable. Solution compaction is quite visible in the ooids underlying the more open-packed laminations. The ooids in the laminations are generally of even size, small and if irregular-shaped, with elongate axes parallel to bedding. A black, remnant blue-green algal mat is visible in the lowermost portion of the sample. The cement type is blocky, uniform, clear sparry calcite which may be syndepositional. Evidence supporting this is seen when observing the open packed lamination between layers of close or overpacked ooids displaying solution compaction. (See p. 60).

SAMPLE 1-2

PELLETIFEROUS OOSPARITE

This sample represents the beginning of a transition from oosparite to overlying calcisiltites. Ooids are the dominant clasts, with an increasing number of oolitoids, uncoated shell fragments and pellets. Most ooids are complete but an increasing number have superficial coatings only. Ooid sizes cover a greater range than previous samples; between 0.2 and 1.5 mm in diameter and nuclei from 0.1-0.7 mm. The nuclei are composed of foraminifera, shell fragments, spines and pellets. Pellets are elongate ovals and are all about 0.1 mm long. Packing is grain to grain with both ragged and sharp clast boundaries present. Moderate micritization is evident in some ooids. Ooids are well sorted and display sorting of smaller ooids and pellets into lenses. Elongate axes of coated grains and oolitoids are unorientated. Grapestone lumps consist of two to four ooids, oolitoids or coated grains are also common. Two cement types are present; sparry calcite and a carbonate silt, calcisiltite. The spar is clean and blocky, composing 90% of the cement. The calcisiltite is restricted to the top centimeter of the sample, with less grain to grain contacts between ooids. The spar appears to be early post-depositional, with evidence similar to that described in sample 1-1. The calcite silt size is approximately 0.1 mm diameter and is well rounded.

SAMPLE 1-3

FOSSILIFEROUS OOSPARITE

(CALCISILTITE)

Gastropods (discoidal and pupiform), ostracods, foraminifera, crinoid fragments, brachiopod shell fragments and spines make up the bioclastic component of this oosparite. These clasts have sharp boundaries and are angular to well rounded. They form the nuclei of the ooids also. Ooids oolitoids and pellets make up the majority of the non-bioclastic grains, with few coated grains. Ooids are generally complete with concentric growth rings and algal borings, but ooids with larger nuclei are merely superficially coated. The ooids are larger than those in lower units; 1.2 mm diameter with ooids smaller than this rare. The ooids display grain to grain packing in most cases, with some overpacking and solution compaction. Micro-stylolites are present, parallel to bedding. Grapestone lumps are rare, and are comprised of only two ooids. The sample displays no sorting with respect to size, but does with shape, this being the orientation and assembling of spines and shell fragments in irregular layers. The packing of clasts is similar to that in other ooid-bearing samples, with zones of undeformed, nearly open-packed clasts bounded above and below by deformed and overpacked clasts. Remnant algal mats are present in the sample, being highly irregular and discontinuous. The cement is composed of carbonate silt, with the occasional patch of sparry calcite which is also seen to fill shell voids. Within these spar-filled shells are well preserved, oval pellets, (0.1 mm long). It would appear from observations on the packing of clasts in this sample and others (1-1, 1-2), that cementation was either syndepositional or early postdepositional. (See p. 60).

SAMPLE 1-4

BIOCLASTIC OOSPARITE

(CALCISILTITE)

This sample contains a large and varied number of fossils and non-bioclastic fragments. Bioclasts include echinoderm plates (crinoidal), echinoid spines, brachiopod fragments, foraminifera and ostracods. Grain boundaries are sharp, with the clasts themselves being angular to well rounded. Non-bioclastic clasts are composed of 90% complete ooids with the remaining 10% made up of oolitoids and coated grains. Ooid size is highly variable; from 0.3-1.4 mm with concentric coatings and prominant algal borings. Nuclei sizes are from 0.1-1.0 mm and composed of bioclastic fragments and rarely, pellets. Ooids are observed as scattered patches in the lower centimeter of the sample with grain to grain contact rare. The top centimeter of this 2 cm thick sample contains ooids as individuals in the calcisiltite matrix. Grapestone lumps are rarely present.

No sorting of grains is evident, however elongate axes of clasts are parallel to bedding in most cases. The sample seems to have been subjected to extensive burrowing by unknown organisms. Carbonate silt; calcisiltite, composes the matrix-cement, with a grain size of approximately 0.1 mm diameter. Sparry calcite is present as a pore filling.

## SAMPLE 1-5

## FOSSILIFEROUS OOSPARITE

Within this sample the percentage of bioclastic and non-bioclastic components is equal. Ostracods, brachiopods (sometimes complete) and crinoid fragments are abundant, while foraminifera and gastropods are rare. Dasycladacean green algae fragments can be observed but are hard to recognize. Clast boundaries are sharp and most clasts are well rounded. Ooids are generally well preserved with a few relict ooids present. About 75% of the ooids are complete where as the remaining 25% are merely superficial coatings. Complete ooids show well developed concentric-coatings and algal borings. Nuclei of the ooids are made up of bioclastic fragments and pellets. Lithoclasts are not abundant, however they appear regularly throughout the sample. They are about the same size as ooids, well rounded, equidimensional and composed of calcisiltite. Both bioclasts and ooids display random orientation and exist as a homogeneous mass. The main cement is blocky calcite spar with the spar also as a void filling, especially in brachiopod shells. Calcisiltite is a minor component restricted to the top of the sample, however, it is occasionally observed as a shell filling throughout the sample. Where the shells are spar-filled, pellets can be observed as small groups nestled in the bottom of the shell. A lack of compression and/or alteration of the clasts, no overpacking and a retention of open space packing indicate probable early post-depositional cementation of the sediment.

## SAMPLE 1-6

## OOLITE BEARING BIOSPARITE

Bioclastic remains predominate in this lithology, with crinoid fragments, echinoid plates and spines, brachiopod shell fragments, dasyclad algal branches and rare foraminifera and ostracods. The clasts are fragmented, rounded and have sharp clast boundaries. Ooids are uncommon, making up less than 5% of all clasts in the sample. They are mostly complete with regular coatings and evidence of boring algal filaments. Their size averages 1 mm in diameter with 0.1 mm nuclei of ostracods, forams or spines. There is no size or shape sorting, however, unlike sample 1-5 there is orientation of elongate axes of shells and spines parallel to bedding. Packing is open, with no evidence of compression or overpacking. Carbonate silt comprises the major portion of the matrix, with sparry calcite found in small, irregular patches, vertical fractures or as a void filling. The spar is blocky and in areas of veins or patches shows destruction of clasts

It is probably post-depositional in origin.

SAMPLE 1-7

BIOSPARITE

(CALCISILTITE)

Various phyla and classes of organisms are represented in this very homogeneous sample, such as crinoids, echinoid spines and plates, brachiopod fragments and spines and Dasycladacean green algae. Ostracods are rarely seen. All remains are fragmented and well rounded with sharp grain boundaries. No ooids are present. Most bioclasts are small in size, from 2-4 mm. Equidimensional rounded intraclasts are scattered irregularly throughout the sample. Flattened intraclasts are orientated parallel to bedding. Their composition is the same as the matrix, only lighter in color. Size and shape sorting of clasts is present, with elongate axes parallel to bedding; however some of this has been destroyed by burrowing organisms. The burrows are about 1 cm deep and are either spiral or wavey in shape. Burrowing appears to have taken place while the sediment was still viscous. The matrix consists entirely of carbonate silt, light grey in color with a grain size of approximately 0.05 mm. No sparry calcite is present as a cement.

SAMPLE 1-8

INTROCLASTIC BIOSPARITE

(CALCISILTITE)

This sample is very similar to sample 1-7, as the same types of bioclasts and matrix are present. However, the bioclasts tend to be larger (up to 8 mm as compared to 4 mm), more angular and less fragmented. Dasycladacean algae fragments are abundant, as are thick walled brachiopods. Intraclasts are 1-1.5 cm long, plate-like and are of the same composition as the matrix. Three types of burrows are present; vertical, horizontal and inclined. They are unlined, and up to 2 cm long and/or in diameter. Bioclastic debris fills the larger burrows. The sample has inclined bedding, with some areas rich in bioclasts and others composed of only fine, light grey carbonate silt. Some sorting is discernable, but burrowing has altered most of the sample's original texture. Carbonate silt comprises the matrix/cement and is also seen as an infilling of some shells.

SAMPLE 1-9

CALCISILTITE

Bioclasts are very rare in the unit from which this sample was taken, being only echinoid spines and plates. Small ovate horizontal worm tubes are visible in the polished section and on the bedding surfaces, are 'spagetti-like'. The calcisiltite is massive and exhibits a rough, parallel parting. The carbonate silt grain size is slightly larger than that of the biosparites 1-7 and 1.8, being about 0.07 mm in diameter. The sample is quite gritty, with a large quartz silt content (see Appendix III).

## SAMPLE 1-10A

## INTRAPELSPARITE

Unidentified shell fragments are the only bioclasts present and are not very common. They are parallel to bedding, concave downwards. Small ovate worm tubes (similar to 1-9) are frequently seen. Peloids comprise the bulk of the sample. They are grumulous, and clotted in appearance and are of uniform size (between 0.02-0.03 mm diameter). The peloids are generally better preserved under the shell fragments. Lithoclasts are prominent, being flat (1 cm x 0.4 cm average), darker than the matrix and appear to be of a slightly different composition than the matrix. Faint parallel laminations are present in the sample. Small rounded gypsum crystals are occasionally present, only about 0.2 mm in size. Microspar calcite forms the cement, which has probably altered the original pelleted texture of the sediment. It also displays a series of faint parallel laminations.

## SAMPLE 1-10

## BIOSPARITE

Abundant brachiopods, echinoids, crinoids, dasycladacean algae fragments and occasional gastropods comprise the biota of this sample. The clasts are fragmented (echinoid plates and spines, crinoid plates, brachiopods) or whole (brachiopods and gastropods). Fragments are larger than those in the lower biosparites of the section. All bio-clasts are well preserved with sharp boundaries. There is good size and shape sorting of clasts, which results in the formation of wavy beds or lenses in the sample. Some of these beds consist only of carbonate silt. The amplitude and wavelength of these bioclastic beds is 2.0 cm and 0.5 cm respectively. The upper and lower quarters of this sample consist of carbonate silt incorporating large, whole brachiopod shells in living positions. The upper contact between the bioclastic debris and overlying barren carbonate silt is very sharp and appears to be erosional. Bioclasts in the centre display no preferred orientation. The matrix/cement of the sample is composed of carbonate silt with a grain size of 0.03 mm; smaller than the silt in the underlying biosparites. Sparry calcite fills a few cracks and several irregularly shaped fractures. Carbonate silt also fills the interiors of all intact brachiopod shells. Microspar appears to be the dominant cement in the central bioclastic-rich section of the sediment, possibly from the transformation of the carbonate silt to spar. Some silt however is present as patches within this zone of spar.

SAMPLE 1-11

PELSPARITE

Rare clam fragments are scattered throughout the sample, some of which are broken and are in unstable positions, ie., their long axes in the vertical direction. Small horizontal worm tubes are present on bedding surfaces and within the sample. Matrix material appears vaguely pelleted, probably due to alteration of pellets or pelloids during the formation of the microspar cement. The pelsparite exhibits very fine, alternating light and dark brown laminations some of which are truncated by low angle crossbeds. Some shells exhibit umbrella structures containing pellets better preserved than those in the matrix. Also present under some shells and within certain laminations are rounded to elongate white gypsum crystal casts. Their size ranges from 0.2 mm (rounded) to 0.8 mm (elongate). Some of these casts have been replaced with white colored microspar calcite.

SAMPLE 1-12

MOTTLED SPARITE

Unlike the majority of samples, the color of this sample is unique, as it has a greenish tinge over a light tan base color. This weathers to a medium pea-green with a waxy appearance similar to serpentine. Rounded, irregular mottles with an average size of about 3-5 mm are darker than the matrix. Some of these mottles are linked to each other and have elongate axes parallel to bedding. Weathering of the rock shows the mottles as dark pebble-like forms in a greenish tan matrix. A few clam fragments are present, and some show geopetal structures with the original clotted, lighter colored matrix clearly visible. Irregular, dendritic cracks are common, either parallel to bedding or following the outlines of the mottles which were shown to be slightly harder than the matrix during polishing. There is no visible textural or compositional difference between mottles and matrix. Both are composed of microspar. Some small, 0.3 mm ovals filled with sparry calcite are scattered throughout the samples and are of unknown origin. Larger voids are filled with spar cement showing centripetal growth, and resemble stromatactis voids. However, they cannot be positively identified as such.

## SAMPLE 1-13

## MOTTLED SPARITE

Sample 1-12 is very similar to this sample, but here the mottling is much more pronounced. The mottles are up to 3 cm long and form large, irregular masses parallel to the horizontal, with few small and round mottles. Horizontal dendritic cracks are also present with larger, less dendritic spar filled fractures. No vertical cracks are in evidence. The mottles are darker than those in sample 1-12 and have an outer zone or 'halo' about 0.1 mm thick, lighter in color surrounding the mottles. Shell fragments are variously inclined throughout the sample and display umbrella structures when the shells are oriented concave downwards and most strangely when the concave portion of the shell is sideways (fig. 16, pg. 29 ). As in sample 1-12 no difference could be observed in the composition of the microspar matrix/cement and mottles. Minute (0.1 mm) peloids and structures identical to those in the previous sample (gypsum casts) are clearly visible under shells displaying umbrella structures. Blocky calcite is present as a void filling; the nature of the voids unknown. Some of this calcite spar is ferroan in composition and is smokey brown in color.

## SAMPLE 1-14

## PELSPARITE

This sample appears to mark the upper limit of the mottling so conspicuous in samples 1-12 and 1-13. It is seen only in the lower quarter of the rock with an upper boundary deliniated by a continuous 'fracture'. The mottles are large (1-3 cm) and elongate to the horizontal with minor rounded mottles in the lower portion of this zone. The 'fracture' marking the upper limit of the mottles is undulating and shows linear fenestral structures of about 1 mm thick. This 'fracture' is probably algal in origin, ie. remains of a blue-green algal mat. Spines, shell fragments and very well preserved gypsum crystals are found about this fenestral zone. Small, ovate, horizontal burrows are occasionally present throughout the sample; also observed, a larger 1 cm deep funnel-shaped burrow protruding from the top of the sample into lower underlying sediments. The aforementioned bioclasts and gypsum are observed on the upper surfaces of low angle crossbeds which are faintly visible. All have elongate axes parallel to bedding. The cement is microspar calcite which has a clotted appearance. Pellets or peloids are not noticeably present, but may have existed before the formation of the microspar cement. Clear and smokey calcite have replaced echinoid (?) spines, plates and voids of unknown origin.

## SAMPLE 1-15

## PELSPARITE

Several remnant blue-green algal mats and the associated fenestral structures are the only bioclastic remains in the sample. The algal mats themselves have been destroyed resulting in irregular, wavy fractures parallel to bedding or as horizontal veins of white dogtooth spar with a few open calcite-lined voids. The sample contains very fine, light to dark brown laminations with rare low angle crossbeds. Numerous small, rounded gypsum crystals are associated with the algal mats, most abundant at the top and bottom of the sample. Irregular, dendritic, non-continuous fractures are also present, but are not associated with the algal mats. Cement is microspar calcite, which appears nodular about the algal mats and laminoid fenestrae. The microspar has a clotted appearance, with very faint peloidal structures occasionally discernable. One, 1 cm deep vertical tubular burrow is present.

## SAMPLE 1-16

## PELSPARITE

Clam nests are easily seen on the upper surface of this sample and in other rocks near the sample in the section itself. Stromatactis-like structures are present, but cannot positively be identified as such. These structures are associated with remnant algal mats and their linear fenestral fabric. Gypsum crystals; elongate, rounded or euhedral are abundant throughout the sediment, especially above and below the algal mats. They can be parallel to bedding, or less commonly unorientated in the sediment, usually as the result of burrowing organisms. A few 1 cm deep vertical tubeshaped ones are visible, projecting downwards from the clam-rich bed. Peloids are ovate, about 0.05 mm in length and are somewhat clotted or fuzzy in appearance. The sample has more massive bedding than previous samples, and the crossbeds are steeper. Microspar constitutes the cement. Irregular, discontinuous fractures are present, similar to samples 1-14 and 1-15 however here they are more prominent.

SAMPLE 1-17

PELSPARITE

This sample is unusual in that it displays two characters; one that is massive and slightly fractured and adjacent to it, a highly brecciated portion. Both parts consist of the same lithology but strangely the brecciated portion has much better preservation of clasts and matrix than the unbrecciated portion. The breccia contains little evidence of any movement of the clasts, as laminations can be traced from the massive, undisturbed portion into and across the breccia. No slickensides or bent clasts are present. Stylolites are present, rarely seen in the breccia clasts. The breccia fragments are cleanly separated and contain vertical and horizontal cracks. The fractures and breccia clasts are filled or lined with clear, blocky calcite, and large voids are lined with spar displaying centripetal growth. These cracks are interpreted as probable dissication (vertical) and buckle (horizontal) cracks. Similar cracks are present in the unbrecciated portion, but are less numerous and less well developed. The entire sample contains fine dark to light brown laminations, high angle crossbeds and scour surfaces. Bioclasts present include rare clam shells and thick (up to 1.5 mm) remnant algal mats (seen only in the breccia portion). Small ovate worm tubes are also present. Fecal pellets are very well preserved, especially in the breccia. They are spherical to slightly oval and are about 0.02 mm in diameter. Gypsum crystals are occasionally seen, being euhedral in shape and unorientated and replaced by calcite spar. Cement is microspar calcite with blocky or dogtooth calcite spar as the breccia cement. The breccia is interpreted as a collapse breccia from the adjacent removal of sediment, somewhat like that seen in the banks of small tidal channels.

SAMPLE 1-18

ALGAL PELSPARITE

Remnant algal mats constitute the only fossil remains in the sediment. Associated laminar fenestrae is poorly developed, however the upper and lower surfaces of the sample display a black, pitted, undulatory surface typical of algal mats. Peloids are vaguely discernable, and there are no laminations of sediments in the sample. Burrows like those described in samples 1-14, 1-15, and 1-16 are also present. Irregular dendritic fractures of unknown origin like those discussed in samples 1-15 and 1-17 are quite abundant. Microspar is the only form of cement and it has an oval or rounded form when associated with algal mats. Although immediately above sample 1-17, grain preservation of the pellets as compared to 1-17 is very poor.

## SAMPLE 1-19

## ALGAL PELSPARITE

This algal pelsparite directly overlies the previous sample. No fossil remains except the algal mats are present. The algal mats are continuous or in pieces within the sediment. The upper and lower surfaces of the sample display the black, pitted undulatory surface typical of algal mats. Laminoid fenestrae are very distinct, some of which lead to large (1-2 cm long) voids, flattened at the bottom and a rounded, dome-shaped roof. These half-lensoidal voids are lined with dogtooth spar; some voids being completely filled. The algal mats show entrapment of carbonate silt, especially in the centre area of the void. In plan, these voids are cookie shapped and in essence could be thought of as hollow cookies. Other voids, filled with clear sparry calcite have some rib-like structures composed of material from the matrix. These voids have been interpreted as algal blisters (Davies ,1970; Logan et al., 1974; Hoffman, 1976). Peloids appear as vague oval forms. A few small (1-3 mm long) flattened lithoclasts of carbonate silt are present in the sediment trapped by the algal mats. Cement is clear microspar, again exhibiting a nodular appearance about the algal mats. The sample has faint parallel laminations, and no crossbeds or scours are present. Gypsum crystals are present and associated with the algal mats. The crystals are euhedral to rounded in shape.

SECTION 2

## SAMPLE 2-1

## PELSPARITE

This is a silty, finely laminated pelsparite with few organic remains. A few clam fragments are present, and remnant blue-green algal mats within the upper centimeter of the sample (identified from linear fenestral fabric). Peloids are vaguely defined, similar to those described in samples from Section 1 that are lithologically similar. Very fine light and dark brown colored laminations are visible, and show rare, low angle crossbedding. Small (3 mm), ovate (in cross-section) horizontal worm tubes are common throughout, and 1 cm long inclined burrows are also present. Rounded gypsum crystals are common, increasing in number upwards in the sample, either scattered throughout the sediment or concentrated with centain laminae. They are more elongate than those described in Section 1, and are well preserved, especially under clam shells. Cement is composed of microspar calcite, which contains abundant carbonate silt grains and imparts on the sample a gritty, earthy appearance.

## SAMPLE 2-2

## PELSPARITE

This pelsparite is analogous to sample 2-1, however some differences are present. The sample displays more obvious and numerous low angle crossbeds. Algal structures (laminoid fenestrae) are present in the lower centimeter of the sample as well as the upper centimeter

Numerous long (up to 4 cm) and very narrow (0.10-0.01 mm) vertical cracks filled with clear calcite spar occur throughout the sample. They show no signs of slippage or tension; rather a neat, clean separation of the sediment, similar to prism or dessication cracks. The sample also displays burrowing on a greater scale and intensity than in sample 2-1.

## SAMPLE 2-3

## MOTTLED PELSPARITE

Vague laminations and crossbeds are obscured by a dark brown, spotted mottle. The mottles are diffuse, between 2 and 4 mm in diameter and are roughly circular. No textural differences could be observed between the mottles and the unaltered matrix. This sample is different from the mottled samples in Section 1 (1-12, 1-13) in that it has a dark greyish brown color, and no waxy appearance. Worm tubes and clam fragments are rare, as are the rounded gypsum crystals, which are concentrated within certain laminae. However, they do show a relative increase in numbers towards the top of the sample. They can also be seen 'falling' into small burrows. Irregular, dendritic and verticle cracks are visible, which are not open nor filled with spar as is normally the case in other samples. The cement is a fine, clear microspar, with faint peloids visible within. There is little carbonate silt present, which appears to give the sample a greater hardness than samples 2-1 and 2-2.

## SAMPLE 2-4

## PELSPARITE

Outwardly, this rock resembles samples 2-1 and 2-2. The sample also displays a vague mottling not unlike that in sample 2-3, however it occurs only as a 2-3 cm band running across the centre of the sample. Fossil remains are rare, composed of a few clam fragments and worm tubes. The odd spine (unknown origin) is found on the upper and lower surfaces of the sample. Discrete peloids make up the matrix, cemented with a microspar cement. Gypsum crystals are also present, but are few in number.

## SAMPLE 2-5

## ALGAL PELSPARITE

Blue-green algal mats (now black) are the dominant fossil forms which result in wavy, undulating laminations with associated laminoid fenestral. Numerous small (1-2 mm) cusp-shaped wisps of algal mat are abundant in the matrix between the larger, preserved mats. Shell fragments are present in small numbers. Peloids comprise the matrix and are somewhat better preserved than those in previously described samples from this section.

Casts of gypsum crystals are common, most of which are euhedral. The sample is characterized by many small (0.5 mm) irregularly shaped solution pits which appear to be the result of dissolving of unknown clasts or specific areas within the matrix. Small (up to 0.5 mm in size) dark brown patches of micrite are also present, imparting a dotted appearance to the sample. Minute irregular fractures are abundant and are seen to connect the previously described solution pits. The cement is microspar calcite, however this sample is quite hard relative to others. Dolomite was shown not to be present after etching and staining of the sample. The hardness could be the result of recrystallization of the microspar, but since no thin section was produced from this sample this is speculative.

SAMPLE 2-5A

ALGAL PELSPARITE

This lithology overlies sample 2-5 and displays similar features. However, shell fragments (brachiopods ?) are seen with the original shell material destroyed and replaced by a dark ferroan calcite. Small burrows are also present. The sample has more distinct laminations than sample 2-5, with rare, low angle crossbeds. These laminations could be algal in origin, however the expected laminoid fenestrae is poorly developed. Fractures in the rock are larger, and more noticeable, with a few very large cracks perpendicular to bedding, extending the entire thickness of the sample. The microspar cement is grey-brown in color, but still clear to a degree. The hardness of the sample is like that of the previous sample. Small gypsum crystal casts parallel to bedding are also present. Dark brown micrite stringers can be observed under high power magnification in the polished slab.

## SAMPLE 2-5B

## LEACHED CARBONATE

The lower portion of sample 2-5A is represented by a chalky, yellowish-tan unstructured leached carbonate rock. It is usually observed as a weathered out, hollow zone up to 10 cm thick beneath sample 2-5A, with which its contact is transitional. This unusual lithology is not observed in sections 1 and 3, east of section 2, but is distinct in the section west of section 2. In sections 1 and 3, this lithology exists as a continuation of the rock type described for sample 2-5A, which may show that sample 2-5B was lithologically equivalent to 2-5A, but was transformed into its present state by dissolving waters.

## SAMPLE 2-6

## ALGAL PELSPARITE

This rock directly overlies sample 2-5A. It is a relatively massive rock, with abundant remnant algal mats at the top and bottom of the sample. Pisolitic structures are present in the lower algal mats, being roughly rounded, 5 mm in diameter and loosely surrounded by algal filaments. It would appear that these pisolite-sized clasts moved very little after the time of their formation. They may simply be small pieces of carbonate mud which have been moved by water action over a short distance and stabilized and/or captured by the algal mats. The algal mats are black, very irregular and have a dark, pitted undulating surface. Unidentified, rare shell fragments are found associated with the algal mats in irregular positions (i.e., concave upwards). Lamnoid fenestrae are well developed about the algal mats. The matrix is vaguely pelleted; the pellets probably being altered during the formation of the microspar cement.

SAMPLE 2-7

ALGAL PELSPARITE

High porosity is characteristic of this sample. Abundant voids range in size from 0.5 to 4 cm across, and are roughly lensoidal in shape with flattened bottoms (Fig. 18 pg. 35). In plan, they are circular with bulged roofs and radiating cracks. Some voids show distortion, with one portion of a void bent upwards and from which verticle cracks emerge. Voids above these disrupted areas are distorted also (see Fig. 18 pg.35). Voids in the upper half of the sample are irregular in shape and are interconnected by enlarged laminoid fenestrae. In the lower half, the voids are lined with white dogtooth spar displaying centripetal growth, or are completely filled by the spar. Other voids filled with spar show different stages of dissolution of the spar. Upper voids display a lacework-pattern of the brown carbonate matrix. Remnant algal mats are abundant along with the associated laminoid fenestrae. The algal mats arch over the voids and in some cases carbonate silt is present at the bases of the arches, exhibiting a wind shaddow type of structure. From the shape, size and fillings of the voids, and the presence of algal mats, these voids are interpreted as algal blisters, formed during the heating of the algal sediment by the sun and the subsequent release of organic gases from decaying matter to form blisters in the algal mats (see Davies, 1970; Logan et al., 1974; Hoffman, 1976).

Gypsum is present in some of the blisters growing over the dog-tooth spar in the form of large (1 cm long) euhedral tabular crystals, or, as fine prismatic masses or small lensoidal, rounded crystals in the carbonate matrix. Several blisters are filled with white gypsum exhibiting structures similar to those observed in the calcite filled voids; the lacework structures always present. They have the same shape and appear to be primary; i.e., gypsum growth probably formed these structures, not gas (Fig. 19 pg.35).

The algal mats occur as black, irregular laminations, and a vague, pustular algal texture is present between the algal mats which contain the associated laminoid fenestrae. No other types of bioclasts are present. The matrix consists of a clotted microspar, containing few pellets or pellet-like structures. Staining of the sample indicated an absence of dolomite. Limonite is abundant within the unlined voids at the top of the sample.

SAMPLE 2-8

PELSPARITE

Immediately overlying the previous sample is a fresh, unaltered, well preserved pelsparite. It has fine laminations with high angle crossbeds and associated scours. Numerous deep prism cracks cut the sample vertically, the largest of which extend from the top of the sample to the bottom, and are filled with clear calcite spar. Smaller cracks start and end at different laminae within the sample. Remnant algal mats are not common but do dilineate or follow major laminae. The associated laminoid fenestrae produce fracture planes along these laminations. The thicker mats are located at the top and bottom of the sample. A few shell fragments are present. Pellets (likely fecal in origin) are well preserved, with moderately sharp clast boundaries. They are all identical; 0.02-0.03 mm in diameter and are nearly spherical. Gypsum crystals are abundant and show no preferred orientation, and are probably in growth positions. They are found only within certain laminae, and are concentrated towards the top of the sample. Fine clastic silt is visible in the polished slab when held near a light source. It appears as minute bumps on the surface, and can be seen to concentrate in the laminations, following crossbeds and scours. Clear calcite spar comprises the cement.

## SAMPLE 2-9

## PELSPARITE

Although analogous to sample 2-8, this rock displays some unusual features. Burrowing is very extensive, with numerous trumpet-shaped depressions, the largest being 5 cm in diameter at the top and 2.5 cm deep. The bedding is more massive than 2-8, and crossbeds are at a higher angle. Numerous deep prism and buckle cracks are present, however, few are filled with calcite spar, most are filled with fine microspar. Euhedral to subangular gypsum crystals are very abundant, and show concentrations within different zones of laminations. They are also observed 'falling' into the burrows. Irregular patches of blocky calcite (∿ 1 mm) surrounded by microspar are associated with the gypsum; some of these patches being interconnected. These could once have been anhydrite patches (Elf-Aquitaine, 1975); however no analytical or textural observations can confirm this. Shell fragments are rare, present in the top of the sample only. Remnant algal mats form a black, shaly coating on the upper and lower surfaces of the sample.

SAMPLE 2-10

PELSPARITE

Several features separate sample 2-10 from the previously described pelsparites (2-8, 2-9). Brachiopod shells are not well preserved, being altered to microspar. Trumpet-shaped burrows and prism cracks are less abundant, however horizontal, 'spagetti-like' worm tubes are quite numerous. Gypsum casts are also less frequently observed.

SAMPLE 2-11

PELSPARITE

The pelsparite is considerably different from the underlying ones previously described in this section. It is light tan in color, not dark brown as are the others, laminations are fainter and cross-beds are less well developed, with lower angles to the horizontal.

Pellets are very well developed and show no evidence of overpacking. They are larger, about 0.05 mm diameter and are more ovate than those in the other samples. No gypsum is present. The lithology contains numerous, pear-shaped solution vugs, 6-9 mm in size which are lined with blocky calcite spar (Fig. 24 pg.41). Smaller voids are completely or nearly filled with calcite spar. The vugs are orientated with the bulged portion being the bottom. In other rocks of the same layer, vugs up to 2 cm diameter have been observed. Fractures are common, many of which are filled with clear spar and pass through or connect the vugs. Most fractures are vertical, and extend to the top of the sample. These vugs appear to be the result of random dissolution of carbonate sediments near or at the end of the numerous fractures. Vertical burrows are common and are about 1 cm deep. No bioclastic debris is present.

SAMPLE 2-12

PELSPARITE

Although similar to the previous sample, this sample contains no vugs. It is relatively massive with few faint laminations and is dissected by many wide (1-2 mm) prism cracks filled with calcite spar. Gypsum crystal casts are present in moderate amounts, also filled with clear spar. Pellets, fecal in origin, are well preserved, and no bioclasts are present.

## SAMPLE 2-13

## LAMINATED MICROSPARITE

Laminations are crinkly, irregular and diffused, and display pinching out features. They are about 1 mm apart and are lighter in color (buff to tan) than the dark brown microspar matrix. In thin section however, these laminations are composed of dark brown micrite (?). No laminoid fenestrae are present. The matrix has a clotted, nodular appearance with dark brown horizontal micrite stringers. These features are best observed in thin section. Several small vertical fractures cut through the entire sample. The surface of the sample before it was cut and polished displayed a series of solution pits lined with fine blocky microspar, identical to those in sample 2-11. An ostracod and shell fragment at the very bottom of the sample are the only bioclasts present, both of which are heavily altered to microspar. Limonite is present in the voids located at the top of the sample.

## SAMPLE 2-14

## PSEUDOBRECCIATED PELSPARITE

Original bedding is still visible, however it is disrupted by numerous, irregular 0.5-2 cm voids lined with dogtooth spar or more commonly, blocky calcite. The larger voids in the upper portion of the sample have lateral connections. Numerous, unoriented suture-like fractures connect the smaller voids. The matrix is intact in the lower portion of the sample, whereas the upper portion is more disrupted with much larger voids. No fossil fragments are present. Gypsum casts are very abundant throughout the lower portion of the sample, most of which are orientated horizontally. The crystals are either elongate or equant, most of which are euhedral. The matrix is vaguely pelleted with a clotted appearance. The pellets or peloids probably have been altered during the formation of the solution cavities.

# SECTION 3

SAMPLE 3-1

OSTRACODAL INTRAPELBIOSPARITE

This is the lowest carbonate unit in the sequence. The sample is characterized by four bands or layers, each layer being quite distinct from the other. The lowermost layer is 3 mm thick and contains an even mixture of well preserved ostracods and relict ooids in a dark brown ferroan microspar cement. The ostracods display some fragmentation and the ooids are generally dissolved about their nucleus. The ooids are about 1 mm in diameter, composed of fine microspar calcite, have few concentric laminations and nuclei composed of ostracods, approximately 0.5 mm in size. The second layer is 7 mm thick and displays a highly irregular "spongy" or fenestral fabric. However, no algal remanents are present. Following this unit is a fossiliferous band containing ostracods and rare brachiopods which is about 10 mm thick. The ostracods are very well preserved, and are nearly homogeneous with respect to their orientation. They are contained in a clear calcite spar cement with irregular, flattened, 1-2 mm patches of ferroan calcite. Small, 0.04 mm rounded pellets are common. The uppermost layer is the reverse of the previous one, with pellets as the dominant clast and ostracodal fragments scattered throughout. Faint laminations can be observed in the pelleted sediment. Black, soft remanent algal mats are present at the top and bottom of the sample. The upper mats display a poor fenestral fabric in the sediments immediately underlying them.

## SAMPLE 3-2

## BIOINTRAOOSPARITE

The three major clast components as indicated in the lithology name occur irregularly scattered throughout the sample. Ostracods are present and are similar to those described in sample 3-1. Ooids are found as individuals or in lenses and lumps, with their abundance increasing towards the top of the sample. The ooids found in large 2 cm x 2 cm lumps are cemented by a milky white calcite spar as opposed to the clean spar cementing the remainder of the sample. This may be evidence for an early stage of cementation for some ooids before their transportation and deposition in the ostracodal-rich muds. The ooids display fine growth lines with nuclei of shell fragments, spines and silt grains. Intraclasts are flattened and rectangular in cross-section, and are composed of the same lithology as described in the second band or layer of sample 3-1. Shell fragments, like the ooids, increase in abundance upwards in the sample. Pellets, 0.3 mm to 0.5 mm in size are also present, being associated with the ostracod rich areas in the sample. Some pellets are elongate and hollow. The sample is moderately to poorly sorted, with the greater number of clasts having their elongate axes orientated along the horizontal plane.

## SAMPLE 3-2A

## OOSPARITE

This sample is identical to the oosparite samples 1-1, 1-1A and 1-2 described in Section 1 of this appendix.

## SAMPLE 3-3

## FOSSILIFEROUS CALCISILTITE

The abundance and diversity of bioclasts is very prominent in this lithology, similar to sample 1-7 of Section 1. Crinoids, echinoid fragments and spines, dasycladacean green algae plates, brachiopods, clam fragments, sponge spicules and rare ostracods compose the biota of the sample. Most bioclasts are fragmented and well rounded, with their long axes parallel to bedding. The sample is highly bioturbated, with large (1-2 cm across) funnel-shaped burrows filled with clean carbonate silt, and small tubular, inclined burrows abundant in the upper portion of the sample. The matrix is a fine-grained, 0.05 mm diameter, very light grey carbonate silt. Patches rich in bioclasts show alteration to clear microspar.

## SAMPLE 3-4A

## CALCISILTITE

Although similar to sample 1-9 of Section 1, this sample only contains some brachiopod fragments and rare echinoid (?) spines. The matrix is clean, well sorted carbonate silt, with faint laminations. Evidence of burrowing in the form of disrupted laminations is also present. Silt-sized quartz fragments are abundant.

## SAMPLE 3-4

## FOSSILIFEROUS CALCISILTITE

This sample represents the shaley lithology found between beds of the flat, finely laminated pelsparites (see samples 2-1, 2-2, 3-5).

The matrix is a granular microspar, and is a calcisiltite. Bioclasts include numerous clam fragments and a few brachiopods and their spines. Small, complete tests of brachiopods are filled with calcite spar, as are small (1-2 mm) elongate patches of unknown origin. Fenestral fabric is present in small amounts in the upper portion of the sample. The calcisiltite is faintly laminated and quite friable. All clasts are orientated parallel to the horizontal.

SAMPLE 3-5

PELSPARITE

Algal mats with fine fenestral fabric are noticeable in the upper and lower portions of this lithology. Clam fragments and small brachiopod shells are found in various orientations throughout the sample. Gastropods are infrequently seen. The matrix is composed of finely laminated and crossbedded pellets, 0.02-0.04 mm in size. Several small 6-8 mm deep funnel-shaped burrows can also be observed. Rounded gypsum clasts are common in the upper half of the sample. Laminations which contain these rounded gypsum crystals are truncated by other laminations and/or scour fillings which also contain these gypsum clasts.

SAMPLE 3-6

MOTTLED PELSPARITE

This sample is similar to sample 3-5, but has very faint, dark brown mottles, similar to the mottling seen in sample 2-3 of Section 2. Burrowing is also more extensive than sample 3-5, with larger trumpet or trench-shaped burrows, with sediments slumping into them. Rounded gypsum crystals are abundant and beds or laminations rich in gypsum show sharp truncations with the overlying laminations.

# SECTION 4

## SAMPLE B-1

## PSEUDOBRECCIATED PEL(?)SPARITE

This sample is analogous to the sample described in section 2 (2-14). The sample is within the same unit, but above 2-14. It displays a more brecciated character, and contains no gypsum casts. The lower portion of the sample is light tan in color, and is only slightly brecciated. Remnant algal mats with well developed laminoid fenestrae are present within the clasts, and contain small 1-3 mm ovals of calcite spar. The matrix is probably recrystalized micrite, now a microspar. The upper half of the sample is similar to sample 2-14. It appears less brecciated, however the voids are lined with larger (1-2 mm compared to 0.5 mm in 2-14) crystals of dogtooth spar displaying centripetal growth. Meniscus cementation between points of contact of brecciated clasts is also present. Intensely brecciated clam or brachiopod fragments are common in the clasts. Root trubules are visible in the slide of the sample. Angular chunks of dark brown microspar can be observed "floating" in the lighter colored microspar. Dark brown micrite stringers and geopetal drops of apparently precipitated laminated micrite under the larger breccia clasts are displayed in thin section. The probable original pelleted character of the sediment is also best seen in the thin section of the sample. The pellets were likely destroyed or altered during recrystalization.

## SAMPLE B-2

## PSEUDOBRECCIATED PELSPARITE

Sample B-2 is nearly identical to sample 2-14, as previously described in Section 2. There are however, some differences. Sample B-2 was taken from the top of the pseudobreccia unit, and is capped by an algal crust. This crust is the probable remains of blue-green algal mats, which are moderately preserved along with their laminoid fenestral fabric. Verticle cracks cut the crust and extend a centimeter or so into the underlying pelsparite. The cracks are filled with clear calcite spar. Smaller, unfilled dendritic cracks are common throughout the sample, connecting the voids. The voids or vugs are roughly flat oval in shape to irregular, crack-like shapes. The vugs are lined with a very fine dogtooth spar. The numerous voids tend to create the impression of a breccia, in uncut and unpolished samples. However once polished, the 'breccia' is actually a psuedobreccia with no angular clasts present in a matrix; however, some minor slumping of sediment into underlying voids is present.

Gypsum casts are frequently present within certain laminations. Limonite is abundant as a fracture coating and a lining of the voids, also as botryoidal masses within the vugs. No limonite or other iron oxide is present within the sediments themselves though.

## SAMPLE B-3

## LAMINATED MICROSPARITE

The laminated microsparite directly overlies sample B-2, and is analagous to sample 2-13; however it is about twice the thickness of 2-13. The laminations are widely spaced (about 1 cm apart) in the sample, except the upper 0.5 cm which displays a separation of laminations of about 1 mm. Several of the lower laminations tend to pinch out into the overlying lamination.

## SAMPLE B-3A

## PELSPARITE BRECCIA

The angular pelsparite clasts show no preferred orientation and are cemented together by microspar in the form of meniscus cementation. There appears to have been little shuffling of the clasts as the clasts can be seen to have matching clasts adjacent above each other. Dogtooth spar lines the irregular voids between the clasts, and microspar fills small cracks. Fine laminations in the pelsparite are preserved, while the pellets appear clotted and irregular in shape probably due to their recrystalization to microspar. Some of the pelsparite is not in the form of clasts, but appears to have flowed between or over some of the clasts, possibly indicating that the sediment may have been 'soft' during brecciation. No cracks similar to those observed in sample 2-14 are present. Some breccia clasts contain dark nodules in a matrix of lighter, sugary microspar, of which their origin is unknown. Fossil shell fragments in the breccia clasts are very rare. Limonite is also present as faint coatings in voids.

SAMPLE B-4

CHALKY RUDSTONE

This light tan to dark brown colored rudstone is very friable, displays no bedding or laminations and has a saccharoidal (sugary) texture. It is composed of irregular, unoriented and poorly cemented microspar and sparry calcite crystals, with minute voids between each calcite grain. Dark brown micrite stringers seen in thin section show orientation perpendicular to and level with the horizontal. Silt grains are common in the rudstone, and are well rounded. No fossils are present.

The upper third of this sample is dark brown in color, displays on irregular contact with the lighter rudstone beneath, and is more consolidated than the lower portion. It is composed of irregular clasts of microspar, with larger voids between each clast. Root tubules are common in this portion of the sample. They are 3.5 mm in diameter, and can be followed up to 1.5 cm distant. Bending and entwining of the root trubules is common. They are filled with dark ferroan calcite and surrounded by brown micrite "haloes" in cross-section. The roots form a nucleus around which microspar is cemented, producing the irregular shaped 'clasts'. When broken, the dark brown microspar gives off a strong, petroliferous smell. The sample also contains limonite as a fine coating. Small 1 cm rounded siltstone clasts are present, especially in the lighter, tan colored rudstone, scattered irregularly throughout the sample.

SAMPLE B-5

LAMINATED GRAINSTONE

Matrix grain size is slightly smaller than sample B-4; about 1.0-1.5 mm diameter. Therefore, this sample is more consolidated and contains very few minute voids between grains. The grainstone is light brownish grey in color with a few dark brown patches of microspar. Dogtooth spar is not present in any voids. Thin (6 mm) beds of laminated microspar 'float' in the fine saccharoidal calcite matrix. These beds are broken by regularly spaced (9 mm separation) cracks, and the fragments are roughly cuspate in form (concave upwards in cross-section). These cusps appear on the top of the sample as small (1-2 cm) shallow 'saucers', with 2-5 mm irregular voids immediately un-erlying the 'saucers'. Limonite staining is common, and forms rough, diffuse zones or 'beds' in the matrix, and are laterally continuous.

In thin section, numerous micrite stringers are present, which are parallel or perpendicular to bedding. No fossils of any kind are present. However, for about 3 cm below the uppermost 'saucers', faint, verticle lineations are visible. These lineations are composed of orientated calcite grains and voids, and could possibly be the result of root systems disturbing the sediment in their search for water. Fine quartz silt is very common in the sample.

This carbonate is the uppermost member of the entire carbonate sheet.

## SAMPLE B-6

## ALGAL-LAMINATED SPARITE

Separated from the main carbonate sheet by about 50 cm of red and green conglomeritic silt is a medium grey, laminated, microsparite. Algal mats are very fine, black wisps, irregular in shape and sometimes discontinuous. Laminoid fenestrae are poorly developed. No other bioclasts are present. Sub-angular to rounded calcite grains, 1-3 mm in size are found in the upper portion of the sample, which is massive and contains no algal laminations. The grains appear to be birdseye structures. Soft, red and green silt clasts are also found in this massive zone. They range in size from 2-5 mm and are flattened discs or spherical shaped. Sub-angular to angular quartz grains are prominant in the upper and lower portions of the sample. They are large, up to 4 mm in size and are very clear. Rare biotite mica fragments may also be present.

# APPENDIX II

# LEGEND

## SKELETAL GRAINS

- Algae : Dasycladaceans
- Algal Stromatolites
- Brachiopods
- Crinoids
- Foraminifera
- Gastropods
- Ostracods
- Pelecypods
- Root tubules
- Shell fragments
- Spines : type unknown
  - › brachiopod
  - › echinoid
- Spicules
- Stromatoporoids

## LITHOCLASTS

- Lithoclasts : angular
- Intraclasts : angular
- Intraclasts : rounded

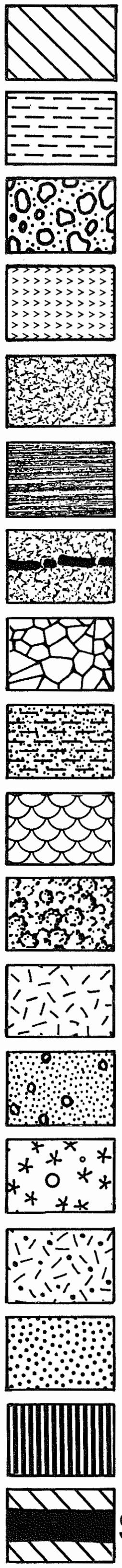
## NONSKELETAL GRAINS

- Pelletoids
- Pellets : fecal
- Superficial Ooids
- Ooids
- Pisolites
- Grapestone
- Gypsum crystals

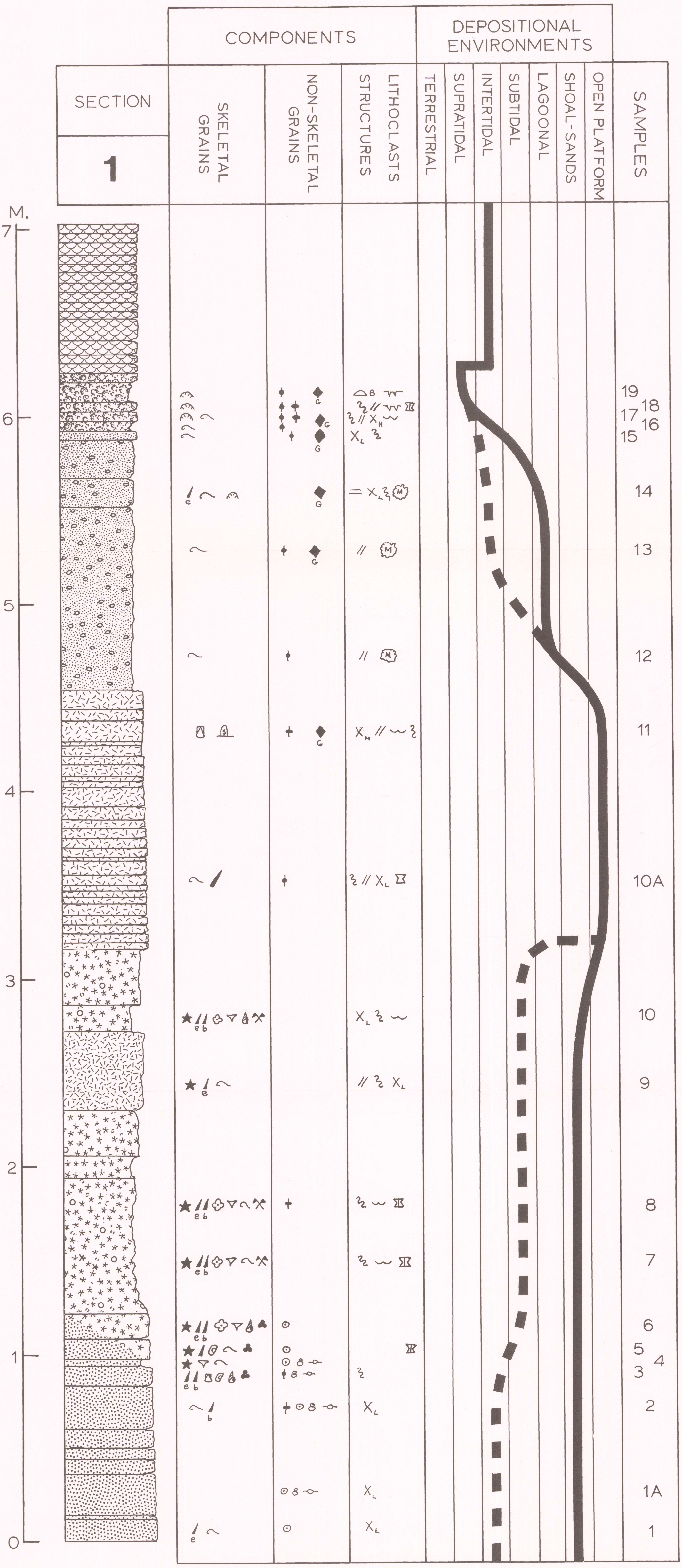
## STRUCTURES

- Parallel laminations
- Inclined bedding
- Crossbeds
  - L : low angle
  - M : medium angle
  - H : high angle
- Scours
- Prism cracks
- Buckle cracks
- Mottles
- Algal blisters
- Worm tubes

## LITHOLOGIES



- Siltstone — Rd : red , Or : orange, Gy : grey , Gn : green
- Algal Sparite
- Fanglomerate
- Spar Rudstone
- Spar Grainstone
- Fetid Spar Grainstone
- Laminated Sparite
- Pelsparite Breccia
- Pelsparite Pseudobreccia
- Undulating Pelsparite
- Algal-laminated Pelsparite
- Flat Pelsparite
- Mottled Flat Pelsparite
- Biosparite/Calcisiltite
- Calcisiltite
- Oosparite
- Ostracodal Biosparite
- Sh Black Shale



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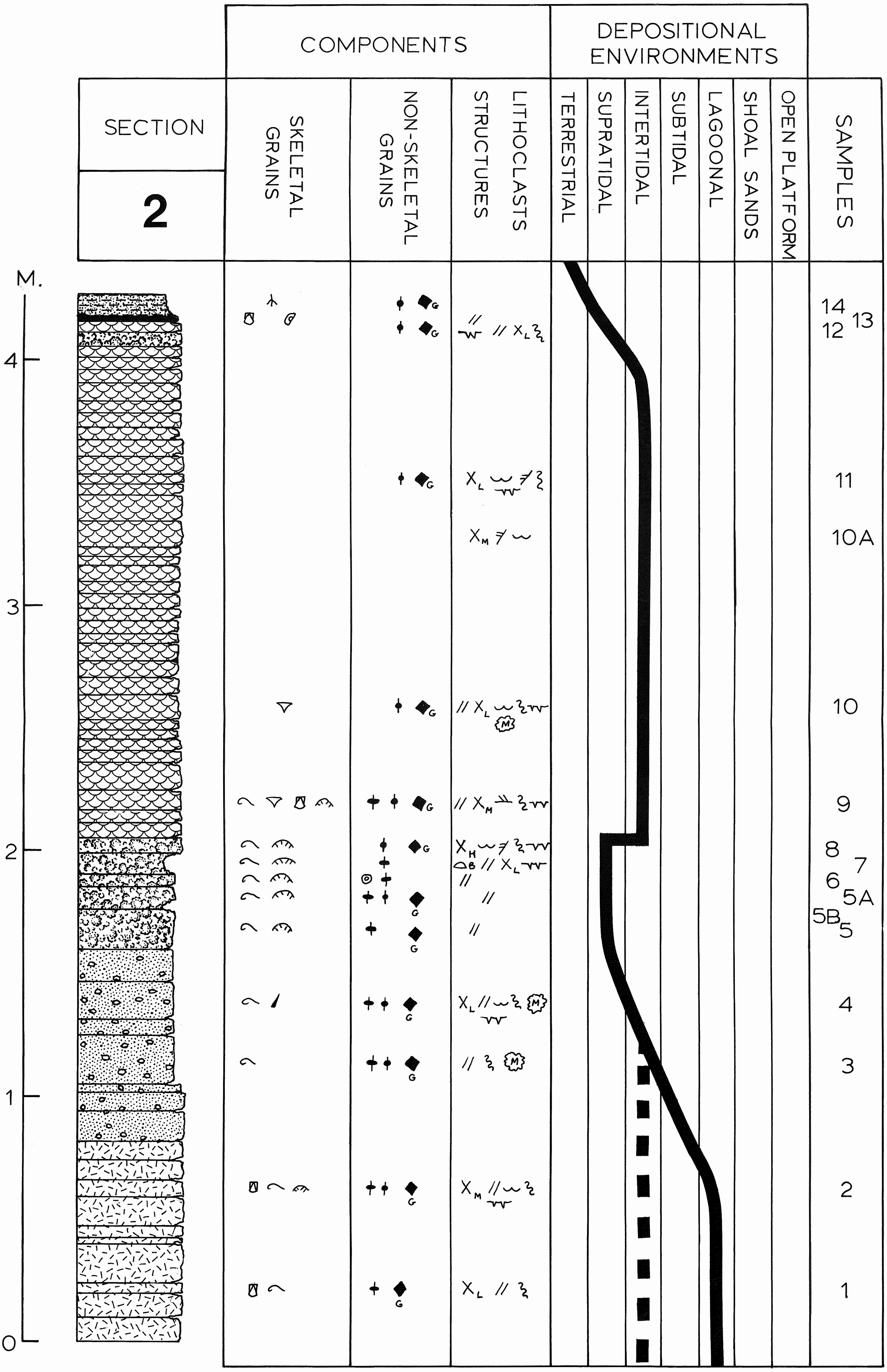

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INTERTIDAL
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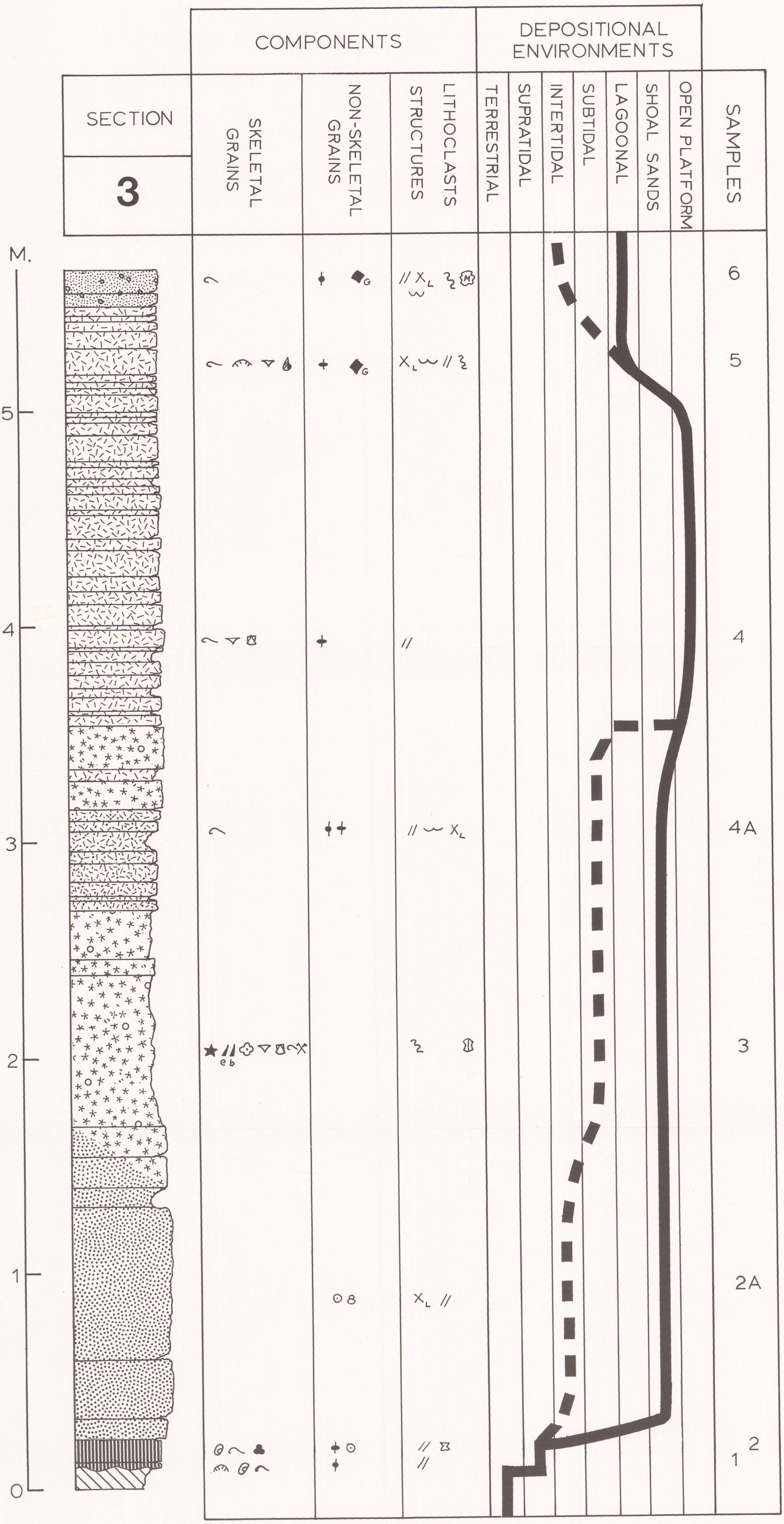

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INTERTIDAL
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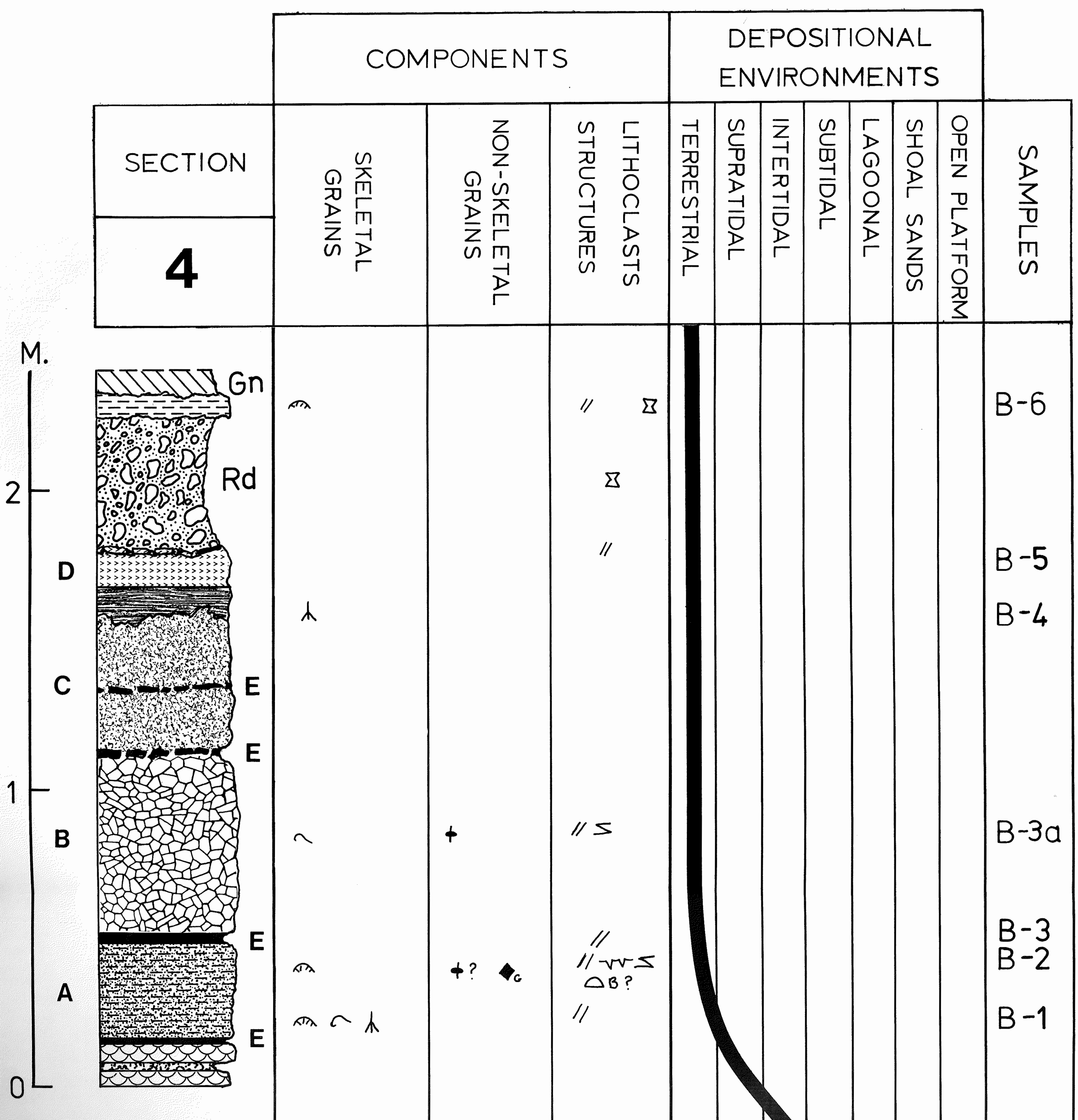
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INTERTIDAL
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LAGOONAL
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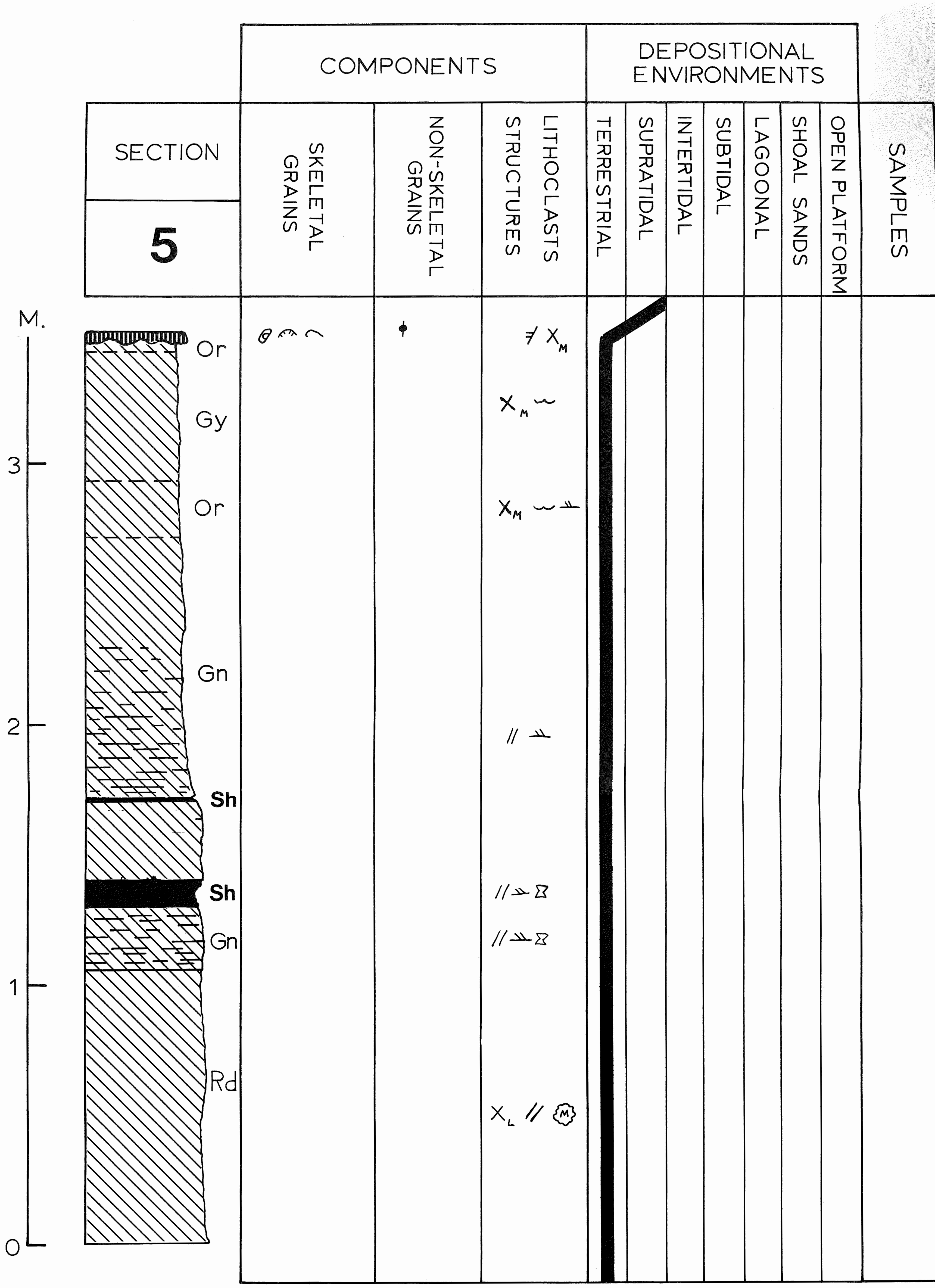

COMPONENTS
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# APPENDIX III

# INSOLUBLE RESIDUE ANALYSIS

Most samples taken from each section were analyzed for their insoluble residue content, calculated in weight per cent. Each sample was crushed and powdered by a jaw crusher and rotary grinder, respectively. Twenty grams of the powdered rock were weighed out and slowly added to 200 ml of a 1: 1 solution of hydrochloric acid and distilled water. This mixture was slowly heated to 90°C, and when the reactions ceased, the residue was allowed to settle out of suspension, and the solution poured off and replaced by distilled water. This was repeated three times and the cleaned residue was then washed into preweighed foil weighing pans, which were then dried slowly in a dessicating oven at 60°C. The dried residue was then weighed and the per cent insolubles for each carbonate sample calculated. Smear slides were made of most samples in order to determine approximate grain size, shape and composition. The results of the analysis are tabulated below.

The composition of the insoluble residue is almost entirely quartz with minor clay particles. Grain size of the quartz averages between 0.02 mm and 0.06 mm inclusively; the size range for fine to medium grained silt (Reineck and Singh, 1975). The grains are very well rounded and are well sorted in most cases with respect to size. Observations taken with the electron microscope reveal frosted surfaces on the quartz grains.

INSOLUBLE RESIDUE WEIGHT PERCENT

| SECTION 1 | | SECTION 2 | | SECTION 3 | | SECTION 4 | |
|---|---|---|---|---|---|---|---|
| SAMPLE NUMBER | RESIDUE WEIGHT % | SAMPLE NUMBER | RESIDUE WEIGHT % | SAMPLE NUMBER | RESIDUE WEIGHT % | SAMPLE NUMBER | RESIDUE WEIGHT % |
| 1-1 | 4.45 | 2-1 | 18.65 | 3-1 | 4.85 | B-2 | 7.14 |
| 1-5 | 4.60 | 2-2 | 12.45 | 3-2 | 2.30 | B-3 | 10.53 |
| 1-7 | 23.10 | 2-3 | 4.00 | 3-3 | 23.71 | B-4 | 16.89 |
| 1-8 | 25.15 | 2-4 | 16.40 | 3-4 | 31.53 | B-5 | 12.50 |
| 1-9 | 33.00 | 2-5A | 4.20 | | | | |
| 1-10 | 11.90 | 2-5B | 8.35 | | | | |
| 1-11 | 7.70 | 2-6 | 9.10 | | | | |
| 1-12 | 7.98 | 2-7 | 14.85 | | | | |
| 1-13 | 7.80 | 2-8 | 3.50 | | | | |
| 1-14 | 8.95 | 2-9 | 14.65 | | | | |
| 1-15 | 5.90 | 2-10 | 4.25 | | | | |
| | | 2-11 | 4.00 | | | | |
| | | 2-12 | 4.85 | | | | |
| | | 2-13 | 6.10 | | | | |