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CYCLIC SEDIMENTATION
IN THE MIDDLE DEVONIAN
OF SOUTHERN ONTARIO

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IN THE MIDDLE DEVONIAN
OF SOUTHERN ONTARIO

By

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ABSTRACT

The Edgecliff member of the Onondaga Formation is exposed in an abandoned quarry 1.2 km west of Port Colbourne, Ontario on the north shore of Lake Erie. An investigation of the Port Colbourne Quarry has resulted in the definition of four major and three minor carbonate Facies:

(1) Facies A: Biocalcarenite
(2) Facies A-1: Biocalcarenite with in situ stromatoporoids
(3) Facies B: Fissile biomicrite
(4) Facies C: Cystiphyllum-rich fissile biomicrite
(5) Facies B-1: Bioturbated biomicrite
(6) Facies C-1: Packed biomicrite
(7) Facies D: Synaptophyllum-rich sparse biomicrite.

The facies are cyclicly arranged, and are restricted to one of three major units within the stratigraphic column.

Typical cycles begin with the rapid deposition of a coarse grained, lensoidal biocalcarenite bed exhibiting

(1) Sharp scoured bases and vertical (fining upward) size grading;
(2) The abundance of abraded grains, shelter void cements and escape burrows;

(3) The presence of in situ Favosites heads overlying the biocalcarenite indicating minor hiati between sporadic and violent deposition.

In addition, these deposits exhibit:

(1) Abundant transport and abrasion of Cystiphyllum and Favosites;

(2) A general lack of in situ fauna;

(3) The presence of resuspended and redeposited debris between Cystiphyllum.

The depositional environment is deep to shallow subtidal, and a minor regression is evident towards the top of the stratigraphic column. Deposition is interpreted as being the result of sporadic, cyclic, and violent depositional events, probably storm induced.

ACKNOWLEDGEMENTS

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INTRODUCTION

Prior to the Acadian orogeny, at the start of the Middle Devonian Period, the eastern portion of the North American craton was submerged below a transgressing, epeiric sea (Stearn, 1978). This transgression extended eastward as far as the Michigan basin (Figure 1) marking the beginning of carbonate sedimentation upon partially-eroded Lower Devonian strata. The Onondaga Formation, the earliest Middle Devonian (Eifelian) sediments deposited in this sea, extend from southern Ontario and New York southward to West Virginia, with equivalent formations in the Michigan Basin and the Mississippi Valley (Oliver, 1954). The abundance of well-preserved fauna, and the excellent exposures of the formation have inspired a number of biostratigraphic and petrographic studies, the majority being conducted in New York State. These studies have resulted in a generalized environmental and depositional picture for each of the members of the Onondaga Formation. Reports based upon the detailed examination of any one member (other than for regional correlation) are less abundant, although such examinations are fundamental to paleoenvironmental reconstructions.

This study is an investigation of the patterns and processes of sedimentation which resulted in the deposition of the Edgecliff member of the Onondaga Formation, as exposed in a quarry in the vicinity of Port Colbourne, Ontario.

THE ONONDAGA FORMATION

The Onondaga Formation crops out along the north shore of Lake Erie in a narrow band varying from one to twelve miles in width (Caley, 1940). This continues northwestward as a broad semicircle rimming the northern boundary of the Michigan Basin, and eastward into New York where it extends as a farily constant narrow band from Buffalo to Syracuse and further east to Albany. The correlation of the various members of the Onondaga Formation can be seen in Figure 2.

The base of the Onondaga Formation lies unconformably upon the Lower Devonian Oriskany and Bois Blanc Sandstone formations (Siegenian and Emsian age, respectively), and in some areas overlies the Upper Silurian Bertie Akron formation (Sanford, 1967). The Onondaga has been subdivided into four members by Oliver (1954, 1963) according to lithology

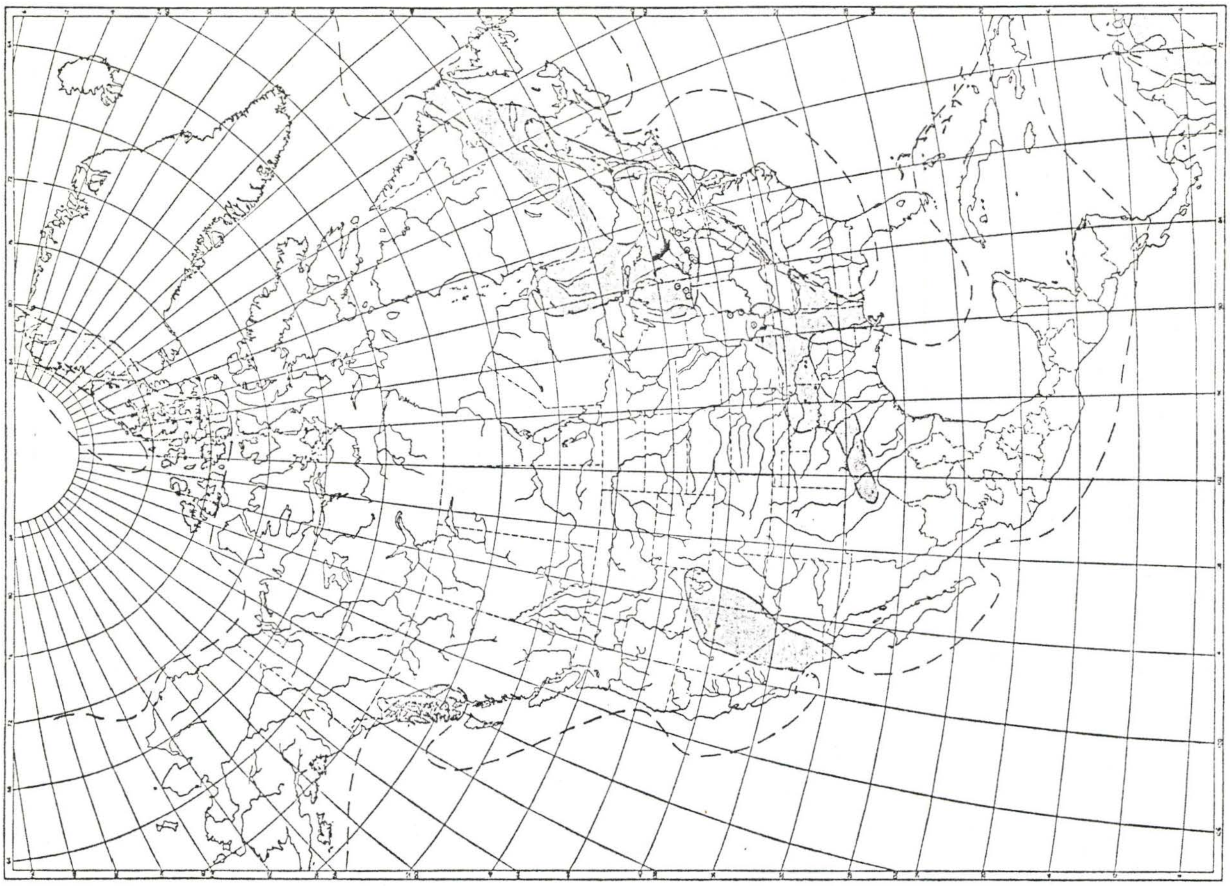


Figure 1

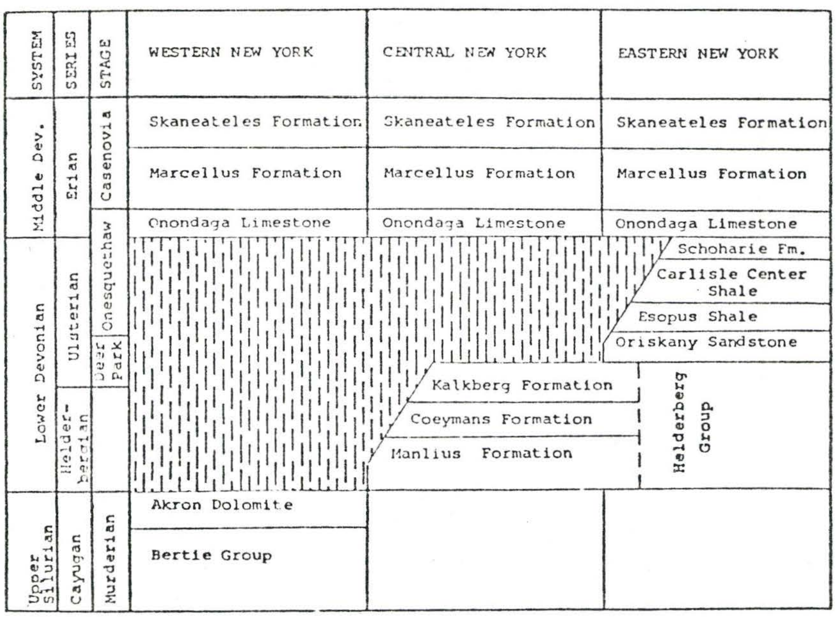


Figure 2. Correlation chart of Onondaga Formation

and faunal content.

The Edgecliff is the basal member of the Onondaga Formation. It ranges from 8 to 22 feet in thickness (200 feet in central Michigan Basin), and consists of a massively bedded cherty, bluish gray, medium to coarsely crystalline fossiliferous limestone noted for its well-preserved coral biostromes and bioherms. The base of the Edgecliff may be marked by a detrital quartz sand bed (Seringvale Sandstone) believed to be due to reworking by the advancing Onondagan sea. This study concentrates on the basal portion of the Edgecliff member.

The Edgecliff is conformably overlain by the Clarence Member (known as the Nedrow member in central New York), which is characterized by fine grained micritic, greyish blue, massive to shaley beds. Fossils are less abundant and poorly preserved. This member may represent an influx of terrigenous muds, reducing optimum conditions for coral growth.

The Clarence member grades upwards into the Moorehouse member, a medium gray, fine grained limestone, with dark grey chert throughout. This member contains the largest and most varied fauna of the Onondaga, indicating a return to an Edgecliff type environment, although bioherm development is not quite as good.

The topmost Seneca member is a dark gray fine grained limestone similar to the Upper Moorehouse Member, but is less cherty and contains very limited fauna. At its base is the Tioga Bentonite bed believed to represent volcanic activity (Oliver, 1963).

The Onondaga Formation is conformably overlain by the Marcellius Black Shale of the Hamilton Group, marking the end of the Eifelian Stage and the start of the Givetian Stage (Sanford, 1967). This influx of non-carbonate muds represents a westward transgression of clastic sedimentation, a result of the initiation of the Acadian orogeny on the eastern North American craton (Stearn, 1978).

In southern Ontario, the Onondaga exhibits a slight southwest dip towards the Michigan Basin, and a decrease in chert content both towards the east and the west. The formation also tends to become dolomitic towards the west (Oliver, 1963; Sanford, 1967).

PREVIOUS WORK

The Onondaga Formation was first defined by Hall (1859) from its type locality in Onondaga County, central New York State. Since then, the most extensive paleontologic and stratigraphic work has been done by Oliver (1954, 1956a, 1956b, 1960, 1963, 1966), Lindholm (1967), and others whose work was generally restricted to New York State. In Ontario, the Onondaga Formation has been studied by Stauffer (1915), Caley (1940) and Sanford (1967). Petrographic examinations of the Onondaga have been conducted by Middleton (1959) and Lindholm (1967). Previous work within the study area consists of several unpublished theses (Parkins, 1977; Cass, 1975).

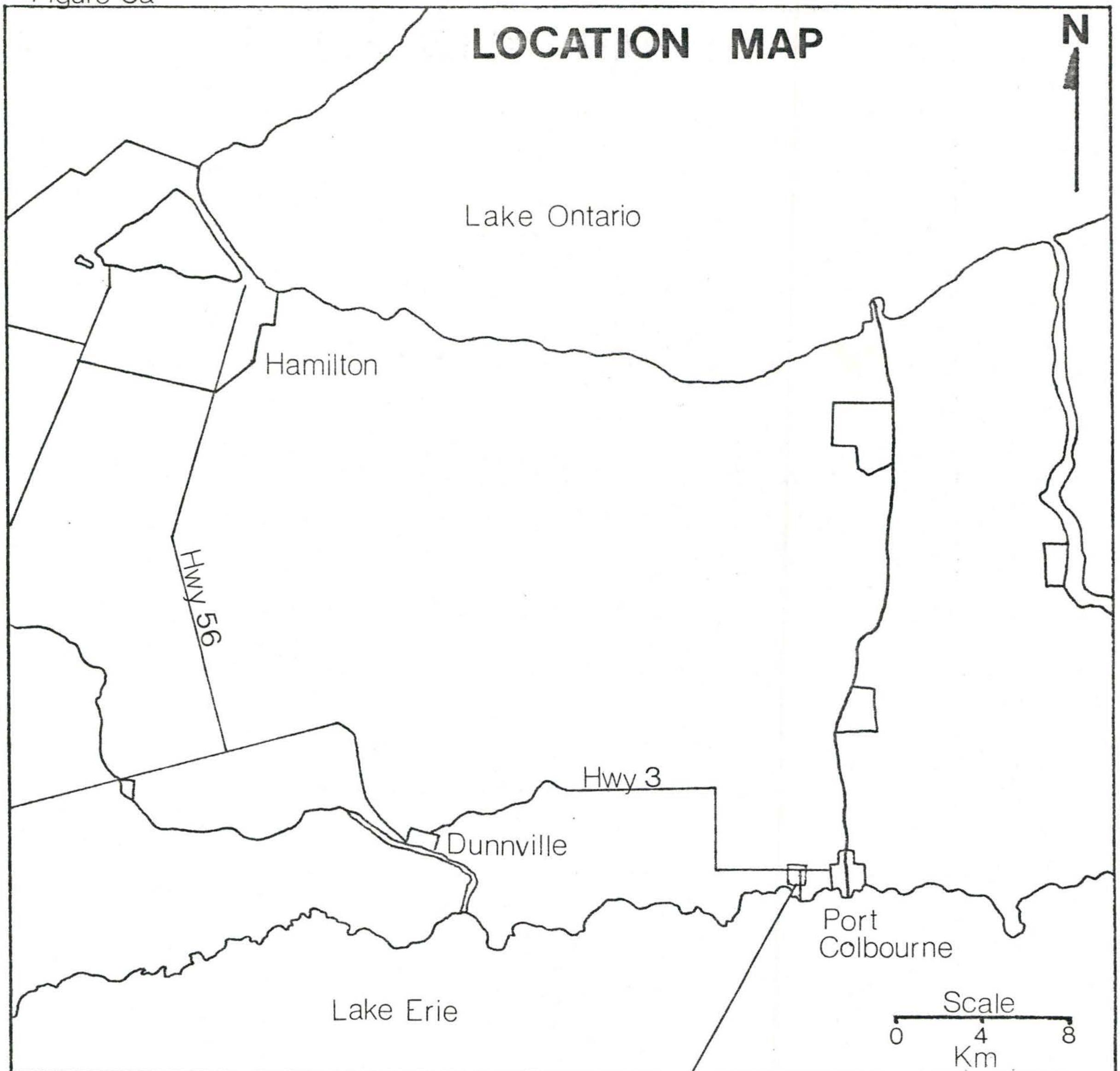
LOCATION AND ACCESS

The study area is located within the abandoned Canada Cement Co. Quarry, hereafter referred to as the Port Colbourne Quarry, 1.2 km west of Port Colbourne, Ontario, along Hwy 3 0.2 km north of Lake Erie on Quarry Road (Figure 3). Access is from a dirt road at the northeast corner. The walls of the roughly rectangular quarry are completely accessible, except at the south end, where the quarry floor is flooded.

PURPOSE AND SCOPE

The factors involved in interpreting carbonate sediments are numerous and complicated, involving the examination

Figure 3a



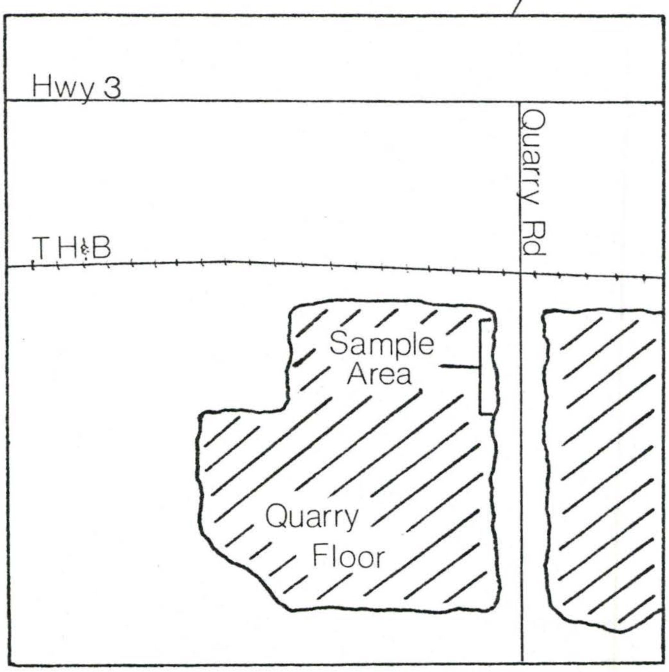


Figure 3b

Plan view of Port Colbourne Quarry and location of sample area.

of both sedimentary structures and fossil evidence.

The purpose of this study was to conduct a detailed stratigraphic, petrographic and paleoecologic examination of the Edgecliff Member of the Onondaga Formation as exposed in the east wall of the Port Colbourne Quarry. The stratigraphic section was subdivided into characteristic facies, and an attempt was made to relate petrographic and biostratigraphic analysis to the depositional environment and possible depositional mechanisms of each facies.

METHODS OF STUDY

(a) Field Work

A total of five days were spent conducting field studies at the quarry during late September and early October, 1978. The stratigraphic section was divided into twenty preliminary units, noting the type of bedding, sedimentary structures, contacts between units and the lateral variation of each unit. A total of 40 hand samples were taken representing each unit, in its entirety with an average lateral extent of 20 cm, accounting for the entire stratigraphic section from two localities ten meters apart. Considerable time was spent making paleoecological observations and collecting macrofossil specimens for identification.

(b) Laboratory Work

The samples were cut, polished by hand with 600 grade abrasive powder, and etched for 10 seconds in 40% hydrochloric acid, rinsing with distilled water. This enhanced observation of the specimens and also prepared them for the making of acetate peels (method in McCrone, 1963, and Katz, 1964). Some of the slabs were stained with Alizarine Red-S immediately after etching (Katz, 1964) to detect areas of possible dolomitization, chert or silica replacement, or detrital non-carbonate minerals. Examination of several slabs indicated extensive dolomitization was not present, and as the deep red stain acquired by the calcite hindered peel analysis, staining was discontinued.

Modal analyses were performed by the point count method (minimum 600 point counts per section) on acetate peels and 20 representative thin sections, using the major petrographic divisions of allochems, matrix and cement, as well as the major taxa of skeletal constituents (Appendix I). One half of several of these thin sections was stained with a combination of Alizarine Red-S and potassium ferricyanide to aid in mineral identification (Friedman, 1959).

Grain size analysis of each unit was undertaken to determine the presence or absence of vertical grading as well as sorting within and between units. All data were acquired from acetate peels, examined with the Shadowmaster projecting screen at 50x magnification and are represented in Appendix II in the form of histograms and cumulative curves. Ten centimeter traverses parallel to bedding were marked out on the acetate peel (glass cover) at 1.0 to 3.0 cm vertical intervals, depending on the thickness of the particular unit. This insured a minimum of 3 horizontal traverses which were situated at the base, the middle, and the top of each unit, where the longest diameter of each grain larger than 3.0 phi that intersected the traverse line was measured. This resulted in slightly truncated grain size distributions; however the hydrodynamic interpretation of these data still provides valuable insights as to the mechanisms of transport (if any) and mechanical energy during deposition. Qualitative observations were made regarding grain shape, orientation, contacts, and amount of abrasion to further aid in the environmental interpretation of each facies.

The effects of bioturbation, preserved in the samples as mottling or distinct burrows, were investigated by cutting 0.6 to 1.0 cm thick serial sections, polishing with 100 grade abrasive powder to remove irregularities, and taking transmission x-ray radiographs. Each serial section was irradiated for approximately 2.0 minutes at 400 k.v. and

100 m.a. (depending on the thickness of the slab), and revealed on a negative print many biogenic structures not seen in the hand specimen.

CHAPTER II

THE PORT COLBOURNE QUARRY

GENERAL STRATIGRAPHY AND STRUCTURE

Exposure within the Port Colbourne Quarry ranges from 7.2 m to 3.5 m from the west to east walls, respectively. The Edgecliff thickens from 14.9 m in southeastern Ontario to 29.2 m in southwestern Ontario (Cass, 1975), and the slight southwest dip of the strata is just barely discernible in the quarry.

Correlation among each of the walls of the quarry is made possible by the presence of a distinct and relatively abrupt stratigraphic boundary between two distinct horizons: a lower horizon (about 2 m thick) generally characterized by bluish-gray regularly and fairly thickly bedded (20-35 cm), fine grained limestone with 5-10 cm fissile interbeds and a fairly low faunal density, and an upper gray to buff coloured massively to irregularly bedded limestone with thin (1-5 cm) fissile interbeds and a richer fauna. Individual beds (units) within each horizon can be easily correlated between the north and west walls as there is little or no lateral variation in the gross lithology of each horizon. Correlation with the east wall however indicates that the lower horizon is generally more shaley and contains a much more abundant solitary rugose coral fauna, particularly Cystiphyllum sp.

Structurally the north and west walls appear undeformed. The east wall, however, shows very gentle localized folding, particularly in the southern portion where the beds dip south at 3° to 4° (Figure 3b).

The sample area (Figure 3b; 4) was divided into 20 units in the field based on bedding characteristics, lithology and faunal content. These units and their subsequent subdivisions are found in Figure 5. The basal 1.1 meters are characterized by thinly bedded coarse grained (1.2 mm) biocalcarenites with sharp, irregular, often scoured bases and gradational upper contacts. Individual beds vary laterally in thickness (Appendix IIA), pinching and swelling over short (<1 m) lateral distances. These are interbedded with relatively unfossiliferous shales.

The biocalcarenite beds tend to increase in thickness from units 2 to 14 (Figure 5), the shaley interbeds becoming much more Cystiphyllum-rich (units 13, 15, 17 and 19) upwards in the section. Immediately below the "upper

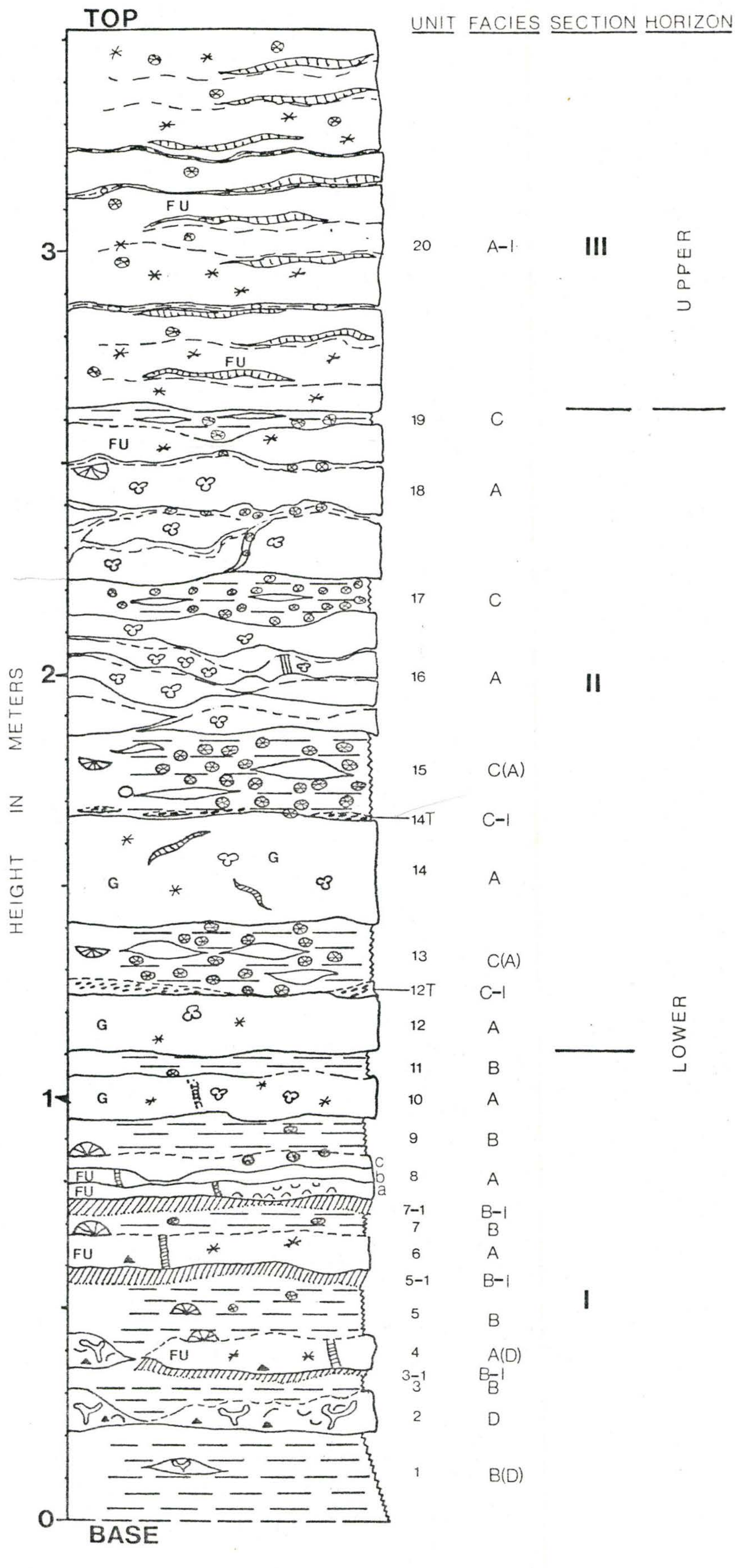
Figure 4. Typical complete section of sample area.
Scale: 3.75 cm = 1.0 m.

LEGEND

- Facies A Biocalcarenite
- Lenticular Facies A Biocalcarenite
- Facies B-1: severely bioturbated
- Facies C-1: abraded elongate grains bedding
- irregular sharp base (boundary)
- gradational boundary
- fissile units (shale)
- mottling
- FU - fining upwards grain size
- G - irregularly graded (fining and coarsening)
- crinoid debris
- *Cystiphyllum sp.*
- Brachiopod valves, convex up or down
- *Favosites sp.*, in situ
- *Favosites sp.*, overturned
- colonial rugose coral: *Synaptophyllum sp.*
- stromatoporoid or encrusting coral
- vertical burrows
- lined vertical burrows

(Also applicable to figures 15,16,29,&34)

FIGURE 5
STRATIGRAPHIC SECTION



horizon" contact seen in other areas of the Quarry unit 20) there are two units (16 and 18) which are characterized by thin, very irregularly bedded, often lenticular biocalcarenites interbedded with thin, Cystiphyllum-rich shaley interbeds. These units are not found elsewhere in the quarry and are believed to be restricted to the sample area. Figure 6 illustrates the lateral lithologic trends both north and south of the sample area along the east wall. The trends from north to south are a general thinning of individual units (particularly units 12 and 14), a decrease in Lst:Shale ratio from 1.48 in the sample area (not including unit 20) to 1.21 only 60 meters south, and a thickening of units 13 to 19 from 60 cm to 93 cm, indicating a slightly disconformable contact between units 13 to 19 and the upper horizon in the east wall (unit 20).

Figures 7 and 8 illustrate the distinctive increase in shaley character of unit 18 south of the sample area. Weathered surfaces of biocalcarenite units showed abundant evidence of vertical (fining upward) size grading (Figures 9 and 10) which prompted grain size analyses of the entire stratigraphic section (Appendix II).

STRUCTURE OF SAMPLE AREA

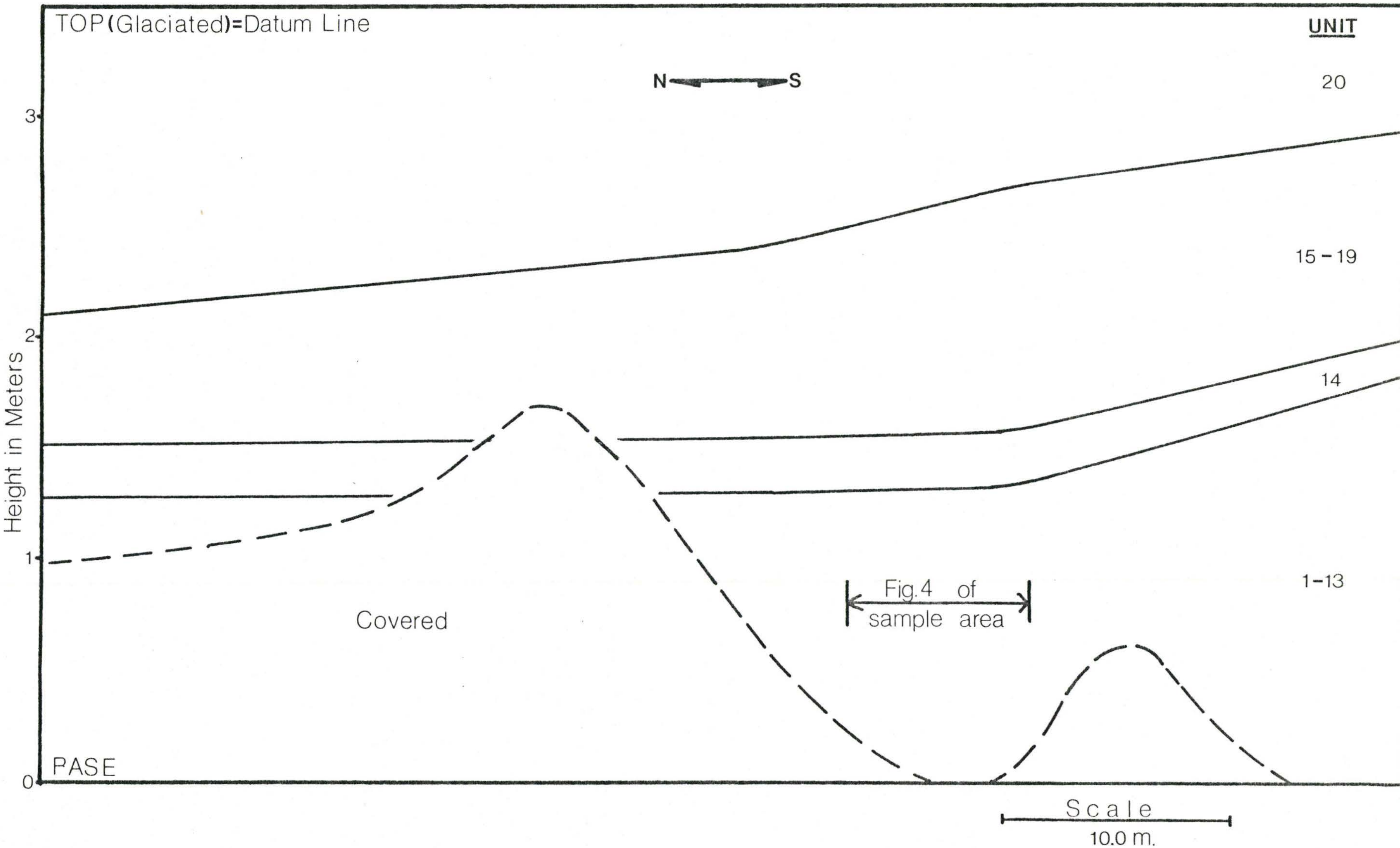


Figure 6

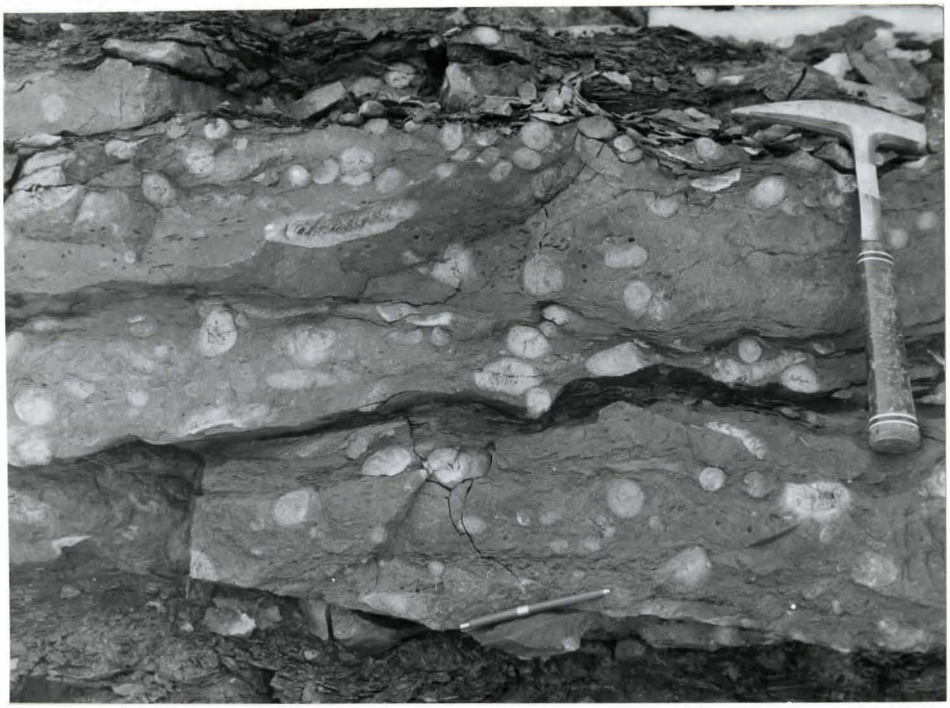


Figure 7. Unit 18, sample area. Note irregular bedding, shaley interbeds, and abundant Cystiphyllum.

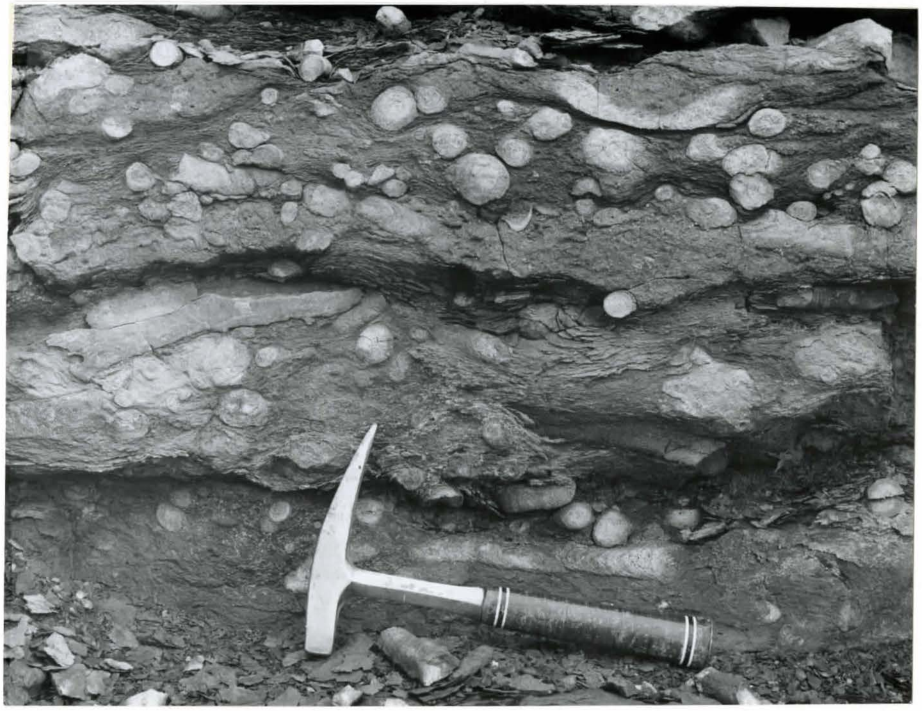


Figure 8. Unit 18, 60 m south of sample area. Note fissile character, draping of shale around Cystiphyllum, and coarse nature of thinner biocalcarenite units.

Figure 9. Crudely graded crinoidal debris within Unit 20, biocalcarenite

Figure 10. Irregularly graded bedding within Unit 14 biocalcarenite

GENERAL PALEONTOLOGY

The preserved fauna of the Port Colbourne Quarry is predominantly corals; colonial tabulates, solitary rugosans and colonial rugosans. The major identified forms are:

- Favosites basalticus
- Favosites sp.
- Cystiphyllum vesiculosum
- Blothrophyllum decorticatum
- Zaphrentis spp.
- Synaptophyllum simcoense

In addition, abundant encrusting corals and stromatoporoids were found, along with minor turbinate and platiceratid gastropods, and rarely articulated brachiopods. Crinoid and bryozoan debris was abundant, generally increasing in abundance upwards in the stratigraphic column.

Solitary rugose corals such as Cystiphyllum and Zaphrentis are most abundant in shaley interbeds and in units 13, 15 and 19 where they comprise >50% of these beds by volume (Figure 11). These corals are never found in life position, show abundant evidence of abrasion (i.e. broken bottoms), and are commonly singly or doubly geniculate. Favosites heads are also rarely found in life position except in the lower portion of the column where they overlie biocalcarenite units (Figures 12 and 13). They are more common in the upper portion of the column (unit 20), and exhibit slight variation in apical angles.

Encrusting corals are usually located at the tops of biocalcarenite units and are overlain by shale (Figure 14), indicating a minor hiatus. Stromatoporoids were only abundant within thicker biocalcarenite units, being restricted to units 14 to 20 with a maximum abundance in unit 20. These were laminar forms with irregular bases.

In the upper horizon (unit 20), the coral forms often developed into buff coloured, lenticular and slightly mound shaped bioherms, five of which were exposed in the quarry sharing the same stratigraphic base, possibly indicating a period of major hard ground development.

Brachiopods and gastropods were generally located in the lower portion of the section within shaley interbeds. Preservation of the above fossils is generally by silicification.

Figure 11. Unit 15, Facies C: Cystiphyllum-rich fissile biomicrite. Note sharp erosional base with Unit 14 (Facies A) biocalcarenite and sharp upper contact (pen) with Unit 16

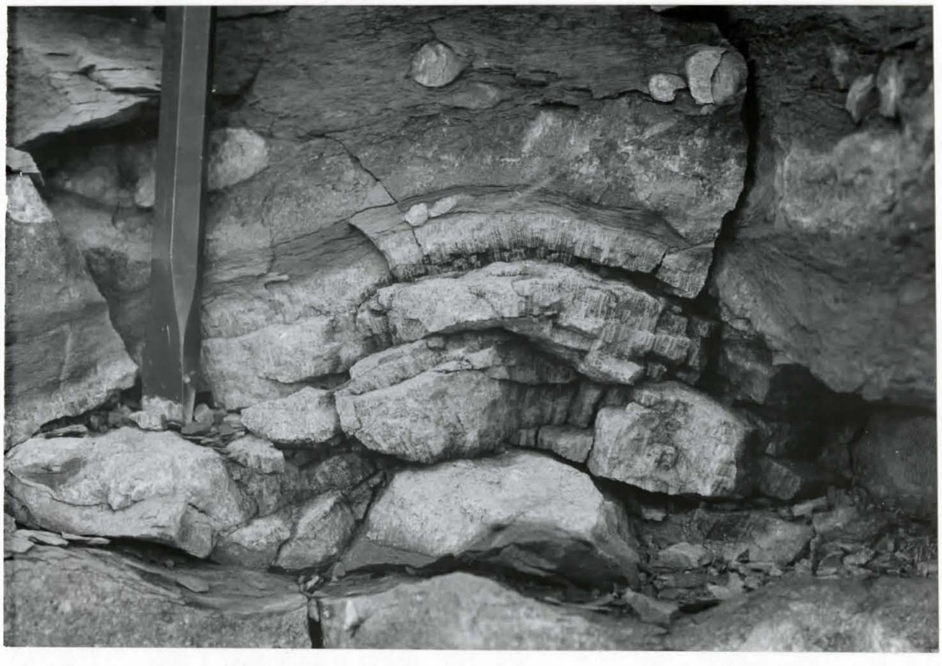


Figure 12. Favosites basalticus, in life position. Note capping by thin fissile (Unit 7) layer. Positioned directly on top of Unit 6 biocalcarenite

Figure 13. Overturned Favosites basalticus head, within Unit 13 (Facies C)

Figure 14. Elongate encrusting coral at top of Unit 10, directly overlain by Facies B

CHAPTER III

FACIES DESCRIPTIONS

The stratigraphic column consists of four major (A, A-1, B, C) and three minor (B-1, C-1, D) facies defined on the basis of lithologic, petrographic and paleoecologic evidence. Modal analyses and grain size data of characteristic units are found in Appendices I and II, respectively, and will be referred to throughout the descriptions.

FACIES A: BIOCALCARENITE

This facies includes units 4, 6, 8, 10, 12 and 14, as well as the biocalcarenite lenses found in units 13, 16 and 18 (Figure 5). It is by far the most abundant facies and is located entirely within the lower horizon already mentioned. Lithologically, each biocalcarenite unit is characterized by a sharp, hummocky, irregular and often scoured lower contact, and grades upwards into overlying fine grained fissile units over a 1 to 2 cm zone. The lenticular nature of the bedding is more pronounced in thinner units (4, 6, 8, 16 and 18) which often pinch and swell over short (1 meter) lateral distances, while the thicker units locally assume a more consistent thickness and massive character (Appendix II(A)). Internal sedimentary structures consist of varying degrees of vertical grading (fining upwards), biogenic mottling, the presence of more than one fining upward sequence within a particular unit (8, 12 and 14; Figure 10), and the scouring and truncation of individual fining upward sequences by similar overlying ones (unit 8; Figure 15). Lindholm (1967) indicates the rare presence of crossbedding in some Edgecliff calcarenites of central New York, but this was not observed in the present study.

Generally, the mean grain size varies from a maximum of -0.47 ϕ (very coarse sand-size) in the basal centimeter of unit 6 to 0.85 ϕ (coarse sand-size) in the basal centimeter of unit 16. The upper centimeter of these two units ranges from a mean grain size of 0.48 ϕ in unit 6 to 1.42 ϕ in unit 16 (coarse sand to medium sand, Appendix IIA). Units 4, 6, 8(a) and 8(b) exhibit the most distinct fining upward sequences as well as the coarsest bases. Structurally, units 4 and 6 are identical, each fining upwards over a range of 0.83 ϕ to 0.95 ϕ respectively, indicated by a decreasing coarse tail from base to top and an increase in fines. This type of fining upward character is also characterized by a

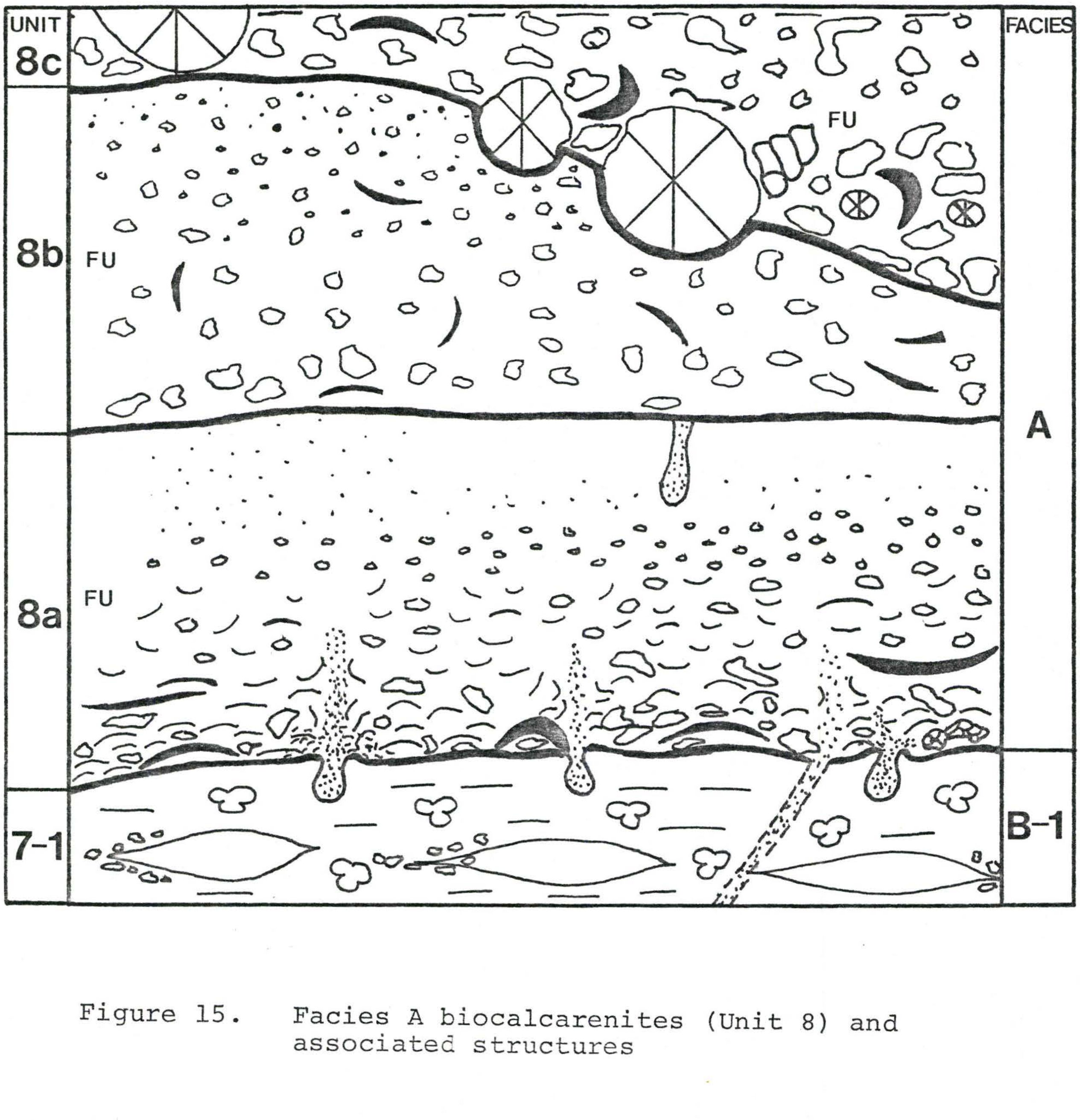


Figure 15. Facies A biocalcarenites (Unit 8) and associated structures

change from positive skewness at the base to negative skewness at the top (Appendix IIB, units 4 and 6). This type of skewness trend is generally accompanied by a decrease in coarse tail, as in units 4 and 6, and is commonly found in graded sandstone beds (Blatt et al., 1972), indicating that mechanisms which affect clastic deposits are also at work in the sand-sized biocalcarenites of the Edgecliff Member.

Unit 8 shows a similar fining upward trend in each of its sublayers (8a and 8b), being generally finer grained than either units 4 or 6, and deferring in the nature of the coarse "lag" at the base of the unit, which is comprised mainly of disarticulated brachiopod valves and coral fragments. Units 6 and 4(P) are dominated by Echinoderm (crinoidal) and coral debris. Units 4, 8a and 8b become better sorted from base to top whereas unit 6 exhibits poorer sorting towards the top as a result of increased fines (Appendix IIA and B).

Folk (1962) groups sorting values (actually standard deviation) for calcarenites of less than 1.0 ϕ as being relatively "sorted" and those values greater than 1.0 ϕ as being "unsorted" or poorly sorted.

The more massive biocalcarenites (units 10, 12 and 14) do not exhibit the same distinct, undisturbed vertical grading pattern just discussed. These units differ by having irregular and gradational vertical and lateral grain size variations. Mean grain sizes (Appendix IIA) vary from 0.80 ϕ and 0.62 ϕ at the bases, to 0.92 ϕ and 1.02 ϕ in the centres of the units, and from 0.70 ϕ to 0.57 ϕ at the top. This gradational coarsening and fining upwards character is due to the presence of scattered coarser debris zones consisting predominantly of crinoid ossicles, resulting in distinctly bimodal distributions (Appendix IIB, units 10, 12 and 14). In addition, the units are "poorly sorted" (sorting values ranging from 1.15 ϕ to 1.7 ϕ), and show an overall increase in fine fraction. Units 14 and 12 differ from other units of this facies due to the presence of an upper erosional contact with overlying <u>Cystiphyllum</u>-rich beds (units 13 and 15). Figure 16 illustrates the nature of this contact as seen between unit 14 and 15, the impingement of <u>Cystiphyllum</u> corals on unit 14, and the nature of the grain size distribution within unit 15 discussed in Facies C.

Units 16 and 18 are composed of 4 and 3 individual subunits respectively, and these lenticular biocalcarenite beds (as well as unit 13) exhibit the most irregular bedding and the lowest degree of vertical grading in the facies. Mean grain sizes vary from 0.82 ϕ to 0.92 ϕ at the base and 1.12 ϕ to 1.42 ϕ at the top of the beds (see Appendix IIA).

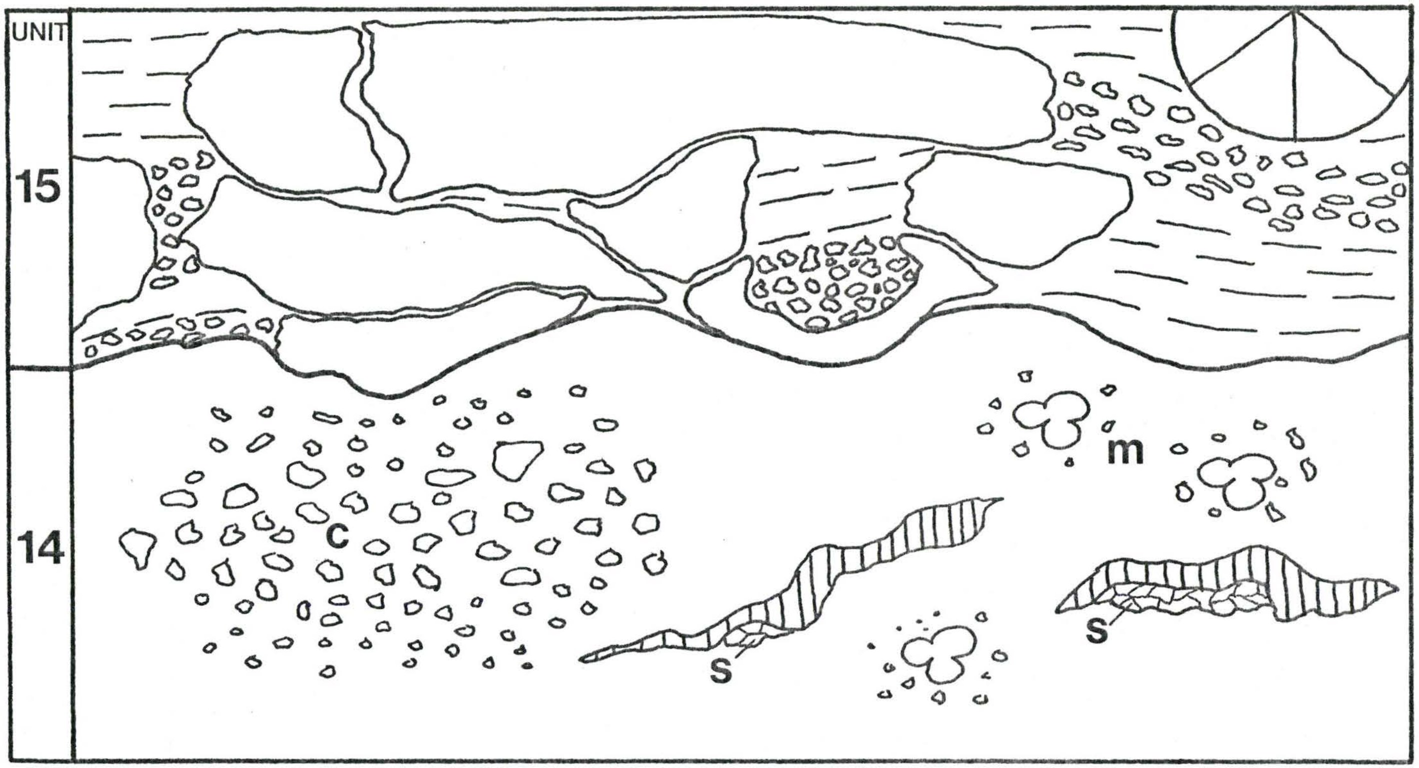


Figure 16. Erosional upper contact of Facies A with Facies C-1. Note shelter voids (s), mottling (m), and coarser grained areas (c) of Unit 14. Note accumulation of coarse crinoid debris (cc), between abraded <u>Cystiphyllum</u>

Only subunit 18ST shows any consistent vertical grading whereas the others are essentially ungraded except at the very top where there is a notable decrease in coarse lag and an increase in fines, giving these units a very gradational upper boundary. Subunit 16N is the coarsest grained of these units with a mean basal grain size of 0.47 ϕ. In general these units contain the highest percentage of fines in the facies, have a bimodal size distribution, and become better sorted towards the top of each unit (Appendix IIA and IIB). These increased fines are combined with a generally mottled appearance due to bioturbation.

Petrography

Mineralogically, Facies A is composed of >95% calcite, in the form of skeletal fragments, sparry cement, and microcrystalline matrix. Staining of characteristic thin sections revealed the presence of 0 to 5% dolomite (Appendix IA) in the form of small (40-60μ) euhedral crystals commonly containing dark, rounded cloudy to opaque interiors. Dolomite crystals are restricted to the fine grained matrix and generally increase in abundance with increased detrital quartz, ranging from <0.1% to 5.4%. This may indicate a detrital origin for the dolomite. Silica replacement is restricted to larger skeletal constituents being most common as partial coarsely crystalline fillings within corallites, and comprises from trace to 2.8% of the thin sections. Additional trace constituents are detrital glauconite and authigenic metallic mineral, probably pyrite (opaques).

The primary petrologic constituents include allochems with varying degrees of matrix and sparry calcite cement. The sand-sized allochems are almost exclusively skeletal and comprise from 48.8 to 73.5% of the facies. The majority of the skeletal material occurs as broken, angular to sub-rounded fragments although whole, rarely articulated brachiopods, ostracodes and gastropods are found. Identification of skeletal material is based on internal structure and overall morphology discussed in Horowitz (1971) and Scholle (1978). The most abundant skeletal constituents are Echinoderm (mainly crinoid) fragments, comprising from 20.4 to 39.7% of the entire facies (Appendix IB). Corals, brachiopods and bryozoans are the next most abundant constituents generally ranging from 3.5 to 8.2%, 2.5 to 5.4%, and from 1.4 to 6.5% of the facies respectively (Appendix ID). Unit 8 shows a different assemblage, being dominantly brachiopodal and coralline (12.8 to 15.2% respectively) with a relatively high percentage of bryozoan fragments (4.3 to 5.9%) and a minimal echinodermal content (3.5 to 4.9%). Other identifiable fragments present in minor amounts are gastropods, ostracodes and rare trilobite moults, all of which are most abundant in unit 8. Sparry calcite cement occurs mainly as syntaxial overgrowths and crystalline mosaics resulting from passive precipitation in voids, and is generally coarser than 62 microns, whereas micrite matrix, also composed of calcite (although impure) is generally considered finer than 62 microns in sand-sized sediments (Horowitz, 1971). Sparry calcite cement:micrite matrix ratios vary considerably within Facies A and within each unit. Units 4, 6 and 8 are the most consistent, characterized by very high spar:micrite ratios (2.0 to 83.7). Units 4 and 6 are termed "well washed" crinoidal biosparites (Folk, 1962, Appendix IC, Figure 17), interpreted as being the result of winnowing of lime mud and sorting of allochems in a higher energy environment (Folk, 1962; Dunham, 1962; Bathurst, 1971; Carrozzi, 1967). Each of the units within this facies contains such area of mainly skeletal fragments and spar, characterized by syntaxial overgrowths, fragments by coarse, clean sparry cement and the less common development of finely bladed calcite crusts at 90° to grain boundaries growing radially inward towards void centres. These voids are infilled with a later more ferroan coarse grained interlocking cement as evidenced from staining. Micrite envelope development is more common on skeletal fragments within mottled or micrite matrix-rich areas (Figure 18).

The thicker units (10, 12, 14) exhibit overall lower spar:micrite ratios due to patchy roughly horizontal zones of micrite matrix which coincide with the graded areas in these units already described (Figure 18).

Folk (1962) suggests that these sediments which are analogous to submature sandstones (due to poor to moderate sorting values) may be remixed with lime mud, if it is available in the environment, by increased water agitation or the activities of burrowers. Investigations of recent carbonates indicate that silt size carbonate is commonly derived from skeletal breakdown (Ginsburg, 1956) and skeletal breakdown due to activities of boring organisms. Mastication and ingestion of organisms may also be important in the formation of fine grained micritic matrix (Lindholm, 1967). These thicker units also exhibit the presence of fine sand-sized (60-80μ) micritic pellets (see Appendix IA) which are confined to the finer grained micrite-rich areas. Pellets constitute as much as 5.4% of these areas within unit 10 and are present in minor amounts throughout this facies reaching maximum abundance (7.2%) in unit 16 (sample 16NB, Figure 19). The presence of these "mottled" pellet-containing areas suggests that these units were reworked by burrowing organisms and that these pellets are fecal.

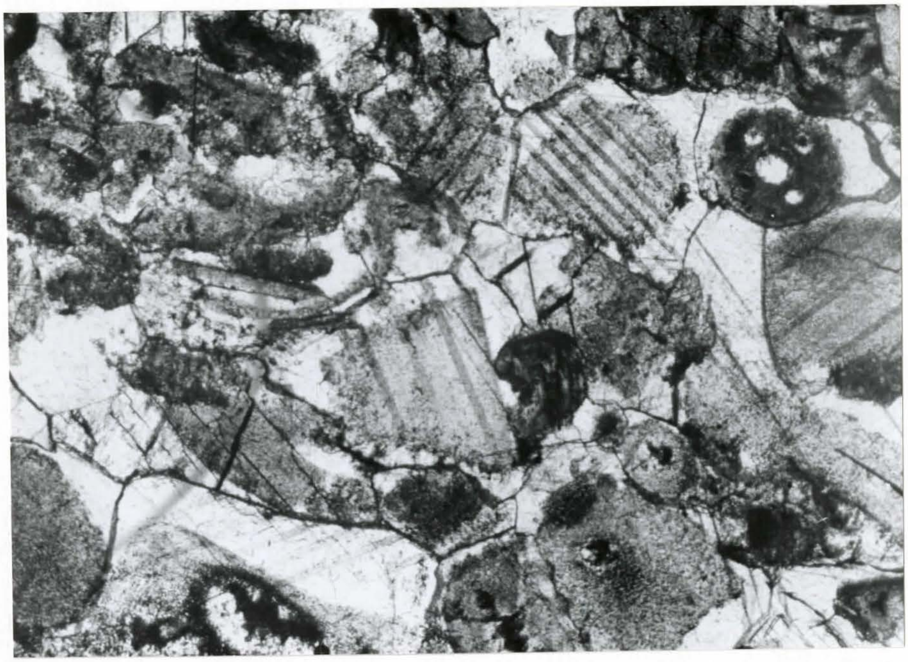


Figure 17. Coarse biocalcarenite : crinoidal biosparite (unit 6, Facies A)

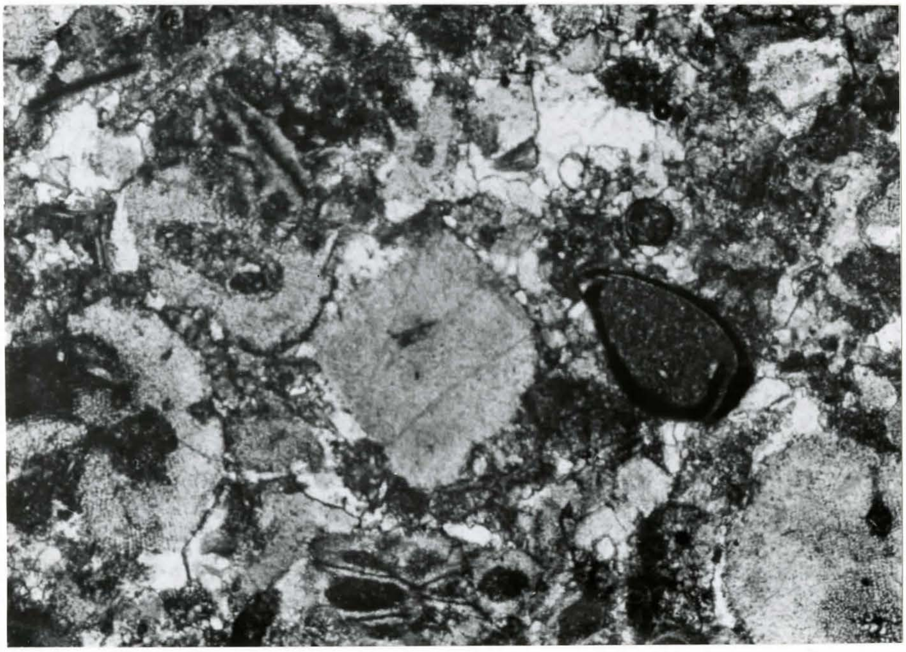


Figure 18. Slight micrite envelope development near mottled zone of unit 10

Ginsburg (1957) indicates that within peloidal sediments in Florida, individual pellets a few feet below the surface cannot be distinguished from matrix due to breakdown under compaction. It may be that the only reason any pellets are preserved in Facies A is that the skeletal framework minimizes compaction effects.

The lenticular biocalcarenite beds of units 13, 16, and 18 (excluding 18ST) contain the highest overall percentage of fine grained matrix (16.7 to 36.3%), low spar:micrite ratios ranging from 0.2 to 1.1 (Appendix IA), and the highest degree of mottling.

Generally, all facies A biocalcarenites are "grain supported" (Dunham, 1962), skeletal constituents show varying degrees of abrasion and roundness, and geopetal fabrics between micrite and sparry calcite are abundant both between skeletal grains, beneath them as shelter voids, and within corallites, gastropods, and rarely articulated brachiopods and ostracodes (Figure 20). These shelter voids are especially common in the coarser grained units and at the base of unit 8, which is dominated by "convex up" brachiopod shells and coral fragments.

Internal structure of skeletal walls may be completely replaced by sparry calcite, remain unaltered, or show well developed micrite envelopes and often discrete algal borings

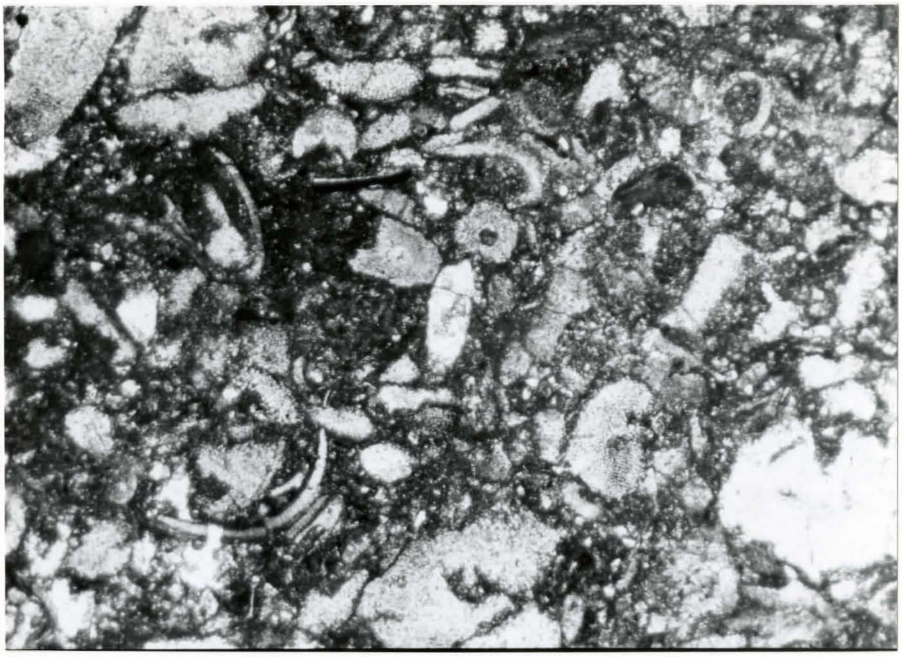


Figure 19. Mottled, micrite-rich zone of Unit 10 (Facies A). Note poor sorting and more extensive envelope development

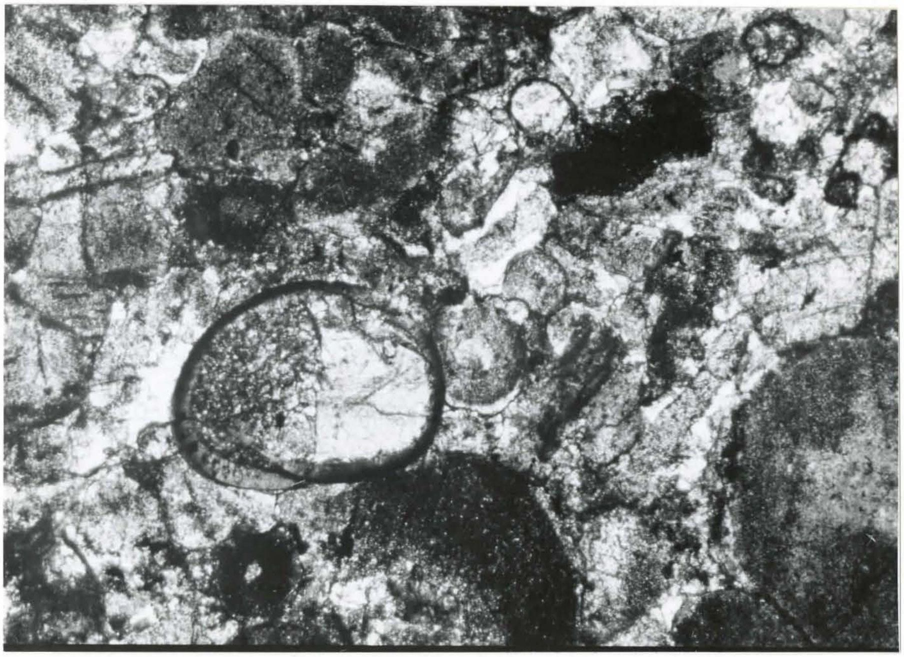


Figure 20. Geopetal indicator within ostracode

filled with peloidal opaque material (Figure 21). These opaques may also be framboidal pyrite formed from the activities of sulfur-reducing bacteria (Kobluk and Risk, 1977).

Elongate grains are present towards the upper gradational boundaries of facies A and often show distinct orientation parallel to bedding. This may be a compaction (diagenetic) or a hydrodynamic effect.

The textural and petrographic names for each of the facies A units, as given by the classifications of Folk, Dunham, and Lindholm, are summarized in Appendix IC. The "energy indexes" implying the kinetic energy that existed in the water in the environment of deposition range from "very high" to "moderate to high" and are also listed in Appendix IC. These relative energy indexes were applied using the criteria given by Plumley et al. (1962) and Carozzi (1967), namely, field investigation, grain:cement: matrix ratios, sorting, rounding, and size of grains.

Finally, facies A units do not show the internal presence of any "in situ" fauna with the possible exception of units 14 and 12. These units indicate the presence of elongate, irregularly based stromatoporoids (under-represented in thin section modal analysis) aligned generally parallel to bedding. It was observed, however, that only the larger

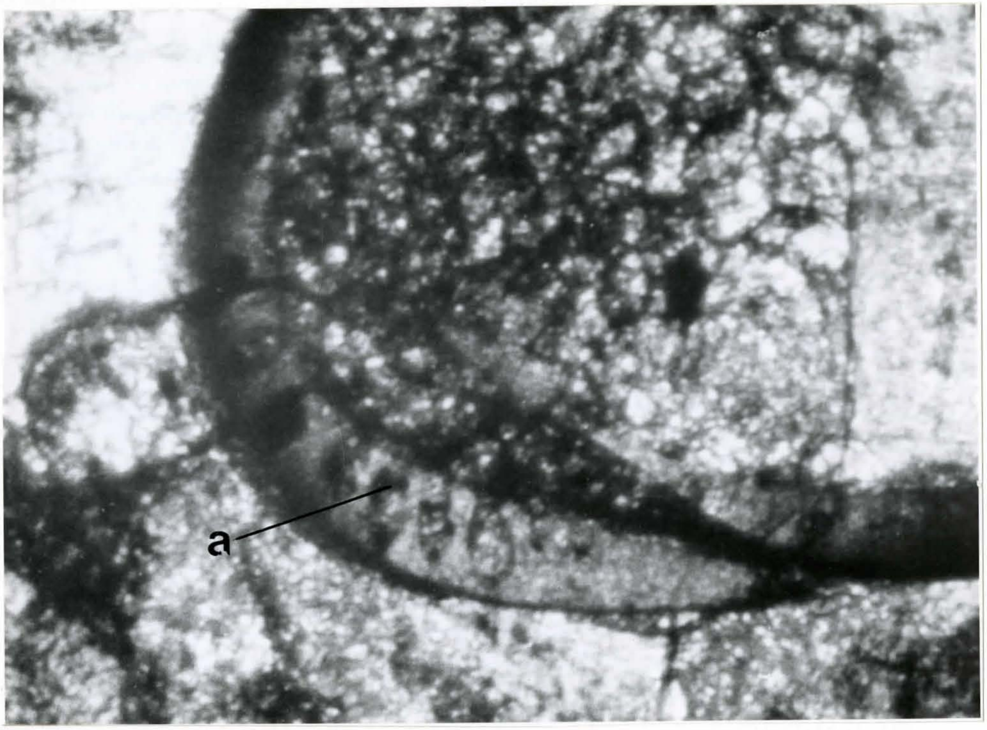


Figure 21. Algal borings (?) within ostracode shell. Note (a) opaques within boring

specimens were so oriented, the smaller ones were often fragmented, oriented up to 20° to bedding, and showed underlying shelter void cement (Figure 16).

FACIES A-1: BIOCALCARENITE WITH IN SITU STROMATOPOROIDS

This facies is characterized by a buff to light gray coloured, massively bedded, well sorted biocalcarenite with very thin (1 cm) shaley partings and scattered chert nodules. It is located entirely within unit 20 in the uppermost 90 cm of the stratigraphic section identified by a very sharp, fairly regular lower contact (Figure 5) which can be correlated throughout the quarry. Individual beds are sharp based, are separated by the shaley partings, and consist of 3 to 4 fining upward sequences which vary laterally from 5 to 12 cm in thickness. Each sequence directly overlies an elongate (>15 cm) and thin (0.5-2.0 cm) in situ encrusting coral or stromatoporoid many of which can be traced laterally for up to 35 cm. Similarly, each fining upward sequence is terminated by another in situ encrusting coral or stromatoporoid which itself marks the start of the next sequence. The entirety of facies A-1 is constructed in this fashion. The facies is devoid of Cystiphyllum-rich shaley beds (Facies C) as seen in the lower units; however, a more diverse coral fauna is seen scattered throughout this facies, and except for the encrusting forms they are rarely found in life position.

Individual sequences are well sorted (0.95 ϕ to 1.17 ϕ) and grade upwards from a mean grain size of 0.55 ϕ to 1.2 ϕ. The distribution is generally unimodal and normal at the bases, becoming increasingly bimodal in the centre of the cycle (due to an increased finer grained fraction, 1.0 to 3.0 ϕ), and increasingly unimodal at the top of the cycle (due to a decrease in the coarser grained fraction, Appendix IIB).

Petrographically, facies A-1 is very similar to facies A, being composed almost entirely of sand-sized skeletal fragments and sparry calcite cement. Micrite is a minor component (0.8 to 4.2%) and is generally in greater abundance at the top of the cycles. Skeletal fragments, which were the sole allochems, comprised from 67.0 to 71.1% of the thin sections. Echinoderm fragments, especially crinoid ossicles accounted for 45.6 to 57.2% with up to 3.1 to 3.2% coral and bryzoan fragments. Brachiopods and gastropods were minor, and ostracodes and trilobite fragments were absent.

Mineralogically these biocalcarenites are almost 100% calcium carbonate with only trace amounts of dolomite rhombs, glauconite, or detrital silica. Authigenic silica is common within corallites (under-represented in modal analyses) and trace pyritization occurs along minute fractures seen in hand specimen (Appendix IA).

Pellets are absent, and the degree of bioturbation is very low compared with facies A biocalcarenites. Individual burrows were also rare and occurred only at the bases of beds (actually the undersides) oriented parallel to bedding. Due to the moderate sorting and generally high energy environment of this facies, it is doubtful whether any pellets would be preserved.

Texturally, facies A-1 is characterized by abundant and well developed clean syntaxial spar overgrowths on well-sorted and often fractured echinoderm debris (Figure 22). Geopetal fabric is common in hand specimen, and in areas of rare micrite accumulation (Figure 23). Microstylolites between adjacent crinoid ossicles as well as tangential and concave contacts indicate compaction of an originally grain-supported sediment.

Facies A-1 is interpreted as having been deposited under high to very high energy conditions. Reasons for this interpretation are:

(a) cycles of well sorted, coarse grained, subrounded and fragmented crinoidal debris;

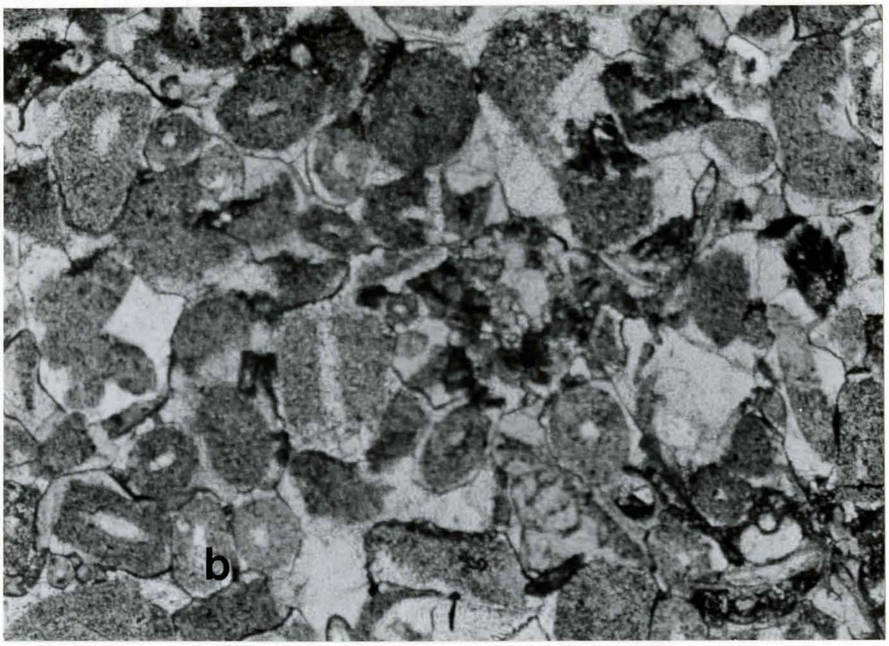


Figure 22. Facies A-1, well sorted crinoidal biosparite. Note
(a) syntaxial spar overgrowths
(b) tangential contacts
(c) fragmented grains

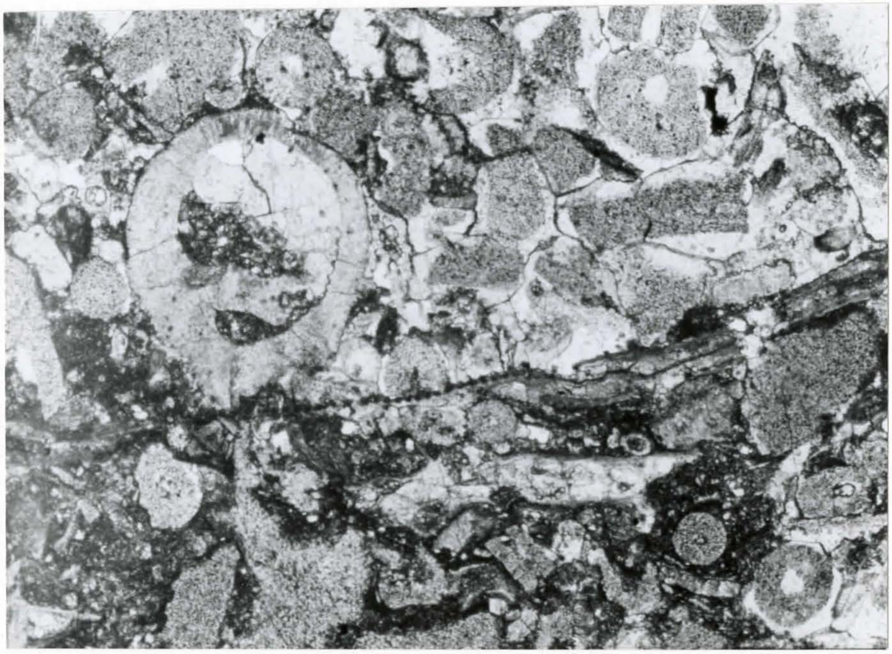


Figure 23. Facies A-1, rare accumulation of fine sediment. Note geopetal relationship within gastropod

(b) the fining upward nature of these cycles possibly indicating transport;

(c) the abundance of in situ stromatoporoids and encrusting coral forms which are wave resistant colonial organisms indicating the need for greater stability in a shallow water high energy environment (Plumley *et al.*, 1962).

FACIES B: FISSILE BIOMICRITE

Facies B is characterized by 3 to 21 cm thick laterally consistent, bluish gray to greenish, laminated, and relatively unfossiliferous, fine grained, fissile units in the lower portion of the stratigraphic section. Specifically, this includes units 1, 3, 5, 7, 9, and 11 which are interbedded with Facies A biocalcarenites and comprise the third major facies of the section (Figures 5 and 14).

These fissile recessive units are thinly laminated (0.1 to 0.3 cm), have gradational lower boundaries and sharp upper contacts with Facies A biocalcarenites, and may locally exhibit areas of up to 10% sand-sized fossil debris and *Cystiphyllum* corals. Occasionally these units overlie in situ encrusting and broad based *Favosites* heads growing on top of Facies A beds (Figures 12 and 14) indicating a minor hiatus and a subsequent mud influx. Grain size analysis indicates little vertical variation among fossil fragments and absence of grading (Appendix IIB).

Petrography

Modal analysis of unit 5 indicates the presence of 10.3% recognizable (but only 3% identifiable) skeletal fragments, 78.8% micrite matrix and 4.8% sparry calcite which is restricted to internal voids of skeletal fragments (Appendix IA and B). Dolomite rhombs (21.4%) and detrital silica (6.1%) are most abundant in this facies, and tend to be more abundant in certain laminae (Figure 24). Some of the dolomite rhombs have slightly rounded edges and none are found within larger skeletal fragments; this may indicate a detrital origin. A possible source of the dolomite may be the erosion of local Silurian dolomite scarps identified by Kobluk and Risk (1977). The laminae themselves pinch and swell and often drape (possibly due to compaction) around matrix supported fossil fragments.

Facies B is interpreted as being slowly deposited under low energy conditions and is termed a fossiliferous to sparse laminated biomicrite (Appendix IC).

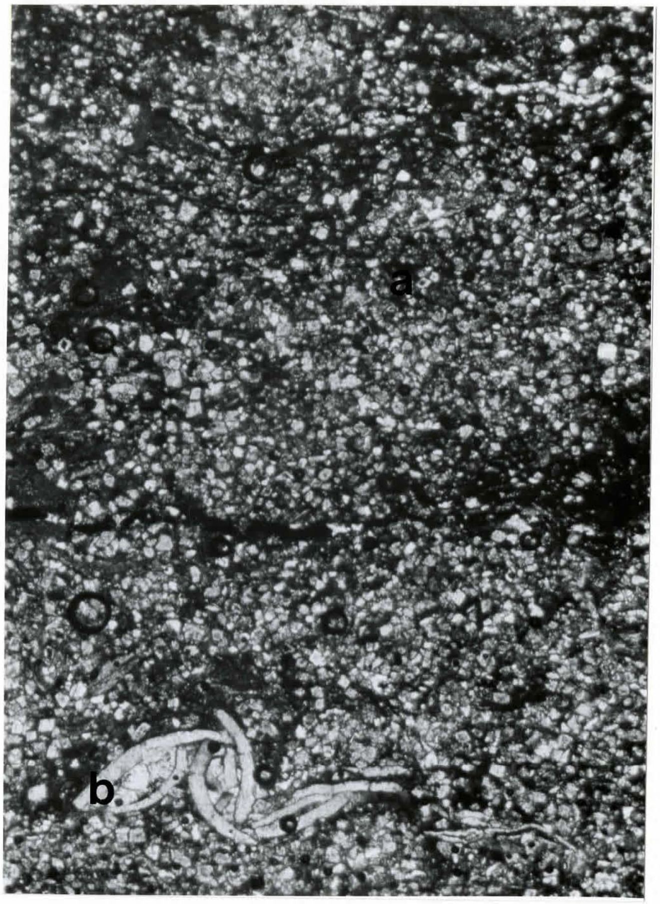


Figure 24. Facies B, fissile biomicrite with dolomitic laminae. Note

(a) cloudy centres of dolomite rhombs;
(b) rare skeletal fragment, compacted and aligned parallel to bedding

FACIES B-1: BIOTURBATED BIOMICRITE

Facies B-1 is a highly bioturbated zone ranging from 2 to 4 cm in thickness located in the uppermost portion of Facies B (units 3, 5 and 7) directly below Facies A biocalcarenites (units 4, 6 and 8). They have been termed units 3-1, 5-1, and 7-1 (Figure 5) and are characterized by being unlaminated, light bluish gray coloured, poorly sorted, and slightly coarser grained biomicrites than Facies B. The coarser grain size and absence of vertical grading (Appendix IIB) as seen in units 3-1 and 5-1 (1.2 ϕ to 1.45 ϕ) is attributed to the burrowing activities of organisms, which may have mixed in a portion of the overlying biocalcarenite units. Large pebble-sized coral fragments are not found within this facies, in contrast to the overlying biocalcarenites (units 4 and 6), indicating that the bioturbated zone was not originally a biocalcarenite reduced to a finer grain size by organisms. Unit 7-1 differs from lower Facies B-1 units by being slightly finer grained (1.85 ϕ), having a sharper contact with overlying unit 8 and exhibiting different forms of burrow traces.

Although modal analyses of these units were not performed, the matrix supported skeletal constituents which comprise approximately 20% to 40% of the facies are generally fragmented beyond recognition and show well-developed micrite envelopes. Sparry calcite cement is absent and the fine grained micrite matrix which comprises the remainder of the facies is believed to have originated both from peloidal material and the breakdown of skeletal fragments by burrowing and grazing organisms.

Facies B-1 therefore records a biological response to the rapid deposition of the overlying coarse grained and graded biocalcarenites. This facies consistently occurs below the calcarenites, pinches out when the calcarenites do, is not greatly bioturbated, and contains what have been interpreted as escape burrows.

FACIES C: CYSTIPHYLLUM-RICH FISSILE BIOMICRITE

Facies C is bluish gray, thinly laminated, fine grained, fissile biomicrite comparable to Facies B but containing more abundant sand-sized skeletal debris and densely packed *Cystiphyllum* corals, the latter comprising upwards of 40% of the bed by volume (Figure 11). This facies is found in the upper 1.4 meters of the lower horizon (units 13, 15, 17 and 19; Figure 5). It varies in thickness from 2.0 cm to 22.0 cm (Appendix IIA) and locally contains small (3.5x23.0 cm) lenses of Facies A biocalcarenites which are more abundant in the thicker units (13 and 15). These thicker units are characterized by a scoured lower contact with underlying biocalcarenites (units 12 and 14), and a sharp upper contact with overlying biocalcarenites (unit 14 especially). The contacts of the thinner Facies C units (17 and 19) are slightly more variable and appear to be locally gradational.

These irregularly scoured lower contacts (Figure 16) often show abraded and fragmented *Cystiphyllum* corals which impinge on the underlying biocalcarenites, indicating that these corals were transported, possibly in traction, with the transporting current scouring and resuspending the lower biocalcarenite sediments. The skeletal fragments have been redeposited between corals in thin bands sub-parallel to bedding (Facies C-1), either due to subsiding water agitation or due to current baffling by the corals themselves. Redeposited skeletal fragments may also accumulate within solitary rugose coral fragments and often show sheared-off upper boundaries (Figure 16).

Facies C units have been interpreted by previous workers (Parkins, 1975) as biostromal beds, indicating that these beds were "built" by sedentary organisms, mainly *Cystiphyllum* (Nelson, 1962).

Although these corals were at one time proliferating in great numbers in the Onondagan sea, none are preserved in growth position and all show evidence of transportation. Also, the density of these corals decreases in the south end of the east wall indicating that Facies C units in the sample area are actually Cystiphyllum "dumps" (Figure 11) that are peculiar to this area.

FACIES C-1: PACKED BIOMICRITE

This is the second minor facies, and is located within Facies C directly overlying the Facies A biocalcarenites of unit 12 and 14 (termed units 12T and 14T respectively; (Figure 5).

These are discontinuous, irregularly bedded accumulations of grain supported, poorly sorted, severely fragmented coarse sand-sized, elongate skeletal fragments within a fine grained micritic matrix. The upper boundaries grade into Facies C fissile biomicrites, while the lower boundaries are generally sharp overlying upper erosional contacts of units 12 and 14. In areas, unit 14T attains a lensoidal shape (Figure 5), but is more commonly found between accumulated Cystiphyllum corals as the redeposited skeletal fragments discussed in Facies C.

Petrography

This facies is composed of 69.9% to 78.4% skeletal fragments, the majority of which are unidentifiable (Appendix IB) and aligned parallel to bedding (Figures 25 and 26). Identifiable fragments were predominantly Echinodermal. Detrital silica, dolomite rhombs, pyrite replacement, and glauconite are present in minor or trace amounts, while pellets are absent (Appendix IA). The micrite matrix is composed primarily of finely comminuted skeletal fragments, and comprises from 16% to 25% of the facies. Sparry calcite cement is generally absent.

The sub-parallel alignment of elongate skeletal fragments may be due to compaction, evident from sutured microstylolitic contacts between grains (Figure 25), or deposition giving an almost imbricated appearance (Figure 26), or some combination of both processes.

As previously stated, Facies C-1 is interpreted as being the resedimented, abraded skeletal fragments of the underlying biocalcarenite units. Water agitation is believed to have been relatively short lived, or not quite high enough to winnow away the micrite matrix. In relation to other facies, C-1 is considered to have been deposited under medium to high energy conditions (Appendix IC).

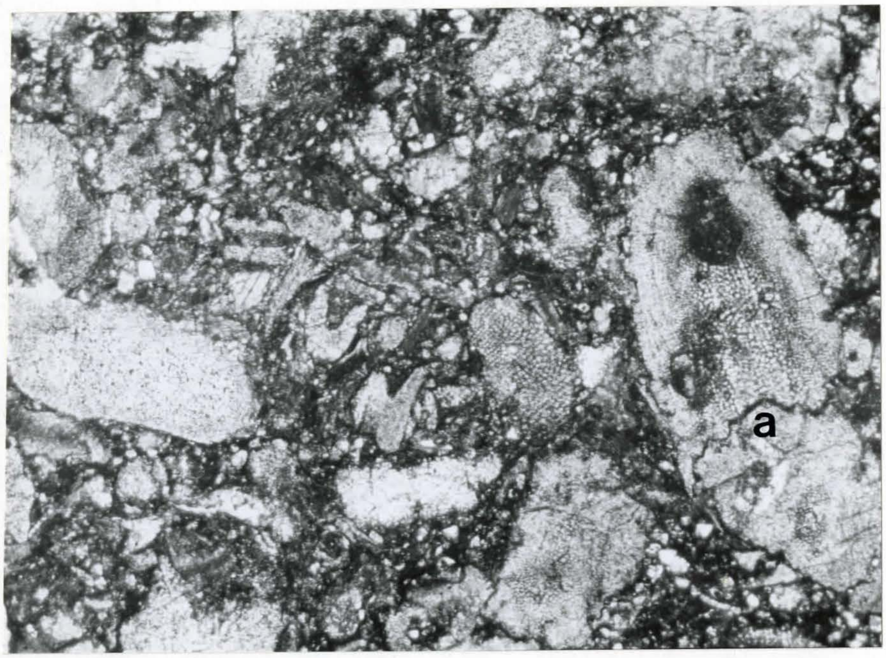


Figure 25. Facies C-1, packed biomicrite (Unit 14T). Note poor sorting, microstylolitic contact (a), and rounded abraded nature of grains.

Figure 26. Facies C-1, packed biomicrite (Unit 12T). Note alignment of grains subparallel to bedding

FACIES D: SYNAPTOPHYLLUM-RICH SPARSE BIOMICRITE

Facies D is a lensoidal (individual units 7-12 cm thick, 1-2 m in extent), dark gray, cherty unit, composed largely of matrix supported Synaptophyllum-rich skeletal constituents. It comprises the entirety of unit 2 in the sample area and is also found at the same stratigraphic level as unit 4, 10 meters south of the sample area. Accumulated skeletal fragments are found within the interstices of in situ Synaptophyllum colonies which comprise the entire framework of these units. These Synaptophyllum colonies are also found locally within unit 1 but do not extend for more than 20 to 30 cm laterally.

Petrography

The interstices of Synaptophyllum corallites contain 23.2% to 44.3% unsorted skeletal allochems which are dominantly disarticulated brachiopod valves and corals (Figure 27). These are relatively well preserved, and some brachiopod valves reach widths of >2 cm. In some areas, abundant fine grained pellets are preserved between corallites which have escaped compaction effects and indicate a fairly quite depositional environment (Figure 28).

Sparry calcite cement is restricted to the internal voids of corallites which are rimmed by a finely bladed calcite crust and filled with coarser interlocking calcite. These corallites often exhibit geopetal fabric and rare chain-like structures (possibly pyrite framboids which have grown in vacated algal burrows).

Dolomite rhombs are absent from peloidal areas (Figure 28), but comprise up to 2% in the upper portions of unit 4 (Figure 27). Chert replacement occurs some time after deposition as dark gray irregularly rounded patches encompassing both matrix and *Synaptophyllum* corals.

Facies D is a true biomicrite (Appendix IC) and is the result of slowly accumulating sediments within a framework of *Synaptophyllum* colonies interpreted as being deposited in a low energy environment.

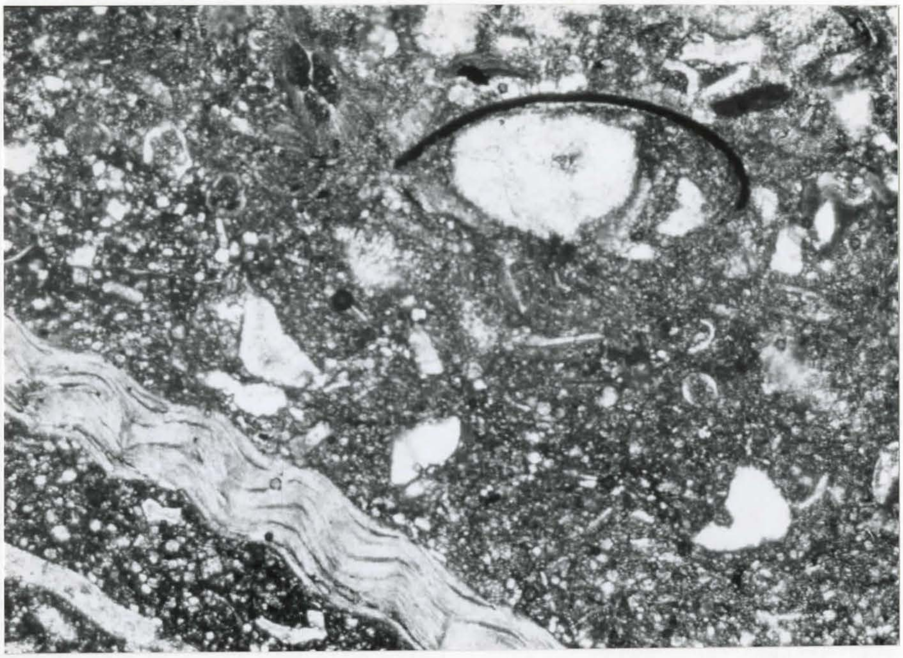


Figure 27. Facies D, sparse biomicrite. Note large punctate brachiopod valve (lower left), and matrix supported nature of fragments

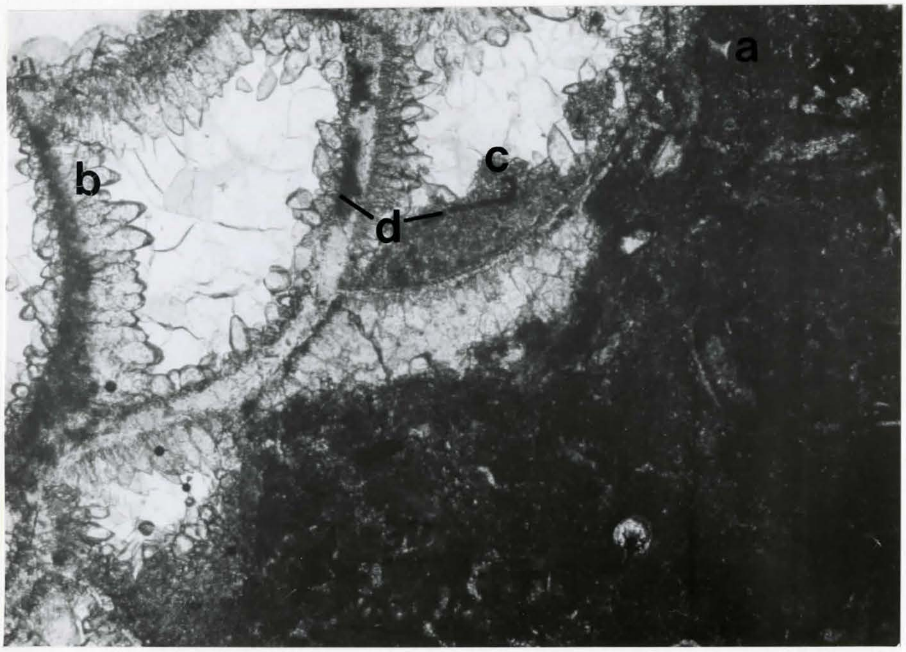


Figure 28. Facies D, cementation of corallite void. Note (a) pellets (b) finely bladed calcite crust rimming corallite (c) geopetal fabric (d) possible evidence of algal activity

CHAPTER IV

PALEOECOLOGY

The stratigraphic column in the study area can be divided into 3 distinct paleoecologic sections, I, II, and III, distinguished by fauna, biogenic structures, and facies succession (Figure 5). The boundary between section I and II is gradational and somewhat subjective, whereas section III is marked by a distinct and sharp lower boundary.

SECTION I

Section I makes up the lower 1.1 meters of the stratigraphic column from the base (unit 1) up to and including unit 11 (Figure 5). It contains 4 of the 7 facies already described, namely Facies A, B, B-1 and D, the latter 3 facies being restricted to this section. Facies D *Synaptophyllum*-rich beds are located within Facies B shales and are restricted to the lower 44 cm of section I. These are overlain by a cyclic arrangement of Facies A, B and B-1 resulting in three distinct cycles.

Each cycle begins with a Facies A biocalcarenite (units 4, 6 and 8), often with sharp, scoured lower bases. The biocalcarenite grades upward into Facies B laminated biomicrite (units 5, 7 and 9), and finally into Facies B-1, bioturbated zone (units 3-1, 5-1 and 7-1) with a sharp upper contact initiating the next cycle (Figure 29).

Units 10 and 12 are underlain by Facies B biomicrites but do not contain the intermittent Facies B-1 bioturbated layer. Unit 10 is included in section I although it does not show the characteristic grading of section I biocalcarenites due to internal mottling (Plate 3) and is considered a transitional unit between section I and section II biocalcarenites.

Facies B-1 underlies the biocalcarenite unit of each section I cycle, and exhibits a variety of traces, both those at the interface between Facies B-1 and A, and those which pass vertically through Facies A into overlying Facies B biomicrites (Figure 29).

Five characteristic bioturbate structures are found within the cycles (Figure 29), none of which show any sign of permanent burrow lining. Those which are restricted to Facies B-1, and do not come in contact with the overlying

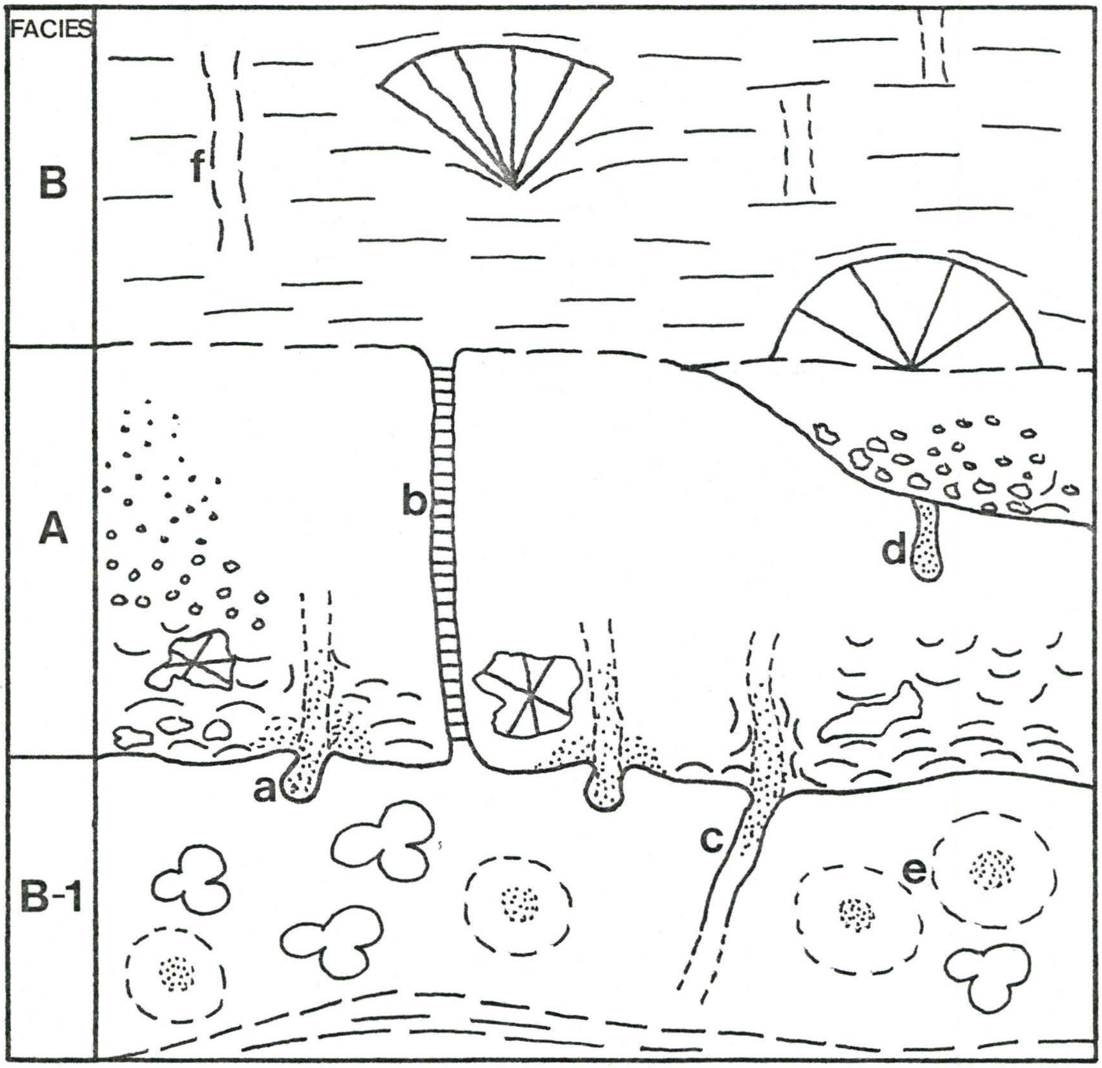


Figure 29. Typical Section I cycle

a, b, c — ESCAPE BURROWS

d — TRUNCATED BURROW

e — HORIZONTAL BURROWS WITH HALOS

f — POSSIBLE BURROWS (X-RAYS ONLY)

biocalcarenite (Figure 29e, Figure 30) are rounded structures (1 to 2 cm diameter) whose cross-sections exhibit finer grained centres and coarser rims due to horizontal burrowing. The consistent thickness of the bioturbated zone containing these burrows, the upper conformable contact with Facies A (Figure 30), and the absence of these burrows in underlying Facies B indicates that these burrows may be a direct reaction to the deposition of the coarse biocalcarenite above. Rapid deposition of Facies A is indicated by the examination of burrow structures at the Facies B-1/Facies A interface (Figure 29a,c) and also of those which pass vertically through Facies A (Figure 29b). Burrows at the interface exhibit:

(1) infilling of coarser skeletal material from the overlying Facies A biocalcarenite (Figure 31; Plate 2);

(2) the introduction of finer grained (Facies B-1) material into the overlying Facies A biocalcarenite unit as a vertical burrow trace of comparable thickness to the original interface burrow (Plate 2);

(3) the disturbance of Facies A sediments around the vertical trace: notably elongate fragments and brachiopod valves are oriented subvertically

rather than subhorizontally (Figure 29a,c).

The author's interpretation is that organisms originally feeding at the sediment/water interface were forced to abandon their burrows, due to the rapid deposition of Facies A biocalcarenites, forming these vertical "escape" structures. It is likely that the vertical structures in Plate 1(b) which extend through the entirety of unit 6 are also escape burrows in response to the rapid deposition of coarse debris upon the environment of Facies B.

A quiet depositional environment for Facies B is indicated by the presence of fine grained laminations and in situ *Favosites* heads characterized by a high apical angle (135°), which either occur directly over Facies A biocalcarenites (indicating a hiatus, Figure 12) or entirely within Facies B (Figure 30). Evidence of slight bioturbation is also found in Facies B (Plate 1f).

Unit 8 (8a especially) differs both in grain size and composition from units 6 and 4, being generally finer grained and composed largely of disarticulated brachiopod valves and coral fragments. Within the basal centimeter of unit 8a these valves show a distinct difference in orientation and size distribution from those 2 cm above the base. Of all of the valves measured at the base, 54% are oriented

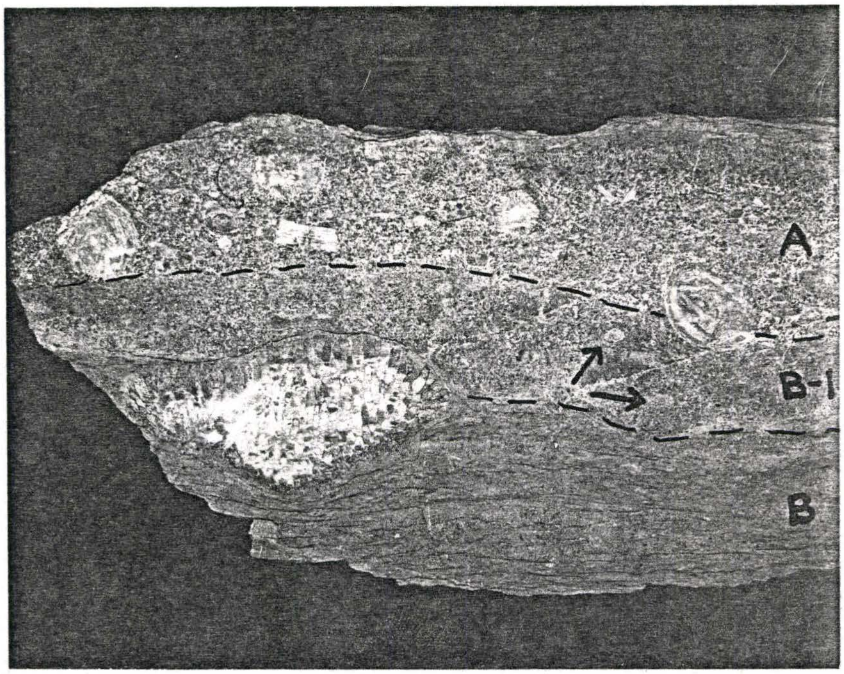


Figure 30. Slabbed and etched surface of complete Section I cycle.

Note Facies B-1 rounded burrow halos; fining upward character of Facies A (Unit 6); in situ Favosites within Facies B

Figure 31. Slabbed and etched surface of complete Section I cycle, unit 7-1, 8a, 8b.

convex-up and parallel to bedding and 61% have a cross-sectional width larger than 0.0 ϕ. 2 cm above the base, only 22% of all valves measured are oriented convex-up and 22% are larger than 0 ϕ (Figure 32). The basal measurements indicate that larger valves tend to be oriented convex-up, while 2 cm above the base valves tend to be oriented concave-up due to their smaller size (from sorting) and a sharp decrease in current velocity, allowing valves to settle out gently and remain in concave-up position (Figure 33).

The abundance of convex-up valves, and shelter void cements can be attributed to high energy deposition due to storm generated currents. Although the brachiopod valves do not reach "coquinoid" concentrations, it is believed that they are analogous to coquinas interpreted by recent authors to be representative of storm generated "lag" deposits (Brenner et al., 1973; Aigner et al., 1979; Kreisa, 1979). Keunen et al. (1952) suggest that vertically graded bedding can occur in shallow seas as a result of sediment suspension by storm waves, which is a plausible origin of the graded Facies A biocalcarenites of section I.

Unit 8 is composed of two of these fining upward cycles (8a and 8b) separated by a minor hiatus, allowing the re-establishment of burrows (Figure 29d) which were eroded

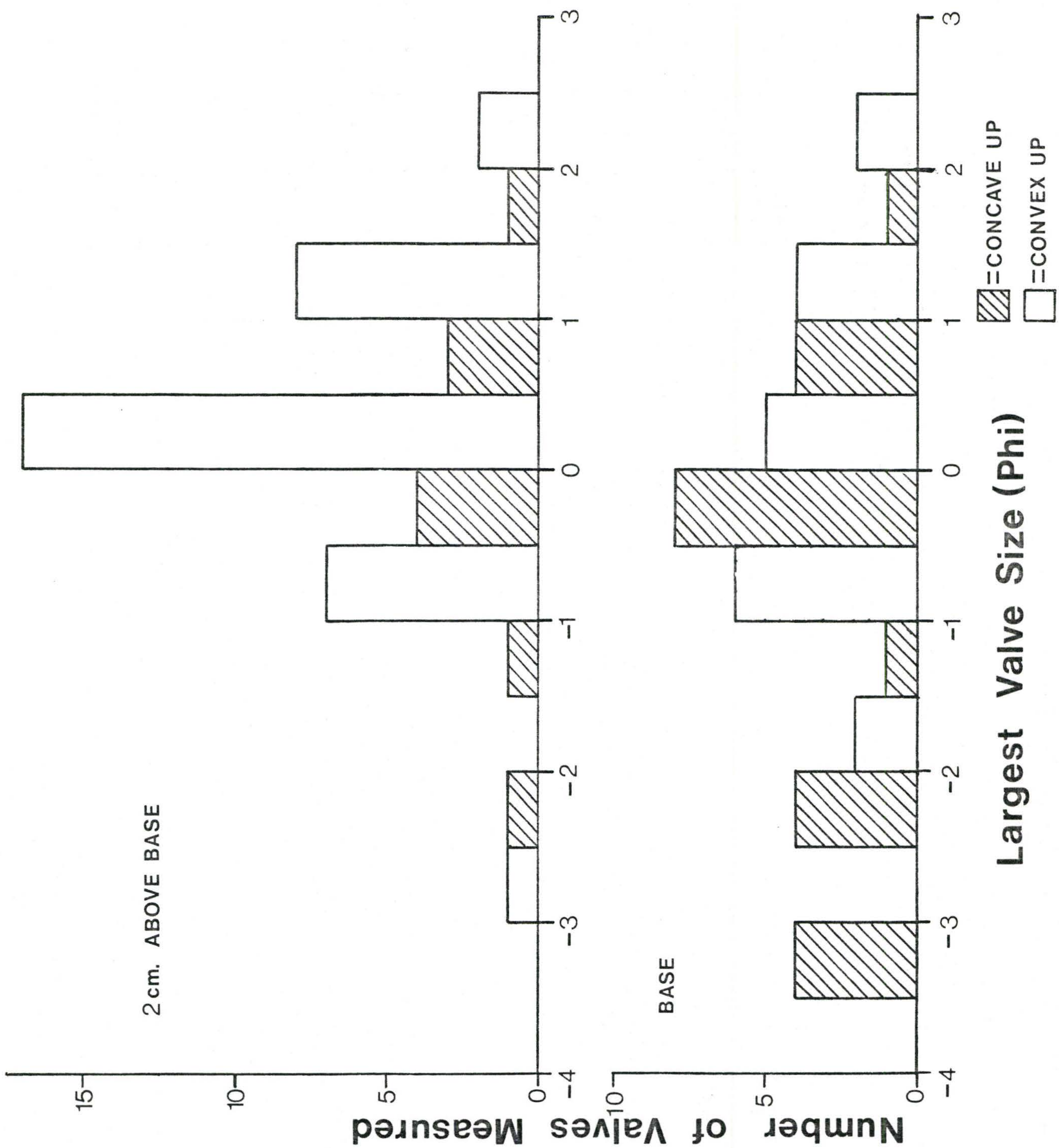


Figure 32. Relationship of brachiopod valve orientations to size and relative position within Facies A biocalcarenite (Unit 8a).

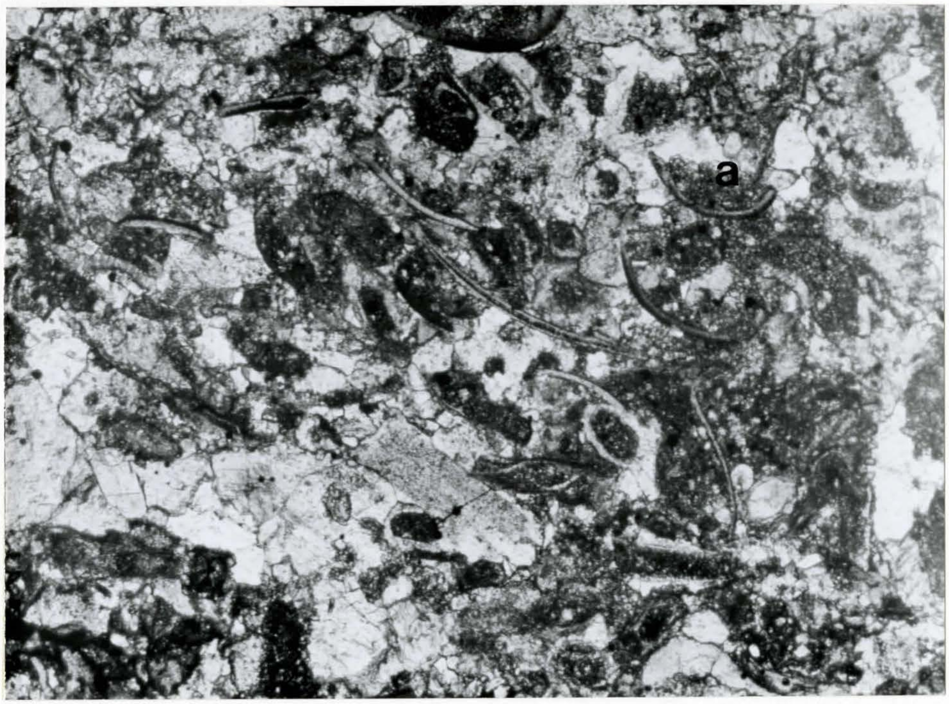


Figure 33. Concave-up brachiopod valves in upper 2 cm of Unit 8a.

Note (a) trapping or infiltering of fines within concave up valve.

by the influx of the second fining upward biocalcarenite unit. Finer grain size than units 6 or 4 may indicate lower energy currents possibly from a more distal source arriving in a series of closely spaced waning "pulses" and accounting for better preservation of the ancient sediment (Facies B-1)-water interface (Figure 31).

The general depositional environment of section I is believed to be shallow to deep subtidal, just below effective normal wave base. This is supported by the low Lst:Sh ratio and low energy interpretation for Facies B. Coarse grained, fining upwards, relatively thin and lensoidal biocalcarenite beds indicate that water depth was not below effective storm wave base (100 meters, Lindholm, 1967) and that severe storms were the most probable mode of deposition. The presence of escape burrows reinforces this interpretation.

SECTION II

Section II comprises the upper 1.53 meters of the lower horizon, from the base of unit 12 to the base of unit 20 (Figure 5). It contains 3 of the 7 facies described, namely Facies A, C and C-1, the latter two being restricted to this section.

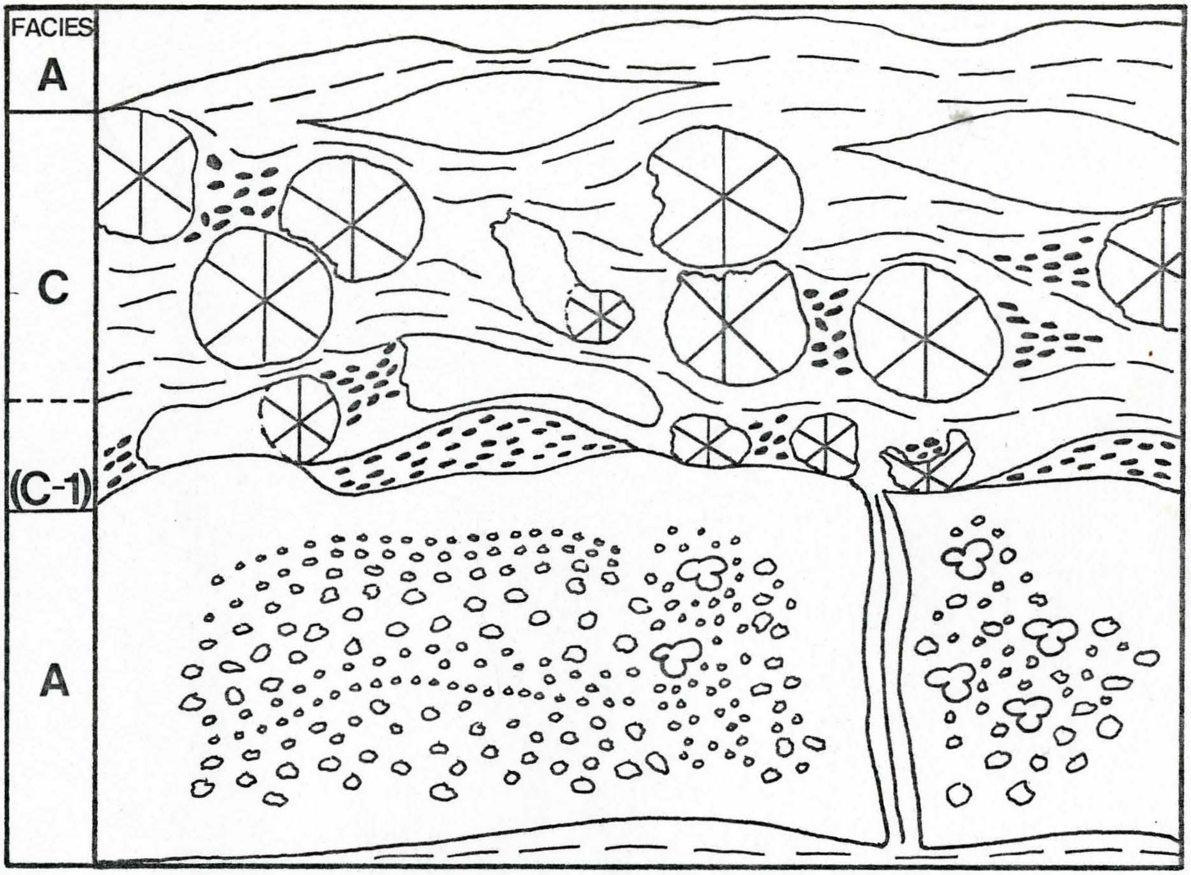
Section II is composed of 4 cycles, each beginning with the deposition of Facies A biocalcarenites characterized by irregularly scoured bases and tops. These may be quite massive (units 12 and 14) or irregularly and more thinly bedded, as in units 16 and 18. Facies A has a scoured erosional upper contact with overlying Facies C Cystiphyllum beds (units 13, 15, 17, 19) which locally contain small Facies A lenses. Above units 12 and 14, Facies A and C are discontinuously separated by Facies C-1 (units 12T and 14T), interpreted as resedimented Facies A biocalcarenites. Facies C-1 may also be found interspersed within thinner Facies C units (17 and 19; Figure 5). The typical section II cycle is illustrated in Figure 34.

Possibly as a result of bioturbation, section II biocalcarenites do not exhibit the distinct fining upward size grading seen in section I, and generally have lower sparry calcite cement:micrite ratios.

Biogenic structures are distinctly different from section I and are restricted to (a) extreme mottling and (b) rarely preserved lined vertical burrows (Figure 35; Plates 4 and 5). The lined burrow is analogous to the burrow of a nereid polychaete that burrows from the sediment surface downward headfirst, turns after 8 to 10 cm and digs upwards toward the surface while secreting mucus and pushing

Figure 34. Typical Section II cycle

Figure 35. Abandoned vertical neireid-like burrow


FACIES
A
C
(C-1)
A


CM
1
2
3
4
5
6
7
8
9

the mucus-soaked walls of the tube, resulting in a 4 to 6 mm wide burrow with self-supporting walls and an open connection to the surface (Figure 35; Schafer, 1972).

Characteristics of the burrow are:

(1) fine grained (<5 ϕ) lining, varying from 1-3 mm thickness and showing lineation parallel to the walls of the burrow;

(2) thickening and thinning of the burrow from 3-6 mm over short (1 cm) vertical distances;

(3) absence of branching (revealed by serial sections);

(4) the lower 7 cm is sub-vertical, becoming increasingly accurate and thin in the top 2 cm;

(5) the burrow passes upwards through the entirety of a Facies A lenticular bed, includes sediment from the underlying shaley layer within the lower 1 cm, and is infilled by a coarser grained sediment with a higher spar:micrite ratio than surrounding sediments;

(6) the burrow is surrounded but not interrupted by severe mottling in the surrounding sediment (Plates 4 and 5).

The relative thickening and thinning of recent nereid burrows is attributed to rapid sedimentation, causing the polychaete to leave its well-lined feeding burrow and burrow upwards to the new sediment/water interface (Schafer, 1972).

The burrow preserved in Facies A is believed to be primarily a feeding burrow, as seen by the well developed lining. The infilling of the burrow top with coarser sediment, the rapid thinning of the burrow and lining in the top 2 cm, and the introduction of finer sediment from below the unit indicate that this burrow was quickly abandoned and that the organism escaped vertically.

This response may have been initiated by rapid sedimentation caused by severe periodic storms known to be effective to depths exceeding 100 meters (Dunbar *et al.*, 1958, *in* Lindholm, 1967). This interpretation is reinforced by the presence of *Cystiphyllum* "dumps" (Facies C) which show abundant evidence of transportation and directly overly Facies A, often scouring the biocalcarenite surface and resuspending the sediments (Facies C-1). These coarser, resuspended sediments would have easily found their way into simultaneously abandoned feeding burrows (Plates 4 and 5). The abundance of overturned *Favosites* heads and the absence of any in situ fauna within section II may be additional evidence for a severely agitated environment. Section II is is interpreted as being shallow subtidal, just above mean wave base. This is supported by the greater abundance and thicknesses of Facies A biocalcarenites (showing remnant bedding and grading in the thicker units), the presence of abundant transported Cystiphyllum and the severe mottling of the biocalcarenites. The locally thicker Facies C units in the sample area may indicate the presence of a localized high where water agitation would be increased, thereby favouring Cystiphyllum growth.

SECTION III

Section III is located in the uppermost 90 cm of the stratigraphic column (unit 20) and consists entirely of Facies A-1. It is devoid of preserved mottling, or discrete burrows and contains abundant in situ stromatoporoids and encrusting corals. The very high spar:micrite ratio (>10) and the well sorted, fining upward nature of an almost exclusively crinoidal biocalcarenite indicates deposition under high energy conditions. Heckel (1972) suggests that well sorted, mud free calcarenites that are composed of one type of shell (echinoderms) and show no abrasion or cross-bedding indicate nothing more than local proliferation of organisms or lack of dilution. Rhoads (1967) shows that biogenic reworking of subtidal sediments can produce graded bedding by preferentially extracting fines upward to the sediment/water interface where they may be easily winnowed. Neither of these theories accounts for Facies A-1 biocalcarenites, which show abundant abrasion and rounding of grains and a lack of biogenic structures.

The cyclic nature of section III units is due to successive fining upward sequences bounded by stromatoporoids or encrusting corals. Although there are no slopes to speak of in an epicontinental marine setting such as this, the fining upward cycles indicate pulses of sediment from an area rich in crinoids, separated by minor hiati. Section III biocalcarenites are composed entirely of crinoids and corals (plus minor bryozoans) almost to the exclusion of other marine invertebrates. It may be that these rapidly shifting crinoidal sands hindered the establishment of burrowing organisms.

Section III is interpreted as being shallow subtidal above mean wave base. The presence of scattered bioherms (patch reefs) in this section (and only in this section) may have provided local slopes and shelf channels between bioherms, accounting for the transport and abrasion of crinoidal biocalcarenites. It is suggested that deposition occurred in water no deeper than 250 ft and probably less than 100 ft (Lindholm, 1967), indicating a minor regression from section I to III.

SUMMARY

Passing upward from section I to III, the following trends are present within the east wall of the Port Colbourne Quarry:

(1) an increase in the relative abundance of
   - (a) crinoid debris within biocalcarenite units,
   - (b) stromatoporoids and encrusting corals,
   - (c) <u>Cystiphyllum</u> sp.;

(2) a decrease in the relative abundances of
   - (a) <u>Synaptophyllum</u> colonies,
   - (b) preserved biogenic structures;

(3) an increase in biocalcarenite bed thickness coinciding with an increased Lst:Sh ratio and decreased dolomite content.

CHAPTER V

DISCUSSION

In most marine environments sediment deposition is sporadic (Raup *et al.*, 1971). The importance of storms, hurricanes and similar periodic phenomena as dominating processes in the buildup of the stratigraphic record have only recently been emphasized, although Darwin was well aware of catastrophic events in the geologic record. Intermittent violent episodes are probably more preferentially preserved in the record than "non-catastrophic" processes (Ager, 1974). It has been shown in recent years that hurricanes and storms can resuspend and redistribute great quantities of sediment very quickly (Bambach *et al.*, 1978; Aigner *et al.*, 1979; Jones et al., 1976; Brenner *et al.*, 1973, etc.). The characteristics of such storm deposits are that they:

(1) show evidence of violent disturbance of pre-existing sediments followed by rapid redeposition in shallow water (Ager, 1972);

(2) exhibit graded-bedding, sharply truncated bases and transitional tops, resembling "turbidites" but lack erosional sole marks (Ager, 1972);

(3) are usually preserved in "one-event" beds, often coquinas, which contain shells aligned parallel to bedding, often convex up at the base of these beds exhibiting abundant shelter void cements (Aigner *et al.*, 1979; Kreisa, 1978, etc.);

(4) commonly contain escape burrows;

(5) exhibit a marked periodicity.

Each of the above characteristics are exhibited in the Port Colbourne Quarry.

CHAPTER VI

CONCLUSIONS

The Edgecliff member of the Onondaga Formation within the Port Colbourne Quarry exhibits 4 major and 3 minor carbonate facies:

(1) Facies A: Biocalcarenite

(2) Facies A-1: Biocalcarenite with in situ stromatoporoids

(3) Facies B: Fissile biomicrite

(4) Facies C: Cystiphyllum-rich fissile biomicrite

(5) Facies B-1: Bioturbated biomicrite

(6) Facies C-1: Packed biomicrite

(7) Facies D: Synaptophyllum-rich sparse biomicrite.

Different arrangement and development of these facies, in turn, allows subdivision of the section into 3 major units.

The basal section (I) represents deposition in a shallow to deep subtidal environment, below normal wave base, and above storm wave base. Facies A units are thin and lenticular, and represent storm lag deposits. Evidence is:

(1) The cyclic arrangement of Facies A, B and B-1.
(2) The sharp scoured base, coarse grain size, and vertical (fining upward) size grading.
(3) The abundance of abraded grains, shelter void cements and escape burrows.
(4) The presence of in situ _Favosites_ heads within Facies B or directly overlying Facies A, indicating minor hiati between sporadic and violent deposition.

Section II represents a minor regression, and deposition in a slightly shallower subtidal environment than section I. The cyclic arrangement of thicker Facies A units, Facies C and Facies C-1 are also overprinted by storm reworking. Evidence is:

(1) The presence of _Cystiphyllum_ "dumps" showing abundant evidence of transport and abrasion.
(2) Lack of any in situ fauna.
(3) Scoured tops of underlying Facies A units.
(4) Resuspended and redeposited debris (Facies C-1) between _Cystiphyllum_ and directly overlying Facies A.

(5) Presence of abandoned nereid-like polychaete burrows.

Section III represents further regression and deposition in a shallow subtidal high energy environment due to:

(1) The presence of bioherms indicating an environment conducive to reef development.
(2) The reduced Lst:Sh ratio and massive character of Facies A-1 biocalcarenites.
(3) The abraded nature of an almost exclusively crinoidal sediment, whose rapidly shifting nature resulted in graded bedding and hindered the establishment of burrowing organisms.
(4) The presence of in situ wave resistant fauna such as stromatoporoids and encrusting corals.

In summary, this investigation has indicated that deposition of the Edgecliff member was not a result of slowly accumulating shelf carbonates, as previously believed, but probably the result of sporadic, cyclic, and violent depositional events, probably storm induced.

CHAPTER VII

FURTHER RESEARCH

The importance of sufficient input prior to the development of any depositional "model" cannot be overemphasized. Before any firm conclusions can be drawn concerning the storm deposition of Edgecliff sediments, the author recommends that the remaining walls of the Port Colbourne Quarry be examined for a more detailed comparison with the present study.

To determine the local extent of these "sporadic" events, examination of numerous other quarries well exposed in southern Ontario is essential.

Locally, however, a sound paleoecologic understanding of the effects of storm deposition might be obtained through the application of numerical analysis within a particular "cycle". In this way, perhaps, a more distinct correlation between faunal assemblages and their response to storms in similar recent environments can be made with the cycles of the Edgecliff member in the Port Colbourne Quarry.

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PLATES

Transmission X-ray Radiographs:

1. Units 5, 5-1, and 6 (dark):

   b: vertical biogenic structures within Facies A;

   f: vertical biogenic structure within Facies B.

2. Units 7-1, 8a, 8b:

   a,c: escape burrows, note lighter (finer) sediments extending into above Facies A;

   d: truncated burrow at base of overlying Facies A (unit 8b).

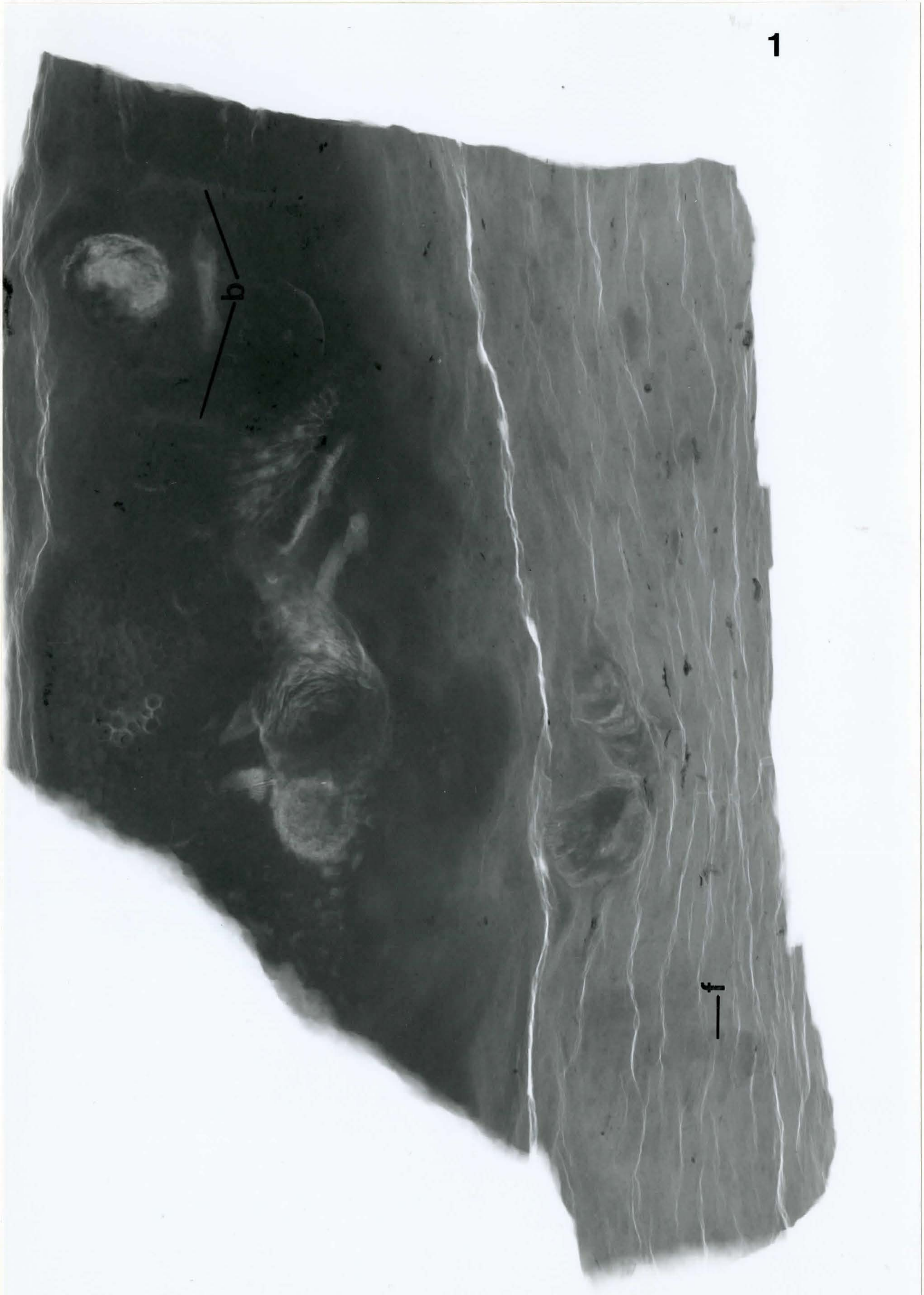
3. Unit 10, Facies A:

   m: mottled area.

Thin Sections of Abandoned Burrow:

4. Unit 16, Facies A; lower portion (4 cm) of vertical nereid like burrow; note lighter halo adjacent to burrow wall.

5. Unit 16, Facies A; upper 4 cm of same burrow, note well developed lining, type of infill, and arcuate top.


1
b
f

2


3
m


4


5

APPENDIX

I(A) Petrographic Modal Analysis

I(B) Skeletal Modal Analysis

I(C) Textural and Petrographic Name; Energy Index

II(A) Grain Size Data

II(B) Histograms and Cumulative Curves

APPENDIX I(A)

Petrographic Modal Analysis

Thin Section or Peel (P)	Sparry Calcite Cement	Micrite Matrix	Sk Frags	Pel	Si Det.	Total Allochems	Dol	Si Rep.	Op	Gl	Total Point Counts
78-E-20	28.1	0.8	71.1	-	-	71.1	-	-	tr	-	980
78-E-20T	25.6	4.2	68.3	-	tr	68.3	0.1	-	tr	tr	852
78-E-20(P)	28.6	2.5	67.0	-	0.2	67.0	0.1	1.1	tr	-	600
78-E-18ST	20.3	8.7	58.5	1.9	tr	60.4	0.2	tr	-	-	840
78-E-18NT	9.4	19.2	60.9	1.7	1.3	63.9	0.5	tr	tr	-	892
78-E-18B	18.1	16.7	57.1	0.6	0.4	58.1	0.4	tr	tr	-	811
78-E-16NB	6.9	36.3	48.8	7.2	0.8	56.8	0.1	1.9	tr	-	922
78-E-16N(P)	17.1	28.7	53.1	1.1	-	54.2	-	0.8	-	-	600
78-E-14T	3.8	25.5	69.9	-	0.2	70.1	2.1	tr	tr	tr	830
78-E-14	23.1	14.7	64.0	1.8	-	65.8	0.1	tr	tr	-	920
78-E-13	6.1	21.2	73.5	0.5	0.3	74.3	2.8	tr	tr	tr	630
78-E-12T	4.8	16.0	78.4	-	0.8	79.2	0.9	-	tr	tr	800
78-E-12B	19.3	14.2	69.6	2.1	-	71.7	0.1	tr	tr	-	835
78-E-12(P)	22.5	8.7	72.0	3.2	-	75.2	0.7	tr	tr	-	600
78-E-10	23.7	17.2	64.0	4.9	-	68.9	1.9	1.7	tr	tr	910
78-E-10(P)	24.3	18.5	62.6	5.4	-	68.0	2.2	-	tr	-	600
78-E-8-1	24.7	12.9	57.1	-	5.4	62.4	4.3	2.8	0.4	-	650
78-E-8-2	24.6	11.2	61.9	-	2.3	64.2	5.1	1.7	0.6	-	630
78-E-7(P)	-	76.8	20.2	1.2	1.8	23.2	9.9	-	0.9	tr	600
78-E-6	33.5	0.4	66.5	-	-	66.5	-	tr	tr	-	750
78-E-5	4.8	78.8	10.3	-	6.1	16.4	21.4	-	tr	.15	600
78-E-4	3.7	73.4	23.2	?	0.3	23.5	10.2	1.2	tr	tr	650
78-E-4(P)	32.0	8.5	59.5	-	-	59.5	2.3	4.9	tr	-	600
78-E-2	12.0	43.7	44.3	-	-	44.3	1.1	7.3	tr	tr	600

tr = <0.1%

Sk = skeletal; Pel = pellets; Si Det = Detrital silica; Si Rep = replacement
Op = opaques; Gl = glauconite

APPENDIX I(B)

Skeletal Modal Analysis

Thin Section or Peel (P)	Total Skeletal Content	Ech %	Bra %	Co %	Ga	Bry	Os	Tr	Unidentifiable Fragments	Total Point Counts
78-E-20	71.1	57.2	1.1	2.5	<1	2.1	-	-	7.2	980
78-E-20T	68.3	48.7	1.0	2.1	<1	3.0	-	-	11.5	852
78-E-20(P)	67.0	45.6	1.8	3.1	<1	3.2	-	-	12.3	600
78-E-18ST	58.5	30.1	3.8	5.7	<1	1.8	<1	-	15.1	840
78-E-18NT	60.9	32.8	5.1	7.2	1.1	2.1	<1	-	12.6	892
78-E-18B	57.1	20.4	5.4	3.8	1.4	3.1	<1	-	22.0	811
78-E-16NB	48.8	12.1	4.2	6.1	<1	6.5	<1	-	18.9	922
78-E-16N(P)	53.1	24.3	4.9	8.1	1.1	4.0	<1	-	10.7	600
78-E-14T	69.9	21.0	2.1	3.3	<1	1.2	<1	-	41.3	830
78-E-14	64.0	39.7	3.1	5.8	<1	2.0	<1	tr	11.2	920
78-E-13	73.5	23.4	5.4	5.1	1.2	3.1	1.1	-	34.2	630
78-E-12T	78.4	26.9	2.0	4.3	<1	2.2	<1	-	41.0	800
78-E-12B	69.6	31.4	2.5	4.6	<1	3.8	<1	-	25.3	835
78-E-12(P)	72.0	34.6	2.9	5.4	<1	2.7	<1	tr	24.4	600
78-E-10	64.0	27.9	3.8	3.9	<1	1.4	1.2	tr	22.9	910
78-E-10(P)	62.6	24.5	4.8	3.5	1.2	2.1	2.1	-	24.4	600
78-E-8-1	57.1	3.5	15.0	12.9	1.4	5.9	1.5	<1	16.9	790
78-E-8-2	61.9	4.9	12.8	15.2	3.2	4.3	2.1	<1	20.4	800
78-E-7(P)	20.2	1.4	2.1	1.8	-	2.2	-	-	12.7	600
78-E-6	66.5	30.3	4.7	8.2	1.0	2.4	1.1	-	18.8	750
78-E-5	10.3	<1	0.8	<1	-	2.2	-	-	7.2	600
78-E-4	23.2	1.3	4.9	2.2	1.2	1.8	<1	tr	10.8	650
78-E-4(P)	59.5	28.9	3.0	7.0	<1	1.5	<1	-	17.1	600
78-E-2	44.3	1.5	3.4	31.2	1.1	<1	<1	-	5.1	600

tr = <0.1% Ech = Echinoderms (crinoids); Bra = Brachiopods; Co = Corals; Bry = Bryozoans; Os = Ostracodes; Tr = Trilobites

APPENDIX I(C)

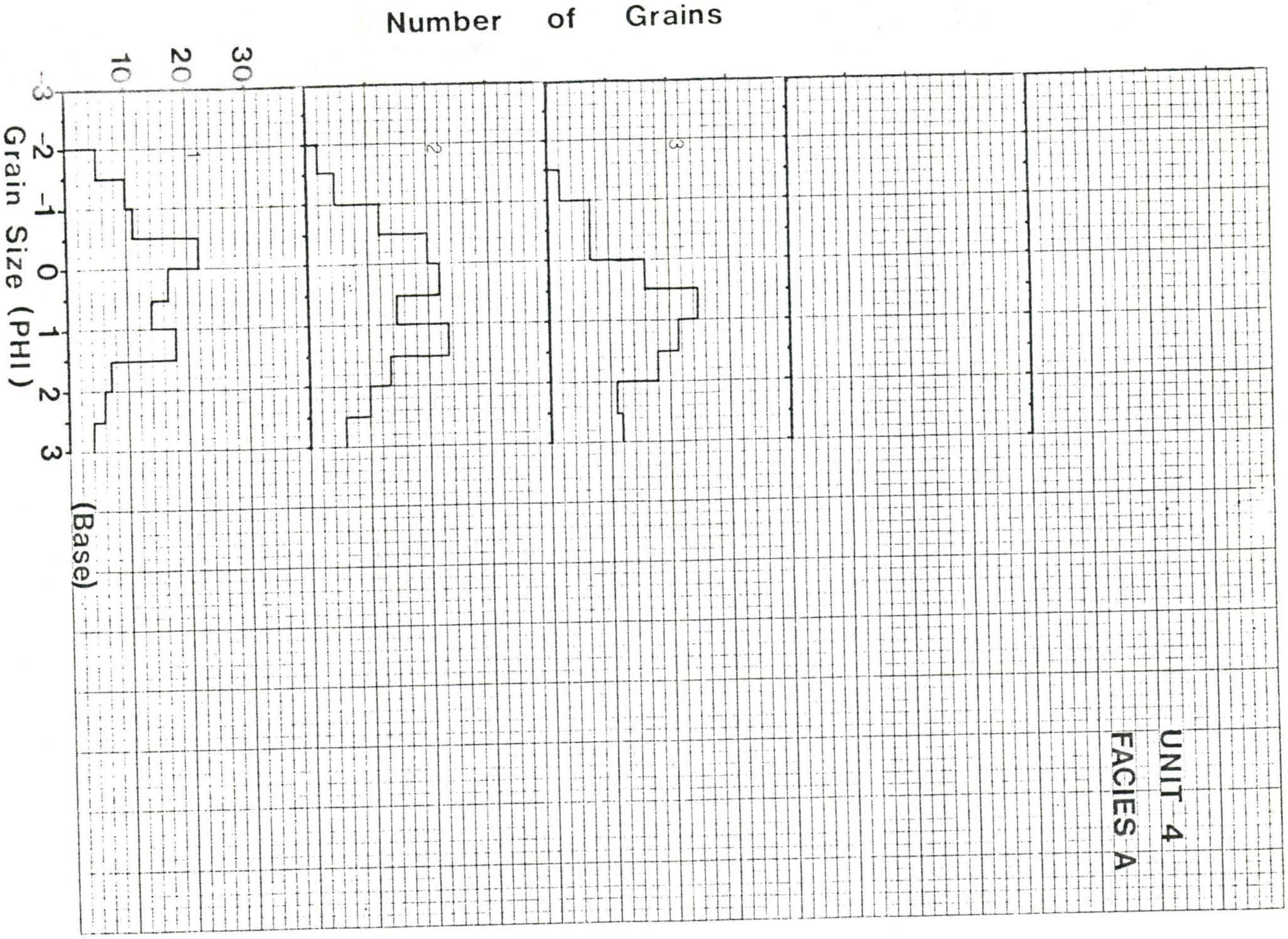
Thin Section or Peel (P)	TEXTURAL AND PETROGRAPHIC NAME: Folk (1962)	Dunham (1962)	Lindholm (1967)	Energy Index (Plumley, 1962, Carozzi, 1967)	Facies
78-E-20	Moderately to poorly sorted, well washed, coarse biocalcarenite: crinoidal biosparite	Crinoidal Grainstone	As Folk	high to very high	A-1
78-E-20T				high to very high	A-1
78-E-20(P)				high to very high	A-1
78-E-6				very high	A
78-E-4(P)				very high	A
78-E-18ST	Moderately to poorly sorted, well to poorly washed, coarse biocalcarenite: crinoidal biosparite	Crinoidal Grainstone to Packstone	As Folk; packed biocalcar-enite to biocalcisil-tite	high	A
78-E-14				high	A
78-E-12(P)				high	A
78-E-12B				high	A
78-E-10				med-high	A
78-E-10(P)				med-high	A
78-E-8-1	As above, predominantly coralline to brachiopodal	Brachiopodal-Coralline Packstone	As Folk	high	A
78-E-8-2				high	A
78-E-18NT	Moderately to poorly sorted, poorly washed, medium to coarse biocalcarenite: packed crinoidal to brachio-podal biomicrite	Crinoidal to Brachiopodal Packstone	As Folk: packed biocalcisil-tite	med-high	A
78-E-18B				med-high	A
78-E-16NB				med-high	A
78-E-16N				med-high	A
78-E-13				med-high	A
78-E-14T	Poorly sorted, poorly washed coarse biocalcarenite: sparse to packed crinoidal biomicrite	Crinoidal Packstone	As above	med-high	C-1
78-E-12T				med	C-1
78-E-4	Poorly sorted, sparse coralline-brachiopodal biomicrite	Coralline-brachiopodal Wackestone	Sparse biocalcisil-tite	low-med	D
78-E-2				low-med	D
78-E-7(P)	Fossiliferous to sparse laminated biomicrite, partially dolomitized	Fossiliferous Wackestone		low	B
78-E-5				low	B

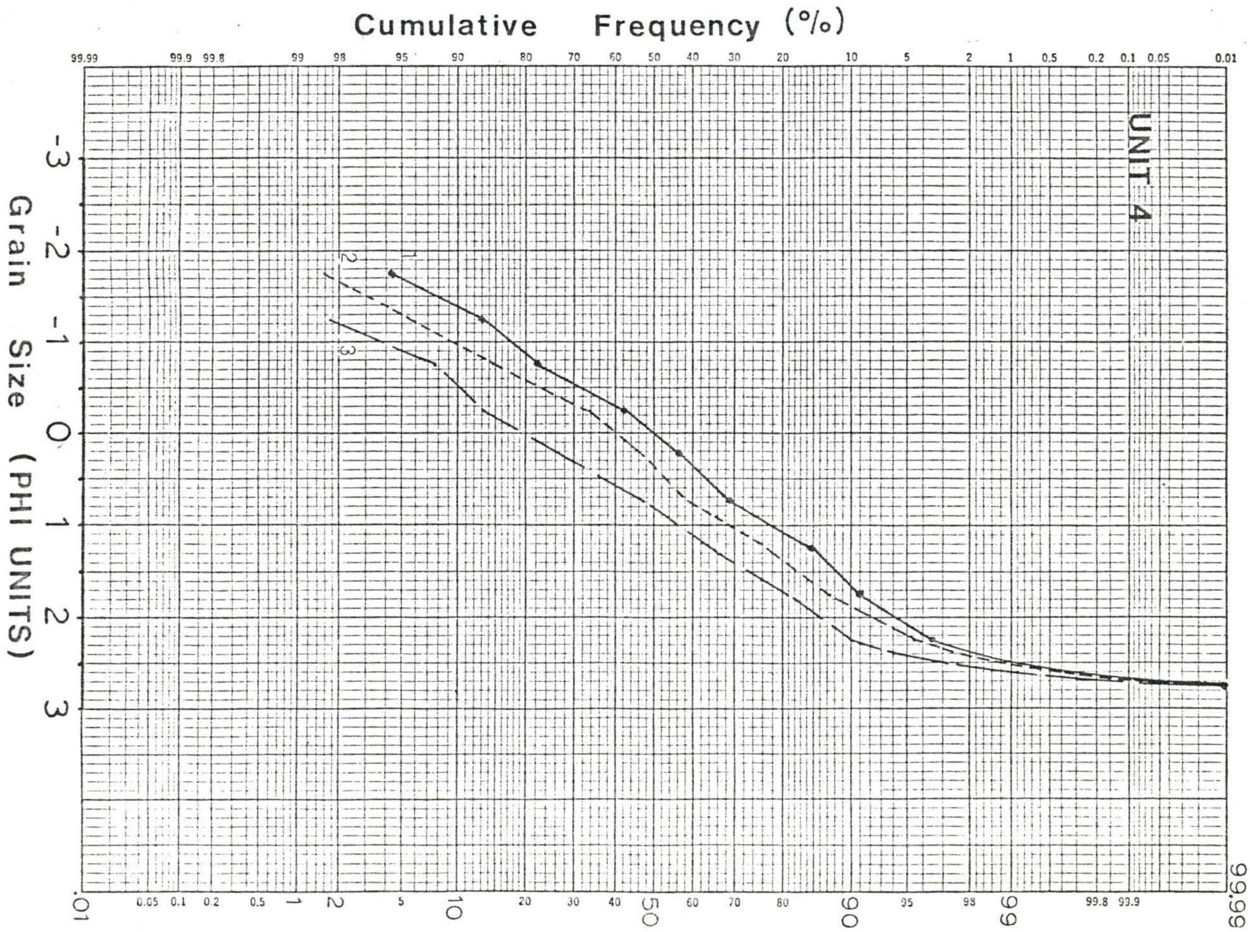
APPENDIX II(A)

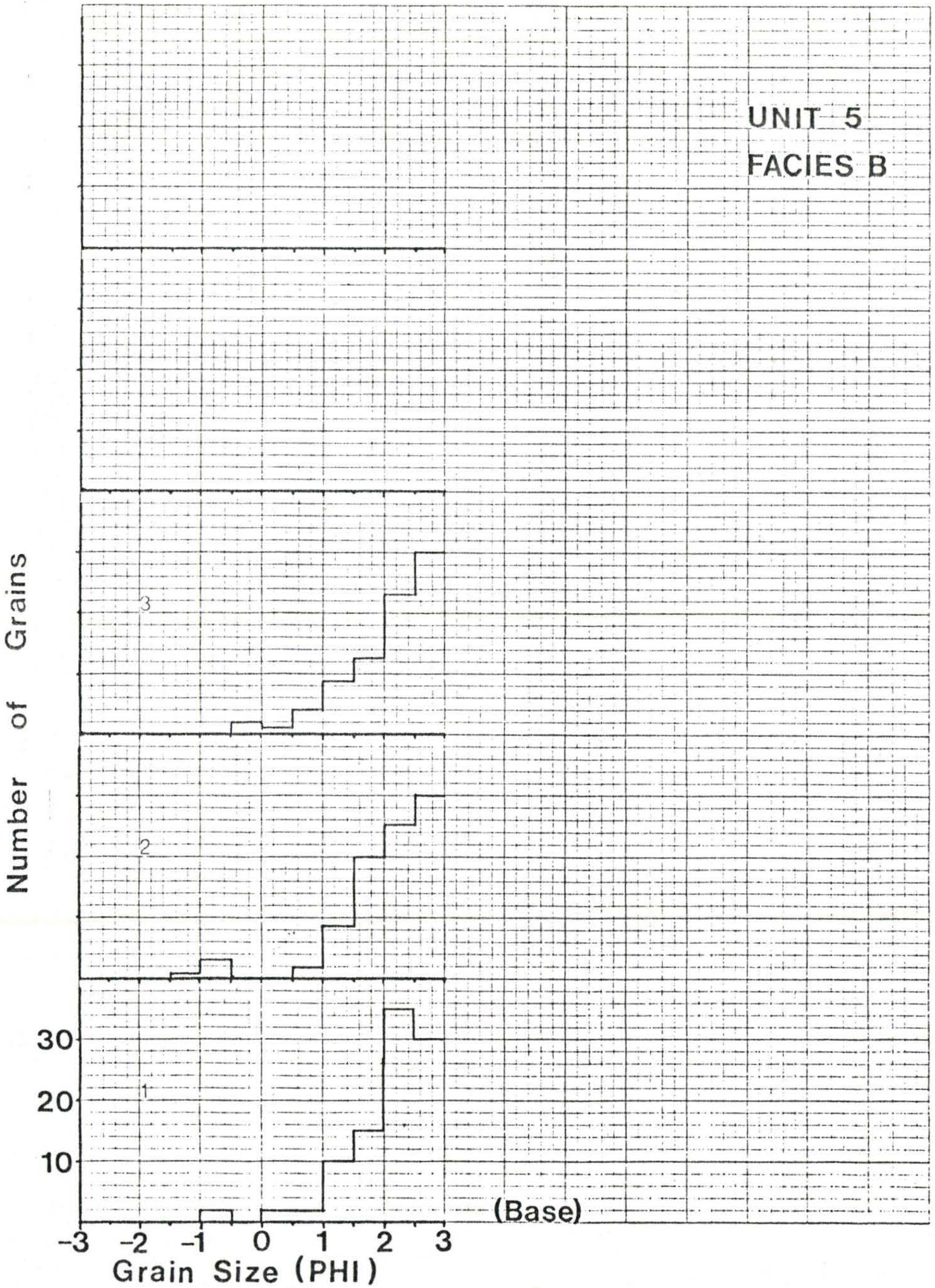
Grain Size Data

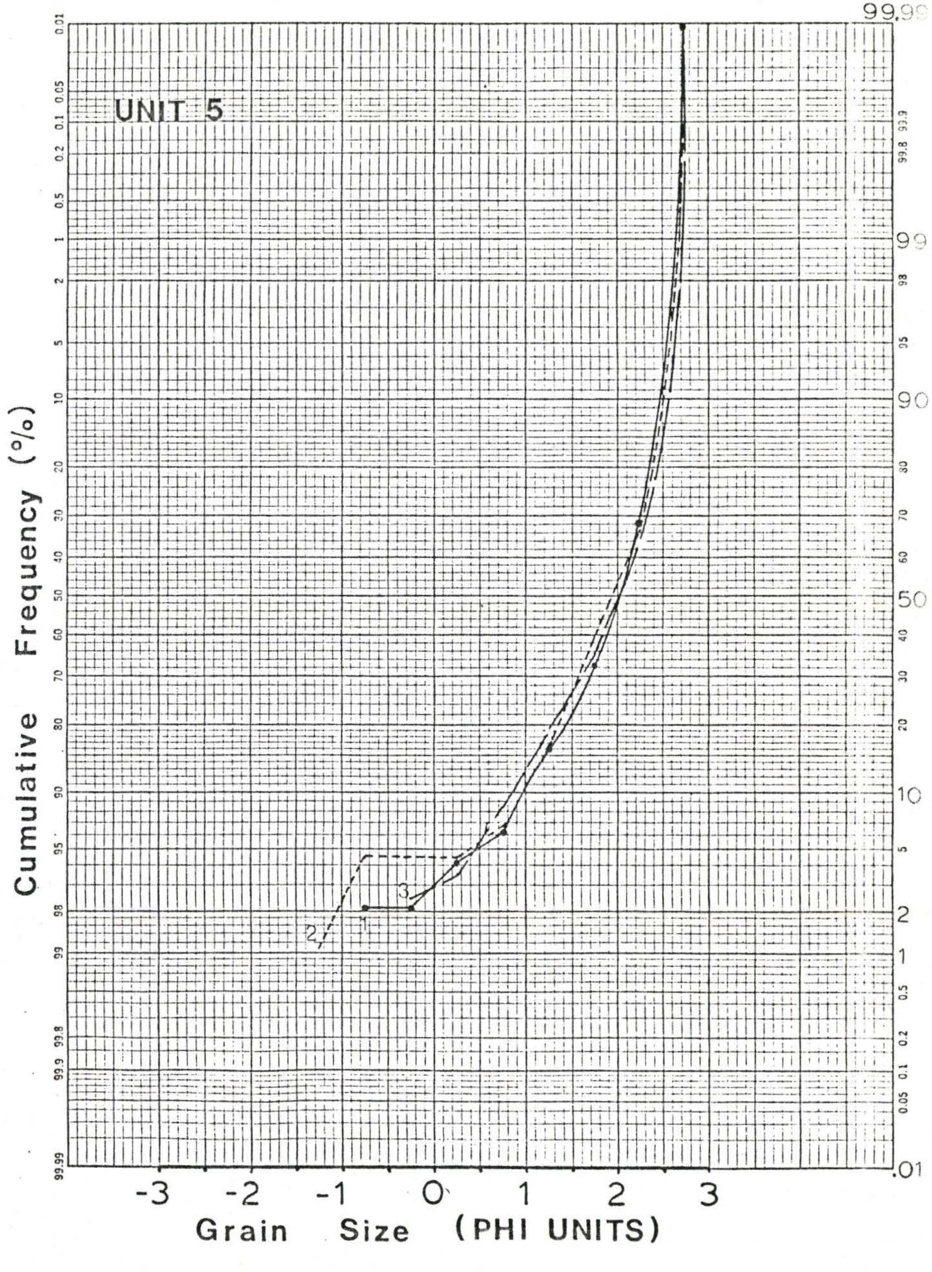
Unit	Facies	Unit Thickness (cm)	Mean (Mϕ) Grain Size			Sorting (σϕ)			Degree of Mottling	Discrete Burrows (x-rays & peels)
			Base	Middle	Top	Base	Middle	Top		
20	A-1	90	0.55	1.10	1.20	0.95	1.17	1.00	very low	rare
19	C	2-6	-	-	-	-	-	-	not seen	not seen
18ST	A	8-12	0.82	1.05	1.22	1.22	1.10	1.07	moderate	not seen
18M	A	9-12.5	0.92	0.85	1.00	1.32	1.05	1.05	moderate	not seen
17	C	5-10	-	-	-	-	-	-	not seen	not seen
16N	A	2-6	0.47	0.37	1.12	1.12	1.07	0.92	low	not seen
16NB	A	0-8	0.85	0.92	1.42	1.17	1.15	0.97	moderate	common
15	C	6-22	-	-	-	-	-	-	not seen	not seen
14	A	22-28	0.80	0.92	0.70	1.15	1.2	1.25	low	not seen
13	C	12-14	-	-	-	-	-	-	low	not seen
12T	C-1	0-4	-	-	-	-	-	-	low	not seen
12	A	13-17	0.77	0.82	0.9	1.08	1.1	1.15	low	not seen
11	B	4-8	-	-	-	-	-	-	not seen	not seen
10	A	7-11	0.62	1.02	0.57	1.32	1.32	1.70	moderate	rare
9	B	10-13	-	-	-	-	-	-	not seen	not seen
8b	A	5-1.5	0.15	0.36	1.17	1.25	0.93	0.97	low	common
8a	A	3-4.5	0.15	0.95	1.32	1.65	1.12	0.92	low	common
7-1	B-1	2-4	1.37	1.30	1.85	1.07	1.15	0.70	extreme	present
7	B	3-6	-	-	-	-	-	-	not seen	not seen
6	A	6-8	-0.47	0.02	0.48	0.97	1.17	1.33	low	present
5-1	B-1	2.3-4	1.20	1.02	1.45	1.10	1.17	0.95	extreme	present
5	B	8-17	1.81	1.79	1.80	0.65	0.65	0.65	not seen	not seen
4	A(+D)	7-9	0.07	0.42	0.90	1.17	1.12	1.0	low	present
3-1	B-1	2-2.5	-	-	-	-	-	-	extreme	present
3	B	3-8	-	-	-	-	-	-	not seen	not seen
2	D	7-12	-	-	-	-	-	-	not seen	not seen
1	B(+D)	21	-	-	-	-	-	-	not seen	not seen

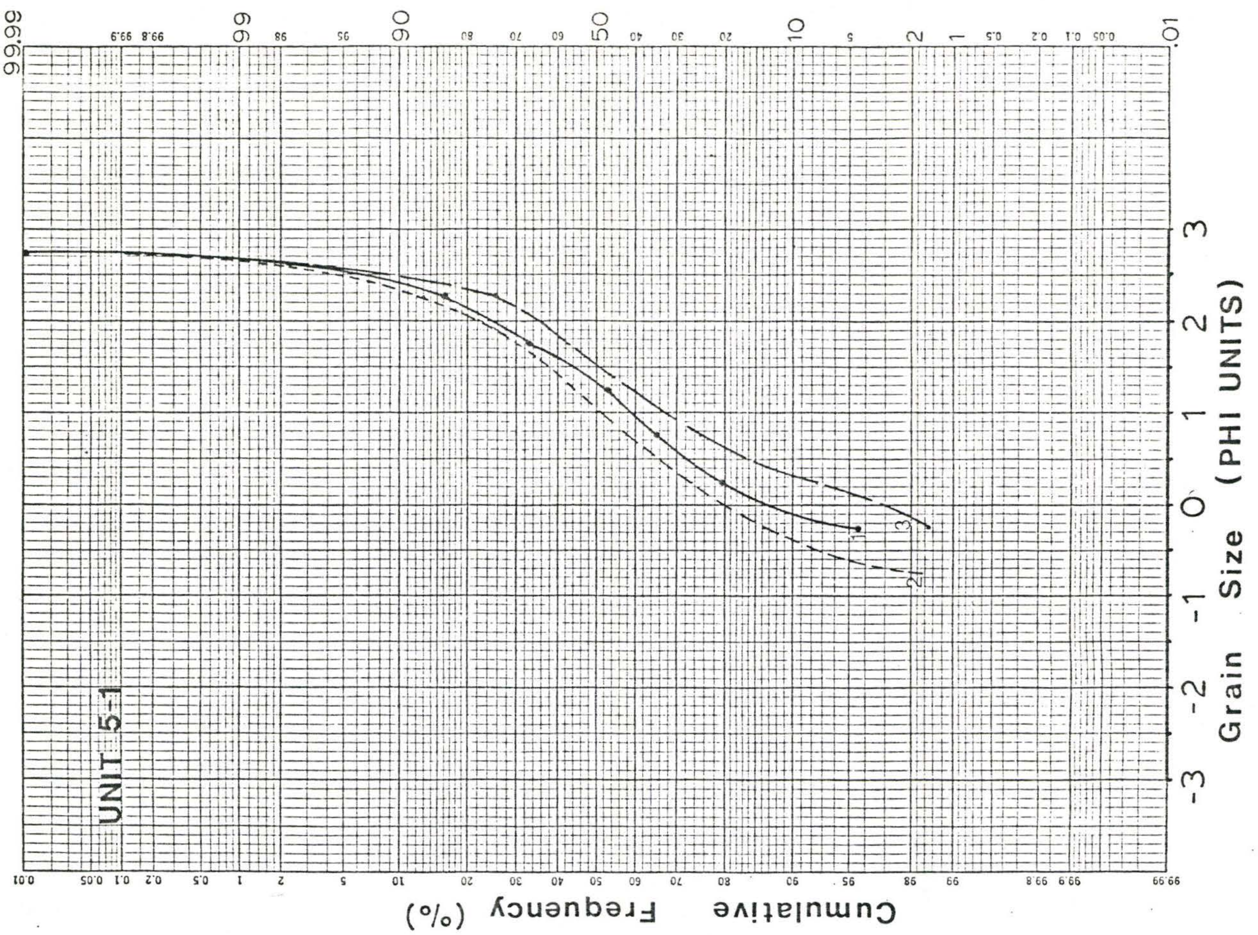
APPENDIX IIB

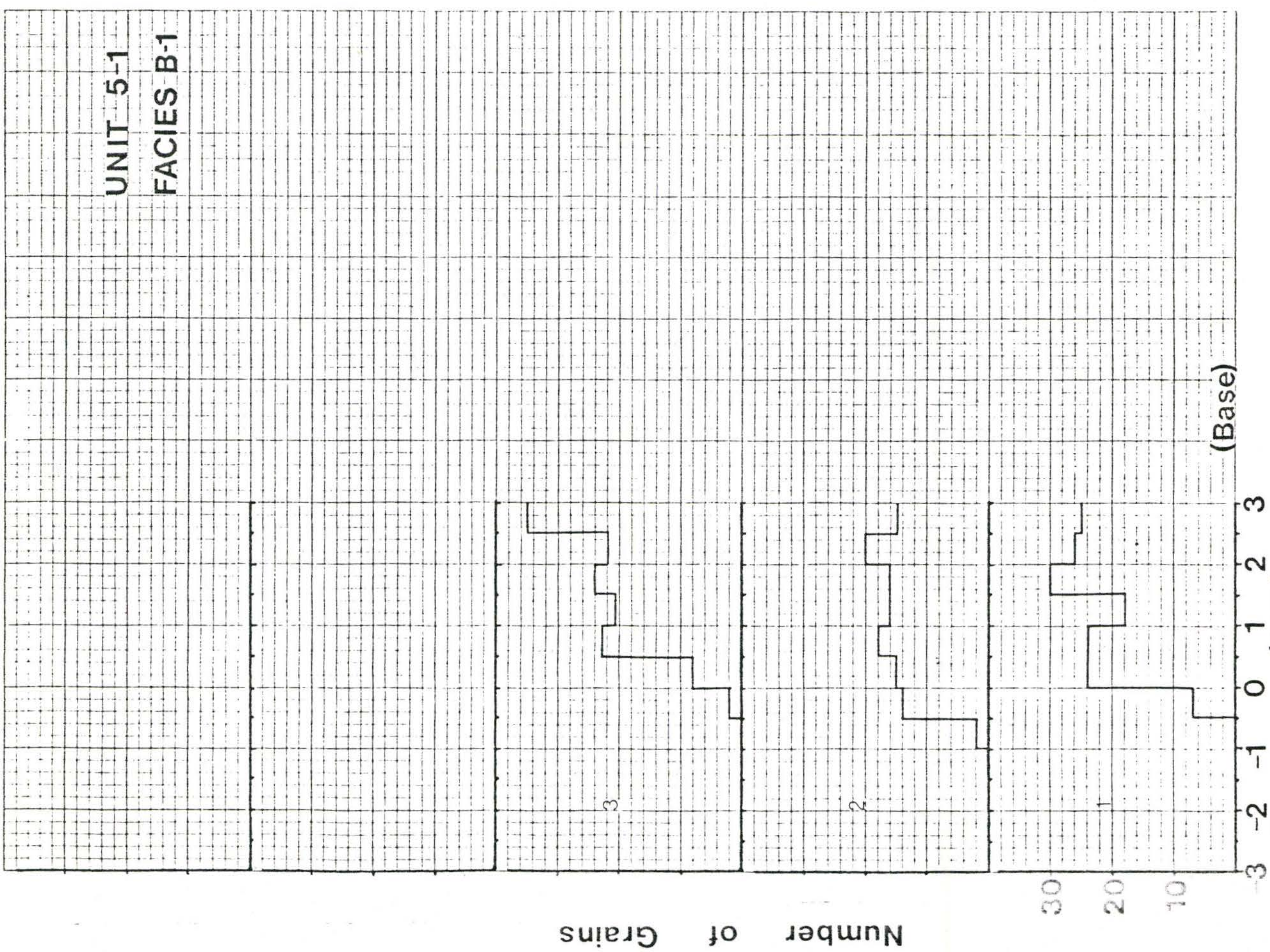

Number of Grains
10
20
30
Grain Size (PHI)
(Base)
UNIT 4
FACIES A

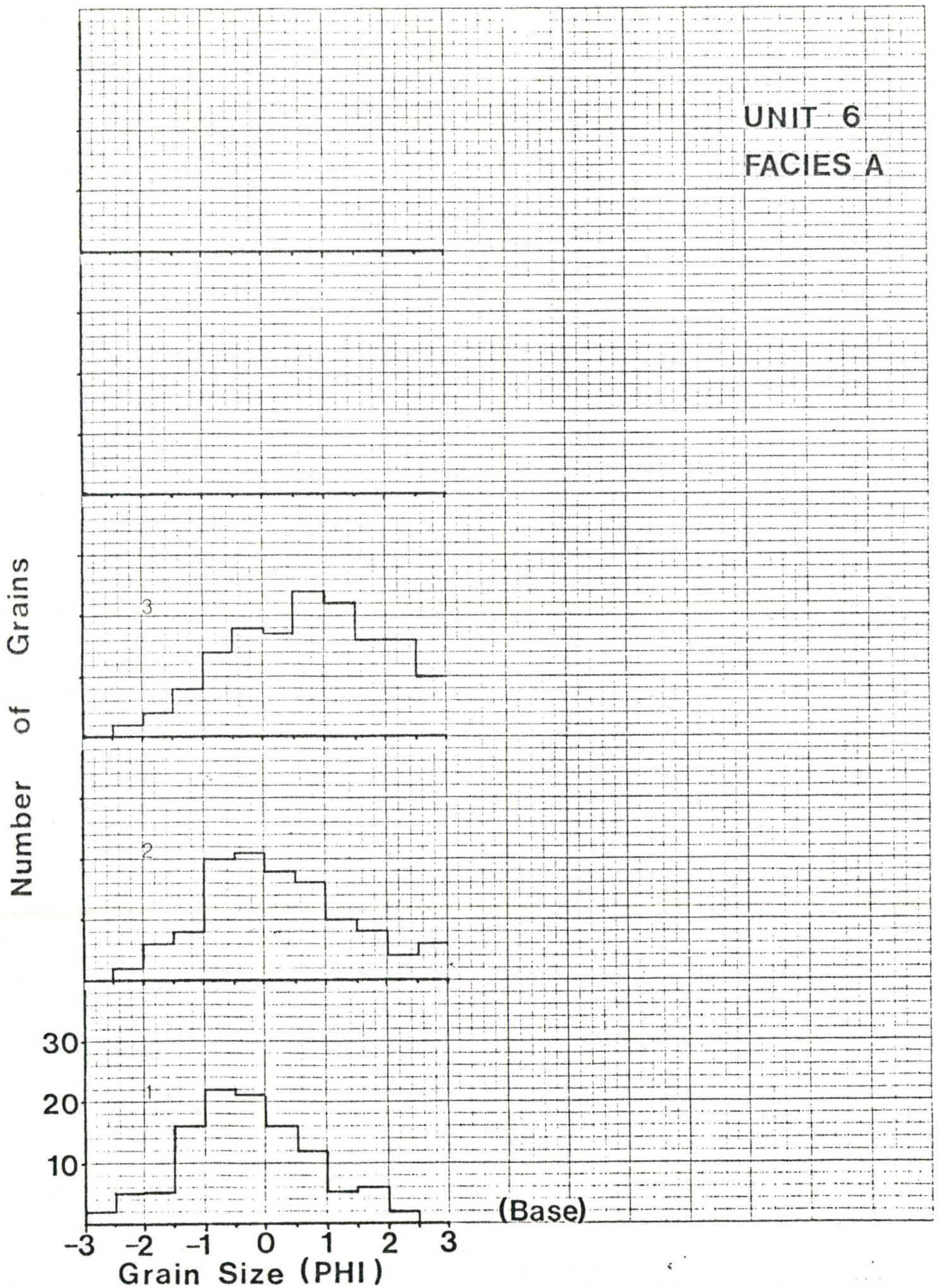

Cumulative Frequency (%)
Grain Size (PHI UNITS)
UNIT 4

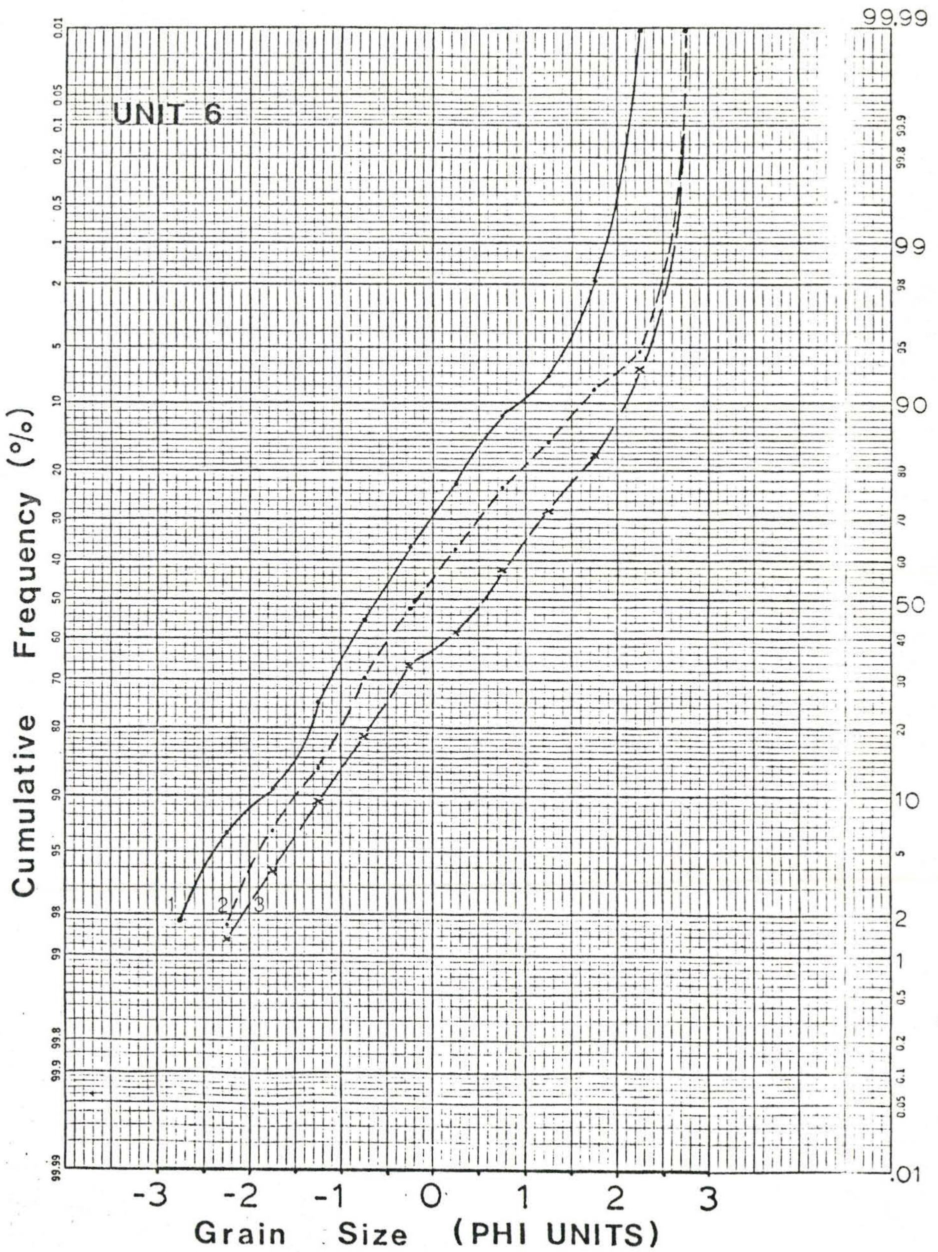

UNIT 5
FACIES B
Number of Grains
30
20
10
3
2
1
(Base)
-3 -2 -1 0 1 2 3
Grain Size (PHI)

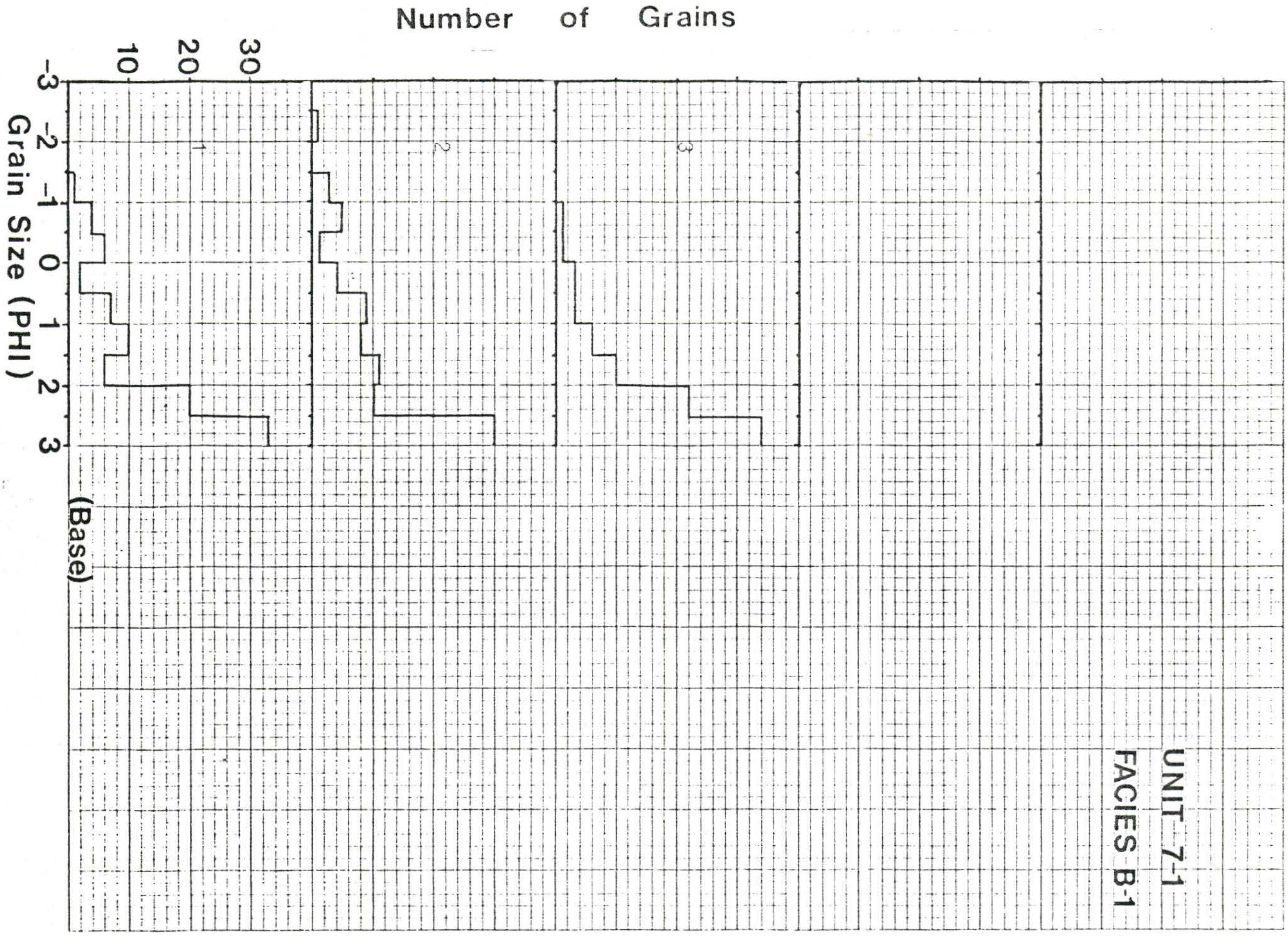

UNIT 5
Cumulative Frequency (%)
Grain Size (PHI UNITS)
-3 -2 -1 0 1 2 3
99.99
99
90
50
10
2
1
.01

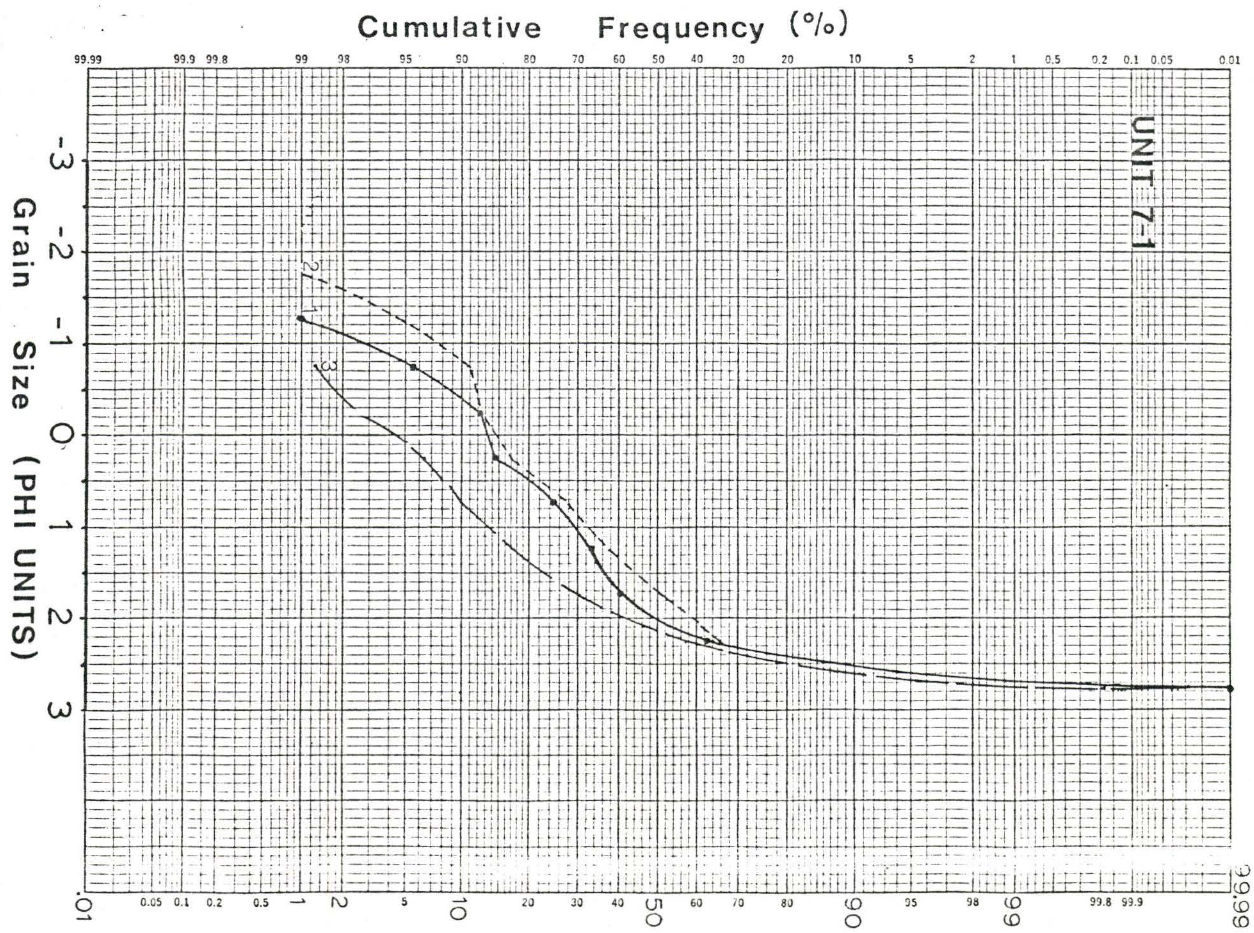

UNIT 5-1
Grain Size (PHI UNITS)
Cumulative Frequency (%)
-3
-2
-1
0
1
2
3
1
2
3

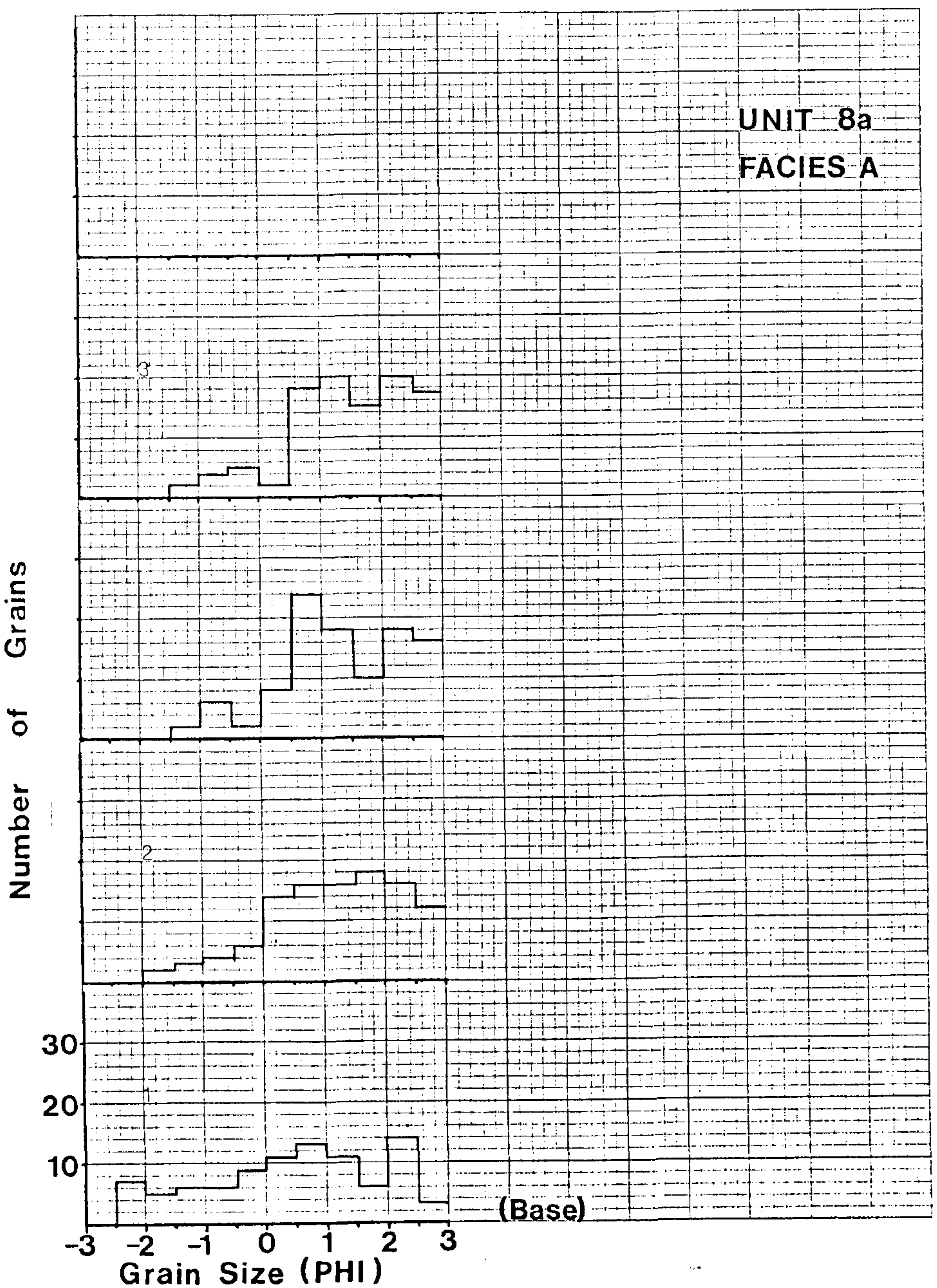

UNIT 5-1
FACIES B-1
(Base)
Grain Size (PHI)
Number of Grains
30
20
10
-3
-2
-1
0
1
2
3

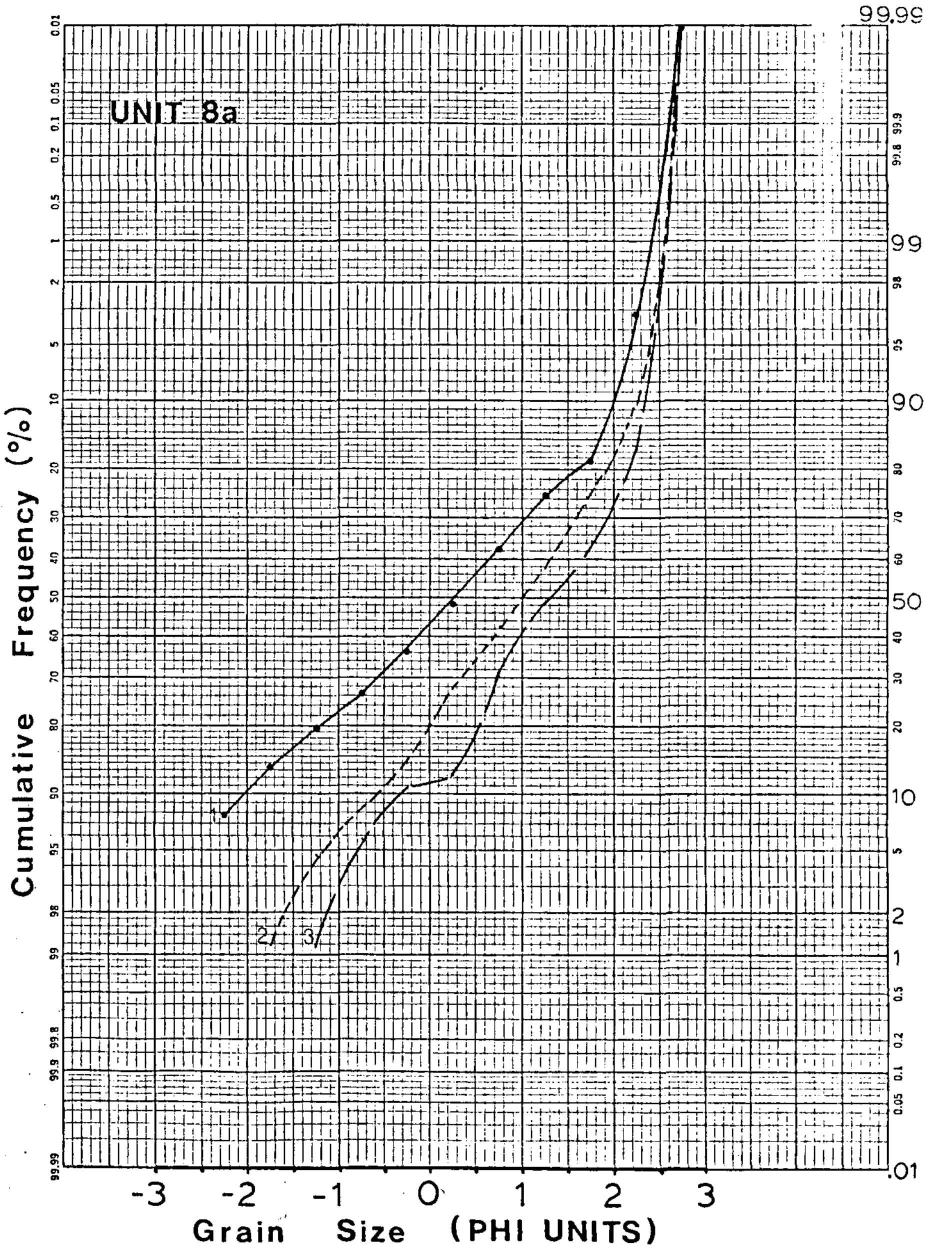

UNIT 6
FACIES A
Number of Grains
30
20
10
3
2
1
(Base)
-3 -2 -1 0 1 2 3
Grain Size (PHI)

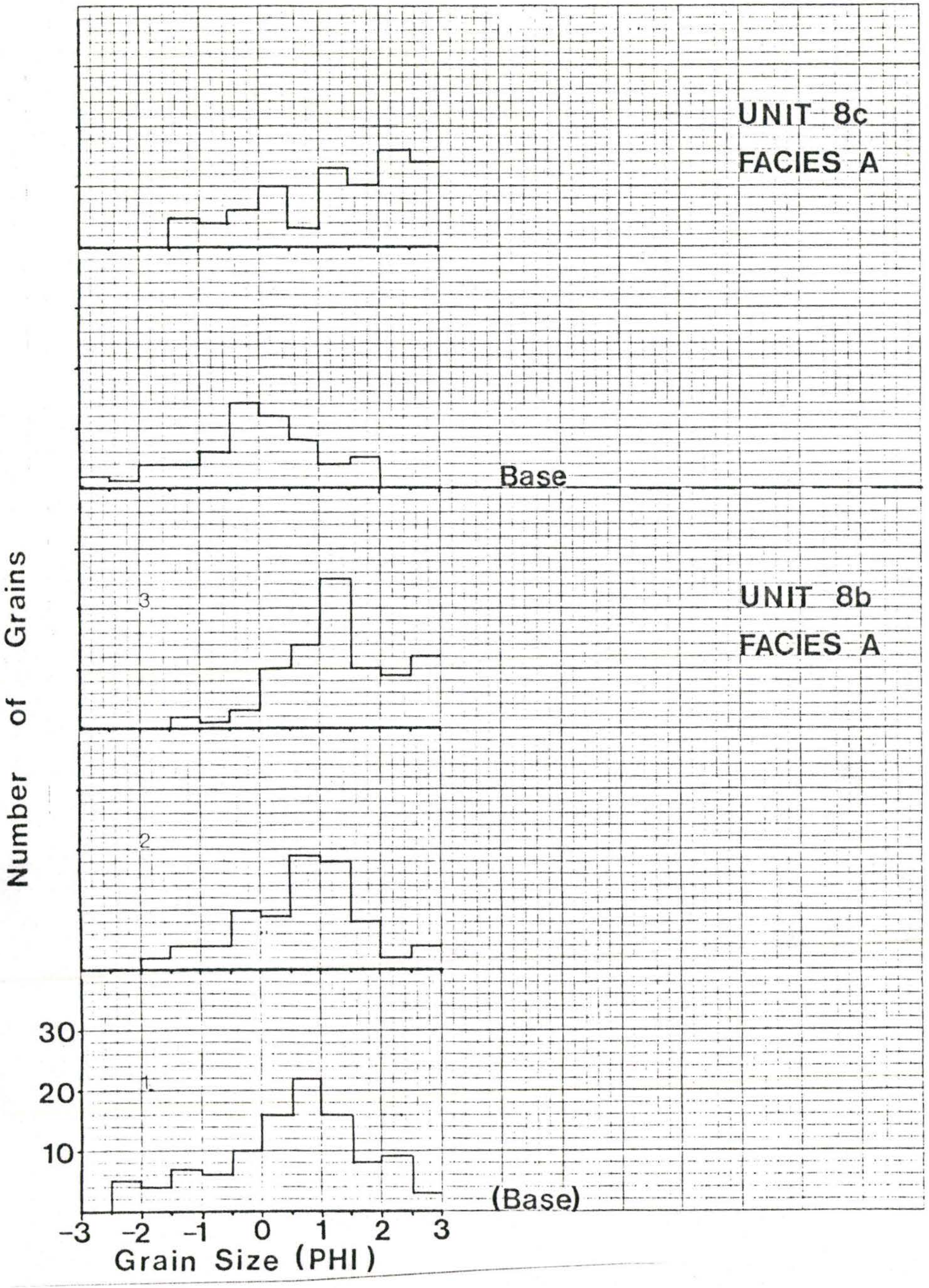

UNIT 6
Cumulative Frequency (%)
1
2
3
99.99
99
90
50
10
2
1
.01
-3 -2 -1 0 1 2 3
Grain Size (PHI UNITS)

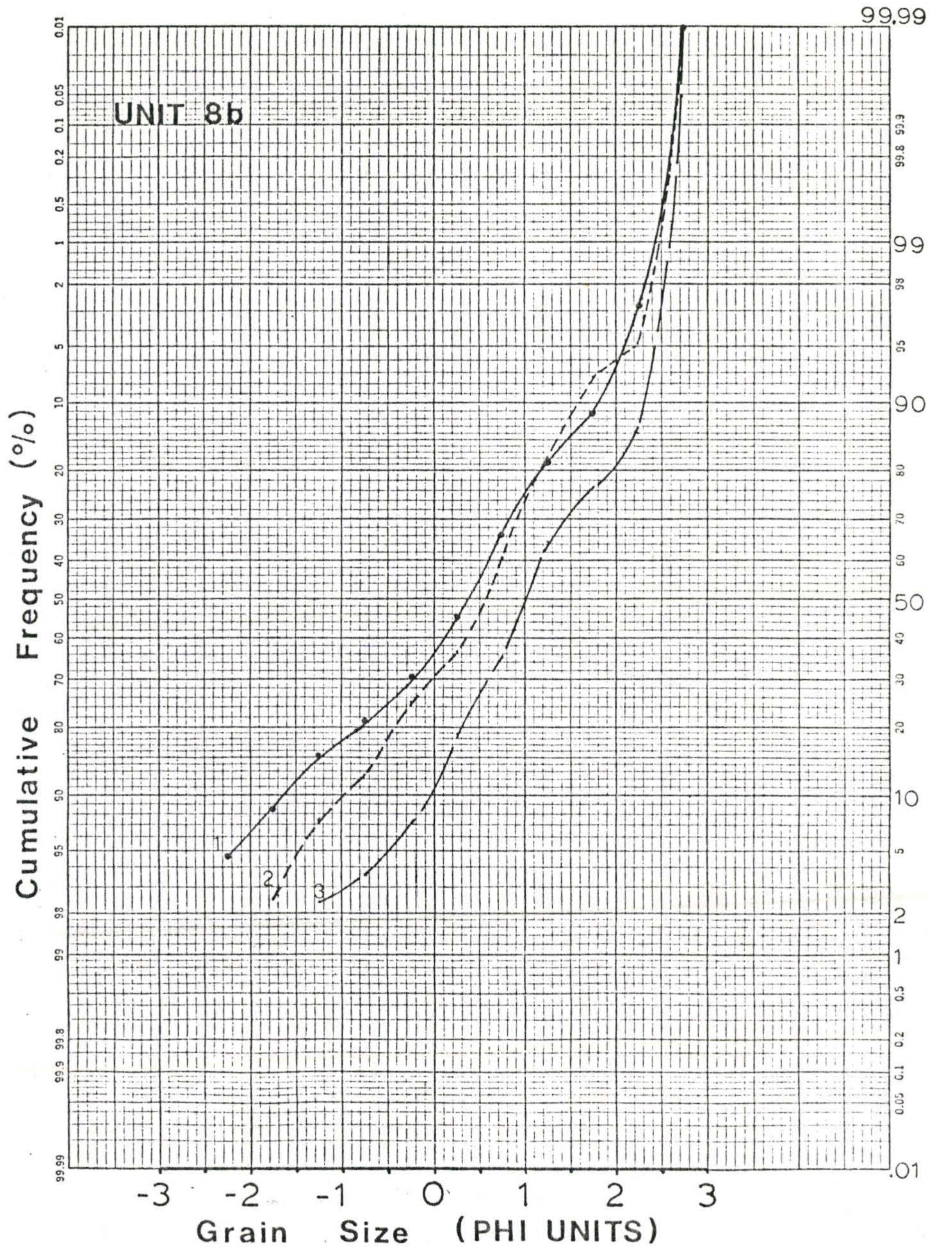

Number of Grains
10
20
30
Grain Size (PHI)
-3
-2
-1
0
1
2
3
(Base)
UNIT 7-1
FACIES B-1

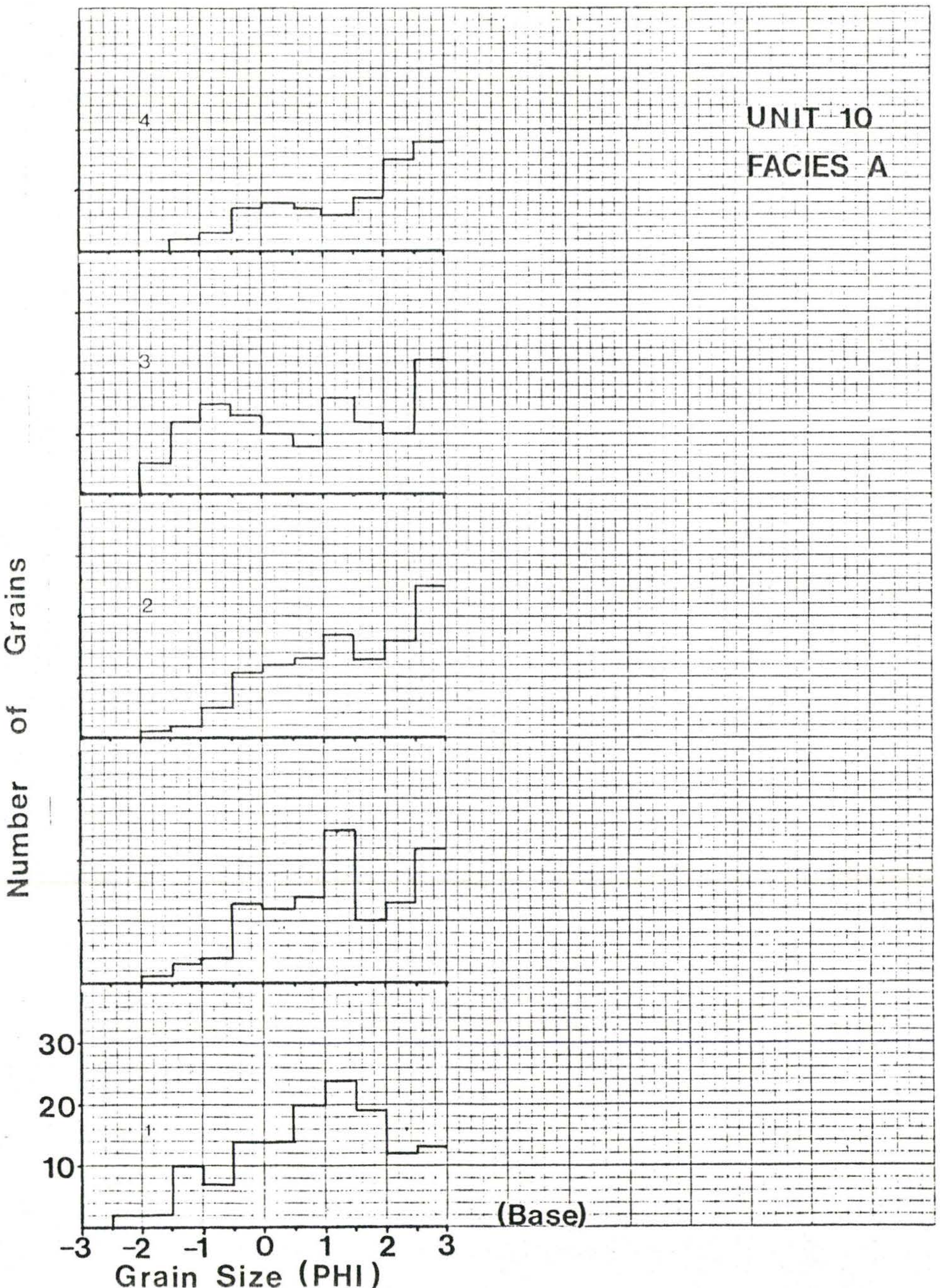

Cumulative Frequency (%)
Grain Size (PHI UNITS)
-3
-2
-1
0
1
2
3
UNIT 7-1
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01

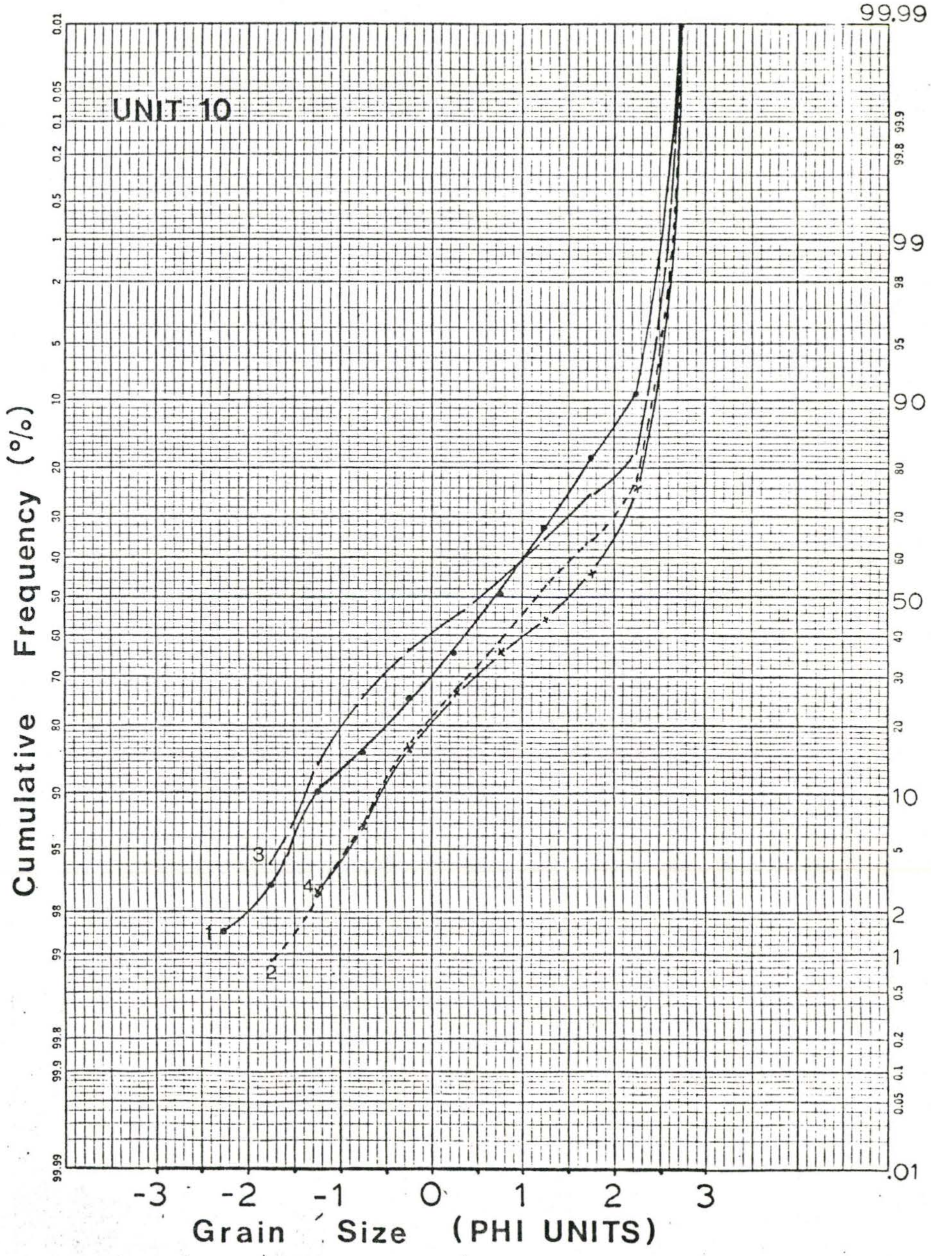

UNIT 8a
FACIES A
Number of Grains
30
20
10
3
2
1
(Base)
-3 -2 -1 0 1 2 3
Grain Size (PHI)

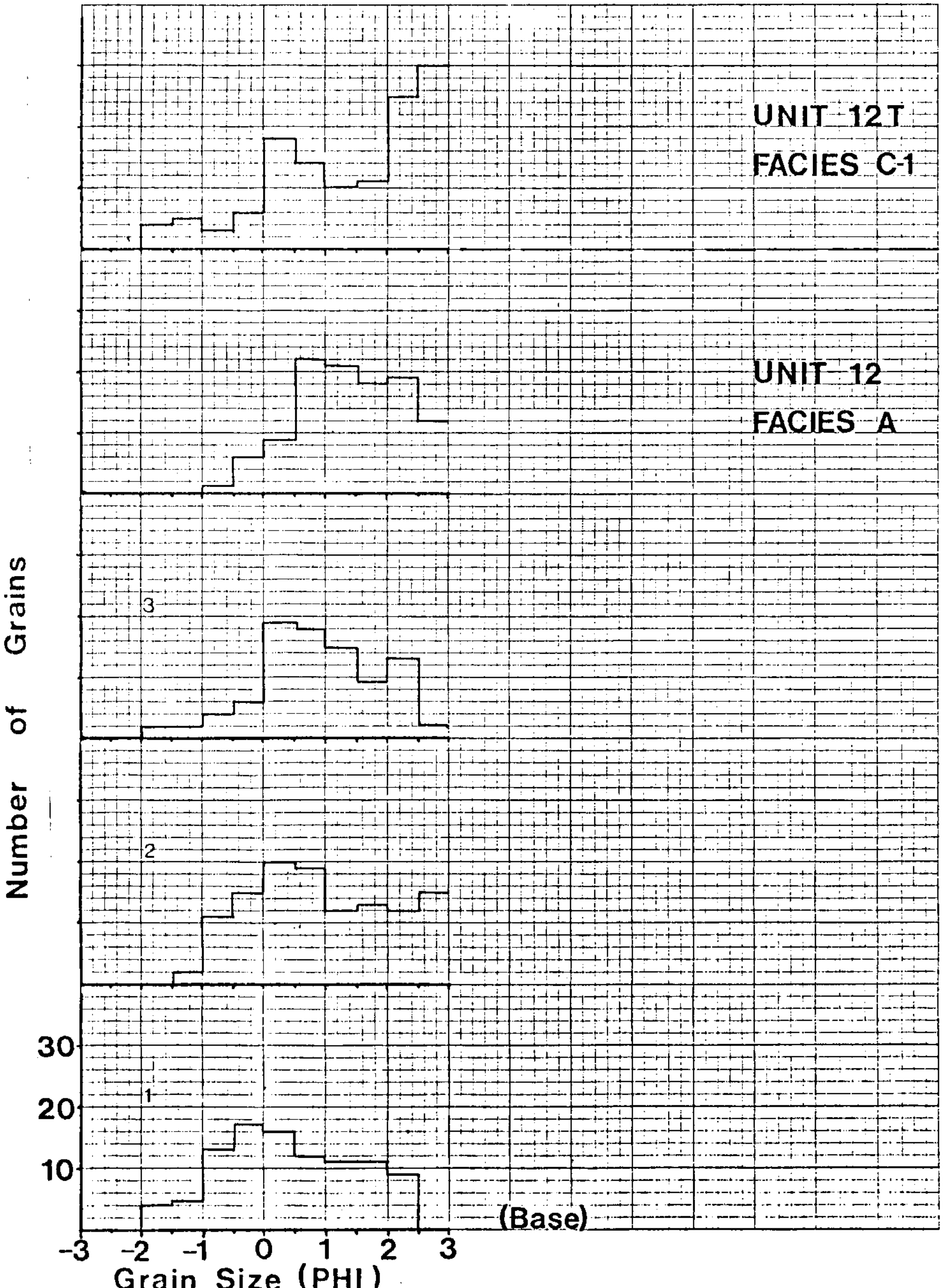

UNIT 8a
Cumulative Frequency (%)
99.99
99
90
50
10
2
1
.01
2
3
-3 -2 -1 0 1 2 3
Grain Size (PHI UNITS)

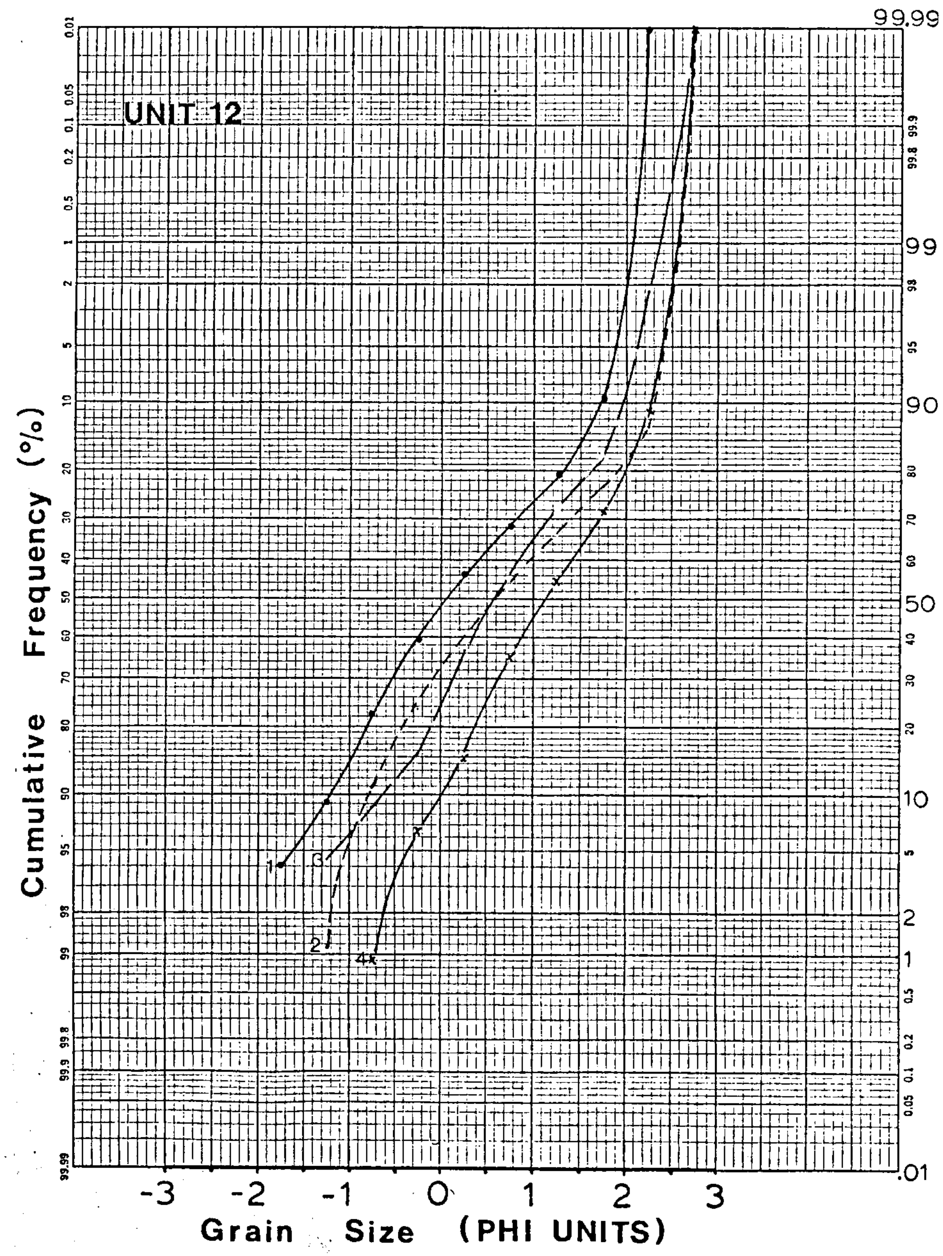

UNIT 8c
FACIES A
Base
UNIT 8b
FACIES A
(Base)
Number of Grains
Grain Size (PHI)

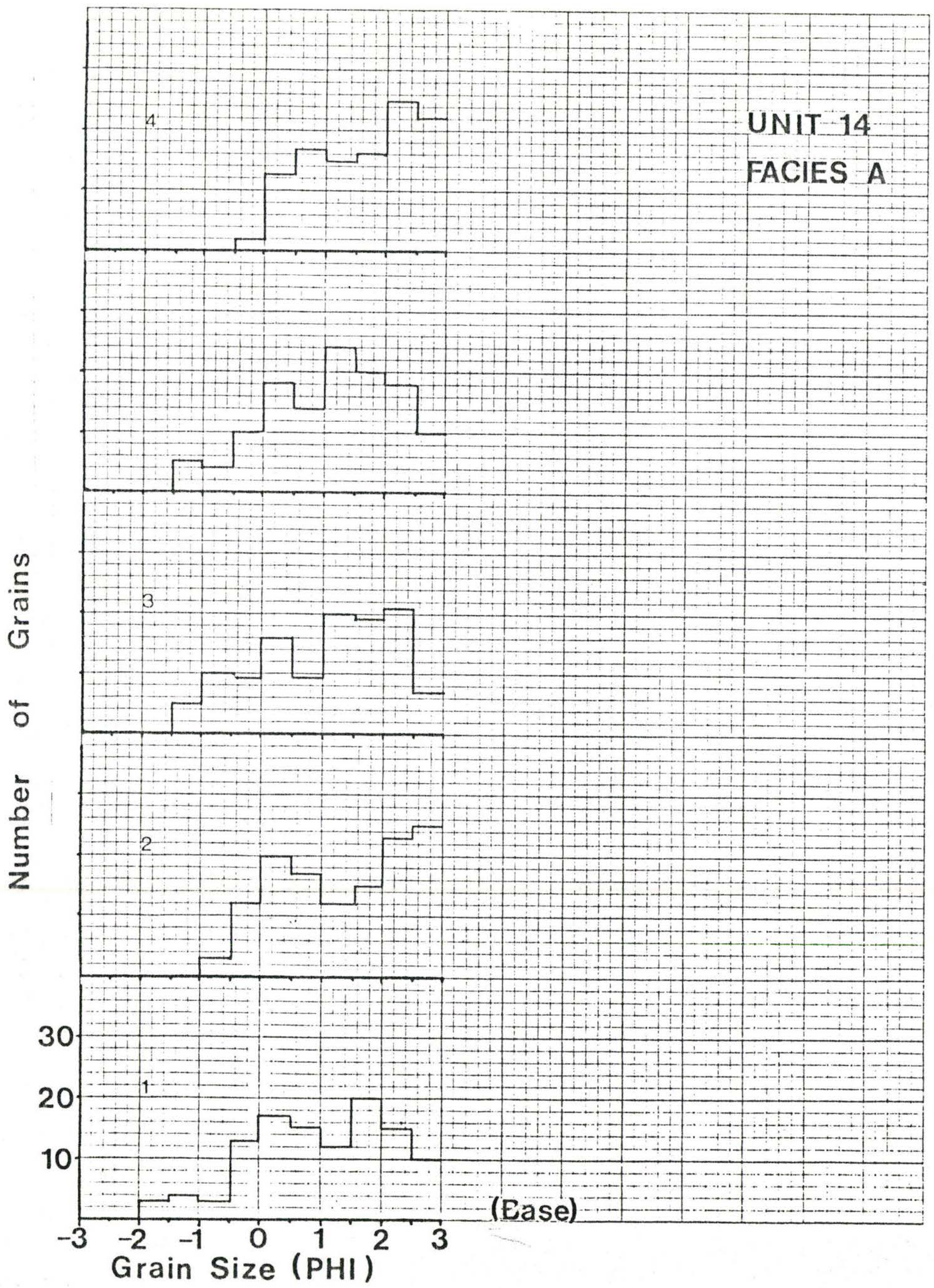

UNIT 8b
Cumulative Frequency (%)
Grain Size (PHI UNITS)


UNIT 10
FACIES A
Number of Grains
Grain Size (PHI)
(Base)

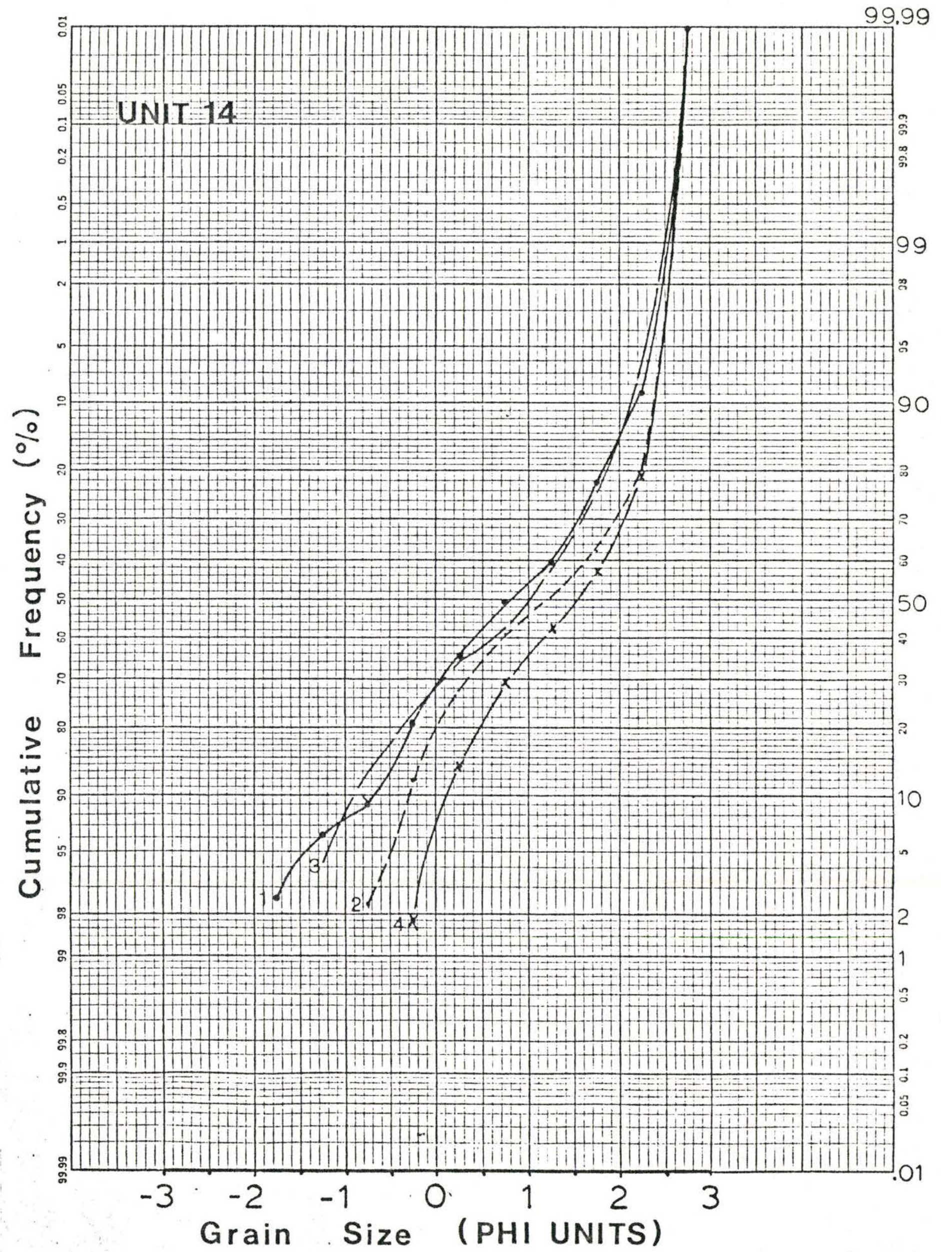

UNIT 10
Cumulative Frequency (%)
Grain Size (PHI UNITS)


UNIT 12T
FACIES C-1
UNIT 12
FACIES A
3
2
1
Number of Grains
30
20
10
(Base)
-3 -2 -1 0 1 2 3
Grain Size (PHI)

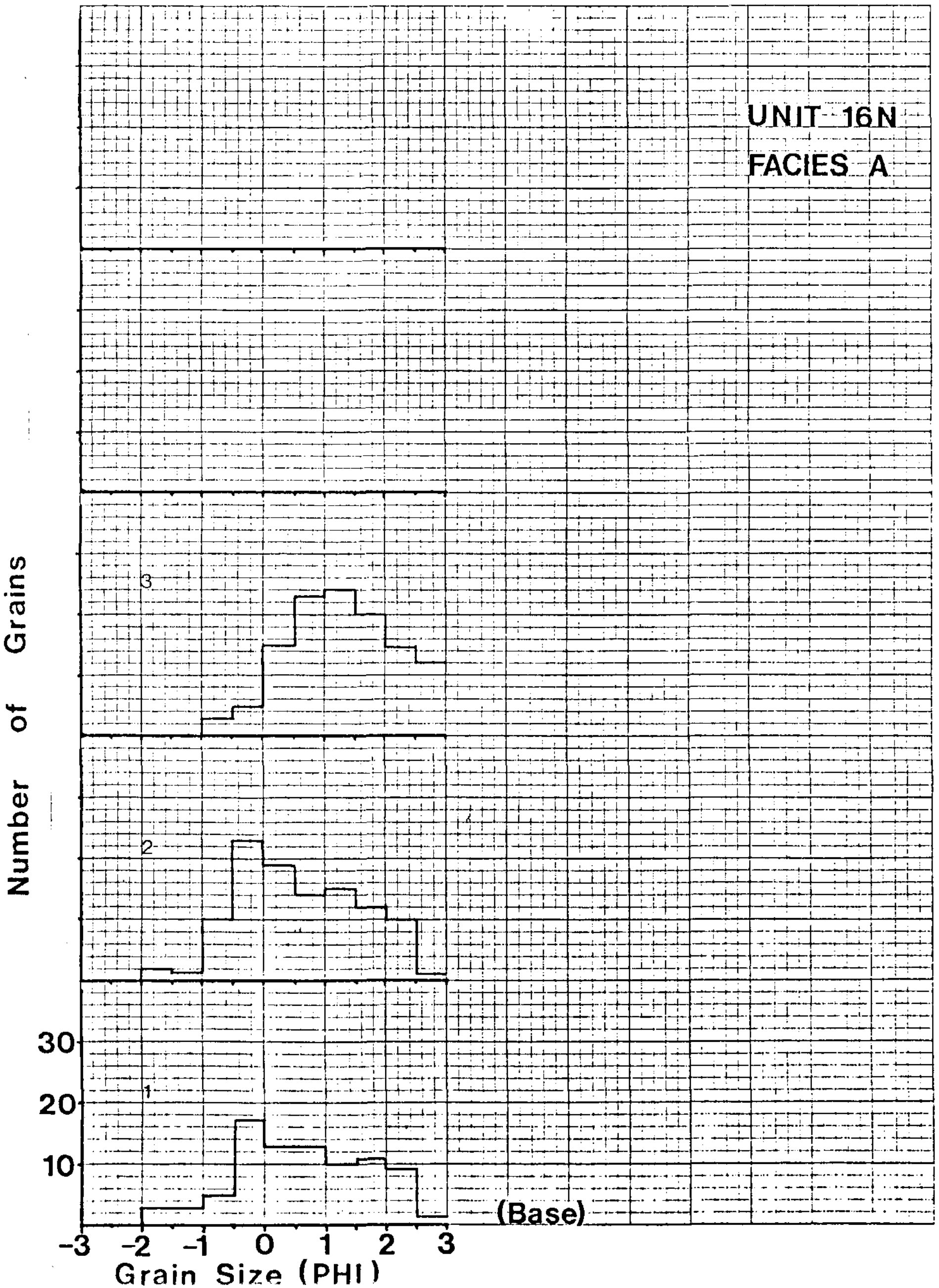

UNIT 12
Cumulative Frequency (%)
Grain Size (PHI UNITS)
-3 -2 -1 0 1 2 3
99.99
99
90
50
10
2
1
.01
1
2
3
4



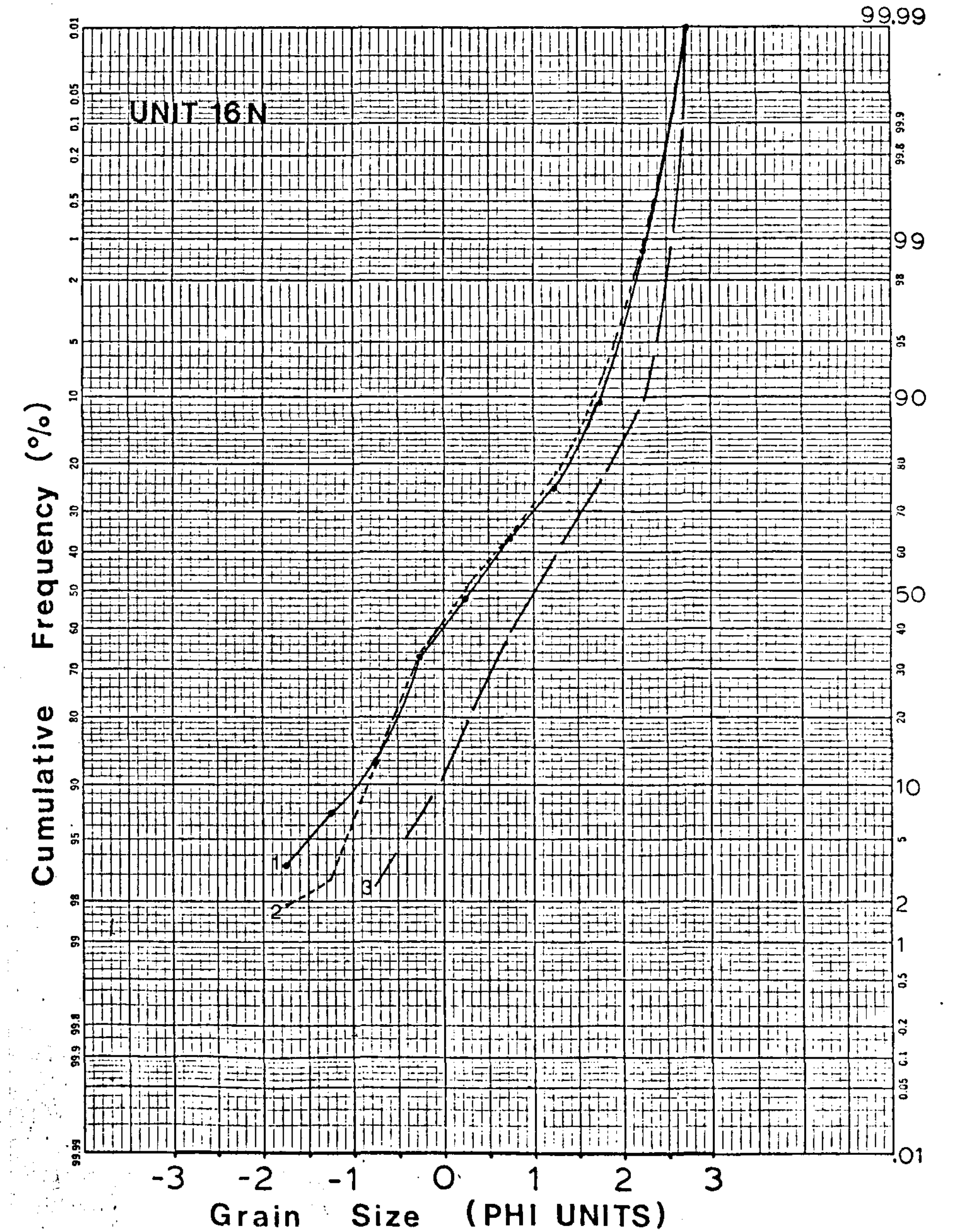
UNIT 14
FACIES A
4
3
2
1
30
20
10
Number of Grains
-3 -2 -1 0 1 2 3
Grain Size (PHI)
(Base)



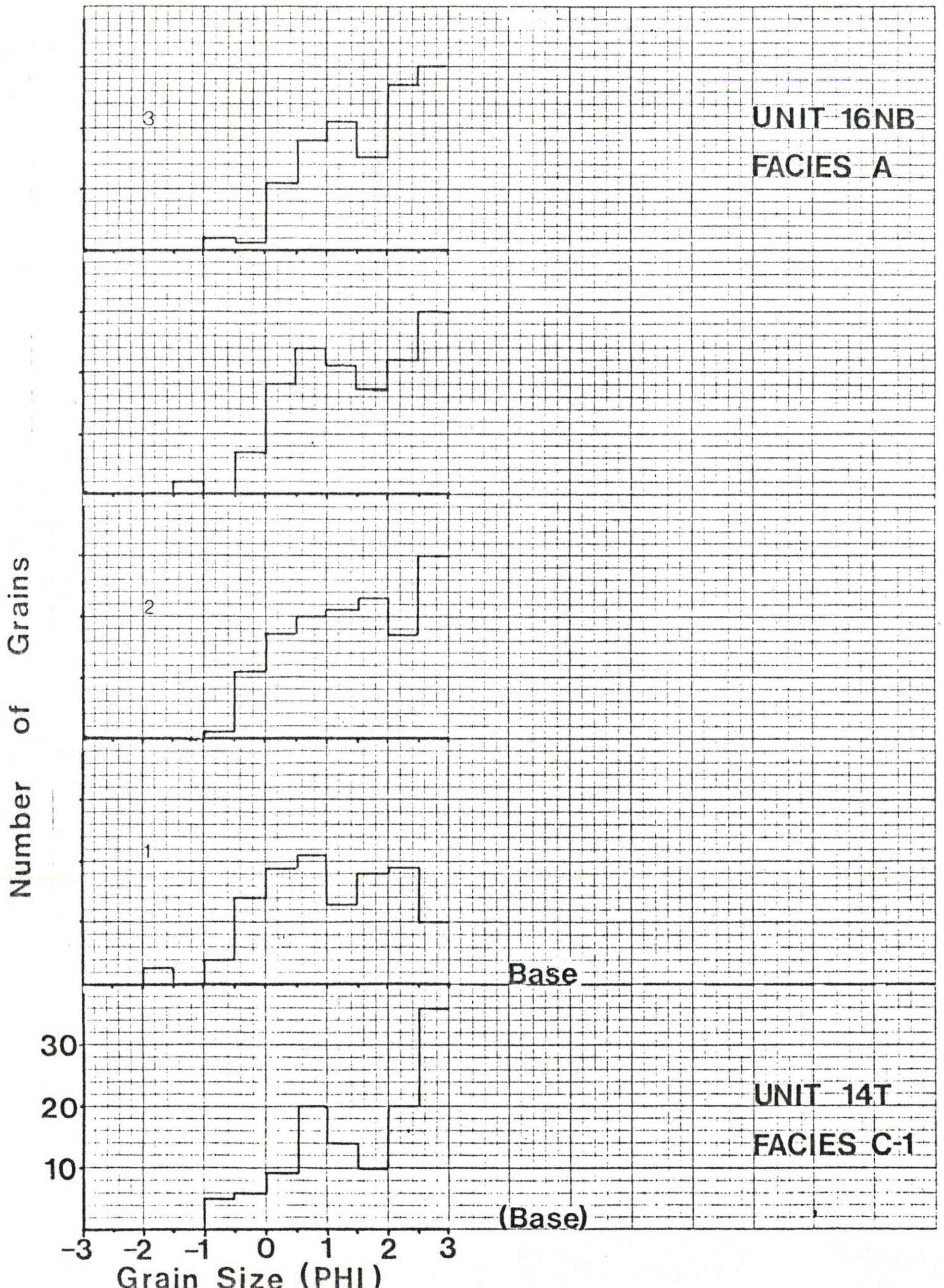
UNIT 14
Cumulative Frequency (%)
99.99
99
90
50
10
2
1
.01
1
2
3
4
-3 -2 -1 0 1 2 3
Grain Size (PHI UNITS)

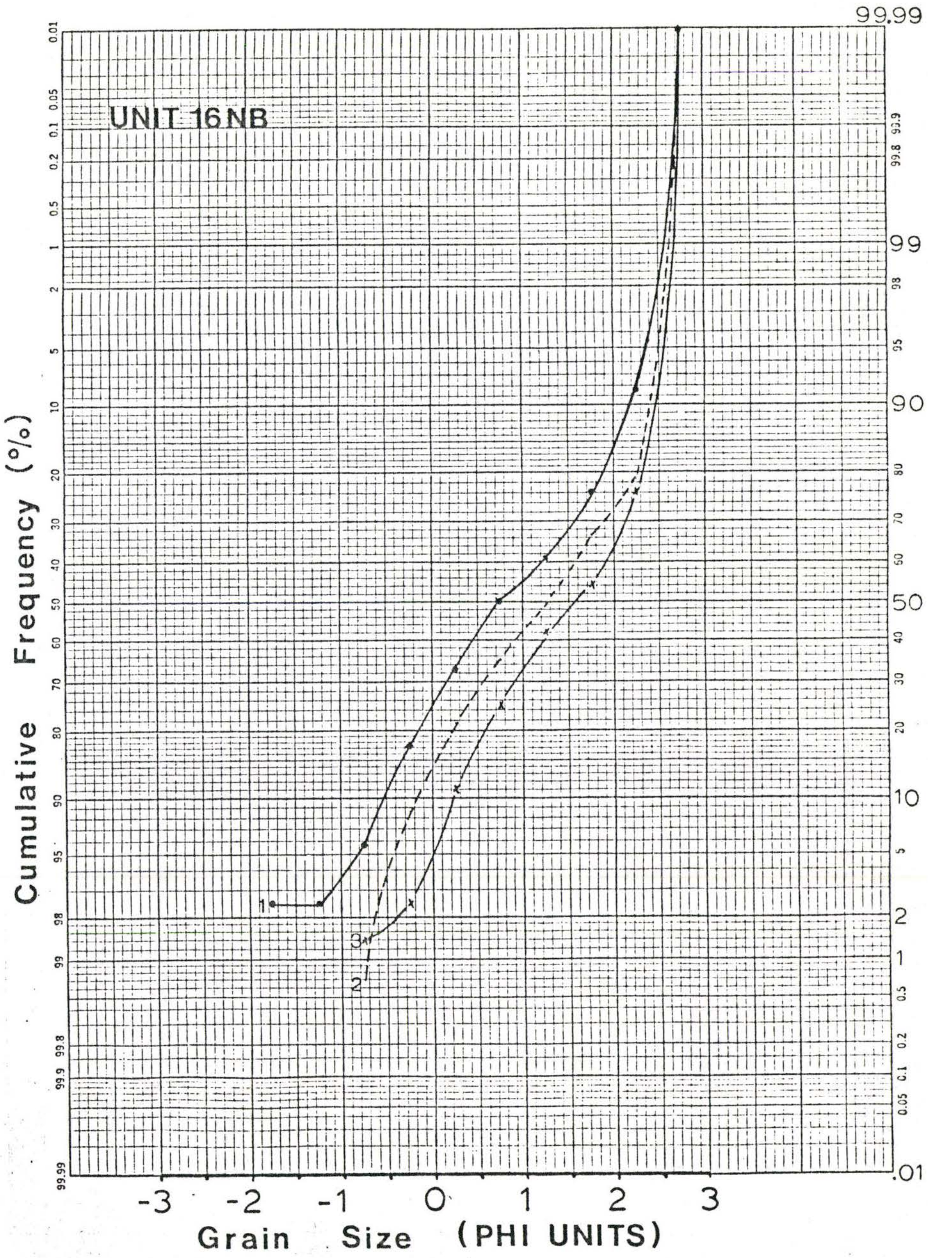


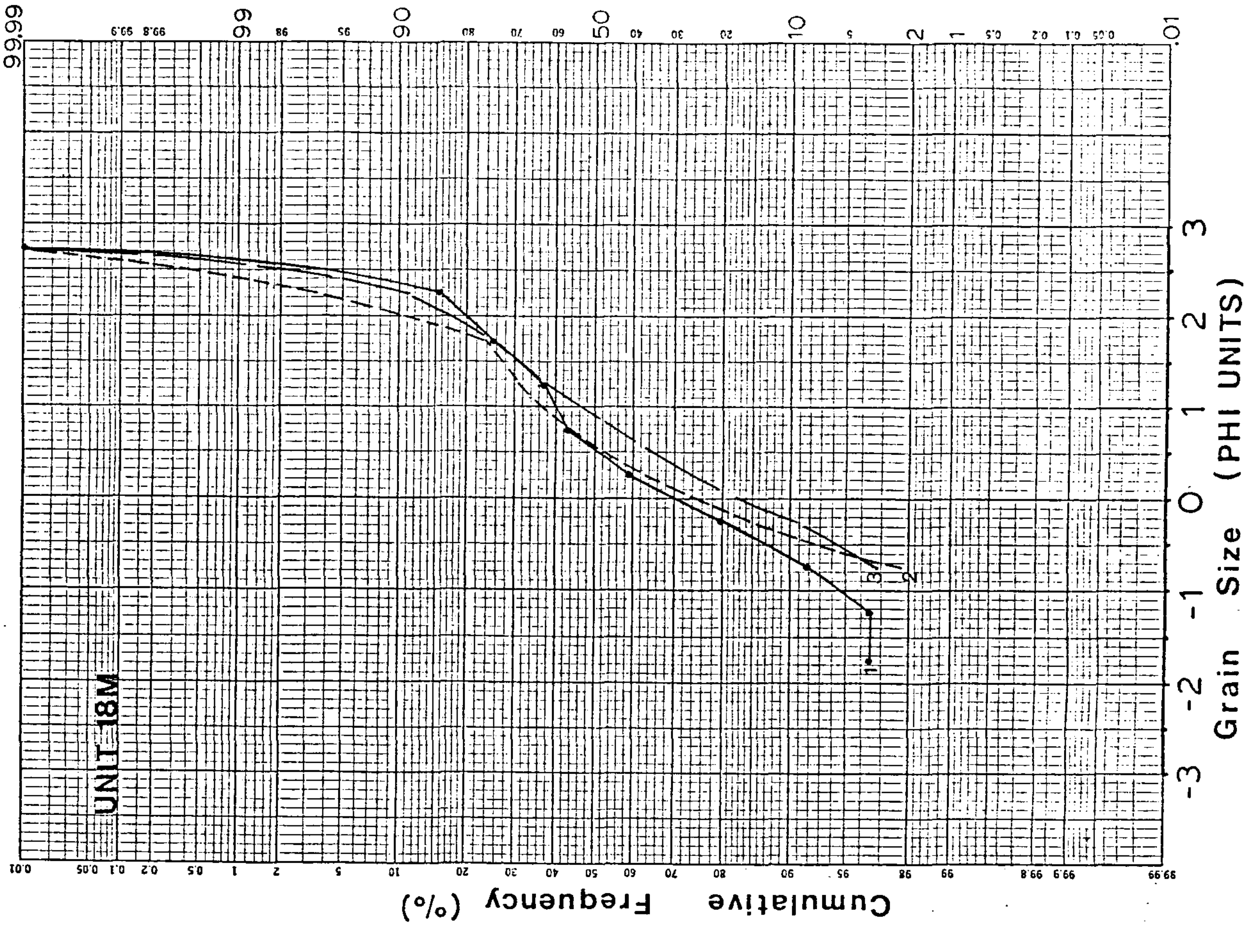
UNIT 16N
FACIES A
Number of Grains
Grain Size (PHI)
(Base)

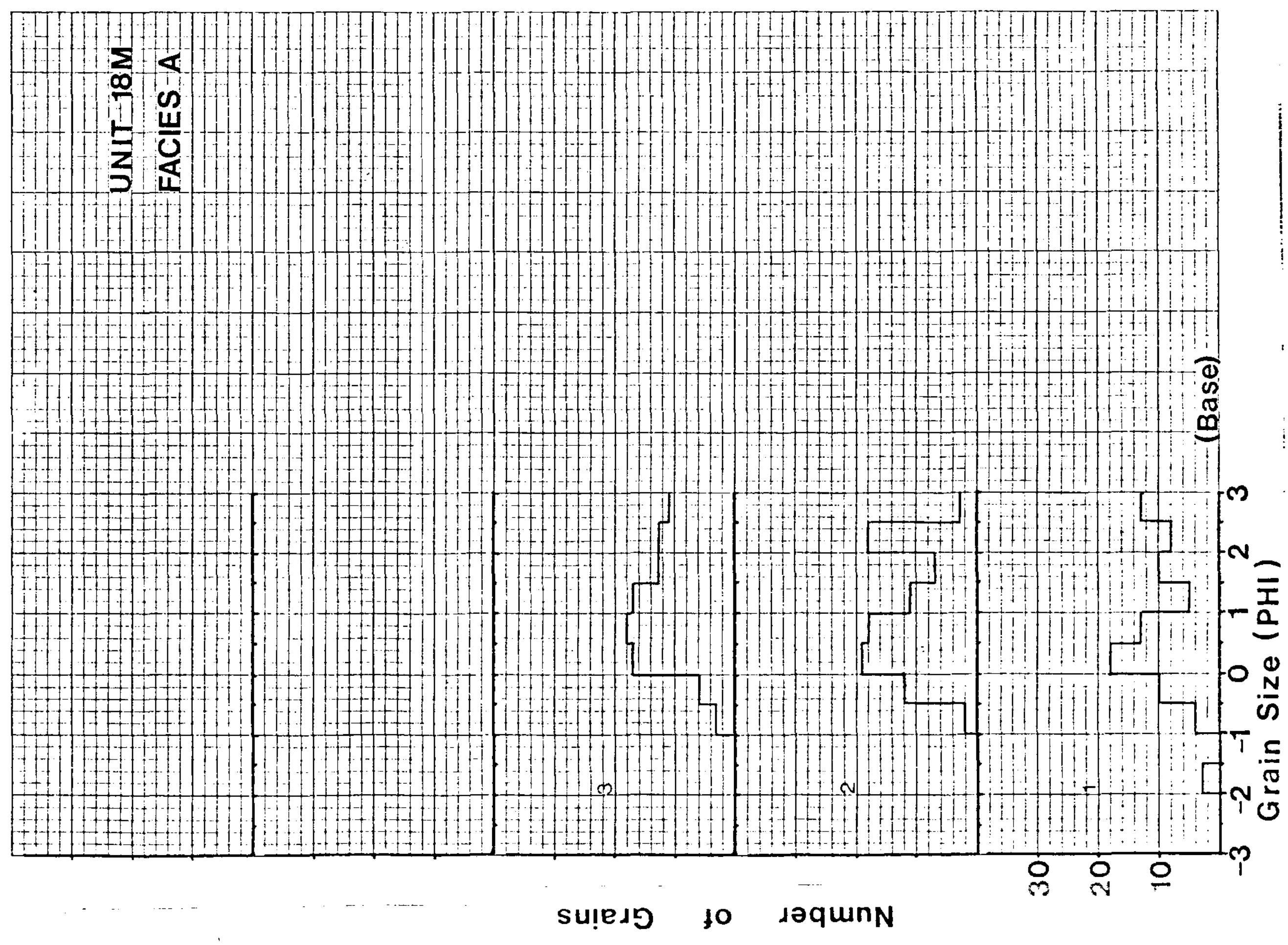


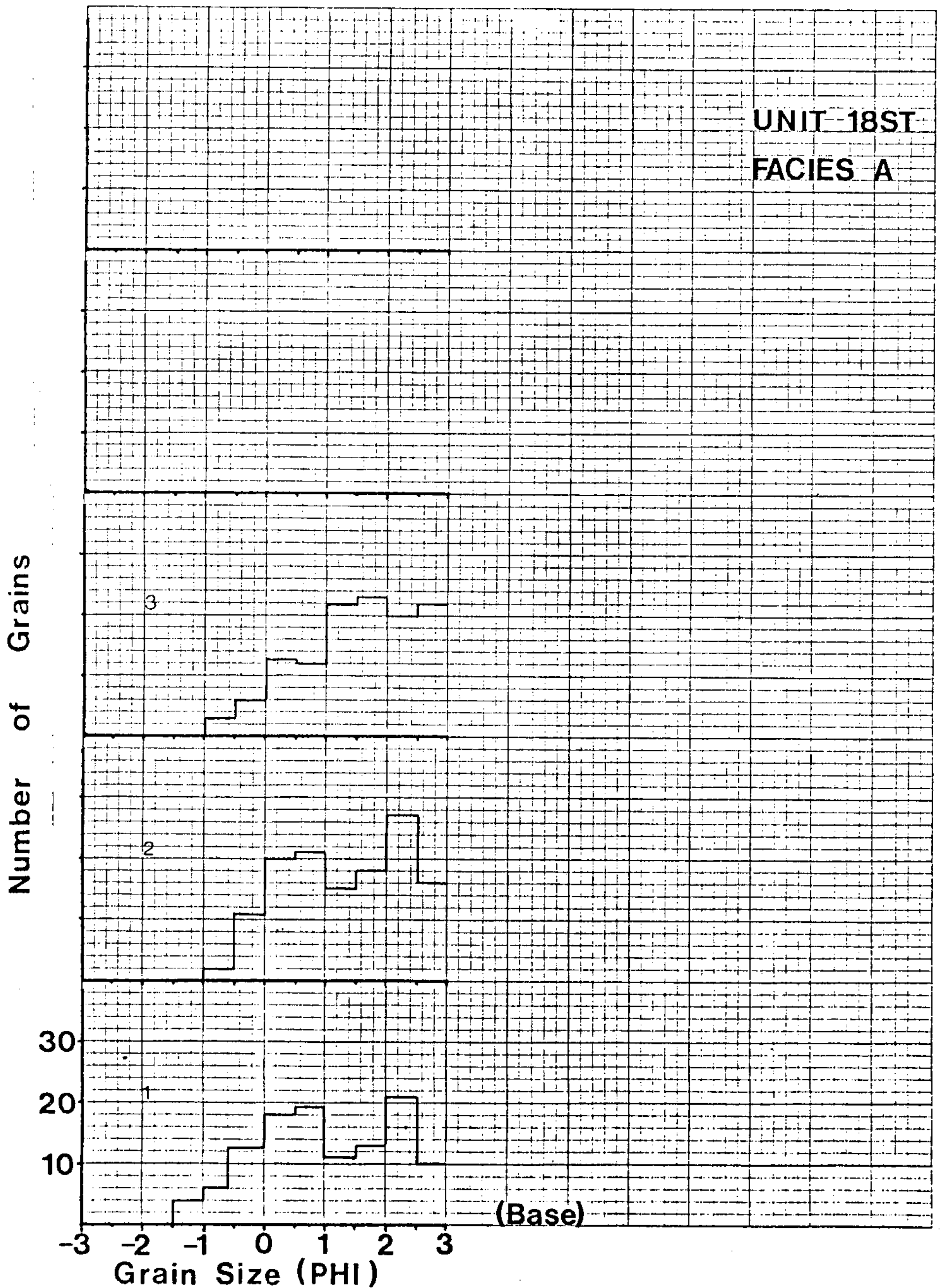
UNIT 16N
Cumulative Frequency (%)
Grain Size (PHI UNITS)

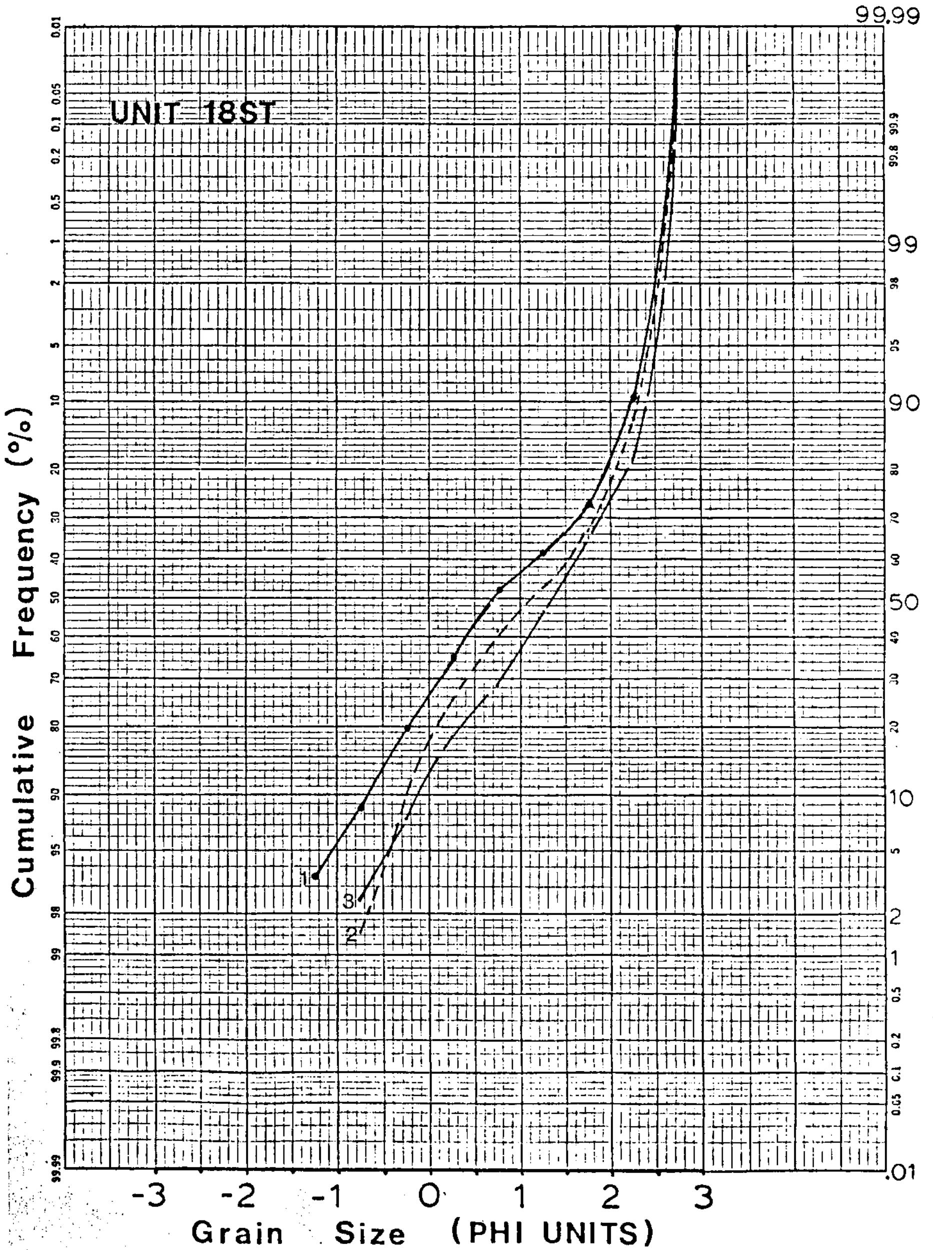

UNIT 16NB
FACIES A
3
2
1
Base
UNIT 14T
FACIES C-1
(Base)
Number of Grains
30
20
10
-3 -2 -1 0 1 2 3
Grain Size (PHI)

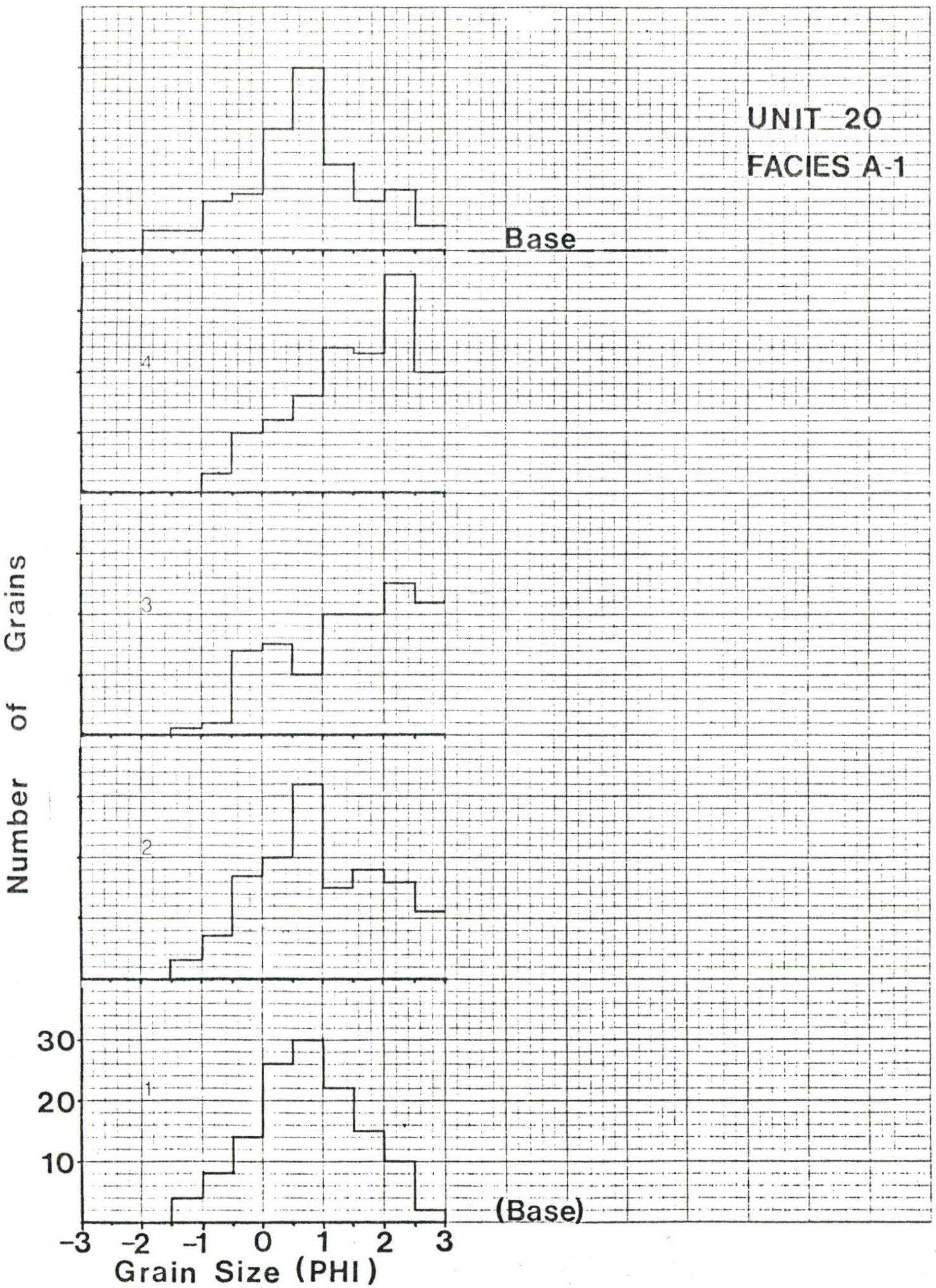

UNIT 16NB
Cumulative Frequency (%)
99.99
99
90
50
10
2
1
.01
1
2
3
-3 -2 -1 0 1 2 3
Grain Size (PHI UNITS)

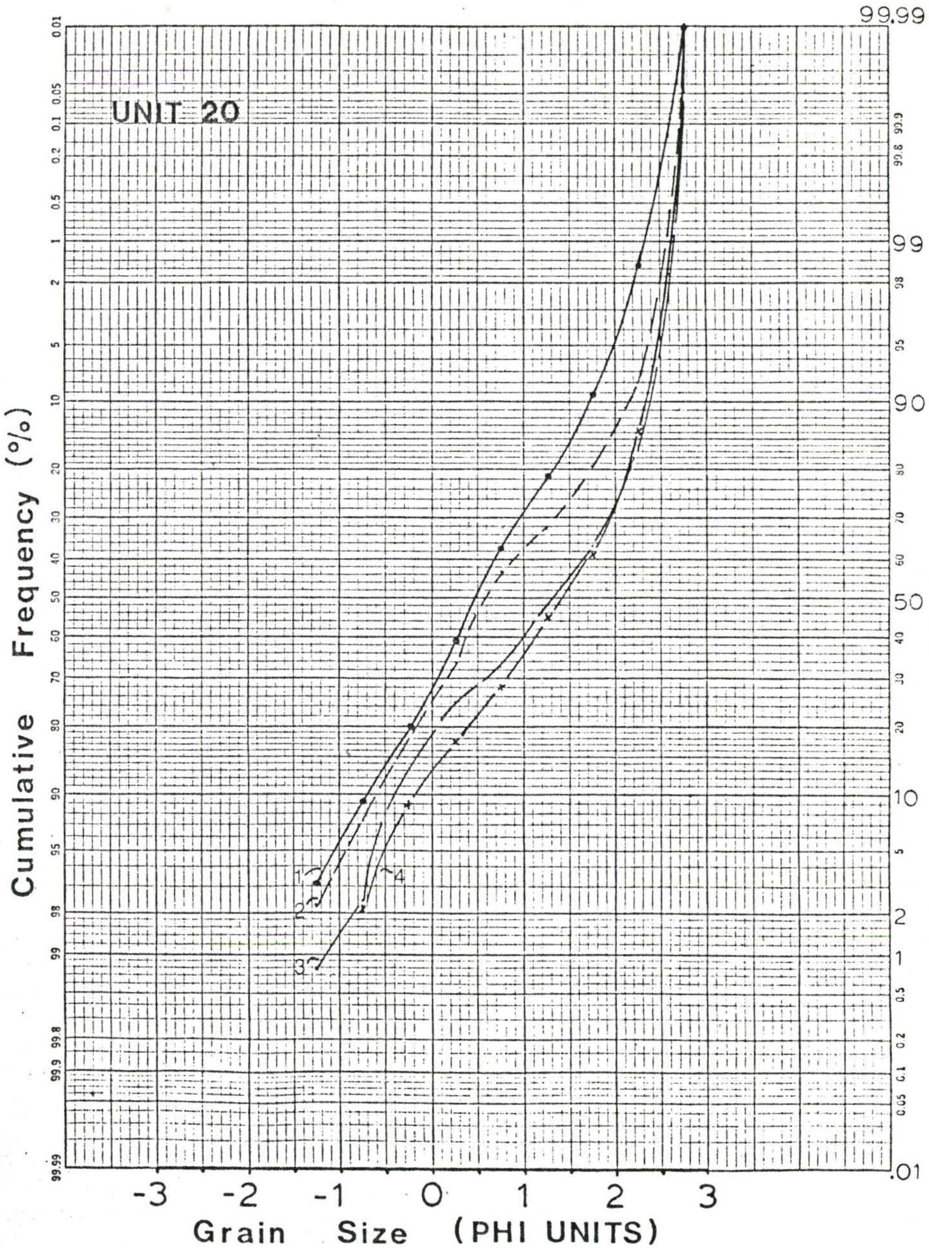

UNIT 18M
Grain Size (PHI UNITS)
Cumulative Frequency (%)
-3
-2
-1
0
1
2
3
99.99
99
90
50
10
2
.01
1
2
3


UNIT 18M
FACIES A
(Base)
Number of Grains
Grain Size (PHI)
30
20
10
-3
-2
-1
0
1
2
3
1
2
3


UNIT 18ST
FACIES A
3
2
1
Number of Grains
30
20
10
(Base)
-3 -2 -1 0 1 2 3
Grain Size (PHI)


UNIT 18ST
Cumulative Frequency (%)
99.99
99
90
50
10
2
1
.01
1
3
2
-3 -2 -1 0 1 2 3
Grain Size (PHI UNITS)


UNIT 20
FACIES A-1
Base
(Base)
Number of Grains
30
20
10
-3 -2 -1 0 1 2 3
Grain Size (PHI)


UNIT 20
Cumulative Frequency (%)
Grain Size (PHI UNITS)
-3 -2 -1 0 1 2 3
99.99
99
90
50
10
2
1
.01