

Vincent N. DiRenzo, Jr. Petrology and depositional environments of the Little Valley Limestone (Upper Mississippian) Washington County, Virginia. (Under the direction of Dr. Donald W. Neal) Department of Geology, April 1, 1986.

The Upper Mississippian Little Valley Limestone is a natural gas producing unit of mixed carbonate and siliciclastic composition transitional between largely terrigenous units below and carbonate units above. It was deposited during the inundation of the Virginia-Carolina delta complex. The Little Valley Limestone is approximately 220 meters thick in the study area, which is located in the Greendale Syncline in Washington County, Virginia. Petrographic point count data, geophysical logs and detailed hand sample characterization were used in both environmental and diagenetic determinations.

Seven microfacies are recognized: (1) lime mudstone, (2) lime wackestone, (3) lime packstone, (4) lime grainstone, (5) calcareous muddy sandstone, (6) calcareous mudrock and (7) secondary gypsum. These microfacies were deposited during a marine transgression and represent three distinct environments. They are, in ascending stratigraphic order: (1) restricted, high intertidal mudflat to bordering supratidal sabkha containing algal-laminated evaporites (gypsum and anhydrite) and dolomitic shales; (2) low intertidal to shallow subtidal, siliciclastic shoal containing interbedded calcareous-sandstones and mudrocks with a sparse biota; and (3) open marine, subtidal, with shelf lagoons characterized by lime- mudstones, wackestones, packstones and grainstones with an abundant stenohaline

7

fauna.

Diagenetic alteration of this unit consists of micritization, calcite and aragonite stabilization, microspar development, syntaxial overgrowths, and bladed and blocky spar cement formation, framboidal pyritization, dolomitization, silicification, secondary gypsum formation, stylolitization and vein and microfault formation.

PETROLOGY AND DEPOSITIONAL ENVIRONMENTS OF THE
LITTLE VALLEY LIMESTONE (UPPER MISSISSIPPIAN),
WASHINGTON COUNTY, VIRGINIA

A Thesis

Presented to

The Faculty of the Department of Geology
East Carolina University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Geology

by

Vincent N. DiRenzo, Jr.

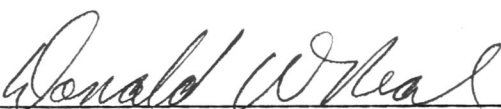
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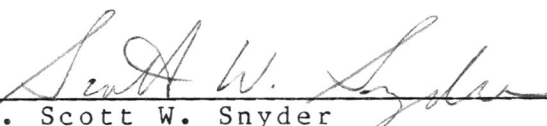
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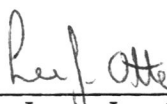
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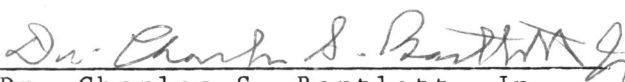
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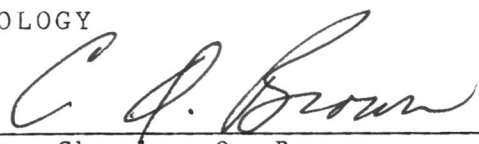
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INTRODUCTION

The Little Valley Limestone is an Upper Mississippian (Meramecian Series) unit which correlates with the lowermost member of the Greenbrier Group (Cooper, 1961) and is geographically limited to southwestern Virginia and southeastern West Virginia. Outcrops of the Little Valley Limestone occur within the Greendale Syncline in the Valley and Ridge physiographic province of Virginia. Here it is part of one of the most fossiliferous and complete exposures of Mississippian rock (greater than 2,134 meters) in North America (Cooper, 1948). The Little Valley Limestone is a natural gas producing, argillaceous unit which contains sandstones and evaporite units. It represents a "mixed"-composition transitional unit, lying stratigraphically between a lower predominantly terrigenous system and an upper predominantly carbonate system.

The Little Valley Limestone is economically important in the Early Grove Anticline, a small flexure within the Greendale Syncline, in both Scott and Washington Counties, Virginia. It produces natural gas from granular anhydrite beds in the lower portion of the formation (Bartlett and Biggs, 1982). Production from the Early Grove Gas Field first began in 1931 from the Elkin 1 Ridgeway well with a flow rate of 1,750 million cubic feet per day. From 1942 until 1957, seven producing wells supplied gas to the Bristol, Virginia area. The field was subsequently abandoned due to low production. It was reopened in March of 1980, with production from the Lower Mississippian Price Sandstone. Additional wells were drilled and

completed in the Price Formation and in the anhydrite zone of the Little Valley Limestone, which had near virgin pressures of 1,200 to 1,400 pounds per square inch. Production continues within the Early Grove Gas Field.

PREVIOUS WORK

The Little Valley Limestone has not previously been the subject of a detailed study; however, many reports dealing with the Central and Southern Appalachians make reference to it. Butts (1940), reporting on the geology of the Virginia Appalachian Valley, briefly described the character and distribution of Warsaw-age rocks (Little Valley Limestone). Similar regional studies by Cooper (1948), Bartlett and Webb (1971), Blancher (1974), deWitt and McGrew (1979), Gathright and Rader (1981), and characterized the stratigraphy and/or depositional and tectonic systems of the Mississippian System in Virginia. Little is known of the petrology of the Little Valley Limestone.

Economic interest in the Little Valley Limestone and bounding units spawned many Virginia Geological Survey publications. Two of the most pertinent are Butts' 1927 report summarizing the oil and gas potential of the Early Grove area of Scott County, Virginia, and Averitt's 1941 report on the Early Grove Gas Field in Scott and Washington Counties, Virginia.

Butts' report was significant for it contained the initial description of the Warsaw-age unit, whereas Averitt's study formally named the Little Valley Limestone and produced the first detailed map of Upper

Mississippian units in the area. Although relevant information on the Little Valley Limestone was presented by Butts and Averitt, there was little descriptive detail. Similarly, Huddle et al. (1956), Withington (1965), LeVan (1981), Bird (1981), Bartlett and Biggs (1982), LeVan and Rader (1983) and Sweet (1983) presented historical and updated reports on Virginia's economic minerals and oil and gas deposits.

Cooper (1966) discussed the geology of the salt and gypsum deposits within the Maccrady and Little Valley Formations in Smyth and Washington Counties, Virginia. De Witt and McGrew (1979) noticed local accumulations of evaporites (mainly gypsum and halite) in the lower portion of the Little Valley Limestone in the vicinity of Saltville, Virginia.

The faunas within the Little Valley Limestone have been recorded by Butts (1927, 1940, and 1941) and Bartlett and Webb (1971). Chaplin (1975) studied the conodont biostratigraphy of the Little Valley and Hillsdale Limestones in southwestern Virginia.

OBJECTIVES

The objectives of this study are: (1) to characterize the mineralogy and petrology of the Little Valley Limestone (especially the bedded gypsum recognized in the lower Little Valley Limestone); (2) to characterize microfacies and determine the nature and extent of diagenetic change within each microfacies; and (3) to determine the depositional and tectonic history of the Little Valley Limestone. The study is limited to Washington County, Virginia where good exposures

of Little Valley Limestone are present (Fig. 1).

GENERAL STRATIGRAPHY

Stose (1913) included Warsaw-age carbonates (the Little Valley Limestone) within the Maccrady Formation of the Greendale Syncline, Smyth County, Virginia. He defined the lithologies of the Maccrady as red and gray shales, sandstones, black carbonaceous shales, and gray limestones. The incorporation of the Little Valley Limestone within the Maccrady Formation was questioned by Butts (1927) because the upper portion of the

Maccrady Formation contained a distinct Warsaw-aged fauna. The fauna included Anistrypa tuberculata, Fenestralia sancti-ludovici, Hemitrypa proutana, and Productus altonensis; all of which are confined to the Warsaw and are correlative with other Warsaw faunas. Butts also pointed out that the Maccrady shale not only had a fauna of New Providence age, but that it was separated from Warsaw-aged Limestones by an unconformity. As a result, Butts suggested that the use of "Maccrady" be restricted to the red beds.

Averitt (1941) formally separated the Warsaw-age lithologies from the Maccrady Formation based on distinct lithologic and faunal differences. Averitt designated the Warsaw-aged unit the "Little Valley Limestone" because of its low topographic expression in Little Valley, Scott County, Virginia.

The Little Valley Limestone, according to Blancher (1974), is equivalent to the lowest beds of the Greenbrier Limestone of West Virginia. The Greenbrier Limestone was designated by Rogers (1879)

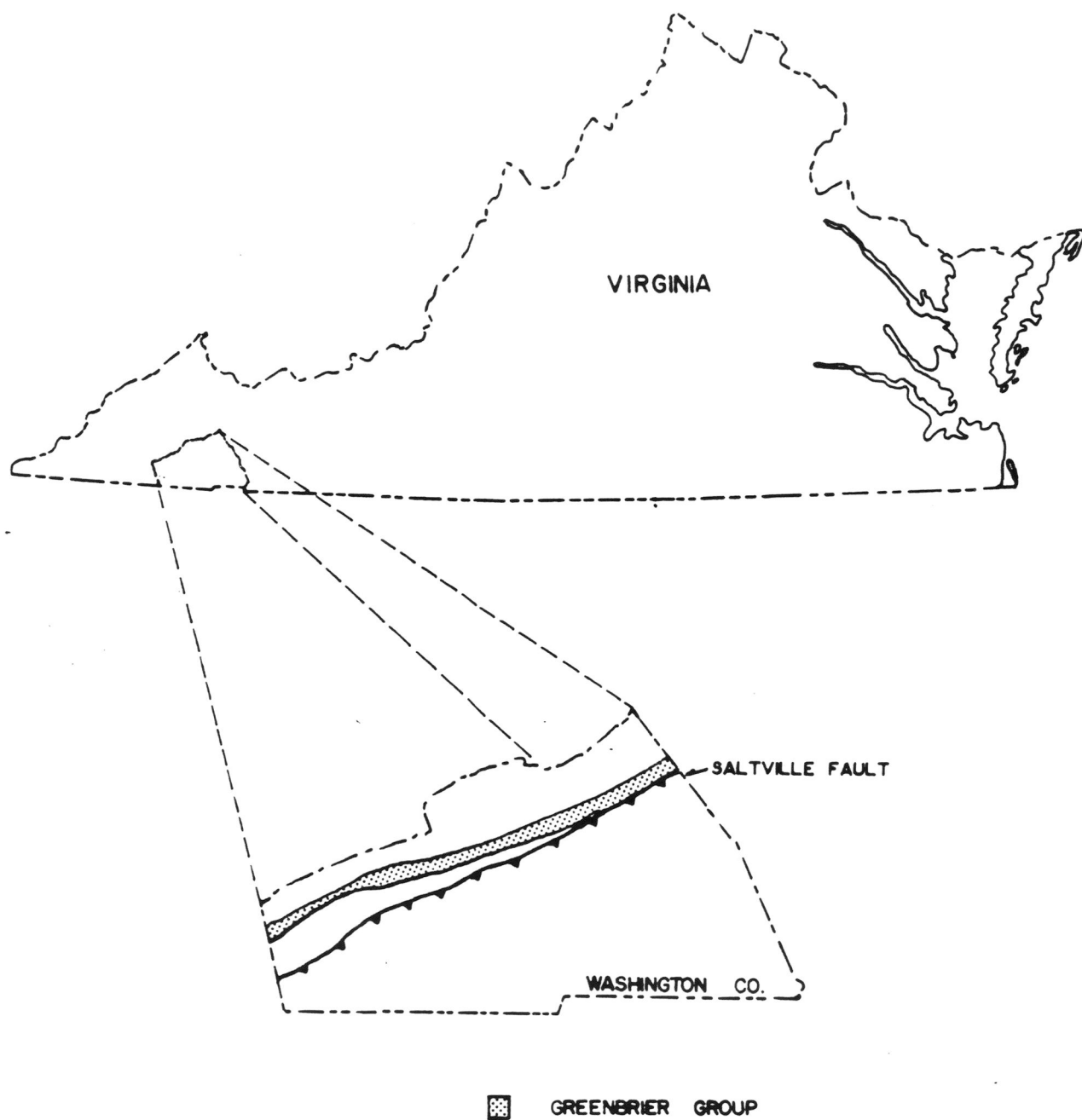


Fig. 1. Location map of field area and outcrop belt.

for limestones exposed along the Greenbrier River, Pocahontas County, West Virginia. Blancher (1974) suggested that the Greenbrier Limestone of the Greendale Syncline consists of, in ascending order, Little Valley Limestone, Hillsdale Limestone, Ste. Genevieve Limestone and the Gasper Limestone.

The Little Valley Limestone represents a unit of "mixed" lithologies transitional between predominantly siliciclastic rocks below and carbonate rocks above (Fig. 2). The underlying Maccrady Formation consists primarily of interbedded, soft, maroon and light green, micaceous shale or thinly bedded mudstone with minor amounts of maroon siltstone and light gray to red, fine-grained sandstone (Bartlett and Webb, 1971). The Hillsdale Limestone overlies the Little Valley Limestone and is predominantly composed of dense, light-to dark-gray, fine-grained, fossiliferous limestone which contains bedded and nodular chert. Oolitic and argillaceous beds are sparse, but are also present (Bartlett and Webb, 1971).

STRUCTURE

Most major structural features in Washington County are oriented northeast-southwest with beds dipping to the southeast. Included are portions of the Greendale and Beaver Creek Synclines, the Early Grove Anticline and the Saltville, Pulaski-Staunton, Spurgeon and Bristol Thrust-fault Blocks.

The Little Valley Limestone and other Mississippian to Silurian-age units have been folded in the Greendale Syncline (a northeast trending southwest, plunging fold) by movement of Cambro-Ordovician

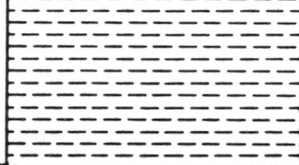
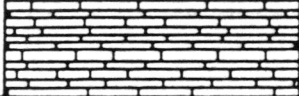
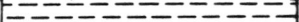
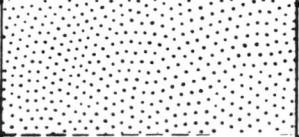
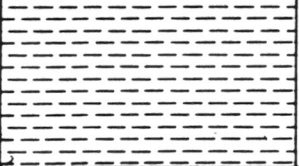
FORMATIONS	GENERAL LITHOLOGIES	THICKNESS (meters)
PENNINGTON		407 +
COVE CREEK		306-372
FIDO		16 ±
GIRKIN		226-266
SIO. GENEVIEVE		361-367
HILLSDALE		84 ±
LITTLE VALLEY		173-220
MACCRADY		18 ±
PRICE		172 +
BIG STONE GAP		300 +

Fig. 2. Outcrop stratigraphic sequence of the Mississippian Formations of the Greendale Syncline of Washington County, Virginia.

carbonates of the Saltville thrust sheet (Fig. 3). The thrust sheet covers the southeastern limb of the syncline (a total displacement of over 4,878 meters), placing the Mississippian Pennington Formation in contact with the Lower Cambrian Rome Formation and the Middle Cambrian Honaker Dolomite in the southwestern portion of the county and the Maccrady Formation in the northeastern portion of the county (Bartlett and Webb, 1971).

METHODS

The procedures used in this investigation encompass both fieldwork and laboratory operations. The field operations include detailed measurement and description of the Little Valley Limestone from outcrop and core. Outcrop samples were taken at a road cut one-eighth of a mile south of the North Fork of the Holston River along U.S. Highway 19 and Alternate 58, and at five exposures along Virginia State road 622 (Fig. 4). The basis for outcrop selection was the extent of exposure (at least 4.5 meters) because complete sections of the Little Valley Limestone are not available. The core, Bonnie-Dell (BD) 61-5, was obtained from United States Gypsum in Plasterco, Virginia, and contains approximately 83.8 meters of the basal Little Valley Limestone. Lithologies, fossils, textures and sedimentary structures, along with overall stratigraphic relationships, were studied and samples were taken that best represent the lithologies present. Samples from both outcrop and core were taken at changes in lithology and/or every 1.5 to 2.0 meters within uniform lithologies

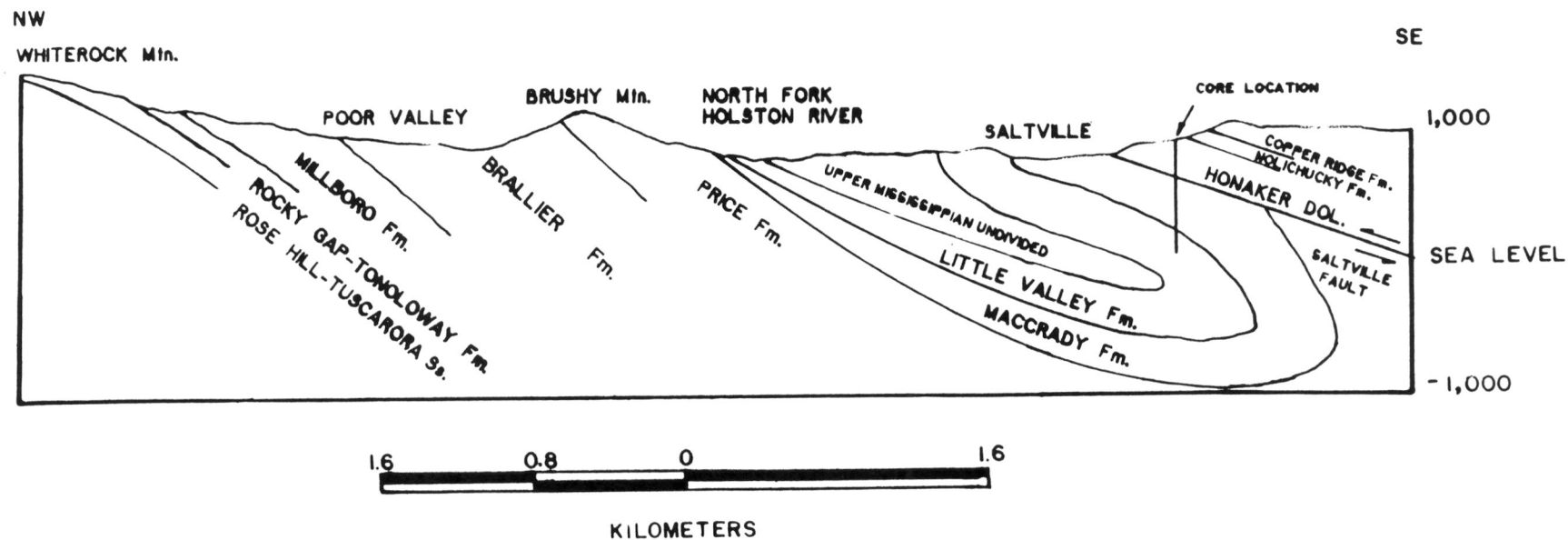


Fig. 3. Cross section of the overturned portion of the Greendale Syncline through Saltville, Virginia showing core location (modified from Cooper, 1966).

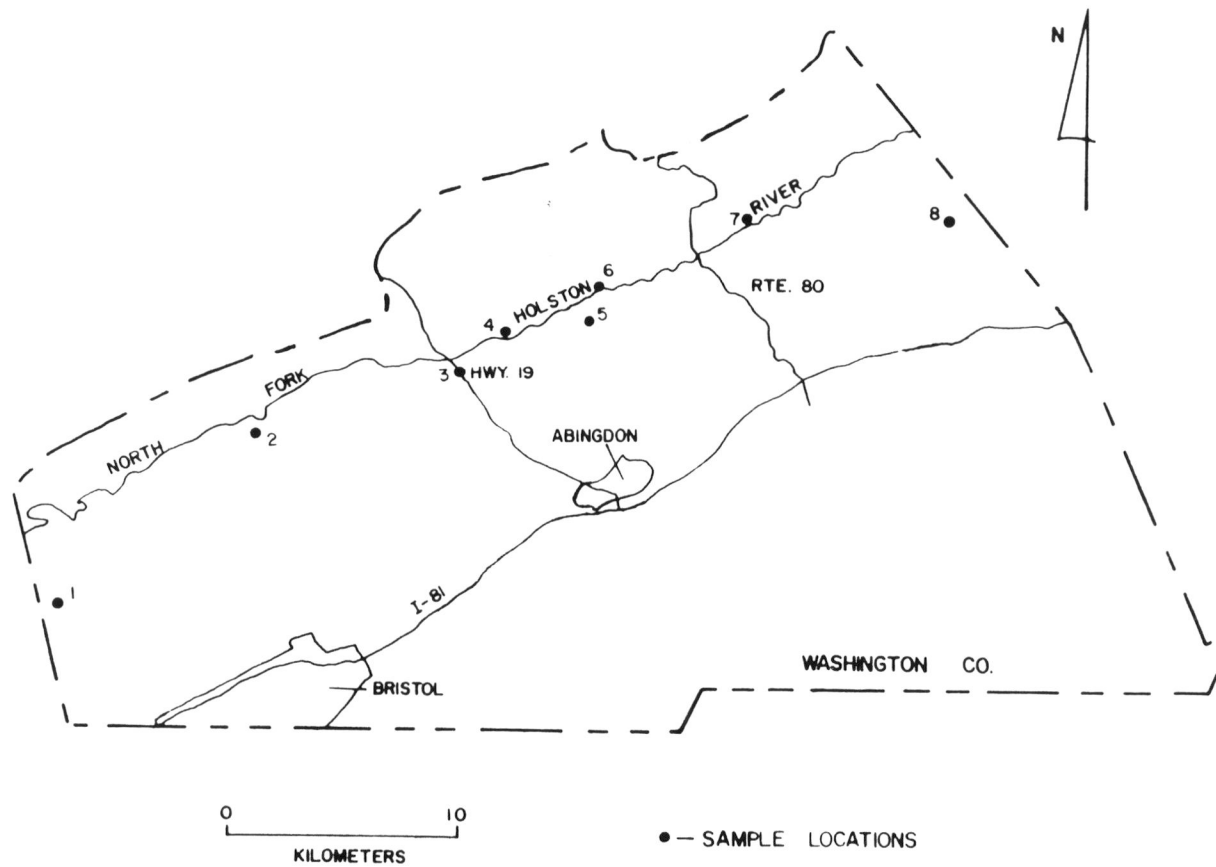


Fig. 4. Sample locations.

(Appendix A). Using this method, 250 samples were collected. Photos were taken of each outcrop and of core samples.

Laboratory operations involved examination of constituents and fabrics of the rocks in thin sections and polished hand samples. Thin sections from each sample were stained with a solution of Alizarin Red S and potassium ferricyanide in a 0.05 molar solution of hydrochloric acid. This technique stains calcite red and ferroan calcite mauve, while dolomite does not stain and ferroan dolomite and ankerite stain blue. Petrographic analysis involved 235 thin sections, 160 of which were point counted by Dunham's (1962) "grain bulk" method such that any material or open pore space within a particle is counted as the particle. Three hundred points per slide were counted. All thin sections were classified according to the system devised by Dunham (1962).

Scanning electron microscopy was used to aid in petrographic determinations. Weight percents of insoluble residues were obtained for 106 samples from both the U.S. Highway 19 outcrop and the Bonnie Dell core (Appendix B). The insoluble residues were obtained by dissolving approximately 20-25 grams of sample in industrial grade hydrochloric acid until carbonate was fully leached. Residue was then weighed and a weight percent was calculated for each sample.

STRATIGRAPHY

The Little Valley Limestone is approximately 220 meters thick within the Greendale Syncline. Individual outcrops of the Little Valley exhibit anywhere from 6 to 150 meters of exposure (Fig. 5, enclosed in pocket).

Stratigraphically, the Little Valley Limestone can be informally subdivided, based on lithology, into an upper and lower section (Fig. 6). The lower section of the contains interbeds of medium-to-light gray, calcareous to dolomitic shale and siltstone with argillaceous lime mudstone and lime wackestone. The base of this lower section also contains bedded gypsum and anhydrite. Fossils are scarce and are predominantly composed of algae, ostracodes, and thin-shelled pelecypods. Locally abundant zones of bryozoans, echinoderms and brachiopods are found. This lower section of the Little Valley Limestone contains varying bed thicknesses ranging from a few centimeters to greater than 30 meters without a discernable break. The degree of interbedding between the different lithologies in this section is variable, however, thicker, more uniform lithologic compositions prevail. Outcrop exposures of this section are typically highly weathered (especially muddier compositions), appearing fissile and friable.

The upper section of the Little Valley Limestone largely consists of interbedded, medium-to-dark argillaceous lime mudstones, lime wackestone and lime packstone. This section also contains localized beds of black carbonaceous shale, cherty limestone, lime grainstone

GENERALIZED LITHOLOGIES OF THE LITTLE VALLEY LS.

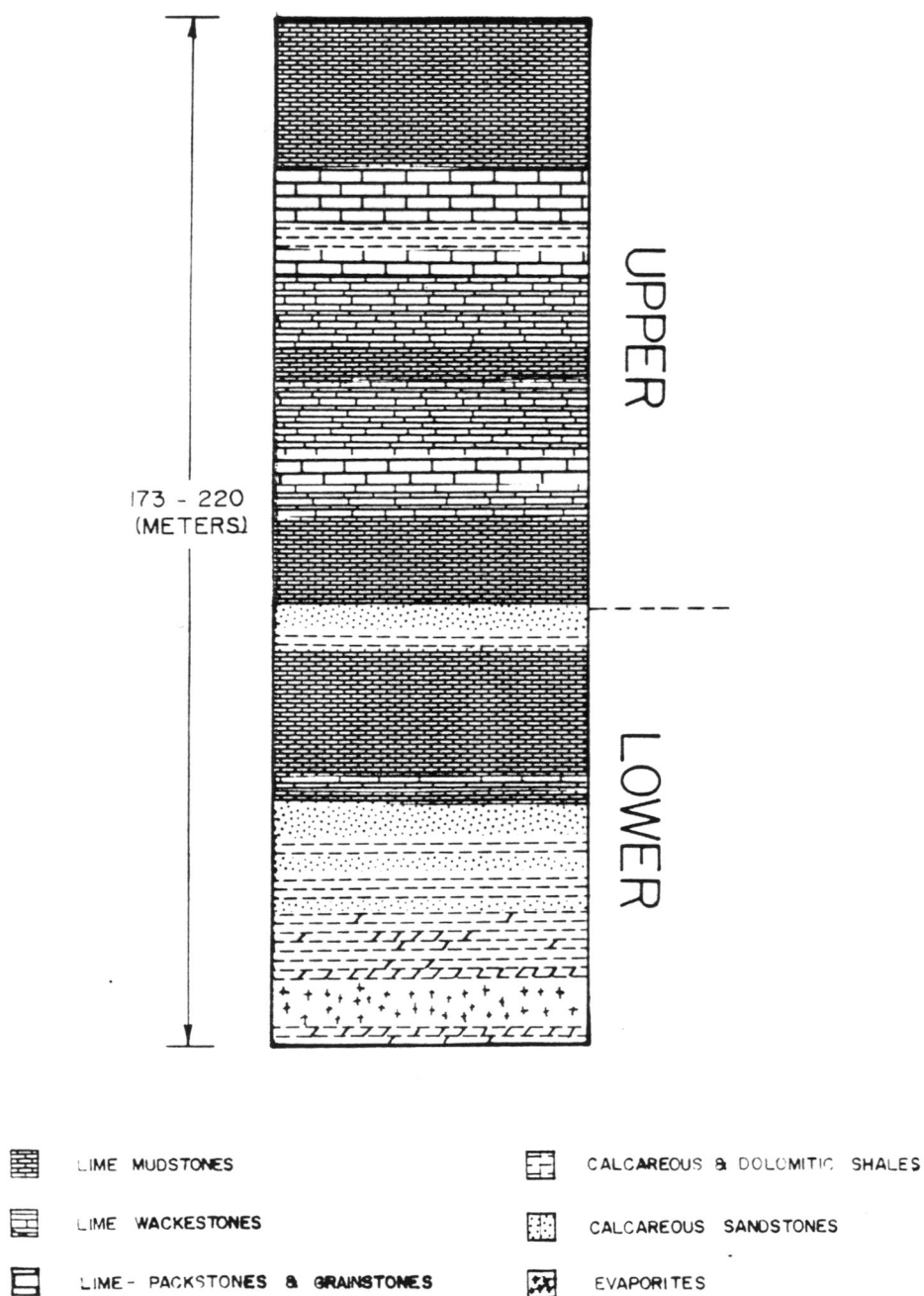


Fig. 6. Characteristic lithologies of the Little Valley Limestone with informal lower and upper subdivisions.

and calcareous fine-to-medium sandstone. Fossils are very abundant in most lithofacies with brachiopods, bryzoans and echinoderms predominating, but also containing localized occurrences of pelecypods, corals, foraminifers, stromatolitic algae and conodonts. Similar to the lower section, the upper section of the Little Valley Limestone contains varying bed thicknesses (centimeters to tens of meters), however, the upper section's lithologies are highly interbedded. Outcrop exposures of the upper section characteristically weather less severely than the lower section (although the muddier lithologies are similarly fissile and friable) containing resistant lime packstones, lime grainstones and calcareous sandstones. The lime packstones and lime grainstones commonly contain fossils exposed on weathered surfaces and silicified zones. The lime packstones of the upper most portion of the upper section of the Little Valley Limestone are commonly interbedded with a black, fossiliferous shale and are highly petroliferous. Therefore, forming excellent marker beds for recognition of the upper section.

PETROLOGY

The petrology of the Little Valley Limestone involves the characterization of both carbonate and siliciclastic components due to the "mixed" nature of this unit. Depositional characteristics of "mixed" lithologies cause problems with interpretation because uniquely carbonate or siliciclastic depositional features do not exist. Diagenetic overprints are also invariably controlled by the high percentage of terrigenous material. Therefore, in order to more precisely characterize "mixed" features, a thorough description of all components from both hand sample and thin section is necessary.

Petrologically, constituents of the Little Valley Limestone can be subdivided into three major categories: (1) matrix, (2) constituents (both carbonate and siliciclastic) and (3) orthochems (cement).

MATRIX

The main components composing the matrix within the Little Valley Limestone can be subdivided into two groups: (1) carbonate components, which include micrite, and (2) siliciclastic components containing chlorite, illite, muscovite and silt- and sand-sized quartz.

Carbonate Components

Micrite

Micrite within the Little Valley Limestone is usually dark brown

to dark gray colored, has a grain size of less than 1 micron, and commonly contains a tightly cemented, grumous texture (patchy, clotted fabric of the matrix). Its clotted texture is caused by a complex mixture of terrigenous clays and silts with neomorphic microspar and dolomite. Framboidal pyrite is also a common associate. The micrite matrix is rarely homogeneous. Micrite is common to nearly every microfacies (especially lime mudstone and wackestone) and is considered the precursor to most, if not all, microspar in this unit.

The formation of the micrite within the Little Valley Limestone is thought to have occurred by one or all of the following processes: (1) bioerosion associated with organism borings and/or ingestion; (2) mechanical breakdown of skeletal grains, principally by wave or current activity; (3) direct inorganic precipitation in the form of "whittings"; and (4) organic production of micrite sized skeletal grains by algae and other calcite- and aragonite-secreting organisms.

Siliciclastic Components

Clays

Two prominent clays (illite and chlorite) were identified by x-ray diffraction from samples of the Little Valley Limestone. Kaolinite is also present in minor amounts. Texturally, phyllosilicates are usually homogeneously intermixed with carbonate muds, although they are sometimes concentrated between microspar crystals and in localized pockets within the matrix (possibly caused by bioturbation). The most prominent fabric created by the mixture of phyllosilicates and carbonate mud is a grumose texture (Plate 1).

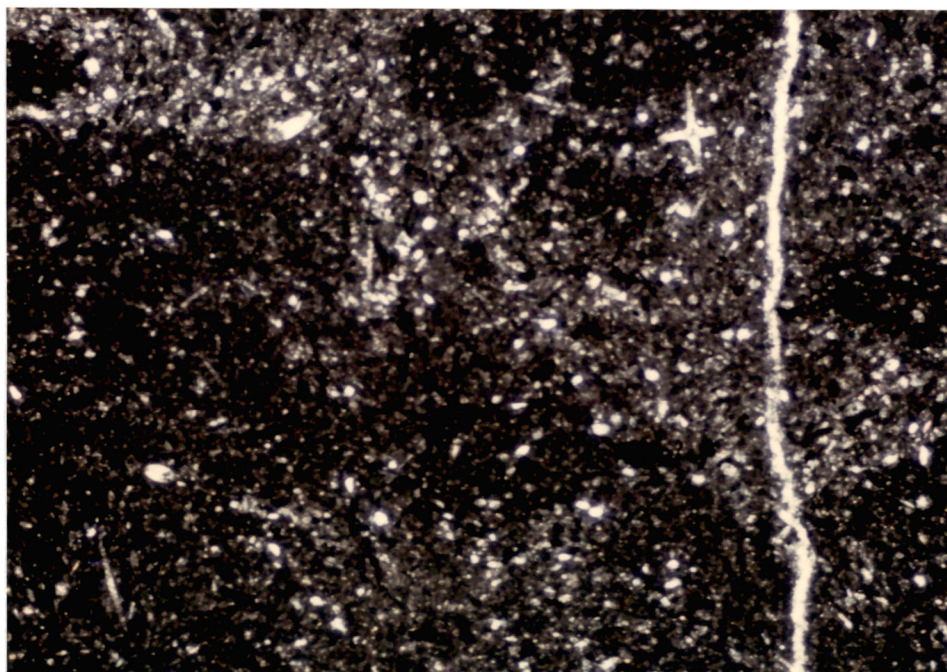


PLATE 1. Photomicrograph of a grumose texture. 1 cm = 0.25 mm.

Clay mineralogy is useful as an environmental indicator, but the Paleozoic contains an illite-dominated clay mineralogy (as does the Little Valley Limestone)(Blatt, 1972). Several theories have been suggested for this dominance: (1) increase in silicic crystalline rocks (plagioclase source), (2) change in the biologic controls of chemical weathering, (3) climate (temperate in illite's case) allowing for preferential clay mineral formation and (4) diagenetic alteration due to increased temperatures and depths of burial.

Because the Little Valley Limestone has been buried to depths probably greater than 1,200 meters and exposed to temperatures greater than 100 degrees centigrade (as determined from Chaplin's (1975) conodont CAI studies) diagenesis is thought to have been the major cause for high concentrations of illite.

Muscovite

Muscovite is common within the more argillaceous units of the Little Valley Limestone where its elongate, A-axis is oriented parallel to bedding. Petrographically, muscovite is colorless to pale green, exhibits excellent cleavage (001), and is biaxial negative with fourth order interference colors. Its crystals range in size from 0.01 to 0.2 mm. Muscovite is an important constituent in the calcareous mudrock and calcareous muddy sandstone microfacies.

Silt and Sand Sized Quartz

Quartz silt and sand are pervasive throughout the Formation, ranging from less than 1% to nearly 80% of any particular rock. The individual grains are subrounded to angular, usually highly pitted and

range in size from .03 to 0.5 mm. Petrographically, quartz is colorless and is uniaxial positive with first order interference colors. Quartz grains may also be polycrystalline and/or monocrystalline exhibiting an undulose extinction. Quartz is commonly associated with feldspar and chert grains.

CONSTITUENT PARTICLES

Introduction

The constituent particles within the Little Valley Limestone can be subdivided into carbonate allochems and noncarbonate particles. Allochems found in the Little Valley Limestone include very fine sand-sized (0.075 mm) and larger fossils, ooids, intraclasts and extraclasts. The most abundant allochems within this unit are fossils, predominantly brachiopods, bryozoans, echinoderms and ostracodes. However, foraminifers, corals, trilobites and gastropods, although less abundant, are locally common. Similarly, nonfossiliferous allochems (ooids, intraclasts and extraclasts) also lack ubiquity but predominate locally. Conodonts and plant fragments, not considered allochems, are locally common within the Little Valley Limestone.

Major Allochems

Brachiopods

Brachiopods are diverse and prolific within the Little Valley Limestone. The following brachiopods were identified: Syringothrididae, Inflata ?sp., and Productus (Dictyoclostus) inflatus McChesney. Brachiopods in the Formation are very well

preserved, probably due to their original calcitic composition. They are commonly whole but may be fragmented, and they range in size from 0.05 cm to greater than 8.0 cm in maximum dimension. Their shell characteristics include plications, smooth to spinose surfaces and various overall morphologies.

Petrographically, brachiopods were identified by their "fibrous" texture (composed of oblique calcitic layers) and their external morphology. Both endopunctate and pseudopunctate forms were common. Variations in microstructural organization were recognized, especially in calcitic layer orientation (8-10 variations seen), associated with different shell characteristics (Plate 2).

Bryozoans

Bryozoans are another prevalent fossil found throughout the formation. Generally, bryozoans are structurally well preserved (due to an original calcitic composition), although they are commonly partially or entirely recrystallized and/or pyritized. Colonies are commonly fragmented, except for robust cryptostome varieties.

The two predominant types of bryozoans associated with the Little Valley Limestone are (1) fenestrate varieties characterized by regularly spaced, bifurcating branches and fronds containing large amounts of zooecia; and (2) cryptostome varieties containing thickly branched (stick-like) colonies with zooecia radially or uniformly spaced. Microstructurally, the bryozoans' wall structure is a thinly to thickly laminated, fibrous layer which is longitudinal and tangential to its architectural form. The cryptostomes are usually

very finely laminated forms and appear fibrous to structureless. Fenestrate varieties show a diagnostically coarse, fibrous microstructure (Plate 3).

Echinoderms

The term "echinoderm" includes any invertebrate belonging to the phylum Echinodermata. These are solitary, marine organisms characterized by radial endoskeletons composed of crystalline calcite plates (or ossicles) and a water-vascular system (Bates and Jackson, 1980). The most common subphyla within Echinodermata are echinozoans, crinozoans and blastozoans.

Within the Little Valley Limestone, echinoderms are not usually the most abundant fossils, but they are the most cosmopolitan. Well preserved echinoderm fragments are found in lime grainstones, packstones, mudstones and even calcareous mudstones. Petrographically, echinoderm fragments are easily identified by their single unit extinction under crossed nicols and by their dusty appearance (due to mud inclusions within their porous structure). Morphologically, echinoderm fragments can have various shapes ranging in size from 0.01 to 2.0 cm but are often circular and/or columnar in section.

Bivalves

Bivalves are benthic mollusks characterized by two approximately equal valves joined by a hinge. Within the Little Valley Limestone, they are commonly well preserved, with smooth to plicated external shell morphologies. Their test thickness ranges from very thin (0.4



PLATE 2. Brachiopods common to the Little Valley Limestone.
1 cm = 1.7 cm.

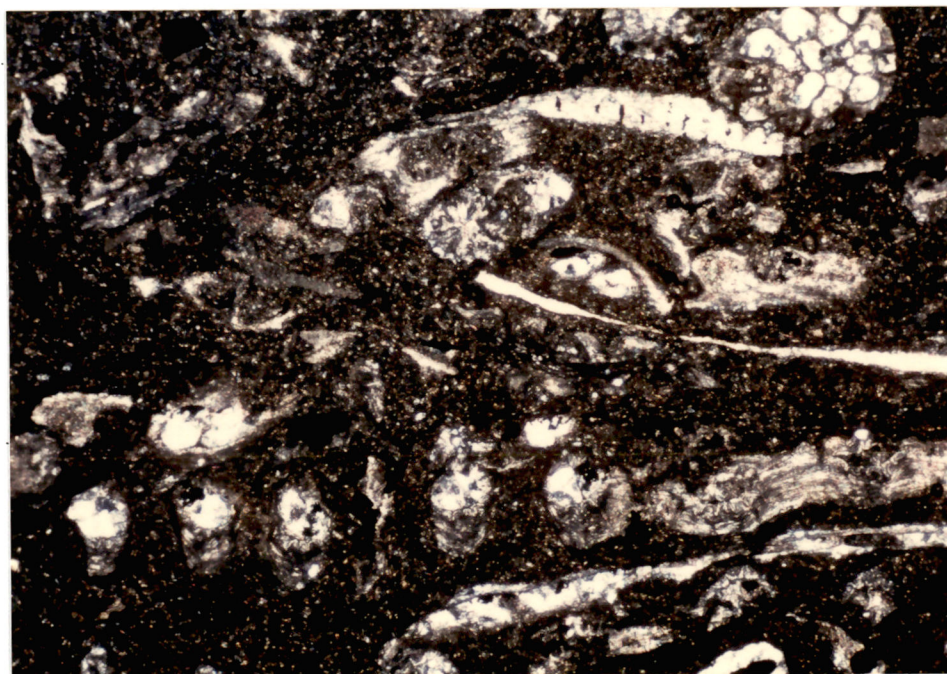


PLATE 3. Photomicrograph of bryozoans (bryozoan 1.5 mm in cross section).

mm) to thick (1.0 mm), while their maximum dimensions vary from 0.25 to 6.0 cm. Pelecypods identified include Posidonomya or Caneyella?sp., Tetrachamera?sp. and Aviculopecten?sp.

Microstructurally, two dominant shell characteristics are observed: (1) a smooth, parallel interlamination which make bivalves seemingly structureless; and (2) a prismatic structure which has polygonal calcite blocks arranged in a columnar fashion (both simple and composite columns) oriented normal to the shell surface.

Bivalve preservation was greatly enhanced in muddier microfacies where whole or nearly whole specimens are found. In contrast, bivalves associated with sandier (whether carbonate or siliciclastics) microfacies are generally highly fragmented and contain only a prismatic columnar microstructure (Plates 4 and 5).

Other Allochems

Ooids

Ooids are carbonate grains, subspherical to spherical in shape and composed of one or more uniform concentric laminae encompassing a particulate nucleus. The ooids within the Little Valley Limestone range in size from 0.15 to 0.5 mm. They invariably have a radial fabric, possibly due to recrystallization, and range from light brown to a darker carbonized black. Ooids are mostly very mature, containing many uniform concentric laminations, although some superficial ooids are also present. Ooid nuclei are composed of various particles, but the most abundant particles in any microfacies (sand-sized quartz, fossil fragments, etc.) are usually the core constituent. Ooid maturation affects the size variance between



PLATE 4. Bivalves common to the Little Valley Limestone.
1 cm = 2 cm.



PLATE 5. *Posidonomya* ?sp., a bivalve common to the upper section
of the Little Valley Limestone. 1 cm = 2 cm.

ooliths. Mature ooids are nearly uniform in size, while immature ooids show the greatest size variance.

Most of the black, highly carbonized ooids, individually or in clusters, contain a conspicuous darker, spar cement than the surrounding spar cement. Therefore, they are thought to be intra- or extraclasts.

Foraminifers

The foraminifers within the Little Valley Limestone are benthic varieties. In thin section, foraminifers are characterized by their test morphology, which is subcircular to circular, planispiral to low trochospiral, regular to irregular coiling, multichambered and ranging in size from 0.5 to 1.0 mm. Microstructurally they have a microgranular test with a dark and dusty textural appearance caused by complete micritization. The dominant type of foraminifers identified include Endothyranopsis?sp. E.compressa., Brunsia?sp., Zellerina designata and Pseudoammodiscas?sp.

The foraminifers are unusually well preserved, suggesting an original calcitic test composition. Some recrystallization and pyritization has occurred (Plate 6).

Corals

Two types of coral are found in the Formation: (1) a horn coral, thought to be Lithostrotionella prolifera (Hall), and (2) a branching coral identified as Syringopora virginica Butts. The horn coral is an elongate form which tapers away from the calycine and has parallel

costae running the length of the coral. Horn corals range in size from 4.0 to 6.0 cm, and are found in localized patches. Branching corals are thin (0.3 cm), elongate, irregularly intergrown corallites which range in size from 14.0 to 17.0 cm and generally occur in localized patches.

Petrographically, horn corals are characterized by an outer wall and an internal network of radially arranged septa perpendicular to the outer wall. Well preserved corals contain a fine fibrous microstructure, although a lack of microstructure is more common due to complete recrystallization. Generally, corals are associated with high porosities where multiple stages of calcite spar growth and silica partially infill (plate 7).

Ostracodes

Ostracodes are bivalved arthropods which are cosmopolitan in the Little Valley Limestone. Though they never predominate, ostracodes are present in most lithologies throughout the formation. They are recognized by their thin, overlapping carapaces which are generally smooth and lack ornamentation.

The microstructure of ostracodes is characterized by radial-fibrous calcite crystals which, under crossed nicols, show a diagnostic sweeping extinction. Ostracodes range in size from 0.3 to 1.5 mm and are mostly disarticulated, although articulated specimens do occur. The thickness of carapace walls varies. Ostracodes in this unit are very well preserved due to their original calcitic composition.

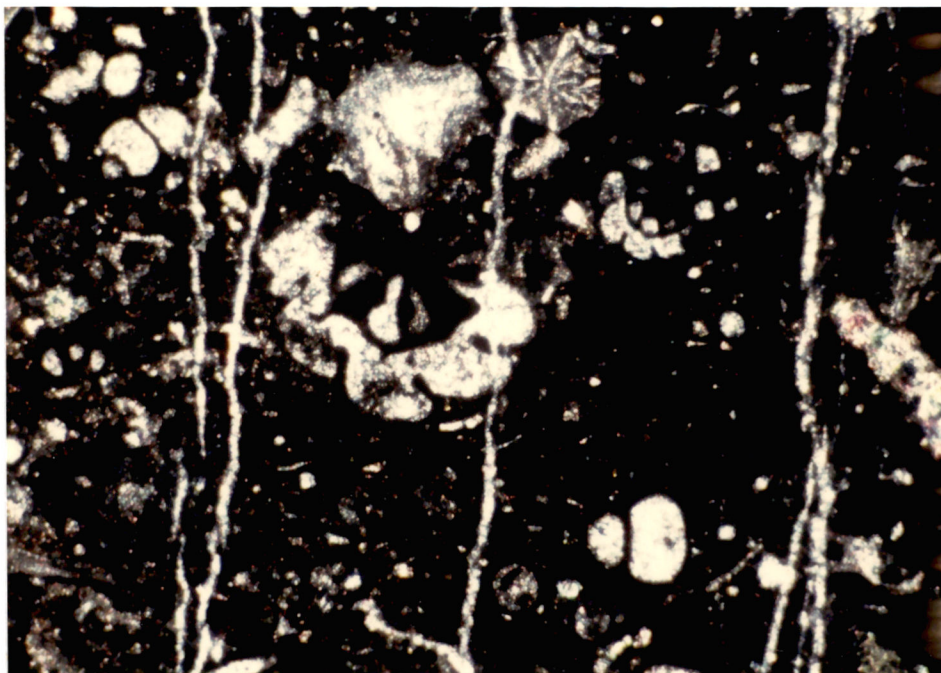


PLATE 6. Photomicrograph of foraminifers (0.7 mm in maximum dimension).



PLATE 7. The coral Syringopora virginica Butts (12.0 cm in maximum dimension).

Trilobites

Trilobites fragments are sparse and only locally present. Their microstructural characteristics are similar to those of ostracodes, having a silky textured, calcitic radial-fibrous structure which shows sweeping extinction bands under polarized light. In contrast to ostracodes, the shell morphologies of trilobites are commonly sinuous to convolute shaped (sometimes resembling a shepherd's crook). The trilobites are very well preserved, showing little recrystallization, but some have been broken and abraded. Trilobite fragments range from 1.5 to 8.0 mm in maximum dimension.

Gastropods

Gastropods are rare within the Little Valley Limestone, possibly owing to lack of preservation rather than initial absence. These gastropods which are preserved are highly recrystallized to calcite spar, thereby, reveal no microstructural properties. Their diagnostically coiled shells (which are much larger than foraminifers) range from highly spired (large whorl translation along their coiling axis) to nearly planospiral, which are much rounder and flatter (little whorl translation). Two species of gastropods are identified from the Little Valley Limestone: Bellerophon sublaevis Hall and Streophostylus carlexanus Hall. They range in size from 1.0 to 3.5 mm (Plate 8).

Intraclasts/Extraclasts

Intraclasts are reworked carbonate particles from a previous weakly lithified substrate within the basin of deposition. In the Little Valley Limestone they are subrounded to angular, elongate, sometimes dolomitized, lime mud particles probably produced by dessication and/or wave and current activity in a low intertidal and supratidal environment. They range in size from 0.5 to 3.5 mm.

Extraclasts are similarly defined except that they are derived from a source area outside the depositional basin. Extraclasts here are black, highly carbonized ooids and clusters of cemented ooids which range in size from 0.1 to 0.5 mm (Plate 9). The conspicuously dark color of the ooids and their remnant spar cement, in contrast to the other much lighter allochems and cements, allows for easy identification. In addition, the dark extraclasts occur together with terrigenous particles, particularly quartz and feldspar fragments. According to Flugel (1982), distinct color differences along with siliciclastic associations are indicative of extraclasts.

Other Constituents

Conodonts

Conodonts within the Little Valley Limestone are light-to-dark brown (in plane light) cones or serrated bars which range in size from 0.5 to 2.0 mm and contain faint concentric inner laminations (especially in their basal areas). Due to their calcium phosphate composition, conodonts are isotropic in polarized light. Conodonts are most commonly associated with black carbonaceous shales of the



PLATE 8. Photomicrograph of gastropods (1.5 mm in maximum dimension).

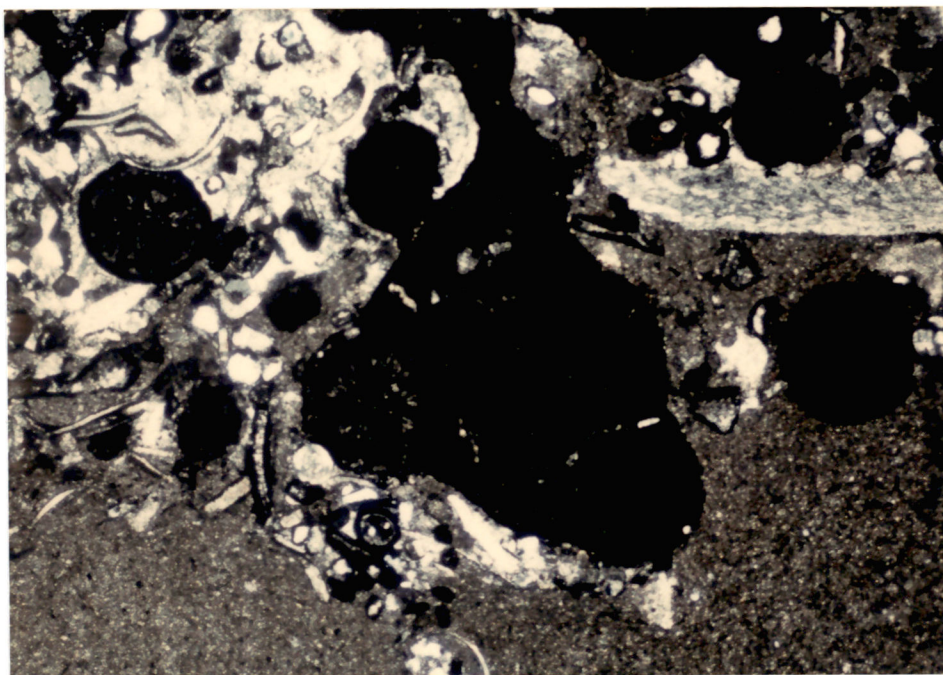


PLATE 9. Photomicrograph of ooid extra- intraclasts (0.5 mm in diameter) containing darker spar cement.

upper Little Valley Limestone.

Plant Fragments

Plant fragments are black, carbonaceous and/or pyritized particles which have fibrous to netted morphologies. According to Horowitz and Potter (1971), preservation of plants or plant fragments occurs from the infiltration of numerous mineral types, especially calcite, quartz and pyrite, into internal porosity or molds. Within the Little Valley Limestone the plant fragments are primarily preserved through pyritization, allowing only gross morphologies to be identified.

ORTHOCHEMS

Orthochems are precipitates, recrystallized sedimentary components and replacement minerals formed by direct chemical action within a depositional basin or diagenetically within the sediment. The Little Valley Limestone is characterized by many orthochems, but microspar, dolomite and silica are predominant.

Microspar

Microspar is one of the most prominent matrix components in the Little Valley Limestone, occurring diagenetically by the aggradational neomorphism of micrite and/or one step neomorphic calcitization of aragonitic mud to microspar (Lasemi and Sandberg, 1984). Microspar is distinguished from micrite by its slightly larger crystal size (0.005 to 0.01 mm) and its higher birefringence. Microspar crystals are

anhedral containing irregular crystal boundaries, especially when in contact with micrite and/or phyllosilicate muds. Therefore, microspar texturally creates a tightly cemented grumous fabric characterized by a patchy mixture of various sized constituents. Microspar predominates in lime mudstone, lime wackestone, and calcareous mudrock microfacies.

Dolomite

Two distinct types of dolomite occur in the Little Valley Limestone: (1) large, euhedral crystals ranging in size from 0.025 to 0.5 mm and associated with gypsum and anhydrite, and (2) finely disseminated to densely packed (crystal supported) anhedral dolomite which is generally less than 0.25 mm in size and commonly situated within lime mudstones, wackestones, packstones and calcareous mudrock microfacies.

The large euhedral dolomite most common in the lower Little Valley Limestone is classified using Gregg and Sibley's (1984) textural classification into idiotopic-E and idiotopic-P dolomite. Idiotopic-E dolomite is characterized by nearly uniform euhedral rhombs which are crystal supported and contain terrigenous muds in open intercrystalline areas. Idiotopic-P dolomite is characterized by euhedral crystals suspended in a matrix of terrigenous mud gypsum and anhydrite.

Fine-grained dolomite most common in the upper Little Valley Limestone (not associated with the evaporites) is characteristically anhedral and texturally classified (again according to Gregg and

Sibley's classification) into (1) xenotopic-P, finely dessiminated and clustered anhedral dolomite (dolomicrospar) suspended in micrite and muds; and (2) xenotopic-A, tightly packed anhedral dolomite crystals with covered and pitted crystal boundaries. Within the Little Valley Limestone, xenotopic-P dolomite frequently surrounds siltier units or zones (laminations or burrows) within lime mudstones. Xenotopic-A dolomite is most commonly associated with lime wackestones and packstones (Plate 10).

Syntaxial Overgrowths

Syntaxial overgrowths are early diagenetic cements which are in optical continuity with a carbonate particle. Within the Little Valley Limestone syntaxial overgrowths (which occur mostly on echinoderm fragments) are restricted to the lime grainstone microfacies where they are commonly associated with other fresh water phreatic cements, particularly bladed and blocky spar which coarsen towards the center of the pore (Longman, 1980). Though syntaxial, bladed and blocky cement occur together, syntaxial cements predominate the interparticle area. In rare instances, syntaxial overgrowths include two or more echinoderm fragments forming a poikilotopic cement (Plate 11).

Bladed and Blocky Spar

Bladed and blocky spar cements of the Little Valley Limestone are most characteristic of lime grainstone and packstone microfacies. Within interparticle pore spaces the cementation sequence progresses from an isopachous, nonferroan, bladed spar into an equant, sometimes

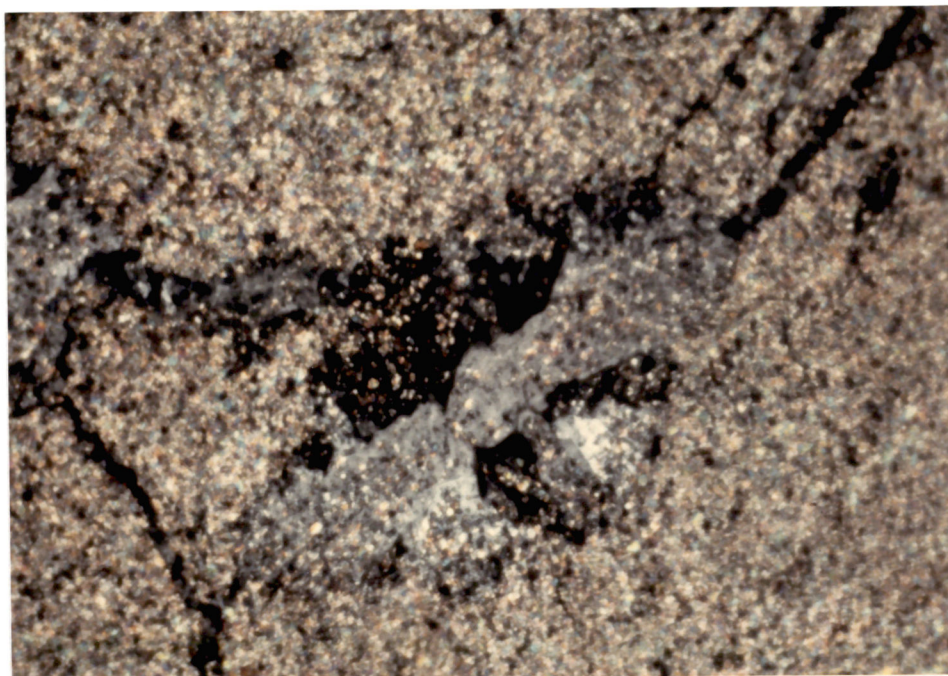


PLATE 10. Photomicrograph of finely disseminated xenotopic-P dolomite associated with gypsum. 1 cm = 0.25 mm.

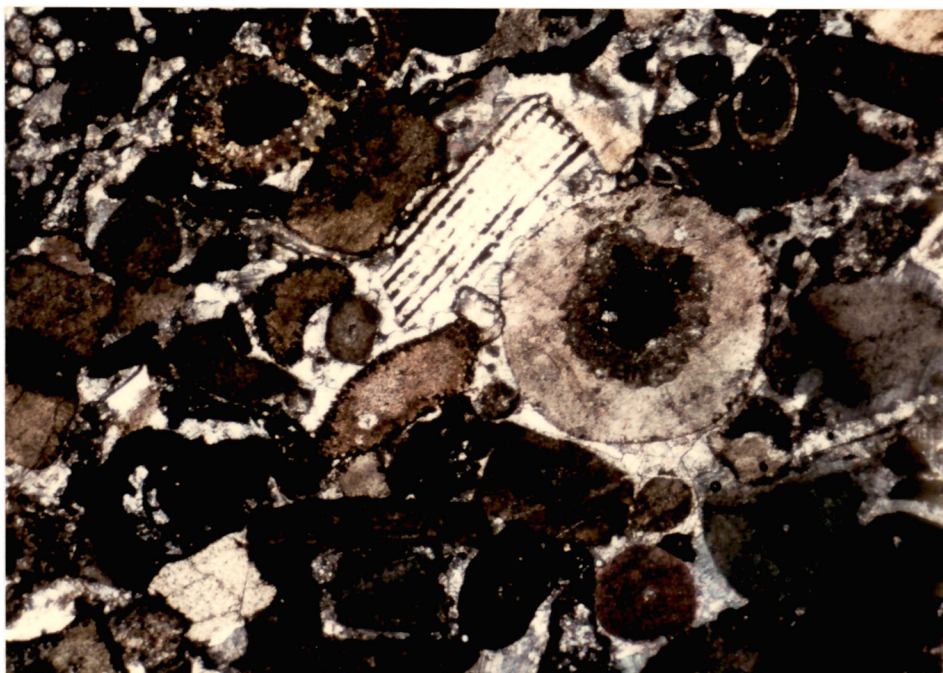


PLATE 11. Photomicrograph of a syntaxial overgrowth on a echinoderm fragment. Echinoderm 0.7 mm in diameter.

ferroan, blocky spar. The isopachous bladed spar precipitated first around allochems as relatively equant xenotopic crystals ranging in size from 0.02 to 0.1 mm. Towards interparticle pore centers, bladed crystals grade to equant blocky spar. Equant blocky calcite crystals are fine-to-medium crystalline (0.062 to 0.5mm), hypidiotopic to xenotopic, and increase in size towards the pore center.

Silica

Silicification is pervasive in the Little Valley Limestone. Most samples have silica partially or completely replacing some allochems. Although rare, some samples have complete silicification of both allochems and matrix forms chert nodules and/or bands.

Silica replacement of allochems is usually in the form of chert and megaquartz. Depending on type of allochem, composition and microstructural characteristics, distinct replacement textures occur (Kuslansky and Friedman, 1981; Schmitt and Boyd, 1981; and Neal et al., 1984). Fibrous calcitic microstructure in brachiopods and bryozoans is commonly replaced by subhedral megaquartz and chert. The megaquartz and chert usually mimic the fibrous microstructural characteristic by nucleating and replacing the calcitic layers parallel to the elongate axis of the megaquartz. Echinoderms most commonly contain spotted, circular chert nucleations in their single calcite crystal composition. According to Kuslansky and Friedman (1981), calcite nucleations selectively replace echinoderms along the calcite crystals cleavages, thus attributing to silica's spotted nucleations (Plate 12).

Where silicification of both allochems and matrix has occurred, chert and megaquartz are predominating forms of silica, although chalcedony also occurs (Plate 13). Chert nodules and bands within the Little Valley Limestone protrude from the unit's weathered surfaces, and are located stratigraphically above calcareous sand and siltstones.

Secondary Gypsum

Secondary gypsum occurs through the hydration of original (primary) anhydrite. The preserved anhydrite is characteristically nodular or "chicken wire" form. Hydration obliterates nearly all original morphology. The two prominent gypsum textures within the Little Valley Limestone include: (1) prophyroblastic and (2) alabastrine (similar to Holliday's 1970 terminology). The prophyroblastic gypsum is anhedral to euhedral containing corroded anhydrite relics. It creates no volume increase. This form of secondary gypsum forms during early diagenesis (Holliday, 1970). Recently, secondary gypsum has been found forming penecontemporaneously in anhydrite deposits of the Trucial Coast (Shearman, 1978).

Alabastrine secondary gypsum shows a variety of textures due to some degree of lattice disorder associated with hydration. This form of gypsum was most common in the Little Valley Limestone and can be subdivided into two types of alabastrine, which are texturally gradational between each other: (1) individual "feathery" gypsum grains in which poorly defined crystals have undulose or irregular

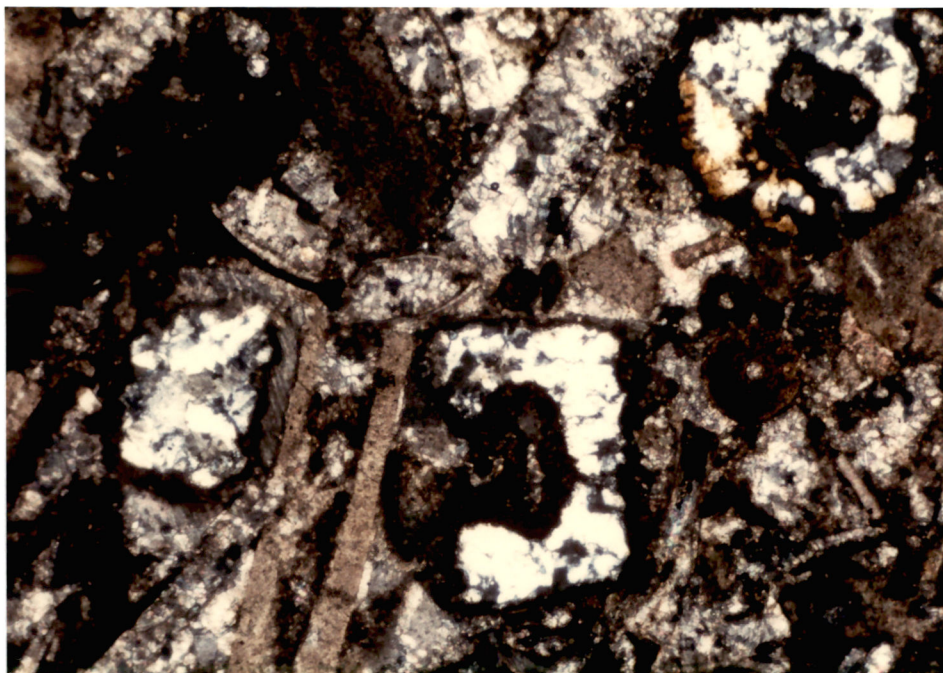


PLATE 12. Photomicrograph of silica nucleations on an echinoderm fragment (0.7 mm in maximum dimension).



PLATE 13. Chert nodules exposed on weathered outcrop surface.

extinctions, and (2) granoblastic secondary gypsum with interlocking (curved or reentrant boundaries), well defined, anhedral, but equidimensional grains. Alabastrine gypsum forms during a late stage of diagenesis associated with hydration by near surface ground waters (Plate 14).

Framboidal Pyrite

Pyrite framboids (FeS) are microscopic, spheroidal aggregates of pyrite which normally form in clusters. Pyrite framboids are common to all lithofacies within the Little Valley Limestone, although they are most abundant in darker lime mudstones and calcareous mudrocks. Coalescence of framboids ordinarily occurs in both matrix and allochems. Dense clusters of framboids primarily exist in sheltered pore spaces under convex upward allochems. Although rare, complete pyritization of allochems and algal laminations also occurs (Plate 15).



PLATE 14. Photomicrograph of secondary alabastrine gypsum and a satin spar gypsum vein. 1 cm = 0.25 mm.

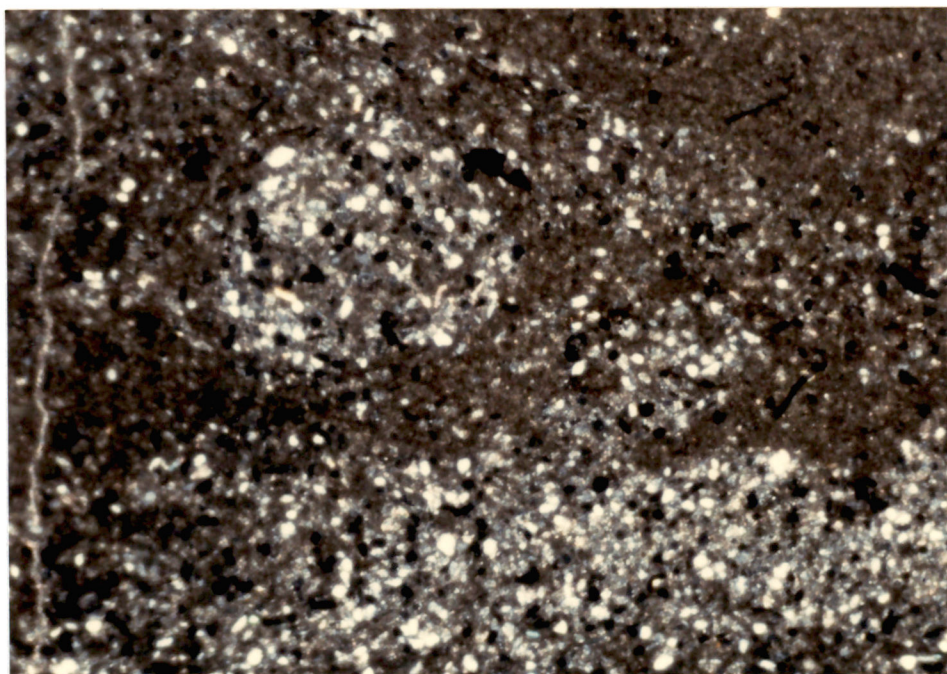


PLATE 15. Photomicrograph of disseminated pyrite framboids in a lime mudstone. 1 cm = 0.25 mm.

MICROFACIES

INTRODUCTION

A microfacies, as defined by Flugel (1982), is the comprehensive classification of thin sections, peels and polished slabs, paleontological and sedimentological components. More specifically, this includes allochems, matrix, cements, fabrics and textural characteristics of the particles, and fossil types including their associated structures and fossil associations. Because limestones are highly susceptible to neomorphic crystallization, diagenetic alterations such as mineralogical replacement and cementation are included in microfacies descriptions.

Microfacies in this study include the most abundant lithologic types according to Dunham's classification. Thus, frequency of matrix and/or cements, and particle types are the distinguishing factors for different microfacies (Appendix C). Microfacies within the Little Valley Limestone are subdivided into two classes: (1) carbonate microfacies, which only include rocks with greater than 50% carbonate material and (2) noncarbonate microfacies which only contain rocks with less than 50% carbonate material (Table 1). The carbonate microfacies compose the majority of the Little Valley Limestone and include lime mudstones, wackestones, packstones and grainstones; while noncarbonate microfacies include calcareous muddy sandstone, calcareous mudrocks, and secondary gypsum. A graphical comparison of the percentage of microfacies constituents is presented in Figure 7. Within this section, specific diagenetic characteristics corresponding to particular microfacies are characterized.

SUMMARY OF MICROFACIES POINT COUNT DATA (TOTAL AVERAGE PERCENT)

TABLE 1

Carbonate Microfacies

Lime Mudstone Microfacies

Matrix—————	88.0%
Allochems—————	2.0%
Terrigenous Sand—	10.0%
	<u>100%</u>

Lime Packstone Microfacies

Matrix—————	35.0%
Allochems—————	57.5%
Terrigenous Sand—	2.8%
Calcite Spar————	4.7%
	<u>100%</u>

Lime Wackestone Microfacies

Matrix—————	73.4%
Allochems—————	19.8%
Terrigenous Sand—	5.6%
Calcite Spar————	0.2%
	<u>100%</u>

Lime Grainstone Microfacies

Matrix—————	3.3%
Allochems—————	60.3%
Terrigenous Sand—	4.7%
Calcite Spar————	31.7%
	<u>100%</u>

Noncarbonate Microfacies

Calcareous Muddy Sandstone Microfacies

Matrix—————	28.0%
Allochems—————	5.0%
Terrigenous Sand—	58.8%
Calcite Spar————	8.2%
	<u>100 %</u>

Calcareous Mudrock Microfacies

Matrix—————	82.3%
Allochems—————	3.3%
Terrigenous Sand—	13.4%
Calcite Spar————	1.0%
	<u>100%</u>

Secondary Gypsum Microfacies

Matrix—————	32.0%
Evaporites—————	68.0%
	<u>100%</u>

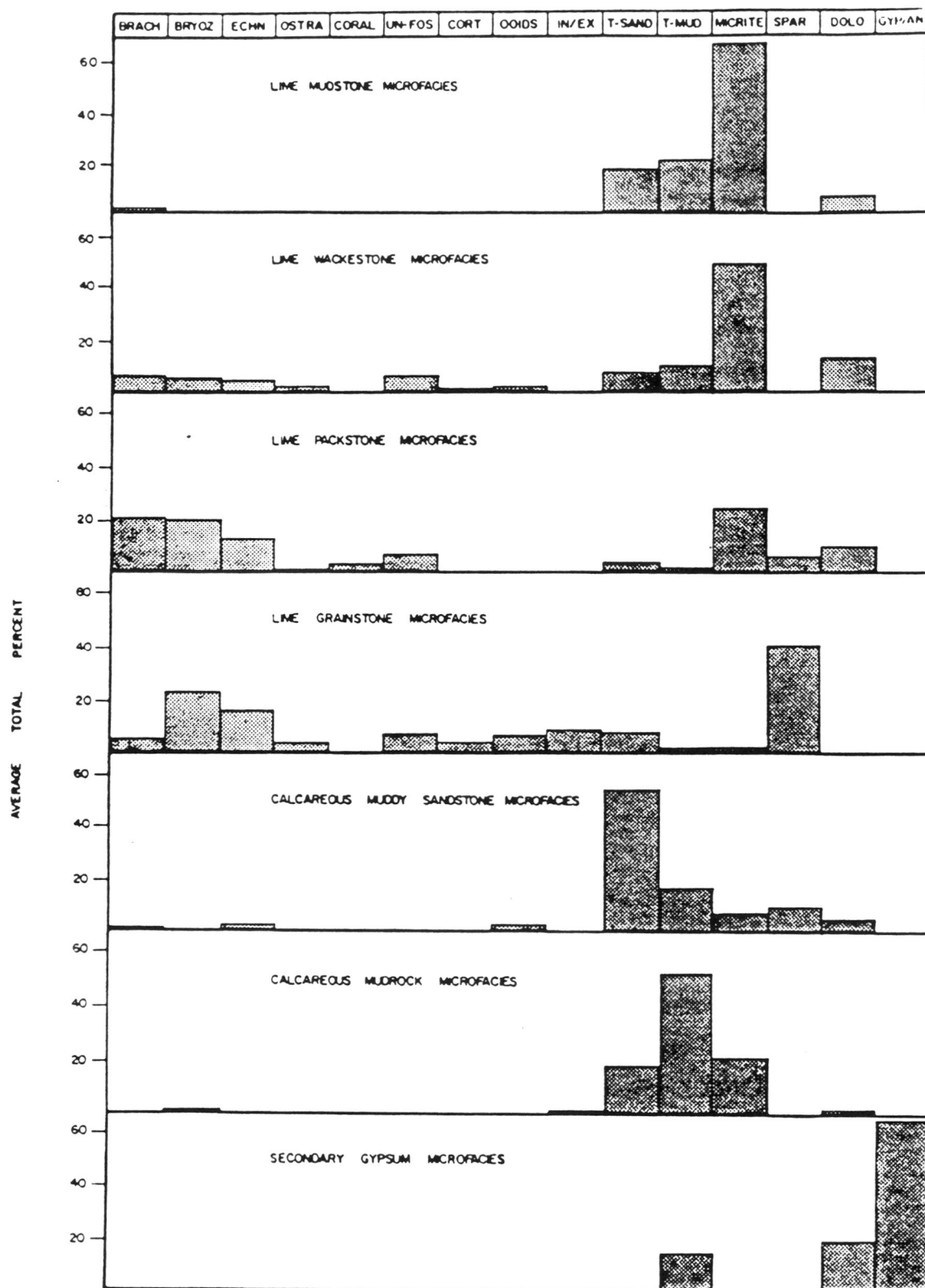


Fig. 7. Average total percentage of constituents of each microfacies.

LIME MUDSTONE MICROFACIES

The lime mudstone microfacies consists of 88% matrix, 2% allochems, 10% very fine sand-sized quartz and feldspar and trace amounts of pyrite, spar cement and plant fragments. One lime mudstone sample in the lower Little Valley Limestone contains 3% gypsum. The matrix is predominantly composed of microspar/micrite (68%), phyllosilicates (15%) and mud sized (0.02 mm and less) dolomite (4.8%). The microspar/micrite commonly has a grumose texture, and comprises the majority of this microfacies, ranging from 34% to nearly 96% of any given sample. Dolomite and phyllosilicate muds compose only 30% of the rock. Allochems comprise a small percentage of this microfacies where brachiopods, bryozoans and echinoderms predominate. These fossils are preferentially oriented preferentially parallel to bedding in condensed zones (zones composed almost entirely of fossils and fossil fragments) and/or sparsely disseminated throughout the matrix.

Two prominent types of lime mudstone occur within this microfacies: (1) a light gray, cryptalgally laminated and/or silty laminated, bioturbated, argillaceous lime mudstone containing disseminated fossils and localized gypsum accumulations; and (2) a dark gray, cryptalgally-to-finely laminated, fossiliferous, bioturbated lime mudstone containing disseminated and condensed zones, where fossils are oriented parallel to bedding (Plates 16 and 17). Based on composition and stratigraphic position, a subdivision of this microfacies into shallow intertidal and deeper subtidal deposits



PLATE 16. Algal laminated lime mudstone.

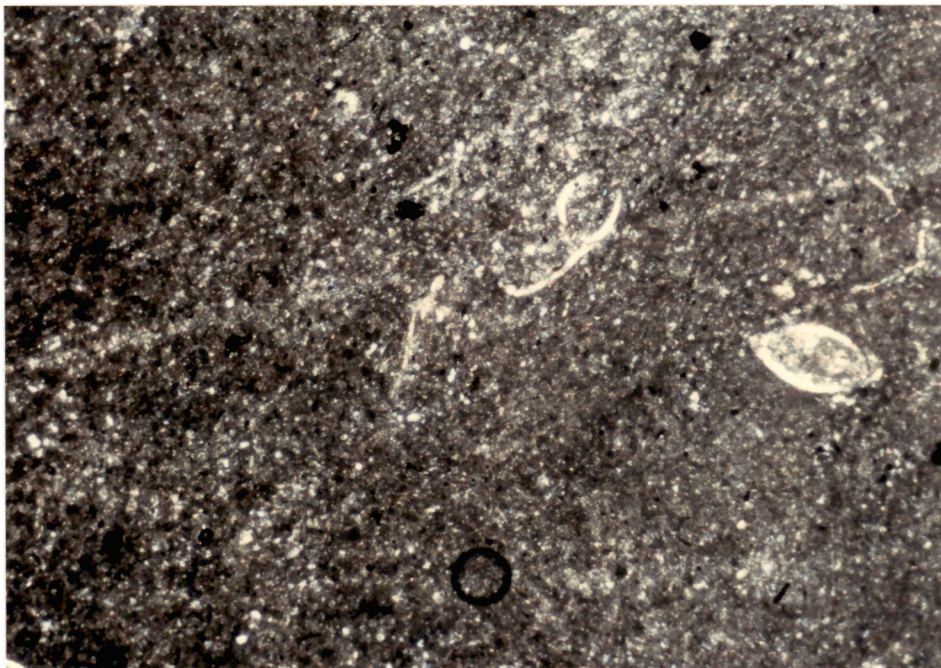


PLATE 17. Photomicrograph of ostracodes (0.25 mm in maximum dimension).

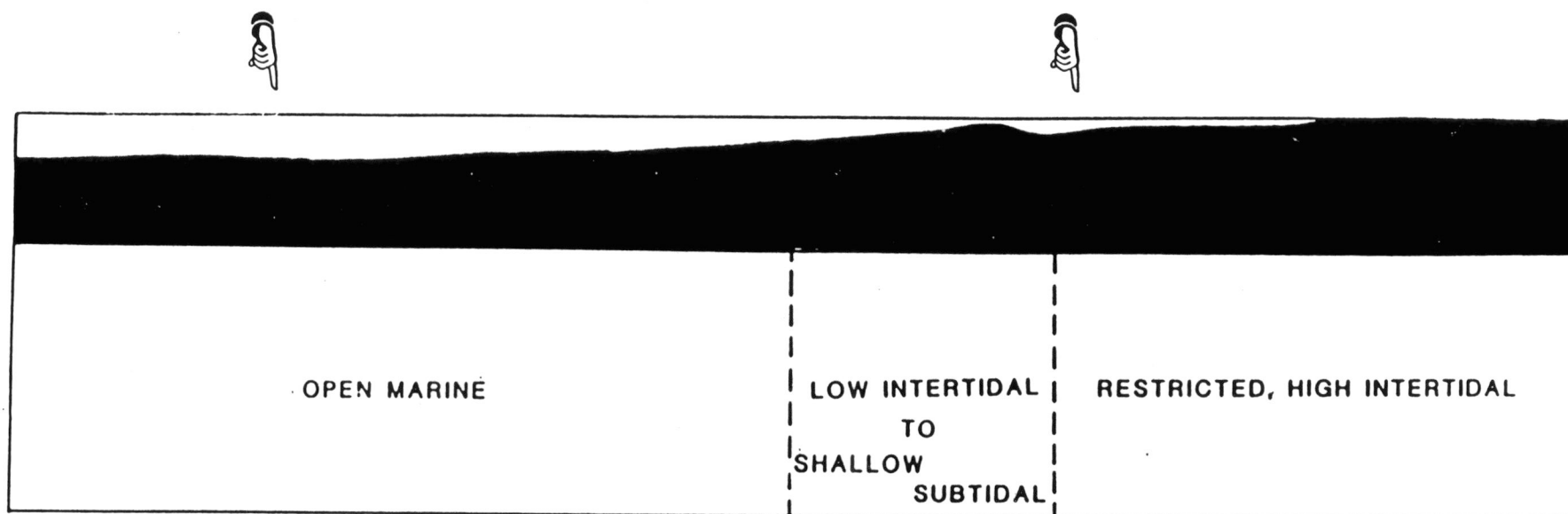


Fig. 8. Location of the lime mudstone depositional environments.

(corresponding to Wilson's (1975) standard microfacies (SMF) numbers 19 and 20, respectively) is possible (Fig. 8).

Lime mudstones, associated with the lower Little Valley Limestone, are virtually unfossiliferous (except for an occasional fossil fragment and/or algae), argillaceous and silty, and represent an intertidal mixed carbonate-siliciclastic mudflat. Irwin's (1962) model of epeiric, clear-water sedimentation applies to this study in that slightly fossiliferous lime mudstones are classified as shallow intertidal deposits. He suggested that the lack of fossils is due to poor water circulation associated with a diminished nutrient supply. Blue green algae, however, can survive in this type of environment. He considered the restricting mechanism to be very shallow water conditions which promote unstable environmental conditions. The shallow water depth also aids in dissipation of wave and current activity allowing muds to accumulate, although higher energy pulses must have occurred in order for very fine sand and silt layers to be deposited.

Within the Little Valley Limestone this type of lime mudstone is usually located stratigraphically above or interbedded with unfossiliferous, calcareous, very fine grained, ripple laminated sandstones and siltstones that represent shoaling intertidal deposits. Stratigraphically below the lime mudstones are unfossiliferous, calcareous siltstones and algal-laminated dolomitic mudstones containing bedded evaporites (gypsum, anhydrite, and halite). These deposits are interpreted as a low intertidal-supratidal deposit.

The stenohaline fauna, especially brachiopods, bryozoans, and

echinoderms, found in these lime mudstones are derived from open marine, subtidal environments, while the in situ fauna (identified by life positioning and well preserved delicate structures) is composed almost exclusively of ostracodes, which are cosmopolitan. The ostracodes are smooth shelled varieties found most commonly in restricted marine environments (Benson, 1961). Therefore, the combined faunal and lithologic characteristics of this lime mudstone, along with stratigraphically adjacent lithologies, indicate a restricted, shallow water, mixed siliciclastic- carbonate intertidal environment. Similar intertidal lime mudstone environments exist in the Upper Mississippian Newman Group in east- central Kentucky (Ettensohn, 1975) and in the Greenbrier Group within the Hurricane Ridge Syncline of southwestern Virginia (Blancher, 1974).

The second lime mudstone associated with the upper Little Valley Limestone, contains horizontally laminated, terrigenous clays and silts, with 1) large disseminated fossils and 2) smaller preferentially oriented fossils within condensed zones. Although the overall percentage of allochems within this microfacies is low, samples within condensed zones contain more than 65% of the fossils within the microfacies. Predominant fossils include brachiopods, bryozoans and echinoderms. Although ostracodes are not abundant, they are pervasive in these lime mudstones. Disseminated in a fine grained matrix, large productid brachiopods and fenestellid bryozoans characteristically retain their delicate skeletal components (spines and fronds, respectively), suggesting in situ accumulation in a quiet

water environment. Stromatolitic algae and vertical burrow structures are locally significant within this microfacies. In the past, the presence of stromatolitic algae was misinterpreted as a diagnostic indicator of an intertidal environment, despite other atypical intertidal characteristics (abundant biota). Monty (1977) discounted the limitation of stromatolites to intertidal environments stating that during the Paleozoic and Mesozoic, stromatolites also grew in open marine, fauna-rich subtidal environments, such as lagoons, shelves and reefs.

Condensed zones of fossils, sedimentary boudinage structures and the lack of very fine sand and silt sized quartz grains are highly suggestive of a quiet water, subtidal environment. Condensed fossil zones are interpreted as storm deposits which swept biota out of shallower, highly fossiliferous subtidal environments into more restricted environments. Flugel (1982) and Wilson (1975) recognized similar discontinuity planes associated with condensed faunal zones in deeper marine environments. Sedimentary boudinage structures occur due to differential compaction (in this case between argillaceous lime muds and purer lime muds). This type of structure has been recognized by Wilson (1969, 1975) as a deeper marine deformational feature. Finally, the lack of silt or larger sized detritus (quartz grains in particular) characterizes a quieter, deeper water marine environment (Heckel, 1972). A deeper water (further offshore) environment lacks the water energy to retain the silt and sand sized particles in suspension, so they must have been deposited inshore before reaching this environment.

Stratigraphically bordering these lime mudstones above are fossiliferous lime- packstones and wackestones, which are associated with a rich stenohaline fauna typical of open marine subtidal environmental conditions. Interbedded with the lime- packstones, wackestones and mudstones is a 70 cm bed of highly organic black shale which contains sparse fossil fragments (mostly brachiopods and echinoderms) and an abundance of conodonts. The constituents of the black shale and its stratigraphic position between marine lime- packstones and mudstones suggests a subtidal environment with anoxic bottom water conditions. The semi-restricted, reducing nature of the upper lime mudstone is suggested by its dark color (preserved organic matter) and a high percentage of pyrite. The upper lime mudstone biota, sedimentary structures and lithologic associations are interpreted to represent a deeper subtidal, semi-restricted shelf or lagoonal environment which remained within the photic zone.

The lime mudstone microfacies of the Little Valley Limestone has undergone a complex and variable diagenetic history which includes: neomorphism of both matrix and allochems, various generations of spar cement growth infilling intraparticle pore spaces, dolomitization, silicification, pyritization, continuous and discontinuous irregular stylolitization and calcite vein, microfault and gypsum vein formation.

LIME WACKESTONE MICROFACIES

The lime wackestone microfacies consists of 73.0% matrix, 19.0% allochems, 6.0% quartz and feldspar grains, 1.0% spar cement and 0.3%

organic material. The matrix is composed of microspar/micrite (46.3%), dolomite (14.2%) and phyllosilicate muds (8.0%). Micrite/microspar range from a high of 75.3% to trace amounts in certain samples. Dolomite ranges from a high of 49% to zero in individual samples. Only a few samples contain terrigenous muds, however, when present, they sometimes comprise 25% of the sample (Plates 18 and 19).

The allochems represent approximately 19% of this microfacies and include brachiopods (5.1%), bryozoans (4.2%), echinoderms (3.3%), unidentifiable fossil fragments (3.2%), ostracodes (1.3%), ooids (1.3%), and cortoids (1.0%). Foraminifers, conodonts, trilobites and intraclasts are also present though combined they comprise less than 0.5% of this microfacies. Although foraminifers only appear as a small percentage of the total microfacies, they compose as much as 4.0% of individual samples. The larger fossils within this microfacies are usually broken and abraded. Overall, preferential alignment of elongate fossils parallel to bedding is common, especially when they are broken and abraded.

Quartz and feldspar grains are subrounded to subangular, moderately sorted and range in diameter from 0.025 to 0.5 mm. Quartz is always more abundant than feldspar. The exact composition of the feldspar grains is impossible to determine optically because of their size. Albite twinning suggests that they are some type of plagioclase.

Spar cement is rare within this microfacies occurring in only



PLATE 18. Cored section of a typical lime wackestone (5.0 cm in diameter).



PLATE 19. Photomicrograph of a lime wackestone. 1. cm = 0.25mm.

one sample. The spar is composed of nonferroan calcite, comprises approximately 12% of that sample and is found within the siltier zones.

Organic fragments make up only a small portion of this microfacies, but individual samples may contain as much as 2.0% organic matter. These fragments are highly carbonized and/or pyritized and are thought to be plant fragments. Structurally, these fragments contain a netted fibrous network with an irregular outline.

Environmentally, the lime wackestone microfacies is closely related to Wilson's (1975) standard microfacies (SMF) numbers 8 and 9, representing a shelf environment with open water circulation. The predominance of brachiopods, bryozoans and echinoderms combined with a high percentage of mud is indicative of a subtidal, shelf environment with open circulation. Brachiopods, bryozoans and particularly echinoderms thrive in normal marine conditions (stenohaline); Horowitz and Potter, 1971; Heckel, 1972; Tucker, 1981; and Flugel, 1982) associated with efficient water circulation. Both brachiopods and echinoderms can exist in environments associated with soft substrates and relatively high accumulations of mud (Tasch, 1973). Bryozoans, however, prefer a firm substrate. Bryozoans probably used accumulations of brachiopod and echinoderm skeletal debris as the substrate on which they developed.

The dominant component of this microfacies is matrix, which comprises nearly 75% of the rock. Lower energy, tranquil water is necessary for the accumulation of fine-grained matrix material. These muds were deposited into deeper (or protected) portions of a shallow

marine shelf subject to constant temperatures and salinities. Therefore, they were able to sustain a more diverse biota as long as currents replenished nutrients and kept the bottom oxygenated. Fossil orientation within this microfacies is highly suggestive of moderate wave and/or current activity (Fig. 9).

The lime wackestone microfacies contains a variety of diagenetic modifications. The major diagenetic alterations include: silicification, stylolitization, spar infilling, neomorphism of both allochems and matrix, dolomitization, microfaulting, pyritization, calcite veins and micritic enveloped gypsum replacement.

LIME PACKSTONE MICROFACIES

The lime packstone microfacies is consists of 35% matrix, 56% allochems, 5% spar cement and 3% fine-to-medium quartz and feldspar sand. The matrix predominantly consists of microspar/micrite (23.4%), dolomite (9.8%) and terrigenous muds (1.8%). Microspar/micrites range from a high of 75% (although still grain supported) to only trace amounts. Dolomite crystals are subhedral to anhedral and 0.04 mm and less in size. Dolomite ranges from only trace amounts to a high of 46%. Terrigenous mud is rare within this microfacies.

The allochems account for greater than half of the constituents of the lime packstone microfacies. Three major allochems comprise nearly 50% of this microfacies: brachiopods (21%), bryozoans (19%) and echinoderms (10%). Other allochems, including bivalves, ostracodes, trilobites, foraminifers, corals, conodonts, gastropods, ooids,

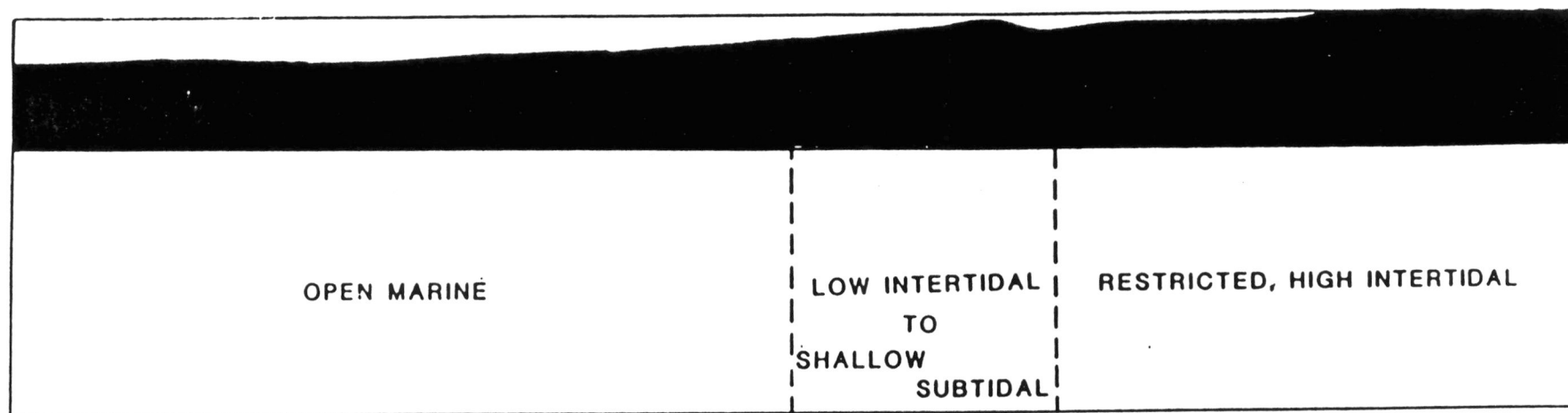


Fig. 9. Location of the lime wackestone depositional environment.

cortoids and intraclasts, individually make up less than 1% and combined approximately 2% of this microfacies. Ooids occasionally comprise greater than 5% of a particular sample. Allochems are mostly benthic sessile varieties which range from whole and well preserved to highly broken and abraded. Elongate allochems are preferentially oriented parallel to bedding.

Spar cement is a minor component in this microfacies, although a few samples exceed 30% spar. The spar cement is composed of 0.03 to 0.5 mm long bladed to drusy calcite crystals, which rarely form syntaxial overgrowths and poikilotopic cements on echinoderm fragments.

Quartz and feldspar grains are subrounded to subangular, poorly sorted and range in size from 0.025 mm to 1.0 mm. Some of the quartz grains suggest metamorphic source terrains due to their polycrystalline, semi-composite nature and their strong undulose extinction. Chert grains are also commonly associated with quartz. Feldspar within this microfacies is considered to be from the plagioclase group because it contains albite twinning. No feldspar compositional determinations were made because of the lack of a statistically valid sample. Within packstones, quartz is more abundant than feldspar or chert. Although quartz and feldspar grains make up only a small percentage of this microfacies, some samples contain nearly 23% quartz and feldspar.

Sedimentary features within this microfacies include ripple-laminations, moderate sorting, preferential orientation of elongate allochems, graded bedding and geopetal structures, all of which are

indicative of shallow subtidal environments influenced by wave or current activity.

Environmentally, the lime packstone microfacies within the Little Valley Limestone is most similar to Wilson's (1975) standard microfacies 5, which he locates on a shelf bordering a shoaling environment. This microfacies is interpreted as a shallow subtidal (at or below wave base), normal marine deposit, as evidenced by its large percentage of fossils, the majority of which are stenohaline varieties (brachiopods, bryozoans, echinoderms and corals) (Fig. 10). Another feature indicative of this environment is increased diversity and slightly lower predominance of the biota in this microfacies as compared to the microfacies previously discussed. Lithologies are characterized by an abundance of fossils which are larger, grain supported and associated with a lime mud matrix. Similarly, Tyrrell (1969) found the shallow shelf-edge environment of the Capitan Formation to consist of lime- wackestones, packstones and boundstones which commonly contain large skeletal material (pebble sized and larger) in a fine grained matrix. The distinctive Capitan shelf-edge biota includes red algae, bryozoans, and calcareous sponges, with brachiopods, crinoid debris and foraminifers being common. To a lesser extent, corals and trilobites are also present. Heckel (1972) also characterized deep water environments which are well oxygenated and below wave base as having diverse biota (sand sized or coarser) within a mud matrix (Plates 20 and 21).

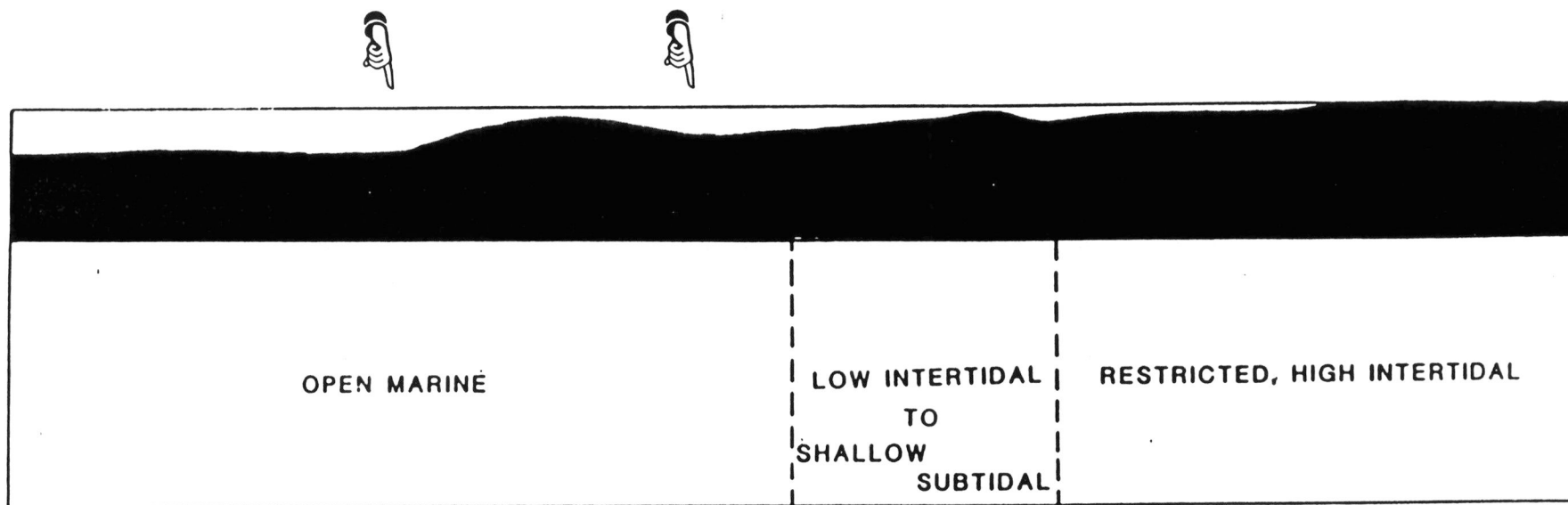


Fig. 10. Locations of the lime packstone depositional environments on either side of the carbonate shoal.



PLATE 20. Cored section of a brachiopod bearing lime packstone (5.0 cm in diameter).

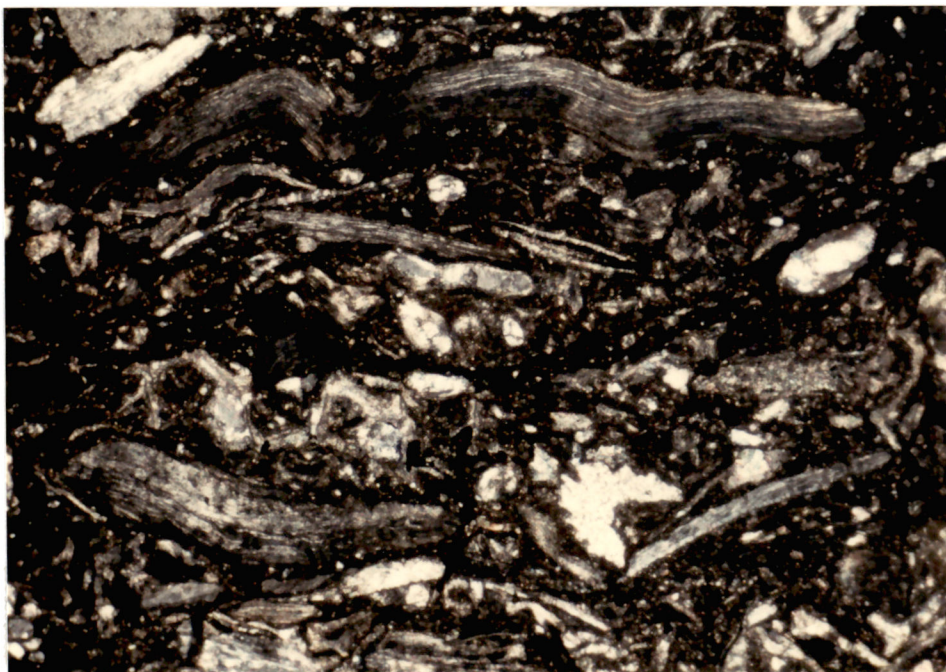


PLATE 21. Photomicrograph of broken and abraded allochems common to lime packstones. 1 cm = 0.4 mm.

This microfacies exhibits a complex diagenetic history comprising various types of alteration. The major processes of diagenesis include: silicification, neomorphism of both allochems and matrix, infilling of intra- and interpore areas by spar, dolomitization, pyritization, calcitic veins and stylolitization.

LIME GRAINSTONE MICROFACIES

The lime grainstone microfacies consists of 3.0% mud-sized material (0.0625 mm and less), 60% allochems, 32% spar cement and 5% very fine sand and silt sized quartz and feldspar. The mud sized material is composed of both micrite and siliciclastics. Major allochems include bryozoans (21%), echinoderms (15%), intraclasts (6%), brachiopods (4.5%), unidentifiable fossil fragments (4%), ooids (3%), cortoids (2%), and ostracodes (2%). Other allochems individually and combined comprise less than 1% of this total microfacies, and include trilobites, foraminifers, bivalves and gastropods.

Allochems are large with a predominance of robust forms ranging in size from 0.05 cm to greater than 5.0 cm. Fossils are generally well preserved, although some are broken and abraded. Elongate allochems are preferentially oriented parallel to bedding. Sorting of allochems and the quartz and feldspar grains is bimodal, such that allochems are 0.5 mm and greater whereas quartz/feldspar grains range from 0.15 mm to 0.25 mm.

Quartz and feldspar grains are subrounded to subangular and moderately to well sorted. The assemblage of quartz, feldspar and

trace amounts (less than 1%) of chert grains is highly suggestive of a metamorphic source terrain. Furthermore, quartz grains are both polycrystalline and monocrystalline and exhibit undulose extinction. Feldspar grains commonly exhibit albite twinning and are considered to be within the plagioclase group (no compositional determination was made due to insufficient sample size). Quartz is much greater in abundance than feldspar.

Spar cement is a major component, composing nearly one third of rocks in this microfacies. Spar usually occurs in a three generation progression into open pores spaces: (1) fibrous, (2) bladed and (3) drusy or blocky. Occasional poikilotopic spar cements form syntaxial overgrowths on echinoderm grains.

Environmentally, the lime grainstone microfacies within the Little Valley Limestone is interpreted as a very shallow subtidal deposit, most similar to Wilson's (1975) standard microfacies SMF - 11 (agitated shoal environment) (Fig. 11). Indicators of this environment include broken and abraded allochems, thicker and larger shelled (greater than 0.625 mm), more robust forms of fossils (especially bryozoans and ostracodes), decrease in brachiopods (inhospitable sessile environment), increase in corals, ooids and intraclasts, and siliciclastic sands.

In shallower water zones (within reach of effective wave base) higher water energies inhibit mud accumulation, allowing sand sized and coarser material to settle out. A lack of detrital influx allows largely skeletal debris from a relatively diverse fauna to be concentrated by water agitation. Typically, skeletal material becomes

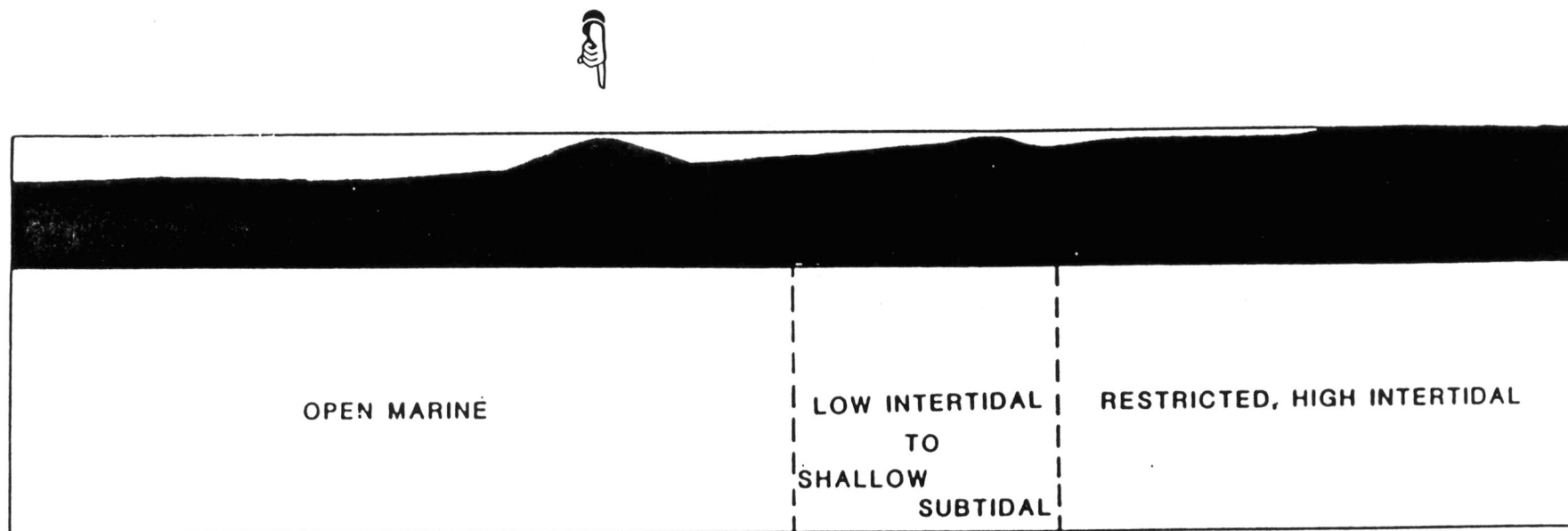


Fig. 11. Location of the lime grainstone depositional environment.

more robust, especially in bryozoans and ostracodes, with increasing water agitation in order to protect against high wave energy. Many fossils are fragmented and abraded, showing moderate to poor rounding and sorting. The decrease in sessile-benthic fauna requiring stable substrates suggests an inability to adapt to the high energy conditions. This is particularly reflected in the brachiopods, which significantly decrease in abundance within this facies.

Increases in cortoids (allochems containing micritized coatings due to boring endolithic algae), ooids and intraclasts also suggest increased water agitation. According to Flugel (1982), cortoids can be used in microfacies determination as evidenced by distribution patterns of ancient shelf reef carbonates where cortoids occur preferentially in lime grainstones of high energy, shallow shoal environments. Ooids and intraclasts similarly originate within higher energy conditions where at least periodic strong water movements occur. Siliciclastic matrix within this microfacies is generally free of mud-sized material. According to Heckel (1972) both abraded calcarenites and quartz sand collect in zones of agitated water above wave base where abrasion of large grains and winnowing of fine grains occurs (Plates 22 and 23).

Diagenetic alteration within this microfacies is similar to the other microfacies. Neomorphism of both allochems and micrite, progressive growth of spar (fibrous, bladed to blocky) in intraparticle pore spaces, silicification of allochems, partial pyritization of allochems, syntaxial overgrowths, micrite envelopes,



PLATE 22. Cored section of a echinoderm bearing lime grainstone (5.0 cm in diameter).



PLATE 23. Photomicrograph of a lime grainstone. 1 cm = 0.25 mm.

localized stylolites, calcite veins and localized dolomitization of spar.

CALCAREOUS MUDDY SANDSTONE MICROFACIES

The calcareous, muddy sandstone microfacies is positioned within the lower section of the Little Valley Limestone and consists of approximately 28% matrix, 5% allochems, 58% terrigenous very fine to fine sand-sized grains, 8.2% spar and trace amounts of organic fragments and pyrite. Gypsum was encountered in two samples within this microfacies, in one of which it constitutes just less than 10% of the total sample. The matrix is predominantly composed of phyllosilicates, including clay minerals and muscovite (19%), micrite/microspar (5.8%) and dolomite (3.5%). Illite and chlorite (as determined by x-ray diffraction), comprise the majority of the phyllosilicates in this microfacies. Muscovite grains are characteristically elongate flakes containing fourth order interference colors and ranging in size from 0.03 to 0.06 mm. Micrite/microspar is seen as very fine grains comprising a grumose texture. Dolomite (xenotopic-P) is the least significant matrix component. Its distinguishing features include subhedral and anhedral crystals which range in size from 0.01 to 0.05 mm and do not stain when subjected to Alizarin Red S stain.

The most prominent allochems include ooids (2%) and echinoderms (1.4%). Brachiopods, bryozoans and trilobites comprise less than 2% of this microfacies. Ooids, the most abundant allochem of this microfacies, are characteristically highly recrystallized (containing

a radial axial texture) and range in size from 0.3 mm to 0.5 mm. Their nuclei are either quartz or plagioclase grains, although an occasional echinoderm fragment can also be recognized.

Echinoderms are the second most abundant allochem and the most abundant fossil type within this microfacies. The echinoderms present are fragmented plates and ossicles which are recognized by their porous microstructure and their unit extinction in polarized light. The brachiopods, bryozoans and trilobites are generally highly fragmented and abraded, although rarely, large brachiopods also are present.

Terrigenous sand sized grains, which include quartz, chert and feldspar, comprise greater than half of this microfacies. The quartz grains are the predominant constituent, comprising greater than 55% of this microfacies. Quartz grains are subrounded to subangular, moderately to well sorted and range in size from 0.075 mm to 0.2 mm. The quartz grains are generally monocrystalline and contain strong to moderate undulose extinction. Trace amounts of biotite and subhedral grains of zircon are also present. Chert comprises only 1.5% of the microfacies. Chert grains are subrounded to subangular, ranging in size from 0.5 mm to 0.75 mm. Within this microfacies feldspar grains are the least abundant of the terrigenous sand grains, comprising just over 0.5%. Feldspar grains are subrounded to subangular, albite twinned and range in size from 0.075 mm to 0.1 mm.

Spar cement is common to this microfacies where it grows in stages (bladed to blocky) or forms poikilotopic cements. Both ferrous

and nonferrous calcite varieties of spar exist, with nonferroan being the most common. In some instances, calcitic spar has been partially to totally dolomitized, with preservation of the pre-existing crystal forms.

Although not abundant, gypsum is present within this microfacies, characteristically in satin spar veins (associated with remobilization) and/or within calcite veins. Depositional forms of gypsum or any other evaporite mineral were not observed within this microfacies.

The depositional environment for the calcareous muddy sandstone microfacies within the Little Valley Limestone is a shallow intertidal environment most similar to Wilson's (1975) standard facies belt 8 (Fig. 12). Specific lines of evidence within this unit which suggest this type of environment include ripple marks, tangential crossbedding, highly fragmented and abraded allochems, sparse occurrences of ooids, low fossil content, interbedded terrestrial muds and sands, cryptalgal laminations, high bioturbation and pyritized plant fragments. Stratigraphically adjacent lithologies include underlying algal-laminated, dolomitic and terrigenous mudrocks with mudcracks and evaporites, interpreted as high intertidal or supratidal flat deposits; and overlying semi-restricted shelf lagoonal deposits associated with lime- mudstones and wackestones containing a less restricted biota.

The sedimentary structures and the abundance of sand-sized siliciclastic components are sedimentologically characteristic of shallow, agitated water conditions in which the substrate is above

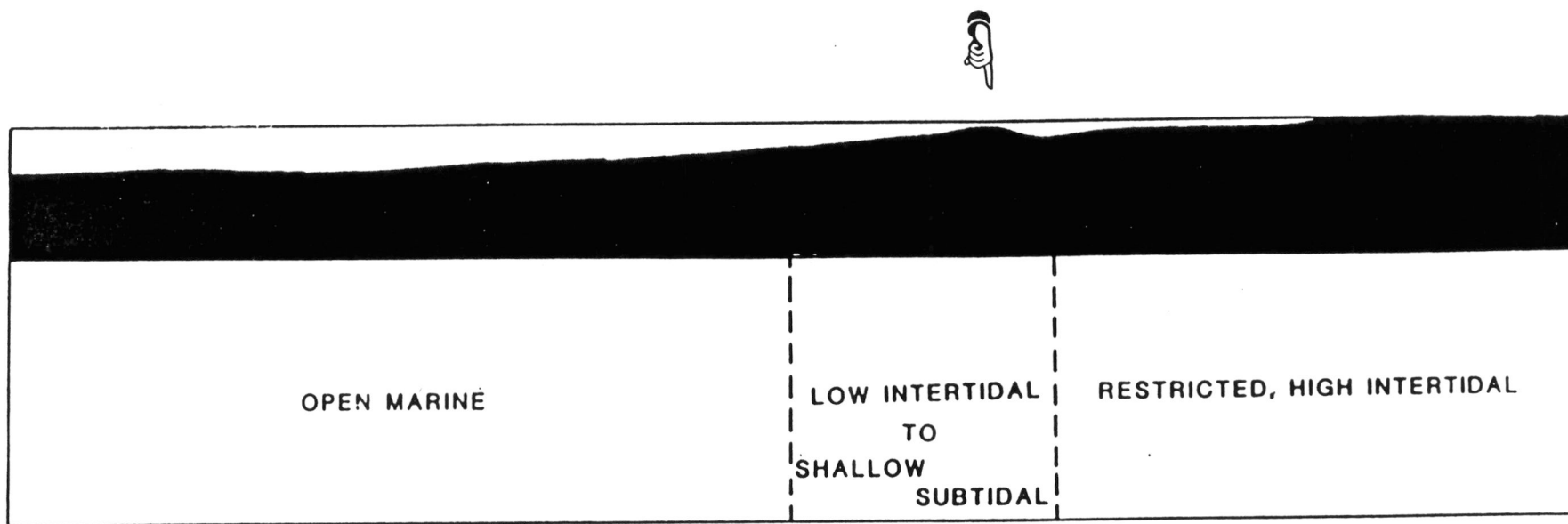


Fig. 12. Location of the calcareous muddy sandstone depositional environment.

wave base. Although rare, due to extensive bioturbation, ripple laminations are present, averaging approximately 5.0 cm in wave length and 1.0 cm in amplitude. The ratio of sand sized grains to mud-sized grains is 2.25 to 1.0. Although there is nearly 30% mud-sized material within this microfacies, it should be noted that muds are generally concentrated in thin beds, ranging in thickness from 0.05 cm to 2.5 cm. This interbedded relationship of sands and muds suggests deposition from nonuniform water energies (discontinuous competency) such that higher energy pulses are associated with winnowing fines and deposition of coarser material, whereas waning energy episodes allow fine grained material to settle out of suspension.

Fossils, although rare within this microfacies, are primarily restricted to muddy interbeds within the sands, although highly fragmented and abraded brachiopods and echinoderms are found within the sands. The muddy units are characterized by brachiopods, bryozoans, ostracodes and cryptagal laminations. The overall lack of biota within this microfacies suggests stressed environmental conditions associated with intense water agitation, and/or major salinity fluctuations. More common to this microfacies are plant fragments which are usually completely pyritized. The plant fragments suggest relatively nearshore environments (Flügel, 1982). Bioturbation is extensive within this microfacies where vertical burrows have nearly or completely homogenized the sediments. Therefore, increase of quartz sand and phyllosilicate mud, decrease in marine faunal diversity and increase in plant material imply a

barrier in close proximity to the coastline (Flügel, 1982) (Plates 24 and 25).

The calcareous muddy sandstone microfacies is diagenetically characterized by partially silicified allochems, syntaxial calcitic overgrowths of echinoderms, neomorphism of micrite and allochems, partially pyritized allochems, dolomitization of allochems (especially brachiopods and bryozoans) and cement, localized stylolites, bladed to blocky poikilotopic spar cements, ferroan calcitic spar cements, calcite veins (some gypsum associated with them), gypsum interpore areas and micro-normal faulting (displacement of 2.5 mm).

CALCAREOUS MUDROCK MICROFACIES

The mudrock microfacies consists of 82% matrix, 3.3% allochems, 13% quartz sand and trace amounts of spar and organic fragments. The matrix consists of phyllosilicates (61%) and micrite/microspar (20%). Dolomite (1.4%), is never present in high concentrations but is found throughout the microfacies.

The phyllosilicates are dominated by terrigenous clays. Illite and chlorite were identified by x-ray diffraction. Muscovite is also present, composing approximately 2% of this microfacies. Muscovite is found as elongate, bladed grains exhibiting fourth order interference colors and ranging in size from 0.03 to 0.06 mm. Generally, muscovite grains are oriented with their elongate axes parallel to bedding.

Micrite is dark brown-to-gray and lacks any birefringence, whereas microspar has similar colors (although lighter) but has slightly

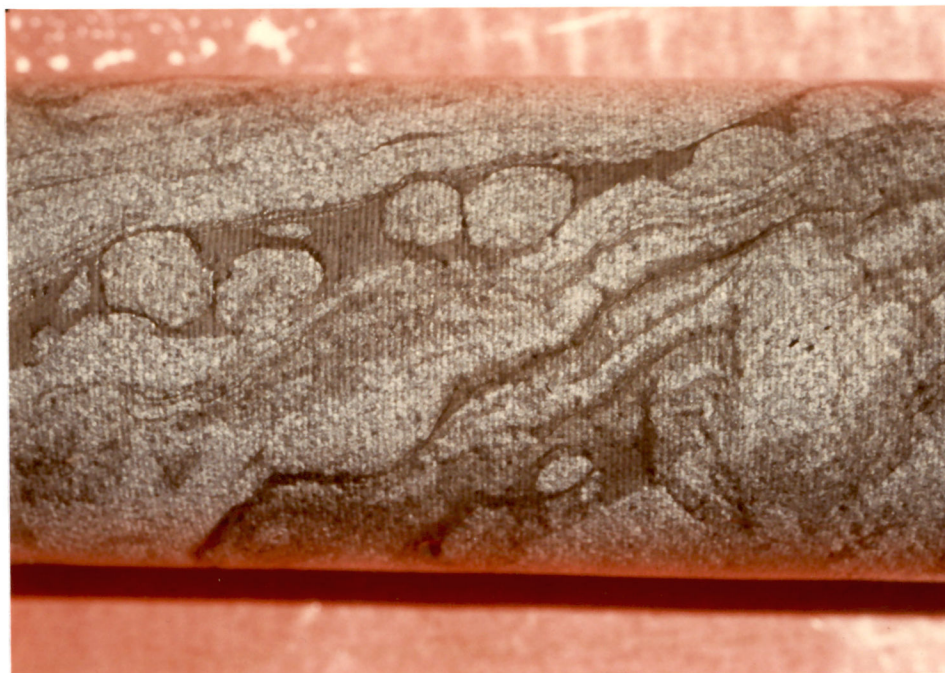


PLATE 24. Cored section of a bioturbated, muddy calcareous sandstone (5.0 cm in diameter).

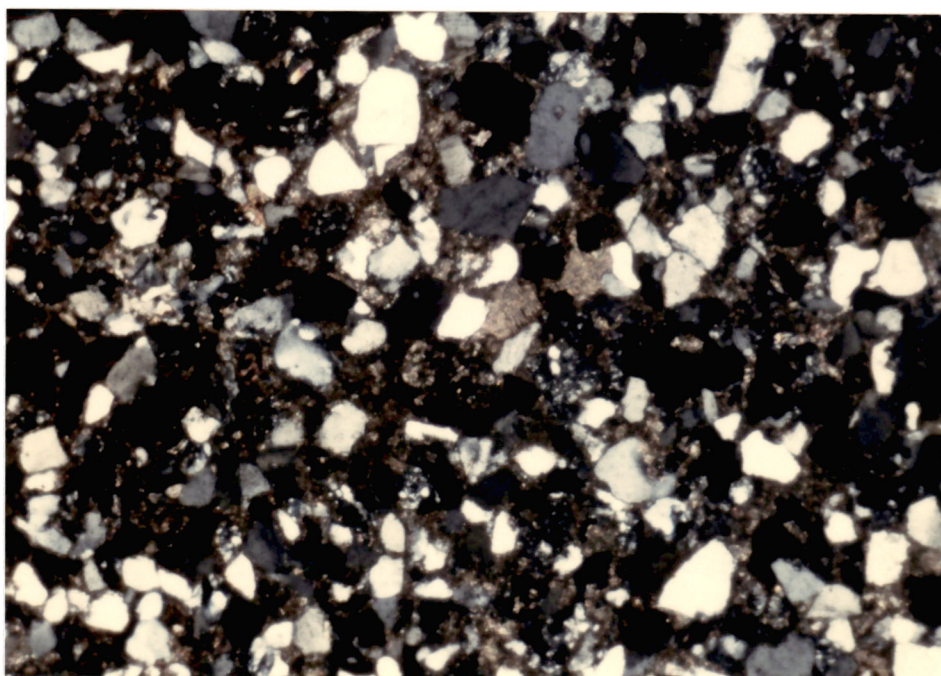


PLATE 25. Photomicrograph of a calcareous muddy sandstone.
1 cm = 0.25 mm.

higher birefringence. A grumose texture is observed. Dolomite is the least abundant matrix constituent even though it is present in nearly all samples. Non-ferroan dolomite is characteristic of this microfacies. Dolomite is finely disseminated through the matrix as very fine, anhedral crystals which are approximately 0.02 mm and less in size.

All the allochems individually comprise less than 1.0% of this microfacies. Bryozoans (fenestrate varieties) are the most abundant, making up 0.6%. Echinoderms, although composing only a small percentage of this microfacies (0.3%), are present in most samples. Allochems are generally whole and well preserved, although some are broken and abraded.

Quartz is subrounded to subangular, moderately to well sorted and ranges in size from 0.02 to 0.1 mm. Monocrystalline quartz is most abundant, and most of it has an undulose extinction. Nonferroan calcite spar is rare, making up less than 1.0% of this microfacies. Spar is primarily associated with siltier zones (especially burrow structures) where it infills interpore areas.

Plant fragments are also rare, composing less than 1.0% of this microfacies. Although plant fragments are completely pyritized, an elongate, finely netted microstructure is still observable. The plant fragments are restricted to the calcareous mudrock of the lower (rather than the upper) Little Valley Limestone where they comprise only a small percentage of the total rock, but they are present in most samples.

The calcareous mudrock microfacies of the Little Valley Limestone are representative of two different environments based on both compositional and adjacent lithologic and/or microfacies differences. The lower calcareous mudrocks are associated with the lower section of the Little Valley Limestone, where it is interbedded with the lower lime mudstone microfacies.

The environmental interpretation of the lower calcareous mudrock microfacies is a shallow intertidal, mixed siliciclastic-carbonate mudflat (Fig. 13). This environment is most similar to Wilson's (1975) standard microfacies belts 23 and 19. The overall lack of fauna, with the exception of smooth shelled ostracodes, and the predominance of algal laminations suggest shallow water (within the photic zone), restricted marine conditions (Heckel, 1972; Wilson, 1975; and Flugel, 1982). The presence of ripple marks, interbeds of mud and silt-sized material, dolomitic rip-up clasts (thought to be derived from dessication features within the adjoining nearshore supratidal environment) and plant debris are considered indicators of coastal proximity. In this case, calcareous mudrocks were deposited in restricted marine conditions associated with very shallow water behind offshore sandy shoals. The combined effect of the outer sand barrier and shallow water depths caused dissipation of both wave and current activity and allowed for subsequent deposition of finer grained material. Silty interlaminations represent storm deposits where outer sands were swept landwards into the shallower, intertidal areas. The stratigraphically adjacent lithofacies of the lower calcareous mudrock include: 1) underlying low intertidal/supratidal

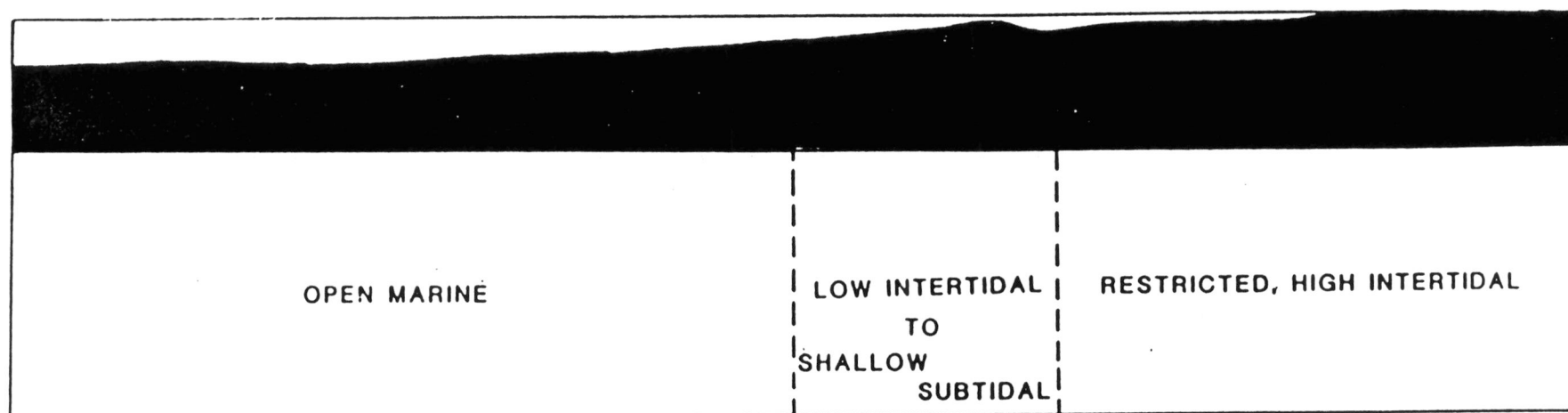


Fig. 13. Location of the calcareous mudrock depositional environment.

deposits associated with unfossiliferous siltstones and algal-laminated, dolomitic mudstones containing bedded evaporites; and 2) overlying calcarous, fine grained, ripple-laminated sandstones and siltstones representing a deeper water intertidal deposit.

The upper calcareous mudrock is associated with the upper Little Valley Limestone and is characterized by more than twice the number of fossil taxa and approximately half as much terrigenous silt and/or sand-sized material as the lower mudrock. The upper calcareous mudrock is much darker colored and contains more micrite. Conodonts and other phosphatic intraclasts are also found within the upper mudrock, while plant fragments are no longer present. The upper calcareous mudrock's stratigraphically adjacent lithofacies and/or microfacies are also very different from these of the lower calcareous mudrock. Underlying units, lime wackestones and lime mudstones containing a relatively diverse stenohaline fauna are interpreted as an innershelf, lagoonal facies. The overlying lithofacies including lime wackestones, packstones and limited grainstones associated with a diverse normal marine fauna, is interpreted as a subtidal, open marine environment (at or near wave base). Based on compositional and lithofacies environments, the upper calcareous mudrock is interpreted to represent deeper, semi-restricted subtidal shelf environments, similar to the lime mudstone microfacies of the upper Little Valley Limestone. A modern analogy to this environment exists behind the Florida reef tract in the Hawk Channel (a localized depression in the continental shelf) and in lows across the Great Pearl Bank of the

Persian Gulf (Scholle et al., 1983).

Generally, the upper calcareous mudrock is dark gray in color. This unit also contains small localized chert nucleations which are randomly dispersed. A single 0.5 meter unfossiliferous, black fissile shale containing conodonts and scattered fish scales is found interbedded with the mudrock. The deposition and preservation of this black shale can only occur under reducing conditions, such as an anoxic environment in which oxygenating processes have ceased destruction of organic matter and/or iron sulfide. Oxygenated bottom waters are caused by effective current movement, and inhibition of this current activity causes a change in circulation of oxygenated waters. Two possible mechanisms explaining loss of circulation include: (1) density stratification where less dense (lower salinity) water flows on top of more dense (higher salinity) water, thus stopping vertical water movement and promoting the development of anoxic bottom water conditions; (2) a topographic barrier, such as a bar or mound, the migration of which interrupts a previously developed circulation pattern and causes a diversion of oxygenated waters from a particular area, which eventually stagnates. Similarly, Evans (1967) interpreted the black shales of the Pennsylvanian-aged Heebner Shale of Kansas and adjacent states to be a stagnated, deep-silled sea. He recognized a submarine barrier as a stagnating device which inhibited circulation across a portion of the mid-continent sea.

In summary, this calcareous mudrock microfacies can be subdivided into two distinctly different environments: (1) calcareous mudrocks of the lower Little Valley Limestone associated with marginal marine,

mixed siliciclastic-carbonate mud flats; and (2) calcareous mudrocks associated with semi-restricted shelf lagoons (Plate 26).

Diagenetically this microfacies is characterized by neomorphism of both allochems and matrix, dolomitization of both allochems and matrix, partial pyritization of allochems, interparticle pore areas infilled with bladed and blocky spar, partial to complete silicification of allochems and calcite veins.

SECONDARY GYPSUM MICROFACIES

The secondary gypsum microfacies consists of 32% matrix, 10% nodular anhydrite and 58% secondary gypsum. The matrix is primarily composed of dolomite (19.8%) and phyllosilicates (11.9%). Micrite is rare (present only in one sample), composing less than 1% of this microfacies. Dolomite crystals are subhedral to euhedral, contain an idiotopic-E texture and are 0.025 mm and less in size (although rare, some dolomite crystals range from 0.25 to 0.5 mm). Dolomite crystals are nonferroan and considered to be a primary depositional phase.

The phyllosilicates consist of muscovite and illite. Muscovite crystals are elongate and tabular, containing fourth order interference colors and ranging in size from 0.03 to 0.1 mm. Illite, with its 10 Å basal spacing, was recognized through x-ray diffraction procedures.

The evaporite minerals anhydrite (9.9%) and secondary gypsum (58%) comprise the majority of this microfacies. Anhydrite crystals are elongate and tabular, bedded or in nodules, exhibit fourth order

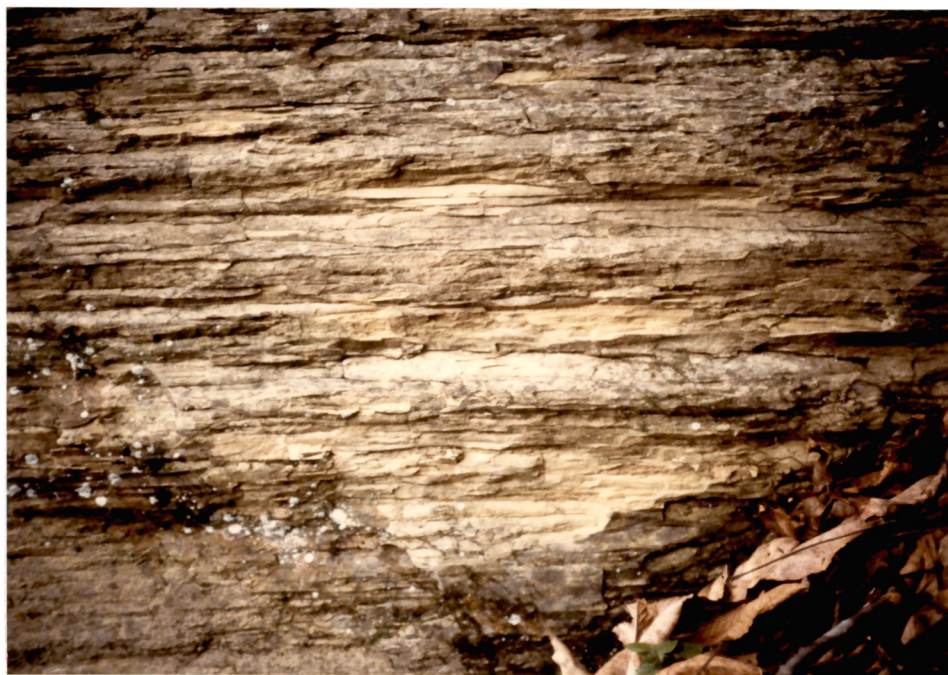


PLATE 26. Laminated calcareous mudrock.

interference colors, have pseudocubic cleavage and range in size from 0.02 to 0.06 mm. Although anhydrite is not the most abundant mineral within this microfacies, it is thought to represent the original depositional form of the evaporites. The exact origin of anhydrite (primary or secondary) is of question (Bush, 1973; Schreiber, 1978). Depositional characteristics have been altered by subsequent (late diagenesis) rehydration, thus allowing for the pervasive development of alabastrine secondary gypsum (Holliday, 1970). The gypsum grains are characterized by irregular extinctions, poorly defined grain boundaries and remnant corroded anhydrite inclusions. With these types of characteristics, the gypsum is considered to have a Type 1 hydration texture (Holliday, 1970) (Plates 27 and 28).

Environmentally this microfacies is interpreted as a high intertidal/supratidal deposit (Fig. 14). This microfacies is most similar to Wilson's (1975) standard microfacies 23. The nearly total lack of biota (except for algae), together with its stratigraphic positioning between 1) underlying red beds with much thicker and more complete evaporites of a sabhka environment (Maccrady Formation) and 2) an overlying mixed siliciclastic carbonate mudflat lithofacies, supply the necessary evidence for interpretation of this microfacies. Similarly, Presley and McGillis (1982) dolomites, evaporites and red beds of the Clear Fork and Glorieta Formations (Permian) of the Texas panhandle to be characteristic of nearshore and supratidal deposits along an arid coast.

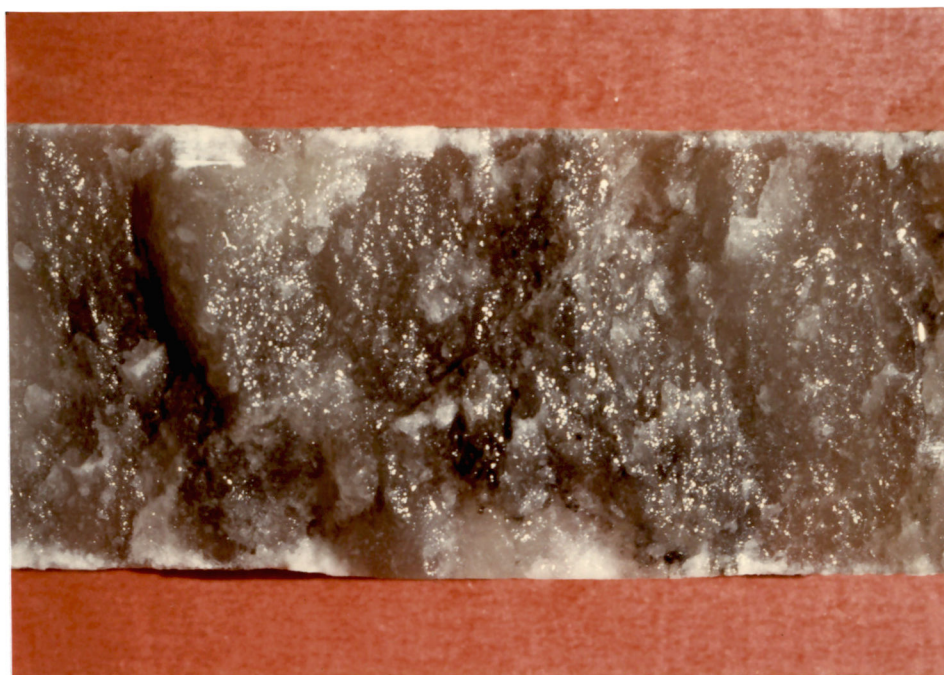


PLATE 27. Cored section of secondary gypsum and anhydrite (5.0 cm in diameter).

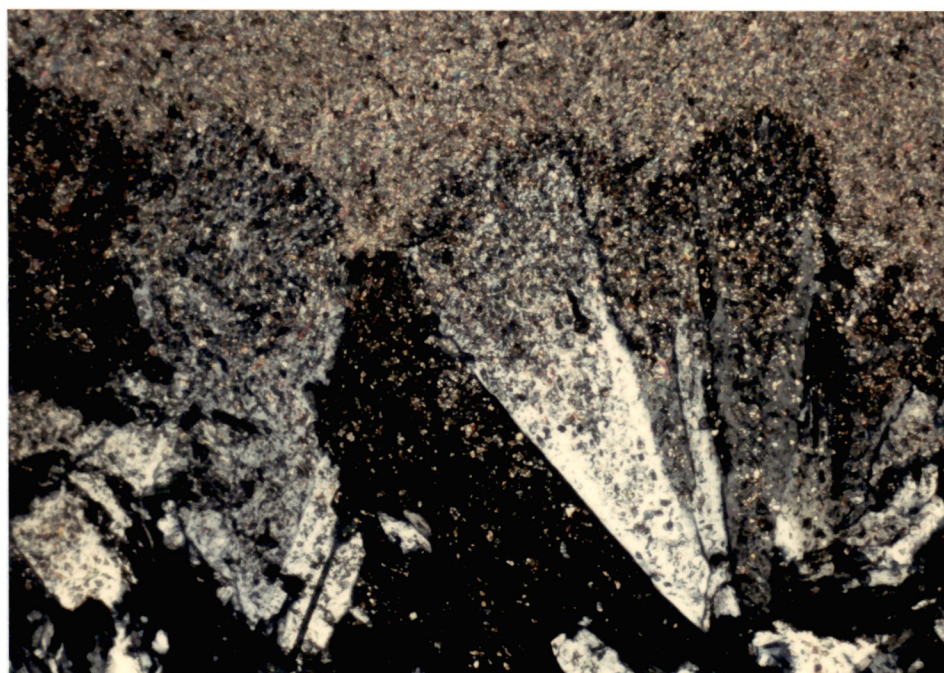


PLATE 28. Photomicrograph of the formation of secondary gypsum through the rehydration of anhydrite. 1 cm = 0.25 mm.

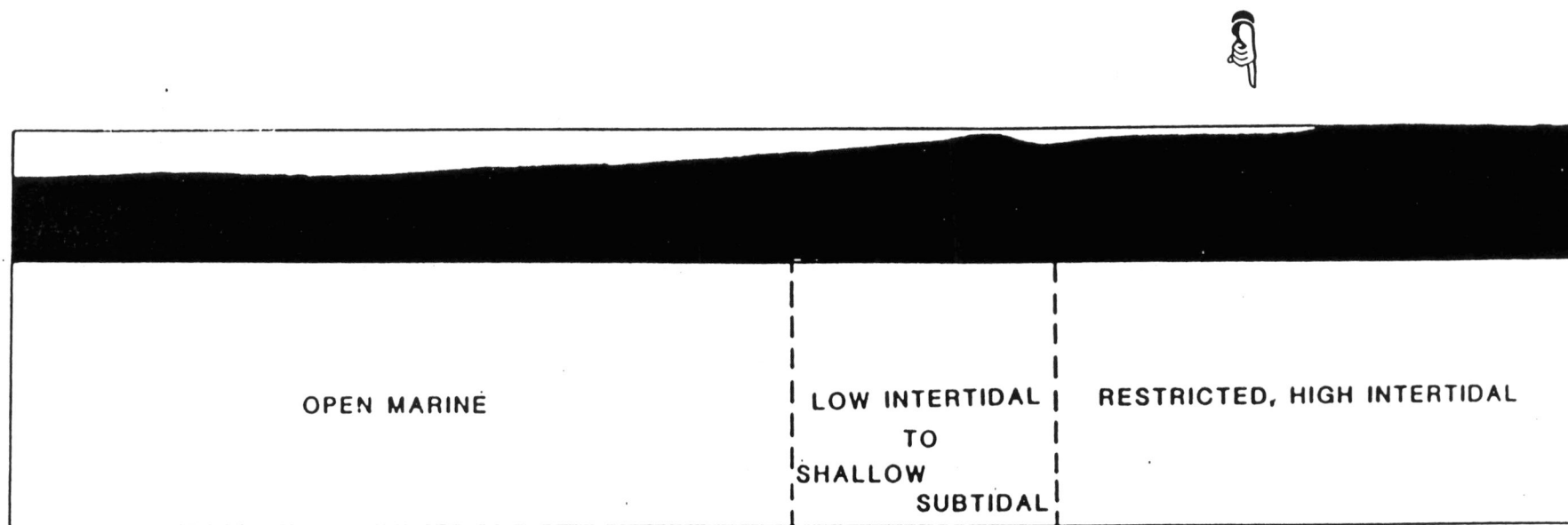


Fig. 14. Location of the secondary gypsum depositional environment.

DEPOSITIONAL ENVIRONMENTS

REGIONAL

The Appalachian Basin during early Meramecian time underwent a decrease in tectonic activity corresponding to a reduction of its eastern border lands (to lowlands) and flooding of the southern two thirds of the basin by a sea (DeWitt and McGrew, 1979). Rising seas entered the basin from the south and spread north along the basin axis and northwest along the shelf areas. Although tectonic quiescence prevailed during Meramecian time, subsidence exceeded terrigenous detritus influx (DeWitt and McGrew, 1979). This is recognized by 1) the sporadic occurrence of thin interbeds of shale and sandstone within thick limestone sequences in the eastern Appalachian Basin, and 2) the near absence of siliciclastic rocks in much of the shelf area to the west.

During the Warsaw Epoch, the Meramecian sea inundated the Greendale Syncline and surrounding areas, depositing Warsaw-aged lithologies the full length of the syncline from northeastern Tennessee to southwestern Virginia (Butts, 1940). Maximum water depths during mid-Meramecian time were associated with the St. Louis sea. The Greendale Syncline's lithofacies during the Meramecian consisted primarily of a thick accumulation of argillaceous and sandy carbonates derived from shallow marine shelf environments within a subtropical to tropical (15 degrees south latitude) climate (DeWitt and McGrew, 1979).

LOCAL

Based on lithologies (microfacies assemblages), biota and sedimentary structures, the Little Valley Limestone can be subdivided into three distinct depositional environments: (1) restricted, high intertidal mudflats to bordering supratidal sabkha; (2) low intertidal to shallow subtidal, siliciclastic shoal and; (3) open marine subtidal, shelf lagoon. Figure 15 shows the stratigraphic distribution of these environments through Washington County.

Environment 1 represents a restricted, high intertidal, mixed siliciclastic - carbonate mudflat bordering a supratidal sabkha. It comprises the uppermost Maccrady Formation and the lowermost Little Valley Limestone. This environment includes the secondary gypsum, lower lime mudstone and lower calcareous mudrock microfacies. As described in the previous section, these microfacies contain a restricted biota (generally ostracodes and algae) and shallow water sedimentary structures including ripples and horizontal to wavy (cryptalgal) laminations. Intermittent subaerial exposure occurred, as evidenced by dessication cracks and associated dolomitic rip-up clasts. Mineralogically, these microfacies have a high percentage of phyllosilicate muds, idiotope-E and-P dolomite, secondary gypsum and primary anhydrite.

The feature causing restriction for this environment is considered to be either an offshore siliciclastic bar or shoal associated with the destructive phase (inundation) of the pre-existing Virginia-Carolina deltaic complex. This shoal, a topographic high on a very shallow, broad shelf aided wave and current

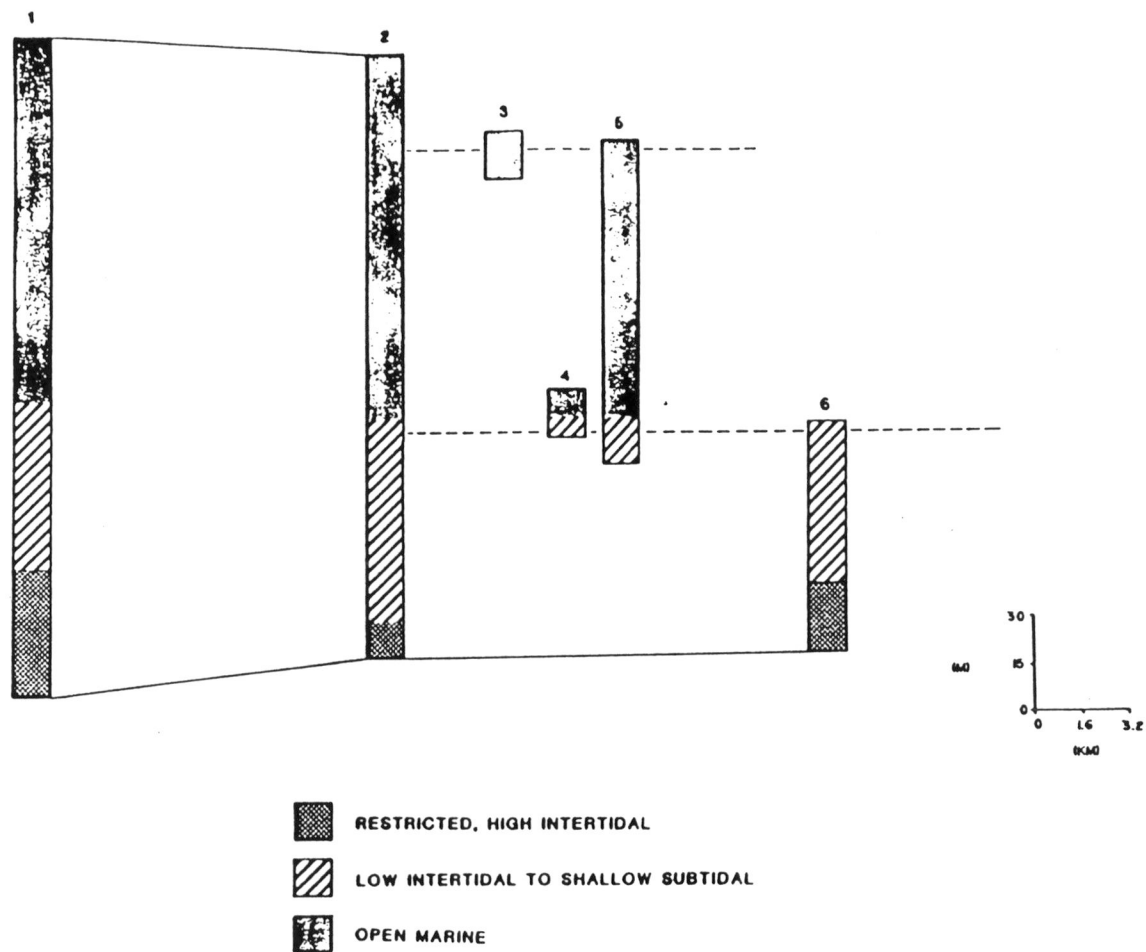


Fig. 15. Stratigraphic cross section of the depositional environments of the Little Valley Limestone through Washington County, Virginia.

dissipation. The decrease in water circulation caused by the shoal created low oxygen and nutrient concentrations within waters of the mudflat area. Therefore, the biota included only groups able to exist in stagnating water conditions. With continued restriction in back bar/shoal areas, hypersaline waters developed through evaporation and concentration of brines. When brines reached sufficiently high concentrations, anhydrite and gypsum precipitation occurred with anhydrite being the initial depositional form of evaporite. Precipitation of anhydrite occurred in thin beds and nodules, whereas gypsum occurred as small (0.1 to 0.5 cm) lensoid crystals, both of which are common in intertidal to supratidal evaporites similar to those of the Persian Gulf (Schreiber, 1978; Achauer, 1982). The evaporites were interbedded within algal-laminated, dolomitic, siliciclastic muds. Farther offshore, evaporites are replaced by interbedded lime mudstones and calcareous mudrocks. These lithofacies frequently contain thin (2.0 - 3.0 cm) silty beds suggestive of overwash of the outer shoal (barrier) area by storm surges that swept coarser grained siliciclastic material inland.

Environment 2, low intertidal to shallow subtidal, comprises the higher energy siliciclastic shoals and/or bar associated with the reworking of the Virginia - Carolina deltaic complex. Similar destructive deltaic morphologic features are described by Reading (1978) for the Nile and Ebro deltas. This environment includes the muddy calcareous sandstone and upper calcareous mudrock microfacies. These microfacies contain ooids, intraclasts and vertical burrows and

are characterized by a lack of skeletal debris. Ripple marks and cross-bedding are very abundant within these microfacies.

The subdivision of the marine shoal environment into two distinct microfacies signifies varying environmental conditions associated with 1) interbedded, relatively clean quartz sands and 2) phyllosilicate muds. This is thought to represent undulating shoal-surface topography where sands represent topographic highs subject to more turbulent water, while muds represent topographic lows in low energy water. Shoal migration is evidenced by the interbedded nature of these microfacies. Enos (1983) described similar microfacies relationships within shelf-intertidal shoals of Florida and Texas.

Additional evidence for a shoaling environment includes lithologies and sedimentary structures present in these microfacies. The calcareous sandstones are composed primarily of quartz grains which are moderate to well sorted, subrounded, ripple-laminated and cross-bedded. They represent bar crests and/or areas influenced by higher energy conditions. Ooids, although not very abundant in this microfacies, suggest shallow, agitated marine waters. Ooid formation in this environment was probably inhibited by conditions not conducive to for carbonate formation (high siliciclastic conditions). In contrast to the calcareous sandstones, calcareous mudrocks primarily are composed of rippled phyllosilicate muds associated with troughs or low energy areas (between the cleaner quartz sands). Within interlaminated terrigenous sand and mud zones bioturbation is extensive, dominated by vertical burrows which are generally associated with higher energy environments. Shoal-trough muds

contain the highest percentage of fossilized material, including brachiopods, echinoderms, ostracodes and plant fragments, although the overall fauna is sparse. This siliciclastic marine shoal aided in the formation of restricted landward intertidal environments landward and trapped most of the sand- and silt-sized terrigenous grains. Suspended terrigenous muds, however, escaped into the offshore marine environments. Offshore of the siliciclastic shoal are lime-grainstones, packstones, wackestones and mudstones of more open marine origin.

Environment 3 is an open marine subtidal shelf which contains shelf lagoons. This environment includes the following microfacies: upper lime mudstone, upper calcareous mudrock, lime- wackestone, packstone and grainstone. The biota within this environment, although overall very abundant, is predominantly comprised of a variety of stenohaline organisms. These assemblages have become progressively more diverse from Environment 1 to 3 where brachiopods, bryozoans, and echinoderms predominate and bivalves, corals, foraminifers, stromatolitic algae (LLH) and conodonts are locally present. The water was normal marine with effective wave or current activity supplying sufficient oxygen and nutrients to support a diverse biota.

The seaward progression of microfacies upward from Environment 2 begins with lime- grainstone to packstone and interbedded lime- wackestone and mudstone microfacies. The lime grainstone and lime packstone microfacies represent carbonate environments at or just

below wave base (carbonate shoal) where fines were winnowed and sand or larger bioclasts were concentrated. Bryozoans and echinoderms are common to the lime grainstone and packstone microfacies due to their need for a stable substrate and vigorous water circulation. Interbedded lime wackestones, lime mudstone and calcareous mudrock microfacies are interpreted to be deposits formed on an undulating shelf topography where relatively unfossiliferous lime mudstones were deposited in low areas across the shelf, while lime wackestone microfacies represent normal marine shelf areas. Lime mudstones and calcareous mudrocks were deposited in shelf lagoons restricted by water depth, which caused poor water circulation and stagnation of the environment. This is reflected in its darker color and restricted biotic assemblage, which is characterized by a small percentage of bivalves, brachiopods and ostracodes. The more normal marine lime wackestone microfacies developed on mid-shelf areas within well oxygenated and nutrient rich waters associated with current activity. Therefore, it has a more diverse fauna, including abundant brachiopods, bryozoans and echinoderms, with localized occurrences of coral communities, foraminifers and stromatolitic algae. Similar microfacies environmental determinations were made by Scholle et al. (1983) for the Florida reef tract where a broad, shallow-shelf, marine environment exists.

In conclusion, the overall lithologic and environmental progression from restricted, high intertidal mudflats bordering a supratidal sabkha to low intertidal or shallow subtidal siliciclastic shoals to more open marine subtidal, mid-shelf environments is

representative of a marine transgression (Fig. 16). This transgressive event had a direct effect on the predominant fauna and the relative percent of terrigenous grains (insoluble residues) throughout the Little Valley Limestone. As seen in Figure 17 (enclosed in pocket), the abundance of the predominate fauna fluctuates locally in response to terrigenous influx and increases overall towards the top of the Formation. The Little Valley Limestone represents a mixed carbonate-siliciclastic formation bordering the destructive phase of the Virginia - Carolina delta (involving the Price and Maccrady Formations) at its base and a normal marine shelf environment at its top.

MODEL OF DEPOSITIONAL ENVIRONMENTS

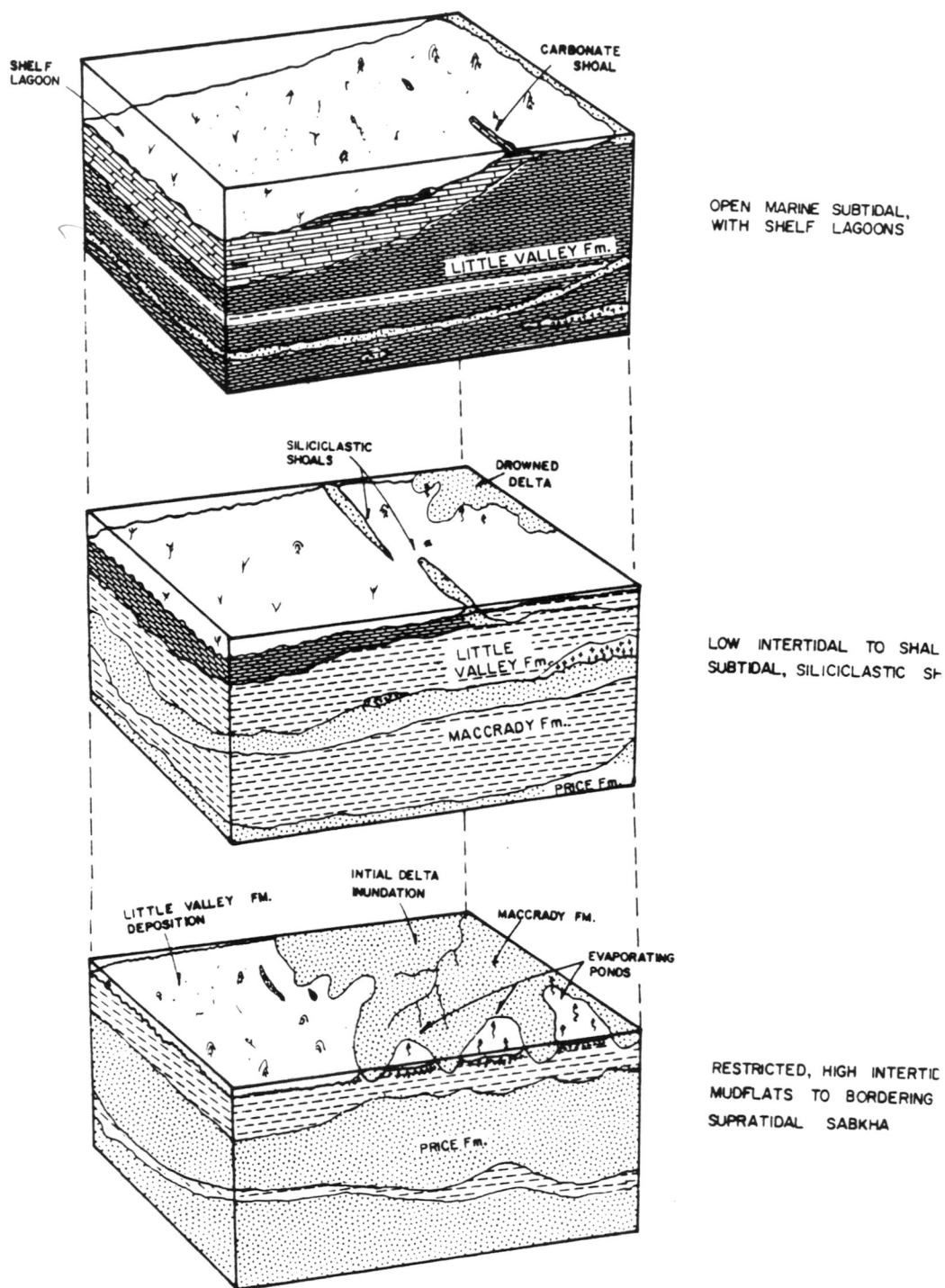


Fig. 16. Sequential depositional model for the Little Valley Limestone.

DIAGENETIC PROCESSES AND THEIR ENVIRONMENTS OF FORMATION

INTRODUCTION

Diagenesis includes all physical, chemical and biological variations, excluding weathering and metamorphism, occurring in sediments after initial deposition. Carbonate rocks may undergo constructive (carbonate aggradation) and/or destructive (carbonate degradation) diagenetic changes. The most common is constructive diagenesis associated with cementation or lithification of the carbonate sediments. Many factors influence the rate and/or extent of alteration in carbonates. The primary factors include: time, temperature, depth of burial, sedimentary composition, porosity, permeability, tectonic terrain and environment of deposition. Because of the complexity of the factors controlling diagenetic alterations, the sequence and environment of these alterations is difficult and sometimes impossible to determine. Where possible, the following discussion will position diagenetic events in a sequential order (early to late) with respect to their depositional environments (Fig. 18).

MICRITE ENVELOPES

Micritization of allochems is an early diagenetic event associated with microbiotic borings that result in the formation of micritic envelopes. Micrite envelopes develop within shallow marine waters at or near the sediment-water interface (Bathurst, 1975 and Flugel, 1982). Micro-organisms that bore include endolithic blue green, green and red algae, fungi and lichens that catalyze the

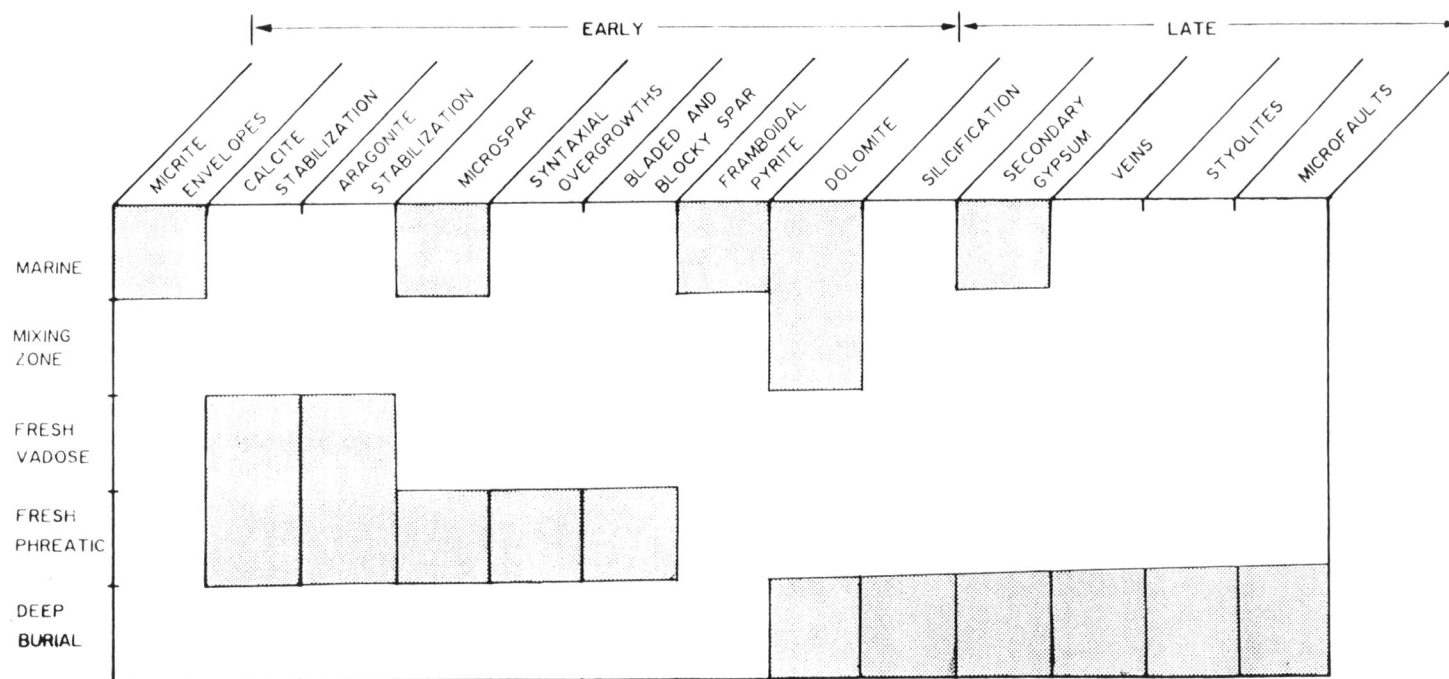


Fig. 18. Diagenetic environments of the Little Valley Limestone.

inorganic precipitation of calcium carbonate through physiologic activity, thereby infilling the microborings with unoriented micrite (Schneider, 1977). Microborings, usually centripetally oriented, consist of straight to curved tubes ranging in size from less than 1 micron to 50 microns. They are oriented perpendicular to the carbonate particle surface. Micrite, according to Schneider, precipitates as aragonite with a magnesium/calcium ratio greater than 1.0. Microbiota create micrite envelopes relatively quickly, such that envelopes approximately 500 microns thick can be bored in approximately one year (Flügel, 1982). If uninhibited, the microboring organisms can completely micritize a carbonate particle, destroying all or most of the grain's microstructural characteristics.

Within the Little Valley Limestone micrite envelopes are present in higher energy, shoaling environments encompassing lime- packstone and grainstone microfacies. Micrite envelopes are found on most varieties of allochems, some of which are subrounded particles referred to as cortioids. According to Kendall and Skipwith (1969), extensive micritization of an allochem accelerates its susceptibility to rounding by weakening and loosening the carbonate around its outer boundary. Foraminifers undergo complete micritization which obliterates their microstructural characteristics, but they do retain their overall test morphology. Micrite envelopes are resistant to recrystallization, such that they remain microcrystalline while associated allochems undergo complete recrystallization.

CALCITE STABILIZATION

Most allochems and carbonate matrix that formed before the Tertiary Period are considered to have a magnesium calcite composition (Loreau, 1979), although some aragonitic allochems and matrix did occur. Magnesium calcite is differentiated from calcite based upon its mole percent magnesium which ranges from 4 to 20 (Flügel, 1982). High magnesium calcite stability fluctuates with changes in environment, such that it is stable under normal marine conditions (marine photic zone), but it is unstable in meteoritic or freshwater (fresh phreatic zone). Unless subjected to well circulating mixing zone conditions and/or high magnesium concentrated fluids, magnesium calcite will neomorphose to low magnesium calcite by expelling magnesium ions (Bathurst, 1975). Magnesium calcite stabilization occurs by exsolution of magnesium ions to form calcite or by absorption to form dolomite. According to Longman (1977), to produce a 30% dolomite, it takes a minimum of several thousand pore volumes of mixed marine-fresh water to pass through the carbonate sediment.

Within the Little Valley Limestone, calcite stabilization is not restricted to a particular environment, but it is considered an early diagenetic feature. The most prominent components having initially high-magnesium calcite compositions include: micritic envelopes, echinoderms, ooids, algae and some foraminifera. All of the above allochems retained their original microstructural characteristics after neomorphism from magnesium calcite to calcite. However, localized dolomite nucleations did occur on echinoderm grains.

Magnesium calcite muds of the matrix (commonly associated with terrigenous clays) probably stabilized to low magnesium calcite by absorption of their excess magnesium by existing clays. Clay participation in calcite stabilization is thought to be most significant.

MICROSPAR

Microspar, formed by the aggradational neomorphism of micrite and/or neomorphic calcitization of aragonite, is characterized by calcite crystals ranging from 5 to 10 microns in size. According to Folk (1973, 1974), microspar forms in normal marine conditions from micrite which was originally composed of high magnesium calcite or aragonite. Upon burial and diagenesis, the unstable high magnesium calcite and aragonite expel magnesium ions and invert to a more stable low magnesium calcite phase (Longman, 1977). Longman also emphasized that most expelled magnesium ions from the micrite attach to the surfaces of the now low magnesium calcite crystals. Magnesium, an impediment of calcite growth, must be removed before the production of microspar can occur. Magnesium ions can be removed from the microcrystalline calcite by (1) clay absorption, (2) dolomitization and (3) freshwater movement (associated with high porosities and permeabilities) (Longman, 1977).

The second process of microspar formation involves the direct neomorphic calcitization of aragonite to microspar without a micrite precursor (Lasemi and Sandberg, 1984). This process of microspar formation

was recognized by Lasemi and Sandberg (1984) through scanning electron microscopy, which revealed consistent numbers of relic aragonite crystals in all crystal sizes of neomorphic calcite. According to Lasemi and Sandberg (1984), the similar amounts of aragonite relics in various sized neomorphic calcite crystals proves that aggradational neomorphism does not exclusively form by solution-reprecipitation (since this process causes a large reduction in the abundance of aragonite crystals).

The reason for the pervasive occurrence of microspar within the Little Valley Limestone, whether aggradational neomorphism or neomorphic calcitization of aragonite, is unknown. If microspar is aggradational, then it is thought to be primarily controlled by the abundance of terrigenous clays in close association with the carbonate muds. Chlorite, one of the dominant clays within the Little Valley Limestone, has been recognized by Longman (1977) as a magnesium ion "sump". The presence of chlorite, therefore, is very effective in removing the inhibiting magnesium ions from microcrystalline calcite crystals. Finely disseminated dolomite within the matrix also influenced microspar development. Freshwater movement within the Ste. Genevieve Limestone, as described by Choquette and Steinen (1980), similarly affected microspar production within the Little Valley Limestone. Microspar formation must have been early since porosities and permeabilities needed for the transportation of freshwater would have been greatly reduced by cementation and the high degree of compaction associated with late burial.

Environmentally, microspar is ubiquitous in all depositional environments, although it was more prominent in lower energy subtidal shelf areas. Microspar is primarily associated with the lime-mudstone, wackestone and calcareous mudrock microfacies.

ARAGONITE

Aragonite is a polymorphic phase of calcite having an orthorhombic crystal system and a very low magnesium content (less than 5000 ppm). Aragonite's stability field ranges from 25 degrees C at 4 kb pressure to a lower limit of 600 degrees at 14 kb pressure (Clark, 1957). The lower symmetry of aragonite in comparison to pure calcite causes aragonite's much higher solubility, but aragonite in shallow normal marine water is less soluble than magnesium calcite (Bathurst, 1975). Three prominent types of alteration of aragonite occur due to its high susceptibility for reaction and its unstable nature: (1) polymorphic inversion, (2) dissolution and (3) replacement (Folk, 1974 and Lasemi and Sandberg, 1984). Aragonite's polymorphic inversion to calcite is characterized by retention of its original composition and a modification of its original crystal structure (from orthorhombic to rhombohedral). Complete dissolution of an aragonitic allochem creates moldic porosity (as long as a mold of the particle was made before dissolution), usually infilled by sparry calcite. Replacement of aragonite with another mineral of different composition can occur. Dolomite, calcite, silica and pyrite are the most common replacement minerals.

Environmentally, aragonite within the Little Valley Limestone was

most common to the subtidal shallow shelf where lime- mudstone and wackestone prevail. This environment is characterized by the highest percentage of mud sized material (micrite/microspar) and contains possible aragonitic fossils.

The two most common aragonitic fossils include bivalves and gastropods. Bivalves are commonly replaced by blocky spar crystals which obliterate most of their original structure, although their outer prismatic calcitic layer is generally preserved. Gastropods are always entirely replaced by blocky spar, thus retaining no microstructural characteristics. Both of these allochems were probably diagenetically altered by both polymorphic inversion and dissolution.

SYNTAXIAL OVERGROWTHS

Syntaxial cements most commonly form on echinoderm fragments in the active fresh water phreatic zone where they are associated with very rapid growth rates (Longman, 1980). The high rate of syntaxial cement growth associated with echinoderm fragments is evidenced by the large amount of interparticle pore space incorporated by syntaxial cements in comparison to adjacent cements (bladed and/or blocky calcite spar) associated with other types of allochems. The large calcite crystal (echinoderm grain) on which the overgrowth nucleates also aids in cement development. Although syntaxial overgrowths are most common to the fresh phreatic zone, they rarely occur in the fresh vadose and later deeper diagenetic environments. However, syntaxial overgrowths on echinoderms occur only very rarely, if at all, in

marine phreatic zones. Instead, fibrous aragonite or magnesium calcite form (Longman, 1980).

Syntaxial overgrowths are restricted to lime grainstone microfacies of the carbonate shoal environment, and are commonly associated with fresh water phreatic cements. Other fresh phreatic cements include bladed and blocky spar which coarsen towards the center of the pore.

BLADED AND BLOCKY SPAR

Bladed and blocky spar are early diagenetic cements which are most common to an active fresh water phreatic environment. These types of spar cement are associated with lime- grainstone and packstone microfacies of the shallow subtidal shelf (at or near wave base). Blocky ferroan calcite is diagnostic of a fresh water phreatic environment due to the low interstitial Eh conditions (Flügel, 1982). Correspondingly, Longman (1980) suggested that abundant, equant and isopachous bladed calcite cements occurring as interlocking crystals which coarsen towards pore center are characteristic of early diagenesis within a fresh water phreatic environment.

Active fresh water phreatic and/or deep connate water environments associated with bladed and blocky equant spar cements must have magnesium to calcite ratios below 2 to 1, and optimally between the 1 to 10 and 1 to 2 (Folk, 1974). Deeper connate water systems contain waters of marine origin characterized by low magnesium calcite ratios (1 to 2 through 1 to 4) due to magnesium ion removal by clay minerals and by the formation of dolomite (Folk, 1974; Bathurst,

1975; Flugel, 1982). Following the removal of magnesium ions (calcite growth inhibitors), sparry calcite will be allowed to precipitate.

FRAMBOIDAL PYRITE

Pyrite authigenically forms in marine environments during early diagenesis of organic rich, anoxic sediments. The key components for pyrite formation are hydrogen sulfide, which is derived from bacterial reduction of dissolved sulfate through decomposition of organic matter, and free iron (Blatt et al., 1972). Although the compositional origin of pyrite is understood, much controversy (Schneiderhohn, 1923 and Love, 1957) arose over the origin of framboidal texture. Love and Schneiderhohn originally suspected a biogenic origin in which the framboid represents fossilized micro-organisms. Further studies disproved this hypothesis. Berner (1970), through laboratory experimentation, inorganically synthesized framboidal pyrite at low temperatures (65 degrees C) and at a neutral pH (7.8). Berner concluded that elemental sulfur is required for the formation of pyrite if organic matter and micro-organisms are absent.

Pyrite framboids of the Little Valley Limestone are common throughout all microfacies, although they are most abundant in darker lime mudstones and calcareous mudrocks of the deeper subtidal shelf lagoons. Lime wackestone and packstone microfacies associated with high organic productivity commonly have pyrite infillings in sheltered pore spaces under convex upward allochems. This probably occurs due to trapping of hydrogen sulfide gases and/or volatile organic matter (undergoing decomposition) which is later converted to pyrite by

exposure to ferrous ions.

DOLOMITE

Dolomite found in the Little Valley Limestone is considered to have been formed both early and late in its diagenetic history. The timing of dolomite formation is reflected by the crystal morphology of the dolomite. According to Gregg and Sibley (1984), dolomite which crystallizes below the "critical roughing temperature" (CRT, a theoretical temperature) forms smooth euhedral dolomite crystals, and dolomite crystallizing above the CRT favors the formation of rough anhedral crystals. Through experimentation, they determined the CRT to lie between 50 and 100 degrees C. Therefore, euhedral, idiotopic textures characterized by slow atomic building of the dolomite crystal, which creates smooth crystal faces are associated with surface or near surface conditions. Conversely, anhedral, xenotopic dolomite textures involving random addition of atoms to the dolomite crystal faces occurs in deeper subsurface conditions (Jackson, 1958 and Gregg and Sibley, 1984).

Two major textural types of dolomite occur in the Little Valley Limestone: (1) idiotopic-E and -P (diagenetically early dolomite) of the lower Little Valley Limestone and (2) xenotopic-P and -A (diagenetically late dolomite) of the upper Little Valley Limestone. The lower section of the Little Valley Limestone was subjected to lower temperature dolomite crystallization characteristic of early diagenesis, similar to that described by Purser and Evans (1973) in the sabkhas of the Persian Gulf. This dolomite most likely

precipitated as a calcium-rich phase of dolomite (protodolomite) from hypersaline waters by elevation of the magnesium calcite ratios corresponding to gypsum and/or anhydrite (Tucker, 1981). Later neomorphic processes allowed stabilization of the calcium rich protodolomite to a more stoichiometric phase without destroying the original rhombohedral crystal form (Lumsden and Chimahsky, 1980).

The upper section of the Little Valley Limestone was subjected to high temperature that produced dolomite crystal textures thought to be indicative of late stage diagenesis. Two plausible models for late stage dolomitization are considered. The first is localized high magnesium pore fluids created by neomorphic aggradation of micrite to microspar, which not only draws calcium from the pore waters but also releases magnesium ions into it (Longman, 1977). Thus, localized dolomite nucleations as well as more extensive dolomitization are confined to more porous and permeable zones usually containing terrigenous silt and sand. Within the lime- mudstone and wackestone microfacies of the upper Little Valley Limestone dolomitization frequently occurs in close proximity to zones or thin beds of quartz silt. Similarly, Choquette and Steinen's (1980) investigation of dolomitization within the Ste. Genevieve Limestone of the Illinois Basin revealed lime mudstone sequences overlain by carbonate sands which have gradational dolomitization trends that lessen with distance from the contact. They also recognized extensive dolomitization associated with silty burrows within lime mudstones. The second dolomitizing model involves formation water movements which are capable of dolomitization when they have a molar calcium/magnesium

ratio of less than 15 and a temperature of approximately 300 degrees C (Land, 1980). Therefore, late stage diagenetic alteration can occur by infiltration of hydrothermal fluids into more porous and permeable zones, causing dissolution and/or replacement of the calcite crystals (more soluble than dolomite at higher temperatures) by dolomite (Land, 1980). Evidence within the Little Valley Limestone for this hydrothermal dolomitizing model are calcite veins which contain dolomite in their centers.

Dolomitization within the Little Valley Limestone occurs in most microfacies (independent of depositional environment), although dolomite within the lower portion of the Formation corresponds to the low intertidal-supratidal depositional environments.

SILICIFICATION

In some form, silicification occurs throughout the Little Valley Limestone. Silica can be derived from either organic or inorganic sources. Organic sources of silica have been considered the most common to marine environments and include sponges, radiolarians, [diatoms, silicoflagellates] and some terrestrial plant materials evolved after Mississippian (Williams and Creror, 1985). However, inorganic sources also occur, primarily from the diagenesis of phyllo- and tektosilicates. The primary source of silica within the Little Valley Limestone is thought to be inorganic. The lack of evidence of siliceous organic material and the high concentrations of both phyllo- and tektosilicates support this interpretation. The relatively close association of siliciclastic material with carbonate material (matrix and allochems)

allows for an intraformational source of silica, although extraformational silica solutions are locally significant in the formation of chert nodules. The diagenesis of phyllosilicates (mainly montmorillinite to illite) and tektosilicates with pressure solution, dissolution of feldspar (Smale, 1973; Tucker, 1981) and the transformation of feldspar to kaolinite provide sources of intraformational silica (Tucker, 1981). Clay minerals may also supply silica by the leaching of magnesium ions and absorption of hydrogen ions, resulting in an increase of pH of the solution. This creates an alkaline halo around clays which then dissolve quartz grains in contact with them (Thompson, 1959). Solutions which are highly oxidizing (pH of 9-10) can dissolve silica in the form of chert and quartz. In thin section, the boundaries of quartz and feldspar grains are highly pitted and sharp, which is suggestive of dissolution.

According to Meyers and James (1978), varying forms of silica are associated with groundwater which is initially saturated with silica (greater than 125 ppm). Precipitation of opal CT in micropores of matrix and allochems allows the solution to become lower in silica concentrations (25 to 125 ppm), permitting micro- and mega-quartz to precipitate. The recrystallization of the unstable opal CT forms microquartz varieties (chert and chaledony). Likewise, groundwaters permeating the lower siliciclastic zones (source of silica) within the Little Valley Limestone are thought to have permeated along fossiliferous zones where porosities allowed for complete silicification of both matrix and allochems. The time of diagenesis

is considered late since adequate amounts of silica derived from inorganic sources require higher temperatures and pressures for increased solubility of silica. No substantial correlations between silicification and depositional environment were noted.

SECONDARY GYPSUM

Secondary gypsum occurs through the hydration of original anhydrite. According to Hardie (1967), three main hydration mechanisms allow diagenetic alteration of anhydrite to secondary gypsum: (1) solution-precipitation, (2) direct hydration by the addition of structural water and (3) stepwise hydration through the formation of the intermediate sulfate mineral bassinate. Mechanisms 1 and 2 are most favorable for the hydration of the anhydrite within the Little Valley Limestone. Mechanism 1 is associated with the dissolution and hydration of calcium sulfate, and its later precipitation as a hydrated calcium sulfate in the form of subhedral to anhedral, porphyroblastic secondary gypsum. The transformation of anhydrite to secondary gypsum is associated with a considerable increase in volume due to the larger unit cell of gypsum. Therefore, by mechanism 1, volume equilibrium is maintained by the remobilization of some of the hydrated calcium sulfate in the form of satin spar. Mechanism 2 involves in situ incorporation of water into the calcium sulfate structure to form an alabastrine gypsum.

Within the Little Valley Limestone secondary gypsum is restricted to high intertidal-supratidal environments. Within this environment evaporation was sufficient for brine concentrations to precipitate

anhydrate and gypsum. Secondary gypsum comprises its own microfacies, although it is also associated with lower Little Valley calcareous mudrocks.

VEINS

Veins are found within all environments of the Little Valley Limestone where they have various sizes, orientations and interstitial mineralogies. Calcite veins are generally more abundant in lime-packstones and grainstones as compared to calcareous mudstones and lime wackestones of the upper Little Valley Limestone. However, gypsum veins commonly dissect dolomitic mudstones and gypsiferous mudstones of the lower Little Valley Limestone. Overall, the veins cut obliquely across bedding and through allochems and other diagenetic textures, except well developed stylolites. Veins range in size from 0.5 to 2.0 cm in maximum thickness and can mineralogically contain the following associations: (1) calcitic blocky spar, (2) calcitic blocky spar with dolomite in its center, (3) calcite with pyrite in its center and (4) gypsum in the form of satin spar. The most prominent vein mineralogy is blocky or drusy calcite. The calcitic fluids develop from dissolution and/or pressure solution of carbonate rocks (includes allochems, matrix and cements) during compaction. Interstitial waters (connate waters) transport the highly calcitic fluid through fractures or planes of weakness derived from tectonism, precipitating equant calcite spar upon reaching supersaturation. Calcitic veins associated with dolomite in the center are primarily caused by two different mechanisms. The first

involves depletion of calcium in the vein solution, thus allowing super-saturation of magnesium ions with respect to cations and precipitation of dolomite as the last phase within the vein. The second mechanism involves the precipitation of two different generations of vein infill. Pyrite, also associated with the centers of sparry calcite veins, is interpreted as hydrocarbon mobilization through open pore areas inhibiting spar growth and allowing precipitation of pyrite in open pore spaces. The last type of vein mineralogy is satin spar gypsum, which occurs due to the hydration and remobilization of the lower anhydrite beds. The gypsum veins form from the excess sulfate removed in solution during gypsification and/or tectonism (Plate 29).

STYLOLITES

Stylolites are thin solution seams produced in carbonate rocks due to overburden or tectonic pressure. The irregular morphologic pattern of solution seams is attributed to discontinuities in particle strength. Therefore, dissolution seams incorporate most calcite grains and matrix and concentrate less soluble material such as dolomite, opaques, quartz, phyllosilicates and ferrous oxides along their boundaries. The black opaque materials lining stylolites are insoluble residues which include a mixture of clay minerals and organic matter (Tucker, 1981). Stylolites may occur early (before cementation) or late (cutting across all other diagenetic fabrics). Tectonic stylolites develop normal to stress and commonly cut across and displace diagenetically late stylolites (Purser, 1978). Flugel

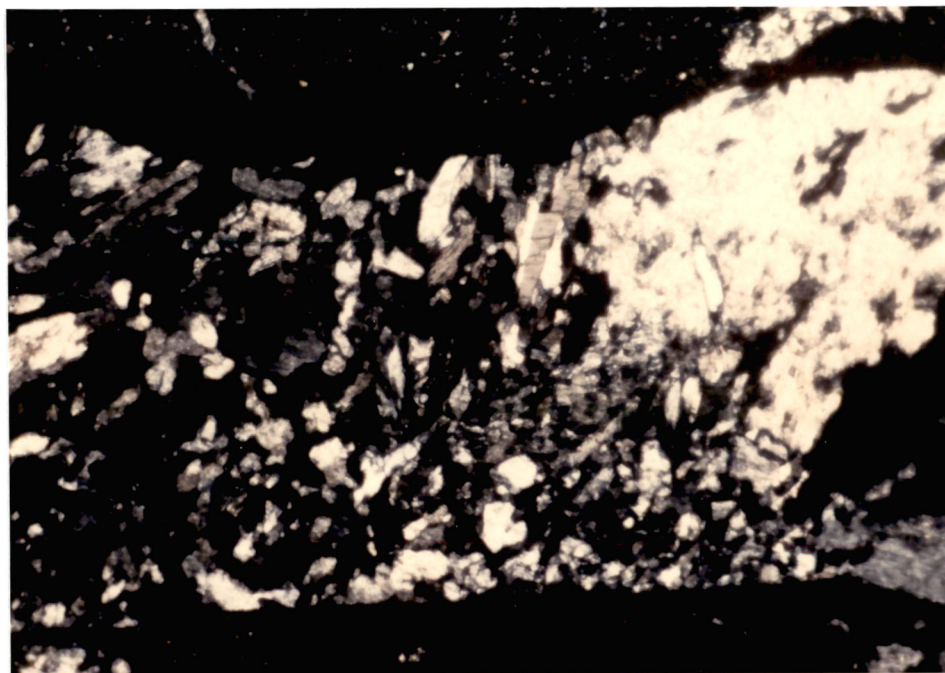


PLATE 29. Photomicrograph of a satin spar gypsum vein (1.5 mm in width).

(1982) subdivide stylolites into two classes based on stylolitic amplitudes: (1) aggregate stylolites, characterized by amplitudes greater than the grain diameters of the host rock; and (2) intergranular stylolites with amplitudes less than the grain diameter of the host rock. Stylolites also have varying patterns due to discontinuities within host rocks. Stylolites may be columnar, irregular, hummocky, etc., and configurations or sets of stylolites may be arranged in parallel sets, conjugate sets, anastomosing sets, etc.

Within the Little Valley Limestone discontinuous, aggregate, and irregular to hummocky individual stylolites are most common, although irregular anastomosing sets occur rarely. These solution seams commonly contain pyrite, dolomite, allochems, quartz grains and opaque films concentrated along their borders. Stylolites within this formation are diagenetically late since they cut across all other diagenetic fabrics except for calcite veins. They have no particular environmental correlations.

MICROFAULTS

Microfaults are limited to the lime mudstones of the lower Little Valley Limestone. They occur due to the remobilization of evaporite minerals, mainly gypsum, underneath the overlying lime mudstones and/or by tectonic movements. Remobilization of the evaporites (by density differential flowage and/or by dissolution from groundwater movement) causes voids to develop into which overlying material (lime mudstones in this case) collapses, resulting in the development of

collapse breccias and microfaulting (Goldstein and Collins, 1984). Tectonic evidence for microfaulting within this unit is the close proximity of microfaulted intervals to the Saltville fault decollement zone within the upper portion of the Maccrady Formation. The microfaults characteristic to the lower Little Valley lime mudstones have displacements ranging from 0.25 mm to 1.25 mm. Nonferroan sparry calcite commonly infills between fault surfaces.

SUMMARY OF CONCLUSIONS

- 1) The Little Valley Limestone is an Upper Mississippian natural gas producing, "mixed"-composition, transitional unit lying stratigraphically between underlying predominantly terrigenous lithologies including the Price and Maccrady Formations and overlying predominantly carbonate lithologies encompassing the remainder of the Greenbrier Group.
- 2) Seven microfacies are discernable from the Little Valley Limestone. They are: lime- mudstone, wackestone, packstone, grainstone, calcareous and muddy sandstone, calcareous mudrock and secondary gypsum. The combination and stratigraphic pattern of these microfacies allowed for identification of depositional environments.
- 3) The depositional environments of the Little Valley Limestone as interpreted from its microfacies, represent a marine transgression proceeding from a restricted, high intertidal mudflat or bordering sabkha to a low intertidal-shallow subtidal, siliciclastic shoal, both containing a paucity of fauna, to an open marine subtidal shelf with shelf lagoons containing a diverse stenohaline fauna.
- 4) The Little Valley Limestone represents the initial marine inundation of the Virginia-Carolina delta complex during a period of tectonic quiescence. Sedimentation was characterized by mixed carbonate-siliciclastic deposition.

5) Various types of diagenetic alteration occurred in the Little Valley Limestone and, to some degree, were controlled by the high concentration of siliciclastic components, the depth of burial and tectonism. Most of the gypsum in this unit is a secondary rehydration phase formed from an anhydrite precursor. Because of the complexity of diagenetic overprinting the sequence and environments of diagenetic alteration are extremely difficult to decipher.

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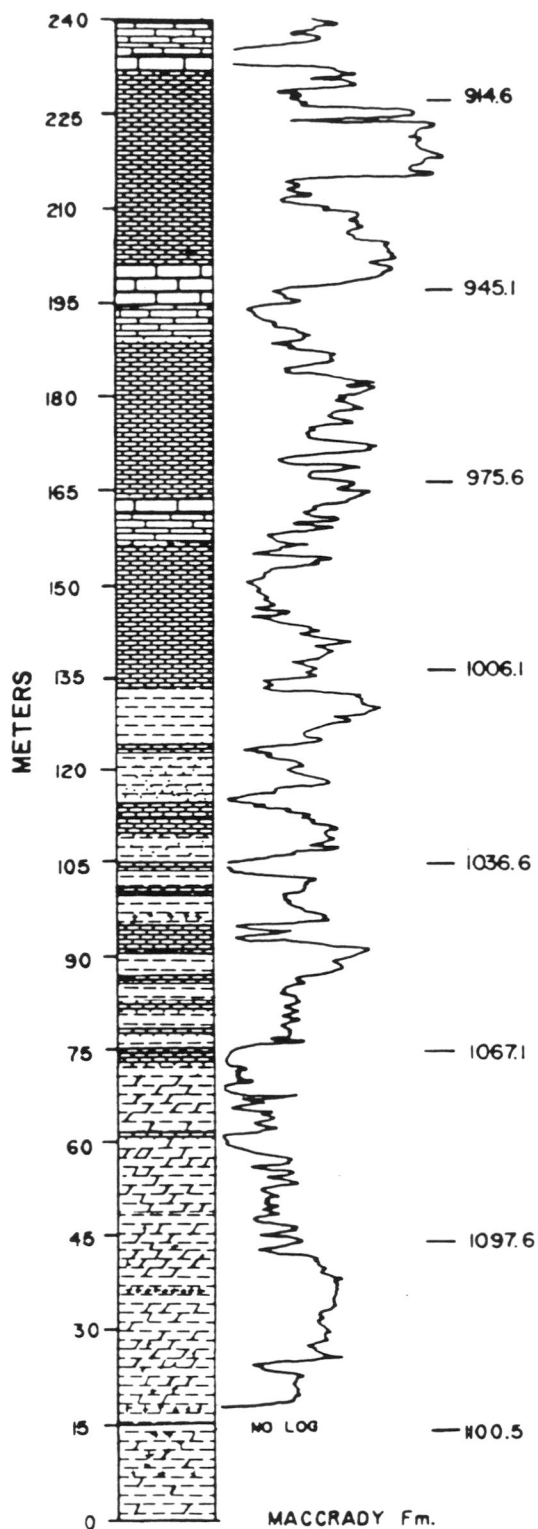
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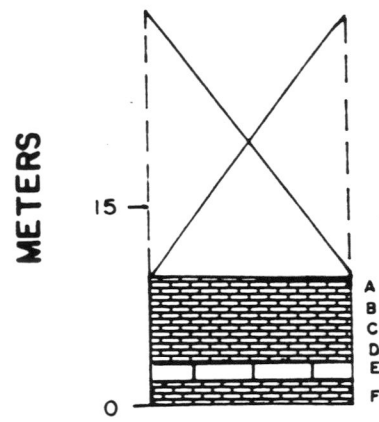
APPENDIX A - MEASURED SECTIONS
FROM OUTCROP AND CORE

Hillsdale Formation

DEPTH (meters)



1: 1 D.W. Dorton sample log with gamma ray log
(provided by Bartlett Energy).

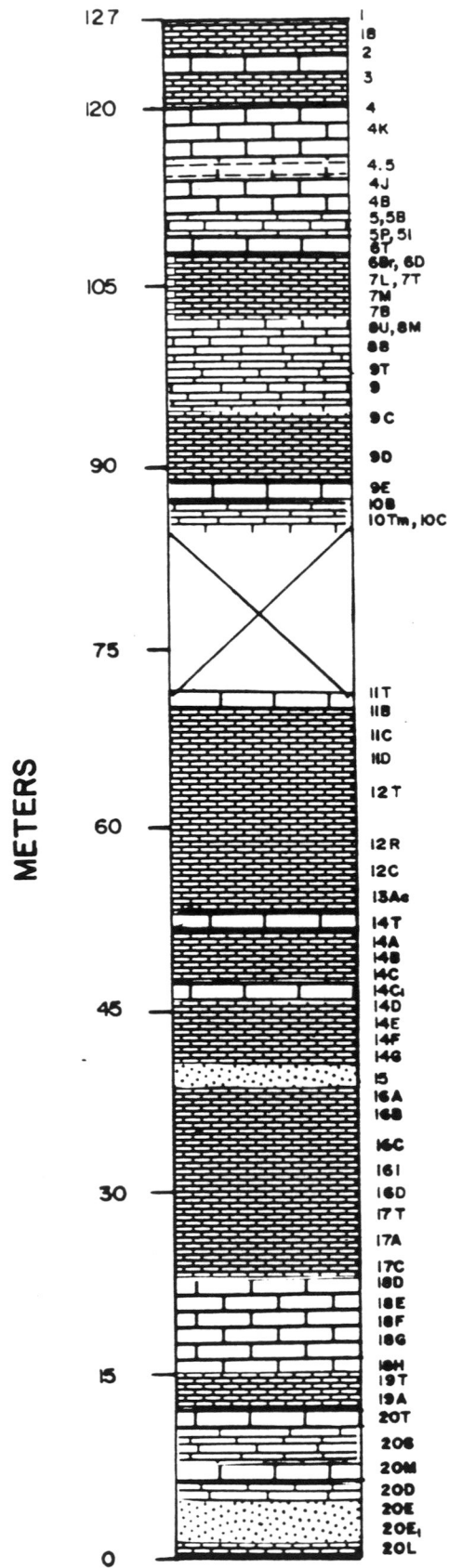


2: Outcrop at Horseshoe Bend.

OUTCROP AND CORE DESCRIPTIONS

2: HSB - Samples from Horse Shoe Bend

Sample No.	Descriptions	Thickness (Meters)
F	Lime mudstone, fine grained, medium bedded, slightly friable, brachiopods show on weathered surface, fresh surface is a medium light gray (N6) weathering to a light gray (N7). _____	1.8
E	Packstone, fine grained, thinly bedded, dense, crinoids show on weathered surface, fresh surface is a medium dark gray (N4) weathering to a medium gray (N5). _____	0.5
B, C, D	Lime mudstone, very fine grained, medium bedded, friable, no fossils seen, fresh surface is an olive gray (5Y 4/1) weathering to a light olive gray (5Y 6/1). _____	4.6
A	Lime mudstone, fine grained, medium bedded, dense, brachiopods show on weathered surface, fresh surface is a medium gray (N5) weathering to a light olive gray (5Y 6/1). _____	1.5



3: Road cut Highway 19.

OUTCROP AND CORE DESCRIPTIONS

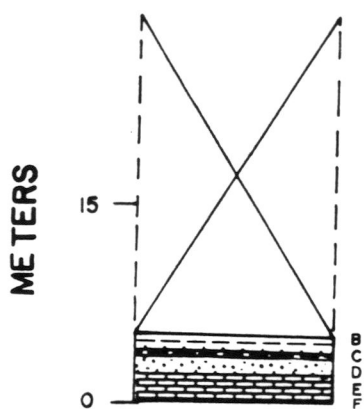
3: LVL- samples from Highway 19

SampleNo.	Description	Thickness (meters)
20L	Lime Mudstone, fine grained, medium bedded, dense, contains small laminations of silt sized quartz grains, fresh surface is medium dark gray (N-4) weathering yellowish gray (5Y 7/2). _____	1.2
20E, 20E1	Calcareous sandstones, very fine grained, medium bedded, contains small tangential cross-beds, fresh surface is light gray (N-7) weathering to a yellowish gray (5Y 7/2). _____	2.4
20D	Wackestone, fine to medium, bedded, contains contains brachiopods and crinoids, fresh surface is a dark gray (N3) weathering to a light olive gray (5Y 5/2). _____	1.8
20M	Packstone, fine to medium grained, medium bedded, crinoids on weathered surface. Fresh surface is medium dark gray (N4) weathering to a olive gray (5Y 4/1). _____	1.2
20S	Wackestone, fine to medium grained, medium bedded, with medium dark gray (N4) bedded and nodular silicified zones, contains brachiopods, bryozoans and echinoderms, fresh surface is dark gray(N3) weathering to medium gray (N5). _____	3.0
20T	Packstone, fine to medium grained, medium bedded, brachiopods and echinoderms exposed on weathered surface, fresh surface is brownish gray (5YR 4/1) weathering to a light brownish gray (5YR 6/1). _____	1.8
19T, 19A	Lime mudstone, fine to medium grained, fissile and friable, brachiopods and bryozoans show on weathered surface, fresh surface medium dark gray (N4) weathering to an olive gray (5Y 4/1). _____	3.4
18D, 18E, 18F 18G, 18H	Packstone, fine to medium grained, interbedded dense mud friable units, brachiopods, bryozoans and crinoids show on weathered surface, fresh surface medium dark gray (N4) weathering to a medium gray (N5). _____	7.9

SampleNo.	Description	Thickness (meters)
17Y, 17A, 17C 16A, 16B, 16C 16I, 16D	Lime mudstone, very fine to medium grained, thinly interbedded, friable and dense units, brachiopods and bryozoans show on weathered surface, fresh surface is a medium dark gray (N4), weathering to an olive gray (5Y 4/1). —————	15.9
15	Calcareous sandstone, fine grained, well rounded and sorted grains, medium bedded, fresh surface is a very light gray weathering to a moderate yellowish brown (10 YR 5/4). —————	1.5
14E, 14F, 14G	Lime mudstone, very fine grained, thin to medium bedded, highly friable, possible algal laminations, fresh surface is a medium dark gray weathers to a medium light gray (N6). —————	4.3
14D	Lime mudstone, fine to medium grained, medium bedded, dense, localized zones of silicification, fresh surface is a dark gray (N3) weathering to a light olive gray (5Y 6/1). —————	0.6
14B, 14C,	Packstone, fine to medium grained, medium bedded, moderately friable crinoid and brachiopods show on weathered surface, disrupted laminations, fresh surface is a medium dark gray (N4) weathering to a light olive gray (5Y 6/1). —————	1.8
14A	Lime mudstone, very fine grained, medium bedded, highly friable, fresh surface is an olive gray (5Y 4/1) weathering to a medium light gray (N6). —————	1.5
14T	Grainstone, fine to medium grained, medium bedded, dense brachiopods and crinoids show on weathered surface, fresh surface is a pale brown (5YR 5/2) weathering to a light olive gray (5Y 6/1). —————	1.8
13A, 13B, 13C	Lime mudstone, fine to medium grained, fissile at top grading to a more dense medium bedded unit at its base, contains zones of brachiopods, fresh surface medium dark gray (N4) weathering to medium light gray (N6). —————	6.1
12T, 12R, 12C 11D	Lime mudstone, very fine to fine grained, medium bedded, very friable, contains rippled laminations, fresh surface is a medium gray (N5), weathering to a medium light gray. —————	7.0

Sample No.	Descriptions	Thickness (Meters)
11C	Lime mudstone, fine grained, medium bedded, algal laminations, friable, fresh surface is medium dark gray weathering to an olive gray (5Y 4/1). —————	1.5
11B	Lime mudstone, very fine grained, thinly bedded, fresh surface is moderate greenish gray (5G 6/1) weathering to a medium light gray. —————	1.5
11T	Wackestone, fine to medium grained, medium bedded, bryozoan and brachiopods show on weathered surface, fresh surface is medium dark gray (N4) weathering to a medium light gray (N6) or a yellowish gray (5Y 7/2). —————	1.8
	Covered interval, no sample. —————	13.7
10B, 10TM, 10C	Wackestone, fine to medium grained, interbeds of fissile and dense medium units, brachiopods and crinoids show on weathered surface, fresh surface is medium gray (N5) weathering to a light olive gray (5Y 6/1). —————	2.4
9E	Packstone, fine to medium grained, medium bedded, dense, bryozoans and brachiopods show on weathered surface, fresh surface is medium dark gray (N4) weathering to a light olive gray (5Y 6/1). —————	1.5
9, 9T, 9C, 9D	Wackestone, fine to medium grained, medium bedded, friable, brachiopods and crinoids show on weathered surface, fresh surface is medium dark gray (N4) weathering to a light gray (N7). —————	6.1
8U, 8M, 8B	Wackestone, medium grained, medium bedded, dense near base becoming more friable near unit's top, abundant bryozoan stems show throughout, some brachiopods also present, slight sulfur odor on fresh break, fresh surface medium gray (N5) weathering to a light olive gray (N7). —————	5.0
7L, 7T, 7M 7B	Lime mudstone, medium to thinly bedded, friable near base, becoming more dense near unit's top localized linear zones of brachiopods following bedding, brachiopods, gastropods and bryozoans also show on weathered surface, fresh surface is medium dark gray (N4) weathering to a medium gray (N5). —————	4.0

Sample No.	Descriptions	Thickness (Meters)
6Br, 6D	Lime mudstone, medium bedded, slightly friable, no fossils seen, fresh surface is a medium gray (N5) weathering to a yellowish gray (5Y 8/1). —————	2.7
6T	Slightly sandy packstone, fine to medium grained, medium bedded, scattered fossil fragments, fresh surface is a medium dark gray (N4) weathering to a light brownish gray (5YR 6/1). —————	1.5
5, 5B, 5P, 5I	Lime mudstone, fine to medium grained, medium bedded, contains spheroidally weathered denser lenses, scattered brachiopods, fresh surface is a medium gray (N5) weathering to a medium light gray (N6). —————	1.2
4J, 4B	Packstone, fine to medium grained, medium bedded strong petroliferous odor, contains small black stain calcite irregular stringers, brachiopod molds, gastropods and crinoid molds show on weathered surface, fresh surface is a medium dark gray (N4) weathering to a yellowish gray (5Y 7/2). —————	3.7
4.5	Shale, fine grained, one thin bed, highly contorted, no fossils seen, fresh surface grayish black (N2) weathering to a dark gray (N3) with a lustrous surface. —————	0.3
4, 4K	Packstone, fine to medium grained, medium bedded, strong petroliferous odor, crinoids and brachiopods show on weathered surface, slightly friable, fresh surface is a medium dark gray (N4) weathering to a medium light gray (N6). —————	4.9
3	Lime mudstone, very fine grained, fissile friable, no fossils seen, laminated, fresh surface is a medium dark gray (N4) weathering to a medium gray (N5). —————	3.0
1B, 2	Packstone, fine to medium grained, medium bedded, ripple laminated, brachiopods, bryozoans and corals show on weathered surface, fresh surface pale yellowish brown (10YR 6/2) weathering to a pale yellowish orange (10YR 8/6). —————	0.6
1	Lime mudstone, fine to medium grained, medium bedded, friable, brachiopod molds and bryozoans show on weathered surface, fresh surface is a medium light gray (N6) weathering to a light gray (N7). —————	2.7



Maccrady Fm.

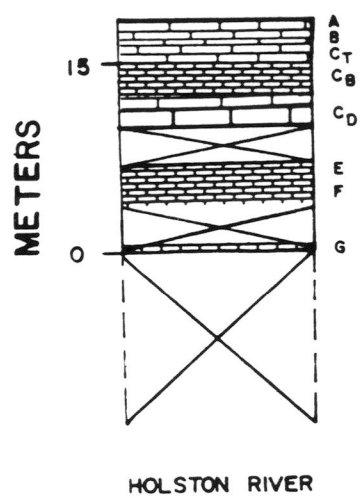
4: Jackson School Outcrop.

OUTCROP AND CORE DESCRIPTIONS

4: JS - Samples from Jackson School

Sample No.	Descriptions	Thickness (Meters)
D, E, F	Lime mudstone, very fine grained, interbedded friable thin bedded and denser medium bedded units, no fossils seen, fresh surface is a medium light gray (N6) weathering to a yellowish gray (5Y 8/1). —————	2.7
C	Lime sandstone, very fine grained, thinly bedded, no fossils seen, fresh surface is a light bluish gray (5B 7/1) weathering to a greenish gray (5G 6/1). ———	0.9
B	Lime mudstone, very fine grained, medium bedded, no fossils seen, fresh surface is medium light gray (N6) to grayish orange (10YR 7/4) in localized areas weathering to a yellowish gray (5Y 7/2). —————	1.2

Hillsdale Fm.



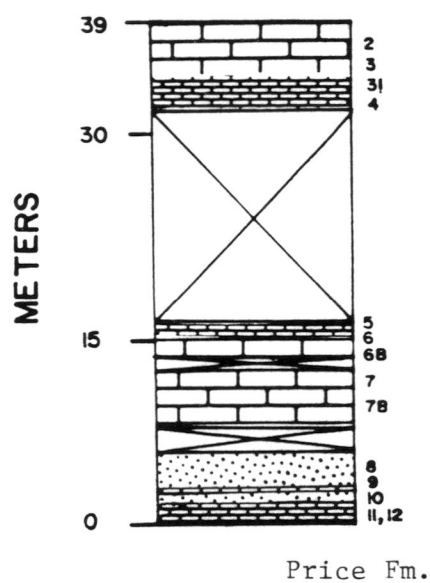
5: UKa - Samples from road cut on S.R. 692.

OUTCROP AND CORE DESCRIPTIONS

5: UKa - Samples from Roadcut on S.R. 692

Sample No.	Descriptions	Thickness (Meters)
	Covered. _____	
G	Lime mudstone, fine grained, medium bedded, bryozoans and brachiopods show on weathered surface, fresh surface is an olive gray (5Y 4/1) weathering to a grayish orange (10YR 7/4). _____	0.6
	Covered. _____	3.0
F	Lime mudstone, fine grained, medium bedded, brachiopods show on weathered surface, fresh surface is a medium light gray (N6) weathering to a light olive gray (5Y 6/1). _____	0.9
E	Lime mudstone, fine grained, medium bedded, slight petroliferous odor upon fresh break, fresh surface is a medium dark gray (N4) weathering to a grayish orange (10YR 7/4). _____	1.5
	Covered. _____	2.4
D	Packstone, fine to medium grained, medium bedded, strong petroliferous odor upon fresh break, crinoids show on weathered surface, fresh surface is a medium gray (N5) weathering to a pale yellowish brown (10YR 6/2). _____	0.9
C B	Wackestone, fine to medium grained, medium bedded, ripple laminated, contains brachiopods, bryozoans, and crinoids, fresh surface is a light gray (N7) weathering to a pale yellowish brown (10YR 8/2). _____	1.5
C T	Lime mudstone, very fine grained, medium bedded, no fossils seen, fresh surface is a light olive gray (5Y 6/1) weathering to a very pale orange (10YR 8/2). _____	1.5
B	Wackestone, fine to medium grained, medium bedded, brachiopods and bryozoans show on weathered surface, fresh surface is a light olive gray (5Y 6/1) weathering to a pale yellowish brown (10YR 6/2). _____	1.5

Sample No.	Description	Thickness (meters)
A	Wackestone, fine to medium grained, medium bedded, brachiopod molds, bryozoans and corals show on weathered surface, fresh surface is a light olive gray (5Y 6/1) weathering to a grayish orange (10YR 7/4).	1.5



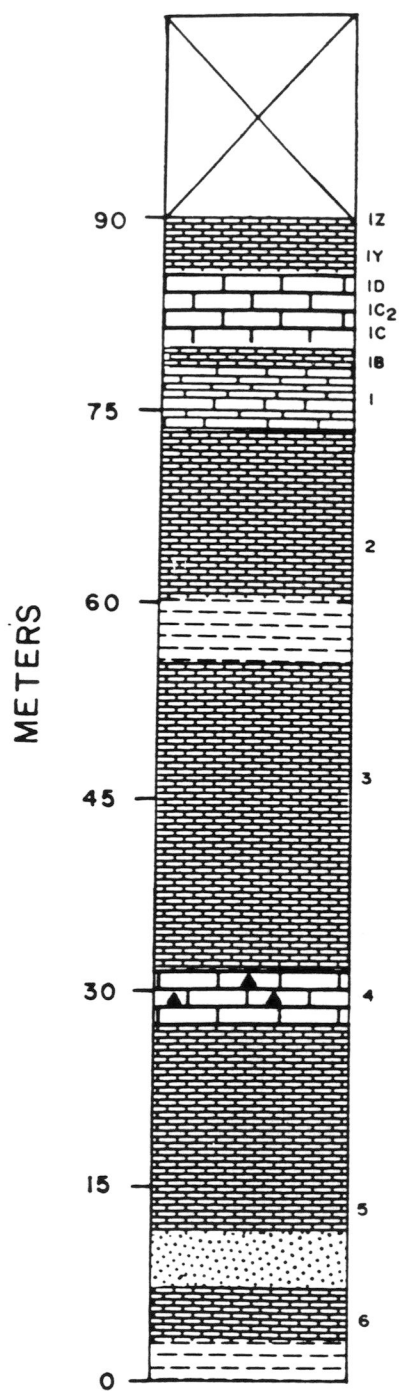
6: River Bend Outcrop.

OUTCROP AND CORE DESCRIPTIONS

6: RB - Samples from River Bend School

Sample No.	Descriptions	Thickness (Meters)
11, 12	Lime mudstone, very fine grained medium bedded, slightly friable, ostracode fragments seen, fresh surface is a medium dark gray (N4) weathering to a light olive gray (5Y 6/1). -----	1.5
10	Calcareous sandstone, very fine grained, thinly bedded, dense, crinoids show on weathered surface, fresh surface is a medium gray (N5) weathering to a light olive gray (5Y 6/1). -----	0.6
9	Sandy packstone, fine grained, medium bedded, friable, ooids, crinoids and fossils fragments abundant, fresh surface is medium gray (N5) to light brownish gray (5YR 6/1) weathering to a medium light gray (N6). -----	0.3
8	Calcareous sandstone, very fine grained, medium bedded, slightly rippled laminated, friable, no fossils seen, fresh surface is a light olive gray (5Y 6/1) weathering to a yellowish gray (5Y 7/2). -----	2.7
	Covered. -----	1.8
7B	Packstone, fine to medium grained, medium bedded, friable, crinoids show on weathered surface, fresh surface is a medium light gray (N6) weathering to a yellowish gray (5Y 7/2). -----	1.2
7	Grainstone, fine to medium grained, medium bedded, partially silicified, crinoids and bryozoans show on weathered surface, fresh surface is a light bluish gray (5B 7/1) weathering to a very light gray (N8). -----	1.5
	Covered. -----	1.2
6B	Packstone, fine to medium grained, medium bedded, contains chert nodules at its base, rugose corals and crinoids show on weathered surface, fresh surface is a brownish gray (5YR 4/1) weathering to a yellowish gray (5Y 7/2). -----	0.9

Sample No.	Description	Thickness (meters)
6	Lime mudstone, very fine grained, medium bedded, dense, contains many calcite veins, fresh surface is a medium gray (N5) weathering to a yellowish gray (5Y 8/1). —————	0.9
5	Wackestone, fine to medium grained, thinly bedded, friable, contains highly fossiliferous zones which parallel bedding, fresh surface is pale blue (5B 6/2) to a pale yellowish brown (10YR 6/2) weathering to a very pale orange (10YR 8/2). —————	0.6
	Covered. —————	16.8
4	Slightly sandy lime mudstone, fine grained, medium bedded, friable, fresh surface is a medium light gray (N6) weathering to a light brownish gray (5Y 6/1). —————	3.0
3	Packstone, fine to medium grained, medium bedded, slightly friable, brachiopods and crinoids show on weathered surface, fresh surface is a medium light gray (N6) weathering to a light olive gray (5Y 6/1). —————	0.9
2	Lime mudstone, very fine grained, thinly bedded, slightly silty, contains bedded chert nodules, no fossils seen, fresh surface is a light brownish gray (5YR 6/1) weathering to a grayish orange (10YR 7/4). —————	0.3
1	Lime packstone, fine to coarse grained, medium bedded, friable, corals and crinoids show on weathered surfaces, fresh surface is a medium gray (N5) weathering to a light olive gray (5Y 6/1). ———	1.5



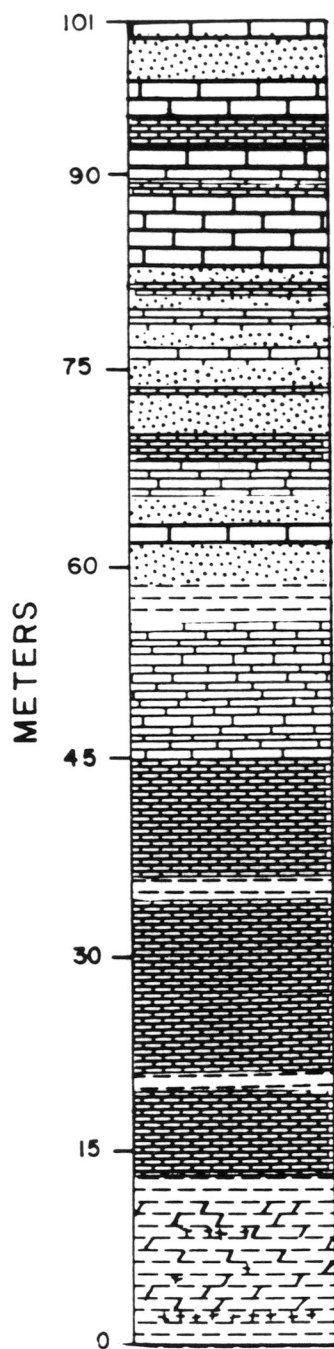
7: UKb - Samples from road cut 622. .

OUTCROP AND CORE DESCRIPTIONS

7: UKb - Samples from Roadcut 622

Sample No.	Descriptions	Thickness (Meters)
1	Mudstone, very fine grained, thinly bedded, friable, brachiopods show on weathered surface, fresh surface is a medium dark gray (N4) weathering to a grayish orange (10YR 7/4). —————	0.6
1B	Packstone, fine to medium grained, medium bedded, dense, strong petroliferous odor upon fresh break, brachiopods show on weathered surface, fresh surface is a medium dark gray (N4) weathering to a yellowish gray (5Y 7/2). —————	0.9
1C	Packstone, fine to medium grained, strong petroliferous odor upon fresh break, dense zones of bryozoans show on weathered surface, fresh surface is a medium dark gray (N4) weathering to a grayish orange (10YR 7/4). —————	0.9
1C 2	Wackestone, fine to medium grained, medium bedded, friable, slight petroliferous odor upon fresh break, brachiopods and bryozoans show on weathered surface, fresh surface is a medium gray (N5) weathering to a grayish orange (10YR 7/4). —————	0.9
1D	Wackestone, fine to medium grained, medium bedded, friable, large brachiopod molds (1") show on weathered surface, fresh surface is a brownish gray (5YR 4/1) weathering to a light olive gray (5Y 6/1). —————	1.2
ly ly-2	Lime mudstone, fine grained, medium bedded, friable, large brachiopod molds (1") show throughout, highly iron stained, fresh surface is a medium dark gray (N4) weathering to a pale yellowish orange (10YR 8/6). —————	3.0
1z	Packstone, fine to medium grained, medium bedded, dense, zones of large brachiopods show on weathered surface, fresh surface is a dark gray (N3) weathering to a pale yellowish brown (10YR 6/2). —————	0.6

Sample No.	Description	Thickness (meters)
1	Lime mudstone, fine grained, thin bedded, fissile, contains 2.0 cm thick beds of shale and has a petroliferous odor when broken, fresh surface is medium dark gray (N4) weathering to a pale yellowish brown (10YR 6/2). —————	6.0
2	Lime mudstone, fine to medium grained, medium bedded, bryozoans and brachiopods present, fissile, fresh surface is medium dark gray (N4) weathering to light gray (N6). ———	20.0
3	Calcareous mudstone, very fine grained, fissile, friable, bryozoans and pelecypods present, fresh surface is dark gray (N5) weathering to a light olive gray (5Y 6/1). ———	30.0
4	Lime wackestone, fine to medium grained, dense, silicified brachiopods and chert nodules exposed on weathered surface, fresh surface is dark gray (N5) weathering to a medium dark gray (N4) —————	5.0
5	Sandy, calcareous mudrock, fine to medium grained, medium bedded, dense, fresh surface is dark gray (N5) weathering to a medium dark gray (N4) —————	9.0
6	Calcareous mudrock, fine grained, fissile, friable, fresh surface is medium dark gray (N4) weathering to a medium gray (N5). —————	5.0



Maccrady Fm.

8: Core (Bonnie Dell), Plasterco, Virginia.

8: BD- core samples from Plasterco, Virginia

Sample No.	Description	Thickness (meters)
16, 17 18, 19	Lime mudstone, fine grained medium bedded, dense, contains algal laminations (some pyritized), microfaults with minor displacements and limited brecciation. Fresh surface is medium light gray (N6).	2.4
20, 21 22, 23 24, 25	Lime mudstone, fine to medium grained, medium bedded, contains 1.0 cm thick darker lime mudstone laminations and condensed zones, algal laminations, calcite veins and microfaults with minor displacements (0.5 mm). Fresh surface is medium light gray (N6).	3.7
26, 27 28, 29 30, 31	Dolomitic, gypsiferous, mudrock, fine grained, friable, algal laminations, contains 2-5 cm thick gypsum beds and satin spar gypsum veins, many microfaults (0.7 mm displacements). Fresh surface is medium light gray (N6)	9.7
32	Calcareous, mudrock, very fine grained, medium bedded, algal laminated containing 0.5 to 1.0 cm solution breccia clasts, and many satin spar gypsum veins. Fresh surface is pinkish gray (5YR 8/1).	2.0
33, 34 35, 36	Calcareous mudrock, fine grained, medium bedded, algal laminated, containing sandy fossiliferous (fragmented brachiopods and echinoderms) oolitic beds which are 5.0 to 6.0 cm thick and calcite veins. Fresh surface is medium dark gray (N4).	2.4
37, 38 39, 40 41, 42 43, 44 45, 46 47	Lime mudstone, very fine grained, medium bedded, dense, fossiliferous (fragmented bryozoans and pelecypods), bioturbated, algal laminated, containing 3.0 to 4.0 cm thick beds of very fine grained quartz sand which is well rounded and sorted. Fresh surface is medium gray (N5).	18.0
48, 49 50, 51 52, 53	Lime mudstone, fine grained, medium bedded, dense, fossiliferous (bryozoans and echinoderms), bioturbated and contain 2.0 to 3.0 cm beds of calcite spar cemented ooids and intraclasts. Fresh surface is medium dark gray (N4).	10.0

Sampleno.	Description	Thickness (meters)
54	Lime grainstone, medium grained, medium bedded, calcite spar cemented, ooids are approximately 0.5 mm in size with many concentric laminations. Fresh surface is medium gray (N5).	0.5
55, 56	Lime mudstone, medium bedded, brachiopods and bryozoans present in zoned concentrations, bioturbated containing thin beds (3-4 cm thick) of terrigenous muds, some calcite veins which cut across bedding. Fresh surface medium gray (N5).	1.5
57, 58, 59, 60 61, 62	Calcareous siltstone, fine grained, well sorted medium bedded, ooid bearing, bioturbated, containing 3.0 - 4.0 cm thick beds of terrigenous muds and calcite veins cutting across bedding. Fresh surface is medium gray (N5).	3.7
63, 64	Calcareous sandstone, very fine grained, medium bedded, bioturbated, ripple laminated, containing 2.0 - 5.0 cm thick beds of terrigenous mud which has satin spar veins cutting across it. Fresh surface is a medium gray (N5).	1.2
65, 66 67, 68 69, 70 71	Calcareous mudstone, fine grained, medium bedded, bioturbated, containing 2.0 - 3.0 cm beds of quartz sand which is well rounded and sorted, calcite veins are common. Fresh surface is medium gray (N5).	4.3
72, 73 74, 75 76	Calcareous sandstone, very fine grained, medium bedded, bioturbated containing terrigenous mud laminated and rippled. Fresh surface is medium gray (N5).	3.0
77, 78 79, 80 81	Calcareous mudstone, fine grained, medium bedded, dense, common quartz sand laminations, contains brachiopods and echinoderms and is rippled	

Sample No.	Description	Thickness (meters)
54	Lime grainstone, medium grained, medium bedded, calcite spar cemented, ooids are approximately 0.5 mm in size with many concentric laminations. Fresh surface is medium gray (N5).	0.5
55, 56	Lime mudstone, medium bedded, brachiopods and bryozoans present in zoned concentrations, bioturbated containing thin beds (3-4 cm thick) of terrigenous muds, some calcite veins which cut across bedding. Fresh surface medium gray (N5).	1.5
57, 58, 59, 60 61, 62	Calcareous siltstone, fine grained, well sorted medium bedded, ooid bearing, bioturbated, containing 3.0 - 4.0 cm thick beds of terrigenous muds and calcite veins cutting across bedding. Fresh surface is medium gray (N5).	3.7
63, 64	Calcareous sandstone, very fine grained, medium bedded, bioturbated, ripple laminated, containing 2.0 - 5.0 cm thick beds of terrigenous mud which has satin spar veins cutting across it. Fresh surface is a medium gray (N5).	1.2
65, 66 67, 68 69, 70 71	Calcareous mudstone, fine grained, medium bedded, bioturbated, containing 2.0 - 3.0 cm beds of quartz sand which is well rounded and sorted, calcite veins are common. Fresh surface is medium gray (N5).	4.3
72, 73 74, 75 76	Calcareous sandstone, very fine grained, medium bedded, bioturbated containing terrigenous mud laminated and rippled. Fresh surface is medium gray (N5).	3.0
77, 78 79, 80 81	Calcareous mudstone, fine grained, medium bedded, dense, common quartz sand laminations, contains brachiopods and echinoderms and is rippled laminated. Fresh surface is medium gray (N5).	3.0
82	Calcareous mudstone, very fine grained, medium bedded, dense, slightly fossiliferous, brachiopods and bryozoans. Fresh surface is medium gray (N5).	1.5
83, 84 85, 86 87	Lime mudstone, medium bedded, dense, fossiliferous (bryozoans and echinoderms). Fresh surface is medium gray (N5).	3.2

Sample No.	Description	Thickness (meters)
88	Calcareous sandstone, very fine grained, moderately rounded and well sorted grains, medium bedded, bioturbated, containing 3.0 - 5.0 cm beds of terrigenous muds. Fresh surface is medium gray (N5). _____	10.0
89, 90 91, 92 93, 94 95	Lime packstone, medium grained, medium bedded, contains interbeds of lime mud, brachiopods, bryozoans and echinoderms are present. Fresh surface is medium gray (N5). _____	4.3
96, 97 98	Lime mudstone, very fine grained, medium bedded, containing 5.0 - 7.0 cm calcareous mudrock interbeds, algal and ripple laminated. Fresh surface is medium dark gray (N4). -----	2.0
99	Lime packstone, fine to medium grained, medium bedded, dense, brachiopods, bryozoans, and echinoderms are abundant. Fresh surface is medium dark gray (N4). -----	2.0
100, 101	Lime mudstone, fine grained, medium bedded, dense, algal laminated, disseminated brachiopods, bryozoans and echinoderms. Fresh surface is medium gray (N5). _____	7.0
102	Lime packstone, fine to medium gray, medium bedded, bioturbated bryozoans and crinoids dominate and fossils oriented parallel to bedding. Fresh surface is medium gray (N5). _____	1.0
103, 104 105	Calcareous sandstone, very fine to fine grained, well rounded and sorted, medium bedded, bioturbated, rippled, cross bedded, containing thin beds (4.0 - 10.0 cm) of terrigenous mud. Fresh surface is medium gray (N5). _____	2.0
106, 107	Lime packstone, fine to medium grained, medium bedded, brachiopods, bryozoans and echinoderms common with elongate forms oriented parallel to bedding. Fresh surface is medium dark gray (N4). -----	3.0

APPENDIX B - INSOLUBLE RESIDUE DATA
FROM HWY. OUTCROP AND PLASTERCO, VIRGINIA CORE

INSOLUBLE RESIDUES

<u>Sample No.</u>	<u>Weight % Insolubles</u>	<u>Sample No.</u>	<u>Weight % Insolubles</u>
LVL-1	64.94	LVL-14E	41.27
LVL-2	52.72	LVL-14F	38.06
LVL-3	75.09	LVL-14G	43.68
LVL-4T	26.19	LVL-15	70.25
LVL-4	20.82	LVL-16T	72.53
LVL-4I	92.61	LVL-16A	72.53
LVL-4K	19.91	LVL-16B	74.35
LVL-4BC	17.54	LVL-16C	68.02
LVL-4J	18.26	LVL-16D	73.54
LVL-4B	30.52	LVL-16I	80.88
LVL-5	59.77	LVL-17T	73.24
LVL-5I	38.48	LVL-17B	69.65
LVL-5P	29.33	LVL-17C	16.89
LVL-6T	41.15	LVL-18D	39.81
LVL-6BR	38.29	LVL-18E	31.79
LVL-6	26.17	LVL-18F	36.11
LVL-7L	41.11	LVL-18G	31.03
LVL-7M	27.97	LVL-18H	44.12
LVL-7T	31.20	LVL-19T	75.36
LVL-7B	55.12	LVL-19A	50.74
LVL-8U	47.28	LVL-20T	19.67
LVL-8M	35.89	LVL-20D	27.86
LVL-8B	30.12	LVL-20E	87.96
LVL-9T	38.13	LVL-20L	24.43
LVL-9	55.68	LVL-20M	25.42
LVL-9C	53.56	LVL-20S	58.43
LVL-9D	52.23	BD-107	48.91
LVL-9E	27.09	BD-105	81.58
LVL-10TM	27.60	BD-101	87.01
LVL-10B	19.99	BD-100	82.35
LVL-11T	19.35	BD-99	37.81
LVL-11B	90.07	BD-96	49.41
LVL-11C	38.24	BD-93	37.35
LVL-11D	59.79	BD-91	31.13
LVL-12T	84.83	BD-89	25.22
LVL-12CA	77.04	BD-84	75.74
LVL-12C	86.23	BD-82	68.57
LVL-12R	76.42	BD-78	40.56
LVL-13T	27.86	BD-76	74.36
LVL-13A	28.48	BD-73	59.92
LVL-13B	57.34	BD-71	17.84
LVL-13C	58.31	BD-66	27.47
LVL-14T	31.35	BD-64	69.26
LVL-14A	84.76	BD-62	88.58

INSOLUBLE RESIDUES (continued)

<u>Sample No.</u>	<u>Weight % Insolubles</u>	<u>Sample No.</u>	<u>Weight % Insolubles</u>
LVL-14B	56.73	BD-59	91.73
LVL-14C	35.40	BD-57	77.11
LVL-14D	30.15	BD-53	62.10
BD-48	20.81	BD-30	81.28
BD-46	77.50	BD-27	85.29
BD-43	81.58	BD-24	63.48
BD-40	79.39	BD-21	35.34
BD-36	57.97	BD-19	34.23
BD-34	47.99		

APPENDIX C - MICROFACIES POINT COUNT DATA

LIME MUDSTONE MICROFACIES POINT COUNT DATA

Sample	Brach	Bryz	Echn	Ostr	Pele	Corl	Form	Tril	Cono	Gast	Unfos	Plant	Cort	Ooid	In/Ex	Spar	Miert	Dolo	Tmud	Tsand	Gyp/An
LVL-1	2.0	0.7	1.3	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	85.7	0.0	4.3	3.3	0.0
LVL-3	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.7	0.0	0.6	2.7	0.0
LVL-5I	1.3	0.0	0.0	0.7	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	85.0	0.0	12.7	0.0	0.0
LVL-5P	0.0	1.7	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	90.0	0.0	6.0	0.0	0.0
LVL-6BR	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	92.3	0.0	5.0	1.0	0.0
LVL-7T	0.0	1.7	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	67.3	29.3	0.0	0.0	0.0
LVL-7L	1.3	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	75.7	20.3	T	2.0	0.0
LVL-7M	4.3	0.7	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	84.7	8.7	0.0	0.0	0.0
LVL-7B	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	60.4	39.3	T	0.0	0.0
LVL-8U	1.3	7.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	56.0	34.7	T	0.0	0.0
LVL-9D	2.0	1.3	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7	0.0	15.0	1.4	0.0
LVL-9C	2.0	1.3	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	78.3	9.3	7.7	0.8	0.0
LVL-11C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	89.0	0.0	1.0	10.0	0.0
LVL-11D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	58.3	0.0	41.7	0.0	0.0
LVL-13T	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	90.0	0.0	10.0	0.0	0.0
LVL-13B	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	79.7	0.0	15.0	1.7	0.0
LVL-14D	1.0	0.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	0.0	0.0	0.0	0.0	0.0	81.0	0.0	2.0	11.4	0.0
LVL-14E	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	65.0	0.0	28.4	6.3	0.0
LVL-14F	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	90.0	0.0	5.0	5.0	0.0
LVL-14G	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.3	0.7	0.0	76.3	0.0	0.4	22.4	0.0
LVL-20L	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	56.0	15.7	T	28.0	0.0
BD-105	0.0	0.0	6.0	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	2.3	0.0	0.0	0.0	0.0	53.7	0.0	34.0	4.0	0.0
BD-79	0.7	2.3	0.3	0.0	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	T	2.0	0.0	34.0	27.0	14.0	16.0	0.0
BD-78	0.0	0.0	1.0	2.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	48.7	0.0	T	48.0	0.0
BD-77	T	T	T	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.3	0.0	54.4	0.0	9.7	35.3	0.0
BD-75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	62.3	0.0	2.7	35.0	0.0
BD-74	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	65.0	0.0	2.7	32.3	0.0
BD-70	0.3	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	56.3	0.0	30.0	12.0	0.0
BD-66	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.0	0.0	25.3	8.7	0.0
BD-65	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	68.4	0.0	8.3	19.3	0.0
BD-50	1.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	61.3	0.0	34.0	2.7	0.0
BD-41	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	59.3	0.0	26.0	14.0	0.0
BD-40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	57.7	0.0	35.6	6.7	0.0
BD-39	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	0.0	58.6	0.0	13.0	26.7	0.0
BD-38	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	0.0	70.3	0.0	22.0	6.0	0.0
BD-37	0.0	0.0	0.0	1.7	T	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	48.7	0.0	47.6	1.0	0.0
BD-34	0.3	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	60.7	0.0	35.3	2.0	0.0
BD-25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	49.3	28.0	20.0	T	2.7
BD-21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	76.0	0.0	23.0	1.0	0.0
BD-20	0.0	0.7	0.7	T	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.7	0.0	48.7	0.0	28.2	15.0	0.0
BD-19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	64.0	0.0	29.0	7.0	0.0
BD-18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	76.3	0.0	20.7	3.0	0.0
BD-17B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	60.7	0.0	19.0	20.3	0.0
BD-16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	70.0	0.0	24.7	5.3	0.0

LIME WACKESTONE MICROFACIES POINT COUNT DATA

Sample	Brach	Bryz	Echn	Ostr	Pelc	Corl	Form	Tril	Cono	Gast	Unfos	Plant	Cort	Ooid	In/Ex	Spar	Micrt	Dolo	Tmud	Tsand	Gyp/An
LVL-8B	9.0	12.3	3.7	0.7	0.0	0.0	0.0	0.0	0.0	0.0	2.3	0.0	0.0	0.0	0.0	0.0	74.7	7.3	0.0	0.0	0.0
LVL-9T	3.7	1.3	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	0.0	0.0	0.0	0.0	62.0	27.7	0.0	0.0	0.0
LVL-10B	4.7	6.3	16.0	1.0	0.0	0.0	4.0	0.0	0.0	0.0	5.0	0.0	0.0	0.0	0.3	0.0	72.7	0.0	0.0	0.0	0.0
LVL-5	20.0	11.3	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	12.0	0.0	0.0	0.0	0.0	0.0	75.3	0.0	10.0	1.0	0.0
LVL-13C	10.3	0.3	12.3	0.0	0.0	0.0	0.0	1.0	0.3	0.0	3.3	0.0	0.0	0.0	0.0	0.0	39.7	0.0	25.7	17.3	0.0
LVL-14C	1.0	4.3	14.3	0.0	0.0	0.0	0.0	0.3	0.0	0.0	5.7	0.0	0.0	0.0	0.0	0.0	67.7	0.0	2.7	4.0	0.0
LVL-19T	6.7	5.7	0.3	0.0	0.0	0.0	0.0	0.7	0.0	0.0	5.7	0.0	0.0	0.0	0.0	0.0	60.0	21.0	0.0	0.0	0.0
BD-71	13.3	0.0	2.7	2.7	0.0	0.0	T	0.0	0.0	0.0	0.0	2.0	0.0	T	0.0	0.0	65.3	0.0	7.0	9.0	0.0
BD-56	3.3	13.0	7.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	2.0	0.0	0.0	0.0	11.7	10.0	38.7	0.0	18.7	0.0
BD-52	2.3	3.0	1.0	4.7	T	0.0	0.0	0.0	0.0	0.0	0.7	1.0	0.0	0.0	0.0	0.0	42.3	37.0	0.0	8.0	0.0
BD-51	0.3	0.7	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	0.0	0.0	44.0	34.7	0.0	9.0	0.0
BD-49A	4.3	T	11.3	9.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	4.7	19.0	0.0	0.0	21.0	34.3	0.0	4.7	0.0
BD-23	8.3	3.0	T	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	69.3	1.7	16.0	1.7	0.0

LIME PACKSTONE MICROFACIES POINT COUNT DATA

Sample	Brach	Bryz	Echn	Ostr	Pelc	Corl	Form	Tril	Cono	Gast	Unfos	Plant	Cort	Ooid	In/Ex	Spar	Miert	Dolo	Tmud	Tsand	Gyp/An
LVL-1B	7.7	23.0	16.0	0.3	T	0.0	0.3	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	52.3	0.0	0.0	0.0	0.0
LVL-2	13.0	4.3	10.0	1.0	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	71.7	0.0	0.0	0.0	0.0
LVL-4	40.0	T	23.3	1.0	0.0	0.0	0.0	0.0	0.3	0.3	7.3	0.0	0.0	0.0	0.0	23.3	2.7	0.0	0.0	9.0	0.0
LVL-4J	20.3	7.7	9.3	2.3	T	0.0	0.0	0.0	0.7	0.0	11.7	0.0	0.0	0.0	0.0	0.0	46.3	0.0	0.0	1.7	0.0
LVL-4B	16.0	16.0	8.3	2.7	T	0.0	0.0	0.3	0.0	0.7	5.7	0.0	0.0	0.0	0.0	0.0	49.3	0.0	0.0	1.0	0.0
LVL-4K	18.7	7.7	23.7	0.3	0.0	0.0	0.0	0.0	0.0	0.0	11.7	0.0	0.0	0.0	0.0	24.7	13.3	0.0	0.0	0.0	0.0
LVL-4U	10.7	10.0	19.0	0.0	0.0	0.0	0.0	0.3	0.0	0.7	10.0	0.0	0.0	0.0	0.0	1.7	47.3	0.0	0.0	0.3	0.0
LVL-6T	0.3	46.7	7.0	0.0	0.0	0.0	0.3	0.3	0.0	0.0	7.0	0.0	0.0	0.3	3.7	3.7	5.7	0.0	0.0	20.7	0.0
LVL-9E	16.0	14.7	2.0	0.0	T	0.0	0.0	0.3	0.0	0.0	4.0	0.0	0.0	0.0	0.3	0.0	62.7	0.0	0.0	0.7	0.0
LVL-10C	12.3	5.7	4.3	T	0.7	T	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	75.0	0.0	0.0	0.7	0.0
LVL-11T	2.7	19.7	6.0	0.0	11.7	0.0	0.0	0.0	0.0	2.0	3.0	0.0	0.0	0.0	0.0	0.0	55.3	0.0	0.0	0.0	0.0
LVL-13A	3.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	45.0	0.0	0.0	0.0	0.0	31.3	9.7	0.0	6.7	3.7	0.0
LVL-18D	13.7	34.0	15.3	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.7	0.0	0.0	1.3	0.0
LVL-18F	18.7	37.3	6.7	0.0	0.0	0.0	0.0	1.7	0.0	1.0	7.7	0.0	0.0	0.0	0.0	0.0	27.0	0.0	0.0	0.0	0.0
LVL-18G	22.3	20.7	2.7	0.3	0.0	0.0	0.0	0.0	0.0	0.0	13.0	0.0	0.0	0.0	0.0	1.7	39.3	0.0	0.0	0.0	0.0
LVL-18H	11.7	4.0	10.3	0.7	0.0	0.0	0.0	0.0	0.0	0.0	5.7	0.0	0.0	0.0	0.0	33.3	11.7	22.7	0.0	0.0	0.0
LVL-20S	23.7	10.7	0.3	0.0	0.0	0.0	0.0	1.0	0.0	0.0	6.7	0.0	0.0	0.0	0.0	0.0	11.3	36.7	0.0	8.7	0.0
LVL-20T	59.7	8.0	4.7	0.0	0.0	0.0	0.0	7.0	1.3	0.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.0	0.3	0.0
LVL-20M	9.0	16.3	41.7	0.0	0.0	0.3	0.0	0.7	0.3	0.0	9.3	0.0	0.0	0.0	0.0	0.0	22.3	0.0	0.0	0.0	0.0
LVL-20D	12.3	3.7	9.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	0.0	3.7	0.0	0.0	11.7	30.0	20.7	0.0	12.7	0.0
BD-106	19.7	23.7	4.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	39.0	0.0	13.3	0.0
BD-99	30.3	12.0	7.0	0.0	0.0	0.0	T	0.0	T	0.0	2.7	0.0	0.0	0.0	0.0	0.0	1.0	46.0	0.0	1.0	0.0
BD-94	15.7	40.3	6.3	0.0	0.0	0.0	0.0	5.3	T	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	31.7	0.0	0.0	0.0
BD-93	12.7	32.3	16.3	T	0.0	0.0	0.0	1.7	T	0.0	2.7	0.0	0.0	0.0	0.0	0.0	13.7	20.3	0.0	0.0	0.0
BD-92	18.7	28.7	6.0	0.0	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	42.7	0.0	1.3	0.0
BD-91	17.3	58.3	11.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	7.3	5.0	0.0	0.0	0.0
BD-90	16.7	59.7	4.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.7	17.3	0.0	0.3	0.0
BD-89	49.0	24.0	13.0	0.0	2.0	0.0	0.0	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.3	0.0	0.0	0.0
BD-54B	14.3	0.0	4.3	7.7	0.0	0.0	0.3	0.0	0.0	0.0	1.3	0.0	9.0	6.7	0.0	3.0	21.0	0.0	25.7	6.3	0.0

LIME GRAINSTONE MICROFACIES POINT COUNT DATA

Sample	Brach	Bryz	Echin	Ostr	Pelc	Corl	Form	Tril	Cono	Gast	Unfos	Plant	Cort	Ooid	In/Ex	Spar	Micrt	Dolo	Truds	Tsand	Gyp/An
LVL-14T	T	89.7	6.3	0.0	0.0	T	T	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.7	0.3	0.0	0.0	0.0	0.0
LVL-14C	0.3	10.3	40.3	T	T	0.0	1.3	0.0	0.0	6.0	0.0	0.0	0.0	0.0	0.6	32.0	7.3	0.0	0.0	1.3	0.0
LVL-17T	6.7	11.7	14.0	0.6	0.3	T	0.0	0.0	0.0	0.0	9.0	0.0	0.0	0.0	0.0	51.7	0.0	0.0	5.7	0.3	0.0
LVL-17C	7.7	11.3	13.0	0.3	1.0	0.0	0.3	0.6	0.0	0.0	8.7	0.0	0.0	0.0	0.0	49.8	0.0	0.0	6.7	0.6	0.0
LVL-18E	14.3	27.0	26.3	0.6	0.0	T	0.0	1.0	0.0	0.0	6.7	0.0	0.0	0.0	0.0	19.3	1.0	0.0	0.0	3.8	0.0
BD-33	0.5	0.0	1.0	7.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	3.3	44.0	20.3	2.3	0.0	0.0	19.0	0.0
BD-48	1.7	0.0	5.3	6.3	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	14.7	20.0	0.0	43.7	0.0	0.0	0.0	7.7	0.0

CALCAREOUS MUDDY SANDSTONE MICROFACIES POINT COUNT DATA

Sample	Brach	Bryz	Echn	Ostr	Pele	Corl	Form	Tril	Gast	Unfos	Plant	Cort	Ooid	In/Ex	Spar	Micrt	Dolo	Tmud	Tsand	Chert	Plag	Gyp/An
LVL-15	0.0	0.3	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	29.0	0.0	0.0	0.0	56.7	9.7	0.0	0.0
LVL-16A	0.0	0.3	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.3	0.0	11.0	72.3	0.0	0.0	0.0
LVL-16C	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	T	0.0	0.0	0.0	0.0	23.1	0.0	25.0	49.3	0.0	0.0	0.0
LVL-16I	4.0	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.3	0.0	35.7	51.0	0.0	0.0	0.0
LVL-20E	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	7.7	0.0	0.0	30.3	55.0	4.3	2.7	0.0
LVL-20E1	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	6.0	0.0	0.0	38.0	55.0	1.0	0.0	0.0
BD-102	14.3	10.3	3.3	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.3	65.3	0.0	0.0	0.0
BD-88	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	3.3	0.0	27.0	0.0	60.3	5.3	3.7	0.0
BD-80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.3	0.0	19.3	15.3	51.0	0.0	0.0	0.0
BD-76	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	25.3	0.0	0.0	19.3	51.3	2.3	1.7	0.0
BD-73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	15.3	27.3	0.0	3.0	54.3	0.0	0.0	0.0
BD-72	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.0	6.0	0.0	1.0	72.0	0.0	0.0	0.0
BD-69	0.0	0.0	8.7	0.0	0.0	0.0	0.0	T	0.0	0.0	0.3	0.0	0.0	0.0	20.0	0.0	0.0	27.0	33.7	0.0	0.6	9.7
BD-67	0.0	0.0	0.3	T	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	39.7	0.0	16.0	43.3	0.0	0.0	0.0
BD-64	0.0	0.0	9.7	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	27.0	11.0	47.7	3.3	1.0	0.0
BD-63	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.0	70.3	3.0	1.0	0.0
BD-62	0.0	0.0	0.3	0.0	0.0	0.0	0.0	T	0.0	0.0	0.6	0.0	0.0	0.0	6.0	0.0	0.0	32.0	61.0	0.0	0.0	0.0
BD-61	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	1.0	0.6	0.0	4.3	0.0	5.7	0.0	0.0	21.6	66.7	0.0	0.0	0.0
BD-60	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	36.7	0.0	11.0	0.0	0.0	14.0	37.7	0.0	0.0	0.3
BD-59	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	27.3	66.3	2.0	3.0	0.0
BD-57A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	2.0	0.0	0.0	0.0	6.0	0.0	0.0	41.0	51.0	0.0	0.0	0.0

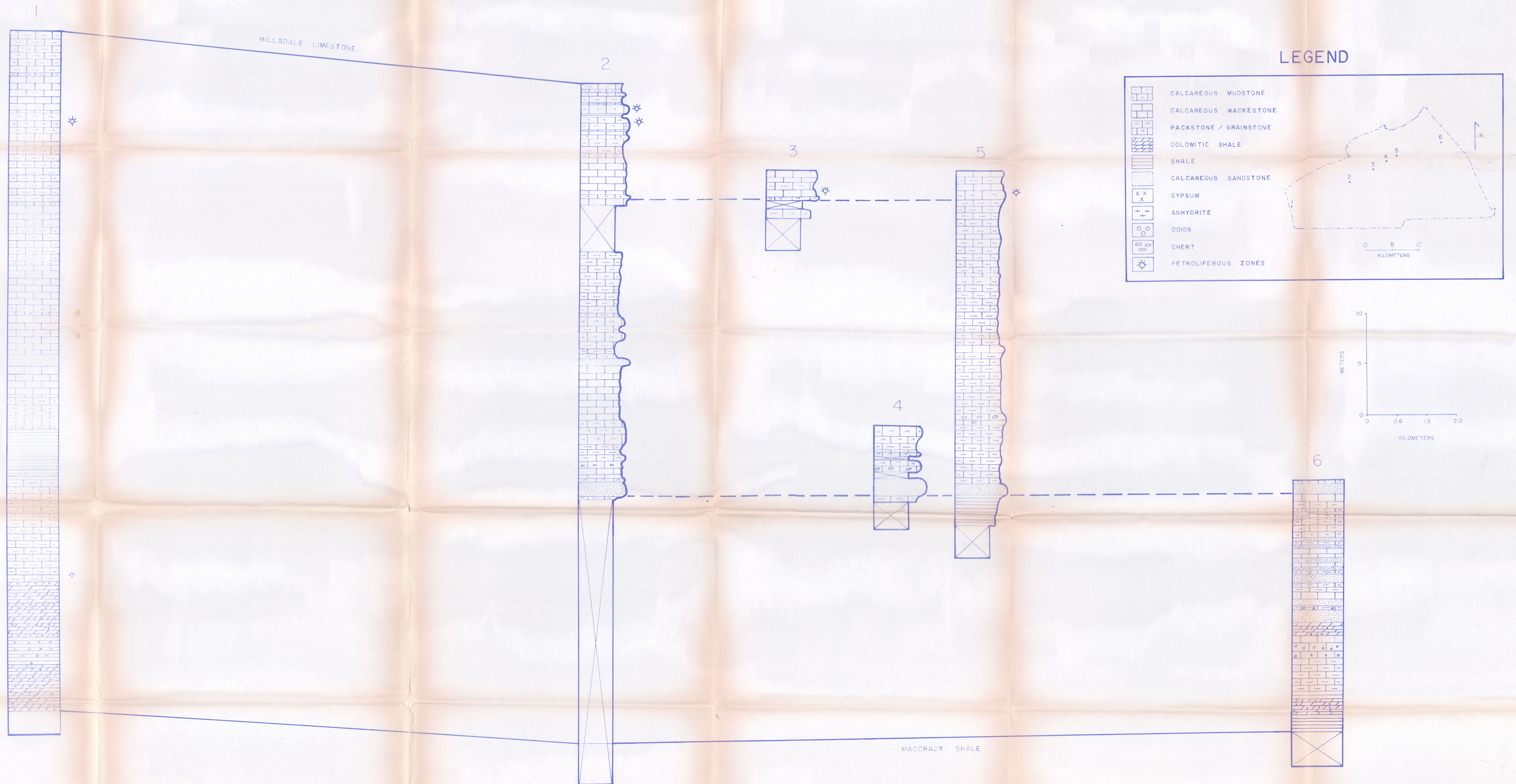
CALCAREOUS MUDROCK MICROFACIES POINT COUNT DATA

Sample	Brach	Bryz	Echn	Ostr	Pelc	Corl	Form	Tril	Cono	Gast	Unfos	Plant	Cort	Ooid	In/Ex	Spar	Micrt	Dolo	Tmud	Tsand	Gyp/An
LVL-4.5	1.3	T	0.3	T	0.0	0.0	0.0	0.0	1.0	0.0	11.7	0.0	0.0	0.0	0.0	0.6	0.0	0.0	75.3	9.7	0.0
LVL-5B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	36.0	T	50.0	12.3	0.0
LVL-9	2.0	0.0	T	T	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	46.7	0.0	50.0	1.0	0.0
LVL-11B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	T	95.0	0.0	0.0
LVL-12T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	90.0	0.0	0.0
LVL-12C	T	0.3	0.3	T	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	23.0	0.0	76.0	0.0	0.0
LVL-14A	0.0	1.0	1.0	T	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	5.0	T	90.0	1.0	0.0
LVL-16T	0.0	0.0	0.6	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.0	0.0	70.1	5.3	0.0
LVL-16B	0.0	0.0	0.3	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.7	0.0	45.0	14.0	0.0
LVL-16D	0.0	1.0	1.0	0.6	T	0.0	T	0.3	0.0	0.0	4.3	0.0	0.0	0.0	0.0	3.7	10.7	0.0	44.0	34.3	0.0
LVL-17B	1.5	0.0	3.0	0.0	0.0	0.0	0.5	0.0	T	0.0	0.0	0.0	0.0	0.0	T	0.0	40.0	0.0	40.0	15.0	0.0
LVL-19A	0.6	0.0	0.3	T	0.0	0.0	0.0	0.0	T	0.0	15.7	0.0	0.0	0.0	0.0	0.0	T	0.0	68.3	15.0	0.0
BD-100	1.3	14.7	0.6	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	T	74.7	8.7	0.0
BD-68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	20.0	0.0	42.0	38.0	0.0
BD-58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	1.0	0.0	T	60.6	38.3	0.0
BD-55	0.3	0.0	0.6	T	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.6	0.0	0.0	0.0	11.7	0.0	T	72.3	12.7	0.0
BD-53	1.0	0.6	0.3	4.0	0.3	0.0	0.0	0.0	0.0	0.0	2.0	0.6	0.0	0.0	8.3	0.0	1.6	0.0	65.0	16.3	0.0
BD-47	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	2.3	0.0	0.0	60.3	37.3	0.0
BD-46	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	31.3	T	45.3	23.3	0.0
BD-45	0.0	T	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.3	28.7	0.0	43.0	23.0	0.0
BD-44	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	34.7	T	53.6	11.7	0.0
BD-43	0.0	T	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	27.0	T	62.0	11.0	0.0
BD-42	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	39.3	0.0	51.7	8.7	0.0
BD-36	0.0	T	T	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	39.7	T	55.3	4.7	0.0
BD-35	0.0	0.0	T	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	0.0	0.0	40.0	T	52.0	8.0	0.0
BD-32B	T	0.0	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	3.3	0.0	34.3	T	46.0	16.3	0.0
BD-24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	0.0	T	0.0	0.0	46.3	45.0	8.7	0.0
BD-22	0.0	0.0	T	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	0.0	23.0	0.0	77.0	T	0.0

SECONDARY GYPSUM MICROFACIES POINT COUNT DATA

Sample	Micrt	Dolo	Sec-Gyp	Anhy	Tmud
BD-31	0.0	54.0	46.0	T	0.0
BD-29	0.0	7.0	45.7	47.3	0.0
BD-28	0.0	27.3	70.3	2.3	0.0
BD-27	0.0	0.0	54.3	T	45.7
BD-26	1.7	10.7	74.0	T	13.7

GEOLOGIC CROSS SECTION OF THE LITTLE VALLEY LIMESTONE WASHINGTON COUNTY, VIRGINIA



PREDOMINANT FAUNA VS. INSOLUBLE RESIDUES TOTAL AVERAGE PERCENT

