THE UNIVERSITY OF MANITOBA

DIAGENESIS AND POROSITY EVOLUTION WITHIN THE UPPER SHUNDA AND TURNER VALLEY FORMATIONS, MOOSE DOME AREA, ALBERTA

by

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Abstract

A sequence of carbonates of Mississippian age was studied in the vicinity of Moose Dome, Alberta, to interpret the relationships existing betwen the original depositional environment, the subsequent diagenetic alterations, and the effects which diageneis may have played in the development of porosity and permeability. The stratigraphic interval studied includes the upper portion of the Shunda Formation and the overlying Turner Valley Formation.

Shunda sediments were deposited within broad systems of shallow, restricted lagoons and intertidal mud flats dissected by tidal channels. Landward, these complexes give way to extensive areas of supratidal flats and marshes. Resultant sediment types contain a high content of carbonate mud, a paucity of coarse-grained skeletal material, and show extensive reworking by mud-scavenging organisms. The nature of their depositional environments renders these sediments susceptible to subaerial vadose zone diagenesis which includes the development of green shale facies,minor erosional breaks, micro-karst surfaces, subaerial laminated crusts or caliche horizons and dissolution features. The majority of the porosity developed within these sediments is of a secondary nature created by selective removal of earlier formed calcite cements and is a direct product of exposure of these sediments to the vadose zone of subaerial diagenesis.

The Turner Valley Formation is comprised of distinctly different sediment types and fabrics formed in response to their deposition in the deeper waters of the open shelf environment or within systems of offshore shoals and bars. Grain supported sediments are common and

are comprised of coarse-grained skeletal material largely of an echinoderm origin. These sediments display few early diagenetic alterations of the subaerial vadose zone.

Much of the porosity and permeability displayed within these sediments is intercrystalline or moldic and is related to a later period of dolomitization and leaching than the porosity observed within the Shunda Formation.

Dolomites of the Turner Valley Formation are more coarsely crystalline than those of the Shunda Formation and are believed to have formed by a mechanism of meteoric and marine water mixing.

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CHAPTER 1

General Introduction

Introduction

The thick sequences of Mississippian carbonate sediments deposited in the Western Canada Sedimentary Basin contain important accumulations of hydrocarbons. Most of the porosity developed within these sediments is of a secondary nature and is therefore intimately associated with the diagenetic history of these sediments.

In recent years many diagenetic studies have been undertaken on the more modern Cenozoic accumulations of carbonate sediments. These studies have greatly increased our understanding of the often complex diagenetic processes affecting carbonate sediments. Much of this knowledge can be directly applied to unraveling the diagenetic histories of the more ancient Paleozoic carbonate sediments.

Area of Study

Excellent localities for the study of ancient carbonates of Mississippian age are provided within the Foothills and Front Ranges of the Canadian Rocky Mountains. An area of study was chosen approximately 45 kilometres west of Calgary, Alberta in the vicinity of Moose Dome at 114° 50' longitude and 50°54' latitude (Figure 1). Moose Dome is an inlier of Mississippian strata surrounded by younger rocks of Jurassic and Lower Cretaceous age. The more southerly portion of the domal structure has been dissected by the valley and tributaries of Canyon Creek. The creek bed provides good exposures of the Mississippian

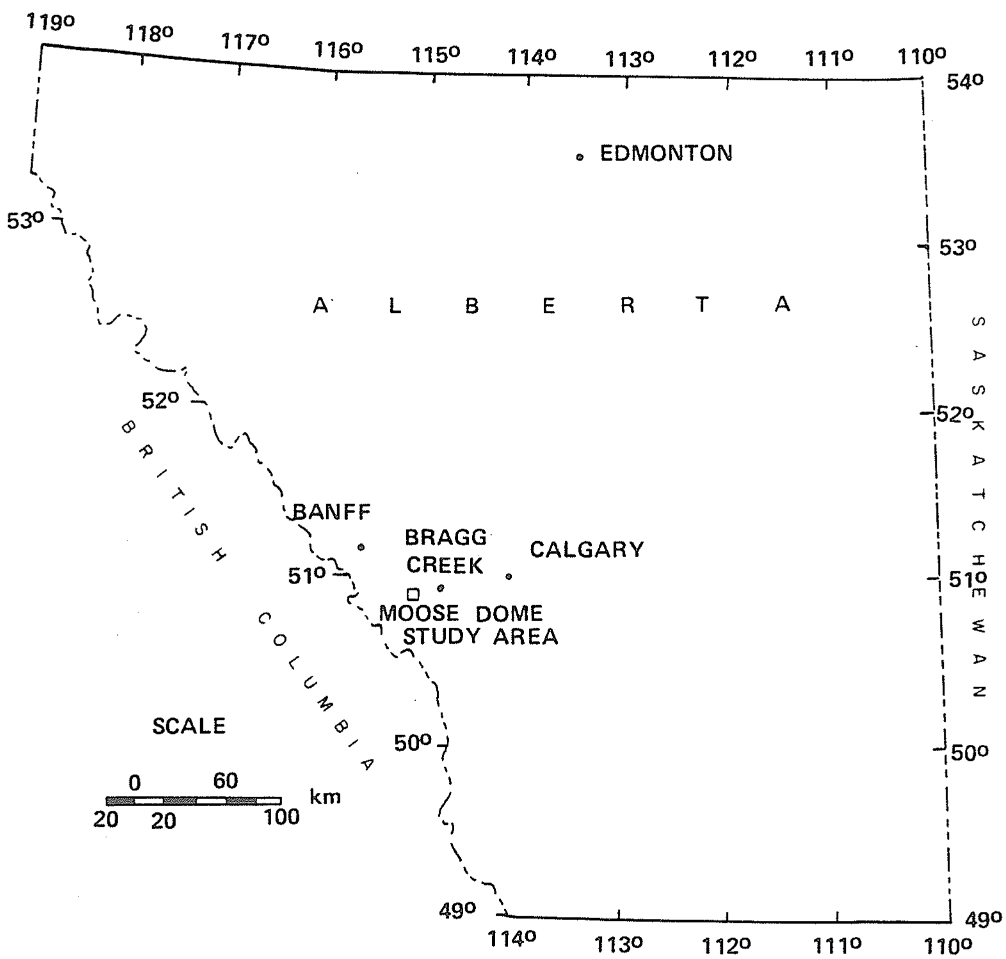

FIGURE 1 LOCATION MAP OF STUDY AREA

strata and an easy means of access to the area via its juncture with the Elbow River.

Good exposures of rock are found on a quarry face which occurs on the eastern flank of the dome (Plate 1-1). Thirty metres of section were measured at this locality. The section comprises the uppermost portion of the Shunda Formation and lowermost units of the overlying Turner Valley Formation.

One hundred and sixty-one metres of section were measured along the creek bed of Canyon Creek on the western flank of the dome (Figure 2). The section commences near the base of the Turner Valley Formation and proceeds up to the lowermost beds of the overlying Mount Head Formation. Several minor covered intervals occur within this section.

Previous Work

The area was mapped by Beach (1943, map 688A) who compiled structural cross-sections and a measured section of the Mississippian (Beach, 1943, p. 19-20, 27-28). Douglas (1958) presented a summary and discussion of Mississippian stratigraphy in southwestern Alberta. Illing (1959, p. 37-52) examined the cyclic nature of carbonate sedimentation in the vicinity of Moose Dome. An investigation of selective dolomitization was carried out by Murray and Lucia (1967) on Turner Valley exposures on the east flank of Moose Dome along Moose Dome Creek. Work of Macqueen, et al (1972) discuss the biostratigraphy, stratigraphy and sedimentology of the Moose Dome and other areas.

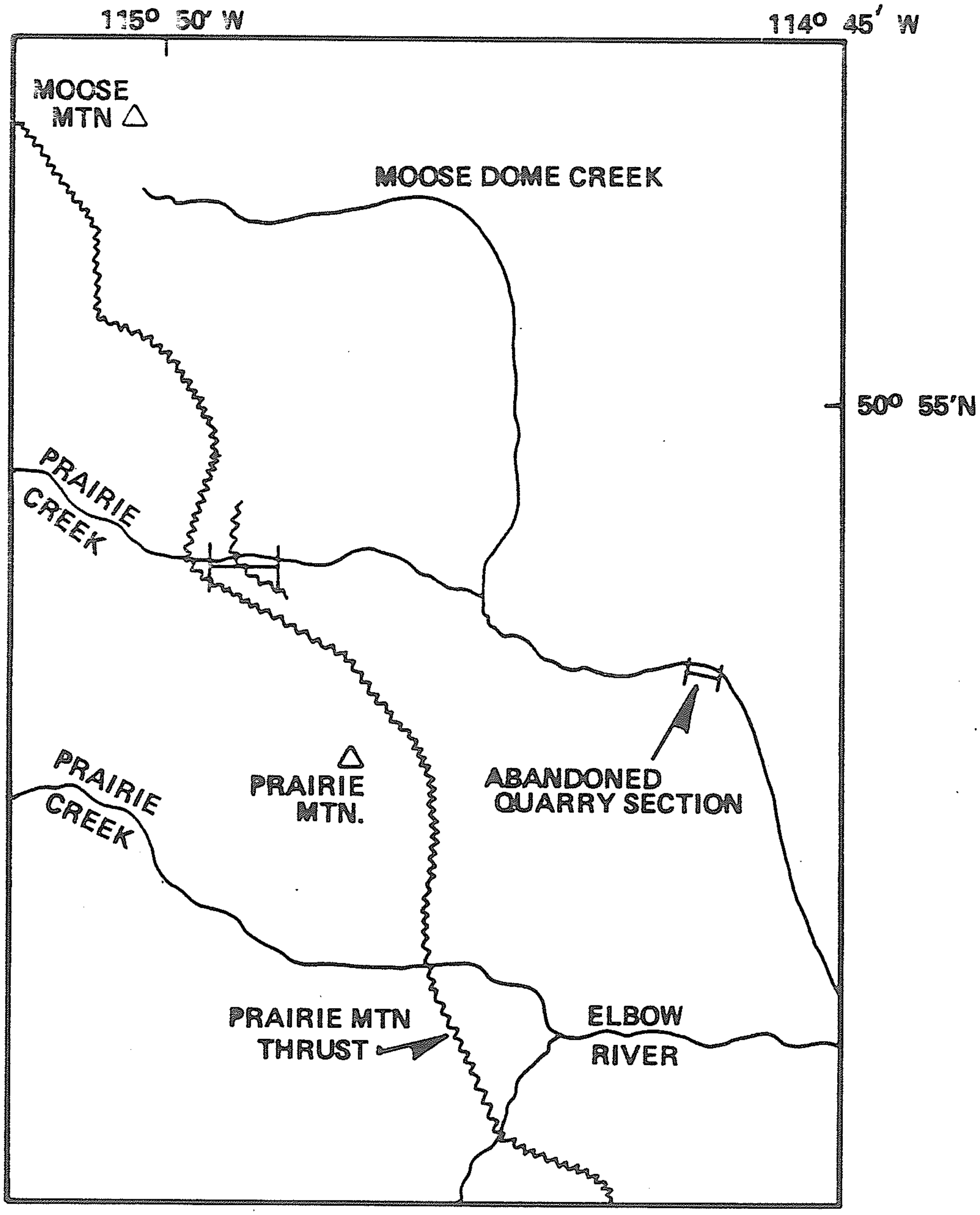

FIG 2. GEOLOGIC SKETCH MAP, MOOSE DOME AREA
MODIFIED FROM BEACH (1943)

Regional Mississippian Stratigraphy

A regional summary of Mississippian stratigraphy of the southern Alberta plains region is given by Penner (1958, p. 263). A more complete description of regional Mississippian stratigraphy in the southwestern Canadian Rockies is given by Macqueen and Bamber (1967).

Mississippian sedimentary rocks within the Western Canada Sedimentary Basin are predominately shallow-water marine deposits. Carbonate rocks predominate in southern Alberta and argillaceous content increases northward. Of the numerous interpretations put forth for Paleozoic sedimentation within western Canada, the most popular postulates relatively continuous sedimentation from Devonian into Pennsylvanian time. Toward the end of the Mississippian,deposition of terrigenous clastics predominated.

The Carboniferous of western Canada is divisible into three mappable units which reflect differing phases of sedimentation (Proctor and Macauley, 1968). At Moose Dome, only the first two are represented, the third unit having been removed by post-Mississippian erosion (Figure 3).

The three map units consist of:

i) A lower unit consisting mainly of siltstones and calcareous shales which is represented at Moose Dome by the Exshaw and Banff Formations.

ii) a middle unit composed of shallow water marine carbonate sequences generally lacking in terrigenous clastic material. This is represented at Moose Dome by the Pekisko, Shunda, Turner Valley and Mount Head Formations.

iii) An upper unit consisting predominately of terrigenous clastic rocks which is not exposed in the Moose Dome area.

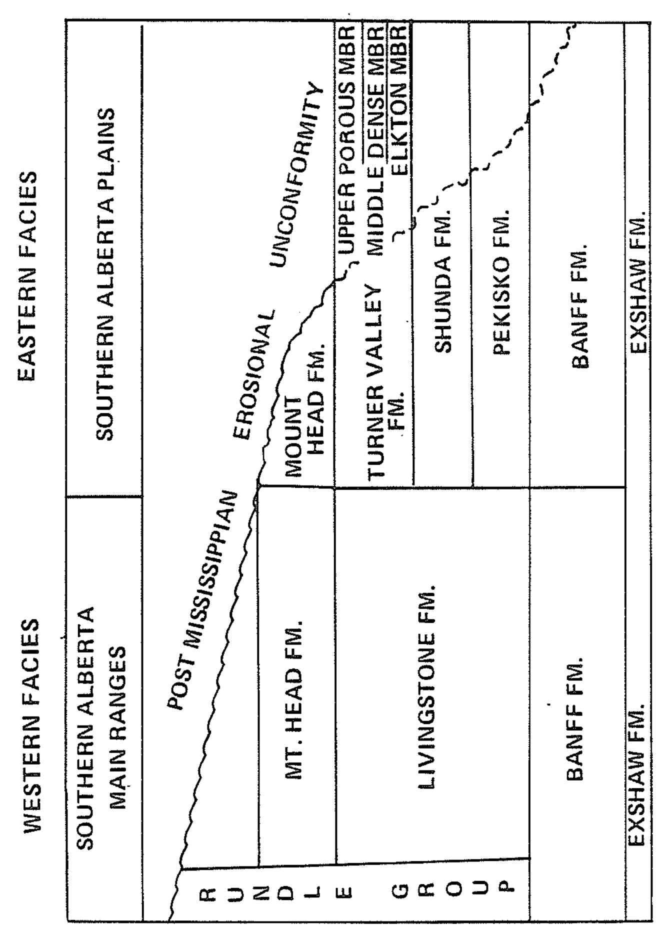

FIG. 3 REGIONAL MISSISSIPPIAN STRATIGRAPHY, MODIFIED FROM PROCTOR & MACAULEY (1968)

Exshaw Formation

The Exshaw Formation consists of recessive black bituminous shales of vast aereal extent and constant lithology and thickness indicating a uniform depositional environment over an almost flat Devonian surface. Bituminous shales are formed in stagnant water conditions such as the deep euxinic waters of ocean basins.

Banff Formation

Overlying the Exshaw Formation are the argillaceous and cherty lime mudstones of the Banff Formation. Illing (1959) interprets these sediments to have been deposited below wave base in an open marine environment with normal marine salinities and circulation conditions. Anaerobic bottom conditions are responsible for the high organic content found within the sediments. Within the Banff are localized horizons of wackestones and packstones. These rocks contain abundant echinoderm detritus and are interpreted by Illing (1959) to represent the development of localized shoals or banks within the deeper water Banff deposits.

Livingstone Formation

Directly overlying the Banff Formation are rocks of the middle map unit. This unit is comprised of an eastern and western facies (Figure 3). The western facies has been termed the Livingstone Formation. The Livingstone Formation is well developed in the vicinity of Banff, Alberta and can be traced southwards through the main ranges of the Rocky Mountains to the Canada-United States boundary. The Livingstone Formation is composed mainly of echinoderm - bryozoan limestones. These form coarse-grained skeletal sands believed to have been deposited in an extensive regional system of shallow-water, current swept echinoderm banks. The more easterly facies equivalent of the Livingstone Formation consists, in ascending order, of the Pekisko, Shunda and Turner Valley Formations. They first appear in the Front Ranges of the Rocky Mountains and continue eastwards into the subsurface of the southern Alberta Plains region. This eastern facies equivalent is well developed in the vicinity of Moose Dome.

Pekisko Formation

The lowermost formation of the middle map unit in the eastern facies is termed the Pekisko Formation. It directly overlies the Banff Formation and is composed largely of resistant echinoderm - bryozoan limestones. These limestones are frequently mud free, well-sorted skeletal sands. They represent deposition in a shallow subtidal environment of current swept echinoderm banks and shoals.

Shunda Formation

Immediately overlying the Pekisko Formation are the recessive units of the Shunda Formation. The Shunda consists largely of shallow-water, silty lime mudstones interbedded with supratidal evaporites and dolomites. The Shunda is interpreted to represent a period of limited regression and sedimentation of the Mississippian seas into stagnant hypersaline lagoons and tidal mud flats (Illing, 1959; Macqueen et al, 1967).

Turner Valley Formation

Overlying the Shunda are the massive bedded resistant echinoderm limestones of the Turner Valley Formation. Variable amounts of fine to medium crystalline dolomites, especially within the subsurface, are present within the formation as well. These sediments were deposited in a high energy subtidal environment. Within the Southern Alberta Plains region it has been further subdivided into the lower porous or Elkton Member, the Middle Dense Member and the Upper Porous Member (Penner, 1958). Rupp (1969) recognized a similar three-fold division within the Turner Valley Formation but further subdivided Penner's Middle Dense Member into three discrete units.

Mount Head Formation

Directly overlying the Turner Valley Formation is a sequence of cryptocrystalline to finely crystalline dolomites, solution breccias and siltstones of the Mount Head Formation. These units are interpreted to represent a period of regression and development of very shallow lagoons and sabkha complexes.

Etherington and Tunnel Mountain Formations

The third map unit overlies the Mount Head Formation. The top of this unit is marked by a major erosional unconformity. Where exposed to the south of the study area this unit consists predominately of clastic rocks.

This period represents a severe shallowing of the seas (McCrossan and Glaister, 1964).

Regional Mississippian Structure

The Mississippian strata of southwestern Alberta form a large portion of the Front Ranges of the Canadian Rocky Mountains. During thrusting of the Laramide Orogeny the Mississippian formations behaved as a structurally competent package of sediments. The Mississippian tends to form elongate gently undulating anticlines, synclines or domal structures such as that occurring at Moose Dome. Internal deformation of Mississippian formations is generally slight to moderate.

In contrast, the less competent Jurassic and Cretaceous strata became actively involved in thrusting, and internal deformation can be severe.

The west limb of Moose Dome is bounded by a thrust fault of major proportions termed the Prairie Mountain Thrust Fault.

Local Mississippian Stratigraphy and Structure

The creek bed of Canyon Creek provides a good cross-section of the local structure at Moose Dome. The Mississippian strata in the core of the dome are essentially flat lying. The western limb dips uniformly 30° to 35° to the west while the eastern limb is appreciably steeper and locally dips as much as 60° eastwards. The oldest exposed strata are flat lying units of the Banff Formation located along the creek bed of Canyon Creek in the core of the dome.

Erosion has not completely penetrated the Banff Formation and thus no exposures of the Exshaw Formation occur in the vicinity of the study area. Only the upper 50 metres of the Banff Formation are exposed. Above the Banff the contact with the overlying Pekisko Formation is generally sharp. Cut and fill structures within the lowermost units of the Pekisko have been described by Middleton (1963). The Pekisko Formation is 111 metres thick at Moose Dome and is a prominent cliff former.

Overlying the Pekisko are 71 metres of the recessive Shunda Formation. The Turner Valley Formation is 115 metres thick at Moose Dome (Beach, 1943; Middleton, 1963). However, on the western limb of the Dome a thrust fault has produced repetition of lower Turner Valley beds and a structural thickening of the Turner Valley Formation to 166 metres occurs. The thrust fault occurs within the middle portion of the formation, but the actual fault trace is obscured by regolith within a gully extending up the north facing slope of Prairie Mountain. On either side of the gully exposed beds have bedding attitudes disturbed in a manner similar to drag folding and small open synclinal flexural folds are also developed.

Overlying the Turner Valley Formation are 160 metres of the Mount Head Formation. Numerous covered intervals occur throughout the formation. The Mount Head Formation is unconformably overlain by black carbonaceous and phosphatic shales of the Jurassic Fernie Group.

Objectives of Study

The purpose of this study is to examine the interrelationships existing between original depositional environments, diagenetic history, and the resultant modification of porosity. The upper portion of the Shunda Formation and the entire stratigraphic interval of the Turner Valley Formation were chosen for study because they span a variety of depositional environments of carbonate sedimentation and because they display economically attractive porosity and permeability development within the subsurface of Alberta.

Methods of Study

Sections were measured in the field by means of a metric Jacobs staff. One hundred and seventy hand samples were taken from outcrop units and from these both polished slabs and thin sections were prepared in the laboratory. Thin sections were stained using the method of Dickson (1965) to accentuate the textures and structures and to determine the composition of both grains and cements. Insoluble residue tests were conducted on four samples dissolving the carbonate in 5 percent dilute HCl. Conventional porosity and permeability analyses were performed on twenty samples by Core Laboratories, Canada Ltd., of Calgary, Alberta.

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CHAPTER 2

Lithofacies and Environmental Interpretation

Introduction

Rock units within the study area have been classified according to Dunham's (1962) classification of carbonate rocks based on their original depositional texture. Minor units of calacareous siliclastic rocks such as calcareous siltstones and calcareous shales occur within the stratigraphic sequence measured. They have not been placed in Dunham's (1962) scheme but their environmental interpretation has been integrated within the carbonate model presented for Mississippian sedimentation.

One of the principal divisions of Dunham's (1962) classification for carbonate rocks is based on whether the rock is grain supported (grainstones and packstones) or whether it is mud supported (mudstones and wackestones). With this context in mind, the sediments studied have been divided into six lithofacies assemblages described in detail below (Table 1).

Grainstones

This facies is comprised of a mud-free, grain supported sediment. The grains consist of pellets, pelletoids, oolites, oncolites, bioclastic debris or intraclasts. The absence of any intergranular mud within these sediments implies a high degree of hydraulic sorting. Any mud which may have been present, has been flushed from these sediments and allowed to settle in areas of lower energy.

GRAINSTONE LITHOFACIES i) ECHINODERM GRAINSTONES ii) SKELETAL GRAINSTONES iii) PELLETAL GRAINSTONES iv) ONCOLITIC - OOLITIC GRAINSTONES
PACKSTONE LITHOFACIES i) ECHINODERM PACKSTONES ii) SKELETAL PACKSTONES iii) PELLETAL PACKSTONES iv) ONCOLITIC PACKSTONES
WACKESTONE LITHOFACIES i) ECHINODERM WACKESTONES ii) SKELETAL WACKESTONES iii) PELLETAL WACKESTONES
MUDSTONE LITHOFACIES
CALCAREOUS SILTSTONE LITHOFACIES
CALCAREOUS SHALE LITHOFACIES

TABLE 1. LITHOFACIES ASSEMBLAGES PRESENT WITHIN THE SHUNDA AND TURNER VALLEY FORMATIONS

Four main varieties of grainstones are present within the sediments studied.

i) Echinoderm Grainstones - This facies typically consists of massively bedded (0.6 to 4 m) resistant units of medium-grained (0.25 mm) to very coarse-grained (2 mm) echinoderm detritus. Bedding planes are indistinct, cross-bedding is rare and interbeds of echinoderm packstones are common. Terrigenous clastics are absent. The echinoderm plates and ossicles show little or no signs of abrasion indicating they are largely _in situ_ deposits. Micritic coatings on grain surfaces are usually absent or else only poorly developed. These units were probably deposited in the regions of highest current energy on the open shelf environment in which crinoid thickets commonly flourished.

ii) Skeletal Grainstones - These units are developed in two manners. The first type occurs as thin beds (0.1 to 0.5 m) with good to very good bedding which commonly show grading and occasionally cross-bedding. Rare solitary corals are found, interbedded with other thin and well-defined beds of skeletal packstones, wackestones, and lime mudstones. The majority of the sediment grains are from skeletal debris but pellets and intraclasts are common. Faunal assemblages are diverse and include echinoderm plates and ossicles, fenestelled bryozoan fronds, brachiopod, gastropod and pelecypod shell detritus, and rare foraminiferal tests.

These units are interpreted to have been deposited within high energy zones of the open shelf environment in which normal marine salinities and circulation patterns prevailed.

A second type of skeletal grainstone occurs as thick massive units displaying cross-bedding. As with the first type, a diverse faunal assemblage is present including echinoderms, bryozoans, brachiopods, and foraminifera. These units differ in that they contain abundant dasyclad algae detritus, oolites are common, oolitic coatings on grains are common, and grain surfaces are extensively micritized and abraded. Non-skeletal grains include pellets, pelloids, and micritic lumps. These grainstones occur as interbeds with skeletal packstones which display similar bedding characteristics and grain textures as the grainstones.

These units represent a reworking by currents of the open shelf sediments into mechanical buildups of shoals or linear bars.

iii) Pelletal Grainstones - These grainstone units occur as well bedded and very thin (0.05 to 0.1 m) interbeds or as sediment in cut and fill structures within sequences of pelletal-birdseye packstones, pelletal waskestones, mudstones or oncolitic packstones to grainstones.

Minor scale cross-bedding is occasionally developed. Small amounts of terrigenous clastic materials are usually present. Constituent grains are composed of micrite and grain shape can be quite variable, from spherical or oblate to irregular in form. Usual size variations are from 0.02 mm to 0.4 mm, but it is not uncommon to find grains as large as 0.7 mm in diameter. Many of the more spherical or oblate grains are probably of fecal origin but a significant proportion may have originated by micritization of fine skeletal debris (e.g., Bathurst, 1975, p. 85).

These sediments are thought to have formed by the sorting and washing by waves and tidal currents of pelleted muds accumulating in the shallow subtidal or intertidal zones.

iv) Oncolitic - Oolitic Grainstones - This facies consists of very thin interbeds (0.01 to 0.1 m) within sequences of oncolotic packstones, pelletal-birdseye packstones, pelletal wackestones and laminated mudstones. Occasionally, this sediment type fills small scour channels which have cut up to 10 cm into the underlying sediments. Pellets, pelletoids and micritic lumps which vary in shape from spherical or ovoid to irregular and vary in size from 0.15 to 2.0 mm form a significant proportion of the sediment. These grains usually have thin superficial oolitic coats developed on their surfaces, which vary in thickness from 0.01 to 0.02 mm. As many as three separate coatings can occur on any given grain.

Oncolites vary in size from 1.0 to 10 mm and can be spherical, elliptical or irregular in form. They are concentrically laminated with laminae varying from 0.04 to 0.2 mm in thickness. Individual lamellae occur in one of three forms: 1) as concentrically radiating calcite crystals approximately 4 by 20 μm in length; 2) as layers of dense micritic carbonate; or 3) as a clotted mesh of light and dark colored crystals of microcrystalline calcite. The latter, clotted mesh may represent preservation of blue-green algae filaments. Individual lamellae vary in color from light to dark gray under plane polarized light. The darker lamellae are possibly richer in semiopaque to opaque inclusions.

Many oncolites have a compound nuclei formed from several smaller oncolites and contain desiccation fractures indicating periods of subaerial exposure.

Associated evidence for an algal origin of these grains is the common occurrence of preserved Kamaenid algal filaments and the close association of these units with stromatolite occurrences.

Oncolites are a feature associated with the high energy zone of the low intertidal to shallow subtidal regime or within the margins of supratidal ponds (Friedman et al, 1973).

The grain supported nature of these sediments and the presence of oolitically coated grains suggest these deposits may have been reworked and deposited in tidal channels which cut across the intertidal zone.

Packstones

This rock type is comprised of grain supported sediment in which mud-sized carbonate material is present in the intergranular pore spaces. Constituent grains include pellets, pelletoids, intraclasts, oolites, oncolites or skeletal debris. These sediments originate within a zone of energy sufficiently high to produce a sorting and packing of the grains but of insufficient strength to remove all of the carbonate mud-sized material from the sediment.

Four main varieties of packstone are present within the stratigraphic interval studied.

i) Echinoderm Packstones - Except for the presence of intergranular mud-sized carbonate material, these units are similar in respects to the echinoderm grainstone facies previously described. The facies typically consists of massive thick bedded (0.6 to 4 m) resistant units of medium grained (0.25 mm) to very coarse grained (2 mm) echinoderm plates and ossicles. Cross-bedding is rare and frequent interbeds of echinoderm plates and ossicles show little or no signs of abrasion, indicating they are largely in situ deposits. Micritic coatings are either very poorly developed or are absent altogether.

These deposits originated in the open shelf environment adjacent to the areas of highest current velocity where crinoid thickets thrived.

ii) Skeletal Packstones - These sediments are identical to the two types of skeletal grainstones previously described except for the presence of intergranular and intraskeletal mud. They accumulated in the same environments as their grainstone counterparts: in areas of reduced energy where the mud faction could not be winnowed from these sediments.

iii) Pelletal Packstones - These units have moderate to poorly defined bed boundaries, in thin to thick (0.3 to 1.5 m) beds within sequences of laminated or birdseye mudstones or wackestones. Poorly defined cross-bedding and laminations are locally present. In outcrop surfaces, these beds appear similar to pelletal wackestones or even mudstones but microscopic examination reveals a packing of micrite grains such as pellets, pelloids, lumps and intraclasts containing intergranular mud-sized carbonate material.

Minor amounts of bioclastic debris such as ostracods, gastropods, calcispheres and algal filaments are usually present. Thin micritic coats are developed on many of the skeletal grain surfaces.

Pellets and pelletoids are generally spherical or elongate in form and vary in size from 0.02 to 0.7 mm. Small amounts of quartz silt are usually present within the matrix or within the intraclasts of these sediments.

Most of the pelletal packstones contain small augen or patches (1 to 20 mm in diameter) of clear sparry calcite. The patches are sharply defined and have a variety of shapes. They commonly form irregular lenticular bodies with their long axes lying in the plane of bedding and fill voids which appear to have been squeezed between and around pellets. The patches are often interconnected via thin films of calcite. The origin of these augen birdseye structures is discussed within Chapter 3.

The pellets which form these packstones probably originated within the shallow subtidal zone where the action of mud scavenging organisms was intense and the production of fecal pellets high. However, pelletal packstones can be found from the open shelf to high intertidal environments.

iv) Oncolitic Packstones - These units are similar in description to the oncolitic - oolitic grainstone facies previously described with the exception of three important features. These features include the presence of mud-sized carbonate material, a scarcity of oolites or oolitic coated grains, and the common occurrence of pellets, pelloids and birdseye structures.

The increased amount of carbonate mud and paucity of oolitic coatings within these sediments indicate they accumulated in an environment of lower energy than the oncolitic - oolitic grainstone facies. The presence of birdseye textures within these units suggest that they accumulated within the intertidal or supratidal environments of deposition.

Wackestones

According to Dunham (1962), a wackestone is a mudstone (micrite) in which the grains (allochems) are mud supported and comprise at least 10 percent of the sediment by volume. Allochem types include pellets, pelletoids, lumps of lithified carbonate material and bioclastic debris.

These sediments are believed to have accumulated in regimes of low energy. Three main varieties of wackestones are to be found within the study area:

i) Echinoderm Wackestones - This facies typically consists of units displaying fair to good bedding. Beds are from 0.5 to 2 m in thickness and contain medium-grained (0.25 mm) to very coarse-grained (2 mm) echinoderm fragments floating in a micritic carbonate matrix. Sedimentary structures such as laminations and cross-bedding are locally conspicuous and these beds are found interbedded with echinoderm grainstones and packstones, skeletal wackestones and mudstones.

Indications of burrowing are common. Some echinoderm particles show signs of pitting and abrasion indicating some degree of transport and reworking. Most echinoderm fragments, however, have smooth unpitted surfaces, and it is not uncommon to find crinoid ossicles joined together, intact crinoid stems, or preserved crinoid calyxes. These features are key indicators of a low energy environment.

Other skeletal debris, mainly of bryozoans and brachiopods, occur in minor amounts within most echinoderm wackestones. With increasing amounts of skeletal debris, this facies grades transitionally into a skeletal wackestone.

Solitary horn corals and colonial syringopora corals occur within this facies. In some instances, intact syringopora corals are preserved in their growth positions.

This facies is composed largely of an *in situ* accumulation of grains. They were probably deposited adjacent to the areas colonized by thickets of echinoderms in the quieter waters of the open shelf environment.

ii) Skeletal Wackestones - These units have similar bedding characteristics to the echinoderm wackestones. They occur as interbeds with units of skeletal grainstones and packstones, echinoderm wackestones and mudstones.

There is an abundance of fine-grained (0.12 mm) to very coarse-grained (2 mm) skeletal debris present, comprised of bryozoans, echinoderms, brachiopods, gastropods, pelecypods and rare foraminifera tests. Grain surfaces show few signs of abrasion, pitting or micritization.

Evidence of burrowing is widespread and the sediment usually contains pellets, pelletoids, and lumps. These units were deposited in quieter portions of the open shelf environment or within portions of the restricted shelf or lagoon.

iii) Pelletal Wackestones - This facies typically consists of well defined, thin (0.1 m) to medium thick (0.8 m) beds which show extensive signs of burrowing and reworking. Well defined laminations are locally conspicuous. Birdseye structures and fenestral fabric are often present. Many of the birdseye structures are flat-floored due to a partial infilling of the former voids by mud-size carbonate material. Bioclastic debris is very fine (0.06 mm) to medium (0.25 mm) in size and consists of a restricted faunal assemblage of ostracod, pelecypod and gastropod shell remains. Calcispheres and remains of the blue-green algae

Proninella are common. Argillaceous material, quartz or feldspar silt and anhedral quartz crystals are present and can constitute up to 15 percent of the sediment. Pellets, pelletoids and lumps can form up to 40 percent of the sediment.

These units occur within sequences of laminated or massive bedded mudstones, skeletal wackestones, pelletal packstones and silty cryptocrystalline dolomites.

Pelletal wackestones can form in either the subtidal or intertidal settings where energy conditions are fairly low.

Mudstones

As defined by Dunham (1962) this facies is comprised of mud-sized carbonate material containing fewer than 10 percent allochems.

The facies usually consists of thin, well defined beds from 0.1 to 0.4 m in thickness, within sequences of skeletal and pelletal wackestones, cryptocrystalline dolomites and pelletal packstones. Laminations and cross-laminations can be present; however, many of the mudstones have been intensely burrowed.

One bed of finely laminated argillaceous and dolomitic mudstone displayed well developed symmetrical ripple marks on its upper surface.

Floating grains within the muds are scarce and include pellets, pelletoids, intraclasts, or more rarely, molluscan skeletal debris.

Argillaceous material and terrigenous clastic silt-sized grains of quartz or feldspar are usually present in minor amounts of 5 to 15 percent.

Under microscopic examination, the carbonate mud consists of equant, anhedral calcite crystals with diameters from 2 to 8 μm.

The laminated muds probably accumulated within an intertidal to supratidal setting while the more massive and burrowed muds are thought to have originated in the subtidal.

Calcareous Siltstones

Two thin units of very well bedded calcareous siltstone occur. Both contain laminations and cross-laminations.

On the upper surface of the thicker unit there are well-defined symmetrical ripple marks with amplitudes of 1 mm and wavelengths of 1 cm. The surface is also pitted, possibly by rain drops or hail.

The silty material consists of detrital grains of quartz, dolomite, plagioclase and potassium feldspar. Most quartz grains have uniform extinction and are probably of an igneous origin, but some exhibit an undulose extinction indicating source from a metamorphic terrain. The matrix consists of argillaceous material and carbonate mud.

Cloudy and inclusion-rich dolomite crystals from 10 to 140 μm in size constitute up to 30 percent of the sediment. The smaller grains have anhedral forms while the larger crystals are subhedral in outline.

Zoning is common within the dolomite crystals and many crystals exhibit rounded inclusion-rich cores. Some dolomite crystals are well rounded and have abraded and pitted surfaces.

The siltsontes are associated with beds of cryptocrystalline dolomites, laminated mudstones, and pelletal wackestones, and are believed to have accumulated within the intertidal or supratidal environments.

Calcareous Shales

A few thin beds of calcareous or slightly dolomitic black shale occur as very thin (1 to 3 cm) well bedded, fissile, recessive, partings within silty and argillaceous dolomitic wackestones or mudstones.

In one instance, a 3 cm thick shale break is developed in a sequence of coarse-grained oolitic skeletal packstones. The shale parting is irregular in its form and cross-cuts bed boundaries of the oolitic - skeletal sands. This shale parting may represent a break in carbonate deposition accompanied by an influx of terrigenous clastic material.

A single thick shale bed occurs within the strata examined. The unit is 0.4 m thick, well bedded, fissile, locally laminated, recessive and varies in color from a grayish hue at its base to a greenish hue at its top. Laminae of argillaceous dolomitic mudstones occur within the unit. This shale overlies a 6 cm thick unit of dense cryptocrystalline dolomite mudstone whose upper portion is formed of angular chips and clasts of dolomite. The upper surface of the dolomite is irregular and represents a possible period of subaerial exposure and weathering.

Similar green shale facies have been described by Havard and Oldershaw (1976) in the Devonian Snipe Lake reef complex deposited in quiet, stagnant waters adjacent to areas of supratidal weathering.

Summary

The Shunda and Turner Valley Formations are comprised mainly of carbonate grainstones, packstones, wackestones and mudstones with lesser amounts of calcareous siltstones or shales. Depositional environments include the high and low energy open marine, marine shoals or bars, restricted shelf or lagoon, intertidal and the supratidal environment.

Inserts A and B, located at the rear of the text, are detailed lithologic strip charts which relate sediment characteristics to environments of deposition.

CHAPTER 3

Environments of Deposition

Introduction

The various lithofacies assemblages and their environmental interpretations have been partially described within the previous chapter. Chapter 3 demonstrates that the vertical sequence of facies represents a pattern of regressions, transgressions, and diastems. These facies transitions occur in both an abrupt and a gradational manner.

The General Depositional Model

Generalized depositional models for Mississippian sedimentation within southwestern Alberta have been constructed by Illing (1959), Macqueen and Bamber (1967), and Mamet (1976).

The writer has presented a modified model incorporating various aspects from each of the three previous models (Figure 4). The model is comprised of five generalized depositional environments. The approximate order in which these occur, proceeding from the open marine toward the land, is as follows:

i) open shelf

ii) offshore oolitic sand bars or shoals

iii) restricted shelf or lagoon

iv) beach and intertidal

v) supratidal

OPEN SHELF	OFFSHORE SHOALS OR BARS	RESTRICTED SHELF OR LAGOON	BEACH	INTERTIDAL	SUPRATIDAL
MEAN HIGH TIDE MEAN LOW TIDE LOW ENERGY - VERY WELL BEDDED - THIN BEDS OF SKELETAL WACKESTONES AND MUDSTONES - IN SITU CORALS	- CROSS BEDDED - WELL BEDDED - OOLITES AND OOLITIC COATS ON GRAINS - GRAINSTONES AND PACK-STONES - ALGAL LUMPS - ECHINOIDS, BRYOZOANS, BRACHIOPODS, FORMS ARE COMMON - GRAINS ARE REWORKED AND ABRADED	- MASSIVE BEDDED - MUDSTONES, SKELETAL AND PELLETAL WACKESTONES - ABUNDANT CALCISPHERES AND BURROWS - LOCAL LAMINATIONS - CRYPTO-CRYSTALLINE DOLOMITE - SILTY AND ARGILLACEOUS	ONCOLITE OR OOLITE GRAINSTONES, STROMATOLITES, LOW ANGLE CROSS BEDDING, FLAT PEBBLE CONGL.	- LAMINATIONS - WELL BEDDED - ABUNDANT INTRACLASTS - BIRDSEYES - FENESTRAL FABRICS - MUDSTONES - PELLETAL WACKESTONES - STROMAT-OLITES - RIPPLE MARKS - BURROWS	- LAMINATIONS - WELL BEDDED - SILTY, ARGILLACEOUS - MUDSTONES, SILTSTONES - CRYPTOCRYSTALLINE DOLOMITE - CALICHE AND SOIL HORIZONS - DESSICATION CRACKS - SOLUTION BRECCIAS - EROSIONAL SURFACES - SOME BIRDSEYES
HIGH ENERGY - COARSE GRAINED ECHINODERM/ BRYOZOAN GRAINSTONES AND PACKSTONES AS SEQUENCES OF THICK, MASSIVE INDISTINCT BEDS					

FIGURE 4. DEPOSITIONAL MODEL FOR MISSISSIPPIAN SEDIMENTATION AT MOOSE DOME. MODIFIED FROM ILLING (1959), MACQUEEN AND BAMBER (1967) AND MAMET (1976).

The characteristics associated with each depositional environment are summarized in Figure 4. In general, any one characteristic is not diagnostic of a single depositional environment. Using several characteristics in conjunction, however, is sufficient to delineate a sediment's depositional site within the overall model.

Environments of Deposition of the Shunda Formation

Introduction

Sedimentation during Shunda time is represented at Moose Dome by an accumulation of sediments within the lagoonal, intertidal, beach, and supratidal settings (Figure 4). Sediments of an intertidal or supratidal origin are volumetrically the most abundant.

The general pattern of sedimentation during Shunda time at Moose Dome was one of broad,shallow systems of lagoons grading landward to extensive areas of intertidal mud flats and supratidal sabkhas (Macqueen et al, 1972). A slight lowering of sea level would result in the isolation and exposure of lagoonal and intertidal sediments to the supratidal environment.

Macqueen et al, 1972, indicated some form of topographic or bathymetric feature such as a system of offshore carbonate shoals must have been present. These shoals separated the shallow lagoon-sabkha complex on the landward side from the open marine on the seaward side.

The Shunda outcrop exposed in the quarry consists of five depositional cycles. Each cycle is an upward shallowing sequence. Individual cycles are from 2 to 8 m in thickness. They consist of lagoonal or intertidal sediments at the base and grade upward into intertidal or supratidal sediments at the top (Insert A).

Lagoonal Sediments of the Shunda Formation

Sedimentation within lagoons consisted of deposition of fine-grained skeletal or pelletal wackestones, mudstones or pelletal packstones.

Evidence of burrowing within these sediments is widespread (Plate 1-2). Intensive burrowing has usually obliterated all other primary bedding structures. Gastropods, pelecypods, and ostracods comprise most of the skeletal debris. Pellets, pelloids, and micritic lumps are the main non-skeletal grains.

Illing (1959) feels a large proportion of the pelloids are fecal in origin, while Beales (1958), interprets them to represent an inorganic *in situ* agglutination of precipitated carbonate needles into grains or 'bahamiths'. However, the presence of skeletal debris and abundant burrows within these sediments suggests to the writer that Illing's (1959) proposed fecal origin of these grains is more probable.

Abundant calcispheres occur within these sediments. In the opinion of Petryk and Mamet (1972) and Bathurst (1975, p. 70), many calcispheres respresent the preservation of algal spore cases. Preserved algal filaments similar in description to the Dasycladacean algae species *Kamaena* described by Petryk and Mamet (1972, pp. 777-779) occur within the lagoonal and intertidal sediments (Plate 1-3). Also present, are abundant thalli of the algae species *Proninella* (Plate 1-4). The thalli exhibit an irregular contorted shape possibly due to collapse during retraction of euxinic muds during lithification (Mamet, 1976, p.27).

Local thin streaks of fenestral porosity and calcite-filled birds-eyes occur indicating these sediments were exposed, part of the time, to the supratidal or intertidal environments.

Intertidal Sediments of the Shunda Formation

In many instances, it is difficult to establish if a given bed has been deposited within the intertidal setting or if it was originally deposited within a lagoonal setting and later subjected to processes acting within the intertidal environment.

Intertidal sediments are generally well bedded and contain laminations, cross-laminations, birdseyes, fenestrae, vertical burrows, irregularly laminated algal mats, stromatolites, and rip-up clasts. Thin beds of oncolotic or oolitic grainstones and packstones occur (Plates 1-5, 1-6, 2-1).

The birdseye structures within muds are common features (Plate 2-2). Illing (1959), proposed an origin by synerisis to be the most likely process to have created the birdseyes. Soon after the sediment was deposited and a few centimetres below the soupy surface conditions within the subtidal, water droplets segregated from the sediment. The water droplets, preserved by the plastic strength of the mud were subsequently filled by a sparry calcite augen. Many of the birdseyes are connected by thin films of sparry calcite which Illing (1959) postulates to be the escape paths of the migrating water droplets.

Illing (1959),also mentions a gas bubble origin as being a possible means of formation of the birdseyes. The writer believes this is the more probable means for formation of the birdseyes and that they are not of a lagoonal origin. Rather, they formed within the intertidal and supratidal zones through gas generation produced within the sediments by rotting algal tissue. The formation of birdseyes within the supratidal and sometimes within the intertidal zones, but not within the lagoonal environment, has been documented by Shinn (1968) based on studies of Recent carbonate sediments.

Shinn (1968) recognized two kinds of birdseye structures:

i) planar isolated vugs 1 to 3 mm high by several millimetres in width, produced by shrinkage resulting from desiccation of exposed sediments; and ii) isolated more or less bubblelike vugs 1 to 3 mm in diameter produced by the generation of gas in a sediment from decomposing organic matter.

Many of the birdseyes are partially or completely infilled by pellets or carbonate mud prior to the precipitation of sparry calcite cement. Many of the paritally infilled birdseyes exhibit geopetal structures having flat bottoms. Thus, large volumes of water were capable of flushing these sediments and transporting material into the birdseyes.

Sediments of an infratidal origin frequently occur as interbeds within intertidal sediments. In this study, the term infratidal is used to denote sediments which accumulated within the low intertidal to shallow subtidal transition zone. Within this environment are found beach deposits of oncolitic-oolitic grainstones occurring as thin, well-defined beds with low angle cross-bedding, minor cut and fill structures probably produced by small tidal distributory channels (Plate 2-3) and the development of stromatolites.

A single occurrence of stromatolite development occurs within the Shunda intertidal sediments. The stromatolite is 1.5 centimetres thick and consists of laterally linked hemispheroids. The stromatolite is laminated and contains fragments of skeletal debris and pellets.

The extent of which algal laminated deposits are preserved is related to salinity controls on the intertidal distribution of grazing and burrowing invertebrates (Mazullo and Friedman, 1977). These invertebrates tend to thrive in areas of near normal salinities, and will thus, destroy the laminated nature of the algal mats. In contrast, algal-laminated deposits are well preserved in those environments of elevated salinities which the algal-scavenging invertebrates find inhospitable.

Petrographic examination of Shunda intertidal sediments discloses the infrequent occurrence of fractures infilled with sparry calcite cement and micritic carbonate (Plates 2-4, 2-5). The fractures are about 1 mm in thickness, several centimetres in length, are slightly undulatory and generally parallel the bedding. These fractures are thought to be sheet cracks produced by desiccation and shrinkage of the sediment during periods of subaerial exposure. The floors of the fractures are mechanically infilled with carbonate mud or pellets. In some instances, the mud and pellets are observed to have filtered down into the sheet cracks through overlying birdseyes or burrows (Plate 2-5).

The upper portions of the sheet cracks are infilled with a sparry calcite cement (Plate 2-6). The cement consists of scalenohedral crystals of sparry calcite which nucleate both on the ceilings of the fractures and upon the geopetal layer of mud and pellets washed onto the floors of the fractures.

Supratidal Sediments of the Shunda Formation

Volumetrically, sediments of a supratidal origin are least abundant within the Shunda section examined. They are found in the uppermost portions of each of the five cycles (Insert A).

Cycle 1 is terminated by a greenish shale 0.4 metres in thickness. The shale disconformably overlies a bed of cryptocrystalline dolomite. The dolomite is very silty and has an irregular upper erosional surface upon which are scattered abraded and reworked clasts of the dolomite (Plate 3-1). The dolomite is friable and weathers a yellowish-red color.

Cycles 2, 3 and 4 also have irregular upper surfaces upon which thin recessive weathering calcareous shales were deposited.

A subaerial laminated crust occurs 1.6 metres below the Shunda-Turner Valley contact (Insert A). The upper portion of the crust has been partially removed by a stylolite surface. The crust is 1 to 2 centimetres in thickness and rests on an erosional surface developed within a birdseye-pelletal wackestone of intertidal origin (Plates 3-2, 3-3). The erosional surface is undulatory, sharp, and transects both matrix and grains. Immediately below the curst, dissolution of dolomite rhombs in the wackestone has taken place. The crust is dense and consists of irregular laminations. Petrographic examination reveals the laminations are due to differing amounts of organic and argillaceous materials. Abundant silt-sized particles of detrital quartz occur. They display pitted and corroded surfaces and have undergone replacement by micritic carbonate. Laminated crusts are believed to form on bedrock surfaces beneath soil horizons, by downward percolating meteoric waters (Multer et al, 1968).

Summary of Shunda Formation Sedimentation

That low energy conditions prevailed during Shunda sedimentation at Moose Dome is attested to by the abundance of mud-sized carbonate material and the paucity of coarse-grained material within the sediments studied. The various sediment types, structures and fabrics all indicate deposition occurred within shallow lagoons, intertidal mud flats or the supratidal environment.

Sedimentation was cyclical in its nature, grading from subtidal deposition into intertidal and then supratidal sedimentation. Frequent periods of subaerial exposure subjected Shunda sediments to a differing suite of early diagenetic processes than for the Turner Valley Formation, as will be discussed later in this chapter.

Environments of Deposition of the Turner Valley Formation

Introduction

Turner Valley sediments at Moose Dome accumulated primarily in the open marine environment. Normal marine salinities and circulation patterns prevailed (Figure 4).

The shallow lagoons and tidal mud flats of Shunda times became inundated with the subsequent development of broad systems of open marine banks and shoals. Echinoderm thickets and bryozoans proliferated in the areas of strongest water circulation and aeration (Murray and Lucia, 1967).

In the highest energy portions of the open shelf occur bars or emergent shoals comprised of oolitically coated grains (Plate 3-4).

These sand bodies may have acted as effective barriers to open marine circulation patterns and be responsible for the development of restricted shelf or lagoonal sediments on their landward sides.

Within the upper portion of the Turner Valley at Moose Dome, occur restricted lagoonal, intertidal and supratidal sediments.

Open Shelf Sediments of the Turner Valley Formation

Open shelf sediments can be subdivided into high energy and low energy deposits. The low energy deposits contain high amounts of carbonate mud-sized material and form poorly sorted wackestones and mudstones. These sediments are commonly argillaceous or silty. Usually, they occur as thin and well-bedded units locally displaying laminations. Commonly, however, intensive burrowing has destroyed all sedimentary lamination. A high faunal diversity is characteristic of these sediments and includes echinoderms, brachiopods, bryozoans, ostracods, gastropods, foraminifera, and abundant solitary horn corals and colonial *syringopora* corals. Corals can often be observed in their growth positions. Heckel (1972), feels that the presence of *in situ* corals is a good indicator of open marine sedimentation. Crinoid ossicles and plates are commonly still connected. Most of the skeletal fragments have relatively "fresh" surfaces and display little evidence of abrasion and transport.

In contrast to the low energy deposits of the open shelf, those of the high energy regime contain an abundance of sand-sized material. They form well sorted grainstones and packstones which lack argillaceous material. They occur as thick massive units which commonly are cross-bedded.

The high energy open marine deposits are similar to those of the low energy in that they contain a high faunal diversity. Crinoid fragments are extremely abundant, often comprising as much as 70 percent of the total rock volume (Plate 3-5).

Marine Shoals or Bars of the Turner Valley Formation

These sediments are thought to have accumulated in linear offshore bars or within broader shoals. They occur as poorly bedded, locally cross-bedded units of skeletal grainstones or packstones. Fossils are abundant and include echinoderm, bryozoan, brachiopod, foraminifera, and gastropod detritus. Abundant micritic lumps are present. They differ from high energy open marine deposits in the following aspects: i) oolites are present; ii) grains are usually oolitically coated; iii) skeletal grains are commonly abraded and their surfaces are intensely micritized by algae; and iv) dsyclad algal detritus is common.

Petryk and Mamet (1976), observed algal lime boundstones within this facies of the Livingstone Formation. Intense micritization of grain surfaces implies extensive colonization of sediments by algae (Bathurst, 1966).

Intertidal and Supratidal Sediments of the Turner Valley Formation

This facies consists of thin and well-bedded units of mudstones containing fenestral and birdseye fabrics. There is a paucity of fossil debris other than calcispheres but an abundance of pellets, pelloids and intraclasts. This facies is found only in the uppermost 30 metres of the Turner Valley Formation.

Rip-up clasts, crinkly algal laminations and vertical burrow systems are locally conspicuous. Cryptocrystalline non-laminated dolomite beds are present in this facies and may represent hypersaline conditions existing within lagoons or supratidal ponds.

The Environmental Sequence of Turner Valley Sedimentation at Moose Dome

Figure 5 summarizes the vertical sequence of Turner Valley sedimentation at Moose Dome. As previously outlined,within the subsurface of the Plains, the Turner Valley Formation consists of three members which include: an Upper Porous Member, a Middle Dense Member and a Lower Porous (Elkton) Member (Penner, 1958). This three-fold division of the Turner Valley Formation is recognizable in outcrop at Moose Dome.

1. Elkton Member or Lower Porous Member

The Elkton Member at Moose Dome consists of an interbedded sequence of high and low energy open marine sediments and open marine oolitic bars or shoals.

The contact between the Shunda Formation and the Elkton Member of the Turner Valley Formation is exposed in a quarry face on the east flank of the Dome (Plate 1-1). The contact is conformable, with clean washed crinoidal grainstones of the Elkton Member (Plate 3-6) deposited upon birdseyed lime mudstones of the Shunda.

Murray and Lucia (1967), studying exposures on the east flank of the Dome, approximately 2 kilometres from the quarry, noted this contact

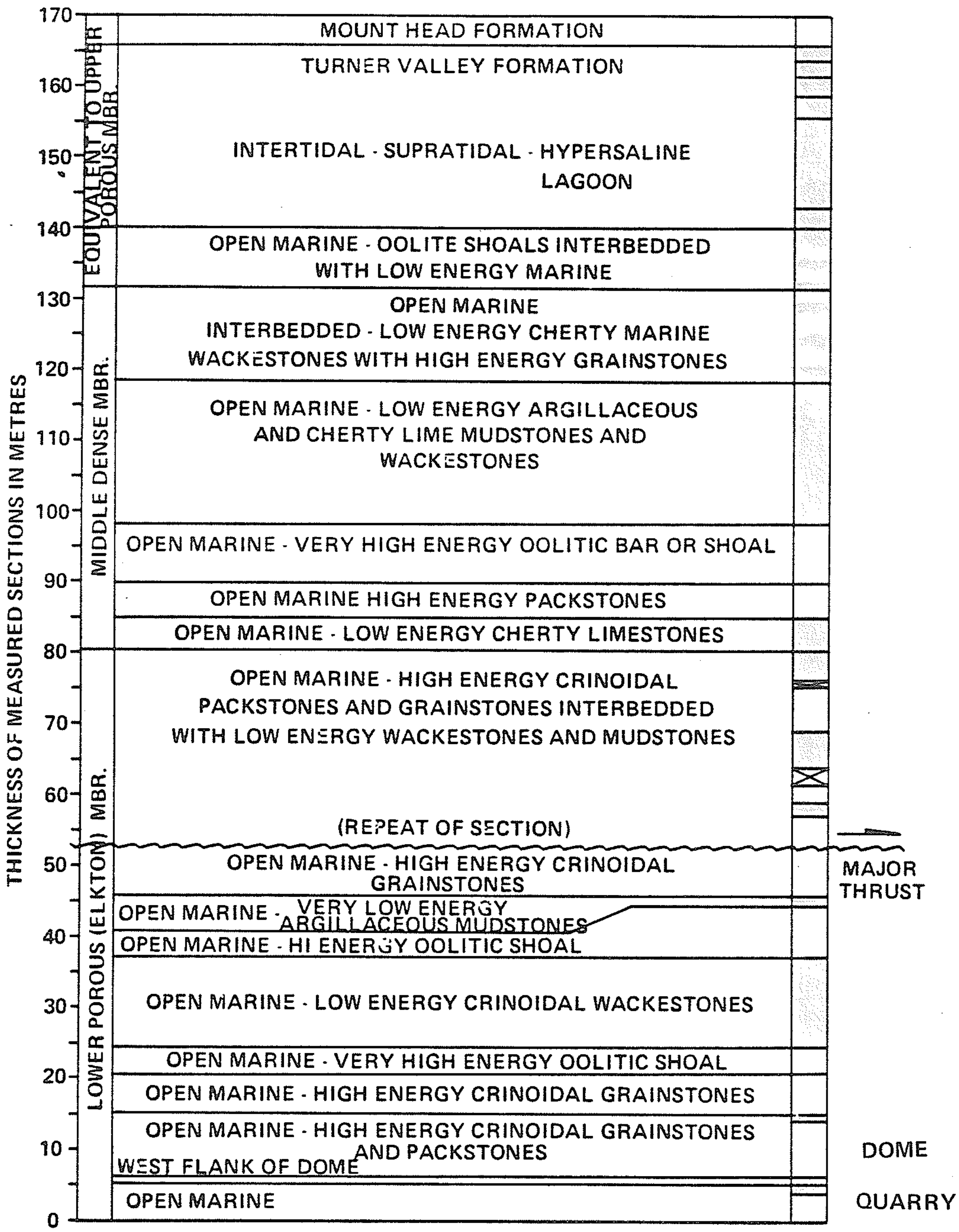

FIGURE 5. GENERALIZED ENVIRONMENTAL SEQUENCE OF TURNER VALLEY SEDIMENTATION

OPEN MARINE: - LOW ENERGY - HIGH ENERGY
- HYPERSALINE LAGOON - INTERTIDAL/SUPRATIDAL

to be irregular. They noted local relief of up to 1 m with overhang in places and interpreted this to represent erosion of the Shunda Formation prior to deposition of a bed of oolite grainstone of the Turner Valley Formation.

In both cases, the Shunda-Turner Valley contact indicates an environmental change from the shallow water intertidal/supratidal Shunda sediments into the high energy open marine deposits of the Turner Valley Formation.

Within the Elkton, high energy open marine grainstones and packstones are interbedded with low energy open marine wackestones and mudstones. Bedding contacts between high and low energy units can be either sharp or gradational (Plate 4-1). Sharp contacts represent rapid changes in the energy of deposition, while gradational contacts reflect a more gradual change in the energy of deposition.

Within both high and low energy deposits, echinoderm detritus is extemely abundant. Murray and Lucia (1967), reconstructed a paleoecological environment for Mississippian crinoids and blastoids. They concluded that the density of echinoderm development was greatest adjacent to those areas of strongest tidal flow crossing the open shelf. The strong tidal action brings nutrients to the echinoderms and is responsible for the removal of the carbonate mud-sized material. The resultant sediment in these areas is largely an *in situ* accumulation of echinoderm grains forming grainstones and packstones. Away from areas of strong current action, the density of echinoderm growth decreases and the amount of mud-sized material increases with the resultant deposition of echinoderm wackestones and mudstones. Within these latter sediments the preservation of intact crinoid stems and calyxs is common (Plate 4-2).

Within the Elkton Member are two units comprised of oolitically coated skeletal grainstones and packstones deposited as offshore marine bars or shoals. These sand bodies probably accreted to just below the normal low tide level and acted to restrict water movement over their crests. This restriction could result in slightly elevated salinities and provide conditions favourable for the precipitation of oolites and oolitic coats on grain surfaces. During abnormally low tides, these shoals were probably emergent. These sand bodies contain clasts of intertidal or supratidal birdseyed mudstones. These clasts are relatively rare however, and may have been transported into the sand bodies having formed in tidal flats elsewhere.

That these sand bodies acted to restrict water movement is supported by the occurrence of very low energy marine mudstones or wackestones overlying the sand bodies. This vertical sequence would be expected to develop by progradation of the low energy muddy sediments over the bar crest as the bars accreted seaward.

Murray and Lucia (1967), measured numerous sections of the Elkton Member at Moose Dome and found it to vary from 36 metres to 39 metres in thickness. The Elkton section measured by the author on the west flank of the Dome is 73.6 metres thick (Insert B; and Figure 5). A thrust fault occurs at 53.3 metres and has caused a repetition of a large portion of the Elkton. No satisfactory correlation of units could be made across this fault.

2. Middle Dense Member

The Middle Dense Member conformably overlies the Elkton Member and is 51 metres thick. Several shear zones present within this member may have produced a slight structural thickening. The Middle Dense Member contains lenticular, black chert nodules (Figure 5). The Middle Dense Member mainly contains very low energy open marine mudstones and wackestones interbedded with higher energy packstones and grainstones. The most common lithologies are fine-grained, poorly sorted echinoderm-bryozoan wackestones and mudstones. Most beds contain from 5 to 15 percent quartz silt and argillaceous material. Horn corals and colonial syringopora corals still in growth positions are common. Evidence of burrowing is widespread. Frequently, the delicate fronds of lacey bryozoans are found intact.

The Middle Dense Member represents a lowering of energy conditions over the open shelf of the Elkton. Energy conditions were reduced and the sluggish currents were of insufficient strength to remove the silts and argillaceous materials transported onto the shelf. Deposition occurred above wave base, however, as preserved oscilation ripple marks occur at 131.5 m (Figure 5 and Insert B).

Higher energy conditions prevailed during portions of the Middle Dense time. A high energy open marine oolictic shoal occurs at 92 m and high energy open marine crinoidal grainstones and packstones occur in the upper portion of the member (Figure 5 and Insert B).

3. Upper Porous Member

The uppermost 35 metres of the Turner Valley Formation, measured on the west flank of Moose Dome, is believed to be equivalent to the Upper Porous Member of the subsurface. The Upper Porous Member of the Turner Valley oilfield is approximately 32 m thick and consists of crinoidal grainstones similar to the Elkton Member (Penner, 1958). Penner (1958), noted the contact between the Middle Dense and Upper Porous Members to be gradational.

The author places the contact between the Upper Porous and Middle Dense Members at 131.9 m (Insert B), just above a prominent symmetrical ripple marked surface. No chert nodules occur above this unit. The basal 9.5 m of the Upper Porous contain crinoidal rich sediments which are similar to the subsurface Upper Porous of Penner (1958). Within this unit, are beds of open marine oolitic shoals interbedded with low energy open marine wackestones.

This shoal became emergent in its uppermost portion. An erosional surface cross-cuts bedding at 139.5 m (Insert B), and has 2 cm of calcareous shale deposited upon its surface (Plate 4-3). An argillaceous wackestone containing shale interbeds overlies the oolitic shoal and reflects deposition in very low energy open marine conditions (Plate 4-4).

At 141.3 m (Insert B),is a bed of buff, laminated cryptocrystalline dolomite mudstone. Illing (1959), interprets this type of dolomite to be primary, forming within hypersaline lagoons. Several of these dolomites occur higher in the Upper Porous section at 150 m, 155.7 m, and 162.6 m (Figure 5, Insert B).

The cryptocrystalline dolomites are separated by units of lime mudstones and wackestones of an intertidal or supratidal origin. Skeletal material is rare within these limestones and consists of forams, calci-spheres, algal filaments and ostracods. Fenerstral and birdseye fabrics are common. Crinkly algal laminations and oncolites are locally present. Pellets, pelloids, lumps and intraclasts are very abundant. Most beds contain 5 to 10 percent quartz silt. An intra-formational conglomerate occurs at 162 m (Plate 4-5). This conglomerate represents rapid and turbulent deposition, such as during storm conditions.

The Turner Valley-Mount Head contact is placed at the top of a bed of supratidal lime mudstone at 166.7 m (Insert B). The basal bed of the Mount Head Formation is a dolomite mudstone containing 40 percent quartz silt. This bed has asymmetrical ripple marks preserved on its upper surface (Plate 4-6). The lowermost Mount Head units are comprised of silty microcrystalline dolomites containing anhydrite. They reflect a further shallowing of the sea resulting in evaporitic hypersaline conditions.

Summary of Turner Valley Sedimentation

Open marine sedimentation prevailed throughout deposition of the Elkton and Middle Dense Members of the Turner Valley. Energy conditions were often high resulting in depostion of coarse-grained skeletal grainstones and packstones. Crinoids flourished and were the dominant producer of sand-sized carbonate particles.

At Moose Dome, the Upper Porous Member is a shallow water facies comprised of lagoonal, intertidal and supratidal muds.

CHAPTER 4

Diagenesis

Introduction

These processes include biological diagenesis, neomorphism, cementation, dolomitization, silicification, pressure solution, pryitization, dissolution and early fracturing associated with compaction. Minor amounts of metamorphic alteration occur in sediments subjected to shearing in zones of thrust faulting.

The relative time relationships, between the main diagenetic processes and their products has been summarized in Table 2.

Dissolution features are present in rocks of the Shunda and Truner Valley Formations bur due to the importance of this diagenetic process to the creation of porosity, it is dealt with in the following chapter.

Biological Diagenesis

These processes include the partial or complete destruction of internal bedding features by burrowing organisms or the alteration of solid surfaces by organisms which bore.

Evidence of soft sediment burrowing and bioturbation with mudstones and wackestones of the Shunda Formation is particularly well developed. Non-laminated mudstones often contain the preserved burrows of mud scavenging organisms. Much of the pelletal material observed within the Shunda Formation is probably of a fecal origin produced by these organisms (Illing, 1959, p.44). The burrows occur as irregular tube-like bodies 1 to 3 mm in diameter and up to 3 cm in exposed length.

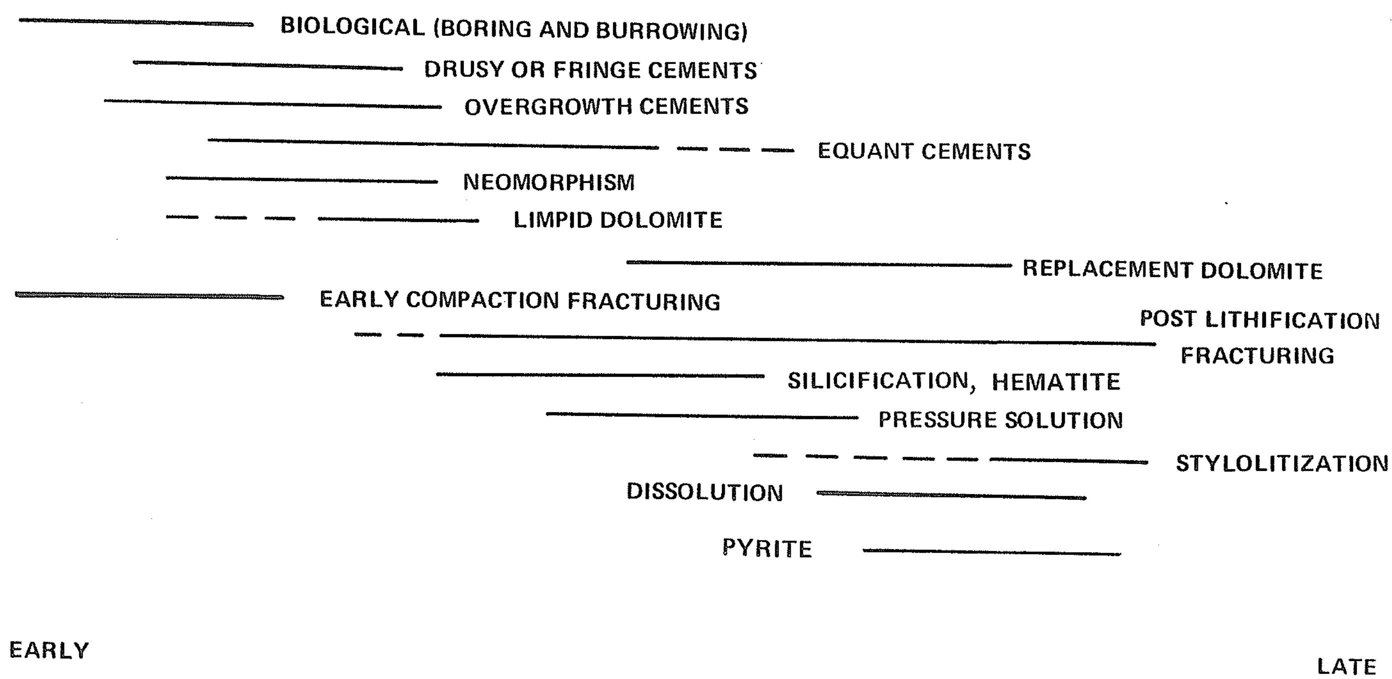

TABLE 2. RELATIVE TIME RELATIONSHIPS OF DIAGENETIC ALTERATIONS IN SEDIMENTS OF THE SHUNDA AND TURNER VALLEY FORMATIONS

They can be empty or infilled by a sparry calcite cement. In some instances, they closely parallel the bedding attitude of the sediment (Plate 4-1). However, in most cases they are oriented in a random fashion (Plate 1-2).

Many grain surfaces have been altered by the boring action of microorganisms (Plate 5-1). Bathurst (1966), refers to this process as micritization. Chemical action by fungi or algae on grain surfaces produces dissolution of material resulting in the formation of bore holes. The process is centripetal in fashion and proceeds from the grain surface inwards. The empty bores, vacated by the borer presumably after death, tend to be filled with micritic carbonate material. Repeated episodes of boring and infilling with micrite will result in completely 'micritized' grains.

Borings investigated by the writer varied in diameter from 2 to 25 μm. The smaller borings, in the size range of 2 to 4 μm are straight and are probably fungal in origin (Bathurst, 1975, p. 382).

The larger bores are irregular in pattern and are probably of an algal origin.

Evidence of bores larger than 25 μm is rare. In one instance, two borings of 0.35 mm in diameter were observed to penetrate a crinoid ossicle (Plate 5-2). These borings are infilled by skeletal debris as well as carbonate mud. Bores of this size are attributed to the boring action of such organisms as arthropods, gastropods or sponges.

Work by Kobluk (1976), on the role of boring algae indicates their role in micritization may be more complex than put forth by Bathurst. Kobluk's observations were based on thin sections, prepared from crystals of Iceland spar which had been subjected to a subtidal environment of natural algal activity. He observed algal filaments to protrude from their bore holes on grain surfaces. Precipitating upon the filaments were crystals of high-Mg calcite or aragonite. In such a fashion an outward accretion of micritic carbonate can develop on grain surfaces, thus enlarging the grains.

It was frequently observed within the present study, that accompanying the centripetal micritization of the outer grain surfaces of crinoid ossicles the process was also occurring in a centrifugal fashion from the axial canal.

All observations indicate that boring and micritization occurred early within the sediments history and pre-dates all generations of cement and dolomitization.

Neomorphism

Folk (1965, p. 21), proposed the term 'neomorphism' to refer to "all transformations between one mineral and itself or a polymorph - whether inversion or recrystallization, whether the new crystals are larger or smaller or simply differ in shape from the previous ones."

The mud-sized fraction of the sediments studied is particularly susceptible to neomorphic alteration. The mud is usually composed of equidimensional and uniform-sized calcite anhedra varying from 5 μm to 20 μm in diameter (microspar) which Folk (1969), believes to have developed through neomorphism of 1 μm to 4 μm sized carbonate particles.

Longman (1977), has recently studied the role of clay minerals in facilitating the formation of microspar from carbonate mud. During the burial and diagenesis of the original aragonite of high-Mg calcite, the aragonite inverts to calcite and the high-Mg calcite loses some of its magnesium to form micrite. The micrite consists of relatively equant blocks of low-Mg calcite that have average diameters of about 2 μm. Most of the Mg++ ions expelled from the carbonate mud during the formation of the 2 μm calcite remain in the micrite and are probably attached to the surface of the calcite crystals. These Mg++ ions form a 'cage' about the micrite crystals which inhibits the recrystallization and enlargement of the micrite to microspar (Longman, 1977).

Removal of Mg++ ions by clay minerals, particularly chlorite and montmorillionite, from seawater is a known phenomenum and the clay minerals can apparently also absorb Mg++ ions in the subsurface environment during diagenesis (Longman, 1977). Thus, the presence of clays may greatly enhance the development of microspar by removing the cage of Mg++ ions.

Within the sediments studied by the author, petrographic examination reveals greater amounts of argillaceous impurities are present within those portions of the sediment displaying the best microspar development (Plate 5-3). The argillaceous impurities occur as inclusions within the microspar and as coatings on crystal surfaces.

When crystals of microspar exceed 50 μm in diameter, the term pseudospar is employed (Bathurst, 1975, p. 567). Crystals of pseudospar are similar in appearance to precipitated calcite cements and vary in size from 50 to 100 μm in diameter. Bathurst's (1975, pp. 417-419), fabric criteria for determining cements in thin section were used to differentiate sparry calcite cement from neomorphic spar. Within the neomorphic spar, the relic internal microstructure of skeletal debris is often preserved.

While the recognition of widespread neomorphic alterations is readily apparent within the thin sections examined, the precise timing of these alterations is more problematic. The following observations and conclusions can be made regarding the timing of neomorphic alterations: 1) micrite which occupies geopetal cavities and borings is partially or completely altered to microspar indicating this type of neomorphism post-dates boring or geopetal infilling of cavities, 2) microspar crystals occur as inclusions within replacement dolomite crystals, syntaxial overgrowth cements on echinoderm fragments and within silicified nodules. These features imply neomorphism pre-dates these diagenetic events.

Cementation

The precipitation of carbonate cements within modern sediments has been documented in a variety of environments (Bricker, 1971). In broad terms, these environments include the submarine environment, the intertidal or beach environment, the subaerial fresh water phreatic or vadose environments and the deep subsurface environment.

Cements are largely responsible for the occulusion of primary and secondary void spaces within the sediments studied. While these cements can occur in a variety of crystal forms and mineralogies, all cements studied consisted of either sparry calcite, micrite, or more rarely dolomite.

As defined by Folk (1959), sparry calcite is a clear, relatively inclusion free accumulation of calcite crystals whose crystal diameters are greater than 10 μm in size. A second variety of calcite cement is present as micritic coatings, consisting of crypto- to microcrystalline calcite crystals. Crystals range in size from less than 1 to 3 or 4 μm appearing petrographically like semi-opague mud.

Calcite crystals, occur in three different habits as defined by Folk (1959). In order of decreasing abundance within thin sections examined these crystal habits are:

i) equant

ii) bladed

iii) micritic

As well as occurring in these differing crystal habits, the cements occur in a variety of morphologies as defined by Folk (1959). In relative order of precipitation of these cements, from earliest to latest, they include:

i) drusy, or fringe cements

ii) syntaxial overgrowths

iii) equant or blocky void fillings.

1) <u>Drusy or Fringe Cements</u>

These cements occur as linings precipitated on void or fracture walls, or as coatings on grain surfaces. Crystal habits can be equant, bladed, or micritic. The long axes of bladed crystals are oriented perpendicular to the grain or pore surfaces. The amount of microscopic inclusions within bladed or equant crystals is variable. Equant crystals vary in diameter from 8 to 25 μm. Bladed calcite crystals vary in width from 5 to 30 μm, and in length from 15 to 120 μm.

Micritic cements contain crystals varying in size from 1 to 4 μm. This type of cement is often irregular in thickness and appears lumpy or pelleted (Plate 5-4).

Drusy cements are found lining cavity walls in birdseyes, fenestral voids, vugs, intergranular pore spaces or desiccation fractures. The cement fringe is generally not more than 150 μm in thickness. Up to three successive generations of drusy cement may be observed to have precipitated on a pore wall.

In some instances, crusts of equant spar and micritic calcite formed syngenetically. Plate 5-4 reveals alternating layers of micritic and equant calcite crystals lining the pore walls of a birdseye.

Plates 5-5 and 5-6 are thin sections from near the top of an off-shore oolitic-algal shoal within the Elkton Member. Plate 5-5 reveals a lithoclast in an oolitic-pelletal grainstone which was initially coated with a layer of equant calcite crystals, followed by a later crust of micritic carbonate. Both generations of druse have been disrupted by an early compactional fracturing event. A somewhat similar sequence of events is show in Plate 5-6 where a lithoclast was initially coated with a layer of micritic druse. The micritic crust was fractured during compaction, exposing a fresh surface of the lithoclast, upon which precipitated a layer of equant druse.

These early generations of cements were probably responsible for stabilization of carbonate sands deposited in offshore bars or shoals. During low stands of sea level, these bars or shoals would be exposed to the intertidal and beach environments of diagenesis. Early diagenetic micritic druses, and less commonly equant druses, are known to form in the intertidal and beach environments of Recent and Pleistocene sediments (Bricker, 1971, pp. 1, 2).

Plate 2-6 reveals a horizontal sheet crack formed in an intertidal sediment as the result of desiccation. The crack was subsequently infilled by a druse of bladed calcite spar which precipitated on both the floor and ceiling of the fracture. This variety of cement is very common in the subtidal environment (Bricker, 1971, p. 27). It probably reflects very early cementation when the tidal flat was inundated by marine waters during high tide.

2) Syntaxial Overgrowth Cements

Syntaxial overgrowths developing in optical continuity with crinoid grains forms the dominant cement in many grainstones. Commonly, the overgrowths fill all available pore space. These cements extend from the crinoid grain surfaces out to the surfaces of adjacent polycrystalline grains or the fringes of drusy cement enveloping these polycrystalline grains (Plate 6-1). This indicates that the syntaxial cements formed later than the drusy cements. Evamy and Shearman (1965), and Purser (1969), present evidence that overgrowth cement on echinoderm grains is early in origin forming in the shallow subtidal environment. Folk (1965), observed that echinoderm overgrowths tend to fill all available pore space and suggests (p. 25) that the overgrowths either formed earlier than or faster than the other types of spar cement.

3) Equant or Blocky Cements

Mosaics of clacite with crystals approximately equal in dimensions are common as pore fillings in the pore systems of both Shunda and Turner Valley sediments (Plates 5-4, 6-2). Equant cements generally contain fewer inclusions than do the drusy or syntaxial cements indicating the equant cements precipitated from solutions containing fewer impurities, or did not incorporate pre-existing material.

Relative to the drusy and syntaxial cements, the equant cements formed last. This is demonstrated by equant cements occurring in the centre of voids lined by earlier generations of drusy and/or overgrowth cements (Plates 5-4, 5-5, 5-6).

The actual time and diagenetic environment of formation of the equant cement is difficult to establish. Equant cements form in the early diagenetic environments of the fresh water phreatic (Land, 1970), Friedman et al, 1971), (Cussey and Friedman, 1977). Late diagenetic equant calcite cements are also associated with deep subsurface and tectonic cementation. The fact that some of the equant cements fill late fractures associated with tectonic movement suggests these cements are late diagenetic.

Moberly (1973), documents equant calcite cement of an early diagenetic origin precipitating in the zoecial openings of bryozoa. Equant cement was observed by the author to occur in skeletal wackestones of the Turner Valley (Plate 6-3).

Equant cements commonly fill birdseyes of the Shunda pelleted lime muds. These cements are commonly associated with geopetel infillings of silt-sized internal sediment. This sediment (Plate 6-4) is very similar to Dunham's (1963), description of early diagenetic vadose silts.

Very minor amounts of equant dolomite cements occur with the equant calcite cements filling birdseyes. The dolomite crystals occur as euhedral rhombs which display an almost perfect crystal form and are virtually inclusion free (Plate 6-5). The individual rhombs are similar to those described by Folk and Land (1975), and Randazzo et al (1977), which they have termed 'limpid', or clear dolomites. Limpid dolomites are believed to have originated in the fresh-water environment by slow precipitation from dilute solutions. This process creates a more perfect stoichiometry and ionic ordering in the rhombs than is found in normal dolomites, hence, their perfect crystal form and clearness. Limpid dolomite crystals line the pore walls of birdseyes and pre-date the precipitiation of equant cements.

Dolomitization

Mechanisms of Formation

Despite much attention within the literature, the actual mechanism of formation of the vast quantities of dolomite in the sedimentary record remains poorly understood. The more common mechanisms of formation found in the literature include:

i) Capillary evaporation of pore waters in hot arid supratidal regions is responsible for the formation of thin beds of fine-grained dolomite (Shinn et al, 1965). This mechanism clearly can not account for large thicknesses of coarse-grained dolomite.

ii) An evaporitic reflux model of dense saline brines percolating downward and laterally through permeable strata (Deffeyes et al, 1965). Hsü and Siegenthaler (1969), object to this mechanism feeling it would require the precipitation of vast quantities of gypsum.

iii) Late stage dolomitization in the deep subsurface by fluids expelled from shale sequences during compaction and burial.

iv) The most recent mechanism is the meteoric water-sea water mixing model proposed by Land (1973a), (1973b) and Badiozamani (1973). The mixing of marine and meteoric waters results in a solution supersaturated with respect to dolomite but undersaturated with respect to calcite (Badiozamani, 1973).

Dolomite Textures

Within the area of study, dolomitization of Shunda and Turner Valley Formation sediments is common. Dolomites of the Shunda Formation usually occur as thin beds of finely crystalline to cryptocrystalline dolomite or as scattered rhombs of dolomite within lime mudstones and wackestones. The style of dolomitization in the Turner Valley Formation is somewhat different, consisting usually of thin to thick beds of coarsely crystalline dolomites.

Dolomites observed within this study occur in four principal groups: (1) dolomitization by total replacement, (2) dolomitization involving aggrading porphyroid and coalescive neomorphism (Folk, 1965), (3) dolomitization by selective replacement, and (4) detrital dolomite.

1) Total Replacement Dolomite

Dolomitization through total replacement occurs in every lithofacies encountered but is most prevalent within sediments containing abundant carbonate mud. In the case of completely dolomitized skeletal sands, recognition of grain 'ghosts' becomes difficult. Their outlines are revealed by the pattern of inclusions and/or variations in size of the replacement dolomite crystals (Plates 6-6, 7-1).

2) Neomorphic Dolomite

The most widespread form of aggrading neomorphism is porphyroid. This type is characterized by discrete euthedral to subhedral rhombs of dolomite scattered through the rock (Plate 7-2).

The rhombs display a tendency to grow larger, develop better crystal forms, and contain fewer inclusions when they replace the cement than when they replace the micrite (Plate 7-3).

Several factors indicate the growth of neomorphic dolomite post-dates the formation of syntaxial overgrowths on echinoderm grains. Within Plate 7-4, the rhomb of replacement dolomite contains ghosts of the glide planes within the overgrowth cement indicating the dolomite formed later than the cement.

Zoning in dolomite rhombs occurs in both the Shunda and Turner Valley sediments. The zoning is enhanced by alternating layers of inclusion-rich and inclusion-poor dolomite. Each zone represents a change in the chemistry and/or detrital content of the pore water from which the dolomite crystal is forming. As many as seven different zonations were observed in a single crystal (Plate 7-5). Bourrouilh (1972) concluded that zonation within dolomite crystals is related to a fluctuating water-table, or a change in ground-water chemistry.

The zoned dolomite rhomb of Plate 7-6 reveals selective dissolution to have affected only the core of the crystal and has left the remainder of the rhomb unaffected. This preferential dissolution may be due to these crystals having relatively unstable, impure, early-formed cores overgrown by more stable rims (Folk and Land, 1975).

3) Selective Replacement Dolomites

Selective dolomitization occurs in a variety of forms. Plate 8-1 shows an oolitic pelletal grainstone in which euhedral to subhedral cloudy dolomite rhombs selectively replace some oolitic coatings and not others. This phenomena may be due to differences in the mineralogical composition of the oolitic coats which renders some layers more susceptible to dolomitic replacement than others. This same selectivity is observed to occur within certain layers of oncolites (Plate 8-2). However, Plate 8-3 displays an oncolitic grain unaffected by dolomitization while the micritic matrix material has largely been altered to dolomite. This selectivity may arise from chemical differences between the matrix and grain or from a difference in micro-permeabilities existing between the relatively impermeable oncolite and the more permeable matrix of micritic carbonate.

The selective and pseudomorphic replacement of echinoderm plates by dolomite was observed to occur within two widely separated units of an echinoderm grainstone and an echinoderm packstone of the Turner Valley Formation (Plate 8-4). This replacement by dolomite affected only the echinoderm plates within the sediments and not the ossicles. This selectively may arise by either, a difference in the mineralogy of the two grain types or by a difference in their permeabilities. Differences in their mineralogies is unlikely since neomorphism had probably converted both types of grains to low-Mg calcite. Plate 8-5, is an enlargement of Plate 8-4 and reveals a permeable microstructure exists within the echinoderm plate. Thus, permeability differences between the plates and the ossicles seem a more likely answer for the selective replacement by dolomite. Selective removal of the calcite by etching reveals the replacement process to be most complete on the periphery of the grains and least complete in the central portion of the grains (Plate 8-6). Thus, this replacement process is initiated at the grain surface and proceeds inwards in a centripetal fashion.

4) Detrital Dolomite

The calcareous and dolomitic siltstone unit of supratidal origin which marks the contact with the Mount Head Formation contains some crystals of detrital dolomite. This siltstone is comprised of alternating lamellae of silt-sized to very fine-grained sand-sized particles of subangular to subrounded quartz, feldspar, and dolomite grains in a matrix of micritic carbonate and argillaceous material (Plate 9-1). Within each lamellae, there is a direct correlation in the size of the terrigenous clastic grains and the size of the carbonate grains which indicates a mechanical sorting of both grain types. The dolomite grains vary in size from 10 to 140 μm and have rounded, cloudy cores (Plate 9-2). Some dolomite grains have clearer subhedral govergrowths developed upon them.

A very similar type of calcareous siltstone with dolomite clasts has been described by Lindholm (1969), from the Devonian Onondaga Limestone of New York. Lindholm (1969, p. 1035) concluded that the dolomite was detrital in origin, derived by erosion and eolian transport from older outcrops. After deposition of the abraded dolomite grains, they were enlarged by subsequent dolomite overgrowths.

Dolomitization of Shunda and Turner Valley Sediments

Illing (1959), Murray and Lucia (1967), and Macqueen and Bamber (1967) have published papers dealing with the dolomites of the Shunda and Turner Valley Formations. Illing's (1959) earlier work interpreted most of the Turner Valley dolomites to have an epigenetic origin produced by migrating magnesium-rich fluids squeezed out during compaction of older buried sediments. In his model, the dolomites post-dated all cements.

Illing's interpretation (1959) for the lithographic, cryptocrystalline (less than 5 μm) dolomites of the Shunda Formation was that they formed as a primary precipitate within hypersaline lagoonal complexes. Illing (1959, p.41) states many of the slightly coarser microcrystalline dolomites (5 - 25 μm) were, however, deposited as fine bioclastic sediment and completely dolomitized during early diagenesis.

However, Murray and Lucia (1967) interpreted the Turner Valley dolomites to have formed by a seepage reflux mechanism from dense brines, accumulating in the overlying evaporitic Mount Head Formation. They document a tendency for these fluids to selectively dolomitize the micrtic mudstones, wackestones and some packstones in preference to the grain suppprted sands. They observed some cements to post-date the dolomite.

The more recent work of Macqueen and Bamber (1968) put forth a somewhat different origin for the dolomites of the Shunda Formation. They interpret the crypto- and microcrystalline dolomites to be of early diagenetic origin forming in a coastal sabkha evaporite environment.

The mechanism of formation of the fine to coarsely crystalline dolomites commonly occurring within the Turner Valley Formation is uncertain. Macqueen and Bamber (1967) suggest they formed by a seepage reflux mechanism of dense brines accumulating in the overlying Mount Head Formation. However, in light of recent work by Hsü and Siegenthaler (1969) and Land (1973a, 1973b), dolomitization by meteoric water sea-water mixing becomes an alternate possibility. Manheim (1967) and Kohout (1967) found that fresh continental waters intrude marine sediments off the east coast of Florida for distances of more than 100 km. Thus, it is possible during Mississippian time that meteoric continental waters accumulated within the supratidal settings of the Mount Head sediments far to the east of Moose Dome. These waters were capable of extending great distances seaward towards the area of study at Moose Dome moving through porous strata of the Turner Valley Formation.

At the present time, too little is known of the processes of either the reflux or of the mixing mechanisms of dolomitization to conclusively support or reject either of these mechanisms as being responsible for the means of formation of the Turner Valley dolomites.

Hematite

The conspicuous reddish-brown to purplish-gray color imparted by the presence of hematite is visible in mudstones and wackestones in some horizons of the upper Turner Valley Formation and the Shunda Formation. Hematite is also constituent of the green shale facies developed in the Shunda Formation. Microscopic examination of grain supported sediments reveals small percentages of disseminated hematite in them as well.

The hematite occurs as irregular or globular blood red grains 10 to 30 μm in diameter (Plate 9-3). The grains frequently form aggregates which can be observed to cut across matrix-skeletal debris boundaries.

Hematite also occurs as globules within oolites and oncolites, as coatings on shell fragments, as globular infillings of dissolution vugs, in stylolites, and in one instance as a replacement of a bryzoan frond (Plate 9-4). This last form of hematite replacement contains inclusions of subhedral dolomite rhombs and equant calcite cement. Some globules of hematite were observed to transect equant sparry calcite filling a fracture.

The actual time of the hematite replacement is difficult to establish. However, it post-dates the development of some dolomite and equant calcite cements but its occurrence as accumulations along stylolite surfaces indicate it formed earlier than the stylolite development.

Pyrite

Although much less common in occurrence than hematite, pyrite occurs as isolated crystals or as aggregates. Individual crystals are commonly euhedral and display square, triangular, or rectangular sections under microscopic examination. In reflected light, the crystals display the characteristic brass yellow color of pyrite. Single crystals vary from 20 to 800 μm in diameter.

The pyrite displays an affinity for silicified coral fragments within sediments of the Turner Valley Formation. The crystals of pyrite tend to replace the skeletal wall material of the coral fragments and contain inclusions of micrite, equant calcite cement or dolomite. The pyrite may also replace the silica which has replaced the coral fragment.

The above criteria point to a rather late post-cementation, dolomitization and silicification origin for the pyrite crystals.

Silicification

Frequently, fossil fragments are replaced by microcrystalline and/or megaquartz crystals or by chalcedonic quartz. Microcrystalline quartz forms a mosaic of interlocking anhedral crystals, 8 to 140 μm in diameter while chalcedonic quartz occurs mainly as circular or elliptical shperulites, 100 tp 800 μm in diameter. Megaquartz occurs in granular mosaics of interlocking anhedral crystals, 50 to 400 μm in diameter (Plate 9-5).

Coral fragments display the greatest affinity for being replaced by silica (Plate 9-6). Internal chambers of the corals are usually lined with microcrystalline and/or chalcedonic quartz while the central portions of chambers are replaced by megaquartz.

Scattered throughout sediments of both the Turner Valley and Shunda Formations are quartz euhedra or anhedra 10 to 150 μm in diameter. They are most abundant in mud-supported rocks and in particular those of the Shunda Formation. The perfect crystal form and lack of inclusions within the euhedra suggest they are authigenic in origin and have not undergone a great deal of mechanical transport or abrasion.

However, the abundant anhedral grains of quartz silt dispersed throughout the carbonate muds are believed to have been introduced to the sediments by eolian transport. Microscopic examination of the peripheries of the quartz grains reveals embayments and inclusions of the surrounding micritic matrix. Thus, some degree of enlargement of the quartz grains has followed their deposition. Dapples (1967) attributes the precipitation of quartz overgrowths on quartz grains to be an early diagenetic event during early burial.

In the central portion of the Turner Valley Formation, there is a 0.6 metre thick unit of an echinoderm grainstone which is cemented by quartz. The quartz occurs as an interlocking mosaic of anhedral crystals which vary in size from 50 to 400 μm. In many instances, the quartz crystals have partially replaced echinoderm grains and extend as far as 20 μm into the surfaces of the grains (Plate 10-1).

It is not uncommon to observe ghosts within these megaquartz crystals of small, equant or scalenohedral crystals from 10 to 20 μm in diamteter, which form a partial druse lining the former pore spaces (Plate 10-2). These are probably the remnants of an early calcite druse.

Large volumes of silica-laden fluids must have been flushed through this unit in order to explain the large amounts of megaquartz observed. The development of the megaquartz in this unit of the Turner Valley Formation is probably an early diagenetic feature. The megaquartz cement post-dates the formation of early diagenetic calcite druses but pre-dates the precipitation of equant pore filling calcite cements or syntaxial overgrowths on echinoderm grains.

Fracturing

Three forms of fracturing occur within the sediments studied: a very early fracturing due to desiccation of sediments within the supratidal setting, an early fracturing of constituent grains during initial sediment compaction, and a much later tectonic fracturing of the lithified sediments.

Early compactional fracturing is generally restricted to grain supported sediments but can also affect skeletal debris floating in a matrix of carbonate mud. Plate 1-5 reveals a fragment of a brachipod shell which has undergone early fracturing probably due to stresses incurred during a differential compaction of the mud matrix in which the shell fragment is floating.

Plates 5-5 and 5-6 reveal compactionally fractured grains which display development of early fringe coments on the fracture surfaces, indicating the fracturing took place prior to the precipitation of any cements.

In many units, well developed fractures are present which transect grains, matrix and cement and represent a later post-lithification event related to burial of the sediment. They are commonly infilled by a mosaic of equant calcite cement.

While the exact time of the late fracturing events can not be accurately determined, it is likely that fractures occurred at several different times in response to stresses produced by an increasing load of overlying sediments.

Pressure Solution

Evidence of post-depositional pressure solution is found within rocks of the Shunda and Turner Valley Formations throughout the study area. Features that illustrate this phenomena include the development of macroscopic and microscopic stylolites and the formation of irregular sutured contacts between grains in grain supported sediments.

The development of sutured grain boundaries between adjacent echinoderm fragments is widespread throughout the grainstones and packstones of the Turner Valley Formation (Plate 10-3). This process may be responsible for the release of large volumes of calcium carbonate which precipitated elsewhere or on adjacent grains as pore filling carbonate cement.

The exact time at which pressure solution between adjacent grains took place is difficult to determine. Syntaxial overgrowth cements on echinoderm grains commonly have sutured contacts with neighbouring rims of overgrowth cement. These sutured contacts indicate pressure solution processes occurred after the development of the overgrowth cement.

Some pressure solution took place prior to the development of replacement dolomite within echinoderm packstones. This is indicated by sutured contacts between echinoderm grains contained as ghosts within the rhombs of dolomite (Plate 10-4).

Stylolites exposed on outcrop surfaces are generally developed parallel to bedding, and are frequently formed at lithologic boundaries. Insoluble material scattered throughout the host rock is concentrated along the stylolite surface and consists of quartz silt, silicified fossil fragments, argillaceous materials, hematite, and pyrite. These observations suggest that stylolitization is a relatively late diagenetic event.

CHAPTER 5

Porosity and Permeability

Introduction

While modern carbonate sediments have porosities as high as 70 percent (Pray and Choquette, 1966), their ancient rock counterparts commonly contain a small fraction of this initial amount. This drastic reduction in the pore space of carbonate sediments is related to a sequence of diagenetic events which follow deposition of the sediment. The volume of pore filling cement in ancient carbonates commonly may exceed the volume of the initial sediment (Pray and Choquette, 1966).

The pores and pore systems within the carbonate sediments studied are normally physically and genetically complex. Sedimentary features which exert the most profound effect on porosity development are fabric, grain size, sorting, and mineralogical composition of the sediment. Adopting the terminology of Choquette and Pray (1970), eight porosity types are recognizable within the sediments investigated. These include interparticle, intraparticle, intercrystalline, moldic, burrow, vug, fenestral, and fracture porosity.

Development of Porosity and Permeability Within The Shunda Formation

The more porous units within the upper portion of the Shunda Formation at Moose Dome have porosity values of from 6.0 to 8.6 percent (Table 3, Commercial Analysis). However, permeabilities are generally low, varying from 0.01 to 0.23 millidarcies.

SAMPLE No.	SAMPLE DESCRIPTION	POROSITY %	PERME ABILITY*
1	SHUNDA FORMATION – DOLOMITIC LIMESTONE MUDSTONE – FENESTRAL, BURROW AND VUG POROSITY	6.9	0.01
2	SHUNDA FORMATION – DOLOMITIC LIMESTONE MUDSTONE – FENESTRAL, BURROW AND VUG POROSITY – SAMPLE COLLECTED FROM BENEATH GREEN SHALE FACIES	8.6	0.01
3	SHUNDA FORMATION – ONCOLITIC OOLITIC GRAINSTONE FACIES – PARTIALLY DOLOMITIZED – INTERGRANULAR AND VUG POROSITY	6.1	0.23
4	TURNER VALLEY FORMATION – SKELETAL GRAINSTONE – DOLOMITIZED – SUCROSIC – INTERCRYSTALLINE AND MOLDIC POROSITY	4.3	0.43
5	TURNER VALLEY FORMATION – OOLITIC GRAINSTONE – 30% DOLOMITIZED – MEDIUM TO VERY COARSE GRAINED – TIGHT IN APPEARANCE – VUG POROSITY	3.3	0.01
6	TURNER VALLEY FORMATION – ECHINODERM WACKESTONE – DOLOMITIC – INTERCRYSTALLINE AND MOLDIC POROSITY	3.4	0.52
7	TURNER VALLEY FORMATION – ECHINODERM WACKESTONE – HEAVILY DOLOMITIZED – ARGILLACEOUS – COARSE GRAINED – MOLDIC AND VUG POROSITY	8.2	0.45
8	TURNER VALLEY FORMATION – ECHINODERM GRAINSTONE – 20% DOLOMITIZED – COARSE GRAINED – NO VISIBLE POROSITY	1.8	0.01
9	TURNER VALLEY FORMATION – MUDSTONE DOLOMITE – BRACHIOPODS – SHALEY PARTINGS INTERCRYSTALLINE POROSITY	2.6	0.01
10	TURNER VALLEY FORMATION – MUDSTONE LIMESTONE – BRACHIOPODS – BIRDSEYES – FENESTRAL AND VUGGY POROSITY IN STREAKS	2.2	0.01
11	TURNER VALLEY FORMATION – SILTSTONE DOLOMITIC AND CALCAREOUS – UPPERMOST UNIT OF THE FORMATION – INTERGRANULAR POROSITY	6.4	0.01

* HORIZONTAL PERMEABILITY TO AIR IN MILIDARCYS

TABLE 3 POROSITY AND PERMEABILITY DATA FOR SELECTED OUTCROP SAMPLES OF THE SHUNDA AND TURNER VALLEY FORMATIONS EXPOSED AT MOOSE DOME

The main porosity types include fenestral, vuggy, moldic, and fracture porosity. Little, if any, of this porosity is of primary origin. Much of the dissolution can be directly associated with erosional breaks in the accumulation of these sediments.

Plate 11-1 displays dissolution phenomena in a birdseye wackestone which underlies a green shale facies. Dissolution has been responsible for the removal of varying amounts of calcite cement from the birdseyes and the removal of small dolomite euhedra from the matrix (Plate 11-2). This sample has a porosity of 8.6 percent and yet contains no effective permeability. The matrix permeability was probably destroyed when the micrite recrystallized into an interlocking mosaic of microspar. Thus, the formation and subsequent dissolution of the cement and dolomite rhombs pre-dates the recrystallization of the matrix to microspar. The dissolution may have occurred early in the sediments history by flushing of meteoric fluids through the poorly lithified muds.

The resultant good porosity reflects the selectivity of the dissolution process to leach material from the isolated birdseyes and dolomite crystals. The poor permeability is due to the later recrystallization of the matrix. Thus, while pore space is being created locally, very little of it contributes to an overall effective porosity within the rock. Most sediments deposited in the intertidal and supratidal environments display some evidence of dissolution phenomena.

Plate 11-3 shows a fenestral and birdseyed skeletal wackestone in which dissolution has removed small scattered euhedral dolomite rhombs and carbonate cements infilling birdseyes and fenestrae.

An example of dissolution which occurs beneath an erosional break is observed immediately beneath the subaerially laminated crust, discussed in Chapter 3. For a short distance of approximately 2 cm beneath the crust, extensive dissolution of dolomite euhedra has taken place.

The development of porosity by dissolution of cements and of dolomite rhombs is variable in both a vertical and a horizontal direction within any bed.

The overall pattern of porosity development within the Shunda Formation shows a direct relationship to its exposure to the vadose zone of diagenesis and flushing by meteoric waters. The large volume of dense and impermeable micritic carbonate which forms the matrix of these sediments renders most porosity developed in the Shunda Formation basically ineffective in contributing to the reservoir potential of the formation.

Development of Porosity and Permeability Within The Turner Valley Formation

Observable porosity types include vuggy, fenestral, intercrystalline, interparticle, intraparticle, moldic, and fracture. The formation of medium to coarsely crystalline dolomites is much more widespread within the Turner Valley sediments than within the Shunda. Turner Valley and Shunda sediments have similar porosities. However, Turner Valley sediments have much greater effective porosities (and thus, permeabilities) than the Shunda sediments. The intercrystalline porosity created by dolomitization is often enhanced by a moldic porosity formed by the later dissolution and removal of skeletal debris within the sediment (Plate 11-4). While in many cases, it is impossible to determine the exact nature of the organisms these molds represent, some clearly indicate echinoderm debris was a main contributor.

The creation of porosity and permeability within sediments of the Turner Valley Formation was markedly different from that of the Shunda Formation. Whereas Shunda porosity is largely a function of subaerial exposure and dissolution, that of the Turner Valley Formation is related to a later dolomitizing and leaching event which created intercrystalline and moldic porosity. Porosity values from eight outcrop samples vary from 1.8 percent to 8.2 percent. Permeability development varies from 0.01 to 0.52 millidarcies (Table 3).

A sample of a dolomitized skeletal wackestone with moldic porosity contains a fairly low porosity of 3.4 percent but displays a permeability of 0.52 millidarcies which is the highest value observed for the samples tested. With better development of porosity and permeability, these dolomitized skeletal wackestones become an important reservoir rock for hydrocarbon accumulation within the subsurface of the Alberta Foothills and Plains region.

As indicated by Murray and Lucia (1967), the dolomitization of these sediments is selective in its nature, and affects those sediments with an abundant carbonate mud fraction rather than the well sorted, clean washed and tightly cemented grainstone units. For example, a very coarse-grained echinoderm grainstone, tightly cemented by sparry calcite, yielded a very low porosity of only 1.8 percent and displayed no measurable permeability.

Although one sequence of echinoderm grainstones within the central portion of the formation was observed to contain a high effective intergranular porosity (Plate 14-5), a close examination of the outcrop indicated the porosity is the result of modern surficial weathering and does not persist for a very great distance into the outcrop surface.

While the dissolution of material within the Turner Valley sediments is usually restricted to the removal of calcite, some leaching and removal of dolomite rhombs has occurred (Plate 14-6). This feature probably results from late diagenetic leaching processes occurring in the subsurface.

Summary

The Shunda Formation contains small amounts of fenestral, vuggy, moldic and fracture porosity. The majority of the porosity is non-effective due to the presence of an impermeable micrite matrix. Most of the porosity is of a secondary origin created by dissolution of cement within birdseyes, burrows and fenestral voids.

The Turner Valley Formation contains localized zones of fair to good porosity primarily of an intercrystalline and moldic nature, within coarsely crystalline dolomite beds. Poor to fair permeabilities are present in these beds due to the intensity of the dolomitization process. The dolomitization displays a preference to occur within mudstones and wackestones and not within packstones and grainstones.

CHAPTER 6

Summary and Conclusions

Sediment Deposition

During accumulation of sediments of the Shunda Formation at Moose Dome, the area was covered by a broad complex of shallow restricted lagoons and intertidal mud flats dissected by tidal distributary channels.

The most striking characteristic of Shunda sediments is their high content of carbonate mud-sized material and their paucity of coarse-grained skeletal material. Preservation of burrows is common and fecal pellets are abundant. Bioturbation by mud scavenging organisms has, in many instances, totally obscured any internal bedding characteristics in the lagoonal sediments and has given rise to thick, homogeneous, indistinct units of mudstones.

Birdseyes and fenestral fabrics developed in the intertidal zone of sedimentation are common. Algal remains and algal related structures are abundant.

The dominant lithologies present include mudstones, skeletal and pelletal wackestones, pelletal packstones with accessory amounts of oncolitic-packstones, pelletal grainstones and oncolitic-oolitic grainstones.

Interbeds of cryptocrystalline dolomite and localized occurrences of calcareous siltstones of supratidal origin occur.

The transition into sediments of the overlying Turner Valley Formation is a rapid one, with no apparent break in the accumulation of sediments occurring. The basal Turner Valley units consist of very coarse-grained and well sorted skeletal grainstones and packstones deposited in the deeper water facies of the open shelf environment. The basal Turner Valley sediments represent a transgression of deeper water sediments over shallow water sediments.

The basal 90 metres of the Turner Valley Formation is comprised largely of open shelf sediments deposited in shoals and bars. The bar and shoal environment is characterized by thick and massive, cross-bedded units of echinoderm and skeletal grainstones. On the landward side of these barriers occur the restricted shelf or lagoonal environments.

A charactertistic feature of the open shelf and shoal environments is their high content of skeletal debris, largely of an echinoderm nature.

Within the uppermost 25 metres of the Turner Valley Formation, were deposited lagoonal - intertidal - supratidal seqeuences of sediments similar to those of the underlying Shunda Formation.

Further shallowing terminated Turner Valley sedimentation and resulted in the deposition of the highly evaporitic supratidal sequence of sediments of the overlying Mount Head Formation.

Diagenetic Alterations

Diagenetic alterations within the Shunda and Turner Valley Formations include biological diagenesis, compaction, neomorphism, cementation, dolomitization, silicification, pyritization, pressure solution, stylolitization, dissolution, and fracturing.

The environments of deposition of the Shunda sediments renders this package of sediments praticularly susceptible to early processes of alteration within the vadose and phreatic zones of diagenesis. Subaerial exposure has resulted in the development of green shale facies, minor erosional breaks, micro-karst surfaces, dissolution features, subaerial laminated crusts and caliche profiles.

Shunda sediments are well cemented by sparry calcite which occurs in a variety of crystal forms which include equant, blocky, drusy or micritic forms.

Dolomites of the Shunda Formation primarily formed as early diagenetic products and they occur in three principal manners: (1) as thin silty beds of cryptocrystalline dolomite with individual crystals varying from 4 to 8 μm in diameter; (2) as euhedral or subhedral crystals varying from 8 to 40 μm in diameter. These occur in a manner varying from isolated occurrences of scattered rhombs replacing carbonate mud, to complete replacement of the host sediment; and (3) as small perfect euhedra of very inclusion poor or 'limpid' dolomite crystals which line birdseyes or fenestrae.

The cryptocrystalline dolomites are believed to have formed in the supratidal setting by an evaporite capillary mechanism. The finely crystalline dolomites are believed to be products of either a seepage reflux mechanism, or a Dorag style of mixing of meteoric and marine waters.

By virtue of their deposition in deeper waters, the Turner Valley sediments were not so readily subjected to early periods of subaerial exposure and alteration.

Cements within the Turner Valley sediments occur primarily as early and rapid syntaxial overgrowth cement on echinoderm fragments or as equant, blocky or fringe cements.

Dolomites of the Turner Valley Formation are coarsely crystalline and display a selectivity for altering mudstone, wackestone and some packstone units in preference to replacing grainstone units. However, the anomalous occurrence of completely dolomitized skeletal grainstone units occur. Within these units, dolomite pseudomorphically replaces fragments of echinoderm plates which indicates a lengthy and slow process of dolomitization. It is possible, therefore, that Turner Valley dolomites are more coarsely crystalline than those of the Shunda Foramtion due to longer episodes of exposure to dolomitizing fluids.

Porosity Development

No primary porosity was recognized within sediments of either the Shunda or the Turner Valley Formation.

The more porous units investigated within the upper portion of the Shunda Formation display porosities of, from 6.1 to 8.6 percent and permeabilities from essentially non-permeable to 0.23 millidarcies. Porosity types include fenestral, vuggy, moldic and fracture.

Cementation was responsible for the occlusion of much of the primary pore space. Present pore space is primarily related to varying amounts of dissolution of this cement, possibly due to exposure to subaerial vadose zone of diagenesis. The low permeabilities observed are a function of recrystallization of the micritic matrix to impermeable microspar.

Selected sediment types of the Turner Valley Formation yielded porosity values from 1.8 to 8.2 percent and permeabilities varying from 0.01 to 0.52 millidarcies. The most widespread form of porosity developed within these sediments is of an intercrystalline nature produced by the formation of coarsely crystalline dolomite rhombs. Variable amounts of moldic, interparticle, vuggy, fracture, intraparticle and fenestral porosity occur as well.

Thus, the development of porosity and permeability within Turner Valley sediments is distinctly different from that of the Shunda Formation and is related to a relatively longer episode of dolomitization.

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PLATE 1

Outcrop Photograph, Sedimentary Structures and Constituent Grains of the Shunda Formation

1. Outcrop photo of Shunda/Turner Valley contact in quarry on the east flank of the Dome.

2. Burrowed lagoonal mudstones of the Shunda Formation.

3. Shunda lagoonal mudstone containing a filament of the Dasycladacean algae species Kamaena (A).

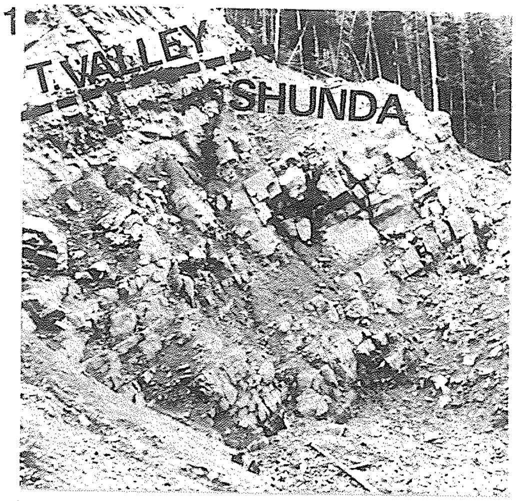
4. Shunda lagoonal mudstone containing thallus of the algae species Proninella (A) and fractured skeletal grain (B).

5. An intertidal oncolitic grainstone unit of the Shunda containing abundant pellets and micritic lumps.

6. Photomicrograph of sample in Plate 1-5.

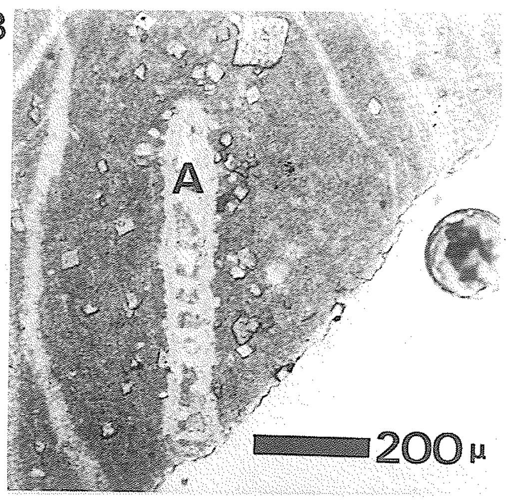
PLATE 1

1-1



1-2

1-3



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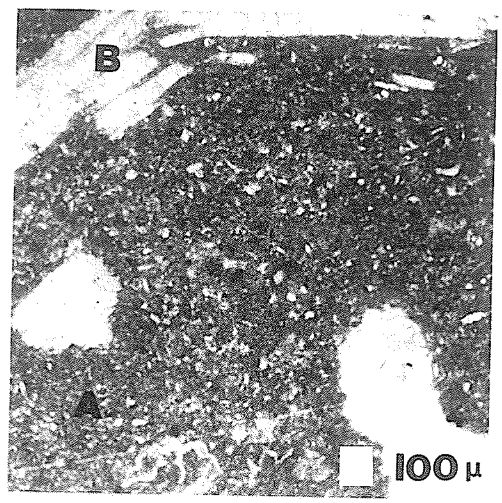

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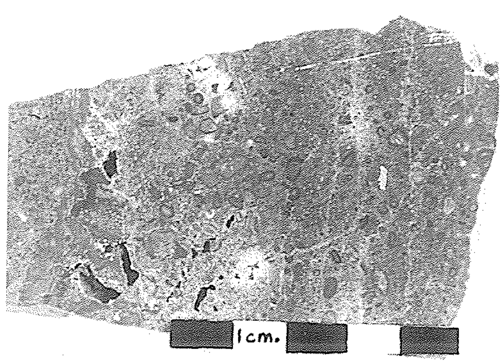

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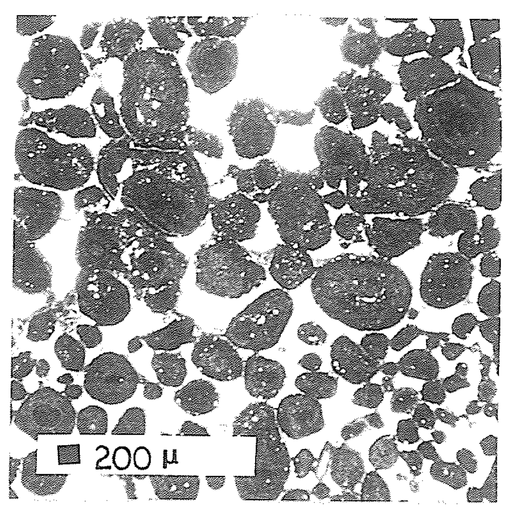


PLATE 2

Sedimentary Structures and Constituent Grains of the Shunda Formation

1. Oncolitic packstone of the Shunda Formation containing abundant birdseyes. Several of the oncolites have compound nuclei.

2. Birdseyed mudstone of the Shunda Formation containing numerous calcispheres.

3. Cryptocrystalline laminated muds of the Shunda (A) have been eroded by a small tidal distributary channel (B). The channel is comprised of an oncolitic grainstone unit. Intertidal birdseyed mudstones (C) cap this sequence.

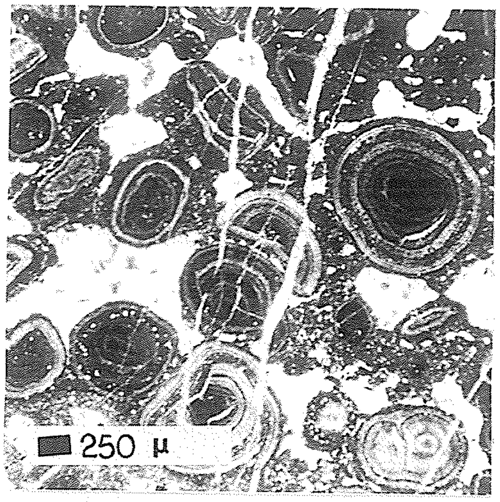
4. Horizontal sheet crack in a birdseye pelletal mudstone whose lower portion is infilled mechanically with micrite and pellets (A) and whose upper portion is infilled by cement (B).

5. Englargement of a portion of Plate 2-4 revealing pellets washed into the sheet crack (A) are very similar to pellets infilling birdseyes (B).

6. Enlargement of sheet crack illustrating mechanically introduced micrite (A) precedes the precipitation of a drusy calcite cement (B).

PLATE 2

2-1



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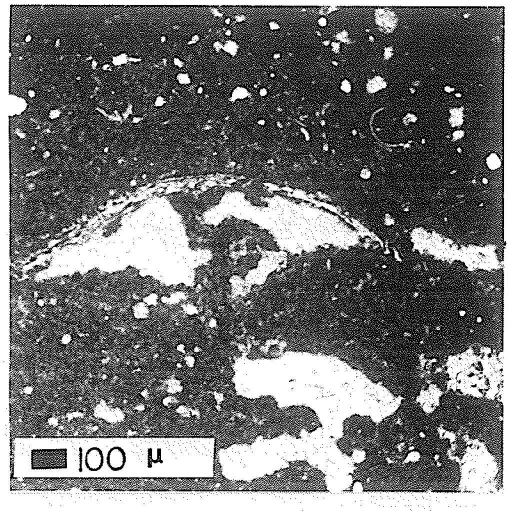

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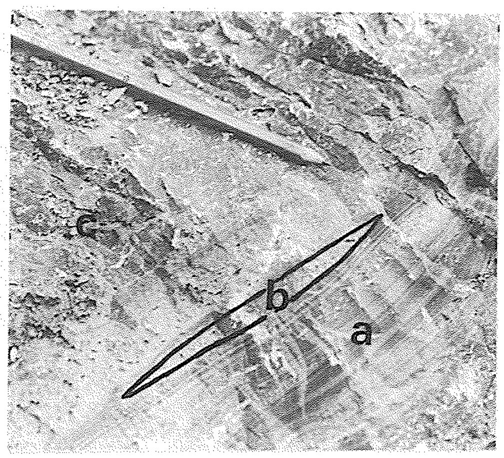

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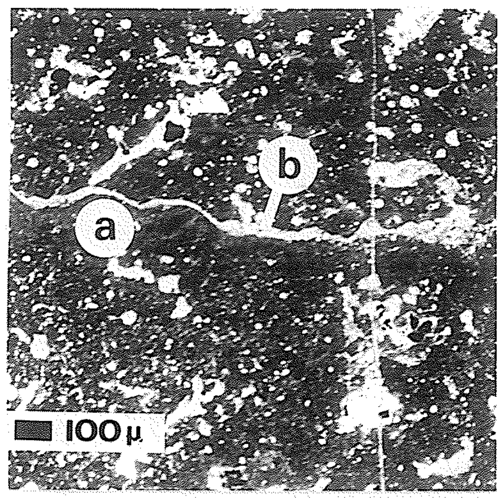

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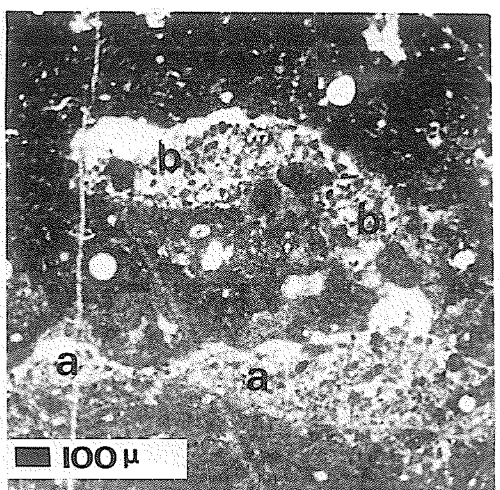

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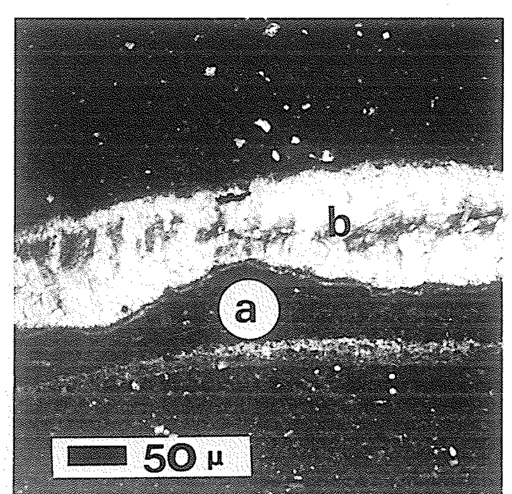
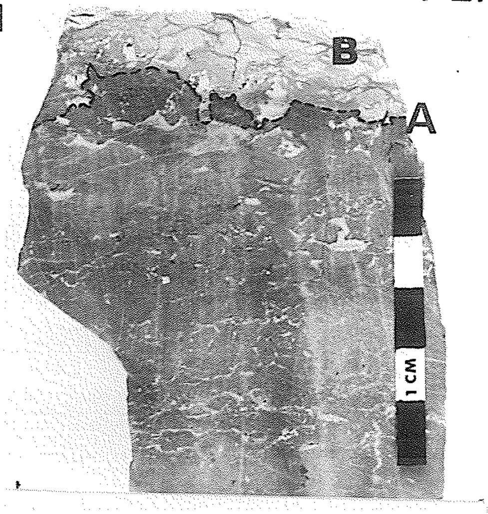


PLATE 3

3-1



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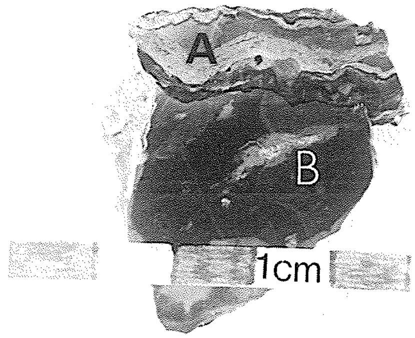
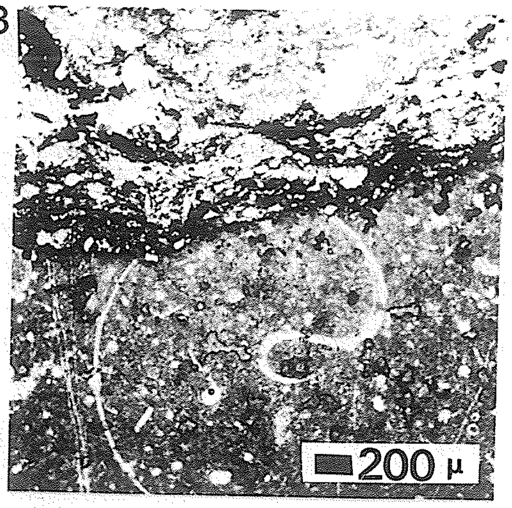


3-3



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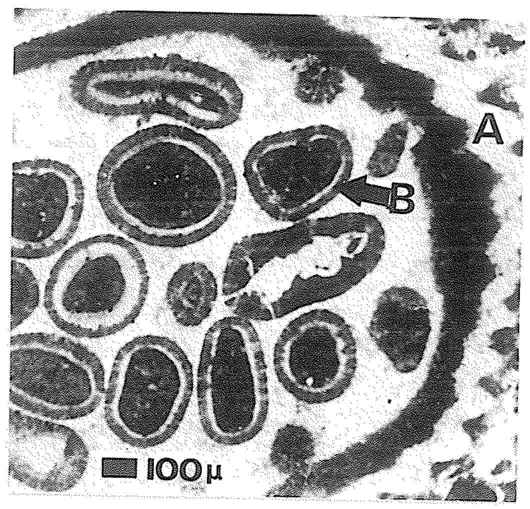

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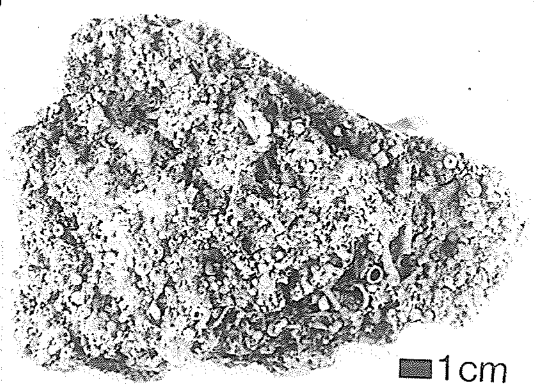

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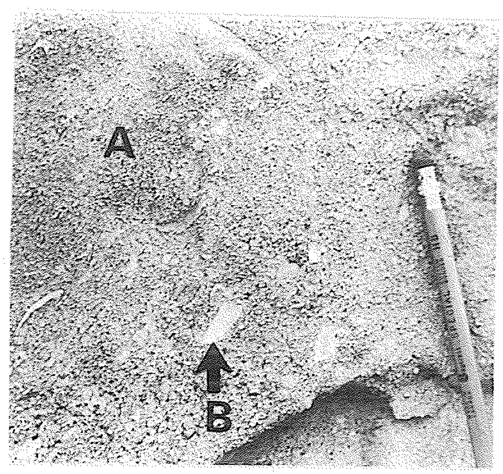


PLATE 3

Sedimentary Fabrics and Textures of the
Shunda Formation and the Turner Valley Formation

1. Photograph of a birdseye dolomite mudstone of the Shunda upon which an irregular erosional surface is developed (A). Reworked and bleached clasts of the dolomite overlie the unit (B).

2. Photograph of a dense subaerial laminated crust (A) developed upon an erosional surface within a birdseye mudstone (B) of the Shunda Formation.

3. Photomicrograph of subaerial crust in Plate 3-2. Note how the erosional surface transects both matrix and skeletal grains.

4. Oolitic grainstone from within an offshore bar or shoal of the Turner Valley Formation. The chamber of a brachiopod (A) has been infilled with oolites (B).

5. High energy open marine deposit of the Turner Valley Formation comprised almost exclusively of echinoderm detritus.

6. The lowermost unit of the Turner Valley Formation is formed largely of echinoderm detritus (A) with lesser amounts of other skeletal debris (B).

PLATE 4

Sedimentary Structures of the
Turner Valley Formation

1. Moderately abrupt bedding contact in the Turner Valley Formation between high energy open marine skeletal grainstone (A) and low energy mudstone (B) which contains numerous burrows (C).

2. Poorly sorted echinoderm wackestone of the Turner Valley Formation which contains intact crinoid stems and calyxs.

3. An erosional surface with calcareous shale deposited upon it (A) cross-cuts the bedding in an oolitic shoal (B) of the Turner Valley Formation.

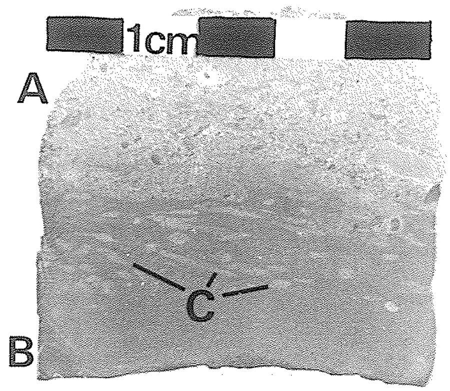
4. Very low energy open marine muds of the Turner Valley (B) containing frequent intercalations of shale (A).

5. Intra-formational conglomerate of the Turner Valley Formation displaying rip-up clasts (A) of lime wackestone (B) which are "floating" in a matrix of skeletal grainstone (C).

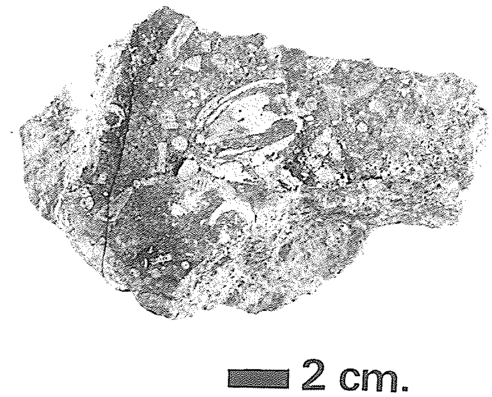
6. The basal bed of the Mount Head Formation consists of a dolomitic siltstone which has ripple marks on its upper surface.

PLATE 4

4-1

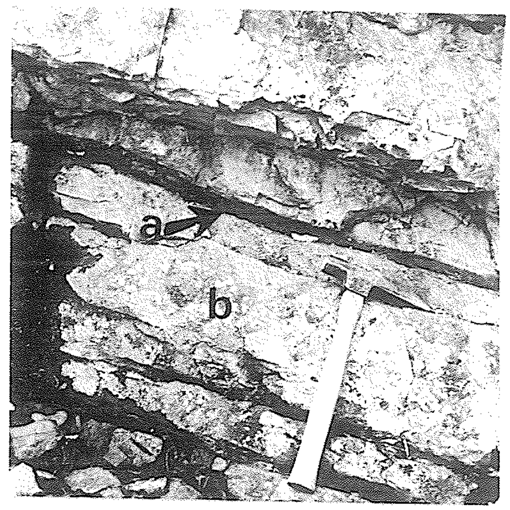


4-2

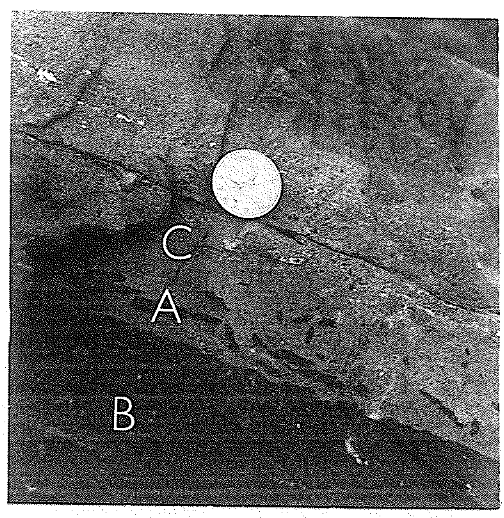


4-3

4-4



4-5



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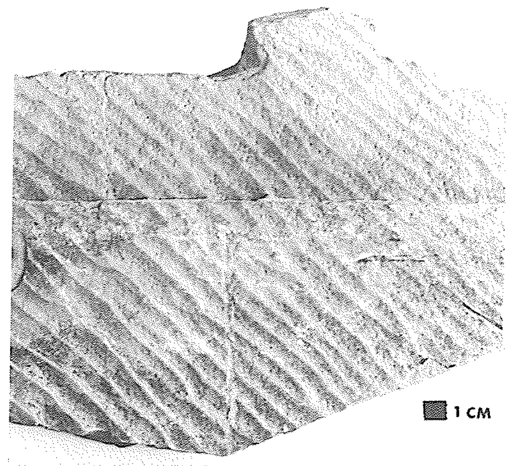


PLATE 5

Diagenesis - Biological, Neomorphism Cementation

1. Boring action of microorganisims (algae?) has drastically altered this crinoid fragment within the Turner Valley Formation.

2. Photomicrograph of a Turner Valley grainstone in which echinoderm fragments (A) have undergone boring (B). The larger borings may have been created by gastropods (C).

3. High amounts of argillaceous impurities are present in the areas of neomorphic spar development (A) in a skeletal wackestone of the Turner Valley Formation.

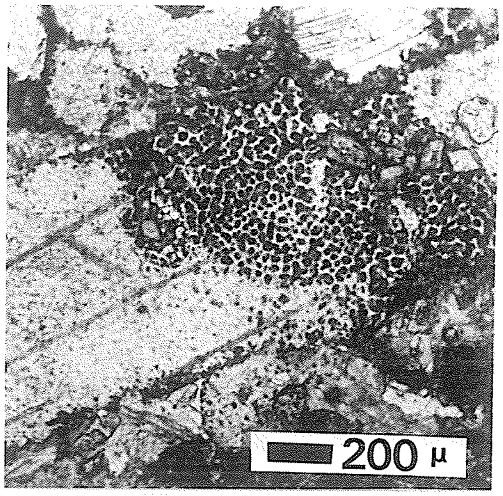
4. Photomicrograph of a Shunda birdseye which is lined with several generations of a "lumpy" micritic druse cement (arrows).

5. Oolitic grainstone from the Turner Valley Formation in which early micritic drusy cements (B) have been fragmented during compaction and fracturing of a lithoclast (A).

6. Ooolitic grainstone from the Turner Valley Formation coated by a layer of micritic druse and then fractured (A). A later generation of equant druse (B) formed on the exposed surface.

PLATE 5

5-1



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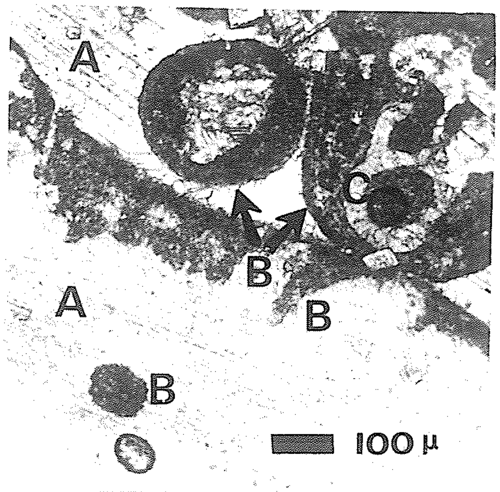

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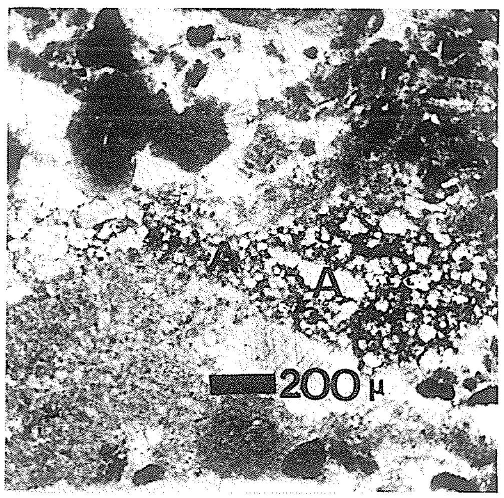

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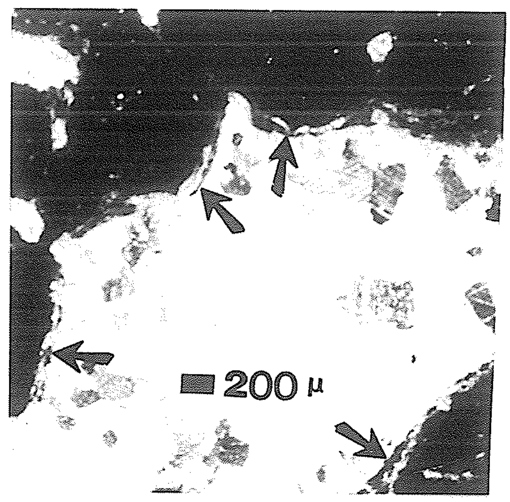

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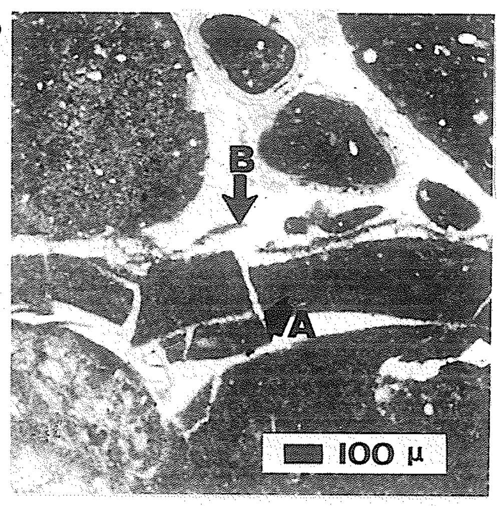

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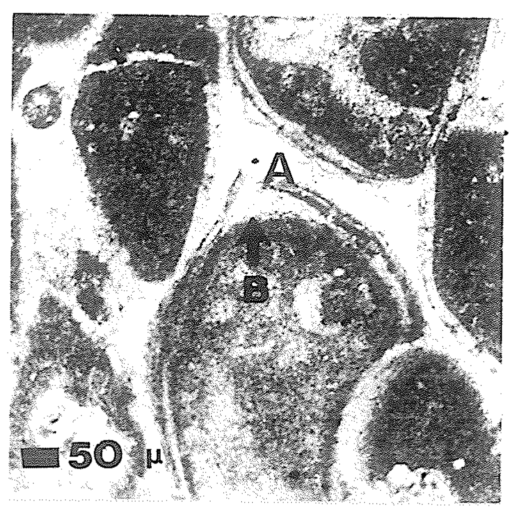


PLATE 6

Diagenesis - Cementation, Dolomitization

1. Echinoderm fragments within the Turner Valley Formation (A) commonly have syntaxial overgrowth cements (B) in optical continuity with the host grain.

2. Equant calcite cements are very common as void fillings in Shunda birdseye mudstones.

3. Equant calcite cement (A) precipitated in the zoecial openings of a bryozoa (B).

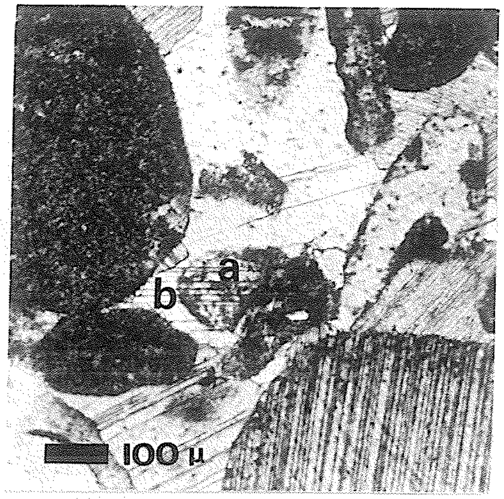
4. Geopetal infilling of vadose silt (A) within a birdseye of the Shunda Formation.

5. Photomicrograph of early diagenetic limpid dolomite cement (A) within a birdseye of the Shunda Formation. Note the clearness and almost perfect crystal form of the dolomite rhomb.

6. The inclusion pattern (A) within complete replacement dolomites of the Turner Valley Formation frequently reveals the presence of skeletal grains.

PLATE 6

6-1



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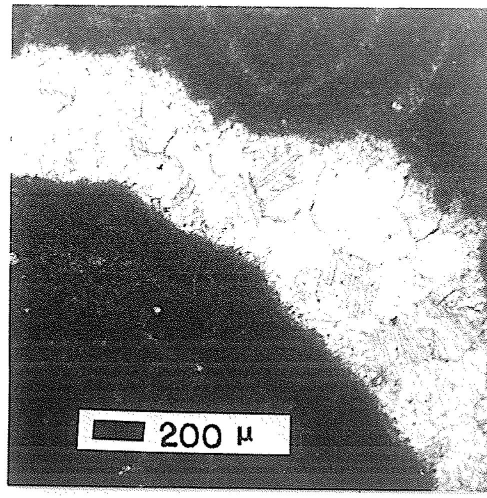

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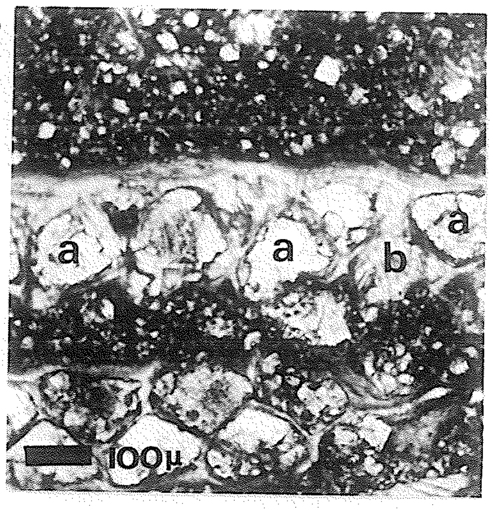

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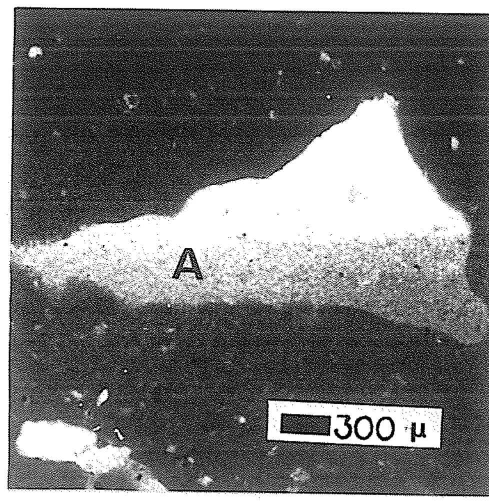

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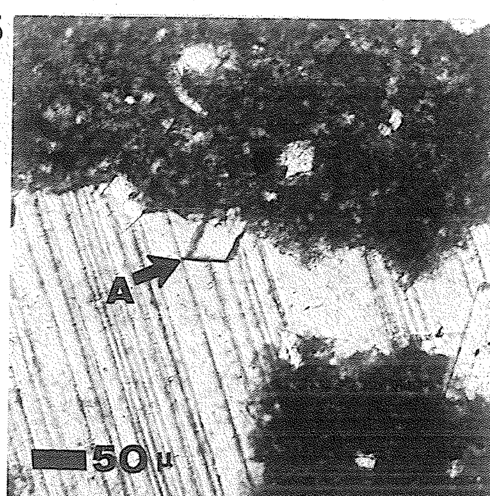

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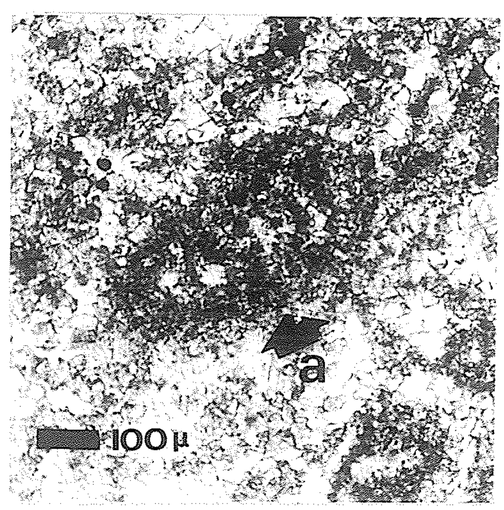


PLATE 7

Diagenesis - Dolomitization

1. Completely dolomitized skeletal sand of the Turner Valley Formation in which a 'ghost' of a skeletal grain (A) is recognizable due to an increase in crystal size and a reduction of inclusions within the dolomite.

2. Aggrading neopmorphic rhombs of dolomite distributed throughout the matrix and cement of a pelletal mudstone of the Shunda.

3. Rhombs of dolomite (A) replacing cement are relatively inclusion-poor in comparison to dolomite which replaces micrite (B).

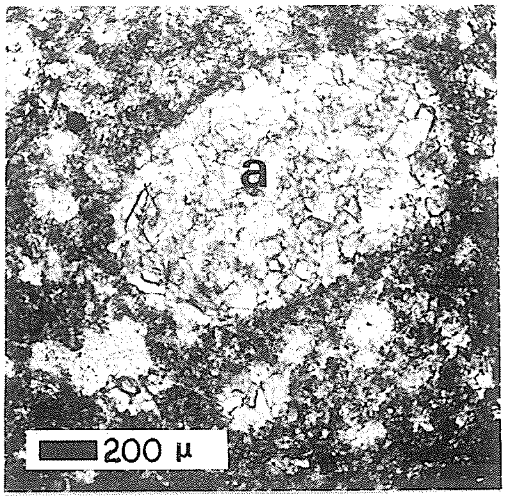
4. Neomorphic dolomite rhomb (A) replacing calcite overgrowth cement on an echinoderm fragment of the Turner Valley Formation.

5. Alternating inclusion-rich and inclusion-poor zones within dolomite crystals (A) of the Turner Valley Formation.

6. A zoned dolomite crystal (A) of the Turner Valley Formation in which the core (B) has been removed by leaching.

PLATE 7

7-1



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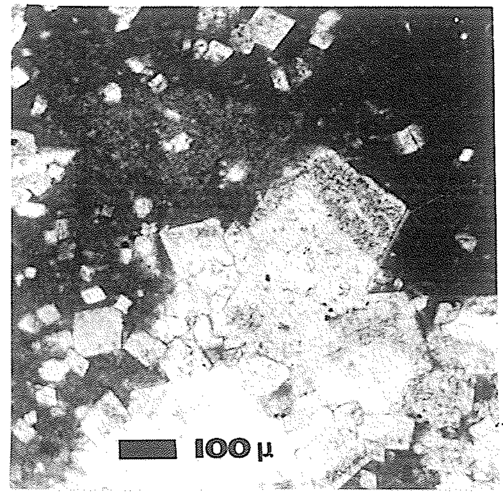

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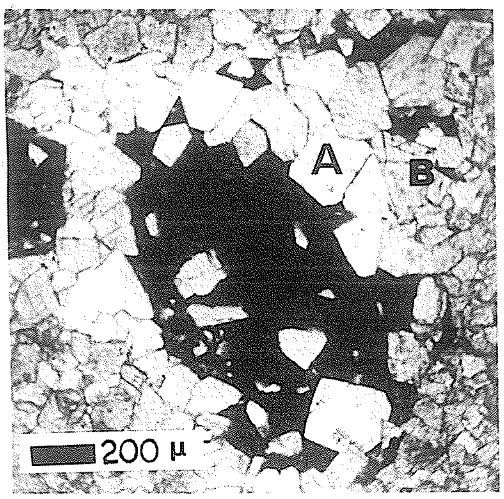

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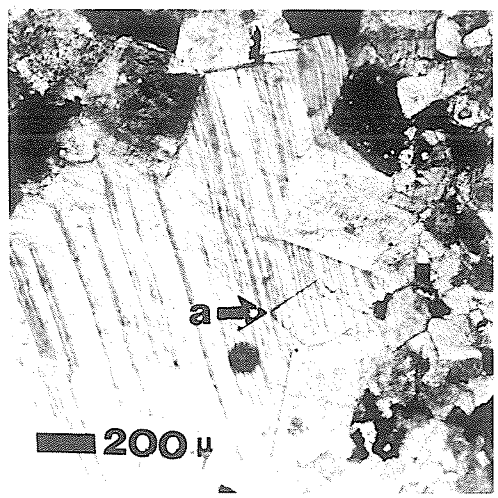

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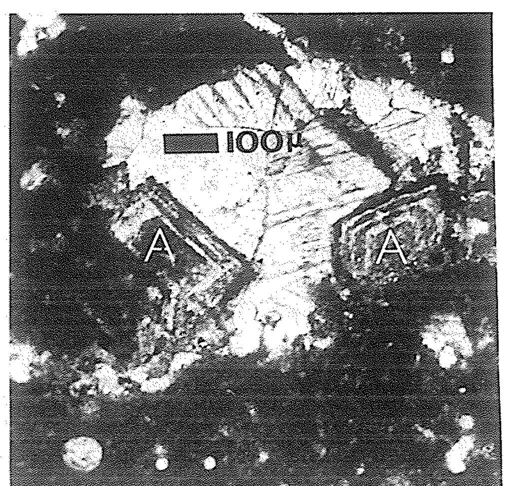

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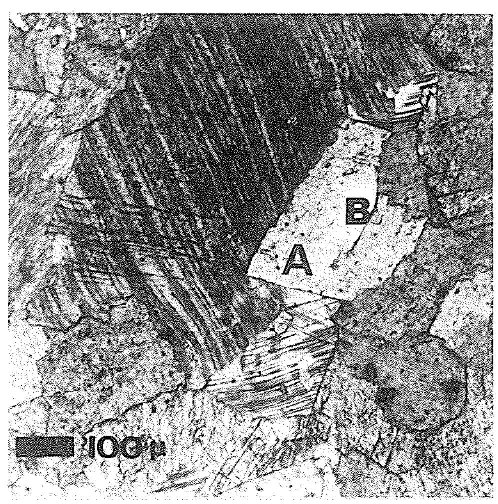


PLATE 8

Diagenesis - Dolomitization

1. Oolitic pelletal grainstone of the Shunda Formation in which dolomite has selectively replaced some cores and layers of oolites.

2. Selective replacement by dolomite (A) of micrite rich layers within an oncolite of the Shunda Formation.

3. Selective replacement by dolomite crystals (A) of micrite matrix surrounding an oncolite of the Shunda Formation.

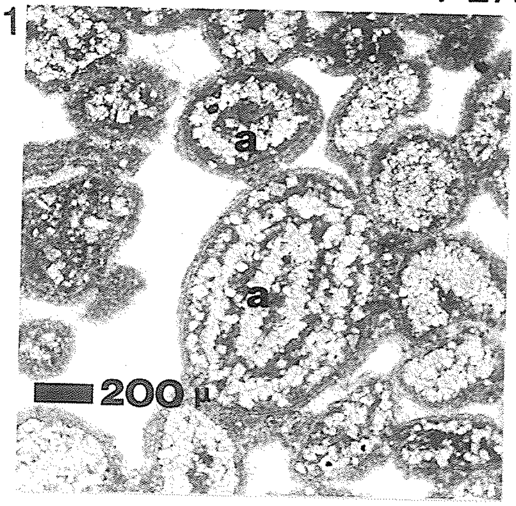
4. Selective and pseudomorphic replacement by dolomite of an echinoderm plate (A) while echinoderm ossicles (B) remain unaltered.

5. Enlargement of Plate 8-4 revealing a permeable microstructure exists within the echinoderm plate.

6. Etching of the calcite portion of the echinoderm plate in Plate 8-4 reveals the dolomitization process to be most complete at the outer grain surface and least complete at the grain centre.

PLATE 8

8-1



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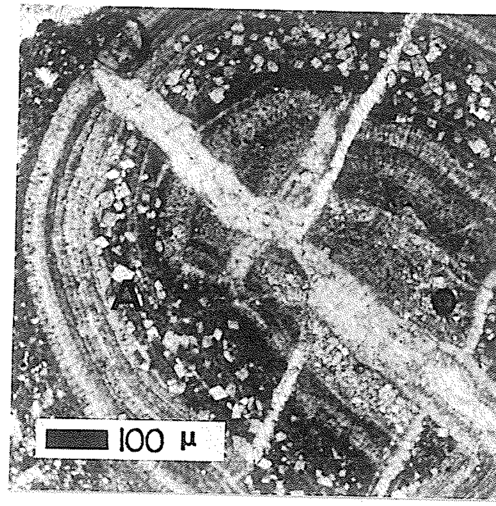

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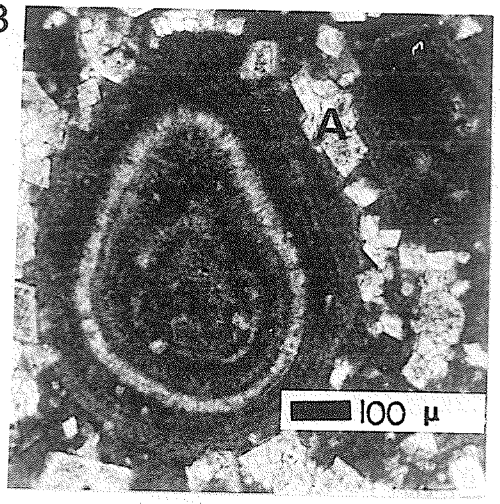

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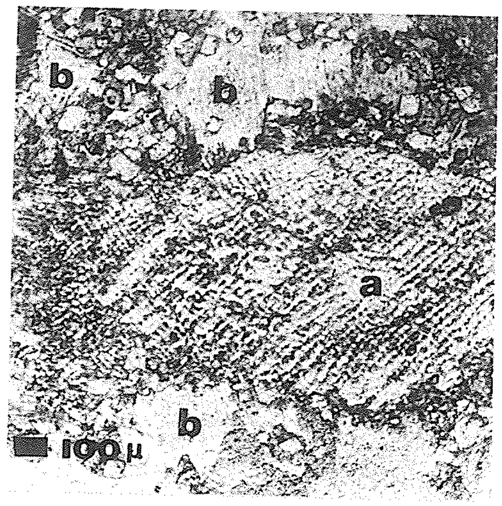

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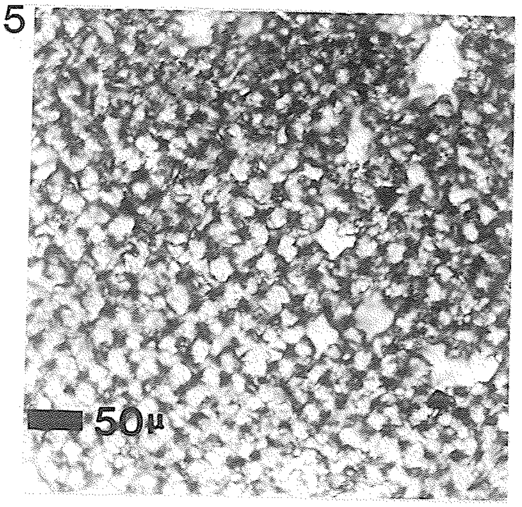

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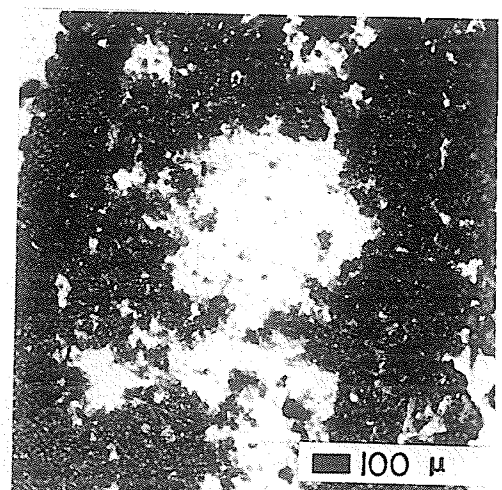
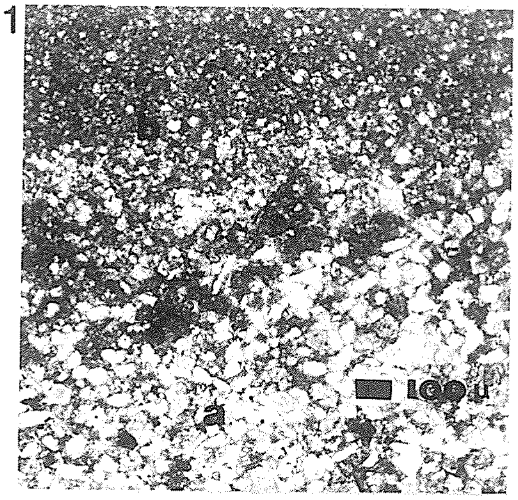


PLATE 9

9-1



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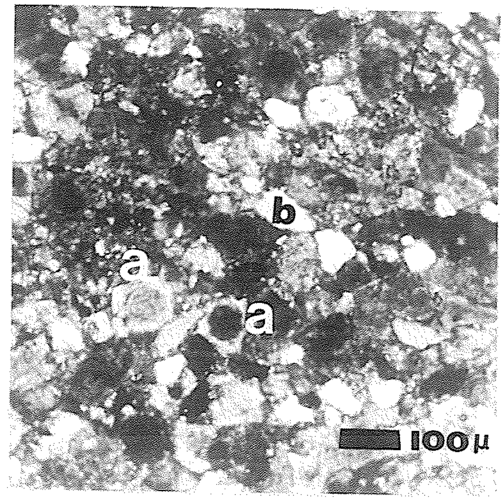

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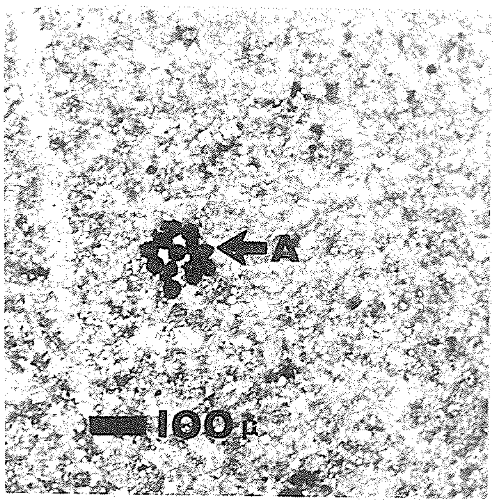

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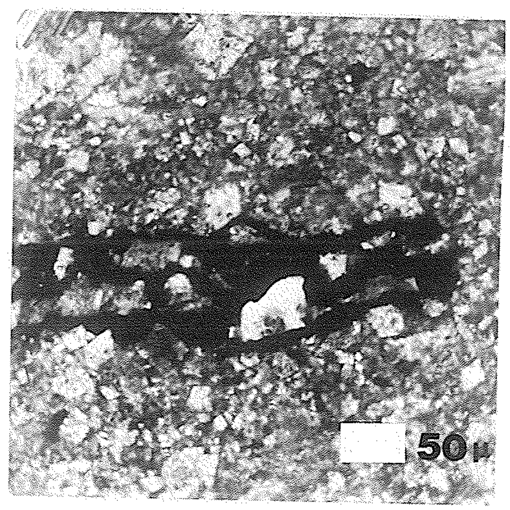

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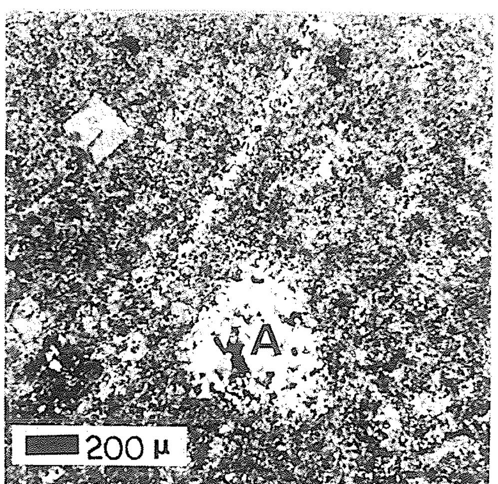

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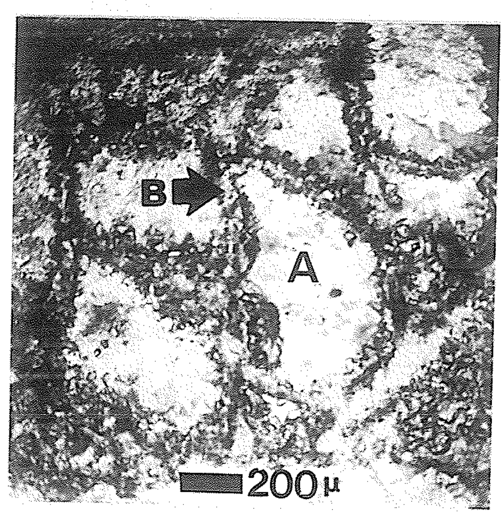


PLATE 9

Diagenesis - Dolomitization, Hematite, Silicification

1. Alternating lamellae of very fine-grained sand-sized (A) and silt-sized (B) particles of detrital quartz, feldspar and dolomite.

2. Enlargement of Plate 9-1 revealing well rounded dolomite grains (B), some of which have clear subhedral overgrowths developed upon them (A).

3. Globular grains of hematite within a dolomite mudstone of the Shunda Formation.

4. Replacement of a bryozoan frond by hematite.

5. Granular mosaic of megaquartz (A) possibly replacing fossil material in a skeletal wackestone of the Turner Valley Formation.

6. Coral fragment with megaquartz cement infilling the chambers of the coral (A) while the chamber walls (B) have been replaced with microcrystalline quartz.

PLATE 10

Diagenesis - Silicification, Pressure Solution

1. Echinoderm fragments (A) in an echinoderm grainstone are cemented with a megaquartz cement (B) which has partially replaced the outer portions of the echinoderm fragments (C).

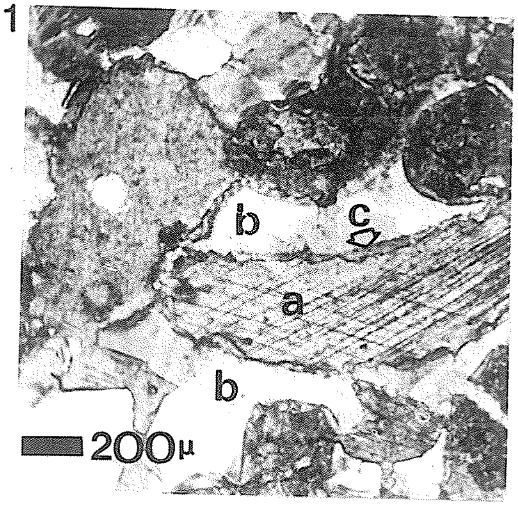
2. An enlargement of Plate 10-1 showing the echinoderm fragment (A); the megaquartz cement (B); inclusions of micrite in the megaquartz where it has replaced the echinoderm (C); and megaquartz replacement of a drusy calcite cement on the echinoderm (D).

3. Development of sutured grain boundaries between echinoderm fragments due to pressure solution (arrows).

4. A rhomb of replacement dolomite contains a 'ghost' of the sutured contact between adjacent echinoderm grains.

PLATE 10

10-1



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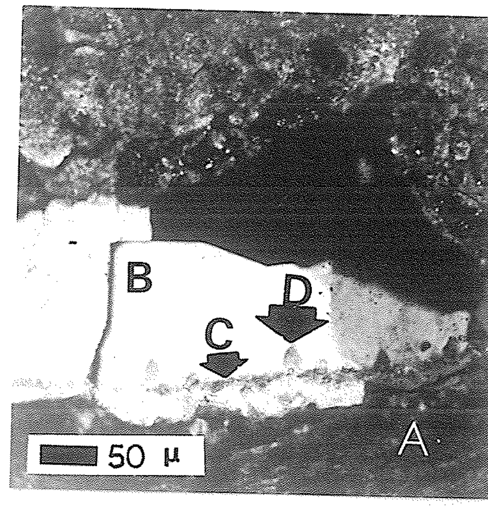

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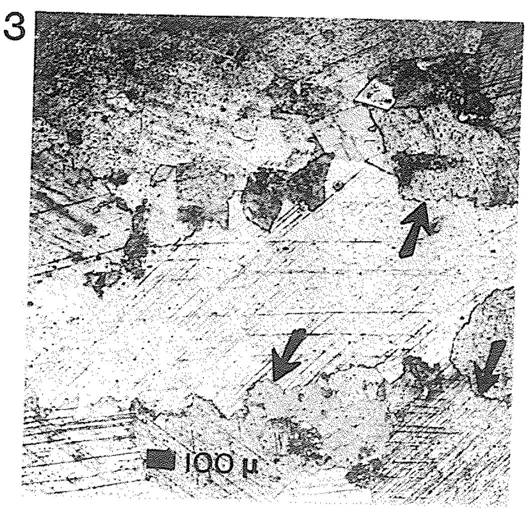


10-4

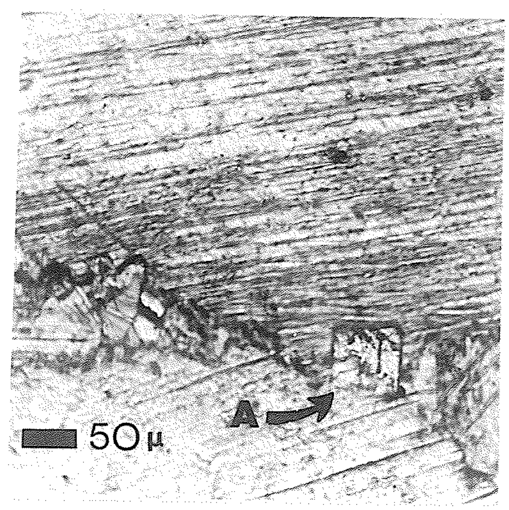


PLATE 11

Porosity and Permeability

1. Dissolution of cement from within birdseyes and fenestrae beneath a green shale facies of the Shunda Formation.

2. Photomicrograph of rock sample in Plate 11-1 showing dissolution of calcite from the birdseye and dolomite from the matrix.

3. Selective dissolution removing cements from birdseyes in a patchy fashion is common within the Shunda Formation.

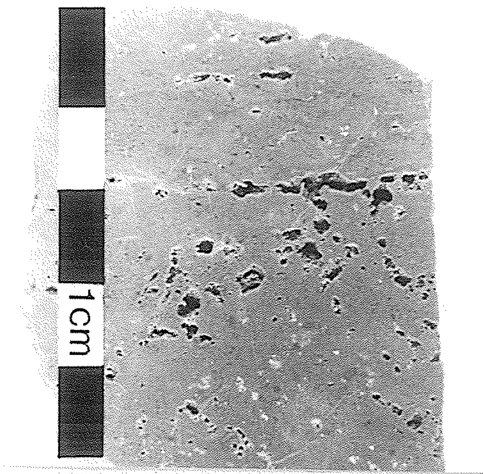
4. Dolomitized skeletal wackestone of the Turner Valley Formation containing intercrystalline and moldic porosity (A).

5. Dolomitized fine-grained skeletal wackestone of the Lower Porous Member of the Turner Valley Formation containing good intercrystalline and moldic porosity.

6. Dissolution of dolomite rhombs (A) which replaced an echinoderm fragment (B) increases porosity locally but does not contribute significantly to increasing permeability.

PLATE 11

11-1



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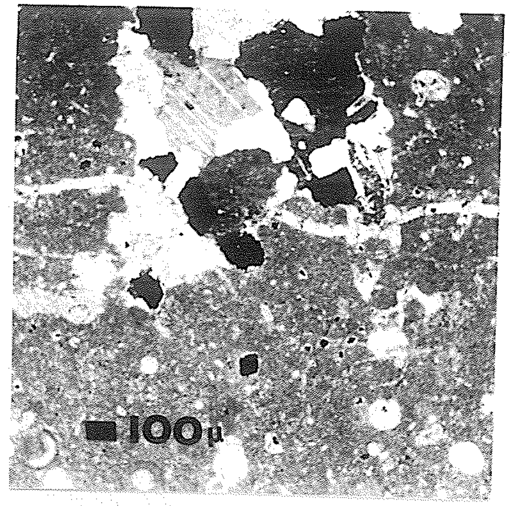

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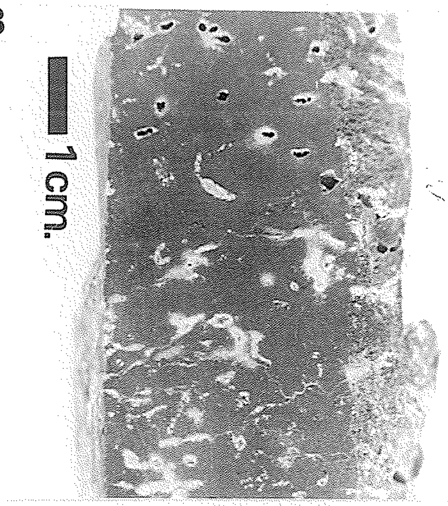
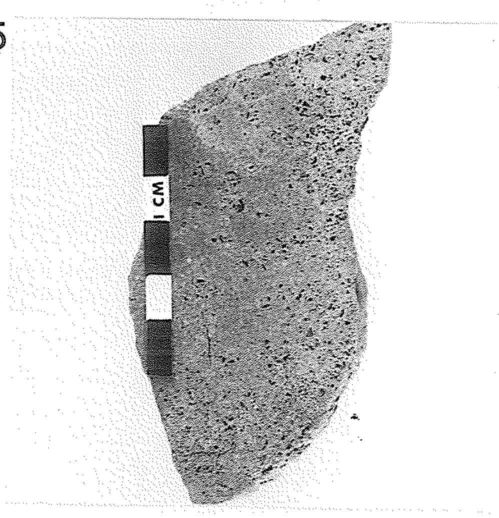


11-4

11-5



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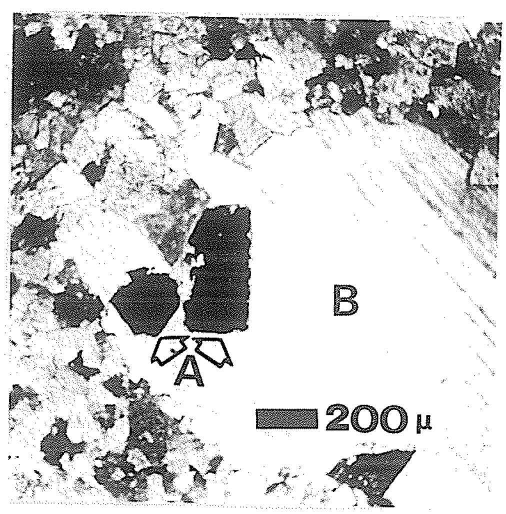

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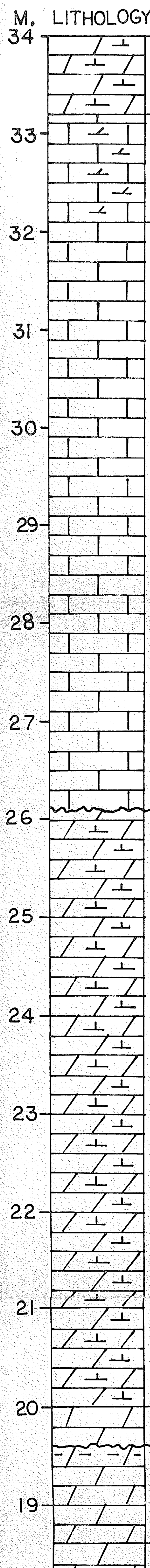
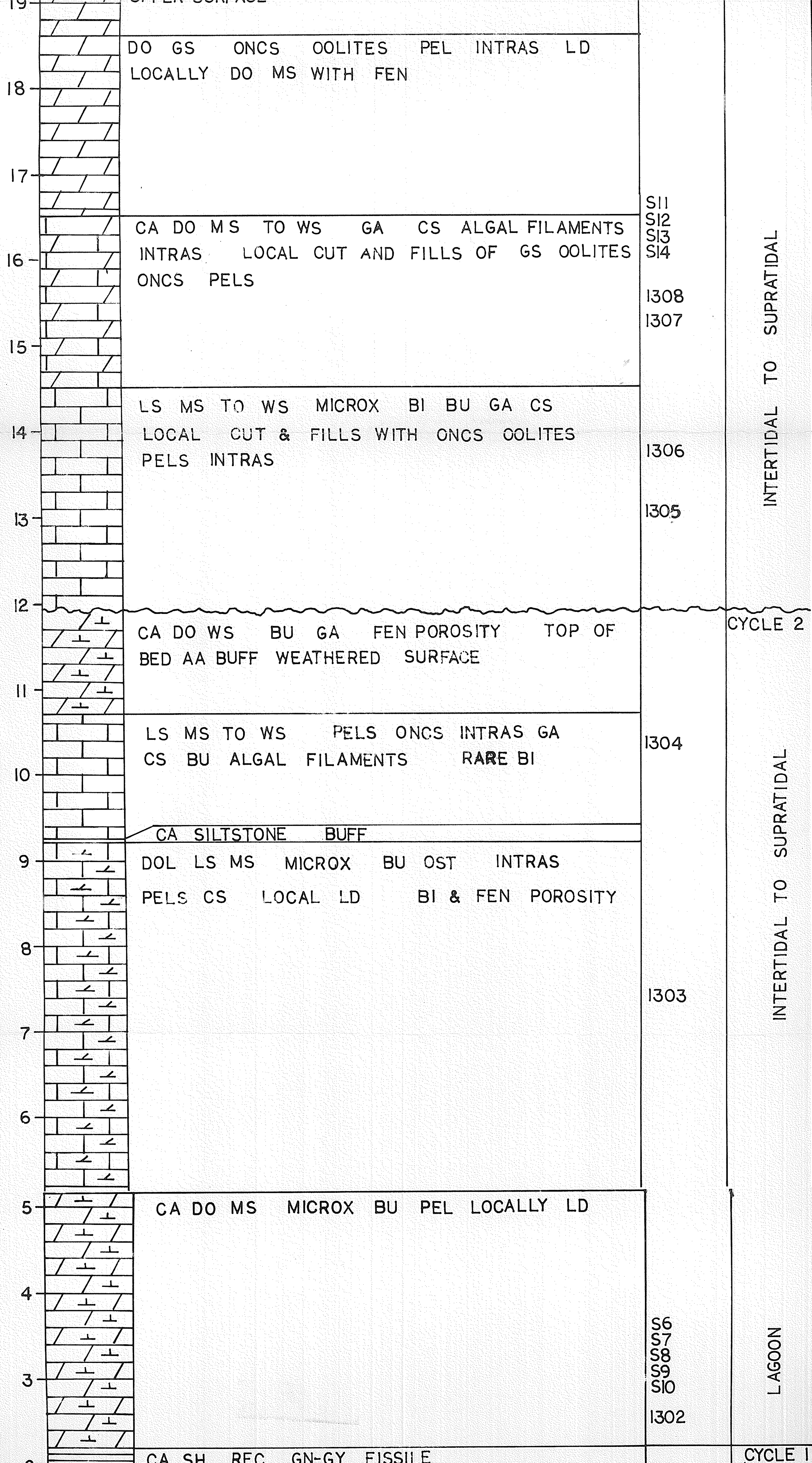
SHUNDA FORMATION



DESCRIPTION	SAMPLES	DEP. ENVIRON.
CA DO MS LT GY CRYPTOX	13 20	CYCLE 5 SUPRA-TIDAL
DOL LS MS IN LS WS PEL OOLITES INTRAS CS GA ALGAL FILAMENTS GEOPETAL STRUCTUR-ES BI	1316 1315 1314 1313	INTERTIDAL
DOL LS MS MA BU BI CS GA INTRAS LOCAL LD OST FEN	1317 1318 1319 1312	INTERTIDAL LOCALLY SUPRATIDAL
DO MS MICROX REC BU PEL OST CS LOCAL LD LOCAL BI FRIABLE WEATHERED UPPER SURFACE	1311 1309 1310	CYCLE 4 LAGOON LOCALLY INTERTIDAL
DO MS CRYPTOX BU		HYPERSALINE LAGOON
DO MS MICROX REC IRREGULAR SHALEY UPPER SURFACE		CYCLE 3
DO GS ONCS OOLITES PEL INTRAS LD		


19
UPPER SURFACE
DO GS ONCS OOLITES PEL INTRAS LD
LOCALLY DO MS WITH FEN
18
17
S11
S12
S13
S14
CA DO MS TO WS GA CS ALGAL FILAMENTS
INTRAS LOCAL CUT AND FILLS OF GS OOLITES
ONCS PELS
16
1308
1307
15
LS MS TO WS MICROX BI BU GA CS
LOCAL CUT & FILLS WITH ONCS OOLITES
PELS INTRAS
14
1306
13
1305
INTERTIDAL TO SUPRATIDAL
12
CYCLE 2
CA DO WS BU GA FEN POROSITY TOP OF
BED AA BUFF WEATHERED SURFACE
11
LS MS TO WS PELS ONCS INTRAS GA
CS BU ALGAL FILAMENTS RARE BI
1304
10
CA SILTSTONE BUFF
9
DOL LS MS MICROX BU OST INTRAS
PELS CS LOCAL LD BI & FEN POROSITY
8
1303
7
6
INTERTIDAL TO SUPRATIDAL
5
CA DO MS MICROX BU PEL LOCALLY LD
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S6
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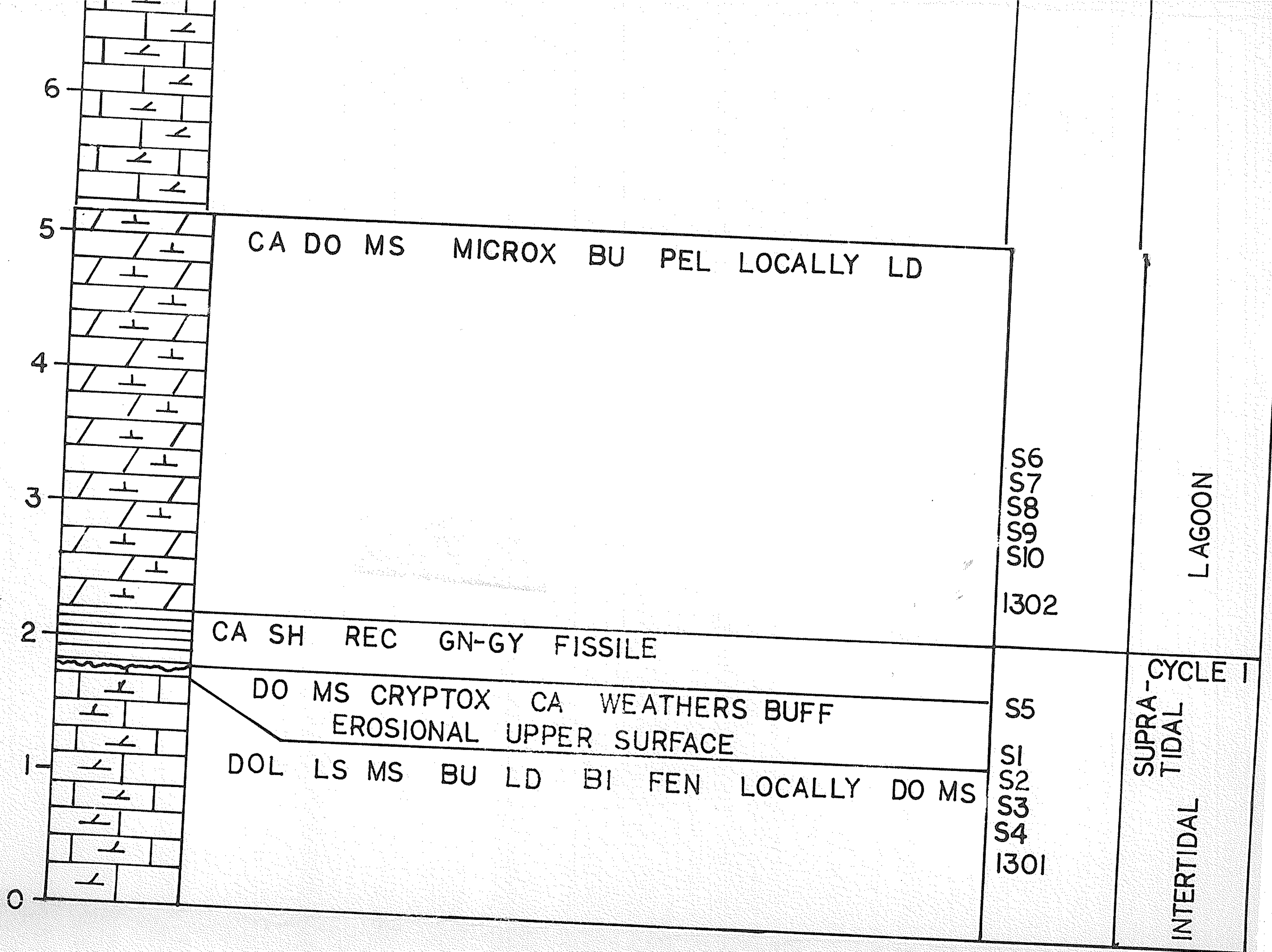
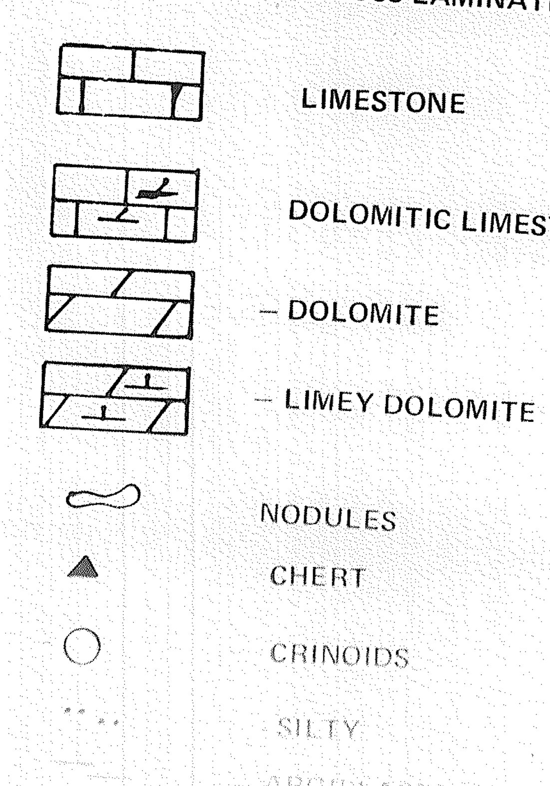
S8
S9
S10
3
1302
LAGOON
CA SH REC GN-GY FISSILE
CYCLE 1



LEGEND

AA – ARGILLACEOUS
BI – BIRDSEYES
BR – BRACHIOPODS
BU – BURROWS
BZ – BRYOZOANS
CA – CALCITE, CALCAREOUS
CG – COARSE GRAINED
CO – CORALS
CR – CRINOIDS
CRYPTOX – CRYPTOCRYSTALLINE
CS – CALCISPHERES
CT – CHERT
DO – DOLOMITE
DOL – DOLOMITIC
ECH – ECHINOIDS
FEN – FENESTRAE
FG – FINE GRAINED
GA – GASTROPODS
GS – GRAINSTONES
GY – GRAY
IN – INTERBEDDED
INTRAS – INTRACLASTS
LD – LAMINATED
MA – MASSIVE
MG – MEDIUM GRAINED
MICROX – MICROCRYSTALLINE
MS – MUDSTONE
ONC – ONCOLITES
OST – OSTRACODS
PS – PACKSTONE
PEL – PELLETS
REC – RECESSIVE WESTHERING
RES – RESISTANT WEATHERING
SH – SHALE
VCG – VERY COARSE GRAINED
VU – VUGS
WS – WACKESTONE
XB – CROSS BEDDED
XLD – CROSS LAMINATED



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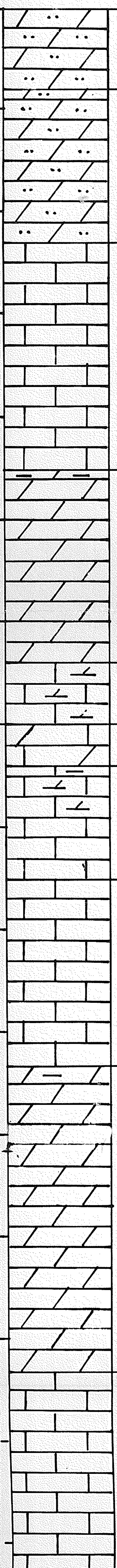
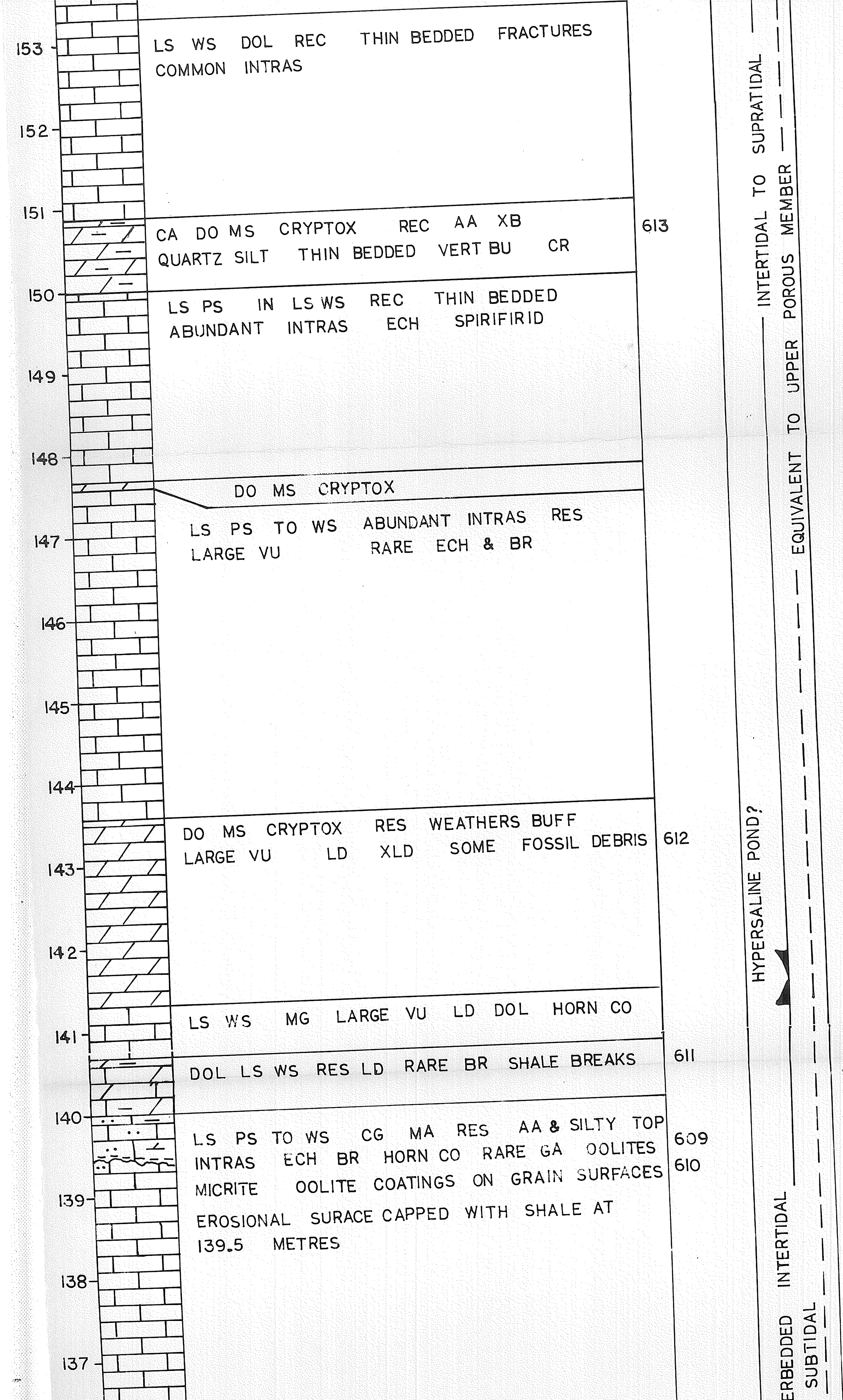
LITHOLOGY



DESCRIPTION	SAMPLES	DEPOSITIONAL ENVIRONMENT
MOUNT HEAD FORMATION DO MS MICROX ANHYDRITIC SILTY		INTERTIDAL TO SUPRATIDAL
DO MS VERY SILTY RES RIPPLE MARKS		
LS MS OOLITES BI FEN POROSITY **TURNER VALLEY FORMATION**		HYPERSALINE POND?
DO MS CRYPTOX AA FISSILE TOP		
LS WS DOL LD ONC		
DOL LS RIP UP CLASTS		
LS MS MICROX BU FEN POROSITY DOL AT TOP		
LS MS CRYPTOX LD FEN BI ALGAE	615	
DO MS CRYPTOX MA REC AA		HYPERSALINE POND?
DOL LS MS MICROX RES LD PEL BI CS OST VERTICAL BU ALGAE	614	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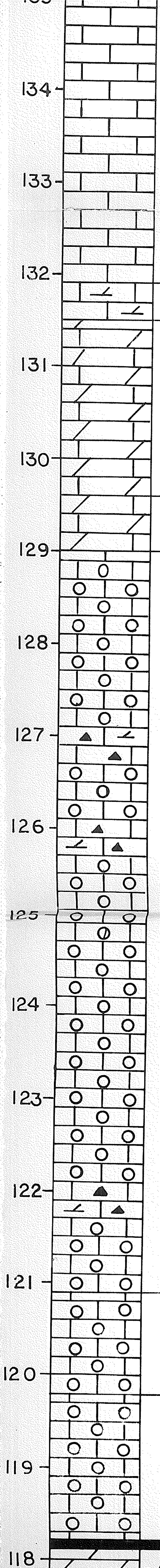
138
137
LS WS DOL REC THIN BEDDED FRACTURES
COMMON INTRAS
CA DO MS CRYPTOX REC AA XB
QUARTZ SILT THIN BEDDED VERT BU CR
613
LS PS IN LS WS REC THIN BEDDED
ABUNDANT INTRAS ECH SPIRIFIRID
DO MS CRYPTOX
LS PS TO WS ABUNDANT INTRAS RES
LARGE VU RARE ECH & BR
DO MS CRYPTOX RES WEATHERS BUFF
LARGE VU LD XLD SOME FOSSIL DEBRIS
612
LS WS MG LARGE VU LD DOL HORN CO
DOL LS WS RES LD RARE BR SHALE BREAKS
611
LS PS TO WS CG MA RES AA & SILTY TOP
INTRAS ECH BR HORN CO RARE GA OOLITES
MICRITE OOLITE COATINGS ON GRAIN SURFACES
EROSIONAL SURACE CAPPED WITH SHALE AT
139.5 METRES
609
610
INTERTIDAL TO SUPRATIDAL
EQUIVALENT TO UPPER POROUS MEMBER
HYPERSALINE POND?
INTERTIDAL
ERBEDDED
SUBTIDAL

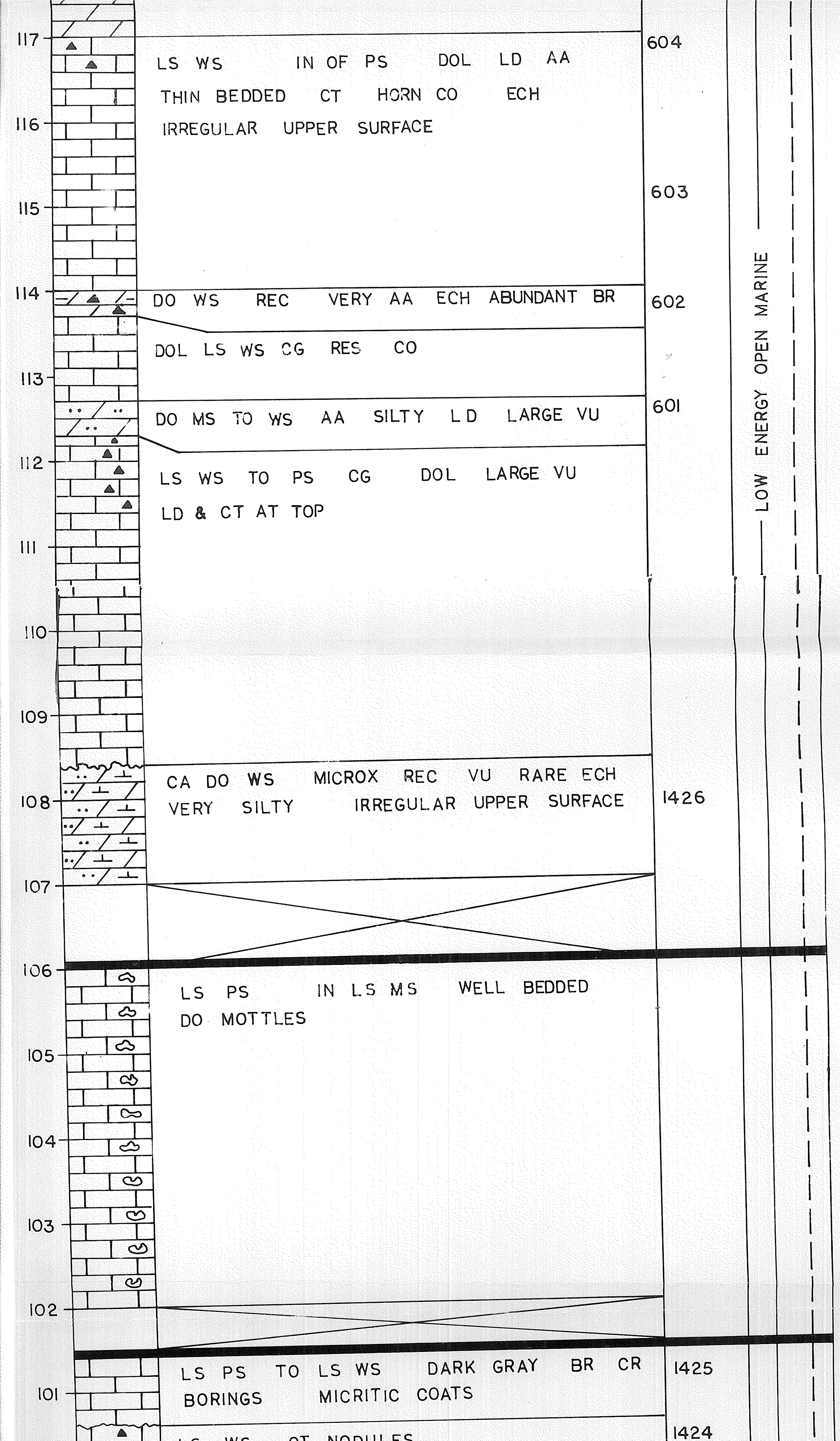


LS MS MICROX DOL LD		
LS WS GRADING UPWARDS TO LS PS DOL RES LD RIPPLE MARKS ON UPPER SURFACE ECH BR CS RARE GA FORAMS ALGAE	607	
LS MS DOL MICROX LD WELL BEDDED		
LS GS & PS CG IN OF DOL LS WS REC THIN BEDDED LARGE CA FILLED VU POOR SORTING ECH BR CO		
DOL LS WS FG AA CT		
DOL LS WS FG AA CT	606	
DOL LS WS FG AA CT		
LS GS CG ABUNDANT ECH BLACK SHALE BREAKS		
LS GS TO PS MA REC ABUNDANT ECH INTACT CALYXES		
MINOR SHEAR PLANE		

TRANSITIO
WITH VE

INTERBEDDED HIGH AND LOW ENERGY SUBTIDAL

MIDDLE DENSE MEMBER


117
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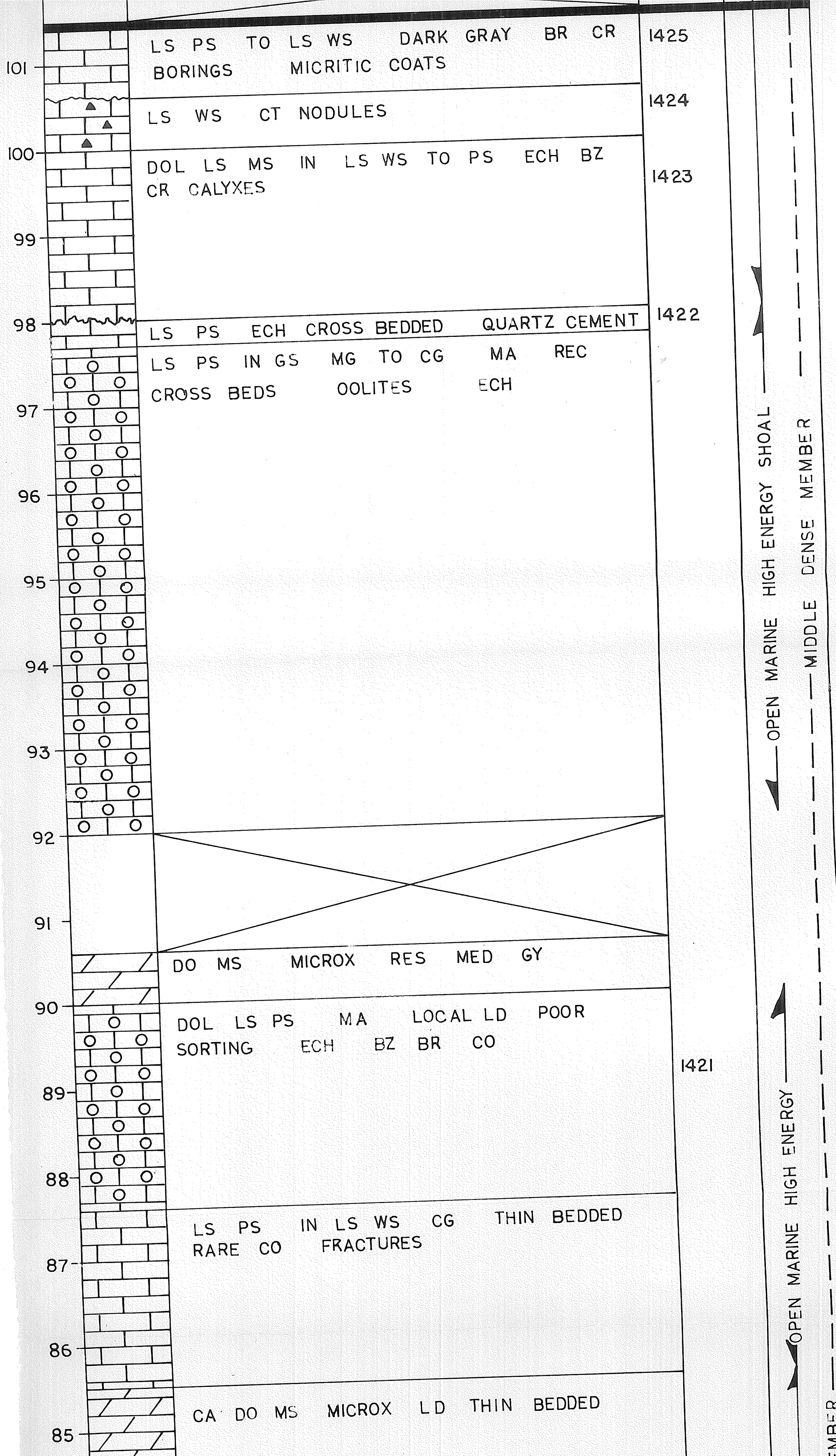
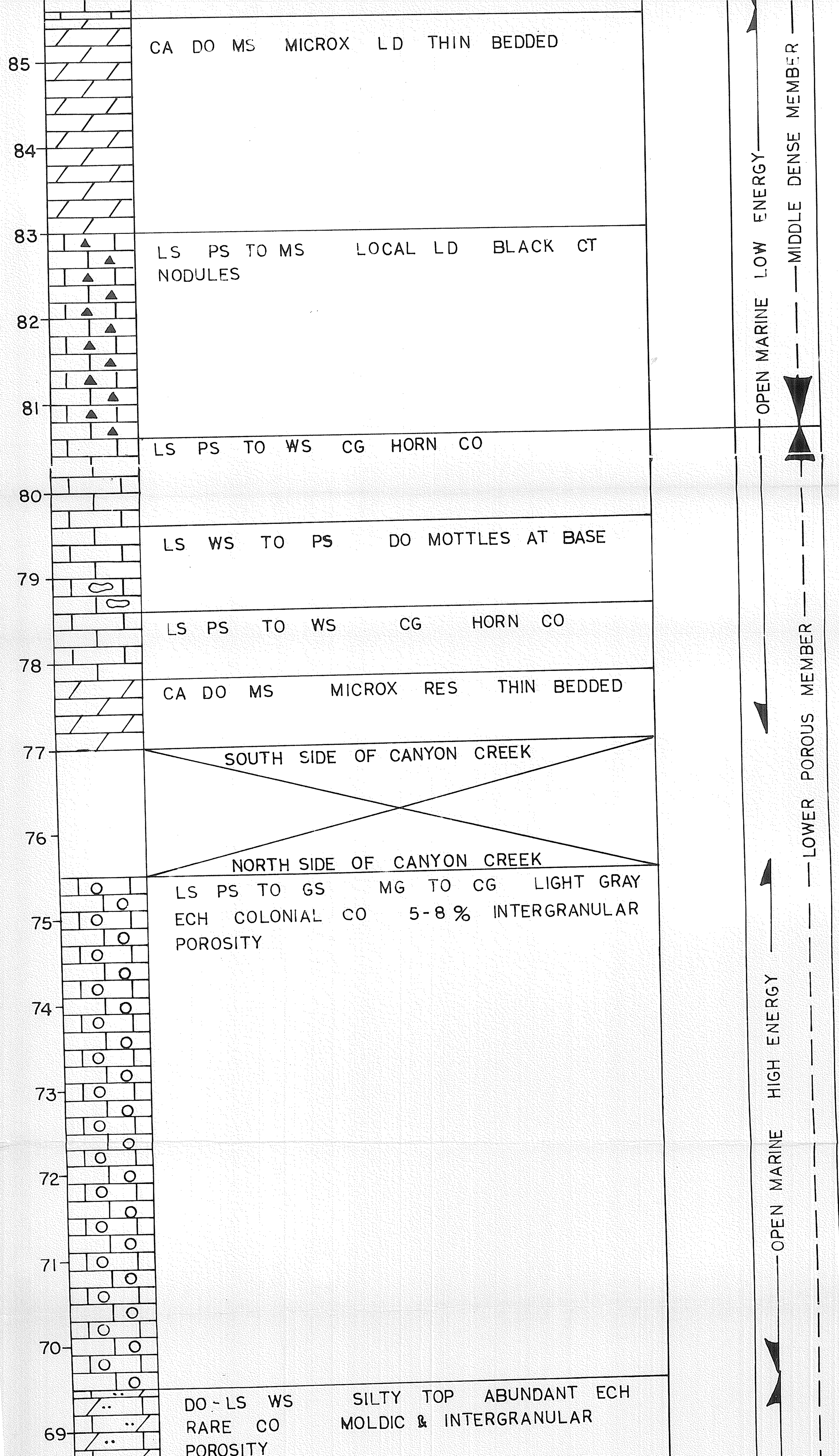
102
101
LS WS IN OF PS DOL LD AA
THIN BEDDED CT HORN CO ECH
IRREGULAR UPPER SURFACE
DO WS REC VERY AA ECH ABUNDANT BR
DOL LS WS CG RES CO
DO MS TO WS AA SILTY LD LARGE VU
LS WS TO PS CG DOL LARGE VU
LD & CT AT TOP
CA DO WS MICROX REC VU RARE ECH
VERY SILTY IRREGULAR UPPER SURFACE
LS PS IN LS MS WELL BEDDED
DO MOTTLES
LS PS TO LS WS DARK GRAY BR CR
BORINGS MICRITIC COATS
604
603
602
601
1426
1425
1424
LOW ENERGY OPEN MARINE


LS PS TO LS WS DARK GRAY BR CR
BORINGS MICRITIC COATS
1425
101
LS WS CT NODULES
1424
100
DOL LS MS IN LS WS TO PS ECH BZ
CR CALYXES
1423
99
98
LS PS ECH CROSS BEDDED QUARTZ CEMENT
1422
LS PS IN GS MG TO CG MA REC
CROSS BEDS OOLITES ECH
97
96
95
94
93
92
91
DO MS MICROX RES MED GY
90
DOL LS PS MA LOCAL LD POOR
SORTING ECH BZ BR CO
1421
89
88
LS PS IN LS WS CG THIN BEDDED
RARE CO FRACTURES
87
86
CA DO MS MICROX LD THIN BEDDED
85
OPEN MARINE HIGH ENERGY SHOAL
MIDDLE DENSE MEMBER
OPEN MARINE HIGH ENERGY
EMBER



85
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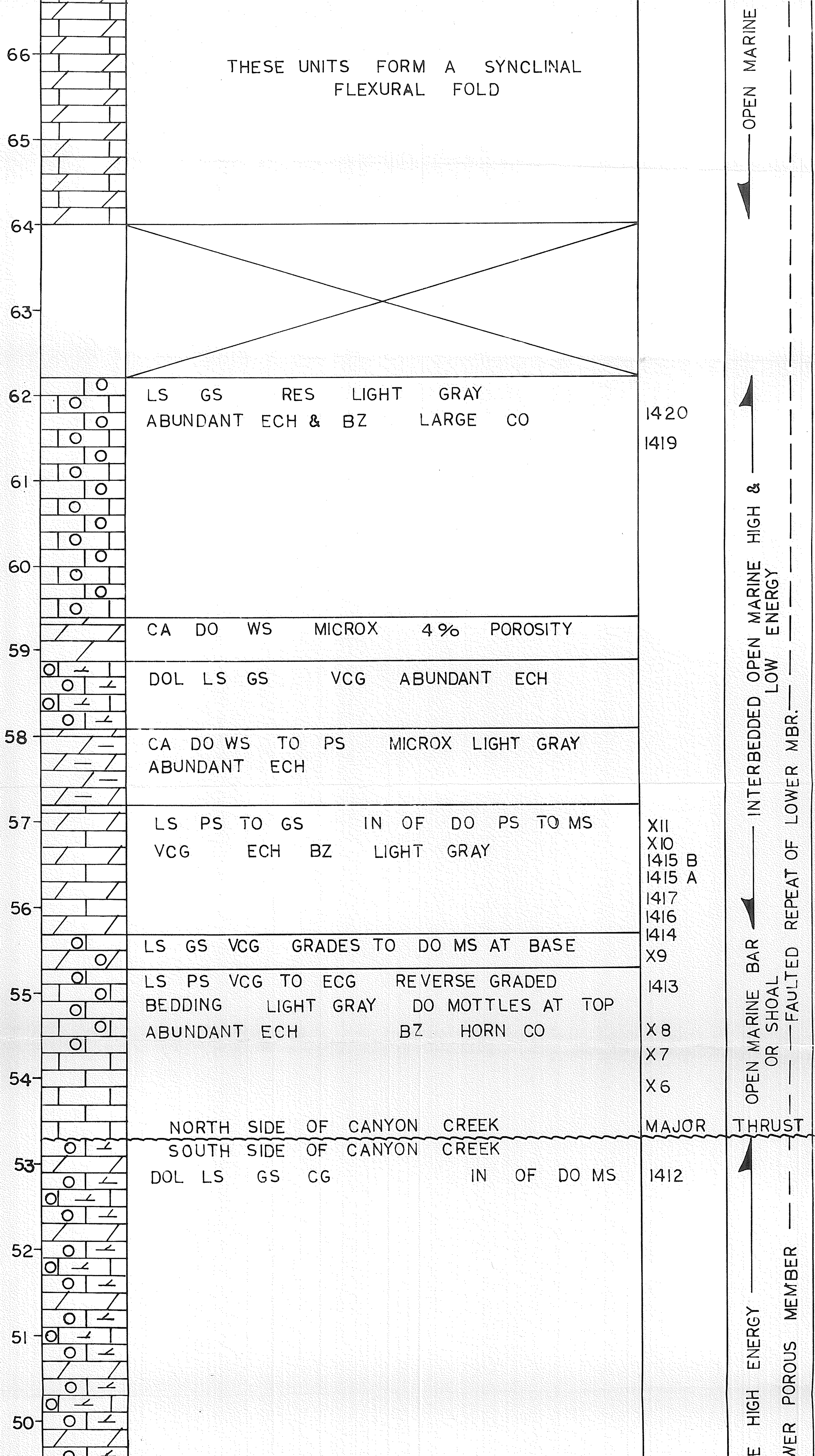
69
CA DO MS MICROX LD THIN BEDDED
LS PS TO MS LOCAL LD BLACK CT NODULES
LS PS TO WS CG HORN CO
LS WS TO PS DO MOTTLES AT BASE
LS PS TO WS CG HORN CO
CA DO MS MICROX RES THIN BEDDED
SOUTH SIDE OF CANYON CREEK
NORTH SIDE OF CANYON CREEK
LS PS TO GS MG TO CG LIGHT GRAY ECH COLONIAL CO 5-8 % INTERGRANULAR POROSITY
DO - LS WS SILTY TOP ABUNDANT ECH RARE CO MOLDIC & INTERGRANULAR POROSITY
OPEN MARINE LOW ENERGY
MIDDLE DENSE MEMBER
LOWER POROUS MEMBER
OPEN MARINE HIGH ENERGY


66
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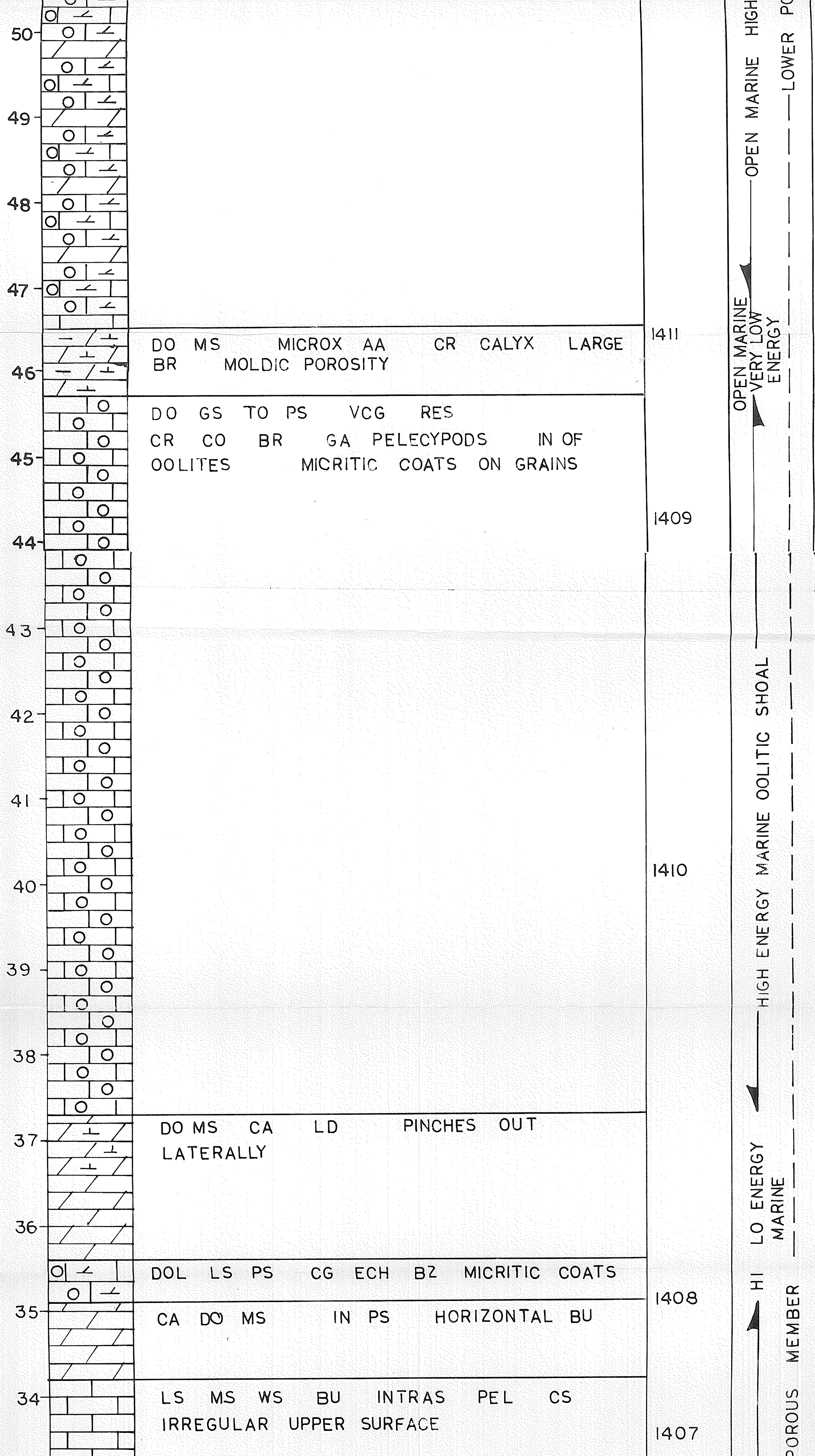
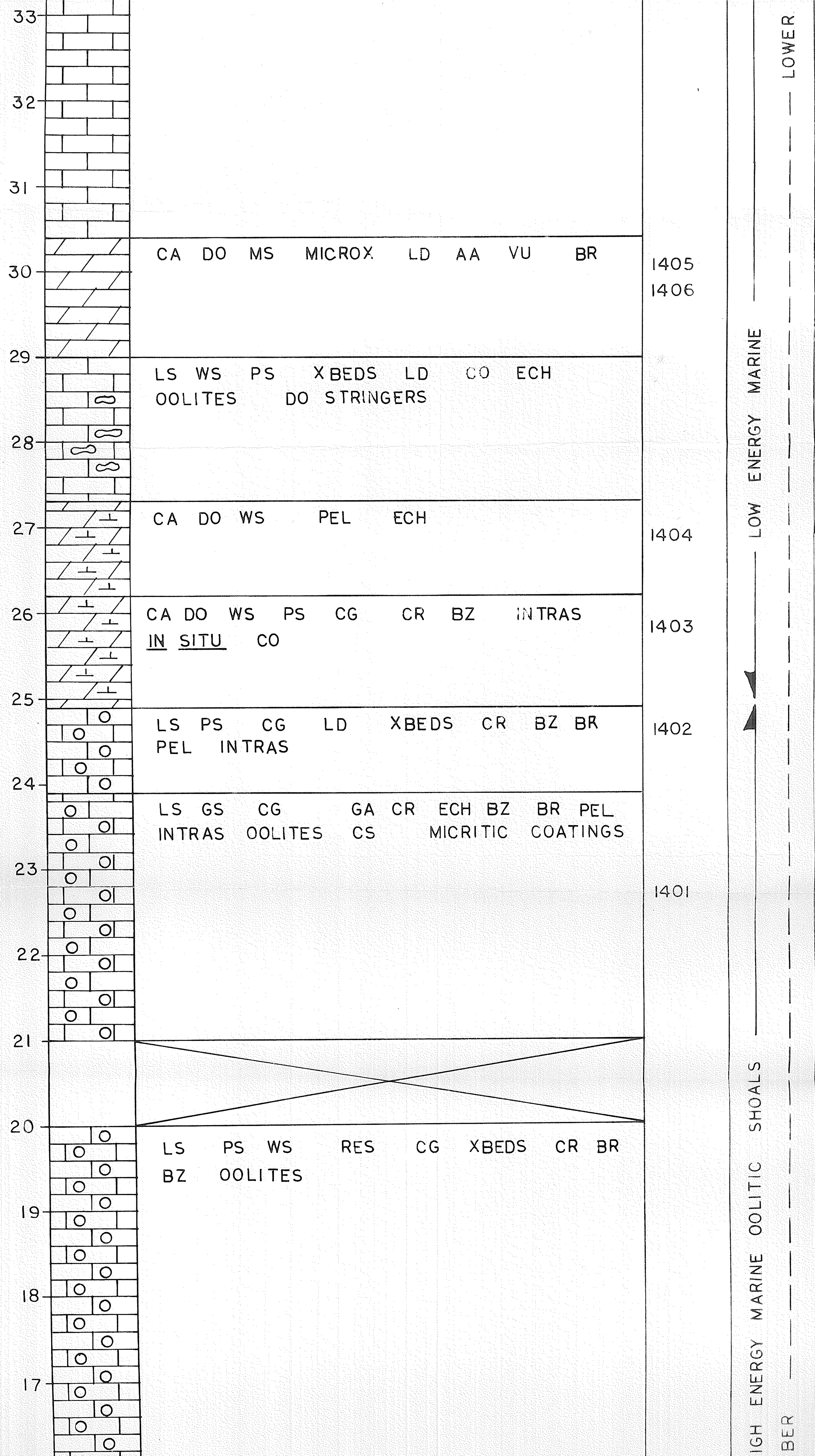
50
THESE UNITS FORM A SYNCLINAL FLEXURAL FOLD
LS GS RES LIGHT GRAY
ABUNDANT ECH & BZ LARGE CO
1420
1419
CA DO WS MICROX 4% POROSITY
DOL LS GS VCG ABUNDANT ECH
CA DO WS TO PS MICROX LIGHT GRAY
ABUNDANT ECH
LS PS TO GS IN OF DO PS TO MS
VCG ECH BZ LIGHT GRAY
X11
X10
1415 B
1415 A
1417
1416
1414
LS GS VCG GRADES TO DO MS AT BASE
X9
LS PS VCG TO ECG REVERSE GRADED
BEDDING LIGHT GRAY DO MOTTLES AT TOP
ABUNDANT ECH BZ HORN CO
1413
X8
X7
X6
NORTH SIDE OF CANYON CREEK
MAJOR THRUST
SOUTH SIDE OF CANYON CREEK
DOL LS GS CG IN OF DO MS
1412
OPEN MARINE
INTERBEDDED OPEN MARINE HIGH &
LOW ENERGY
FAULTED REPEAT OF LOWER MBR.
OPEN MARINE BAR
OR SHOAL
E HIGH ENERGY
WER POROUS MEMBER


50
49
48
47
DO MS MICROX AA CR CALYX LARGE BR MOLDIC POROSITY
1411
46
DO GS TO PS VCG RES CR CO BR GA PELECYPODS IN OF OOLITES MICRITIC COATS ON GRAINS
45
44
1409
43
42
41
40
1410
39
38
DO MS CA LD PINCHES OUT LATERALLY
37
36
DOL LS PS CG ECH BZ MICRITIC COATS
CA DO MS IN PS HORIZONTAL BU
1408
35
LS MS WS BU INTRAS PEL CS IRREGULAR UPPER SURFACE
34
1407
OPEN MARINE
OPEN MARINE VERY LOW ENERGY
HIGH ENERGY MARINE OOLITIC SHOAL
HI LO ENERGY MARINE
LOWER
MEMBER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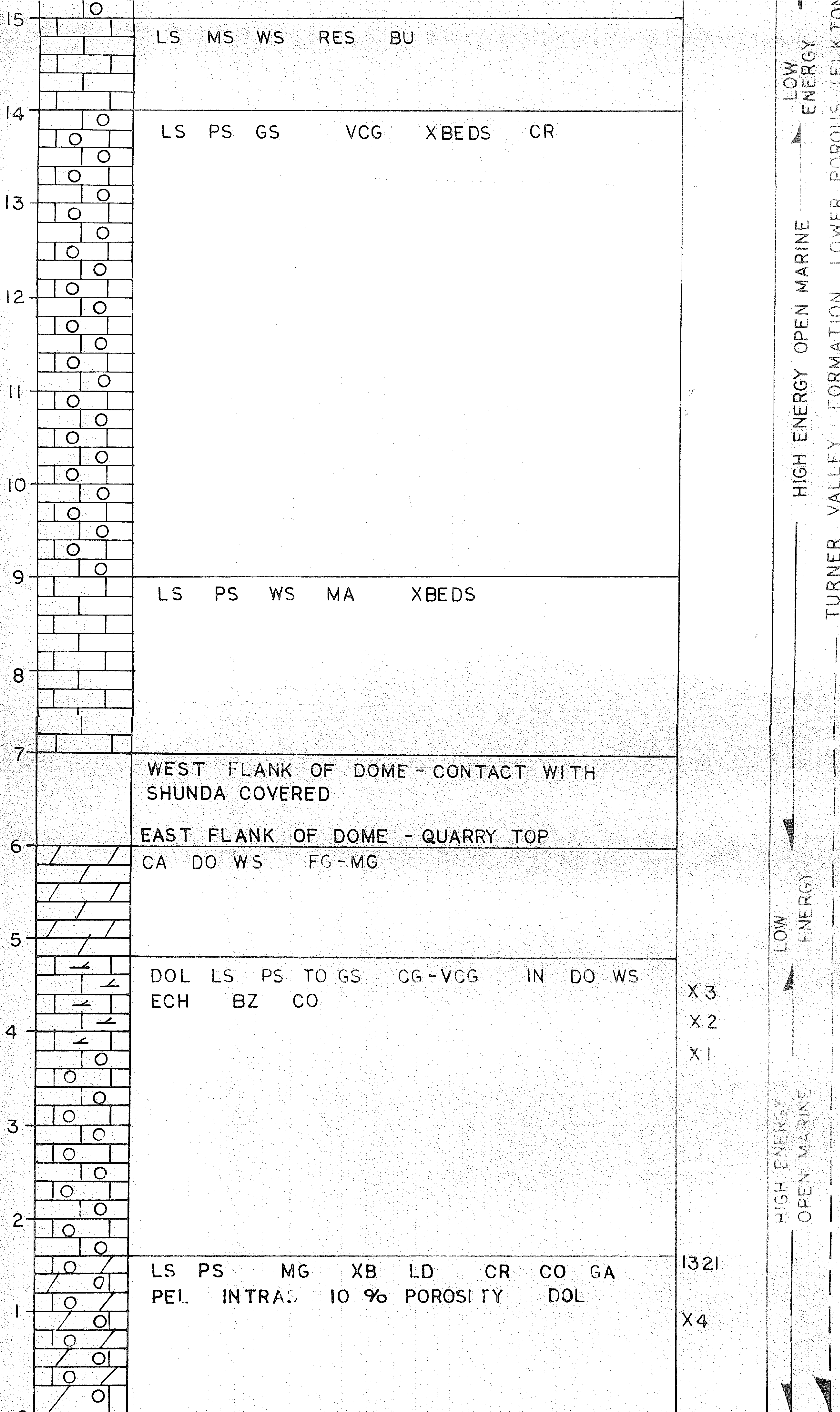
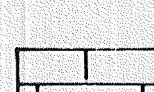
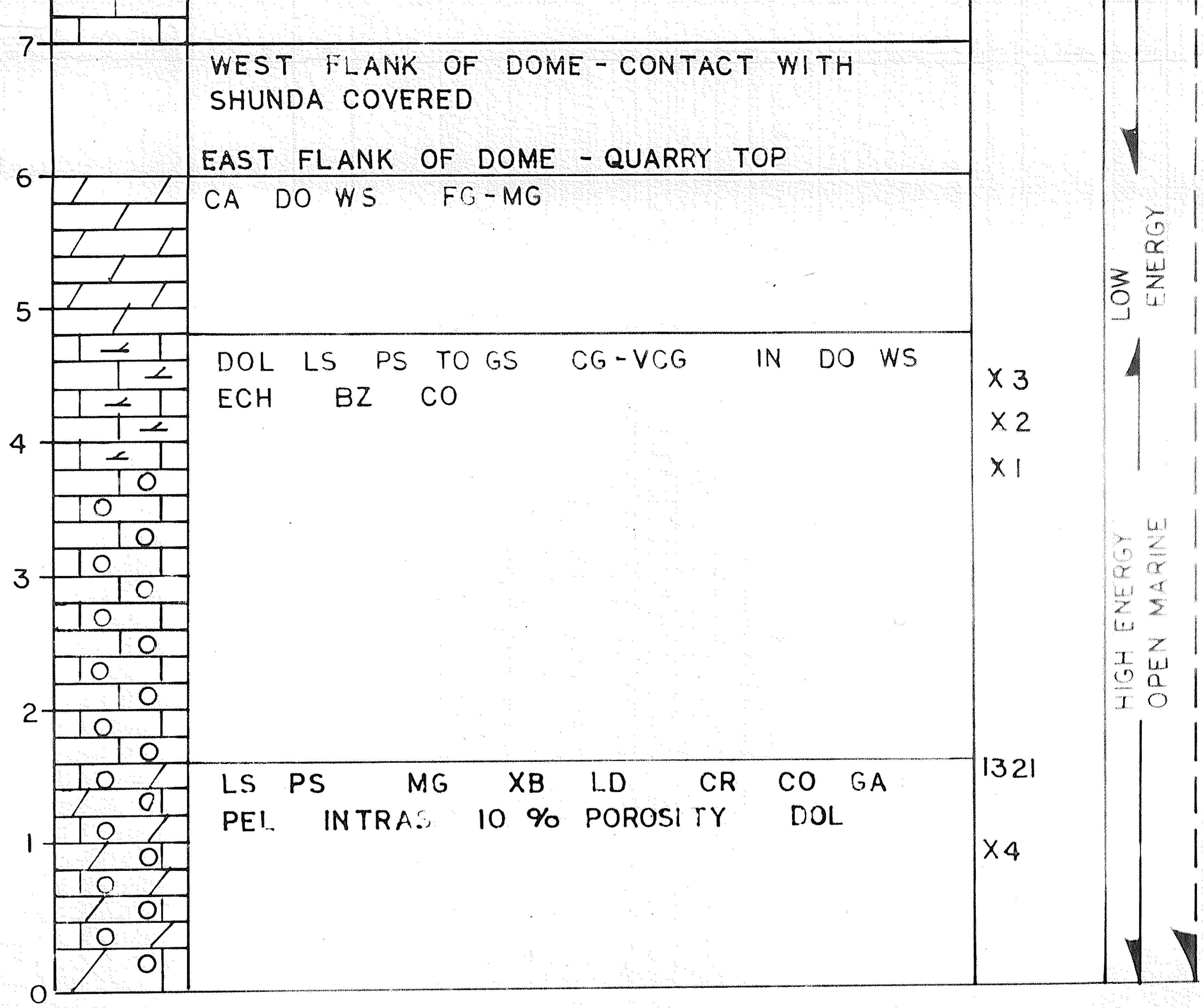
18
17
CA DO MS MICROX LD AA VU BR
1405
1406
LS WS PS XBEDS LD CO ECH
OOLITES DO STRINGERS
CA DO WS PEL ECH
1404
CA DO WS PS CG CR BZ INTRAS
IN SITU CO
1403
LS PS CG LD XBEDS CR BZ BR
PEL INTRAS
1402
LS GS CG GA CR ECH BZ BR PEL
INTRAS OOLITES CS MICRITIC COATINGS
1401
LS PS WS RES CG XBEDS CR BR
BZ OOLITES
LOWER
LOW ENERGY MARINE
IGH ENERGY MARINE OOLITIC SHOALS
BER



LEGEND

AA	–	ARGILLACEOUS
BI	–	BIRDSEYES
BR	–	BRACHIOPODS
BU	–	BURROWS
BZ	–	BRYOZOANS
CA	–	CALCITE, CALCAREOUS
CG	–	COARSE GRAINED


LIMESTONE



LEGEND

AA — ARGILLACEOUS
BI — BIRDSEYES
BR — BRACHIOPODS
BU — BURROWS
BZ — BRYOZOANS
CA — CALCITE, CALCAREOUS
CG — COARSE GRAINED
CO — CORALS
CR — CRINOIDS
CRYPTOX — CRYPTOCRYSTALLINE
CS — CALCISPHERES
CT — CHERT
DO — DOLOMITE
DOL — DOLOMITIC
ECH — ECHINOIDS
FEN — FENESTRAE
FG — FINE GRAINED
GA — GASTROPODS
GS — GRAINSTONES
GY — GRAY
IN — INTERBEDDED
INTRAS — INTRACLASTS
LD — LAMINATED
MA — MASSIVE
MG — MEDIUM GRAINED
MICROX — MICROCRYSTALLINE
MS — MUDSTONE
ONC — ONCOLITES
OST — OSTRACODS
PS — PACKSTONE
PEL — PELLETS
REC — RECESSIVE WESTHERING
RES — RESISTANT WEATHERING
SH — SHALE
VCG — VERY COARSE GRAINED
VU — VUGS
WS — WACKESTONE
XB — CROSS BEDDED
XLD — CROSS LAMINATED