PETROGRAPHY AND DIAGENESIS
OF THE MISSISSIPPIAN LIVINGSTONE FORMATION
(RUNDLE GROUP), SOUTHWESTERN ALBERTA

A Thesis
Submitted to
The Faculty of Graduate Studies
The University of Manitoba

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

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by
Frank T.A. Hutnik
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ABSTRACT

The Mississippian Livingstone Formation consists predominantly of resistant-weathering, thick- to very thick-bedded, medium- to coarse-grained echinoderm-bryozoan limestones, interbedded with fine- to medium crystalline, dolomitic and/or cherty limestones.

Petrographic observations indicate that eight diagenetic processes contributed to the formation of the Livingstone Formation. These were: 1) micritization, 2) compaction, 3) cementation, 4) silicification, 5) dolomitization, 6) pressure-solution, 7) tectonic fracturing, and 8) dissolution. The most extensive of these processes were cementation, dolomitization, and dissolution.

Cementation of the Livingstone Formation is interpreted to have occurred in the phreatic environment, where most of the original depositional porosity was occluded by sparry calcite. Selective dolomitization of the Livingstone Formation served to create secondary porosity in those sediments which were originally mud-supported (ie. packstone and wackestone lithofacies). Subaerial exposure of the Livingstone Formation following the Laramide orogeny permitted the padsage of groundwaters which created the megavug porosity observable in surface exposures of the Livingstone Formation.

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INTRODUCTION

General

Mississippian carbonate rocks of southwestern Alberta are of considerable interest to both the academic and petroleum geologist. The Mississippian succession contains approximately 33 per cent of Alberta's natural gas reserves (Leslie, 1969), and next to the Upper Devonian, ranks second in total hydrocarbons, containing 14.8 per cent of the Province's total recoverable reserves (Parsons, 1973). In the Rocky Mountain Foothills, oil production comes from a small number of thrust-faulted anticlinal structures, whereas in the Interior Plains, hydrocarbon accumulations occur in beds truncated by the post-Mississippian unconformity. In both cases the reservoir rocks are mainly the porous pelmatozoan limestones and dolomitized limestones of the Pekisko and Turner Valley Formations, with minor production coming from the Shunda and Mount Head Formations.

Continued depletion and exploitation of existing reserves, coupled with the development of new seismic tecniques has prompted geologists to focus their attention on the Rocky Mountain Foothills, with the hopes of discovering new structural traps. Exposures of Mississippian carbonates in the Rocky Mountain Foothills and Front Ranges provide excellent opportunity for the study of structural, stratigraphic, and lithologic aspects of potential reservoir rocks. Of particular interest are the coarse-grained echinoderm-bryozoan limestones and associated medium-crystalline dolomites of the Livingstone Formation. Exposures of these rocks contain conspicuous zones of irregular vuggy porosity in grainstone beds, which, if present in the subsurface, should provide excellent reservoir conditions for the entrapment of hydrocarbons.

Unfortunately, thin sections of the Livingstone Formation exhibit little effective porosity, except where dolomitized. Grain-supported rock units, despite their vuggy porosity, are tightly cemented, whereas mud-supported units are partially to completely dolomitized, thus suggesting a possible relationship between diagenesis and original depositional facies. This study is an attempt to provide a detailed interpretation of the diagenetic history (in particular, cementation and dolomitization) of the Livingstone Formation, and forms part of a large scale investigation of Mississippian diagenetic fabrics supervised by Dr. R.S. Harrison.

Objectives of the Study

This investigation is based on detailed examination of exposures of the Livingstone Formation at three localities within the Highwood and Fairholme Ranges. The objectives of the study are fourfold:

1) Todetermine the various lithofacies and microfacies present.
2) To determine the nature and succession of interpreted sedimentary environments represented by the various microfacies.
3) To determine the detailed diagenetic history.
4) To evaluate the nature and types of porosity present.

Method of Study

Field work was conducted during the summer of 1974, and consisted of detailed examination of partial sections of the Livingstone Formation exposed within the McConnell thrust block (Figure 1). Sections were measured in the Highwood Range on the north side of the Highwood River near Mount Head, and also 14 miles (22.5 kilometres) to the south at Plateau Mountain. A section in the Fairholme Range was measured at Pigeon Mountain, 55 miles (88.5 kilometres) northwest of the Highwood River section. Measured section descriptions for the three localities are contained in the Appendix.

Individual sections were measured using a Jacob's staff, and oriented samples of each distinguishable change of lithology were collected. Lithologic units exceeding 30 feet (approximately 9 metres) were sampled at 10-ft. (3 m)

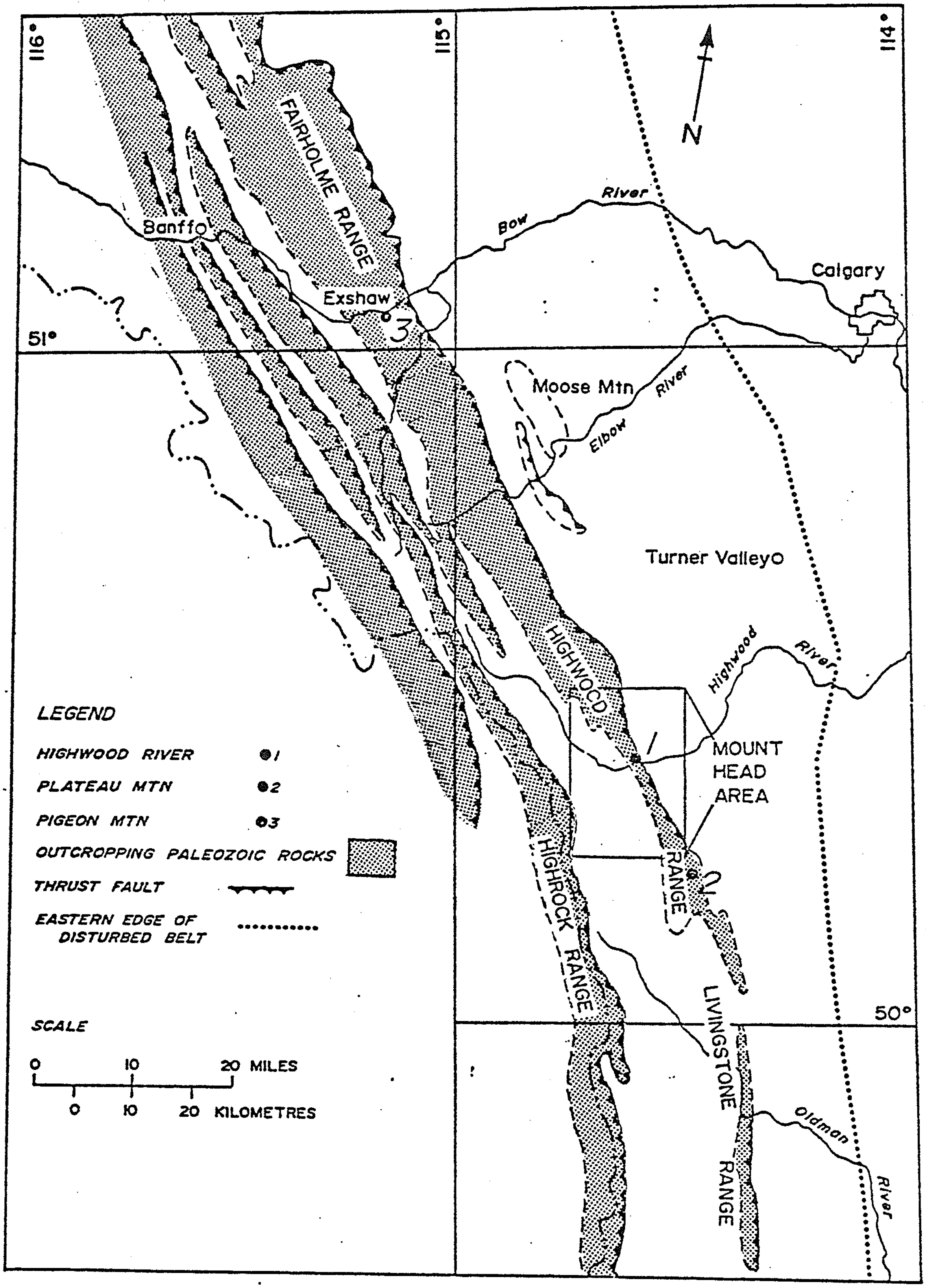

Figure 1. Location of areas investigated (modified from Douglas, 1958).

intervals. Rock samples were slabbed and approximately 100 thin sections were cut and subsequently examined under the petrographic microscope. Selected thin sections were stained according to the methods outlined in Dickson (1966). The carbonate textural classification used is that of Dunham (1962).

Previous Work

Previous investigations have included the Livingstone Formation as part of regional stratigraphic studies. In the Mount Head map-area, Douglas (1953) included the Livingstone sediments as the lowermost member (Member A) of the Rundle Formation. Later, Douglas (1958) elevated the Rundle Formation to Group status, and divided it into three new Formations: the Livingstone, Mount Head, and Etherington. Douglas (1958) further divided the Livingstone Formation into two Members; a lower Pekisko Member and an upper Turner Valley Member, the same as that established in the subsurface of the Turner Valley oil and gas field, about 25 miles (40 kilometres) east of the Mount Head map-area. Norris (1958) mapped the Livingstone Formation in the Beehive Mountain map-area , immediately south of the Mount Head area. Middleton (1963) studied the Livingstone Formation as part of a detailed lithofacies analysis in the Elbow Valley area. Macqueen and Bamber (1967), as part of regional stratigraphic, lithologic, and macrofaunal studies on the Mississippian rocks of the Rocky Mountain Foothills and Front Ranges, recognized the Livingstone Formation as the western facies equivalent of the Pekisko, Shunda, and Turner Valley Formations (see Table 1). Macqueen et al. (1972) described the regional lithologic, macrofaunal, and microfaunal variations of the Livingstone Formation in the southern Canadian Rockies.

PHYSICAL STRATIGRAPHY AND PETROGRAPHY OF THE LIVINGSTONE FORMATION

Regional Setting

In general, the geological history of the Mississippian succession in Alberta is one of major regression, upon which are superimposed several smaller episodes of transgression and regression. The epeiric Mississippian seas shallowed to the northeast towards a strandline on the Canadian Shield, and deepened in a southwestward direction to the present Cordilleran area.

The early Mississippian was characterized by a prolific and geologically unique development of echinoderms. Osagian and early Meramecian ages were distinguished by the development of carbonate banks and shoals over much of southern Alberta. In this area enormous volumes of echinoderm and bryozoan limestones accumulated (Pekisko, Turner Valley, and Livingstone Formations). A widespread sequence of lagoonal and intertidal to supratidal carbonates and evaporites (Shunda Formation) accumulated to the east of the echinoderm-bryozoan banks during late Osagian time. Figure 2 illustrates the extent of these sediment regimes.

Regional Stratigraphy

The Mississippian succession in the study area is

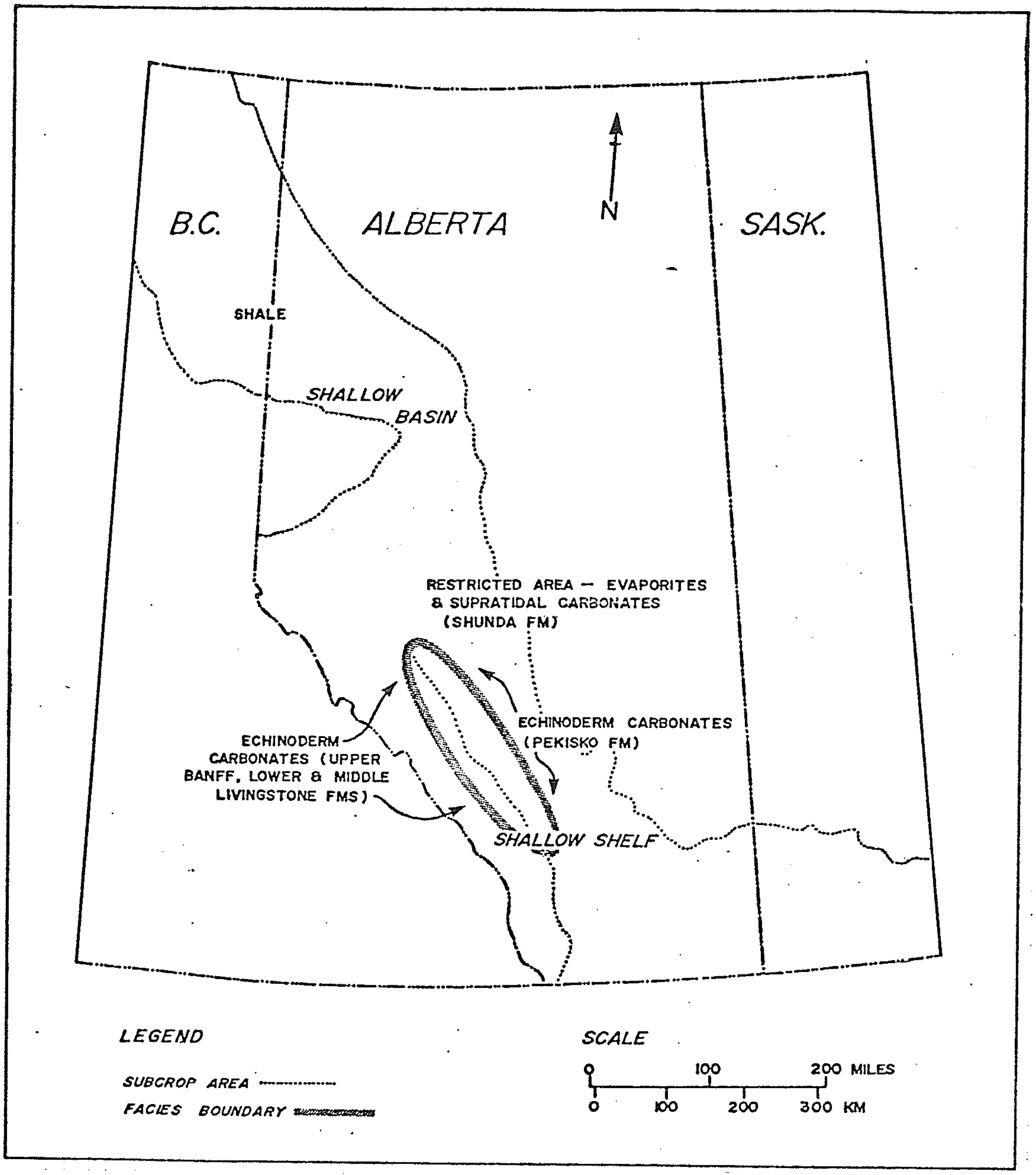

Figure 2. Sedimentary environments in southern Alberta during late Osage and early Meramec times (modified from Macauley et al., 1964).

characterized by two widespread carbonate units: a lower, argillaceous Banff Formation; and an upper, resistant unit, known as the Rundle Group. Table 1 gives the succession in the study area and regional variations outside the study area.

On a regional scale, Mississippian stratigraphy is characterized by a variety of facies changes. In general, two laterally gradational facies belts occur within the Banff Formation and lower Rundle Group, which were recognized as an eastern and a western facies by Macqueen and Bamber (1967). The eastern facies, present in the southwestern Alberta subsurface, Moose Dome, and Banff-Jasper area, includes the Banff Formation and the lower Rundle Group, which is comprised of three Formations: the Pekisko and Turner Valley Formations (predominantly echinoderm limestones and their dolomitized equivalents - Petryk et al. 1970), and the intervening Shunda Formation (dominantly micritic limestone, microcrystalline- to very finely crystalline dolomite, and local solution breccias or anhydrite-dolomite assemblages in the subsurface - Petryk et al., 1970). The western facies (which is present in the study area) consists of the Banff Formation and the Livingstone Formation (echinoderm limestones and their dolomitized equivalents), the stratigraphic equivalents of the above-mentioned formations of the lower Rundle Group.

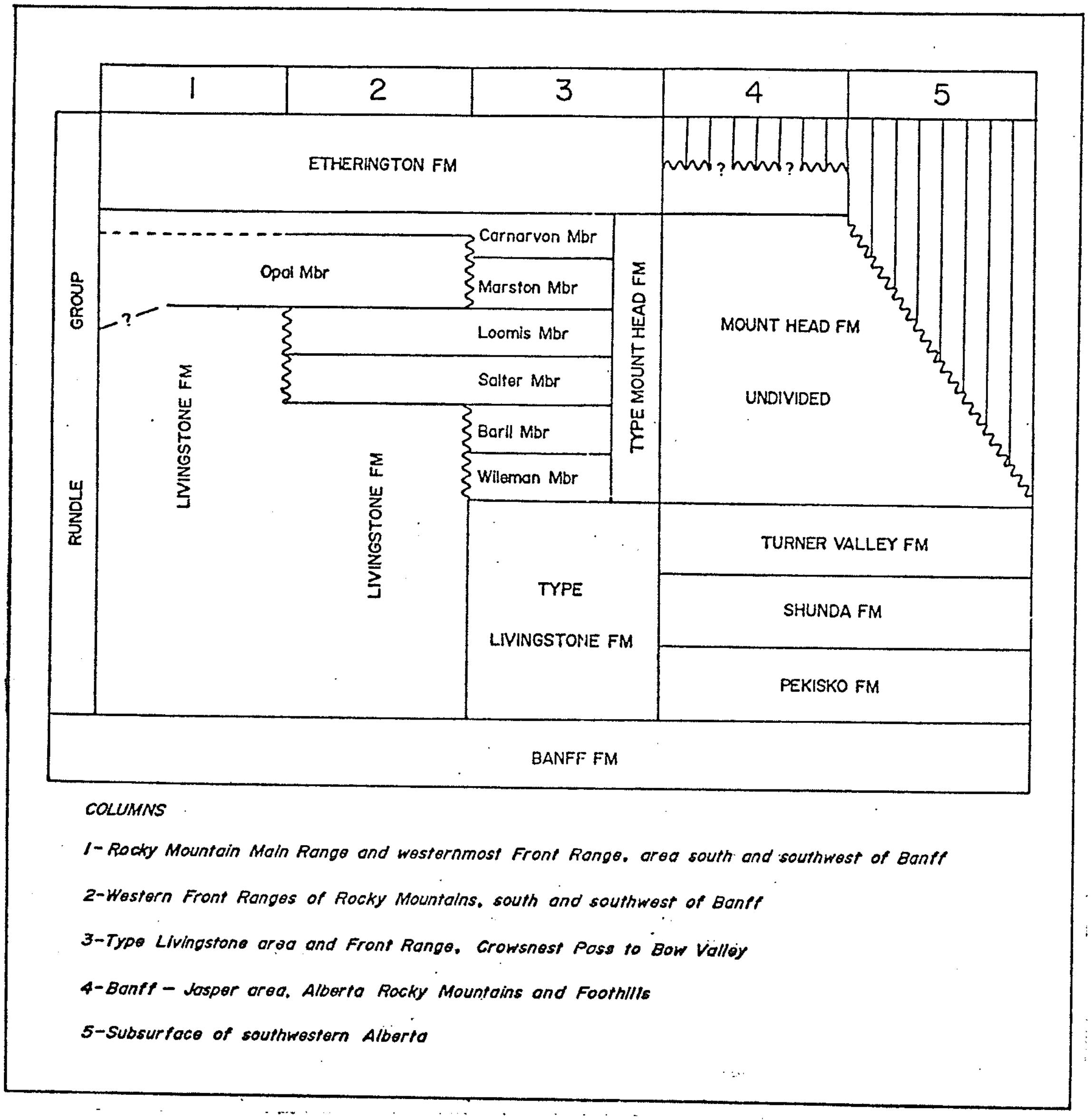

Table 1. Mississippian stratigraphy, southwestern Alberta (modified from Macqueen et al., 1972).

Overlying the Livingstone Formation and its equivalents is the remainder of the Rundle Group, composed of the Mount Head Formation (alternating dominantly non-skeletal limestones with dominantly silty microcrystalline to very finely crystalline dolomites interbedded with local solution breccias - Petryk et al., 1970) and Etherington Formations.

Physical Stratigraphy of the Livingstone Formation

The Livingstone Formation (Douglas, 1953, 1958) consists predominantly of resistant, thick- to very thickly bedded, medium- to coarse-grained echinoderm-bryozoan limestones, interbedded with fine- to medium crystalline, porous and vuggy dolomites and fine crystalline, dolomitic and/or cherty limestone.

The type section of the Livingstone Formation is located within the Mount Head map-area at Flat Creek (Douglas, 1958), where it attains a thickness of approximately 1,100 feet (340 metres). Douglas (1958) divided the type section into two Members: an Upper Turner Valley Member, and a lower Pekisko Member. A summary of the type section showing the division of the Formation into Members is given in Table 2. These subdivisions are not recognizable on a regional scale (Macqueen and Bamber, 1967).

Livingstone Formation	Thickness	
	Feet	Metres
Turner Valley Member		
Upper Porous beds		
Medium- to coarsely crystalline limestone with finely crystalline, cherty, dolomitic limestone in top 100 feet and medium-crystalline dolomite at base	207-230	63-70
Middle Hard beds		
Finely crystalline and fine-grained dolomitic limestone with 56 feet of coarsely crystalline limestone in the middle	153	47
Lower Porous beds		
Coarsely crystalline, massive bedded, vuggy limestones with basal parts altered to medium-crystalline, porous dolomite	147	45
Dark Limestone beds		
Finely crystalline, cherty limestone with thin coarsely crystalline limestone at top and finely crystalline dolomite at the base	82	25
Pekisko Member		
Upper part		
Medium- to coarsely crystalline limestone with medium-crystalline, porous dolomite and rare finely crystalline, cherty limestone	260	79
Lower part		
Medium- to coarsely crystalline limestone interbedded with finely crystalline, cherty, argillaceous limestone	224	68
Total thickness, Turner Valley Member	589-612	180-187
Total thickness, Pekisko Member	484	148
Total thickness, Livingstone Formation	1073-1096	327-334

Table 2. Description and thickness of Livingstone Formation, type section, Mount Head area (Douglas, 1958, p. 38).

Within the study area, the Livingstone Formation locally produces hydrocarbons, forming the main reservoir rock of the Savanna Creek gas field at Plateau Mountain. According to Scott, Hennessey, and Lamon (1957), production comes mainly from fractures in the upper 600-650 feet (183-198 metres), stratigraphic equivalents of which are exposed at the Plateau Mountain section.

Stratigraphic Sections

Highwood River Section

The section was measured in a road cut along the north side of the Highwood River, approximately one-half mile (0.8 kilometres) east of the Sentinel Ranger Station.

230 feet (70 m) of Upper Porous beds (terminology of Douglas, 1958; see Table 2), representing the uppermost one-quarter of the total Livingstone Formation, were measured from the base of the Mount Head Formation. The basal 104 feet (32 m) of section are comprised predominantly of grey, thickly bedded, echinoderm-bryozoan grainstones, which possess large-scale crossbedding and variable amounts of vuggy porosity (Plates 1e,f). The middle 53 feet (16 m) of this unit consist of dense, dark brownish grey, argillaceous pelmatozoan packstone and wackestone (Plates 1c,d). The overlying unit consists of approximately 106 feet (32 m) of grey, thickly bedded, echinoderm-bryozoan grainstomes and

packstones (Plate 1b), which contain scattered solitary corals in the uppermost 10 feet (3 m). Interbedded with the grainstones and packstones are thick units of dark grey, dolomitic pelmatozoan wackestones, in places containing irregular stringers and nodules of chert. The overlying 15 feet (4.5 m) of section consist of dark grey dolomitic wackestones and mudstones, the uppermost 3 feet (1 m) of which contain parallel bands of chert (Plate 1a). A covered interval of 3 feet (1 m) separates the remainder of the Livingstone Formation from the base of the Mount Head Formation. The distribution of lithofacies (and microfacies) at the Highwood River section is presented graphically in Figure 3 (in back pocket).

Plateau Mountain Section

Approximately 380 feet (116 m) of section (representing the uppermost one-third of the total Livingstone succession), 87 feet (126.5 m) of which are covered, were measured on the west side of a south facing cirque at Plateau Mountain. The section encompasses beds which are equivalent to Douglas' (1958) Upper Porous, Middle Dense, and Lower Porous beds of the Turner Valley Member.

The basal 57 feet (17 m) of section consist of resistant, ledge-forming, thickly bedded units of dark grey, vuggy, echinoderm-bryozoan grainstones (Plate 2f), which contain recessive interbeds of light yellowish brown dolomitic wackestone. A covered interval of 5 feet (1.5 m) separates the overlying 40 feet (12 m) of dark grey, thickly bedded, argillaceous, dolomitic mudstone, which contains large, irregular bands of chert parallel to the bedding (Plate 2e). The overlying 150 feet (46 m) of section consist of resistant ledges of grey, thickly bedded, in part crossbedded, partly porous and vuggy echinoderm-bryozoan grainstones (Plates 2c,d). Interbedded wiht these are thin, recessive beds of dark grey, cherty, dolomitic wackestone. The overlying 40 feet (12 m) of section are obscured by talus. Above this covered interval are 13 feet (4 m) of fine-grained, arenaceous grainstone, which exhibit small scale crossbeds and occasional dolomitic intraclasts (Plate 2b). Overlying this are 40 feet (12 m) of predominantly grey to dark grey, echinoderm-bryozoan grainstones, which contain occasional interbeds of grey, dolomitic packstone and wackestone. A covered interval of 40 feet (12 m) separates the remainder of the Livingstone Formation from the base of the Mount Head Formation. Figure 4 graphically illustrates the distribution of lithofacies (and microfacies) at the Plateau Mountain section.

Pigeon Mountain Section

The section was measured in a road cut along the south side of the Trans Canada Highway on the lower slopes of Pigeon Mountain (Plate 3a).

Approximately 670 feet (204 m) of section, representing the lowermost one-half of the Livingstone Formation are exposed at Pigeon Mountain. The basal 135 feet (41 m) of section are concealed beneath a cover, below which lie the argillaceous carbonates of the Banff Formation. Overlying the covered interval are 5 feet (1.5 m) of grey, oolitic grainstone, which is overlain by 10 feet (3 m) of grey, pelmatozoan packstone, which contains solitary corals and nodules of chert. The succeeding 145 feet (44 m) of section are comprised of grey, thickly bedded, porous and vuggy, echinoderm-bryozoan grainstones, which contain occasional interbeds of buff, porous dolomite and dolomitic wackestone (Plate 3f). The overlying 200 feet (61 m) of section are comprised of interbedded grey, cherty, pelmatozoan wackestones (Plate 3e), pale yellowish brown, medium crystalline, porous dolomites, and grey, echinoderm-bryozoan grainstones and dolomitic packstones (Plates 3c,d). A covered interval of 17 feet (5 m) separates the remaining 130 feet (39.5 m) of section, which consists predominantly of light grey, thickly bedded, echinoderm-bryozoan grainstones and dolomitic packstones (Plate 3b). Interbedded with these are thin units of pale yellowish brown medium crystalline dolomite. The distribution of lithofacies (and microfacies) at the Pigeon Mountain section is illustrated graphically in Figure 5 (in back pocket).

Petrography of the Livingstone Formation

The sediments of the Livingstone Formation are typical of the vast thicknesses of pelmatozoan limestones which accumulated during the Mississippian period. They are similar to the pelmatozoan limestones described by Moore (1957) from the Ozark region, and by Carozzi and Textoris (1967) from southwestern Illinois. Similar carbonates have been described from the Lower Carboniferous in England by Sadler (1966).

Rocks of the Livingstone Formation are comprised predominantly of echinoderms and bryozoans, the skeletal remains of which occur ubiquitously in all rock types. Grain-supported accumulations of these remains (ie. grainstones and packstones) form approximately 65 per cent of the exposed rock at the sections studied, the remaining 35 per cent being mud-supported (predominantly wackestones and their dolomitized equivalents). Grainstones, packstones, and wackestones form distinctive lithofacies, which are distinguishable in the field by their characteristic bedding nature, skeletal content, and grain size.

Based on sorting and on the nature and amount of skeletal grains, matrix, and cement, ten distinct microfacies (excluding dolomite) are recognizable in the Livingstone Formation at the sections studied. The distribution of lithofacies and microfacies in the measured sections is illustrated in Figures 3, 4. and 5 (in back pocket).

Grainstone Lithofacies

Grainstones are easily recognizable in outcrop by their coarse- to very coarse grain size. They commonly appear grey or brownish grey in colour, and weather light grey. They are characteristically thick- to very thickly bedded, and frequently exhibit large scale crossbedding and an irregular vuggy porosity.

The majority of Livingstone Formation grainstones are calcarenites and calcirudites comprised almost entirely of varying proportions of sand-sized or larger echinoderm and bryozoan fragments. Columnals and plates form the majority of echinoderm remains, although echinoid spines are sometimes present. Bryozoans are mostly fenestrate forms, occurring as complete fronds, or as scattered bits and pieces of zooaria. Axial canals of echinoderm columnals and bryozoan zooecia are commonly filled with micrite, suggesting reworking of the sediment prior to final deposition. Minor constituents include brachiopods, molluscs, pelecypods, ostracods, ooliths, and peloids.

Grainstones are commonly tightly cemented by sparry calcite, and display little effective porosity. Sparry calcite cement occurs as syntaxial overgrowths on echinoderm fragments, or as clear mosaics of pore-occluding spar.

Four grainstone microfacies are recognizable in the Livingstone Formation. These are: 1) echinoderm grainstones, 2) echinoderm-bryozoan grainstones, 3) oolitic grainstones, and 4) quartz-pelletoidal grainstones.

Echinoderm grainstones: (Plate 4a) These are composed almost entirely of echinoderm fragments (mostly columnals), which form 90 per cent of the skeletal constituents. Echinoderm grainstones are characterized by their coarse- to very coarse grain size, good sorting, and close packing (they are often "pressure welded"). The majority of echinoderm grains and their accompanying rim cements exhibit well-developed cleavage planes and twin lamellae. Up to 20 per cent dolomite occurs as euhedral rhombs developed along intergranular cracks.

Echinoderm-bryozoan grainstones: The majority of Livingstone Formation grainstones consist of closely packed, medium- or coarser grained accumulations of echinoderm and bryozoan remains. Rocks of this microfacies display considerable variations in grain size and sorting, ranging from coarse- to very coarse grained accumulations in which constituent skeletal fragments are well-rounded and well-sorted (Plates 4b-e), to medium-grained accumulations characterized by moderate sorting and abraded skeletal fragments (Plates 4f, 5a). Coquina-like textures, characterized by a layer-like, horizontal stacking of fenestrate bryozoan fronds, are present in some samples (Plate 5b). Several samples display an imbricate alignment of echinoderm columnals (Plate 5c).

Oolitic grainstones: (Plate 5d) This microfacies is rare in the Livingstone Formation, occurring only at the base of the Pigeon Mountain section. Individual ooliths average approximately 1.0 mm. in size, and consist of concentric layers of microcrystalline calcite surrounding nuclei of echinoderm and bryozoan fragments. Subordinate amounts of twinned echinoderm fragments are also present.

Quartz-pelletoidal grainstones: (Plate 5e) This is a peculiar microfacies, occurring only at the Plateau Mountain section between 77 and 93 feet (23.5 to 28 m) below the top of the section (Figure 4). It is a fine- to medium-grained accumulation of peloids and well-rounded echinoderm fragments, containing up to 30 per cent detrital quartz. The quartz is present as subangular fragments, up to 30 microns in size, and occurs randomly disseminated throughout the rock, or in cross-stratified layers alternating with layers of sand-sized skeletal debris.

Intraclasts of finely crystalline dolomite are also present. Weathered surfaces of this microfacies exhibit ripple-marking and crossbedding (Plate 2b), enhanced by the difference in weathering between the quartz and skeletal constituents.

Packstone Lithofacies

Packstones are similar in outcrop character to the grainstones. They commonly occur as thickly bedded units and occasionally display faint crossbedding. They are brown to brownish grey in colour, and tend to weather grey or light grey. Packstones often grade laterally into, or occur interbedded with grainstones and wackestones.

Livingstone Formation packstones are calcarenites and calcirudites composed of echinoderm and bryozoan fragments embedded in a microclastic (Leighton and Pendexter, 1962), partly argillaceous, micritic matrix. Subangular fragments of detrital quartz, 25-130 microns in size, are often scattered throughout the matrix in concentrations of up to 3 per cent. Quite commonly the micritic matrix is partly replaced by euhedral to subhedral rhombs of dolomite. Minor skeletal constituents include brachiopods, pelecypods, solitary corals, and gastropods.

Two packstone lithofacies are distinguishable in the Livingstone Formation: echinoderm packstones and echinoderm-bryozoan packstones.

<u>Echinoderm packstones</u>: (Plate 5f) Sand-sized echinoderm plates and columnals and a micritic mud matrix are the components of this microfacies.

<u>Echinoderm-bryozoan packstones</u>: (Plate 6a) These are essentially similar to the echinoderm packstones, different only in the fact they contain substantial amounts of fenestrate and encrusting bryozoans. Quite commonly, larger fenestrate bryozoan fronds are oriented parallel to the bedding.

Wackestone Lithofacies

Wackestones and mudstones are grouped together here, because in the field they have several characteristics in common. They occur as discrete units interbedded with packstones, or are vertically gradational with them. They commonly occur as thin- to thick beds, brown to brownish grey in colour, weathering buff to grey. Chert is often present, occurring as a variety of brownish nodules, lenses, pods, and stringers.

The majority of rocks in the wackestone lithofacies consist of sand-sized and larger skeletal fragments embedded in a relatively uniform matrix of microcrystalline, partly argillaceous, often dolomitized micrite. Skeletal debris, mainly echinoderm and bryozoan detritus, is usually scattered randomly throughout the matrix, although occasionally, skeletal grains may occur grouped together in pods, or occur as discrete layers alternating with skeletal-poor layers. Vague bedding is discernible in some samples, recognizable by slight colour variations, probably associated with varying concentrations of argillaceous material. The fabric of the rock may vary considerably within short vertical distances (often less than 1 cm), ranging from a mud-supported (wackestone) fabric, to a grain-supported (packstone) fabric. Argillaceous laminae occur in some samples. Fragments of angular detrital quartz, 30-130 microns in size, are often present, usually totalling less than 3 per cent. In 90 per cent of the samples, the micritic matrix has been partly to completely replaced by a network of euhedral to subhedral dolomite crystals.

Four microfacies are recognizable in the wackestone lithofacies. These are 1) echinoderm wackestones, 2) echinoderm-bryozoan wackestones, 3) quartzose wackestones, and 4) micritic mudstones.

Echinoderm wackestones: (Plates 6b,c) These are the most dominant of the mud-supported rocks. Skeletal debris forms up to 30 per cent of the rock, and consists almost entirely of echinoderm remains, which are present as a variety of stem and arm plates, as well as twinned columnals scattered throughout the micrite matrix.

Echinoderm-bryozoan wackestones: (Plate 6d) Echinoderm detritus and fenestrate bryozoan fragments are the dominant skeletal constituents of this microfacies, forming up to 35 per cent of the rock. Large, intact fronds of fenestrate bryozoans are sometimes present, and these are aligned parallel to the bedding.

Quartzose wackestones: (Plate 6e) This microfacies is rare in the Livingstone Formation, occurring only at the Plateau Mountain section between 175 and 180 feet (53.5 to 55 m) from the top of the section. The rock consists predominantly of silt-sized, subrounded quartz grains (in concentrations up to 60 per cent) embedded in an argillaceous, partly dolomitized, micritic matrix, portions of which are stained by iron oxide. Small local concentrations of iron-stained peloids are also present.

Micritic mudstones: (Plate 6f) This microfacies also occurs relatively rarely in the Livingstone Formation, and is included in the wackestone lithofacies due to the fact micritic mudstones are often vertical gradational products of wackestones. The rock consists of a relatively uniform mosaic of dark brown, microcrystalline calcite. Skeletal debris, when present, occurs in amounts less than 10 per cent, and is usually limited to twinned fragments of echinoderms. Argillaceous laminae are usually present, scattered randomly throughout the rock.

Environmental Interpretation of the Livingstone Formation

The vast thicknesses of Livingstone Formation echinoderm-bryozoan limestone represent the first widespread regional development in southern Alberta of shallow water echinoderm banks during the Mississippian (Macqueen and Bamber, 1967). These echinoderm banks formed under open marine conditions of normal salinity on a vast shelf area of low gradient adjacent to the Interior stable platform. Carbonate deposition took place in a series of facies belts bordering the platform. These environments were closely dependent upon water depth, degree of agitation by waves and curremts, and their relative distance from the shore (Macqueen and Bamber, 1967). The amount of carbonate deposited on the shelf represented a dynamic system controlled largely by the amount of carbonate production and rate of subsidence, where small sea level changes produced large horizontal facies shifts.

During the period in which the Livingstone Formation sediments accumulated, the shelf area was characterized by the development of widespread "meadows" densely populated by pelmatozoans and bryozoa. These organisms fluorished in agitated waters and functioned as sediment factories - occasional storm action served to dissaggregate these organisms, dispersing their remains as vast sublittoral blankets of sand-sized and larger debris. Possible modern analogues are perhaps the extensive finger-like colonies of red calcareous algae on the south shore of the Persian Gulf (Macqueen and Bamber, 1967), or the banks of seagrasses described by Hagan and Logan (1974) from Shark Bay, Western Australia.

Considerable proportions of echinoderm and bryozoan debris were subjected to the effects of wave and current action, which served to winnow, sort, scour, and further fragment the calcareous debris. Fine material was winnowed out and deposited in quieter waters. In this manner, vast shoal areas of echinoderm and bryozoan debris were created, which later became cemented to form grainstones. Crossbedded and ripple-marked quartz-pelletoidal grainstones accumulated in the intertidal zone, where detrital quartz was introduced to the platform by tidal channels. If hydrologic conditions on the shoals were suitable, ooliths tended to form.

In contrast to the above, packstone and wackestone deposition were confined to realtively calm, lower energy water, where currents were ineffective in removing carbonate mud. Packstones were probably the result of a late "dumping" of carbonate mud amoung skeletal grains on the sea floor, whereas packstones are the result of dumping of skeletal grains into a quiet water environment. In general, grainstones tend to grade vertically through packstone to wackestone. By analogy with Recent carbonate sediments, lime mud production may have been effected by one or more of the following processes: 1) disintegration of larger skeletal particles due to the decay of their organic content (Purdy, 1963; Stockman et al., 1967); 2) breakdown of skeletal particles by the boring activities of organisms; 3) mechanical abrasion of skeletal fragments (Matthews, 1966; Alberstadt, 1973; Lobo and Osborne, 1973).

DIAGENESIS OF THE LIVINGSTONE FORMATION

Introduction

During diagenesis unconsolidated carbonate sediments are transformed into lithified carbonate rocks. According to Murray and Pray (1965, p. 1), diagenesis, in the broadest sense, "encompasses those natural changes which occur in sediments or sedimentary rocks between the time of initial deposition and the time. . .when the changes created by elevated temperature, or pressure, or by other conditions can be considered to have crossed into the realm of metamorphism."

A significant dichotomy exists between Recent and ancient carbonate sediments. Studies of modern carbonate sediments reveal the presence of the metastable $CaCO_3$ polymorphs, aragonite and high-magnesium calcite. In contrast, ancient carbonates consist almost entirely of the stable polymorph, low-magnesium calcite, or dolomite. The similarity of ancient diagenetic fabrics to modern fabrics implies that the diagenetic processes which have served to stabilize, lithify, and modify ancient carbonate sediments are the same as those operating on Recent carbonates.

This section describes a variety of diagenetic fabrics observed in the Livingstone Formation, ranging from those fabrics interpreted to represent sea floor diagenesis, to those developed during subsequent burial or later subaerial exposure. The main questions to be answered in this section are: "When and how did these fabrics develop, and to what processes and environmental conditions are they related?"

Petrographic studies of the Livingstone Formation indicate the fabrics of eight types of diagenetic processes. These are 1) micritization, 2) compaction, 3) cementation, 4) silicification, 5) dolomitization, 6) pressure-solution, 7) tectonic fracturing, and 8) dissolution.

Micritization

Initial diagenesis of carbonate sediments occurs while the sediment is still in the marine environment. Bathurst (1966) studied the development of micrite envelopes in mollusc grains from Bimini Lagoon in the Bahamas, and concluded that the micritization of the surficial portions of the grain was a centripetal replacement accomplished through the boring activity of microscopic endolithic algae. After their death, the fine tubes bored by the algae become filled with micrite, which may have the composition of aragonite (Bathurst, 1966) or high-magnesium calcite (Winland, 1968).

Submarine diagenesis of the Livingstone sediments is indicated by the presence of microcrystalline calcium carbonate filled borings on skeletal grains. Micrite envelopes similar to those described from Recent carbonates are present on echinoderm and mollusc grains (Plates 4b,c,d, 7b,c, 8c). The extent of the micritization process is variable, ranging from initial peripheral alteration of skeletal grains, to more complete pervasive forms of peloid production. Where present on echinoderm grains, micrite envelopes have prevented the growth of syntaxial rim cement on these particles (Plate 7c).

The effects of the micritization process are not widespread in the Livingstone Formation, as evidenced by the fact that micrite envelopes are usually only present on echinoderm and mollusc fragments in well-sorted, well-rounded grainstones (such as those depicted in Plates 4b,c, d), thus suggesting a preference for this type of biological attack in those sediments lacking a carbonate mud matrix.

Compaction

There exists abundant evidence that the Livingstone sediments underwent compaction to some degree during burial. Embayed grain contacts resulting from pressure-solution at points of stress are present in most grainstones (Plates 4b, c,d). Irregular sutured contacts between adjacent echinoderm grains are evident in many grainstones and packstones (Plates 4b, 5f, 6a). Pressure-welded grainstones, in which bryozoan fragments are present as shredded pieces of zooaria between imbricated echinoderm grains, are common, particularly at Pigeon Mountain. Packstones often exhibit overly close packing (Plates 5f, 6a). In some samples, skeletal grains are fractured or "bent" around overlying or underlying skeletal fragments (Plates 7b, 8c).

The fact that sparry calcite cements in the Livingstone Formation are developed over embayed and sutured grains suggests that cementation probably postdated, or proceeded contemporaneously with the effects of compaction during burial. Presumably, some of the $CaCO_3$ released from grain-to-grain pressure solution may have been reprecipitated locally as cement. The grain-supported fabrics of many packstones are the result of compaction, suggesting the lack of early cement in these units.

Cementation

General

Three morphologic types of sparry calcite cement are observable in the grain-supported rocks of the Livingstone Formation. These are: 1) echinoderm rim cement, 2) drusy fringes, and 3) sparry mosaic cement. The first two cement types appear to be relatively early; the last type relatively late. The cements are composed entirely of low-magnesium calcite, the majority of which are non-ferroan, as revealed by staining with Alizarin Red S and Potassium ferricyanide.

Cement Types

1. Echinoderm rim cement

Monocrystalline syntaxial overgrowths on echinoderm fragments are volumetrically the most abundant cement type in the Livingstone Formation, forming approximately 80 per cent of the observed cements (Plates 4a-f, 5a-c). They are considered to be the earliest cement, their development postdating, or proceeding contemporaneously with, the effects of grain-to-grain pressure solution. They are developed only around echinoderm grains (Plate 7a), but do not occur on those grains which display peripheral micrite rims (Plate 7c). Rim cements often completely occlude pore spaces, and quite commonly, individual crystals may poikilotopically enclose neighbouring skeletal grains.

The majority of echinoderm rim cements consist entirely of non-ferroan calcite, although rarely, some crystals exhibit single bands of ferroan calcite on their outermost edges.

2. Drusy fringes

Intergranular pore spaces and intraskeletal cavities in grain-supported rocks are often lined with fringes of small, equant sparry calcite crystals, 10-40 microns in size. These constitute approximately 10 per cent of the total cement, and are, without exception, composed entirely of non-ferroan calcite. Individual fringes are developed on the surfaces of skeletal grains other than echinoderms, and commonly occur as isopachous linings in voids not occluded by echinoderm rim cement (Plates 7b-e). They are commonly missing or poorly developed on portions of skeletal grains engulfed by echinoderm rim cement, but are well-developed on the free portions of the same grains (Plate 7e).

3. Sparry mosaic cement

Next to echinoderm rim cements, mosaics of sparry calcite are the most widespread cement type (Plate 7f). These fill interskeletal voids not occluded by earlier cements. They are usually underlain by drusy fringes and/or echinoderm rim cements, and form mosaics of large, randomly oriented, clear calcite crystals. In large interskeletal voids, grain size of the crystals commonly increases toward the centre of the void. Individual crystals may range in size from 20-600 microns, and are composed almost exclusively of non-ferroan calcite.

Origin of Cementation

The sparry calcite cements of the Livingstone

Formation are interpreted to have formed in the phreatic environment of the shallow mesogenetic (Choquette and Pray, 1970) zone. The following lines of evidence are advanced in support of the hypothesis that cementation of the Livingstone Formation occurred in the phreatic environment:

1. Isopachous distribution of cements

The uniform development of syntaxial rim cements circumscribing echinoderm grains, and the isopachous distribution of drusy fringes in interskeletal voids argue for the precipitation of these cements in water-filled pores. Pores incompletely filled with water, as in the vadose zone, would be expected to produce gravitational or meniscus-like distributions.

2. Morphology of cements

The equant nature of the crystals in drusy fringes, and the blocky habit of sparry mosaics bear little resemblance to modern submarine and beachrock cements, which commonly form isopachous crusts of micritic and/or fibrous crystals of aragonite and high-magnesium calcite (see numerous articles in Bricker, 1971). According to Folk (1973, 1974), sparry calcite crystallizes from waters deficient in Mg^{++}, which are commonly meteoric phreatic, deep subsurface, or connate in origin.

3. Absence of subaerial features

Features indicative of subaerial exposure, such as the laminated calcareous crusts and caliche profiles described by James (1972), were not observed in the exposed sections studied. Other features suggestive of subaerial exposure, such as vadose silt (Dunham, 1969), meniscus cement (Dunham, 1971), and gravitational cement (Muller, 1971, Freeman, 1971) were not observed.

4. Development of early cements over embayed grains

The fact that echinoderm rim cements and drusy fringes are developed over embayed snd sutured grain contacts implies that the formation of these cements postdates (or proceeded concurrently with) burial of the sediment to a depth sufficient enough to initiate grain-to-grain pressure-solution (thereby eliminating the vadose zone, which has also been ruled out on other evidence).

Timing of Cementation

Cementation of the Livingstone Formation grainstones in the phreatic environment is believed to have occurred during the earlier stages of burial. Initial cementation was characterized by the formation of syntaxial rim cements on echinoderm grains, and by the development of equant sparry fringes on polycrystalline skeletal grains. These two cements probably developed concurrently with each other, the greater volume of rim cement due to the fact that the rate of precipitation of cement on monocrystalline grains is greater than that on polycrystalline grains (competitive cementation of Pray - in Bathurst, 1971, p. 423). Later precipitation of sparry mosaic calcite ensued in those pores not previously occluded by earlier cements.

The exact timing of cementation (or lithification) of sediments with a micrite matrix is difficult to assess. The micrites of the Livingstone Formation display little, if any, recrystallization to microspar or pseudospar. The absence of abundant clay minerals, which Folk (1974) believes are requisite for the formation of microspar, may be a possible reason for this phenomenon. The overly close packing evident in many packstones suggests a lack of early cement in these units.

Partial induration of carbonate mud in the intertidal zone is suggested by the presence of intraclasts exhibiting a wackestone fabric in several grainstone samples (20' and 40' at Highwood River - Figure 3; 84', 160', 280' and 338' at Plateau Mountain - Figure 4 and Plate 8a; 30' and 480' at Pigeon Mountain - Figure 5 and Plate 8b). Whether or not complete cementation of carbonate muds preceeded the complete cementation of carbonate sands is problematic, and cannot be resolved in this study. The mud-bearing sediments were partly or completely dolomitized, whereas the grainstones were completely cemented by sparry calcite, a phenomenon which has an important bearing on the reservoir quality of the Livingstone Formation. Assuming this process was active on a regional scale, it means that those sediments with high initial porosity (ie. rocks of the grainstone lithofacies) are the least attractive as potential reservoir horizins, due to the complete occlusion of porosity by sparry calcite. The mud-bearing sediments (ie. rocks of the packstone and wackestone lithofacies) are the best potential reservoir rocks, due to their selective dolomitization.

Sources of $CaCO_3$ for the Cements

Three sources of $CaCO_3$ are likely for the appary calcite cements of the Livingstone Formation. These are: 1) skeletal aragonite, 2) $CaCO_3$ released from compaction, and 3) extra-formational waters.

1. Dissolution of skeletal aragonite

A portion of the calcite cements in the Livingstone Formation may have been precipitated presumably as the result of solubility differences between metastable carbonate phases and calcite. Waters at equilibrium with respect to aragonite will be saturated with respect to calcite, thus providing a mechanism for calcite cementation or replacement concomitant with aragonite dissolution (Matthews, 1968).

The presence of micrite envelopes around molluscshaped voids now filled with sparry calcite cement implies solution of the original skeletal aragonite, leaving behind an empty micrite envelope, which was subsequently filled with cement. However, there are relatively few mollusc shells and far too much sparry calcite for all of the cement to have formed in this manner.

2. $CaCO_3$ released during compaction

Dissolution during compaction and stylolitization may provide the carbonate needed for cementation (Park and Schott, 1968; Bathurst, 1971; Friedman, 1975; Hudson, 1975). Livingstone Formation rocks contain abundant evidence of compaction, ranging from abnormally closely packed skeletal grains, to the presence of stylolites. Pressure-solution was apparently active before the appearance of first generation cement, as evidenced by the development of drusy fringes over embayed skeletal grains. Undoubtably, pressure-solution phenomena active between skeletal grains was probably a major contributor of $CaCO_3$ for the formation of early cements in the Livingstone Formation.

3. Extra-formational waters

The majority of $CaCO_3$ used to cement the Livingstone sediments most likely had an allocthonous source. Significant quantities of $CaCO_3$ may have been derived from the dissolution of other limestones to yield cement for the Livingstone Formation. The isotopic studies of Hudson (1975) on ancient limestones, led him to speculate that the sources of cement for many limestones were from other limestones or shales in the sedimentary basin.

Quite possibly, some of the Livingstone Formation cement may have been derived from entrapped sea water buried with the Livingstone, or other sediments. Ham and Rowland (1971) have postulated that the $CaCO_3$ cements for the Wapanucka Limestone of Oklahoma were derived from the sea water fluids expelled from mudstones, wackestones, and shales, at depths where elevated temperatures of approximately 75 C existed. These fluids moved updip from basin to shelf, selectively flowing through the more permeable grainstone beds and depositing interstitial calcite until the beds were fully cemented. Folk (1973, 1974) also proposes that sparry calcite may crystallize from sea water trapped in buried sediments.

Silicification

Diagenetic silica shows three modes of development in the Livingstone Formation, occurring as: 1) euhedral quartz crystals, 2) intragranular chert, and 3) matrix chert.

1) Euhedral quartz crystals

Minor amounts of doubly terminated, euhedral crystals, 20-250 microns in size (Plate 8e) are present in the Livingstone Formation. These are present as isolated crystals, or occur as aggregates of several crystals. Individual crystals often contain minute inclusions of calcite, and occur as replacements of micrite, skeletal grains, and cement.

2. Intragranular chert

Many echinoderm grains and their accompanying rim cements show evidence of whole, or partial replacement by chert, which occurs as a mosaic of minute, interlocking crystals, 10-40 microns in size (Plate 8f). The echinoderm fragments are yellow in colour, and stand out in relief from the surrounding cement and/or matrix.

3. Matrix chert

Chert is abundant in the Livingstone Formation, occurring most commonly in beds of wackestone and dolomite. It is present as a variety of brown, grey, or white nodules, lenses, blebs, and stringers (Plates 1a, 3e). In parts of the Plateau Mountain section chert nodules occur close together and parallel to the bedding, providing the rock with a distinct banded appearance (Plate 2e).

In thin section, the chert occurs in the intergranular space between skeletal fragments. It consists of a mosaic of subhedral quartz crystals, 10-200 microns in size (Plate 9a). In rocks with a micrite matrix, skeletal fragments are often observable "floating" in the chert (Plate 9b), suggesting that the chert is a preferential replacement of the matrix. Dolomite rhombs are frequently preserved within chert nodules in dolomitic rocks (Plate 9c).

The replacement of echinoderm grains and their accompanying rim cements by chert, and the presence of dolomite rhombs within chert nodules suggests that silicification of the Livingstone Formation is a late diagenetic event, postdating cementation, and overlapping in time with dolomitization. Intragranular chert may have formed as the result of organosilicic acids generated in the pores of echinoderm fragments. The development of chert nodules likely occurred in the mesogenetic zone, either from intraformational or extraformational silica dissolved from diatoms, radiolarians, or sponge spicules.

Dolomitization

General

Apart from cementation, the most intensive diagenetic process which has operated upon the Livingstone Formation is that of dolomitization. Of the total amount of section studied at the three localities, approximately 53 per cent of the exposed rock is dolomitic (ie. consisting of more than 10 per cent dolomite). The intensity and degree of the dolomitization process appears to have been variable, ranging from complete dolomitization of some beds (eg. Pigeon Mountain), to only partial dolomitization of other beds (eg. Plateau Mountain and Highwood River). Dolomitization of the Livingstone Formation appears to have been a selective process, preferentially altering carbonate mud.

Dolomite Petrography

Dolomites of the Livingstone Formation are the macrodolomites of Illing et al. (1967), and are entirely of secondary replacement origin. Dolomite units may occur as discrete beds intercalated with undolomitized rocks (eg. Pigeon Mountain - Plate 3c), or show vertical gradational relationships to packstone and/or wackestone units.

In outcrop, completely dolomitized beds (particularly those at Pigeon Mountain) appear pale yellowish brown in colour, and weather light brown. They are fine- to medium-crystalline, and are soft and easily eroded (forming recessive notches at Plateau Mountain). Molds of skeletal remains (mainly those of echinoderms and bryozoa) are frequently observable in the dolomite. Incompletely dolomitized beds are often harder than those beds completely dolomitized, and occur as grey to brownish grey units, weathering grey to brown in colour.

Dolomitization of the Livingstone Formation was predominantly a selective process, preferentially replacing sediment that initially was a carbonate mud. Petrographic observations indicate a continuum of the dolomitization process, ranging from initial replacement of micritic matrix, to later pseudomorphic replacement of skeletal fragments. Similar affinities for dolomite to selectively replace micritic matrix in ancient carbonates have been noted by Lucia (1962), Murray and Lucia (1967), and Mossler (1971).

Thin sections of partially dolomitized rocks from the Highwood River and Plateau Mountain sections indicate that dolomite developes initially in the matrix of wackestones and packstones as isolated, euhedral rhombs, 30-125 microns in size, which, in more completely dolomitized rocks, coalesce to form clusters of subhedral crystals (Plates 10a-c). More pervasive forms of dolomitization result in a complete replacement of the matrix by a sucrosic mosaic of dusty, interlocking, subhedral to anhedral dolomite, 30-230 microns in size (Plates 10d-f). Individual skeletal fragments remain unaltered, although dolomite crystals may be observed impinging upon them (Plate 11a). Complete dolomitization, such as that observed at Pigeon Mountain; results in a replacement of skeletal particles (predominantly echinoderm columnals) by euhedral to subhedral dolomite up to 500 microns in size (Plate 11e), which appears much lighter and clearer than the surrounding dusty dolomite which has replaced the matrix (Plates 11c,d). In many ceses, echinoderm columnals have been dissolved, leaving behind molds of the original particle (Plate 11f) as the only remaining vestiges of the original components. Moldic porosity is as high as 20 per cent in some rocks.

Where rocks of the Livingstone Formation are completely dolomitized, porosities average between 5 and 10 per cent (point count data). Most of the porosity is intercrystalline, although, as previously mentioned, moldic porosity is present in some sases. Pyrobitumen was observed in intercrystalline voids in several dolomites from Pigeon Mountain.

In the sections studied, the grainstone lithofacies of the Livingstone Formation has been relatively little affected by dolomitization. Dolomite is generally absent from most grainstones, although grainstones from the Pigeon Mountain section have dolomite contents as high as 15 per cent. Dolomite in grainstones occurs as dusty, euhedral to subhedral crystals, 50-300 microns in size, which are developed along boundaries between skeletal grains, skeletal grains and cement, and in intraskeletal micrite (Plate 4a).

Timing and Control of Dolomitization

Dolomitization of the Livingstone Formation is interpreted as being a relatively late diagenetic event, postdating cementation, and overlapping in time with silicification. Evidence for the post-cementation age of dolomitization is observable in rocks of the grainstone lithofacies, where dolomite rhombs are developed at boundaries between echinoderm rim cements, and at intercrystalline boundaries in sparry mosaic cements, thus implying that formation of the dolomite occurred after the precipitation of these cements, presumably in micropores or cracks between individual cement crystals. The presence of dolomite rhombohedra within chert nodules suggests that dolomitization was possibly contemporaneous with, but more likely earlier than silicification.

It is difficult to assess with any degree of certainty the reasons for the preferential growth of dolomite in sediments which initially contained abundant carbonate mud. Possible reasons, such as solubility differences between carbonate minerals, the greater surface area of micritic carbonate, or permeability differences between carbonate sands and carbonate muds have been suggested by Illing (1959), Murray and Lucia (1967), and Mossler (1971), in other investigations where dolomite has selectively replaced the micritic matrix of carbonate rocks.

Preferential dolomitization of micritic matrix may have preceeded the alteration of the matrix to mow-magnesium calcite, due to variations in sediment reactivity, as suggested by Murray and Lucia (1967) in their investigation of the Turner Valley Formation dolomites at Moose Dome. By analogy with Recent lime muds, the carbonate muds of the Livingstone Formation probably contained considerable amounts of aragonite. Similarly, skeletal particles, such as crinoids and blastoids, were probably composed of high-magnesium calcite (Chave, 1954), which may have been more soluble than aragonite (Chave et al., 1962; Friedman, 1964). Early diagenetic replacement of high-magnesium calcite by low-magnesium calcite may have left the then relatively more soluble aragonite available for selective dolomitization. This susceptibility sequence has been noted by Mossler (1971) in his study of the Upper Pennsylvanian Swope Formation of southeastern Kansas.

The greater surface area of carbonate mud particles (as opposed to carbonate sand particles), as suggested by Murray and Lucia (1967) may have been significant in causing selective dolomitization. Since lime muds have a larger surface area than lime sands, more dolomite crystals per unit volume could nucleate in the mud than in the sand.

Selective dolomitization may have taken place due to permeability differences between the carbonate sands and the carbonate muds, as suggested by Illing (1959) for the Turner Valley Formation dolomites at Moose Dome. Presumably, dolomitizing fluids may have been "channeled" through sediments with a carbonate mud matrix. Cementation of the Livingstone Formation grainstones is interpreted to have preceeded dolomitization (as discussed previously on page 45), whereas cementation of packstones and wackestones may have postdated cementation of the grainstones (see page 36). If cementation of grainstones had occurred before the onset of dolomitization, then dolomitizing fluids would have been "forced" through the mud-bearing sediments by virtue of their relatively higher permeability and porosity (due to partial cementation).

Presumably, all three of the previously mentioned factors (ie. solubility differences, permeability differences, and differences in surface area) may have influenced selective dolomitization of the Livingstone Formation carbonate muds.

Dolomitization of the Livingstone Formation, interpreted as being a late diagenetic event, probably occurred in the mesogenetic zone. Macqueen and Bamber (1967) suggested that the fine- to medium-crystalline dolomites of the Livingstone Formation probably originated by seepage refluxion (Adams and Rhodes, 1960) of Mg-rich brines from the easterly lagoon-sabkha complexes of the Shunda and Mount Head Formations.

Alternatively, dolomitization of the Livingstone Formation may have occurred in the mesogenetic zone of meteoric-sea water mixing. According to Folk and Land (1975), and Land et al. (1975), thick sequences of ancient carbonates may have been dolomitized along a brackish zone produced by the mixing of continental fresh water and downward flowing saline marine or evaporitic waters. Hanshaw et al. (1971) provided hydrogeochemical arguments that Tertiary carbonates beneath the Florida platform are being dolomitized along a zone where potable waters are mixed with ocean water or subsurface brines. Badiozamani (1973) suggested a similar mechanism for Ordovician dolomites in Wisconsin. Similarly, dolomitization of the Livingstone Formation may have been effected at depth by the mixing of seaward-flowing fresh continental ground water from the Interior platform with downward percolating, Mg-enriched, shelf lagoon water from the sabkha complexes of the easterly Shunda and overlying Mount Head Formations.

Tectonic Fracturing

Occasional well-developed fractures were observed in the Livingstone Formation, particularly at the Highwood River section, where parts of the formation are sheared and faulted. The majority of fractures are vertical to subvertical, and are commonly filled with sparry calcite cement, 30-200 microns in crystal size (Plate 9d).

Although quantitatively unimportant in the three sections studied, fractures are of paramount importance in other parts of the Livingstone Formation, viz. the Savanna Creek gas field at Plateau Mountain, where fractures form a considerable part of the reservoir (Scott, Hennessey, and Lamon, 1957).

The development of fractures in the Livingstone Formation is a relatively late diagenetic, post-lithification event. In some cases, an early episode of fracturing, predating the effects of pressure-solution, is suggested where fractures are displaced across stylolite surfaces (Plate 9f). However, the majority of fractures in the Livingstone Formation are presumably the result of stresses imposed on the rock during the Laramide orogeny.

Pressure-solution

Stylolites are well-developed in the Livingstone Formation. The majority of stylolites observed occur parellel or sub-parallel to the bedding of the rock, and generally display amplitudes of greater than 1 millimetre. Insoluble material, generally argillaceous or bituminous material, is concentrated along the stylolite surfaces

(Plate 9e).

Stylolites are present in rocks of all lithofacies, and are frequently developed at lithologic boundaries (ie. between packstone and wackestone), but also occur within a given lithofacies.

Stylolite development in the Livingstone Formation is considered to be a late diagenetic event, as evidenced by the observation that stylolites transect sparry calcite cements in grainstones, and displace fractures which could have only formed after rock induration (Plate 9f).

Dissolution

Beds of Livingstone Formation echinoderm- and echinoderm-bryozoan grainstones are often characterized by the presence of conspicuous zones and layers of vuggy porosity, which occur in the rock in concentrations up to 20 per cent. These vugs are particularly evident at the Highwood River (Plates 1e,f) and Pigeon Mountain sections (Plates 3b,c,f), where fresh exposures of the Livingstone Formation occur.

The majority of vugs are oval in shape, one-half to 6 inches (1-15 centimetres) in their longest dimension, and tend to occur in crude layers roughly parallel to the bedding or base and top of the bed (Plates 1e,f; 2f; 3b,c,f). Slabbing of individual vugs in three dimensions illustrates that the vugs are not connected, but rather occur as isolated cavities. Thin sections through individual vugs illustrate an apparent non-fabric-selective dissolution. Boundaries of the vugs transect both skeletal grains and cement (Plates 12a-c). Halos of dissolution, where small amounts of skeletal grains and cement have been removed, frequently surround the vugs (Plate 12c). Minute cracks, roughly parallel to the bedding, are often observable at vug boundaries. These cracks apparently lead from one vug to another, as evidenced by the observation that, when struck with a hammer, the rocks breaks through several vugs along these lines of weakness (Plate 1f).

The origin of the vugs is interpreted as being very late diagenetic. Vugs of this nature were not observed in the drill core from the P.H.N.T. Savanna Creek 3A, 5-32-14-4W5 well. Several thin sections from the core, however, showed anhydrite occurring as an intergranular cement (Plate 12d). Thin sections of surface samples from the three localities studied showed no evidence of anhydrite. This observation, coupled with the fact that the vugs are apparently absent in the subsurface, suggests that the vugs are the result of weathering in the telogenetic zone, a consequence of subaerial exposure following the Laramide orogeny. The vugs are presumably the result of carbonate dissolution by percolating meteoric waters.

Cursory examinations of samples of the Livingstone Formation by scanning electron microscope (Plate 12e) reveals the presence of sufficient microporosity in intraskeletal micrite and interskeletal carbonate cement in grainstones to perhaps permit the passage of fluids through the rock. Microporosity of this nature is probably absent in rocks of the packstone and wackestone lithofacies, thus explaining the apparent stratigraphic control (ie. preference for grainstone beds) of the vugs. Initial carbonate dissolution presumably commenced along minute cracks at cement boundaries, in the microporosity in intraskeletal micrite, or along stylolite seams. Localization of the vugs may have been controlled by the dissolution of a particularly large echinoderm columnal or other skeletal grain. Once initial dissolution commenced, continued solution of carbonate could occur, either along the walls of the micropores or along cleavage planes in echinoderm columnals and their rim cements (Plate 12f). Elongation of the vugs in a direction roughly parallel to the bedding of the rock could be a function of the horizontality of fractures and minor bedding inhomogeneities. Enlargement of the vugs in a vertical direction could be the result of a micro "caving in" of the tops of the voids following dissolution of intragranular cement.

Admittedly, the reasons presented for the origin of the vugs, their stratigraphic control, elongate shape, and alignment parallel to the bedding, are largely based on speculation. The origin of these vugs is likely to remain an enigma, until more detailed investigations can be undertaken.

SUMMARY AND CONCLUSIONS

Summary

The limestones of the Livingstone Formation are typical of the vast amounts of pelmatozoan limestones which characterize much of the Mississippian in western and central North America.

This study has served to document some aspects of the petrography and diagenetic history of a particular group of Mississippian carbonates - those of the Livingstone Formation. Admittedly, some of the conclusions arrived at in this investigation are speculative, but it is hoped that some of the knowledge about the diagenesis of the Livingstone Formation may be integrated with, and provide a basis for further diagenetic studies of Mississippian carbonates in Western Canada.

Conclusions

With regard to the objectives of this study, the following conclusions can be drawn concerning the petrography, deposition, and diagenesis of the Livingstone Formation:

1. Lithologic and petrographic observations indicate that the Livingstone Formation sediments consist predominantly of three lithofacies ten microfacies

(excluding dolomite). These are:

a) Grainstone lithofacies

i) echinoderm grainstones
ii) echinoderm-bryozoan grainstones
iii) oolitic grainstones
iv) quartz-pelletoidal grainstones

b) Packstone lithofacies

i) echinoderm packstones
ii) echinoderm-bryozoan packstones

c) Wackestone lithofacies

i) echinoderm wackestones
ii) echinoderm-bryozoan wackestones
iii) quartzose wackestones
iv) micritic mudstones

2. Livingstone Formation sediments accumulated under open-marine conditions of normal salinity on a carbonate shelf area of low gradient, characterized by prolific development of echinoderms and bryozoa. Dissaggregation and post-mortem disintegration of these organisms and their subsequent reworking by waves and currents served to create the variety of lithofacies and microfacies observed. Grainstones were formed in areas of high mechanical energy; ie. areas of intense wave and current agitation. These formed vast shoal areas of loose, drifting skeletal debris, behind which extensive lagoons of a restricted and semi-restricted nature existed. Packstones and wackestones accumulated in areas of lower mechanical energy, where currents were ineffective in removing carbonate mud. Lime

mud production probably occurred by disintegration of skeletal particles due to decay of their organic content, breakdown of skeletal particles by the boring activities of organisms, or by mechanical abrasion of skeletal fragments.

3. The fabrics of eight types of diagenetic processes were observed in the Livingstone Formation. These processes and their relative temporal relationships are summarized in Figure 6.

4. Initial diagenesis of the Livingstone Formation sediments occurred in the marine environment by production of micrite envelopes on skeletal grains by boring endolithic algae.

5. The sparry calcite cements of the Livingstone Formation grainstones are composed of non-ferroan low-magnesium calcite. Three morphologic types of cement were observed: echinoderm rim cement, drusy fringes, and sparry mosaic cement. Cementation of the Livingstone Formation is interpreted to have occurred in the phreatic environment of the shallow mesogenetic zone. Cementation postdated, or proceeded concurrently with an initial phase of compaction due to burial. $CaCO_3$ for the cements is believed to have been derived from the dissolution of intra-formational skeletal aragonite, compaction, and extra-formational sources.

6. Diagenetic silica is present as euhedral, doubly

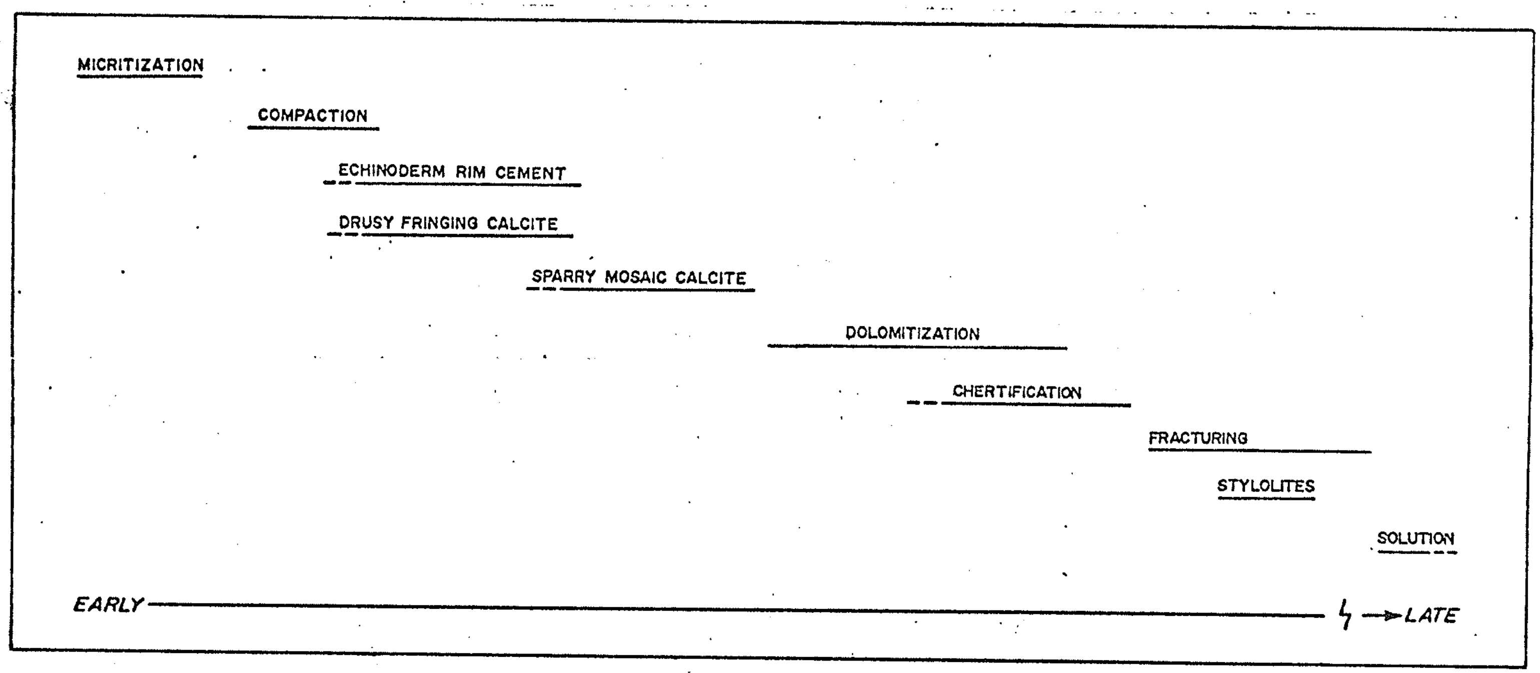

Figure 6. Relative temporal relationships of diagenetic processes in the Livingstone Formation.

terminated quartz crystals, intragranular chert, and matrix chert. Silicification (or chertification) of the Livingstone Formation is interpreted to be a late diagenetic event, postdating cementation and overlapping in time with dolomitization.

7. Dolomitization of the Livingstone Formation appears to have been a selective process, preferentially replacing sediment that initially was a carbonate mud (ie. packstones and wackestones). Petrographic observations indicate a continuum of the dolomitization process, ranging from initial replacement of micritic matrix, to later pseudomorphic replacement of skeletal fragments. Selective dolomitization may have taken place due to solubility differences between high-magnesium calcite and aragonite. Early diagenetic replacement of high-magnesium calcite skeletal particles may left the more soluble aragonitic matrix available for selective dolomitization. Permeability differences between cemented carbonate sands and partially cemented carbonate muds, and the greater surface area of carbonate mud particles may have also been factors in the selective dolomitization of the Livingstone Formation.

8. Dolomitization of the Livingstone Formation is interpreted as being a late diagenetic event, occurring in the mesogenetic zone, by either seepage refluxion of hypersaline brines from the Shunda and Mount Head

Formations, or by mixing of seaward-flowing continental fresh waters with downward percolating, Mg-enriched shelf lagoon waters from the Shunda and Mount Head Formations.

9. Tectonic fracturing of the Livingstone Formation is a late diagenetic event, postdating the effects of pressure-solution. An earlier phase of fracturing is also present.

10. Stylolite development in the Livingstone Formation is considered to be a late diagenetic event, postdating an early phase of fracturing.

11. The conspicuous zones and layers of vuggy porosity present in echinoderm- and echinoderm-bryozoan grainstones are believed to be the result of extremely late carbonate dissolution by percolating meteoric waters in the subaerial (telogenetic) zone. Vug development was permitted due to sufficient microporosity in intraskeletal micrite and interskeletal cement in rocks of the grainstone lithofacies. Initial dissolution presumably commenced along minute cracks at cement boundaries, intraskeletal micrite microporosity, or along stylolite seams.

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PLATES 1-12

PLATE I

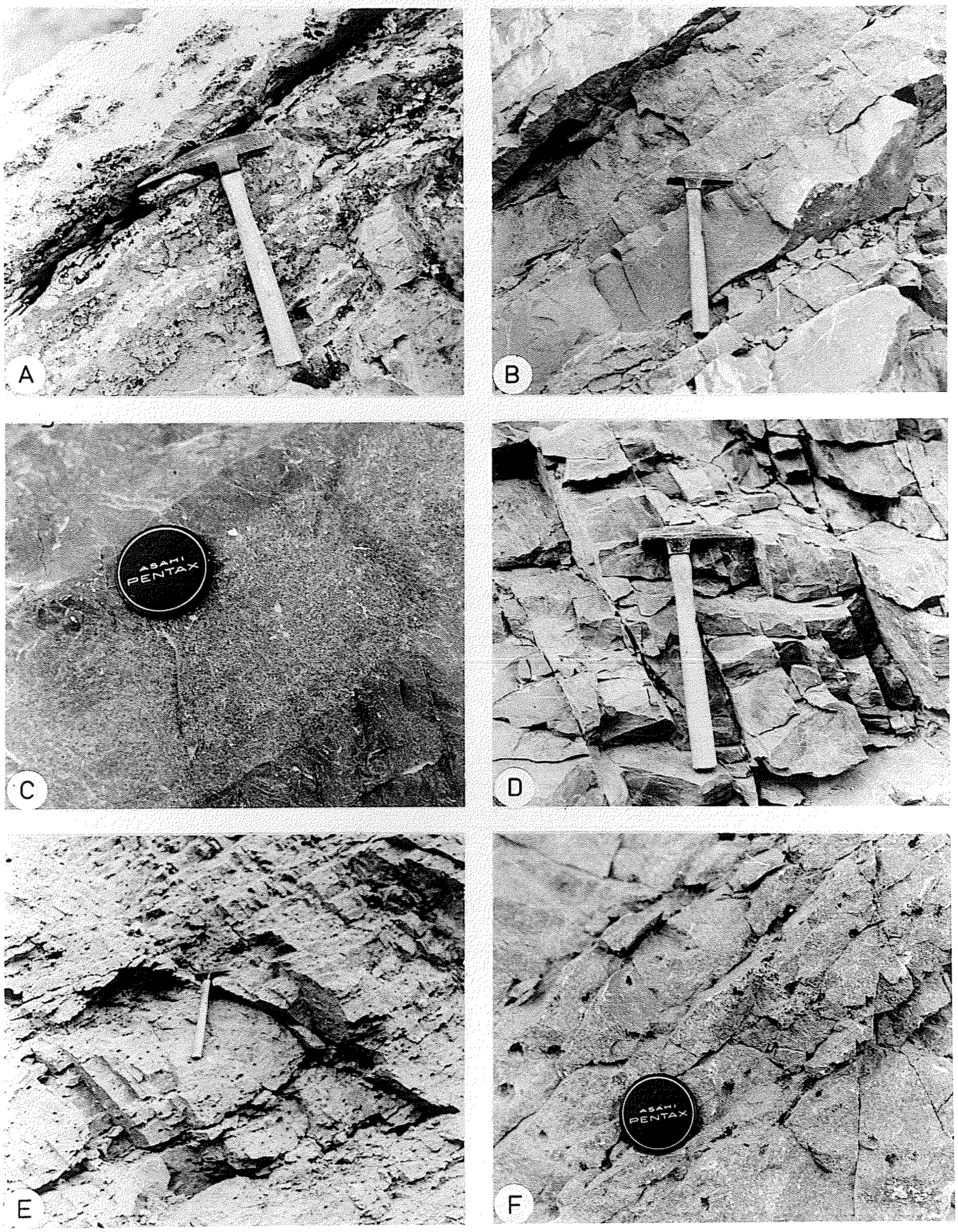


PLATE 1

PHOTOS OF THE LIVINGSTONE FORMATION
AT HIGHWOOD RIVER

a Uppermost bed of section, consisting of fine-grained, cherty, dolomitic limestone. Note chert nodules oriented parallel to the bedding.
4 feet (1 m)

b Coarse-grained echinoderm packstone underlain by dense, finely crystalline dolomitic pelmatozoan wackestone (contact just below hammer head).
31.5 feet (9.5 m)

c Layer of grain-supported pelmatozoan limestone in bed of fine-grained argillaceous mudstone.
175 feet (53 m)

d Bed of dense, fine-grained, cherty pelmatozoan wackestone.
180 feet (55 m)

e Thickly bedded unit of coarse-grained echinoderm-bryozoan grainstone. Note the vuggy porosity present throughout, and the tendency of the vugs to occur in crude layers parallel to the bedding.
207 feet (63 m)

f Coarse-grained echinoderm-bryozoan grainstone, same as in e, illustrating details of the vuggy porosity. Note the tendency of the rock to break through individual vugs.
207 feet (63 m)

PLATE 2

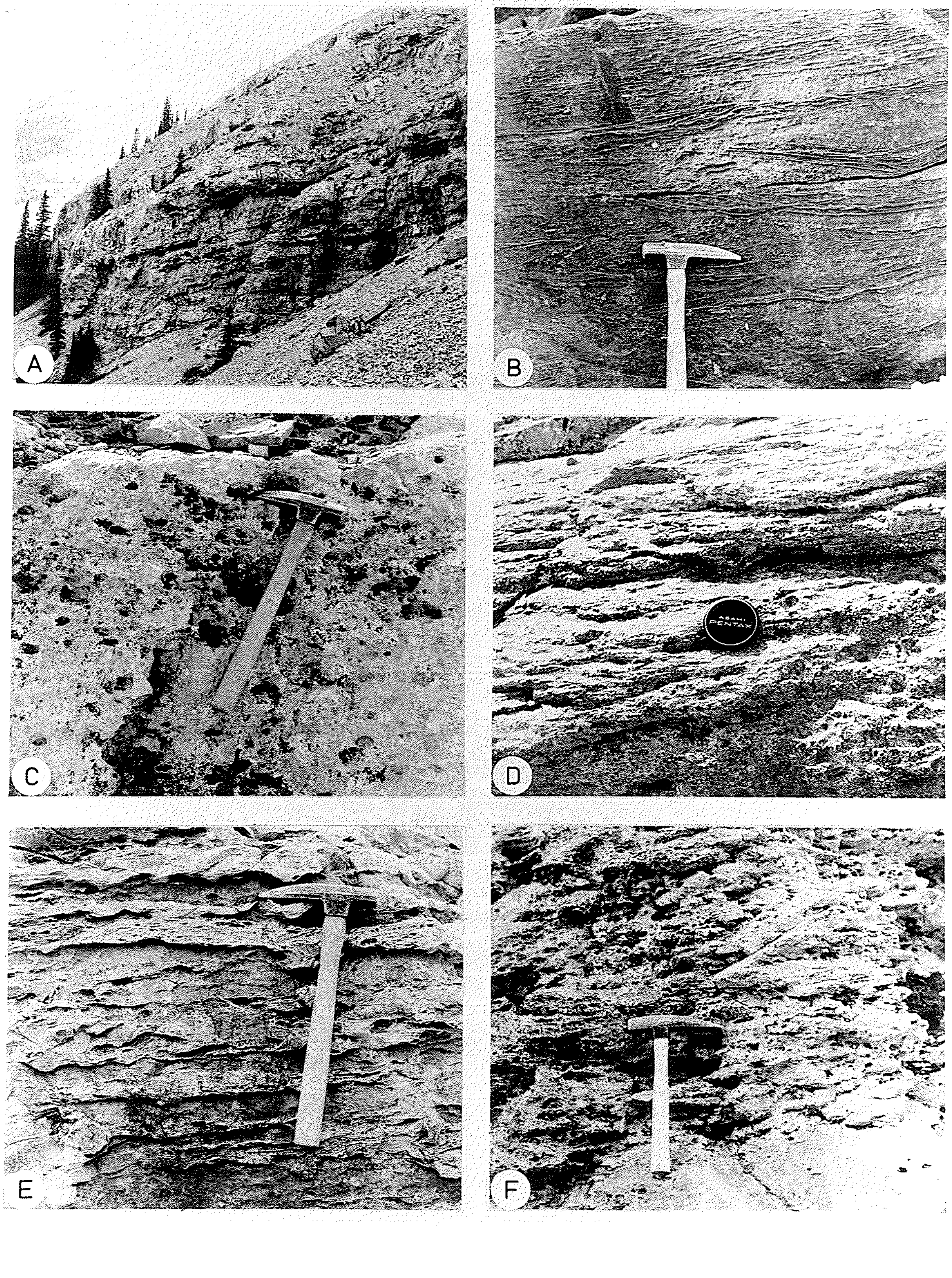


PLATE 2

PHOTOS OF THE LIVINGSTONE FORMATION
AT PLATEAU MOUNTAIN

<u>a</u> Massive, cliff-forming nature of the Livingstone Formation at Plateau Mountain.

<u>b</u> Fine-grained, arenaceous grainstone, exhibiting small-scale quartz crossbeds and dolomitic intraclasts which have weathered out in relief.
92 feet (28 m)

<u>c</u> Thickly bedded, medium- to coarse-grained, echinoderm-bryozoan grainstone, with accompanying vuggy porosity.
245 feet (74.5 m)

<u>d</u> Close-up of coarse-grained, echinoderm-bryozoan grainstone.
270 feet (82 m)

<u>e</u> Fine-grained, argillaceous, dolomitic wackestone, with chert nodules parallel to the bedding. Note the distinct banded appearance of the rock.
300 feet (91.5 m)

<u>f</u> Crossbedded, coarse-grained, echinoderm-bryozoan grainstone. Unit has weathered to a skeletal sand in places.
365 feet (111 m)

PLATE 3

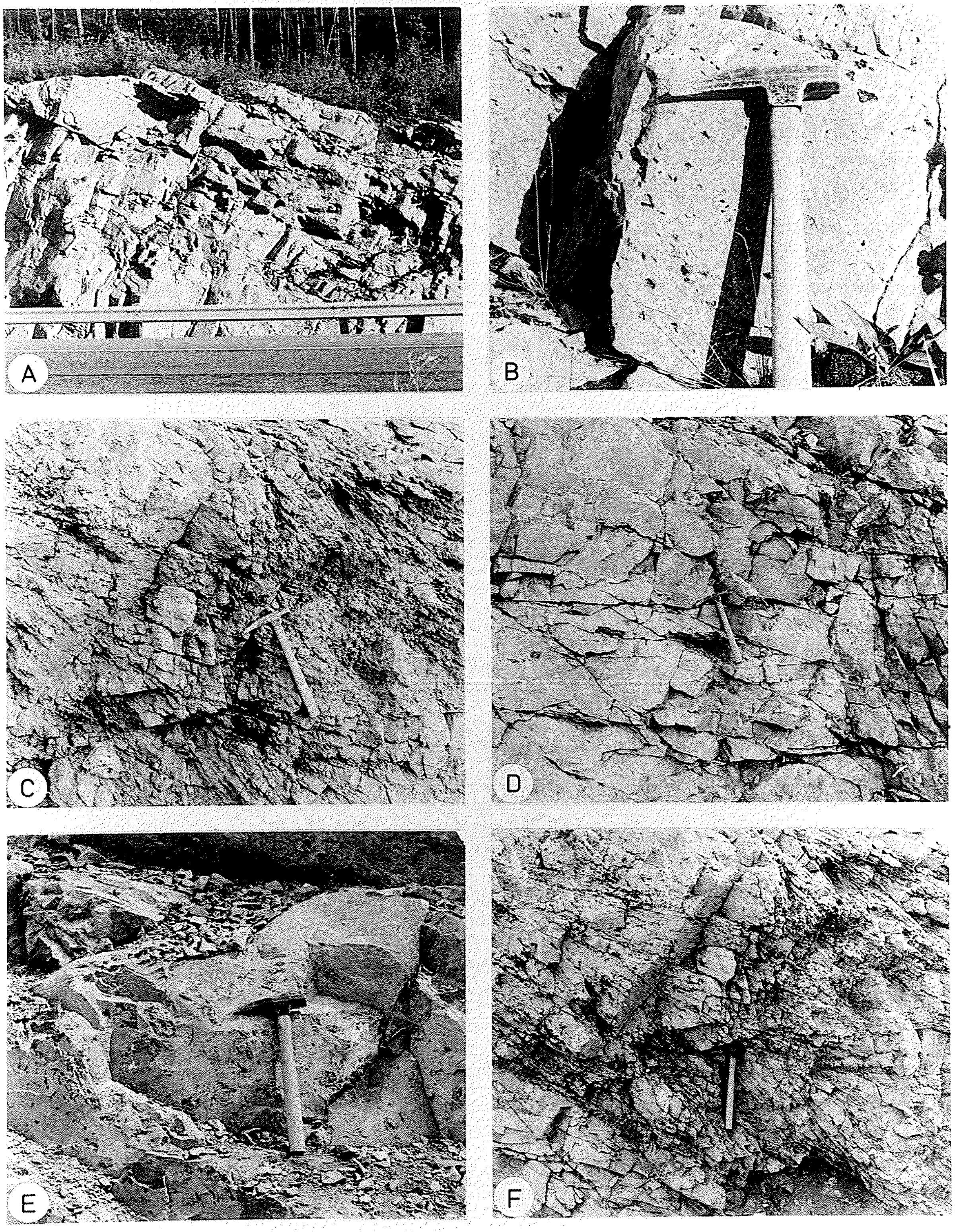


PLATE 3

PHOTOS OF THE LIVINGSTONE FORMATION AT PIGEON MOUNTAIN

<u>a</u> Part of the section exposed at Pigeon Mountain, illustrating the thickly bedded nature of the grainstone lithofacies. Thin bed of dolomite is present in the upper right hand corner.

<u>b</u> Coarse-grained, dolomitic echinoderm-bryozoan grainstone exhibiting vuggy porosity.
65 feet (20 m)

<u>c</u> Crossbedded, coarse-grained, echinoderm-bryozoan grainstone with accompanying vuggy porosity. Note the distinct tendency of the vugs to occur parallel to the bedding. Bed of fine crystalline dolomite is present in lower left corner.
195 feet (59.5 m)

<u>d</u> Thickly bedded, coarse-grained, echinoderm-bryozoan packstone.
280 feet (85 m)

<u>e</u> Dense unit of fine-grained, dolomitic pelmatozoan wackestone. Note the irregular blebs of dark chert present throughout.
370 feet (113 m)

<u>f</u> Crossbedded, coarse-grained, vuggy, echinoderm-bryozoan grainstone. Unit has weathered to a skeletal sand just above hammer. Bed of fine crystalline dolomite is present in lower left corner.
450 feet (137 m)

PLATE 4

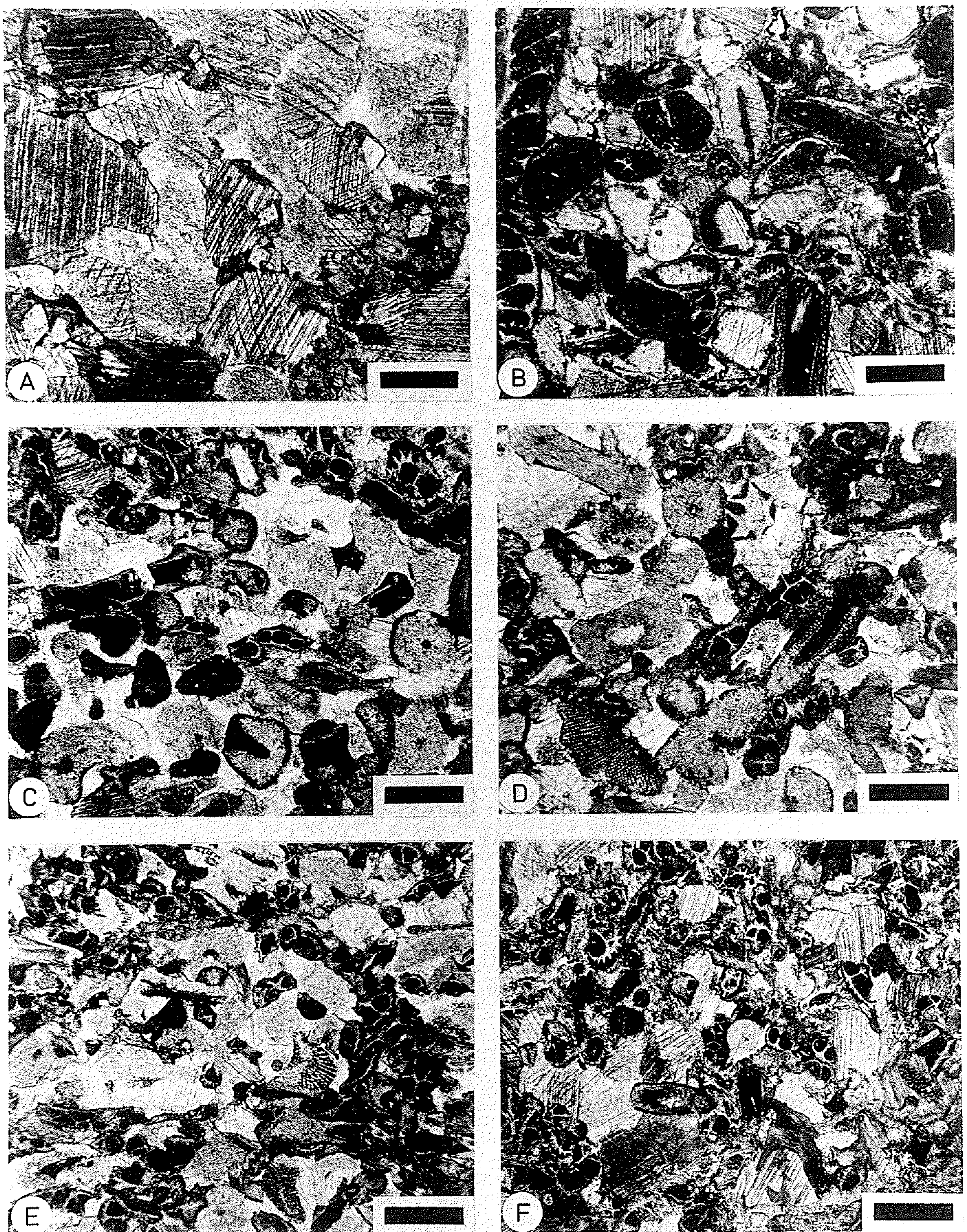


PLATE 4

PHOTOMICROGRAPHS OF
GRAINSTONE MICROFACIES

Plane polarized light.

a Echinoderm grainstone. Closely packed. Echinoderm columnals and their accompanying rim cements exhibit well-developed twinning. Note the development of dusty, euhedral rhombs of dolomite at grain contacts.
Lower Livingstone; Pigeon Mountain; 129 feet (39 m).
Bar scale = 500 microns.

b Echinoderm-bryozoan grainstone. Moderately well-sorted and closely packed. Bryozoan and echinoderm grains are well-rounded. Several echinoderm fragments display well-developed micrite envelopes. Several peloids are also present.
Upper Livingstone; Highwood River; 20 feet (6 m).
Bar scale = 500 microns.

c Echinoderm-bryozoan grainstone. Well-sorted and loosely packed. Note micrite envelopes on echinoderm grains.
Upper Livingstone; Highwood River; 62 feet (19 m).
Bar scale = 500 microns.

d Echinoderm-bryozoan grainstone. Cleanly washed accumulation of echinoderm and bryozoan grains. Well-sorted and closely packed.
Upper Livingstone; Plateau Mountain; 60 feet (18 m).
Bar scale = 500 microns.

e Echinoderm-bryozoan grainstone. Well-sorted and moderately closely packed. Note micrite infilling of bryozoan zooecia. Echinoid fragment visible in centre of photograph.
Upper Livingstone; Plateau Mountain; 68 feet (20.5 m).
Bar scale = 500 microns.

f Echinoderm-bryozoan grainstone. Poorly sorted and closely packed. Note the twinning of echinoderm fragments and their associated rim cements.
Upper Livingstone; Highwood River; 130 feet (39.5 m).
Bar scale = 500 microns.

PLATE 5

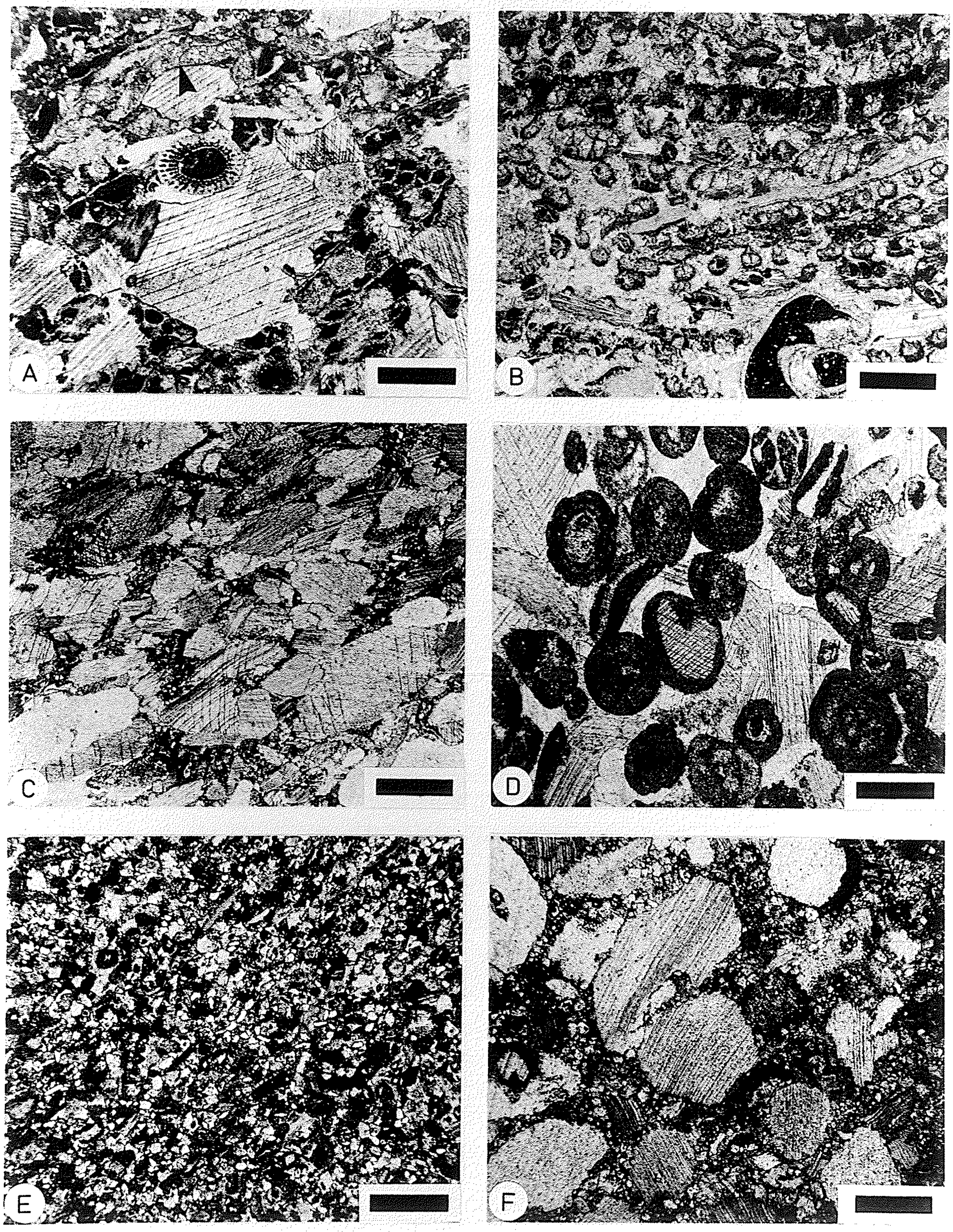


PLATE 5

PHOTOMICROGRAPHS OF GRAINSTONE AND PACKSTONE MICROFACIES

Plane polarized light.

a Echinoderm-bryozoan grainstone. Poorly sorted and closely packed. Echinoderm grains and their rim cements are twinned. Mollusc grain in upper left (arrow) has been dissolved and replaced by sparry calcite. Echinoid spine in centre of photograph.
Upper Livingstone; Plateau Mountain; 270 feet (82 m).
Bar scale = 500 microns.

b Echinoderm-bryozoan grainstone. Note coquina-like stacking of fenestrate bryozoan fronds.
Upper Livingstone; Plateau Mountain; 115 feet (35 m).
Bar scale = 1000 microns.

c Echinoderm-bryozoan grainstone. Note imbricate alignment of twinned echinoderm fragments.
Lower Livingstone; Pigeon Mountain; 338 feet (103 m).
Bar scale = 1000 microns.

d Oolitic grainstone. Nuclei of ooliths composed primarily of echinoderm and bryozoan fragments. Echinoderm fragments and their accompanying rim cements are also present.
Lower Livingstone; Pigeon Mountain; 520 feet (158.5 m).
Bar scale = 500 microns.

e Quartz-pelletoidal grainstones. Comprised mainly of peloids, and subangular quartz grains, with occasional echinoderm detritus.
Upper Livingstone; Plateau Mountain; 88 feet (26.5 m).
Bar scale = 500 microns.

f Echinoderm packstone. Micrite matrix partly replaced by dolomite. Several echinoderm grains exhibit stylolitic interpenetration.
Lower Livingstone; Pigeon Mountain; 510 feet (155.5 m).
Bar scale = 500 microns.

PLATE 6

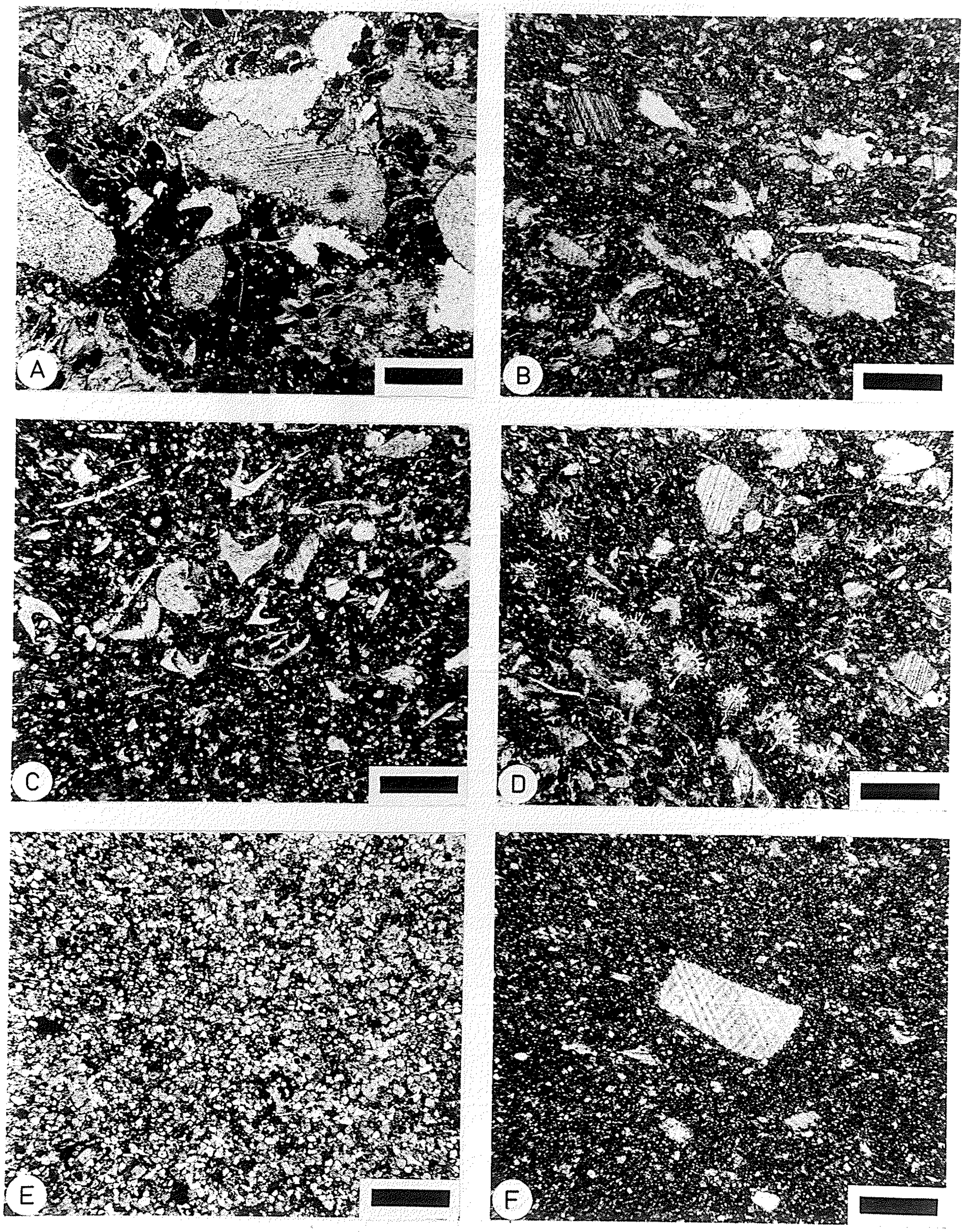


PLATE 6

PHOTOMICROGRAPHS OF PACKSTONE
AND WACKESTONE MICROFACIES

Plane polarized light.

a Echinoderm-bryozoan packstone. Skeletal constituents consist of a poorly sorted accumulation of echinoderm debris and encrusting bryozoans. Matrix is microcrystalline calcite containing small amounts of detrital quartz and sporadic dolomite rhombs. Note stylolitic interpenetration of echinoderm grains in centre of photograph.
Upper Livingstone; Plateau Mountain; 190 feet (58 m).
Bar scale = 500 microns.

b Echinoderm wackestone. Echinoderm debris is embedded in a partly dolomitized matrix of microcrystalline calcite,
Upper Livingstone; Highwood River; 80 feet (24 m).
Bar scale = 500 microns.

c Echinoderm wackestone. Columnals and arm plates, as well as fragments of unidentified skeletal detritus are embedded in a partly dolomitized matrix of microcrystalline calcite. Sporadic fragments of detrital quartz are scattered throughout the matrix.
Upper Livingstone; Plateau Mountain; 140 feet (42.5 m).
Bar scale = 500 microns.

d Echinoderm-bryozoan wackestone. Large fenestrate bryozoan frond in centre of photograph lies sub-parallel to the bedding. Matrix is microcrystalline calcite and finely comminuted skeletal debris.
Upper Livingstone; Highwood River; 203 feet (62 m).
Bar scale = 500 microns.

e Quartzose wackestone. Silt-sized, subrounded quartz grains are embedded in a partly dolomitized, iron-stained, argillaceous micritic matrix.
Upper Livingstone; Plateau Mountain; 178 feet (54 m).
Bar scale = 500 microns.

f Micritic mudstone. Matrix is microcrystalline calcite and finely comminuted skeletal debris. Skeletal fragments are twinned, echinoderm debris. Small rhombs of dolomite can be seen replacing matrix material.
Upper Livingstone; Plateau Mountain; 310 feet (94.5 m).
Bar scale = 500 microns.

PLATE 7

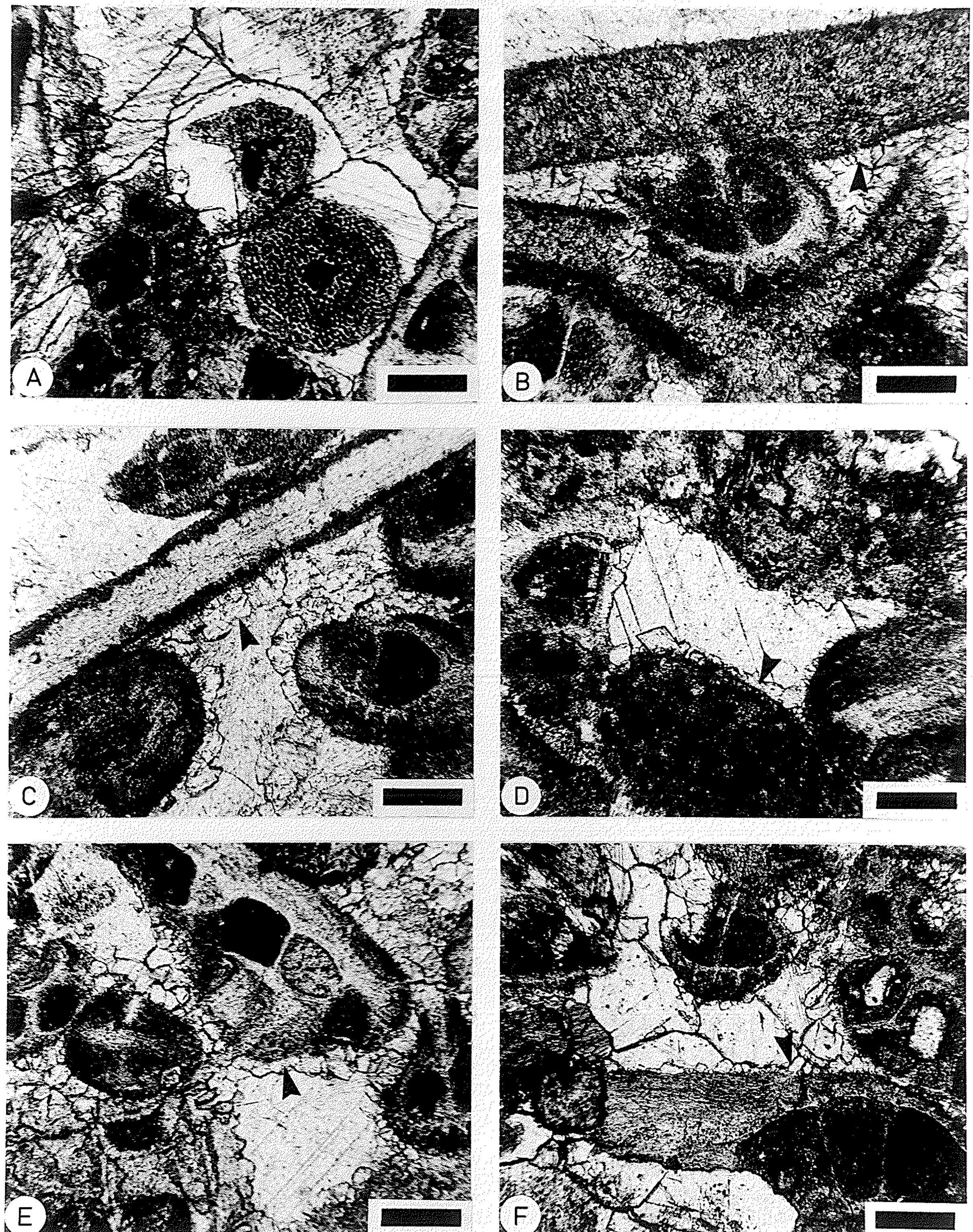


PLATE 7

PHOTOMICROGRAPHS OF
CEMENT MORPHOLOGIES

Plane polarized light.

a Echinoderm rim cement circumscribing echinoderm columnal and plate.
Upper Livingstone; Plateau Mountain; 380 feet (116 m).
Bar scale = 125 microns.

b Drusy fringing calcite (arrow) cementing mollusc and bryozoan grains. Interiors of mollusc grains have been dissolved and replaced by sparry calcite.
Upper Livingstone; Highwood River; 62 feet (19 m).
Bar scale = 125 microns.

c Drusy fringing calcite (arrow) developed over echinoderm and bryozoan grains. Remainder of pore space is filled with echinoderm rim cement. Note micrite envelope on echinoderm grain.
Upper Livingstone; Plateau Mountain; 68 feet (20.5 m).
Bar scale = 125 microns.

d Drusy fringing calcite (arrow) lining void between peloids and bryozoan grains. Remainder of pore space filled with a single, twinned calcite crystal. Dolomite rhomb in centre of photograph transects both the drusy calcite and later pore-filling calcite.
Upper Livingstone; Plateau Mountain; 62 feet (19 m).
Bar scale = 125 microns.

e Drusy fringing calcite (arrow) illustrating equant nature of calcite crystals.
Upper Livingstone; Plateau Mountain; 270 feet (82 m).
Bar scale = 125 microns.

f Sparry mosaic cement. Pore space is completely occluded by large, blocky crystals of sparry calcite. Earlier drusy calcite (arrow) is poorly developed on bryozoan fragments.
Upper Livingstone; Plateau Mountain; 250 feet (76 m).
Bar scale = 125 microns.

PLATE 8

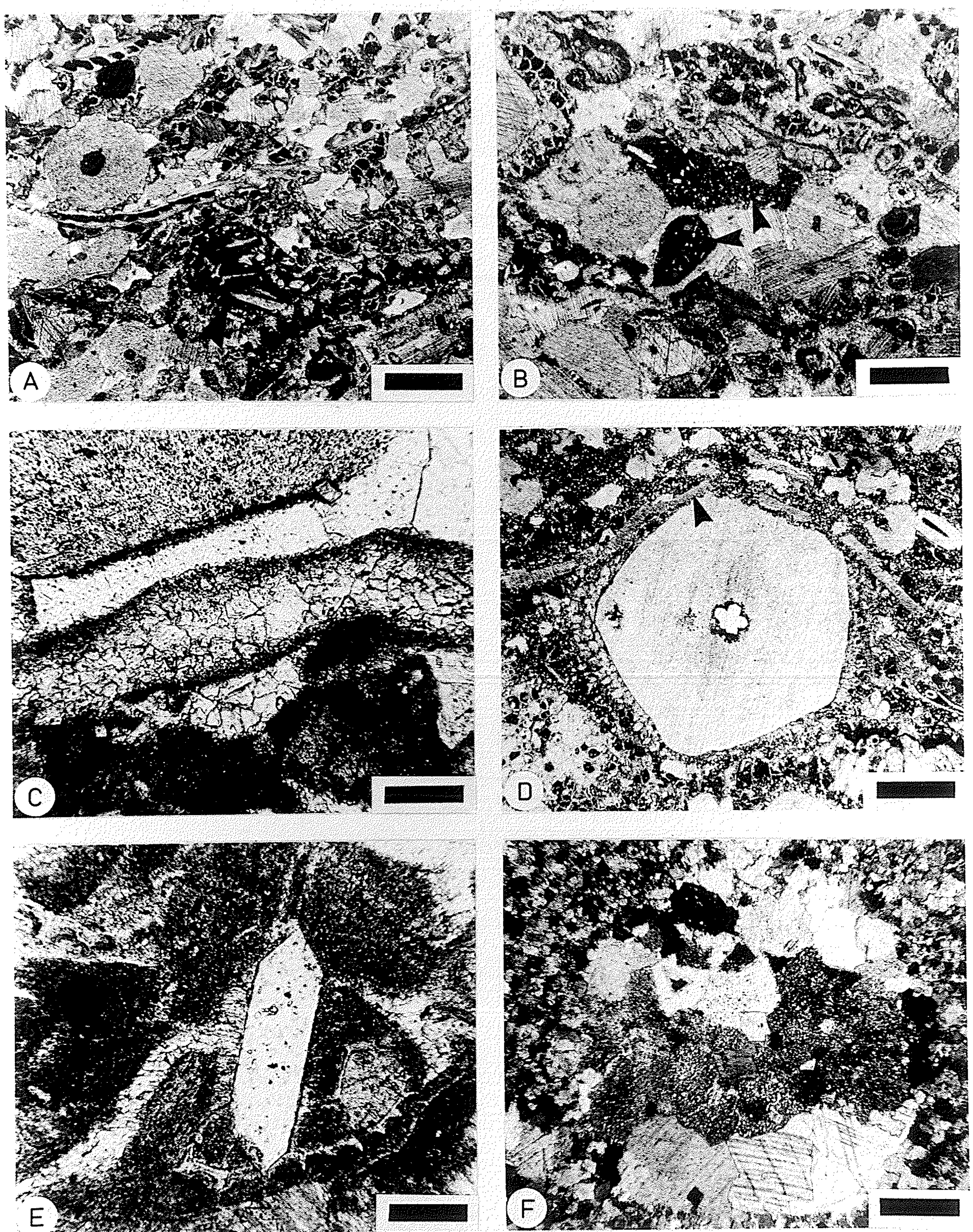


PLATE 8

PHOTOMICROGRAPHS OF
DIAGENETIC FABRICS

a Intraclast exhibiting wackestone fabric (arrow) in echinoderm-bryozoan grainstone.
Plane polarized light.
Upper Livingstone; Plateau Mountain; 280 feet (85 m).
Bar scale = 1000 microns.

b Mudstone intraclasts (arrows) in echinoderm-bryozoan grainstone.
Plane polarized light.
Lower Livingstone; Pigeon Mountain; 30 feet (9 m).
Bar scale = 1000 microns.

c Micrite envelope developed on mollusc grain. Development of the envelope has permitted the dissolution of mollusc material, subsequently leaving behind a cavity which has been filled with sparry calcite. Note the development of sparry fringing calcite and echinoderm rim cements on skeletal grains.
Plane polarized light.
Upper Livingstone; Plateau Mountain; 280 feet (85 m).
Bar scale = 125 microns.

d Pelecypod shell (arrow) bent around echinoderm columnal in echinoderm-bryozoan packstone. This may have resulted due to compaction in the micritic matrix.
Plane polarized light.
Upper Livingstone; Plateau Mountain; 190 feet (58 m).
Bar scale = 1000 microns.

e Doubly terminated quartz crystal replacing bryozoan fragments and sparry calcite cement.
Plane polarized light.
Upper Livingstone; Highwood River; 62 feet (19 m).
Bar scale = 125 microns.

f Intragranular chert partly replacing echinoderm columnal.
Crossed nicols.
Lower Livingstone; Pigeon Mountain; 501 feet (153 m).
Bar scale = 350 microns.

PLATE 9

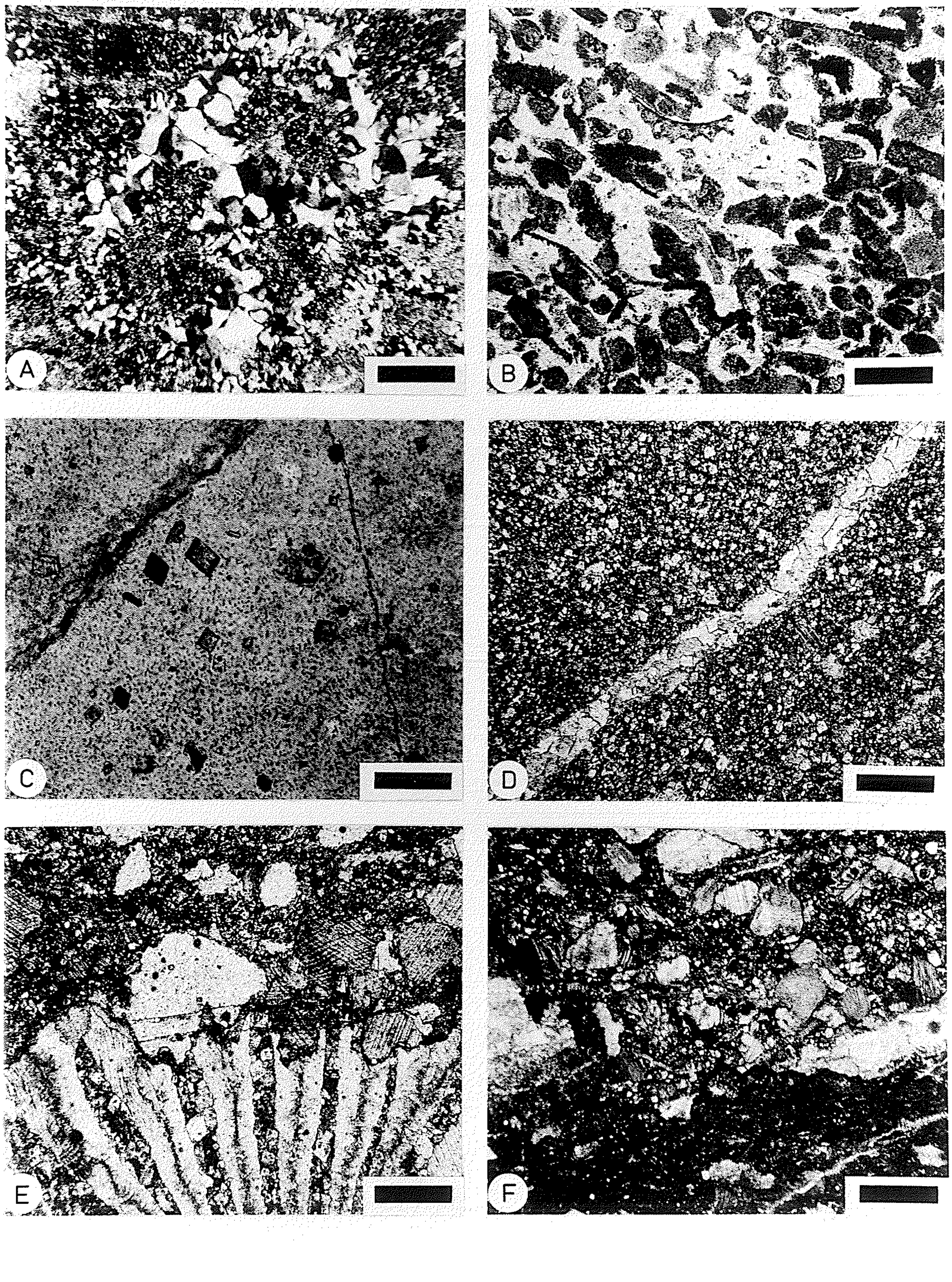


PLATE 9

PHOTOMICROGRAPHS OF
DIAGENETIC FABRICS

<u>a</u> Close-up of chert nodule illustrating large grain size and subhedral nature of the quartz crystals. Finer material is skeletal debris.
Crossed nicols.
Upper Livingstone; Plateau Mountain; 230 feet (70 m).
Bar scale = 125 microns.

<u>b</u> Skeletal debris in chert nodule illustrating original wackestone-packstone depositional texture.
Plane polarized light.
Upper Livingstone; Plateau Mountain; 230 feet (70 m).

<u>c</u> Dolomite rhombs developed in chert nodule.
Plane polarized light.
Upper Livingstone; Highwood River; 4 feet (1 m).
Bar scale = 125 microns.

<u>d</u> Fracture in dolomitic wackestone filled with clear, sparry calcite.
Plane polarized light.
Upper Livingstone; Highwood River; 62 feet (19 m).
Bar scale = 500 microns.

<u>e</u> Stylolite developed in dolomitic packstone.
Plane polarized light.
Lower Livingstone; Pigeon Mountain; 510 feet (155.5 m).
Bar scale = 500 microns.

<u>f</u> Fracture displaced by stylolite in dolomitic wackestone.
Plane polarized light.
Lower Livingstone; Pigeon Mountain; 360 feet (110 m).
Bar scale = 1000 microns.

PLATE 10

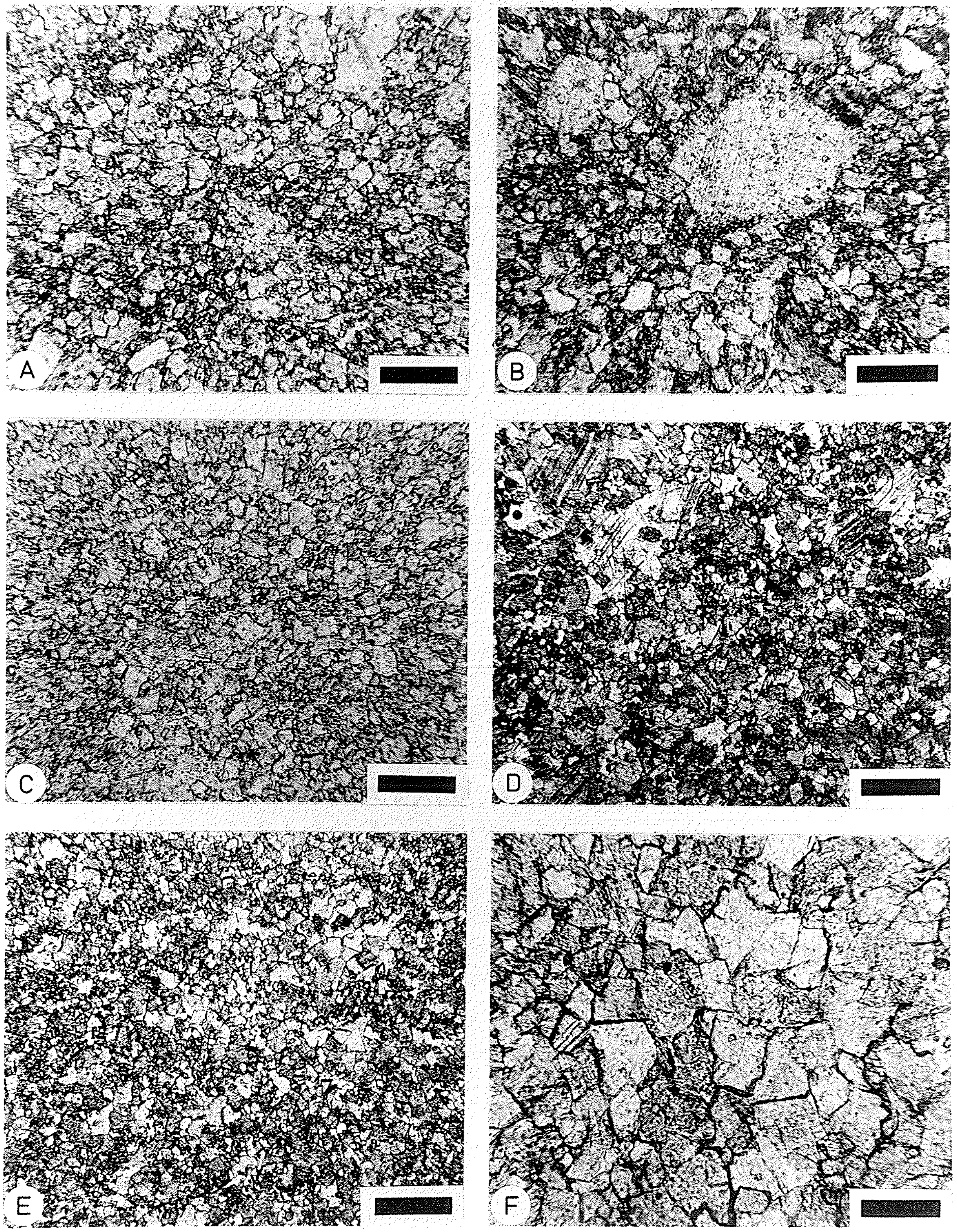


PLATE 10

PHOTOMICROGRAPHS OF
DOLOMITE MICROFACIES

Plane polarized light.

<u>a</u> Euhedral to subhedral rhombs of dolomite replacing matrix in wackestone.
Upper Livingstone; Highwood River; 15 feet (4.5 m).
Bar scale = 125 microns.

<u>b</u> Selective replacement of micritic matrix by euhedral to subhedral dolomite rhombs in wackestone. Note that dolomitization has not yet affected the echinoderm grains.
Upper Livingstone; Highwood River; 35 feet (10.5 m).
Bar scale = 125 microns.

<u>c</u> Portion of matrix in wackestone completely replaced by a network of interlocking, subhedral to anhedral dolomite.
Upper Livingstone; Plateau Mountain; 55 feet (16.5 m).

<u>d</u> Saccharoidal dolomite. Matrix of wackestone is replaced by a network of dusty, euhedral to subhedral dolomite.
Lower Livingstone; Pigeon Mountain; 13 feet (4 m).
Bar scale = 500 microns.

<u>e</u> Complete dolomitization of a wackestone. Matrix has been replaced by a network of dusty dolomite, whereas skeletal grains (now seen as "ghosts" of the originals) have been replaced by clearer, larger rhombs of dolomite.
Lower Livingstone; Pigeon Mountain; 104 feet (31.5 m).
Bar scale = 500 microns.

<u>f</u> Close-up of dolomite in <u>e</u>. Most rhombs are subhedral in shape.
Bar scale = 125 microns.

PLATE II

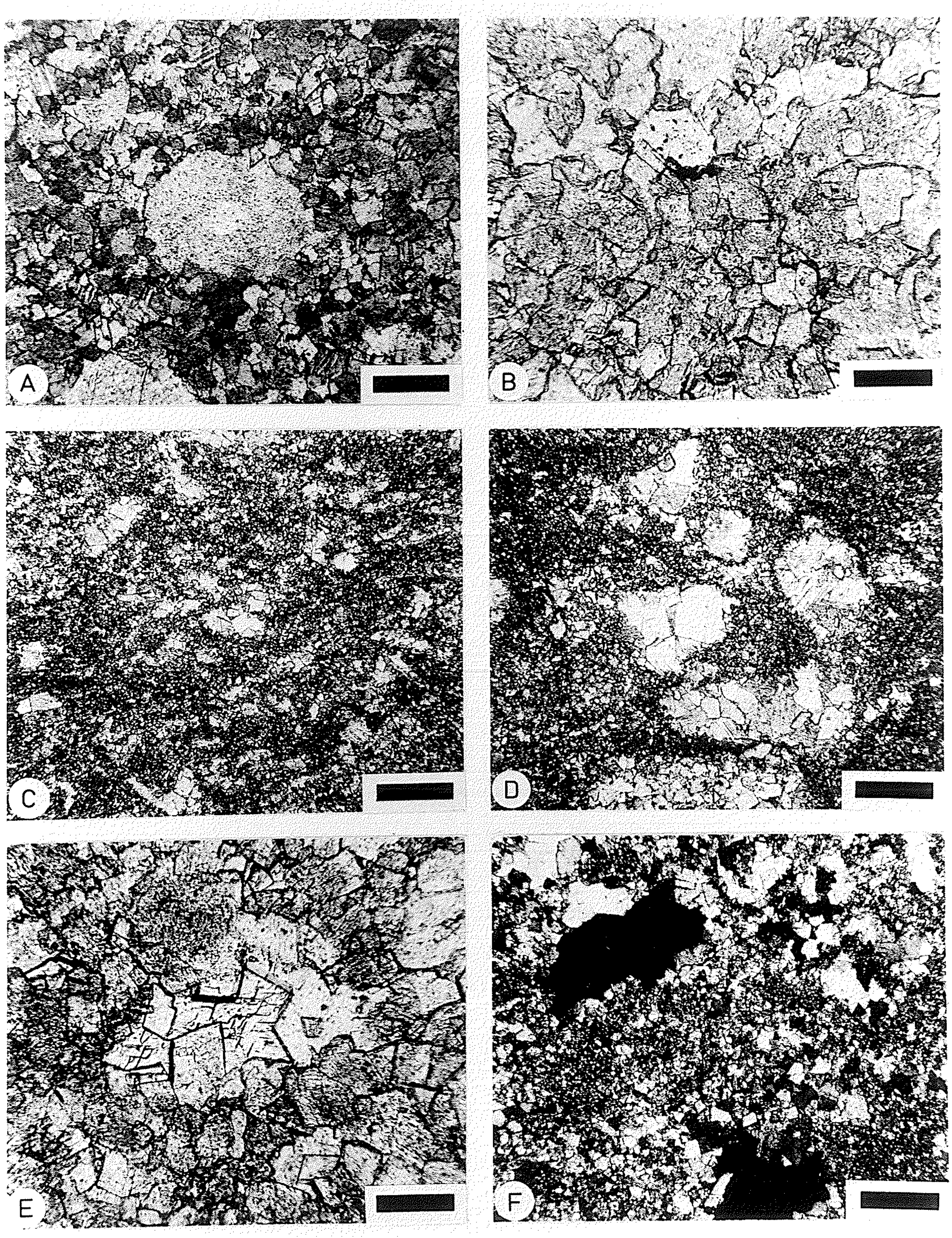


PLATE 11

PHOTOMICROGRAPHS OF DOLOMITE FABRICS

a Matrix of packstone completely replaced by large, dusty, euhedral to subhedral dolomite. Note the impingment of the rhombs upon the echinoderm columnal.
Plane polarized light.
Lower Livingstone; Pigeon Mountain; 430 feet (131 m).
Bar scale = 500 microns.

b Details of dolomite in a.
Plane polarized light.
Bar scale = 125 microns.

c Completely dolomitized sample illustrating details of original wackestone texture. Skeletal fragments are represented by ghosts of clear, euhedral dolomite.
Plane polarized light.
Lower Livingstone; Pigeon Mountain; 240 feet (73 m).
Bar scale = 500 microns.

d Pseudomorphic replacement of echinoderm and bryozoan grains by dolomite.
Plane polarized light.
Lower Livingstone; Pigeon Mountain; 272 feet (83 m).
Bar scale = 500 microns.

e Close-up of dolomite pseudomorphing echinoderm fragment. Dolomite replacing echinoderm grain is clear and euhedral, whereas dolomite replacing the surrounding micritic matrix is dusty and subhedral.
Plane polarized light.
Lower Livingstone; Pigeon Mountain; 290 feet (88.5 m).
Bar scale = 125 microns.

f Dolomitized wackestone illustrating molds of echinoderm columnals.
Crossed nicols.
Lower Livingstone; Pigeon Mountain; 370 feet (113 m).
Bar scale = 500 microns.

PLATE 12

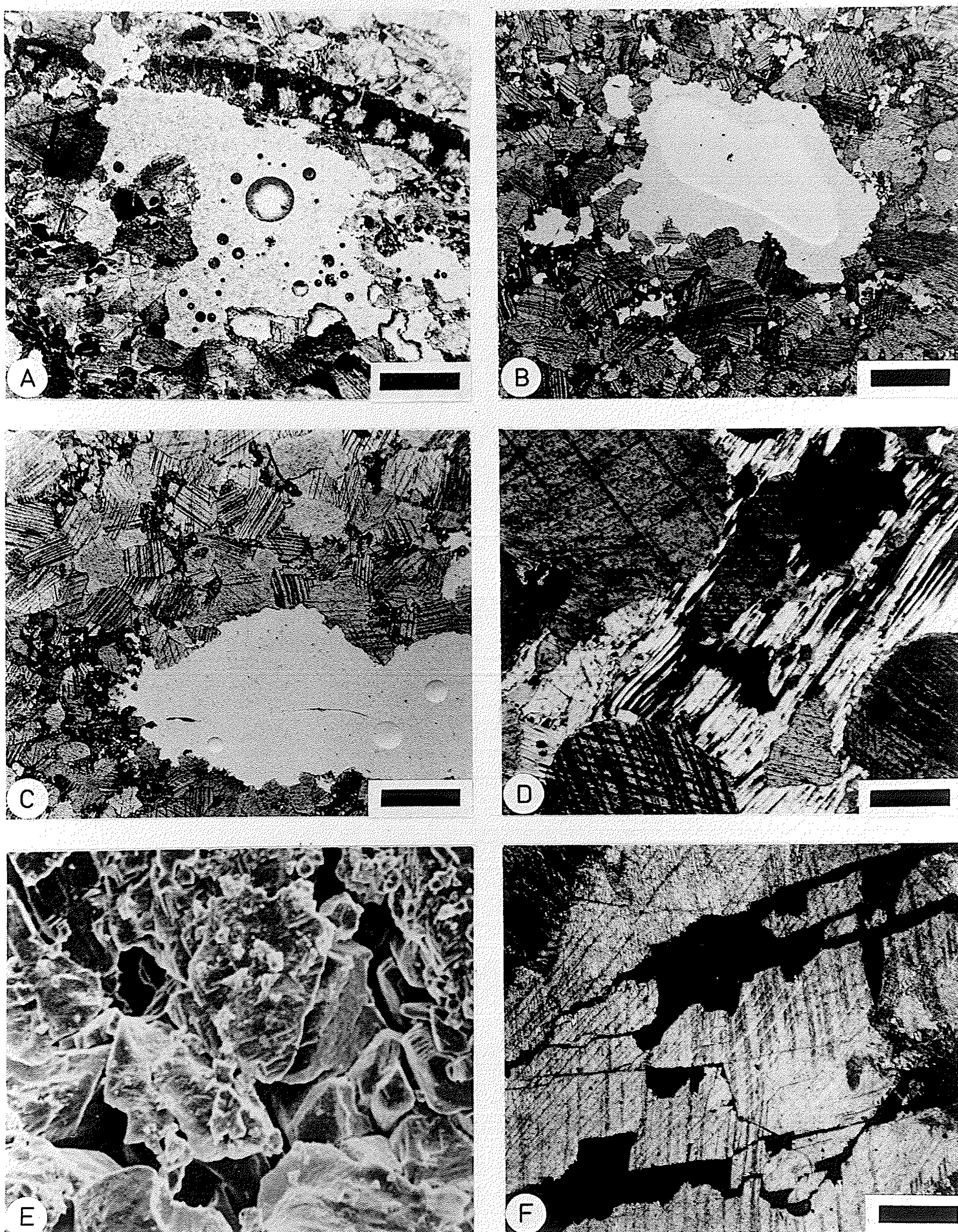


PLATE 12

PHOTOMICROGRAPHS OF
SOLUTION FABRICS

a Solution vug developed in echinoderm-bryozoan grainstone. Note the fact that vug boundaries transect both skeletal grains and cement.
Plane polarized light.
Upper Livingstone; Plateau Mountain; 275 feet (84 m).
Bar scale = 1000 microns.

b Solution vug developed in echinoderm grainstone. Note the oval shape and halos of dissolution surrounding the vug.
Plane polarized light.
Lower Livingstone; Pigeon Mountain; 195 feet (59.5 m).
Bar scale = 1000 microns.

c Vug developed in echinoderm-bryozoan grainstone. Note that vug boundaries transect twinned echinoderm grains and their rim cements, thus indicating a post-cementation age for vug development.
Plane polarized light.
Lower Livingstone; Pigeon Mountain; 430 feet (131 m).
Bar scale = 1000 microns.

d Anhydrite replacing cement in echinoderm-bryozoan grainstone.
Crossed nicols.
P.H.N.T. Savanna Creek 3A, 5-32-14-4W5, 9553 feet (2914 m)
Bar scale = 300 microns.

e Intergranular pore space developed at boundaries of cement crystals in echinoderm-bryozoan grainstone.
S.E.M. photomicrograph, x1000.
Lower Livingstone; Pigeon Mountain; 430 feet (131 m).

f Incipient solution occurring along cleavage planes in echinoderm grain.
Crossed nicols.
Upper Livingstone; Plateau Mountain; 240 feet (73 m).
Bar scale = 300 microns.

APPENDIX

(Details of
measured sections)

Section 1: Highwood River

The section was measured from the base of the Wileman Member of the Mount Head Formation, on the north side of the Highwood River, approximately one-half mile east of the Sentinel Ranger Station.

Cumulative thickness to top of section Feet	Metres	Lithology
0	0	Covered interval.
3	1	Dolomitic limestone; micritic-skeletal; grey to dark grey; contains abundant bands and nodules of brown chert; scattered echinoderm columnals and brachiopod debris.
6½	2	Calcareous dolomite; finely crystalline; brown to brownish grey; weathers buff grey; contains small vugs filled with fluorite and limonite; occasional nodules of chert present.
17½	5	Limestone; skeletal; medium- to coarse-grained; grey to brownish grey; thickly bedded; comprised predominantly of echinoderm columnals, also silicified corals present; occasional nodules and stringers of chert present.
31½	9½	Calcareous dolomite; finely crystalline; brownish grey; one bed; scattered echinoderm columnals.
35½	11	Limestone; skeletal; medium- to coarse-grained; brownish grey; thickly bedded; composed of echinoderm and bryozoan fragments; rare solitary coral present.
43	13	Dolomitic limestone; micritic-skeletal; grey; partly sheared - large gash veins filled with calcite; occasional echinoderm fragments; contains stringers and blebs of light brown chert.

Cumulative thickness to top of section		Lithology
Feet	Metres	
59	18	Limestone; skeletal; medium-grained; pale brownish grey; partly fractured; consists mainly of echinoderms and bryozoan fragments.
66	20	Dolomitic limestone; micritic-skeletal; brownish grey; occasional stylolites; fractured; scattered echinoderm columnals.
78	24	Dolomitic limestone; micritic-skeletal; grey; brown and black chert present in nodules and stringers; fractured; scattered echinoderm columnals.
		Section continued updip.
84	25½	Calcareous dolomite; finely crystalline; dark grey; middle 2 feet are micritic-skeletal dolomitic limestone.
90	27½	Dolomitic limestone; micritic-skeletal; brownish grey; thickly bedded; echinoderm and bryzoan fragments visible on weathered surface.
94	28½	Limestone; skeletal; fine- to medium-grained; dark grey; thickly bedded; composed mainly of echinoderm and bryozoan detritus.
114	35	Dolomitic limestone; micritic-skeletal; brownish grey; thickly bedded; highly jointed; echinoderm and bryozoan fragments visible on weathered surface.
124	38	Limestone; skeletal; coarse-grained; grey; thickly bedded - in part crossbedded; vuggy; comprised mainly of echinoderm and bryozoan fragments.
144	44	Limestone; fine- to medium-grained; dark brownish grey; uppermost 10 ft. are dolomitic, argillaceous micritic limestone;

Cumulative thickness to top of section		Lithology
Feet	Metres	
Cont'd		basal 10 ft. are micritic-skeletal limestone; unit contains stringers and nodules of grey chert.
186	56½	Limestone; skeletal; coarse-grained; grey; thickly bedded; vuggy; comprised of echinoderm and bryozoan fragments.
199	60½	Dolomite; finely crystalline; dark grey; cherty; one bed.
201	61	Limestone; skeletal; coarse-grained; grey; vuggy; comprised predominantly of echinoderm and bryozoan fragments.
203	62	Dolomitic limestone; micritic-skeletal; grey; contains stringers and nodules of brown chert; one bed.
204	62	Limestone; skeletal; coarse-grained; grey; thickly bedded; vuggy; composed of echinoderm and bryozoan debris.

Total amount of section exposed - 217 feet (66 m); 3 feet covered (1 m).

Section 2: Plateau Mountain

The section was measured from the base of the Wileman Member of the Mount Head Formation, on exposures on the west side of a south facing cirque at Plateau Mountain.

Cumulative thickness to top of section		Lithology
Feet	Metres	
0	0	Covered interval.
40	12	Limestone; skeletal; medium- to coarse-

Cumulative thickness to top of section		Lithology
Feet	Metres	
Cont'd		grained; brownish grey; thin to thick bedded; fossiliferous - echinoderm columnals, bryozoa, and silicified horn corals visible on weathered surface; unit becomes dolomitic and skeletal-micritic towards base.
48	14½	Dolomitic limestone; micritic-skeletal; buff grey; unit slightly recessive; echinoderm columnals and silicified bryozoan fronds visible on weathered surface.
50	15	Dolomitic limestone; skeletal-micritic; grey; weathers buff grey; abundant echinoderm columnals visible on weathered surface.
53	16	Calcareous dolomite; finely crystalline; grey; weathers grey; one bed; contains echinoderm and brachiopod fragments.
56	17	Limestone; skeletal; medium- to coarse-grained; brownish grey; weathers grey; massive; resistant; black chert nodules present at top of unit; composed of echinoderm and bryozoan fragments.
66	20	Limestone; skeletal; medium-grained; grey; weathers light grey; thickly bedded; resistant; comprised of echinoderm and bryozoan fragments.
71	21½	Limestone; skeletal; coarse-grained; grey; weathers grey; thickly bedded; resistant; comprised of echinoderm detritus.
77	23½	Dolomitic limestone; fine- to medium-grained; dark brownish grey; weathers grey; massive; base of unit shows pale orange crossbeds and ripple marks, as well as grey, dolomitic intraclasts; abundant quartz present.
93	28	Covered interval.

Cumulative thickness to top of section		Lithology
Feet	Metres	
135	41	Dolomitic limestone; argillaceous; micritic-skeletal; dark brownish grey; weathers grey; thin to thickly bedded; contains chert nodules which parallel bedding - these exhibit fossimoldic porosity; scattered echinoderm columnals present; unit contains thin interbeds of skeletal-micritic, pelmatozoan limestone.
145	44	Limestone; skeletal; medium- to coarse-grained; pale brownish grey; contains zones of vuggy porosity; comprised of echinoderms and bryozoa; unit contains lenses of grey, finely crystalline, cherty dolomite; unit as a whole forms prominent cliff.
175	53	Dolomitic, arenaceous micritic limestone; buff; stained by iron oxide; weathers back to form prominent notch at base of cliff.
180	55	Limestone; skeletal; coarse-grained; brownish grey; weathers grey; suggestion of crossbedding; occasional zones of vuggy porosity; comprised of echinoderm and bryozoan remains.
189	57½	Limestone; skeletal-micritic; grey; weathers grey to buff grey; thin to thickly bedded; skeletal debris consists of echinoderm and bryozoan fragments.
195	59½	Dolomitic limestone; micritic-skeletal; dark brownish grey; weathers grey; massive for the most part; occasional thin interbeds which weather like shale; some stringers and nodules of brown chert; scattered echinoderm columnals and bryozoans.
205	62½	Limestone; micritic-skeletal; grey; weathers grey; vuggy in places - small irregular vugs around bryozoan fronds and

Cumulative thickness to top of section		Lithology
Feet	Metres	
Cont'd		echinoderm columnals; occasional interbeds of finely crystalline calcareous dolomite.
215	65½	Dolomitic limestone; micritic-skeletal; dark brownish grey; weathers grey; thin to thickly bedded; some stringers and nodules of brown chert; scattered echinoderm fragments throughout.
228	69½	Calcareous dolomite; fine- to medium-crystalline; pale grey; weathers light grey; grades into dark grey, dolomitic limestone-skeletal-micritic; entire unit is massive, with suggestion of laminations on weathered surface; chert bands in upper 2 ft. replacing skeletal concentrations.
232	71	Dolomitic limestone; micritic-skeletal; buff grey; weathers buff; thinly bedded; contains recognizable echinoderm and bryozoan debris; occasional small vugs.
235	71½	Limestone; skeletal; medium- to coarse-grained; grey; weathers grey; thin to thickly bedded; crossbedded in places; vuggy; comprised of echinoderm and bryozoan fragments.
285	87	Covered interval.
290	88½	Dolomitic limestone; argillaceous; micritic; dark grey; weathers grey; massive; contains parallel bands of brown chert which give the unit a "banded" appearance.
		Remainder of section measured approximately 50 ft. downdip on side of large cliff.
330	100½	Dolomitic limestone; same as above.
336	102½	Limestone; skeletal; coarse-grained; grey; weathers grey; thinly bedded; occasional

Cumulative thickness to top of section		Lithology
Feet	Metres	
Cont'd		vuggy porosity; comprised mainly of echinoderms and bryozoa.
340	103	Dolomite; finely crystalline; grey; weathers grey.
341	104	Limestone; skeletal; medium-grained; grey; weathers grey; crossbedded; badly weathered - forms deep notches and caves in cliff face; consists predominantly of echinoderm and bryozoan remains.
344	105	Limestone; skeletal; coarse-grained; grey; weathers grey; thickly bedded; vuggy; composed of bryozoan and echinoderm remains.
352	107	Calcareous dolomite; finely crystalline; grey; highly jointed; weathers back slightly.
353	107½	Limestone; skeletal; coarse-grained; grey to brownish grey; weathers grey; thickly bedded; contains crossbedded zones which weather back; very vuggy; composed of echinoderms and bryozoa.
372	113½	Limestone; skeletal-micritic; buff grey; weathers buff; abundant echinoderm columnals present.
375	114	Limestone; skeletal; coarse-grained; grey; weathers grey; thickly bedded; crossbedded; vuggy; comprised of echinoderm and bryozosn remains.
385	117	Calcareous dolomite; finely crystalline; light grey; weathers buff grey; contains recognizable echinoderm remains.

Total amount of section exposed - 387 feet (118 m); 87 feet covered (26½ m).

Section 3: Pigeon Mountain

The section was measured from the top of exposures on a roadside cut below Pigeon Mountain, south side of the Trans Canada Highway.

Cumulative thickness to top of section		Lithology
Feet	Metres	
0	0	Dolomitic limestone; skeletal-micritic; buff grey; thickly bedded; vuggy in places; abundant echinoderm and bryozoan fragments.
8	2	Calcareous dolomite; finely crystalline; grey; thickly bedded; some silicified echinoderm columnals present.
18	5½	Dolomite; finely crystalline; saccharoidal; grey; thinly bedded; contains zones of fossimoldic porosity; also irregular stringers and blebs of chert.
28	8½	Limestone; skeletal; coarse-grained; grey; thickly bedded; vuggy to very vuggy; comprised of echinoderm and bryozoan detritus; unit grades into skeletal-micritic dolomitic limestone, containing abundant echinoderm columnals "floating" in a dolomite matrix.
41	12½	Calcareous dolomite; finely crystalline; grey; thickly bedded; contains echinoderm columnals in dolomitic matrix.
45	13½	Dolomitic limestone; skeletal; medium- to coarse-grained; grey; thickly bedded; vuggy; comprised of echinoderm and bryozoan remains.
74	22½	Dolomite; finely crystalline; grey; some moldic porosity.
76	23	Limestone; skeletal; medium- to coarse-

Cumulative thickness to top of section		Lithology
Feet	Metres	
Cont'd		grained; grey; thickly bedded; vuggy; comprised mostly of echinoderm columnals.
88	27	Dolomite; finely crystalline; saccharoidal; grey; thinly bedded; some moldic porosity.
93	28	Dolomitic limestone; skeletal-micritic; brownish grey; thickly bedded; matrix replaced by dolomite; abundant echinoderm columnals.
100	30½	Dolomite; fine-grained; saccharoidal; grey; thinly bedded; some moldic porosity.
108	33	Dolomitic limestone; skeletal-micritic; grey; thin to thickly bedded; some vuggy porosity; abundant echinoderm fragments in matrix of dolomite.
128	39	Limestone; skeletal; coarse-grained; thickly bedded; contains zones of vuggy porosity; comprised of echinoderm and bryozoan debris.
131	40	Dolomite; finely crystalline; buff; thinly bedded; hackly fracture; some moldic porosity.
144	44	Limestone; skeletal; very coarse-grained; grey; thickly bedded; vuggy; consists of bryozoan and echinoderm remains.
162	49	Dolomite; finely crystalline; saccharoidal; buff; thinly bedded.
168	51	Covered interval.
185	56	Dolomitic limestone; skeletal-micritic; grey; thickly bedded; abundant echinoderm columnals in partly dolomitized matrix; small vugs present.
190	58	Dolomitic limestone; skeletal; coarse-

Cumulative thickness to top of section		Lithology
Feet	Metres	
Cont'd		grained; grey; some crossbedding; comprised of echinoderm debris; partly porous and vuggy.
203	61	Dolomitic limestone; skeletal-micritic; buff; thickly bedded; matrix replaced by dolomite; sporadic vugs; echinoderm remains visible on weathered surface.
208	63	Limestone; skeletal; coarse-grained; grey; thickly bedded; extremely vuggy; echinoderm and bryozoan detritus; weathered to an echinoderm sand in places.
215	65½	Dolomite; finely crystalline; saccharoidal; buff grey; thinly bedded; occasional zones of vuggy porosity; 5 ft. from top of unit is 6-inch silicified zone containing chert stringers.
223	68	Limestone; skeletal; coarse-grained; grey; thickly bedded; extremely vuggy; mostly echinoderm and bryozoan detritus; weathered to a skeletal sand in places.
231	70½	Calcareous dolomite; finely crystalline; buff; grades into grey, finely crystalline dolomite; unit displays good moldic porosity derived from leaching of echinoderm columnals.
252	77	Limestone; skeletal; coarse-grained; grey; thickly bedded; vuggy; mostly echinoderms and bryzoa; contains small interbeds of grey, finely crystalline calcareous dolomite.
263	80	Dolomite; finely crystalline; saccharoidal; buff to grey; thinly bedded with a hackly fracture; good moldic porosity derived from leaching of echinoderms and bryozoa.
276	84	Limestone; skeletal-micritic; grey; thickly

Cumulative thickness to top of section		Lithology
Feet	Metres	
Cont'd		bedded; echinoderm fragments visible on weathered surface.
282	86	Dolomite; finely crystalline; buff to grey; saccharoidal; thinly bedded; occasional stringers and blebs of chert.
308	94	Dolomitic limestone; skeletal-micritic; grey; thickly bedded; vuggy; mostly echinoderm detritus in dolomitic matrix.
315	96	Calcareous dolomite; finely crystalline; dark grey; thickly bedded; scattered echinoderm detritus; some stringers and nodules of brown chert.
333	101½	Limestone; skeletal; coarse-grained; grey; thickly bedded; some chert; mostly bryozoan and echinoderm remains.
343	104½	Calcareous dolomite; finely crystalline; grey; scattered echinoderm columnals.
349	106	Dolomitic limestone; micritic-skeletal; grey; thickly bedded; scattered echinoderm remains; contains irregular stringers and blebs of brown to dark grey chert; grades into echinoderm skeletal-micritic limestone.
382	116½	Limestone; skeletal; coarse-grained; grey; thickly bedded; partly crossbedded in places; vuggy; composed of echinoderm and bryozoan remains.
418	127½	Dolomite; finely crystalline; grey; contains irregular stringers and blebs of chert.
423	129	Limestone; skeletal; coarse- to very coarse-grained; grey; crossbedded in places; very vuggy and porous; comprised of echinoderm and bryozoan remains; unit

Cumulative thickness to top of section		Lithology
Feet	Metres	
Cont'd		contains interbeds of buff, finely crystalline dolomite, exhibiting moldic porosity.
483	147½	Dolomite; finely crystalline; brownish grey; thickly bedded; some skeletal debris; occasional nodules of brownish grey chert.
491	150	Limestone; skeletal; very coarse-grained; grey; thickly bedded; vuggy; consists of echinoderm and bryozoan remains.
500	152½	Dolomite; finely crystalline; buff.
503	153	Dolomitic limestone; skeletal; very coarse-grained; grey; very vuggy; composed mostly of echinoderms and bryozoa; weathered to a skeletal sand in places.
507	154½	Dolomitic limestone; skeletal-micritic; grey; contains irregular stringers and blebs of chert; mostly echinoderm fragments; occasional solitary coral present.
518	158	Limestone; oolitic; coarse-grained; brownish grey.
523	159½	Covered interval. Base is top of Banff Formation.

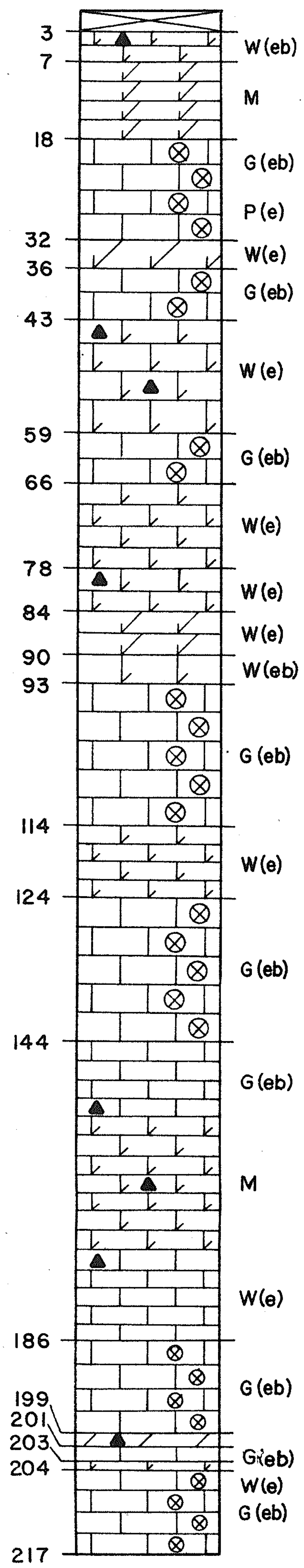
Total amount of section exposed - 658 feet (200½ m); 152 feet covered (46 m).

HIGHWOOD RIVER

50°24'N

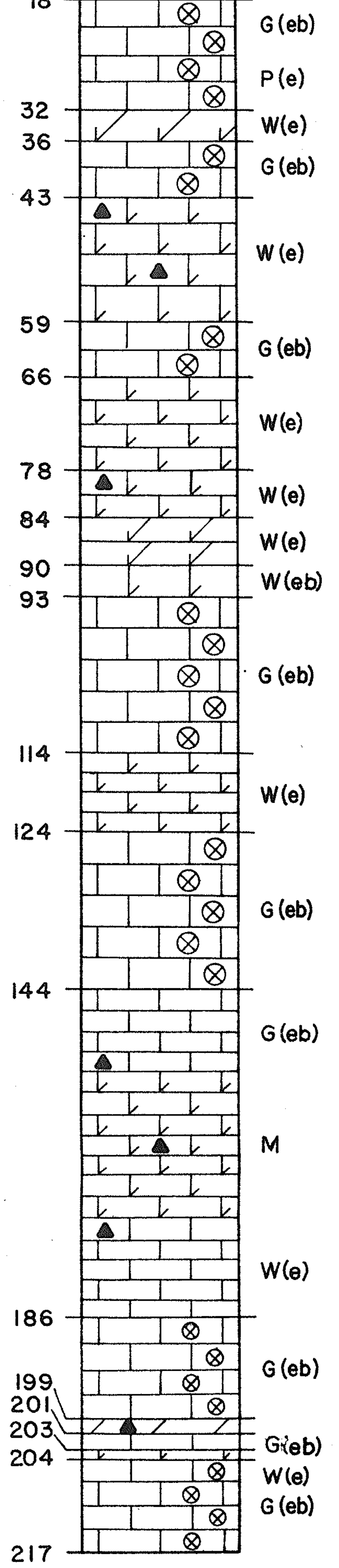
114°37'W

BASE OF MT. HEAD FM.



BASE OF EXPOSED SECTION

LEGEND:



BASE OF EXPOSED SECTION

LEGEND:

Limestone

Dolomitic limestone

Dolomite

Calcareous dolomite

Covered interval

Chert

Comprised mostly of echinoderms, with lesser amounts of bryozoans

Oolites

G — Grainstone

P — Packstone

W — Wackestone

M — Mudstone

eb — echinoderm - bryozoan

e — echinoderm

q — quartzose

o — oolitic

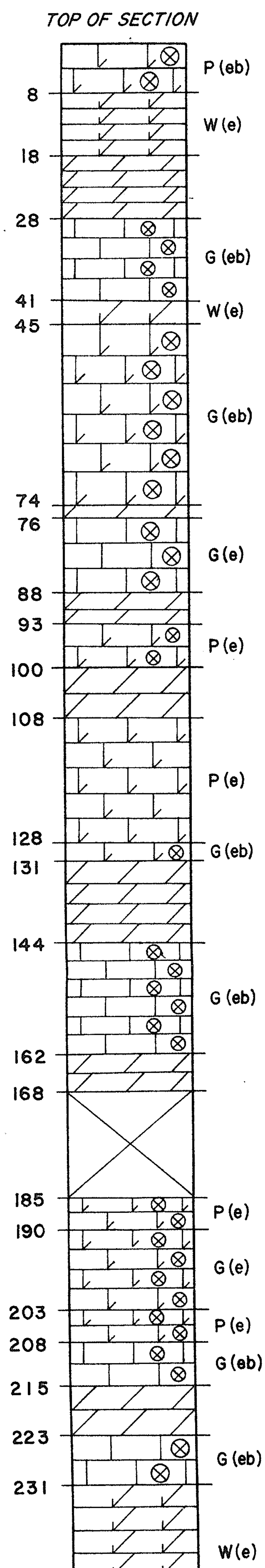
p — Pelletoidal

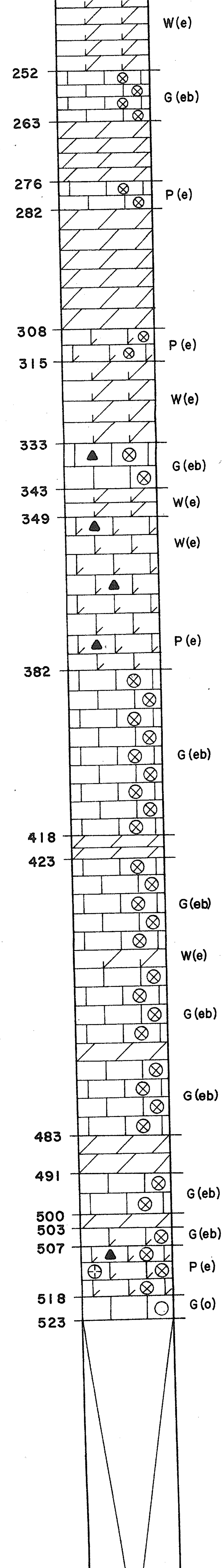
FIGURE 3

PIGEON MT.

51°3'N

115°13'W

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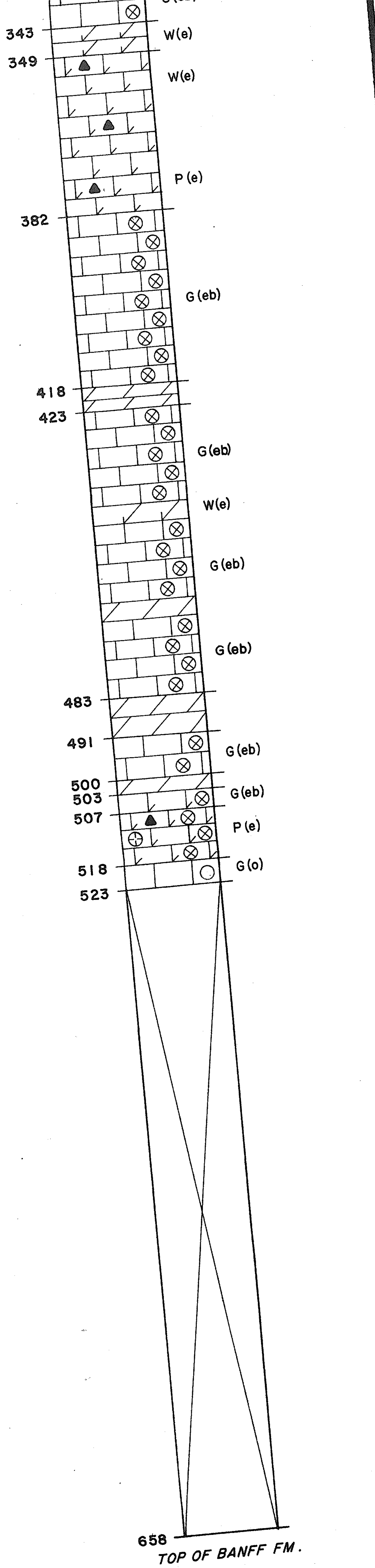
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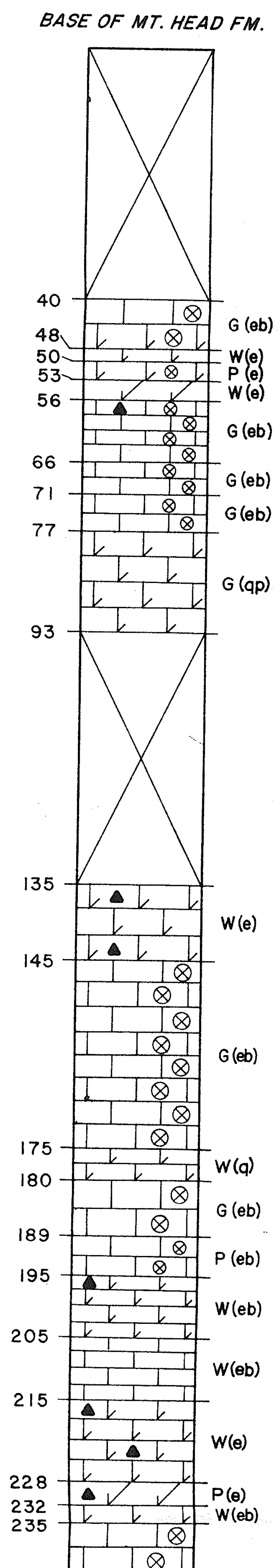
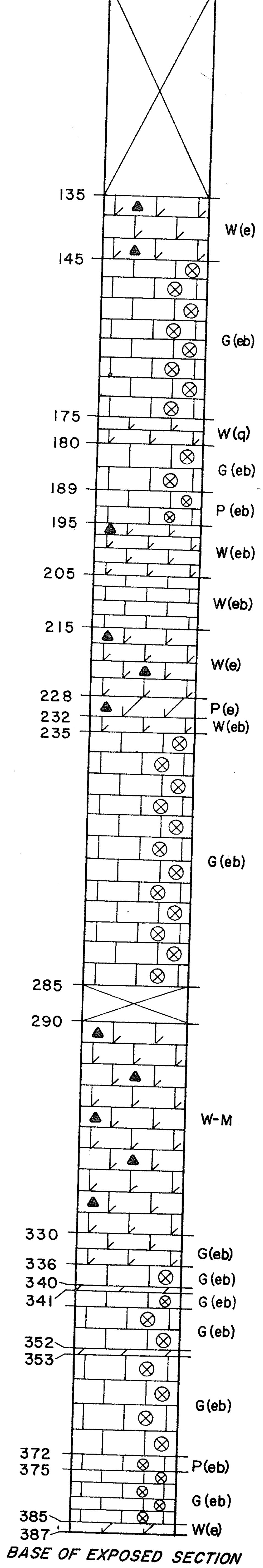
TOP OF BANFF FM.
FIGURE 5

PLATEAU MT.

50°12'N

114°32'W

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BASE OF EXPOSED SECTION

FIGURE 4