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DEPOSITIONAL ENVIRONMENTS AND DIAGENESIS OF PERMIAN SCAPHOPOD-BELLEROPHONTACEAN GASTROPOD-BEARING BEDS IN SOUTHWESTERN MONTANA

by

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TABLE OF CONTENTS

ABSTRACT

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Depositional Environments and Diagenesis of Permian Scaphopod-Bellerophontacean Gastropod-Bearing Beds in Southwestern Montana

Director: Dr. Donald Winston

In southwestern Montana, several sites of exposed Middle Permian rocks display a restricted molluscan fauna characterized by bellerophontacean gastropods and giant scaphopods which is believed to be indicative of shallow-water marine environments (eg. Yochelson, 1968; Bretsky and Birmingham, 1970).

Detailed examination of the vertical and lateral rock successions at five selected mollusc localities provided evidence that the shells were indeed deposited in near-shore sediments, but not necessarily as undisturbed *in situ* communities. Fossils appear 1) as constituents of a storm-beach deposit in a mixed carbonate-terrigenous sandstone-spiculitic chert succession; 2) as channel lag and coarse sediment in a dominantly terrigenous sandstone barrier bar system; 3) as storm lag in a very shallow-water restricted carbonate shelf or lagoon; 4) possibly as an *in situ* peritidal community at a site where carbonate mudstone, spiculitic chert, terrigenous sandstone and phosphorite create a complexly intertonguing sequence. Stresses inherent in these shallow-water habitats (susceptability to strong wave and current disruption, probably fluctuating salinity and recurrent exposure) apparently restricted the biologic community to a low-diversity, dominantly molluscan fauna.

Rocks which enclose the molluscs at these sites are impure dolomite mudstone and/or terrigenous sandstone. Associated lithologies include bedded chert, most of which is interpreted here as very shallow-water deposits,and phosphorite, which also shows textures and structures that probably formed in shallow water. The phosphorite may have originated in a nearby environment that provided a toxic barrier to faunal migration. At two localities nodular chert retains suggestive remnant textures of evaporites that probably formed during early diagenesis in a supratidal sabkha. This is a significant westward extension of Permian evaporitic facies in Montana.

These marine sediments, which were deposited very near shoreline during a time of frequent sea-level fluctuation, experienced early subaerial alteration. That history is reflected especially clearly in fossil preservation. Shell molds formed by fresh-water dissolution of aragonite and subsequently filled with cements which show distinctive vadose-zone textures and with detrital material washed into the molds by downward-percolating waters. All carbonate, except a late blocky calcite cement, was dolomitized during early diagenesis.

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In addition, Jim Peterson shared his knowledge of regional Permian rocks and Stan Riggs, R.P. Sheldon, R.C. Douglas and others also offered their expertise. I am grateful to David Fountain who patiently urged and encouraged completion of this project.

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I owe a general thanks to all these and many others who helped me along the way.

INTRODUCTION

Purpose and Scope

In southwestern Montana Permian strata, beds at several localities are characterized by scaphopods and bellerophontacean gastropods and present some interesting questions:

1) Is this an assemblage of animals that lived together in a community, and if so what sort of community was it?

2) Is it instead a death assemblage concocted by physical processes which mixed shells during sedimentation or selectively preserved mollusc shells during diagenesis?

3) In either case, what combinations of sedimentary environment and diagenetic history created and preserved the molluscan association?

The scaphopod-bellerophontacean assemblage has already received recognition and comment in southwestern Montana (Yochelson, 1968) and elsewhere (see especially Bretsky and Bermingham, 1970) and is suspected to be a distinctive faunal reflection of restricted, shallow-water, possibly hypersaline marine environments. Because of the molluscs' connection with unstable physical conditions and their frequent numerical dominance in rocks where they occur (Yochelson, 1968; Bretsky and Birmingham, 1970), I was interested in pursuing a study of these animals as a community of opportunistic species (Sanders, 1968; Slobodkin and Sanders, 1969; Levinton, 1970; Valentine, 1971; Alexander, 1977). Evidence of energetic sediment and shell transport in three of the five localities refocused attention away from that community approach and highlighted the importance of interpreting the depositional environments. Extreme variation in quality and method of preservation made statistical analyses of the fossils of questionable value, but also provided the opportunity to unravel a fascinating and complex diagenetic history that eventually led to a better understanding of conditions soon after burial and to the unexpected conclusion that all the localities had experienced a remarkably similar sequence of diagenetic events regardless of their specific environments of deposition or original lithologic characteristics.

In the final analysis, the fossils were used largely as a catalyst in this study, leading me to their final resting places, underscoring their rather unstable ancient marine habitats, but giving up only a few secrets about the living communities. The emphasis of my work evolved toward interpreting paleoenvironments of deposition and diagenesis.

Field and Laboratory Procedures

From the molluscan localities described by Cressman and Swanson (1964), Yochelson (1968) and McLellan (1973), I chose five for section measurement, detailed description and sampling (Fig. 1). Sites were selected to obtain maximum geographic dispersion in southwestern Montana and the best possible preservation of fossils.

Four large blocks from Cedar Creek containing silica-filled fossil molds in dolomite matrix were etched in formic acid. Orientation, number and condition of fossils were observed after partial etching and

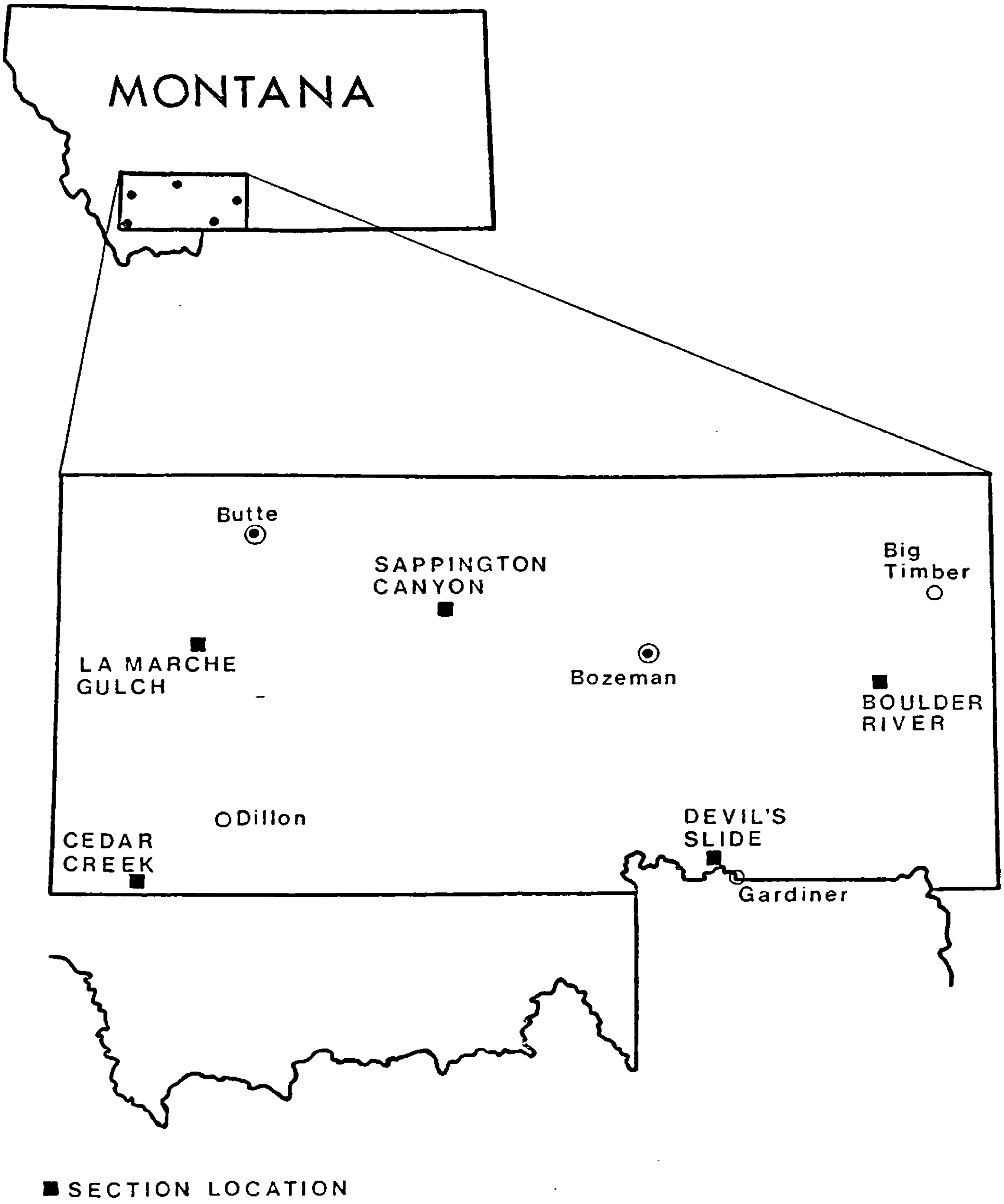


Figure 1. Location of measured sections in Southwestern Montana.

the fossils and insoluble residues were sorted and examined with a binocular microscope after complete dissolution of the carbonate. Blocks from the other localities were similarly treated but those fossils were not silicified so the process yielded no comparable information about the faunal remains at these sites.

Most of the laboratory work consisted of petrographic analysis of polished slabs and thin sections. Slabs were etched with hydrochloric or acetic acid and studied with a binocular microscope. With varying success, selected slabs and thin sections were stained with potassium ferricyanide and alizarin red-S (procedure in Dickson, 1965) or alizarin red-S only (procedure in Friedman, 1959) in an attempt to distinguish ferroan carbonate and differentiate calcite from dolomite. X-ray analyses were performed when petrographic methods were insufficient to determine mineralogy, especially on phosphatic and impure micritic rocks. A few selected chips were observed under a scanning electron microscope.

CHAPTER 1

DEPOSITIONAL ENVIRONMENTS

Regional Stratigraphic Setting

Permian sedimentary rocks in the west central United States are a variety show of geologic oddities including thick sequences of phosphate rock, chert and evaporites with notoriously abnormal faunal assemblages. Luckily, these oddities and the presence of phosphorite ore, oil and uranium attracted the attention of the U. S. Geological Survey and others. Their extensive studies of the physical stratigraphy of the Phosphoria Formation and correlative Permian rocks in Montana, Wyoming, Idaho, Utah and Nevada provide a solid background for more detailed research (see especially McKelvey et al., 1959; Sheldon, 1963; Cressman and Swanson, 1964; Sheldon et al., 1967; McKee et al., 1967; Swanson, 1970; Peterson, 1972, 1980a, 1980b).

Figure 2 is a generalized lithofacies map of Permian rocks in the west central United States, showing major tectonic elements, the approximate position of the paleoequator, and the approximate maximum extent of the Phosphoria Sea, a shallow marine embayment which hosted deposition of the Phosphoria rock complex (terminology from Yochelson, 1968).

Stratigraphy and nomenclature of the Phosphoria and related rocks were summarized by McKelvey et al. (1959), Sheldon (1963), Cressman and Swanson (1964) and McKee et al. (1967). Nomenclature used in this report is adapted from McKelvey et al. (1959), Peterson (1972), and McClellan (1973). The Phosphoria rock complex is broadly divisible into three

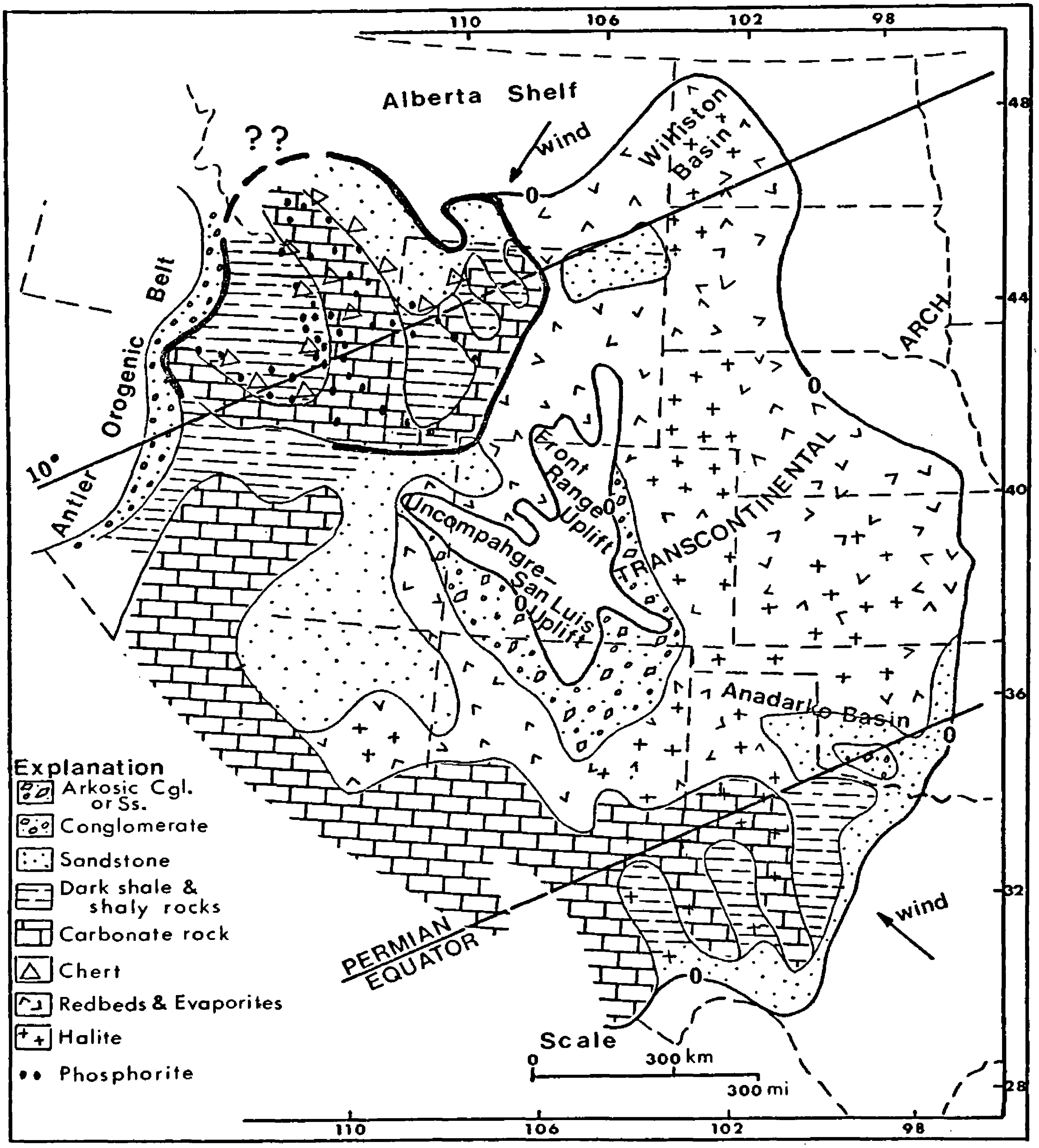


Figure 2. Generalized lithofacies and tectonic map of Permian rocks in west central United States. Heavy black line indicates the approximate maximum extent of the Phosphoria Sea. (Adapted from Peterson, 1980a, 1980b; Scotese et al., 1979; and Sheldon, 1963).

major facies which correlate with the major stratigraphic divisions: 1) western basinal cherts, mudstones and phosphorites (Phosphoria); 2) northern shelf sandstones shed off an exposed land mass in Montana (Shedhorn Sandstone); and 3) central, southern and eastern shelf carbonates (Park City) (Figs. 2 and 3). A warm, low latitude position and perhaps pervailing wind direction off the continent (eg. McKelvey _et al_., 1959; Sheldon, 1963; Cressman and Swanson, 1964; Peterson, 1980a, 1980b) created a hot, dry climate and left red beds and evaporites to mark the easternmost (continental) limit of the Permian marine transgression. Deltaic deposits have not been identified, indicating that rainfall was insufficient to establish permanent rivers.

Oceanward (now westward) on the shelf local basins and swells are recorded by thickness and facies changes in the sediments in Wyoming and eastern Idaho (Peterson, 1980b) and southwestern Montana (eg. Cressman and Swanson, 1964, pl. 25; Swanson, 1970, Fig. 172). On the western side of the embayment Permian rocks thicken across the Paleozoic hinge line and become dominantly dark chert, mudstone.phosphorite and carbonate. Upwelling currents at this western (oceanic) margin have been postulated as the source of phosphate and silica which appear so abundantly in the rocks (McKelvey _et al_., 1953 is probably the earliest discussion of the upwelling theory applied to Phosphoria rocks). The Phosphoria Sea was probably at least partially enclosed on its western margin by a highland variously attributed to activity along a late northern extension of the middle Paleozoic Antler orogeny (eg. Stevens, 1977; Peterson, 1980a) or to a separate late Paleozoic Humbolt orogeny (Ketner, 1977).

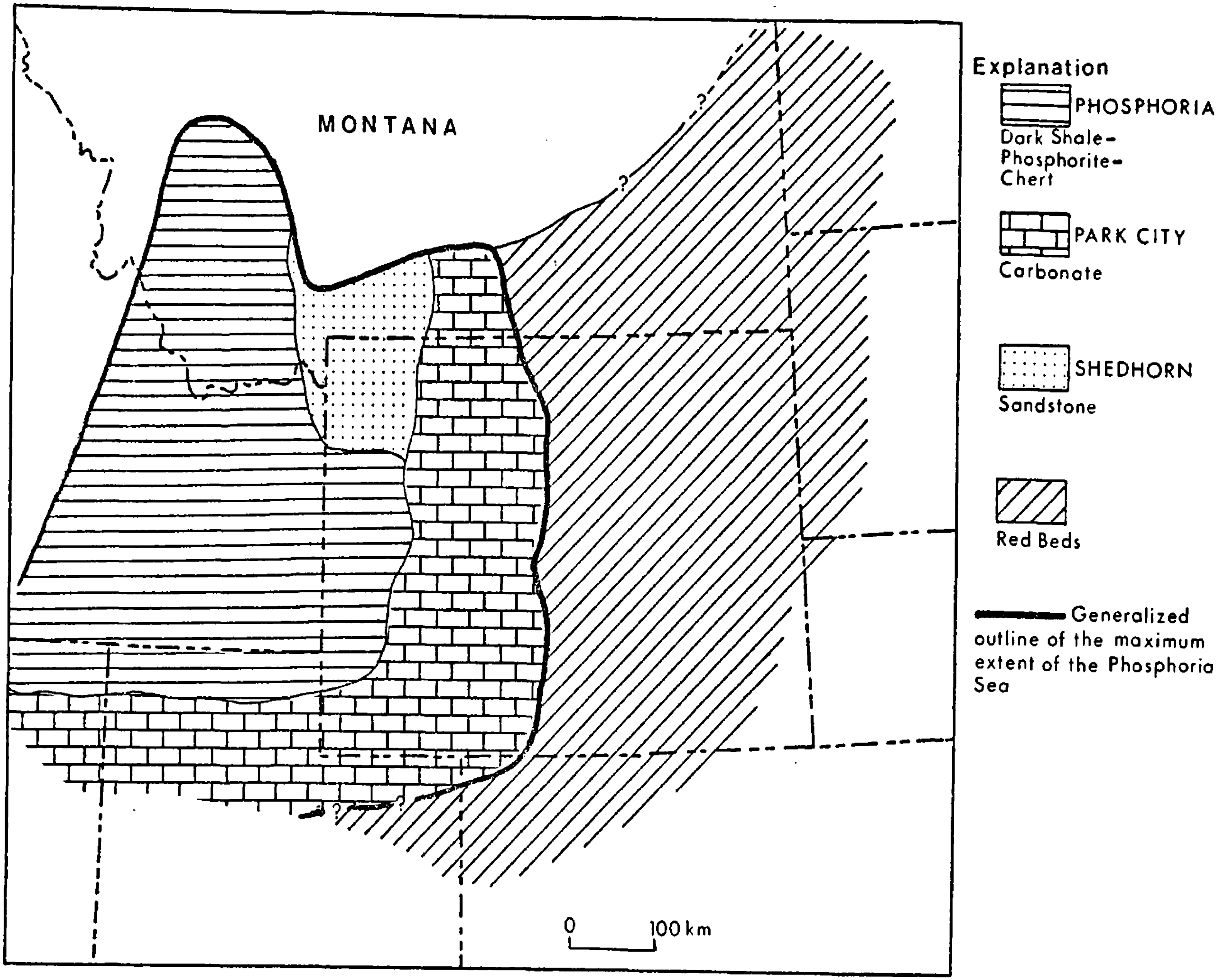


Fig. 3. Dominant facies patterns of Middle Permian age rocks, Phosphoria rock complex and related strata (modified from Sheldon, 1963).

The regional stratigraphic pattern is well-defined by dominant lithologies, but actually various facies shifted back and forth, apparently in response to constant sea level, chemical and/or topographic changes, and left a very complex record of interfingering rock types. My study sites in southwestern Montana are situated along the margin of this sea where water level fluctuations and the migration of varied near-shore environments left relatively thin sequences of intricately intertonguing lithologies with very rapid lateral and vertical facies changes. Figure 4 demonstrates the general east-west facies changes and the terminology adopted by Peterson (1972) and McClellan (1973) to accommodate the thin intertonging lithologies in this area. They assign all Permian rocks in southwestern Montana to the Phosphoria Formation and give member or tongue status to major lithologic units within that formation.

While these anomalous sediments accumulated in the Phosphoria Sea, biologically restrictive conditions there also resulted in a fauna which is notable for its lack of fusulinids and cephalopods, creatures generally used as time-correlative fossils for the Permian System worldwide. Most of the fossils examined by Yochelson (1968) in his survey of available U. S. Geological Survey collections from this area were common, long-ranging genera of Middle Permian age. Consequently, stratigraphic correlations across the western United States have necessarily been based primarily on lithologic relationships. Recent work with conodant and brachiopod correlations (eg. Wardlaw and Collinson, 1979; Wardlaw, 1980) may finally provide a biostratigraphic framework for these rocks.

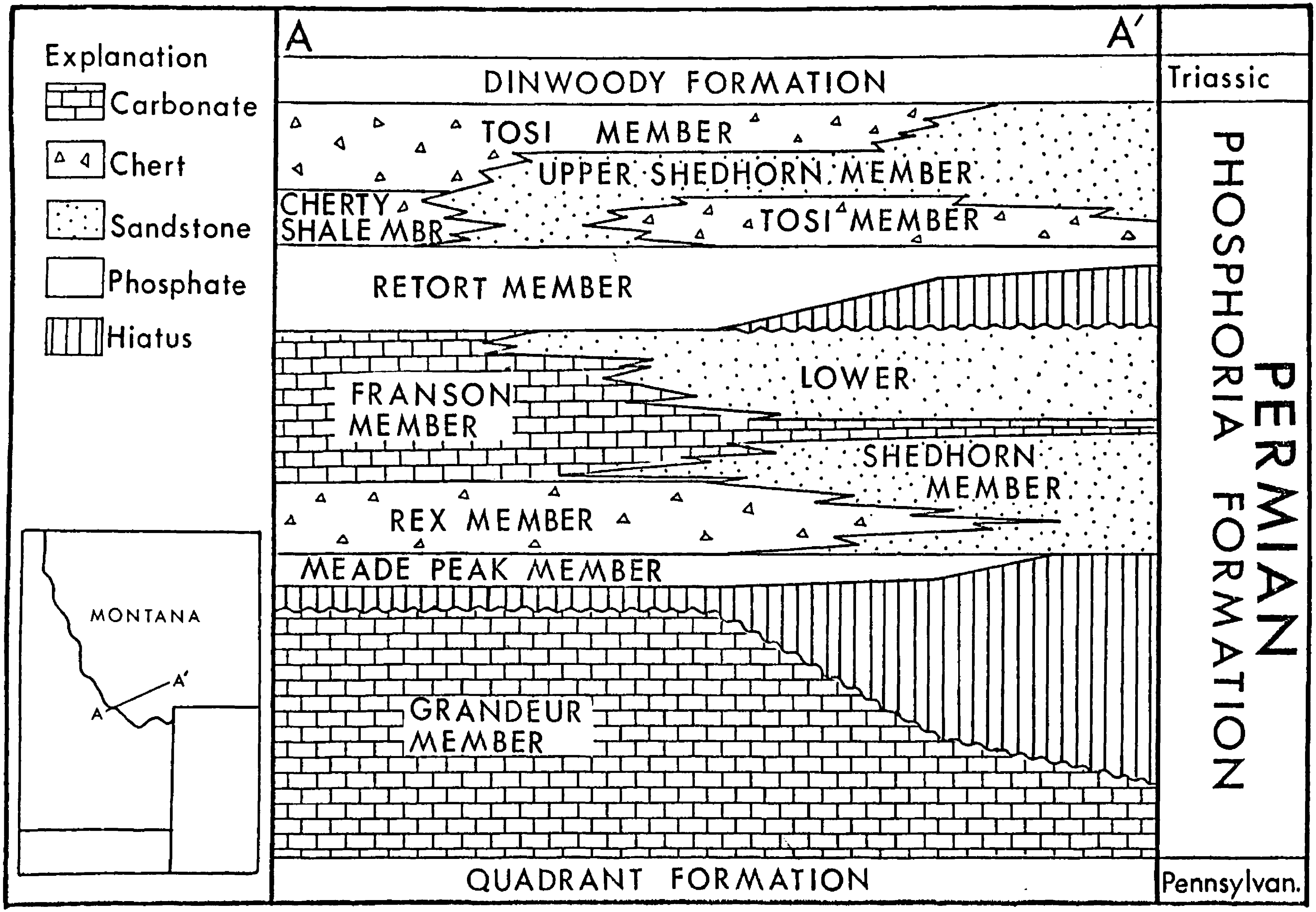


Fig. 4. Stylized cross section through Permian rocks in southwestern Montana showing intertonguing relationships and revised stratigraphic nomenclature (modified from McLellan, 1973).

The molluscs of this study are among the long-ranging fauna and occur literally from the base to the top of the sections. Except for the observation that at each locality the scaphopod-bellerophontacean fossils are usually restricted to a single bed or group of closely spaced, similar beds, there is no reason to believe that they could be used to delineate a time zone within these Middle Permian strata. At the five localities of this study, the molluscan fauna occurs in the Lower and Upper Shedhorn Sandstone, in the Franson Member and in a tongue of what is probably the Ervay Member of the Park City (a carbonate unit commonly found above the Upper Shedhorn Sandstone in Wyoming), and in an undesignated unit above the Pennsylvanian sandstone. On the basis of his conodant and brachiopod studies, Wardlaw (1980) placed the stratigraphic units listed above in early to late Wordian (Middle Permian).

Descriptions and Interpretations of Sedimentary Rocks by Locality

General Statement

This study was directed specifically toward understanding the Middle Permian depositional environments in which the molluscs lived and those where they were finally deposited. Therefore, the stratigraphic sections are limited to rock units most likely to have been contemporary adjacent facies with the fossil-bearing rocks. Section bases were picked at the first erosional unconformity or other obvious surface of non-deposition below the fossils. At Boulder River and Devils Slide this was the conglomerate at the Pennsylvanian-Permian boundary and at La Marche Gulch

North it was an intraformational conglomerate. Both Cedar Creek and Sappington Canyon sections begin at a chert-sandstone boundary because at Cedar Creek it is an undulating erosional contact that marks a distinct facies change and at Sappington Canyon there is a thin, discontinuous, laminated crust at the boundary which appears to be a subaerial exposure feature.

Where possible, upper limits were also picked at unconformable surfaces. The Cedar Creek and La Marche Gulch North sections end above subaerial exposure surfaces at the top of the fossiliferous dolomites (a few meters of overlying sediments were measured at these localities to demonstrate the change in sedimentation after the hiatus). At Sappington Canyon measurement was completed above an intensely burrowed zone which accompanies a lithologic change from sandstone to siliceous dolomite and probably represents a period of non-deposition or very slow sedimentation. It lies above the fossiliferous zone and provided a reliable upper marker all along strike at that locality. Lack of well-exposed outcrop terminated upper measurements at Boulder River and Devils Slide.

1. Cedar Creek

Three partial sections within the Franson Member (Fig. 5a and Appendix Ia) were measured along strike over a distance of about 250 m to demonstrate vertical and lateral variation in bedding, lithologies and thickness of the rock types at Cedar Creek. The middle section is generalized in Figure 5b.

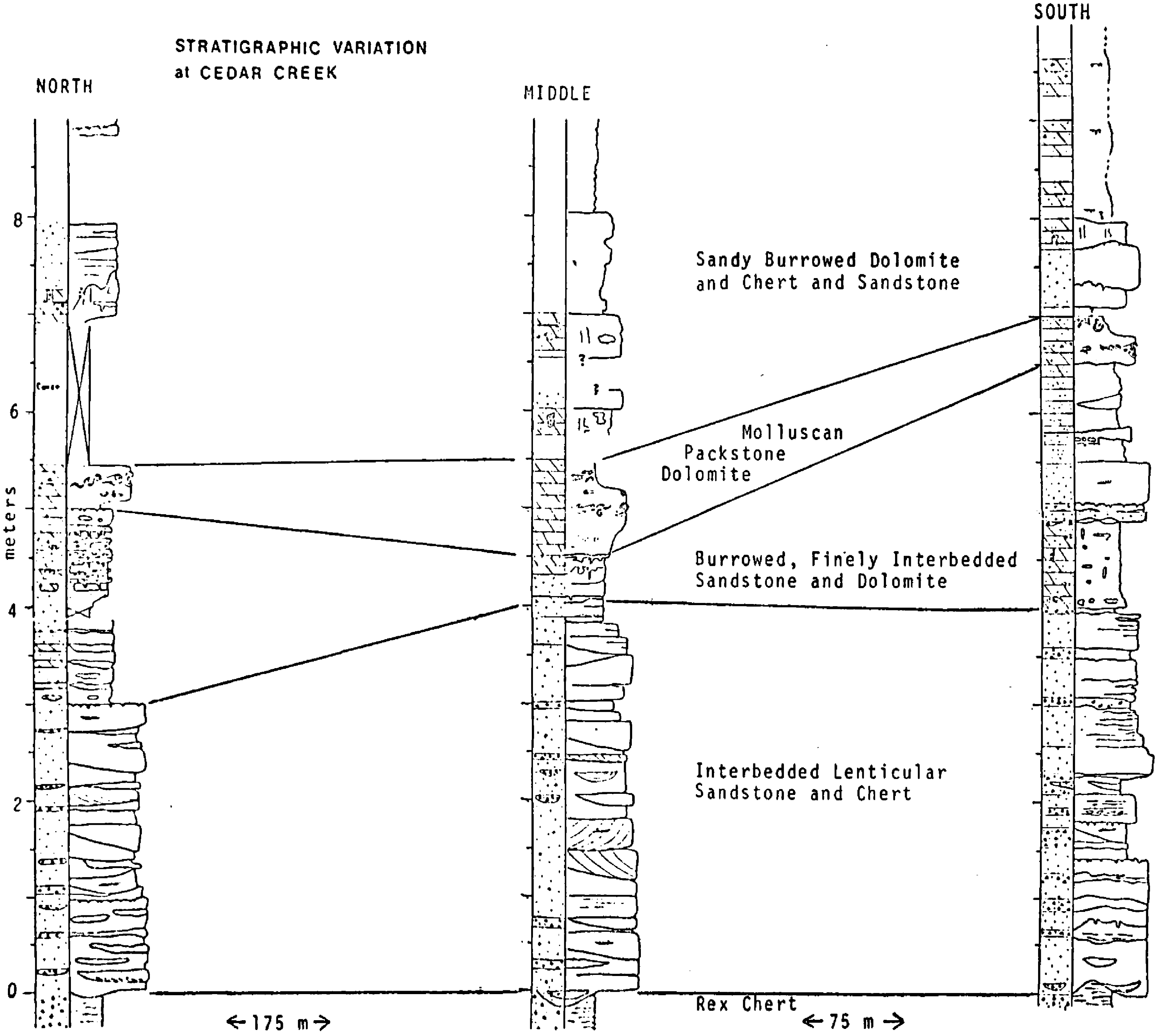


Figure 5a. Three partial sections measured at Cedar Creek.

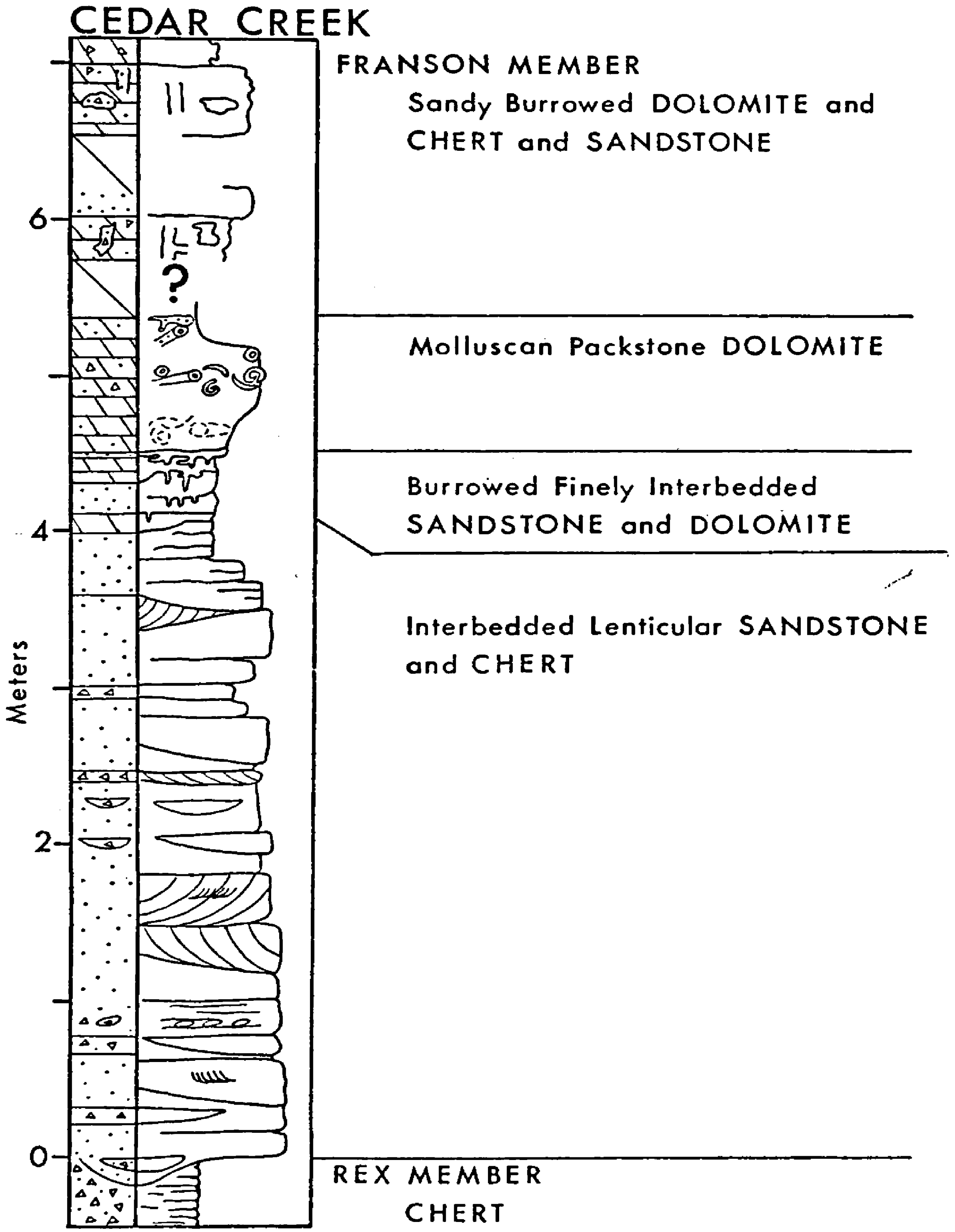


Fig. 5b. Partial stratigraphic section showing the mollusc-bearing rocks and related strata, Cedar Creek (generalized from Appendix Ib).

a. Rock descriptions:

Chert. Immediately below the base of the partial section (Fig. 5), bedded chert of the Rex Member is fairly well exposed. Very thinly horizontally laminated, structureless or mottled white, gray and brown chert at the top of the Rex forms wavy beds generally less than 5 cm thick that are discontinuous along strike over a few tens of cm to 1 m. In thin section the chert is a combination of microcrystalline quartz, chalcedony and megaquartz. Some beds contain abundant relict sponge spicules and/or scattered euhedral dolomite rhombs. Near the Franson contact many chert beds are sandy and a few beds are actually cherty, fine-grained terrigenous chert-phosphate-quartz sandstone. The boundary between these bedded cherts and overlying interbedded lenticular chert and sandstone undulates with up to1m of relief. It is characterized by load casts and channel-shaped, low angle truncations of chert beds, which demonstrate that the siliceous sediment was unlithified when overlying sediments were deposited.

Interbedded Lenticular Sandstone and Chert. There are two interbedded lithologies in this stratigraphic unit (Fig. 5 and Appendix Ia). The dominant lithology is light to medium brown terrigenous sandstone composed of grain-supported phosphate-chert-quartz sand. Grain size and sorting vary from lens to lens, but in general sand is very fine to medium grained and moderately or well sorted in lower beds, with fine- to coarse-grained, poorly-sorted lenses appearing more frequently in the upper part of the interval. Silica is the most common cement and includes syntaxial quartz overgrowths, microcrystalline quartz and chalcedony. Poikolitic calcite and microcrystalline dolomite are common minor cements. Toward the top of the interbedded lenticular sandstone and chert is an interval of platy-bedded calcareous sandstone that is similar in composition, but locally coarser than the underlying sandstone and contains more carbonate and less silica cement (Fig. 5 and Appendix Ia). It is about 1.5 m thick in the south section and it thins and disappears to the north (Fig. 5a).

Bedding takes the form of well-developed, trough-shaped sandstone lenses up to 50 cm thick with crosscutting concave lower margins. Lower sandstone lenses are somewhat thicker (5 to 50 cm) than upper ones (2 to 20 cm), most are much less than three meters long, and they overlap and truncate each other along strike (Fig. 5). Individual lenses cannot be correlated between sections.

Although sedimentary structures within the sandstone lenses are not well preserved, small ripple crossbeds and low- to moderate-angled medium crossbeds (5° to 20°) are recognizable and appear to be the dominant sedimentary structures. Medium crossbeds in crosscutting trough-shaped sand lenses record migration of lunate megaripples (Clifton et al, 1971). Upper surfaces of many lenses are very rough (Fig. 6) and a few retain traces of shallow burrows. These intensely burrowed upper surfaces show that sand transport ceased periodically and that deposition was episodic.

The other major interbedded lithology contains a larger component of authigenic silica and ranges from nearly pure chert to very cherty terrigenous sandstone. Terrigenous chert-phosphate-quartz sand grains and rare tiny silicified crinoid ossicles usually float in a matrix of authigenic silica (microcrystalline quartz, chalcedony and blocky megaquartz) which contains relict sponge spicules that are best recognized

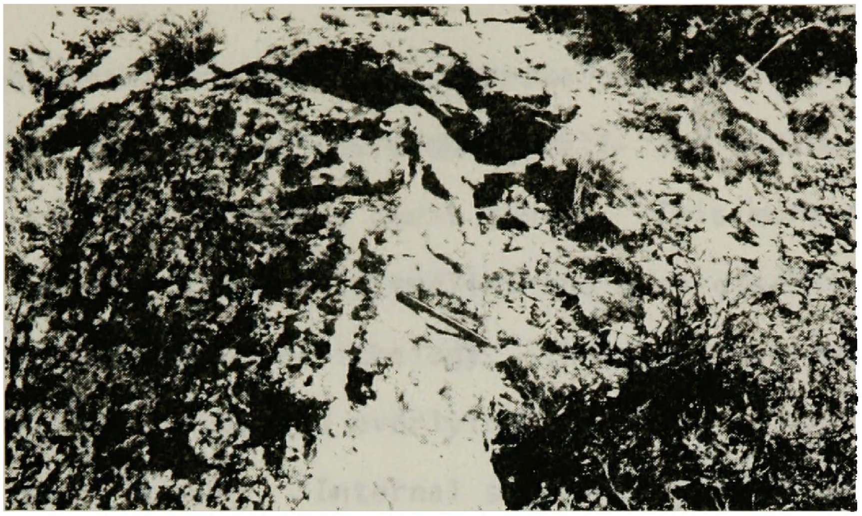


Fig. 6. Very rough (burrowed?) upper surface of a sandstone bed of the interbedded lenticular sandstone and chert rock type (pen for scale).

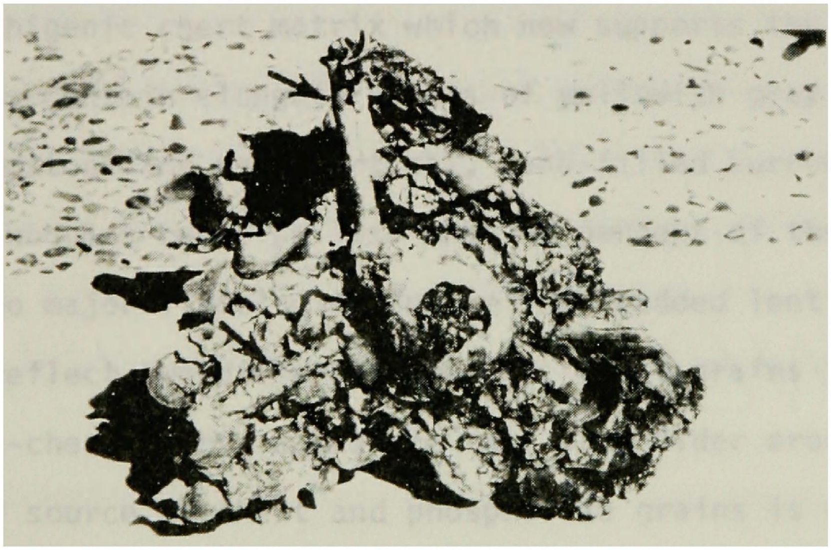


Fig. 7. Partially acid-etched block (about 30x20 cm) of molluscan packstone dolomite. Note the unsorted texture and mixture of whole and broken shells. The pelecypod shell in the middle of the block is worn through at the center. Two giant scaphopod shells are alligned roughly parallel to bedding (arrows).

by their phosphatic canals. Terrigenous sand grains are in grain support where they define individual small- and medium-scale crosslaminae in crossbedded sandy chert lenses. This more spiculitic, siliceous lithology occurs in generally smaller and more discontinuous lenses than the terrigenous sandstone lithology. The siliceous lenses are commonly wavy and discontinuous, and overlying sandstone appears to have produced load structures locally. Internal sedimentary structures are well preserved where sandy laminae accent crossbeds. Medium-grained sand in the crosslaminae is contained within a cherty rock which must have been deposited as very spiculitic, medium to fine-grained sand with somewhat coarser terrigenous sand laminae. Spicules apparently recrystallized to form an authigenic chert matrix which now supports the sand grains. A few chert lenses contain elongate clasts of yellowish gray, silicified dolomite mudstone and rare vertical, sand-filled burrows. Chert beds, lenses and nodules comprise less than 40 percent of the total rock.

The two major lithologies in the interbedded lenticular sandstone and chert reflect two different sources. Most grains in the terrigenous phosphorite-chert-quartz sandstone came from older eroding rocks. The most likely source of chert and phosphorite grains is older exposed Permian rocks (Cressman and Swanson, 1964; Shepherd, 1971). Quartz sand probably records erosion of earlier Paleozoic, especially Pennsylvanian, strata (Cressman and Swanson, 1964; Shepherd, 1971). The spiculitic, siliceous rock also includes some terrigenous sand but it must have originally contained a large proportion of more locally derived sand-sized sponge spicules. In other words, both lithologies were deposited as sands, but one was composed primarily of grains from eroding rocks and the other was composed primarily of grains from a relatively local, biological source.

Burrowed, Finely Interbedded Sandstone and Dolomite. Discrete, but very discontinuous, whisps, lenses and interbeds of sandy dolomite mudstone and very fine- to coarse-grained phosphorite-chert-quartz sandstone characterize this rock type. The fine scale of individual strata (mm to cm thick and cm to 1 m long) contrasts sharply with the underlying rocks. Vertically and horizontally branching, sand-filled burrows about 0.5 cm in diameter and less than 5 cm high are most easily distinguished in the dolomite. This bioturbation did not destroy all the other sedimentary structures, although it may be responsible for the rarity of well-preserved horizontal laminae in the dolomite mudstone. Sands preserve ripple crosslaminae and small scour channels. There are also rare flaser beds and wavy and planar beds. Graded coarse sand-to-dolomite mud beds reflect a depositional system that alternated between high energy bed-load transport and deposition and quiet suspension-load settling.

The thickness of this rock type varies from about 0.5 m to 2.5 m in the three measured sections (Fig. 5a). A poorly developed fining-upward sequence (dominantly sandstone to dominantly dolomite mudstone) at the middle and south sections is accompanied by increasing bioturbation upward. The south section contains anonomously thick planar and lensy sandstone beds and is less dolomitic and also less bioturbated than the other sections (Fig. 5a and Appendix Ia).

Molluscan Packstone Dolomite. A mostly unsorted molluscan grainstone/packstone bed appears abruptly above the unfossiliferous dolomite and sandstone (Fig. 5 and Appendix Ia). Much of the deposit is a chaotic mixture of unsorted sand- to gravel-sized fossil hash in a matrix of finely crystalline, vaguely pelletal dolomite with a few percent sand, silt and clay. Many of the larger fossils are preserved in locally bifurcating lenses (less than 0.3 m by 1 m) of shells which are in grain support. Most fossils which have long axes are oriented parallel with bedding and locally directionally oriented (Fig. 6). In two places, bedding-plane accumulations of scaphopods that must have been deposited in low spots lie radiating from a central area like spokes on a wheel.

The condition of the fossils varies widely. Although some shells are nearly perfectly preserved, most have been broken and worn thin in spots, recording time spent in a turbulent environment (Fig. 7). Pelecypod shells are mostly disarticulated. Some shells are bored or encrusted by worm tubes and it is possible that breakage was partly the work of predaceous fish (see Boyd and Newell [1972] for an example of this type of breakage in a similar Permian fossil zone in Wyoming).

The thickness of the fossiliferous bed varies in the three sections (Fig. 5a) and outcrop disappears and reappears along strike, suggesting that it may be distributed as discontinuous lenses along a single stratigraphic horizon.

The actual contact between the fossil bed and overlying rocks was covered, but the first observed overlying rocks are unfossiliferous sandstone, sandy burrowed dolomite and cherty dolomite which were in a different stratigraphic order at each section.

b. Interpretations of rock types:

Chert. Cressman and Swanson (1964) calculated that siliceous sponge spicules could have provided a large enough source of biogenic opaline silica to account for all the chert in the Phosphoria rocks. They also summarized information available at the time on the transformation of individual sponge spicule grains to chert rock by contemporaneous dissolution of opaline silica and precipitation of quartz (see Blatt *et al*., 1980, for a more up-to-date review of that process). The Permian localities in this study are among those investigated by Cressman and Swanson and they do, at least locally, contain abundant relict remains of sponge spicules. The Rex chert beds at Cedar Creek were probably originally composed dominantly of sponge spicules with varying amounts of impurities, especially quartz sand and silt. Dissolution of opaline silica sponge spicules provided a local source for quartz cementation.

There are, however, some continuing problems with this interpretation. Yochelson (1968) noted the remarkable absence of whole sponge fossils in Phosphoria cherts. It is now apparent that spiculites (beds composed primarily of sponge spicules or their recrystallized remains) very rarely contain complete sponges, and that deposits which do include complete sponges very rarely contain individual beds of spicules (Lane, 1981).

Cressman and Swanson (1964) rejected the possibility that sorting by physical processes created the beds of uniformly large spicules which they studied. More recent workers have re-evaluated the importance of sorting to spiculites. Beds composed primarily of siliceous sponge spicules have been reported in shoreline deposits of deltaic sequences (Cavaroc and Ferm, 1968), in the peritidal zone in and adjacent to rocks containing silicified evaporites (Chowns and Elkins, 1974), and in a sequence of shallow-water limestones just oceanward of coals and fluviatile channel sandstones (Lane, 1981). Either these siliceous sponges were tolerant of much more restrictive conditions than their modern descedents or the spicules were selectively transported into the shallow-water areas from a more normal marine environment. Cavaroc and Ferm (1968) and Chowns and Elkins (1974) suggest that the low specific gravity and small size (silt to fine sand) of sponge spicules allows them to be winnowed from the living communities and concentrated by waves and currents.

Previous environmental interpretations of Phosphoria spiculites have had to accommodate the living sponges' requirements for relatively clear water, moderate currents and normal marine salinity (Cressman and Swanson, 1964). This becomes a problem where the associated fauna is not characteristic of normal marine waters (see, eg., the fossils associated with the Rex and Tosi cherts as described by Yochelson, 1968). The examples of extremely nearshore spiculites cited above open up the possibility of reinterpretation of some of these Phosphoria beds. A few small crinoid ossicles were the only faunal remains besides disarticulated spicules observed in the uppermost beds of Rex chert at Cedar Creek.

These beds are therefore interpreted to be transported remains of a living community that was periodically winnowed by storm waves. The sponge community may have lived oceanward of the site where spiculites were deposited, in or near carbonate bioherms as described by McLellan (1973).

The intertonguing relationship of terriginous and spiculitic sands in the section immediately above the Rex chert suggests that siliceous sediments which became upper Rex chert beds were forming adjacent to, and contemporaneously with, the interbedded lenticular sandstone and chert rock type that overrode them. Perhaps chert lenses within the sandstones represent the coarsest (sand sized) fraction of these winnowed spicules. The Rex chert beds could be a finer (silt to fine sand) fraction that was deposited in quieter water seaward of the sand.

Interbedded Lenticular Sandstone and Chert. Migrating lunate megaripples, which deposited most of these sediments, are produced in the upper lower-flow regime (Simons and Richardson, 1963; Harms and Fahnestock, 1965). In marine nearshore environments they are characteristic of bar-crest sediments (Davidson-Arnott and Greenwood, 1976) or, more commonly, of tidal channel sediments (Davidson-Arnott and Greenwood, 1976). They are formed by highly asymmetrical breaking waves or by unidirectional currents generated by shoaling waves or tides (Clifton et al., 1971; Clifton, 1976; Reineck and Singh, 1975).

Burrowed upper lens surfaces testify to episodic depositional events that were separated by quieter periods that were long enough to permit extensive bioturbation. This means that these sand lenses formed during relatively uncommon high-energy events, most likely storms,and that they were either deep enough or otherwise protected enough to escape postdepositional reworking at the bed surfaces except by burrowing organisms. Storm events are more likely to be preserved in the rock record than bedforms created by fair-weather processes because they are cut to a greater depth and are therefore less susceptible to deep erosion and reworking by normal waves and currents (see, eg., Kumar and Sanders, 1976; Vos and Hobday, 1977; Kreisa, 1981).

Lack of current direction data and information about the large scale morphology of this rock type or of its original spatial orientation to the paleoshoreline leaves interpretation open to a number of possibilities. For example, Ball (1967) studied sand bodies of the Bahamas and Florida and concluded that medium scale ripples of the marine sand belt migrated only during storms. In the tidal bar belt, he noted that bar sands in slightly deeper water than the bar crests were burrowed, and probably also migrated only during storms. Spill-over lobes in both sand belts also contained storm-generated lunate megaripples.

Burrowed, Finely Interbedded Sandstone and Dolomite. The sediments in this rock unit reflect alternating deposition by sand moving in the lower flow-regime and by mud settling out of suspension. This alternation of processes is characteristic of tidal flats and the rocks have most of the sedimentary structures seen on mixed sand and mud tidal flats (Reineck and Singh, 1976, p. 358-359). Absence of flat mud intraclasts, mud cracks, birdseye structures or any other evidence of subaerial exposure suggests that these sediments were usually submerged, which is certainly likely if the rocks represent the seaward edge of a tidal flat where muds and sands interfinger. Thicker sands within this rock type, especially in the south section (Fig. 5a), might be tidal channel deposits, but exposure and preservation of sedimentary structures is too poor to allow positive identification. Again, alternate interpretations are possible. For example, similar intercalated, burrowed, silty-muddy sediments and sands can occur together in tidal deltas or lagoons, where sand is usually brought in by storms (Reineck and Singh, 1975, p. 351).

Molluscan Packstone Dolomite. The unusually coarse fossil grain size (for this sequence), mixed and unsorted nature of the deposit, absence of sedimentary structures and abrupt and unrepeated appearance all argue for a storm coquina interpretation. Texturally it resembles deposits left by modern coastal storms (eg. Ball *et al*., 1967; Maragos *et al*., 1973). This interpretation is strengthened by faunal evidence (Chapter 2) and the diagenetic sequence (Chapter 3).

Sandy Burrowed Dolomite and Chert and Sandstone. These sediments, with their variable lithologies and abundant burrows, filled in over and around the storm deposit recording continued complex migration of this mixed terrigenous and spiculitic sand-carbonate mud system.

c. Summary and environmental interpretation:

The partial section at Cedar Creek apparently records a progradational sequence. Restricted, shallow submarine spiculites (Rex Member) were overridden by a subtidal sand body (interbedded lenticular sandstone and chert) that represents higher energy deposition. A relatively lower energy mixed carbonate mud and terrigenous sand facies (burrowed, finely interbedded sandstone and dolomite) very likely records the marine edge of a prograding intertidal flat, or perhaps a sheltered subtidal zone behind the sand. A large storm abandoned a thick coquina of shells from mixed communities (molluscan packstone dolomite) on top of the burrowed, finely interbedded sandstone and dolomite. The storm deposit was eventually covered by burrowed sediments of mixed lithologies that probably represent a slight rise in sea level.

2. La Marche Gulch North

a. Rock descriptions:

Conglomeratic Sandstone and Dolomite. At the base of the partial section, measured within the upper part of the Park City carbonate (undifferentiated here into Grandeur and Franson, see Cressman and Swanson, 1964), discontinuous lenses of sandy burrowed dolomite separate two thin conglomeratic chert-quartz sandstones (Fig. 8 and Appendix Ib). In each conglomeratic bed pebble- to boulder-sized clasts, some of them identical to the underlying rock types, are mostly confined to a thin basal deposit with an uneven lower contact that partially truncates underlying beds. Each of these is overlain by finer grained, more dolomitic rocks.

Pelletal Wackestone Dolomite. A series of dolomite beds separated by thin siltstone partings is repeated at least nine times in eight meters of rock overlying the conglomeratic zone. Dolomite beds (0.4 to 2 m thick) appear to be tabular over the distance of individual outcrops, although comparison with other measured sections from this area by

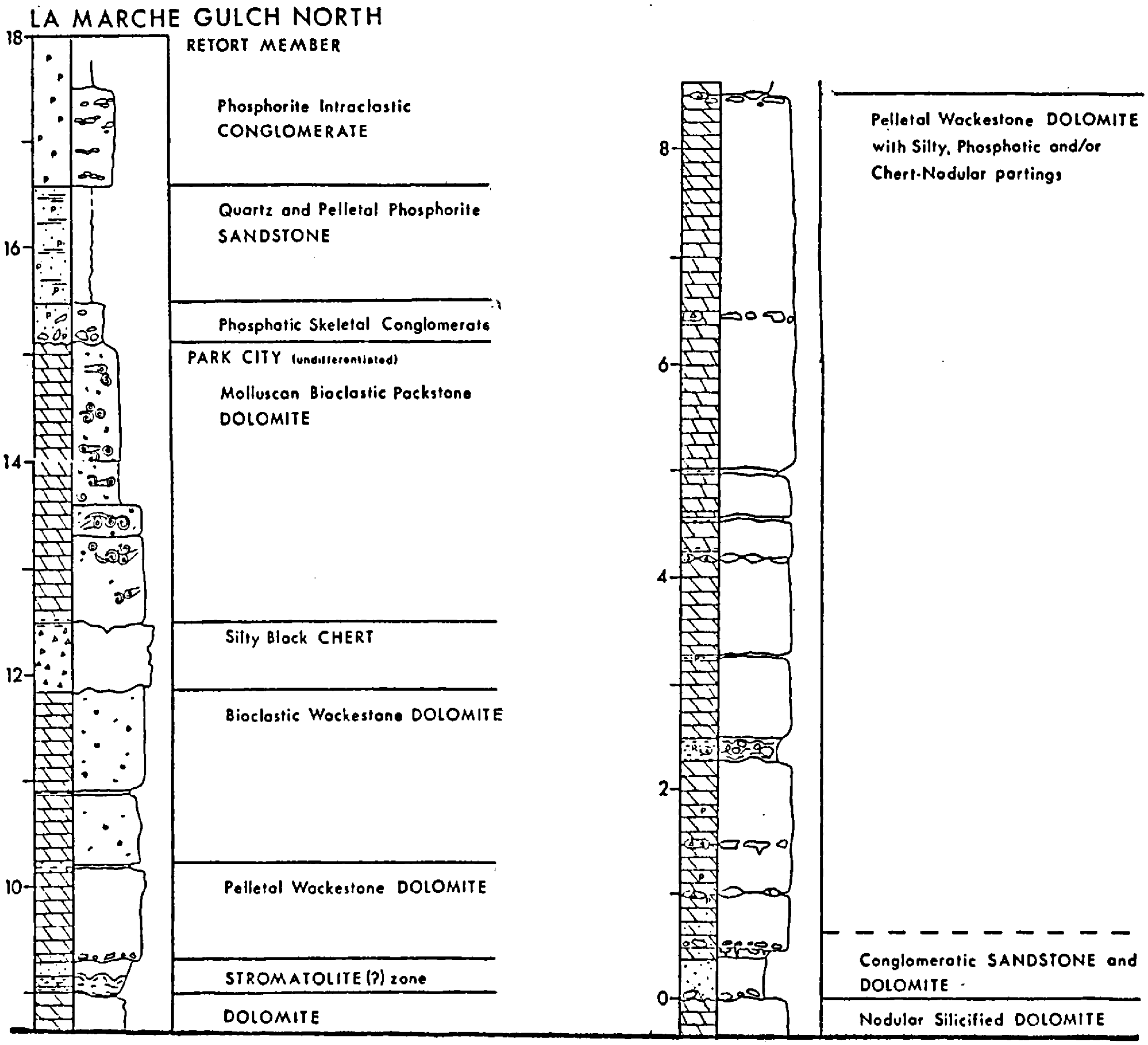


Fig. 8. Partial stratigraphic section showing the mollusc-bearing rocks and related strata, La Marche Gulch North (generalized from Appendix Ib).

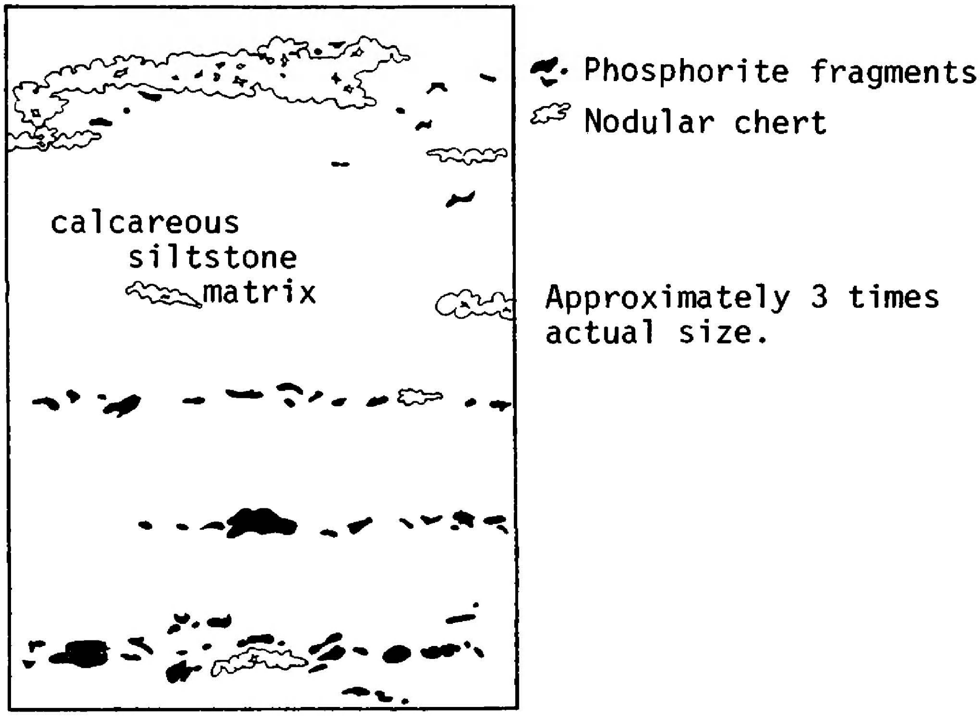
McLellan (1973) and Gosman and Peterson (in Cressman and Swanson, 1964) suggests that thicknesses of beds may vary considerably over larger lateral distances.

The medium-gray dolomite weathers to lighter gray and forms low cliffs or less resistant ledges. Relict pelletal texture is subtly visible in most thin sections (Fig. 9). Dolomite crystals within dark pelletal zones measure .0001 mm to .0005 mm. Outside these areas crystal size increases to .01 mm to .02 mm but scattered rhombs up to .05 mm are common, and large rhombs up to 0.1 mm encircle some pore spaces. Some rocks have a mottled and swirly (burrowed?) texture, but no other sedimentary structures remain, and fossil shells are also absent. Thin sections show up to a few percent scattered, very fine quartz sand and silt and scattered and locally concentrated phosphorite pellets and intraclasts.

Thin partings of dolomitic siltstone which contain varying amounts of fine-grained quartz sand, phosphorite pellets and intraclasts, and authigenic chert nodules separate the individual dolomite beds (Fig. 8). They are a few cm to a maximum of 20 cm thick and usually have narrow gradational contacts with surrounding dolomite beds. Except for the addition of large authigenic chert nodules, these siltstone partings are essentially very thin beds of the same materials which occur as impurities in the dolomite. Quartz silt with minor fine-grained sand and detrital mica are concentrated in wavy, millimeter-scale laminae.

Scattered throughout the lower dolomite beds, but most concentrated in silty partings, are fine sand-sized phosphorite pellets and angular

Fig. 9. Relict pelletal structure (darker circular patches) in dolomite of the pelletal wackestone dolomite rock type.



Approximately 3 times actual size.

Fig. 10. Diagrammatic representation of a silty parting zone of the pelletal wackestone dolomite rock type showing concentration of phosphorite fragments and small chert nocules.

phosphorite clasts (less than 1.0 mm to 1.0 cm long). Some pellets form grapestone-like clusters several mm in size.

Also concentrated within the silt laminae and at parting zones between the dolomite beds are small (up to about 1.0 cm diameter) white quartz nodules and large (up to 10 by 25 cm), silty black or mottled chert nodules. Small nodules are composed of tiny length-slow and length-fast chalcedony rosettes arranged in clusters elongated parallel to bedding (Fig. 10). Their bulbous rounded surfaces distort surrounding sediment and, in densely packed zones, individual nodules are separated from each other by thin partings of matrix and iron oxide-stained styolites. These characteristics demonstrate growth by displacive expansion into a soft matrix. Rounded to elongated larger chert nodules are usually mixtures of chert, chalcedony and blocky megaquartz (Fig. 11). Nodules are cemented by colloform growths of fibrous quartz with alternating layers of length-slow chalcedony (quartzine and leuticite--terminology from Folk and Pittman, 1971) and length-fast chalcedony, often brown with ultra-microscopic inclusions.

Brecciated Dolomite and Stromatolite (?) Zone. Dolomite with a peculiar internal texture overlies a chert nodule zone. Angular fragments of dark gray, sparsely fossiliferous dolomitized dismicrite float randomly or lie in grain support in a matrix of gray dolomicrite (Fig. 12). Dolomitization must have occurred after this texture developed because boundaries between clasts and matrix are indistinct. The unsorted angular texture of darker fragments suggests a breccia. About 10 cm of apparently undeformed gray calcareous quartz siltstone with fine wavy

Fig. 11. Photomicrograph of some large chert nodule textures showing fragments of sandy, silty microcrystalline quartz (right), overgrown by fractured, inclusion-rich colloform chalcedony. A fine overgrowth of chalcedony grading to blocky megaquartz fills the rest of the cavity.

= 1 mm

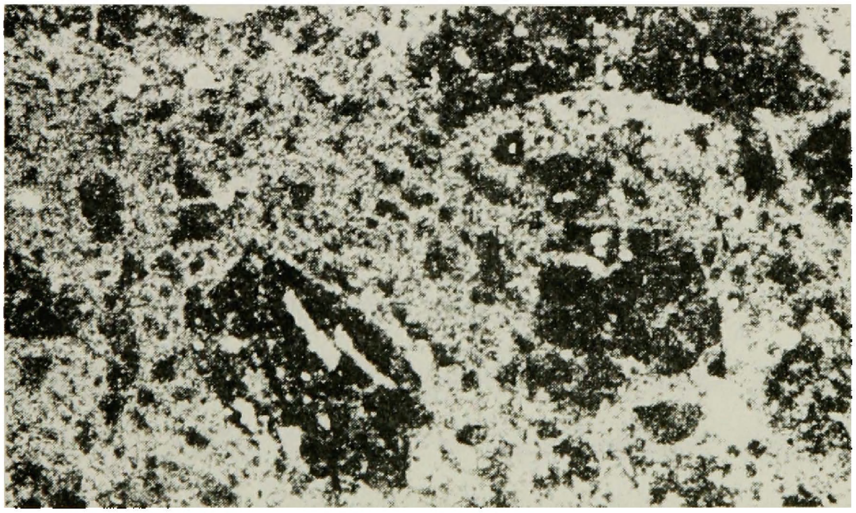


Fig. 12. Photomicrograph of brecciated dolomite rock type showing angular fragments (dark) in lighter matrix.

laminations fills in some minor rough topography on the brecciated dolomite. Brecciation therefore occurred before dolomitization and before burial. Above the siltstone lies 10 to 30 cm of very silty, sandy dolomite. The shape of the upper surface of this dolomite is convex-upward linked hemispheroids up to 15 cm across which resembles laterally-linked hemispheroidal stromatolites (Logan et al., 1964). Iron-oxide stained silt laminae at the surface and within the bed repeat the curved shape and flatten toward the base. There was solution along the silt laminae and it is difficult to directly assess the importance of that diagenetic process in the formation of the stromatolite-like structures. No algal or other biologic structures remain. The uneven upper boundary is filled in and capped by yellowish gray, very fine-grained sandstone. Up to 20 cm of dolomite breccia overlies the sandstone and this breccia grades upward to about 0.5 m pelletal wackestone dolomite.

Bioclastic Wackestone Dolomite. Fragments of gastropods, pelecypods and possibly ostracods appear here in a rock that is otherwise similar to the underlying dolomite. All the fossils are small (less than 0.5 cm long) and most are fragmented and poorly preserved.

Silty Black Chert. The base of this thick chert unit is characterized by lumpy protrusions (1.0 to 30 cm diameter) into the underlying dolomite. It lacks obvious layering or sedimentary structures; it is instead faintly to distinctly nodular and is chaotically crossed by fine white and gray mottles and veins giving it a curdled texture. Locally, angular dark fragments are cemented by a lighter colored matrix.

Microscopic examination also reveals chaotic authigenic quartz textures. Rounded or angular patches of microcrystalline quartz and tiny rosettes of quartzine, leutecite and chalcedonite grade into patches of megaquartz with up to mm-sized grains and cement growth textures (Fig. 13). Some of the microcrystalline quartz patches also have inclusion-rich, multi-layered colloform chalcedony overgrowths. Fractures in this chalcedony are healed by quartz and remaining cavities contain blocky megaquartz cement (Fig. 13). Cement overgrowths and fractures demonstrate that chert patches are the earliest silica form and that they were broken and recemented repeatedly. This chert is lithologically similar to chert nodules in the pelletal wackestone dolomite.

Molluscan Packstone Dolomite. Matrix rock in this unit is similar to the unfossiliferous dolomite below but the major difference is abundant large fossil molluscs. Sedimentary structures are not preserved and the rock has a generally unsorted texture. Smaller (less than 0.5 cm) fossils are distributed more or less randomly throughout but larger ones (up to several cm) tend to occur in discontinuous lenses (2.0 to 10 cm wide by less than a meter long). In these lenses large grain-supported fossils with rare geopetal fillings indicate that the mudstone matrix is a later addition to locally higher energy, winnowed sediments.

Orientation of the larger fossils provide some clues about the processes that deposited them. Pelecypods are disarticulated and oriented parallel to bedding. All scaphopods lie elongate in the plane of bedding, some are telescopically nested and directional orientation is common (Fig. 14). Disarticulated pelecypod shells and telescoped scaphopods as well as large pieces of shell fragments lodged inside the cavities of

Fig. 13. Photomicrograph of chaotic chert textures in the silty black chert rock type. Scale bar = .5 cm.

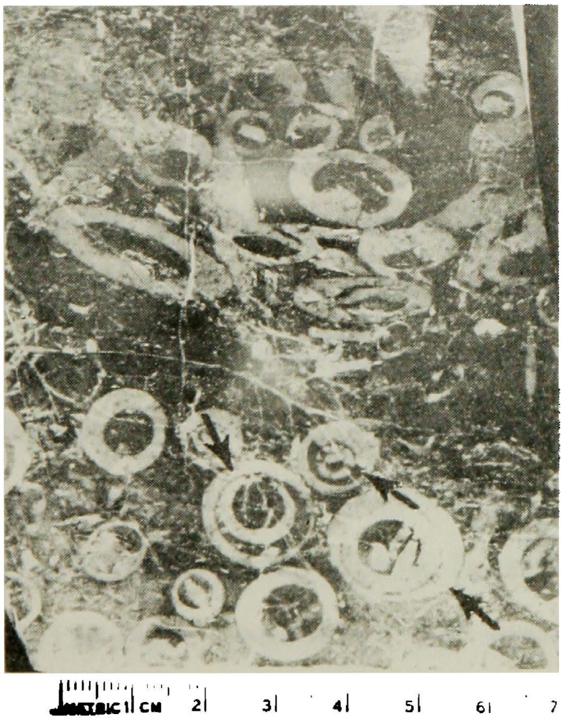


Fig. 14. Large grain-supported scaphopods in the molluscan packstone dolomite rock type. Note the parallel allignment and telescopic nesting of some shells (see arrows).

scaphopods and some gastropods, record transport of the shells after animal bodies had decayed and washed out. The energy regime required to move and orient these large shells was much higher than the normal mud-depositing one.

Retort Member Phosphatic Sediments. A few meters of these sediments were measured to demonstrate the dramatic lithologic change which followed carbonate sedimentation. A basal conglomerate of quartz sand, phosphorite skeletal fragments and dolomite clasts is overlain by pelletal phosphorite sandstone and intraclastic phosphorite sandstone conglomerate (Fig. 8). Poor exposure at the contact with underlying dolomite partially obscures what appears to be a truncating erosional boundary.

b. Rock type interpretations:

The sequence at La Marche Gulch (Fig. 8) presents a very different picture than the Cedar Creek rocks (Fig. 5). Lithologic contrast is significant; at La Marche Gulch clastics are much finer, include mica, and are not crossbedded. Chert is entirely different texturally; dolomite is more pelletal, has fewer impurities and is a more dominant rock type. At Cedar Creek lighologies interfinger on a fairly fine scale while the dominant type gradually changes, leaving the impression of several different interacting environments. At La Marche Gulch, at least on the scale of the available outcrop, each layer is laterally extensive, and significant small-scale interlensing was not seen. The carbonate-producing environment dominated but appears to have been periodically shut off or overwhelmed.

Conglomeratic Sandstone and Dolomite. These thin conglomerates overlie erosional surfaces and record initial deposition during or before the transgressive episode that eventually culminated in a carbonate-producing environment.

Pelletal Wackestone Dolomite. Very finely crystalline, pelletal dolomite with no clastic impurities except a little fine sand and silt and no preserved sedimentary structures probably originated as pelletal carbonate mud in a low-energy subtidal zone. Although a burrowing and pellet-forming fauna lived in the sediments, the environment was apparently not hospitable to even the most tolerant shelly fauna. The possibility that shells existed but were not preserved seems unlikely since a very similar dolomite a few meters higher in the section does contain fossils.

Scattered silt and fine quartz sand was probably mostly wind blown (fine grain size, random distribution) into the area and locally reworked (thin laminations). Preservation of laminated structure in the siltstone partings suggests deposition in a shallower intertidal or supratidal setting out of the range of extensive burrowing. Postdepositional solution played a part in the development of the siltstones, as evidenced by concentrations of iron oxides and other insolubles in sinuous, simple flaser type solution zones (terminology in Garrison and Kennedy, 1977) within and near the silty laminae, but there must have been an initial control on the distribution of solution planes, probably the increased porosity of already-existing silty laminae. Solution amplified lithologic variation by removing original carbonate from the siltier areas and also probably removed some of the dolomite adjacent to the siltstone partings, contributing to the gradational nature of the silt-dolomite contacts.

Speculation about the origin of the phosphatic component in the dolomite and siltstone also indicates shallow water. Angular clasts are very similar to material described as algal mat chips elsewhere (eg. Gill, 1973; Browning, 1973; Budros and Briggs, 1977). These chips form as the subaerially exposed intertidal mat drys and cracks and is reworked by waves. The fact that the material at La Marche Gulch is phosphorite instead of carbonate presents no real problem for the interpretation. Stromatolitic phosphorite described in Indian Precambrian rocks (Banerjee, 1971) demonstrates that algae may play a role in primary phosphogenesis or, alternatively, that very early chemical replacement may occur in this environment.

Certain characteristics of chert nodules in these beds compare closely to nodules described in sediments of Precambrian to Pleistocene age which have been interpreted as mineralogically replaced evaporites (eg. Folk and Pittman, 1971; Siedlecka, 1972; Chowns and Elkins, 1974; Milliken, 1979; Young, 1979). Size, shape and evidence of displacive growth create a texture identical to growth textures of some nodular anhydrite (eg. Shearman, 1966) seen in recent sabhka sediments. Even more convincing are siliceous nodules within silty dolomite a few meters below the base of the measured section in this study. These are practically identical to ones figures by Brown (1973, p. 47), Chowns and Elkins (1974, p. 890) and Young (1979, p. 290) and interpreted to be silica-replaced evaporites. Length-slow chalcedony in the nodules may indicate evaporite replacement (eg. Folk and Pittman, 1971) although the significance is not universally accepted (eg. Chowns and Elkins, 1974). Chaotic and internally brecciated textures are interpreted to be the silicified remains of deformation which occurred during evaporite replacement and/or dissolution.

Dolomite Breccia and Stromatolite (?) Zone. This zone of breccia and stromatolitic structures could be interpreted as a remnant sabhka interval where silty calcareous stromatolites formed in the intertidal zone and evaporites grew and later dissolved leaving the brecciated dolomite.

Bioclastic Wackestone Dolomite. The rock has essentially the same matrix material as the pelletal wackestone dolomite but in addition it has small fossil fragments and is interpreted as having the same shallow subtidal origin. The stunted(?) shelly fauna suggests slightly less restrictive conditions. Absence or scarcity of chert nodules and phosphorite intraclasts suggests deposition farther from the shoreline sabhka.

Silty Black Chert. Many of the micro- and macro-characteristics of the chert are similar to the lower nodular occurrences and also resemble lumpy mottled chert and jasper described by McBride and Folk (1977) and interpreted by Folk to be diagenetic replacement of evaporites. The brecciated appearance and inclusion-rich, banded colloform overgrowths are also like quartz textures in beds Nichols and Silberling (1980) and Rubin and Friedman (1981) interpreted to be evaporite-silcretes. Silcretes form today in arid climates by precipitation of a silica crust on or near the earth's surface (Lamplugh, 1902; Williamson, 1957; Friedman and Sanders, 1978). This region probably had an arid climate through most of the Permian (Cressman and Swanson, 1964), but the presence of a silcrete between two carbonate beds is mineralogically puzzling. If the silica came from sponge spicules they have left no trace in the rocks. If it came from meteoric ground water, why was it selectively deposited in this bed? Rubin and Friedman (1981) infer that electrolytes provided by dissolving evaporite minerals may force the precipitation of silica, providing a possible explanation for the selective deposition here. The silcrete described by Nichols and Silberling (1980) occurs in a dolomite and chert interval that replaces a clastic and biogenic silica-rich limestone. Their observations indicate that the silica became concentrated in lenses and layers of secondary chert separated from relatively pure dolomite during diagenesis.

The bed at La Marche Gulch is probably a silcrete because: 1) it is petrographically similar to other silcretes; 2) it was apparently lithified before carbonate deposition resumed over it because fracturing, brecciation and collapse within the chert bed are not reflected in the overlying rocks; 3) its position between two dolomite beds suggests, by inference from the local stratigraphic cycles, that it may have formed at an exposure surface.

Molluscan Packstone Dolomite. Large mollusc fossil lenses which distinguish this rock from the bioclastic wackestone probably represent lag deposits of storm activity which provided rare and localized bursts of high energy to this quiet basin. The source of normal adult-sized shells was probably outside and seaward of the immediate depositional environment where water was more like normal marine water, but still somewhat restricted.

Retort Member Phosphatic Sediments. The disconformity at the top of the dolomite correlates regionally (Peterson, 1980b) throughout western Montana, Wyoming and southeastern Idaho. Overlying phosphorite pelletal and intraclastic conglomerates and pelletal phosphorite mudstone are the initial deposits of the last major marine transgression recorded in Permian rocks of this area (Peterson, 1980b). The hiatus between carbonate and phosphorite beds may not represent a very long time. The presence of phosphorite chips in the dolomite beds suggests that a phosphogenic environment was nearby throughout the carbonate depositional interval.

C. Summary and environmental interpretation:

The interpreted depositional sequence follows:

1) Basal conglomerates were reworked and deposited, probably during an initial stage of a transgressing sea.

2) In a shallow, restricted lagoon or shelf basin created by the transgression, pelletal carbonate mud accumulated rapidly and was periodically interrupted by intervals of silt deposition. Evidence of phosphatic algal mats and evaporites suggests that the water became extremely shallow and/or hypersaline during silt-depositing episodes, and these conditions temporarily inhibited carbonate sedimentation.

3) An abundant but stunted or juvenile mullusc fauna and ostracods in the uppermost sediments suggest that later in its history the lagoon or shallow shelf became somewhat more hospitable, perhaps because of slightly more open connection to the sea.

4) Lenses of larger mollusc shells and shell debris were transported into the area by storms during the final episode of carbonate deposition. Perhaps the molluscs also indicate increased connection to more normal marine waters.

5) A period of non-deposition preceded the onset of overlying phosphatic sedimentation.

3. Sappington Canyon

a. Rock descriptions:

Four partial sections in the Upper Shedhorn Sandstone (Fig. 15a and Appendix Ic) were measured along strike over a distance of about 500 m to demonstrate how sedimentary structures, bedding, fossil content and lithologies vary laterally and vertically. Section 2, which contains the thickest fossil deposit, became the "type" section of the locality (Fig. 15b).

Tosi Chert and Silicified Dolomite Marker Zone. Bedded chert of the Tosi Member (Fig. 15) underlies the measured sections of fossil-bearing Upper Shedhorn Sandstone. Composition and bedding is similar to that of the Rex Chert at Cedar Creek. Colors range in the grays and browns and most beds have lighter colored or reddish weathering rinds a few mm thick. Locally, sandy zones or color changes outline fine horizontal lamination.

Patchily distributed at the top of the chert is a distinctive horizon of spiculitic and largely silicified dolomite (Fig. 16) that displays rare horizontal lamination. The top of this rock type marks the base of the partial sections. Fresh surfaces are shades of yellow, brown and orange, depending apparently on the amount of black organic material and iron

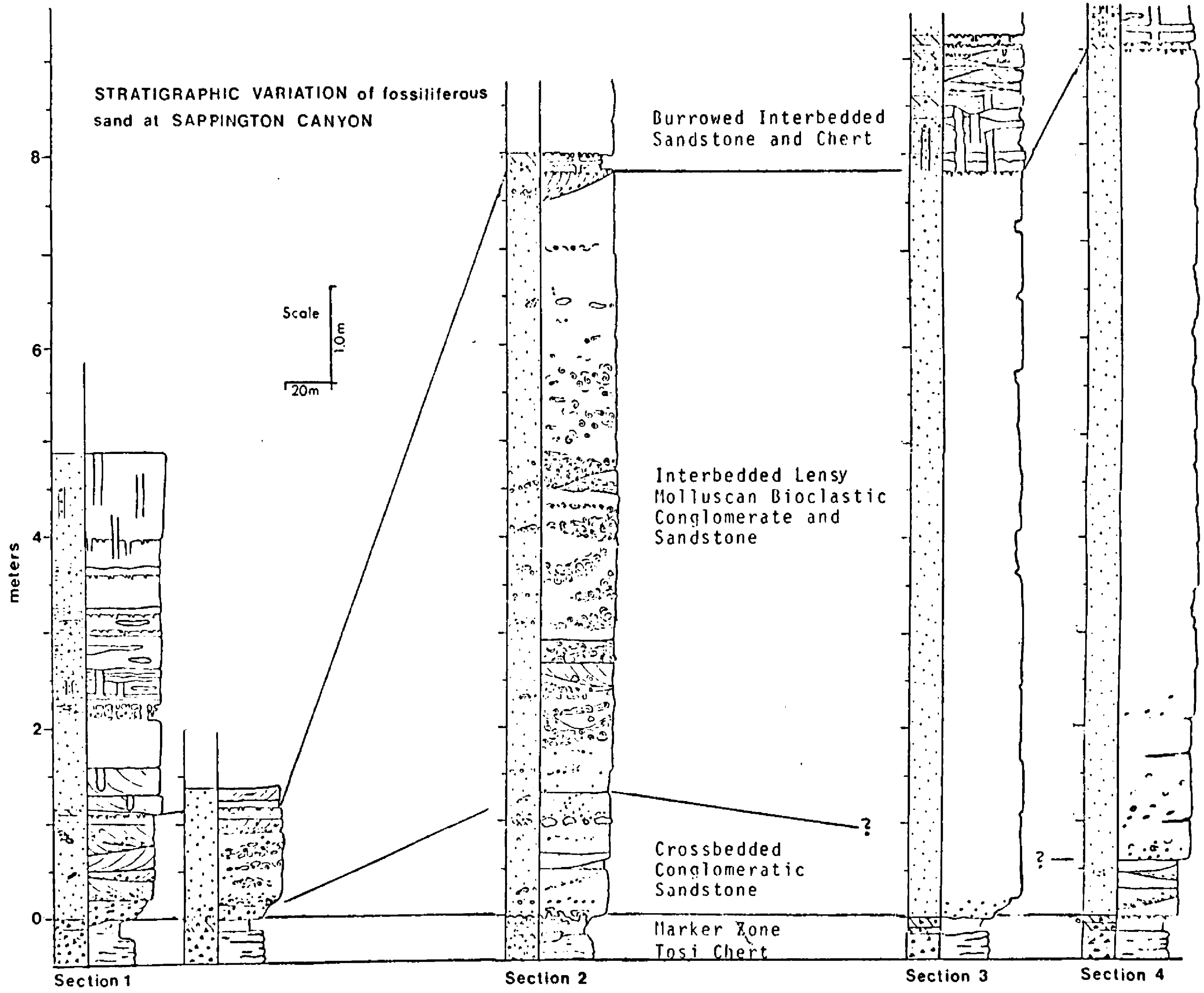


Fig. 15a. Four partial sections measured at Sappington Canyon showing lateral correlation over a distance of about 250 meters.

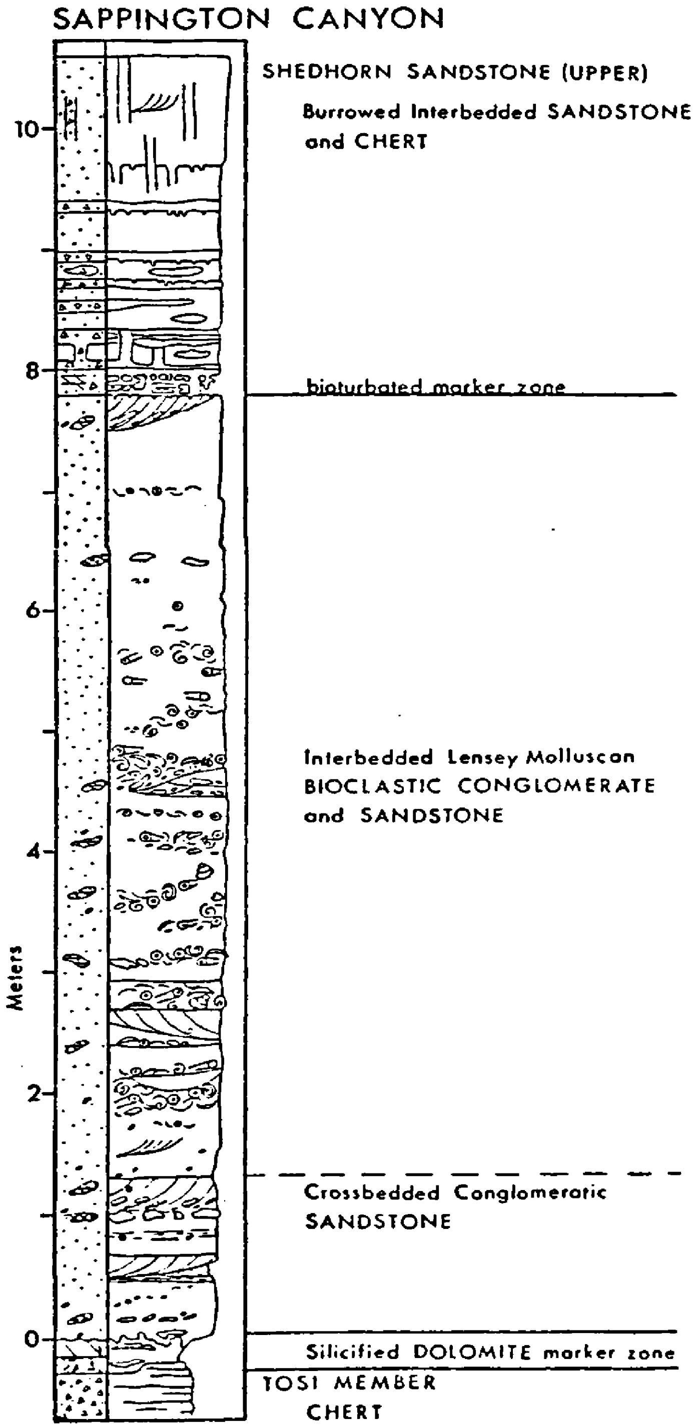


Fig. 15b. Partial stratigraphic section showing the mollusc-bearing rocks and related strata, Sappington Canyon (generalized from Appendix Ic).

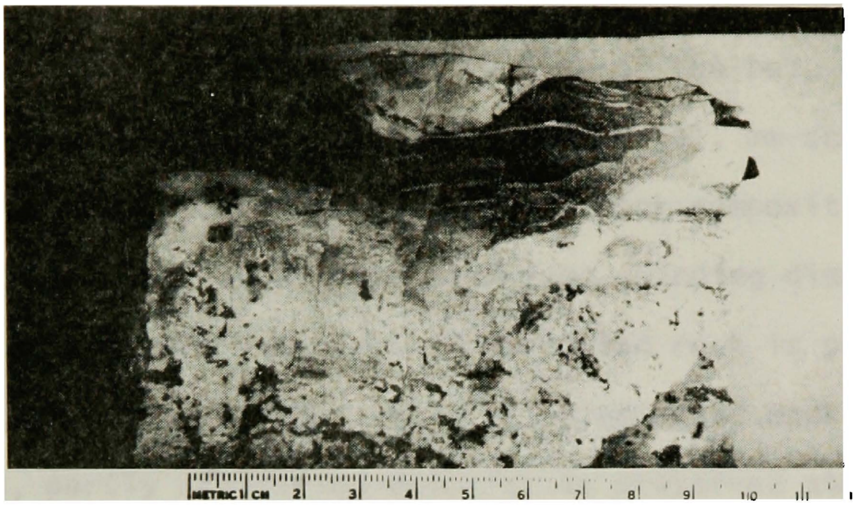


Fig. 16. Slabbed sample of silicified dolomite marker zone rock type showing fractured laminated horizon underlain by mottled rock and partially overlain by dark massive dolomite.

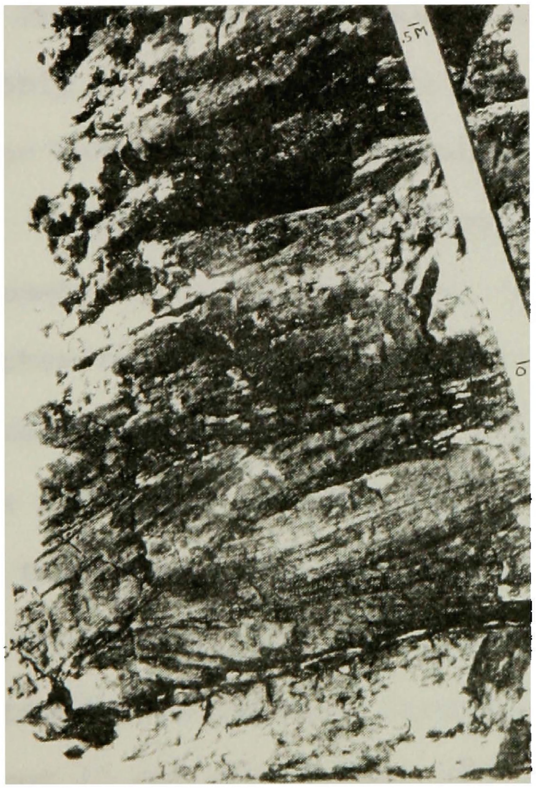


Fig. 17. Trough-shaped crossbeds of the crossbedded, conglomeratic sandstone rock type. Voids, especially in lower zones of beds, are weathered-out dolomite mudstone intraclasts.

oxide in the rock. In the upper 2 to 5 cm of the bed, concentrations of these staining materials form roughly horizontal, mm-scale color banding which appears to be unrelated to original rock composition or textures (Fig. 16). Below the upper laminated zone, banding disappears and the rock takes on a mottled texture. The mottled rock is porous with rare vugs up to several cm across. Rarely, unlaminated dark brown microcrystalline, partly silicified dolomite is preserved above the laminated zone. Brittle fractures in the banded zone become increasingly indistinct and disappear as they are traced into overlying and underlying rocks (Fig. 16), suggesting that when fracturing occurred only the middle zone of banded rock was lithified.

The upper contact between this marker bed and overlying sandstone is probably at least partially erosional; the boundary undulates and the marker unit thins and disappears locally along strike.

Crossbedded Conglomeratic Sandstone. Fine- to medium-grained, medium-brown to brownish gray sandstone composed of quartz plus chert and phosphorite grains overlies the marker bed. Sandstone grains are cemented by quartz overgrowths and/or blocky, locally poikolitic, calcite. Some lense and trough shaped beds (up to 20 cm thick and a few m long) contain low- to moderate-angled crosslaminae which, where measurable, range from 8 to 20 degrees (Fig. 17). Chert and phosphorite pebbles and gravel and flattened dolomite mud intraclasts (commonly 1.0 cm to 3.0 cm long, maximum 10 cm) are concentrated at the base of many beds or alligned parallel to cross laminae.

There is considerable lateral variation in these lowest beds above the marker zone (Appendix Ic and Fig. 15a). In the same horizon at section 1 phosphorite-pebbly sandstone occurs in thinner (2.0 to 4.0 cm) beds with horizontal or very low-angle crossbeds. The amounts of chert pebbles and dolomite intraclastic material vary from bed to bed within measured sections and along strike between them. Trough crossbeds at sections 1 and 2 pass to massive (locally pebbly) sand at section 3 and reappear at section 4 (Fig. 15a).

Interbedded Lensy Molluscan Bioclastic Conglomerate and Sandstone. The main fossil zone, or laterally equivalent unfossiliferous sands (Fig. 15a) overlie and interfinger with the crossbedded, conglomeratic sandstone. Sandstone composition is similar in both units but bed forms and sedimentary structures are not well preserved in the fossiliferous zone except where they are defined by fossil concentrations or mud clasts and pebbles. Scour surfaces are common. Interbedded, well-sorted, unfossiliferous sandstones very rarely preserve crossbedding. At section locations 3 and 4 especially, massive, thick-bedded sands are perhaps too well sorted to display internal structures. The scale of bedding is locally somewhat larger than the lower sandstone; a large trough-shaped lens of well-sorted sand about a meter thick and at least 3 m wide was observed in this zone between sections 1 and 2.

The best development of the fossil zone is at section location 2, where molluscs are found in lenses mostly less than a meter thick and a few meters long (Fig. 18). Trough-shaped lenses with multi-directional orientations are filled with oriented or chaotically arranged fossils or more rarely, sands containing basal pebble deposits. Orientation of the

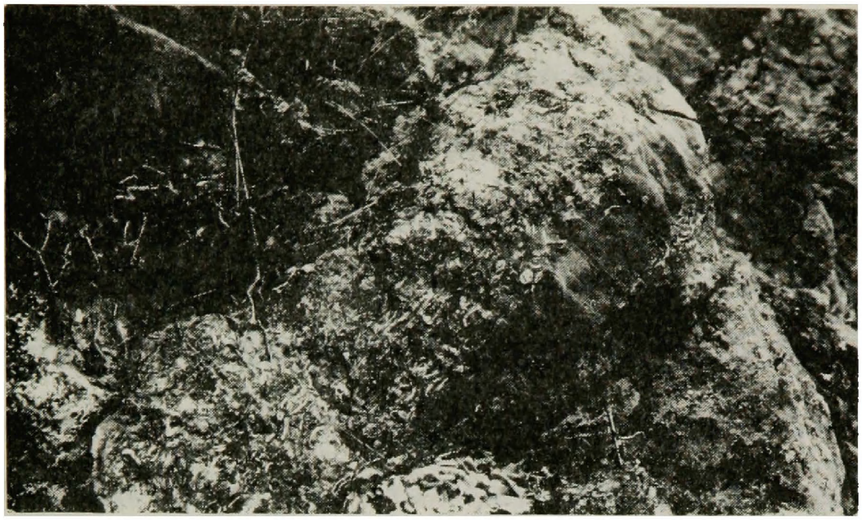


Fig. 18. Unfossiliferous trough-shaped sandstone bed surrounded by molluscan conglomerate of the interbedded lensy molluscan bioclastic conglomerate and sandstone rock type. Vertical view field is about 1 meter.

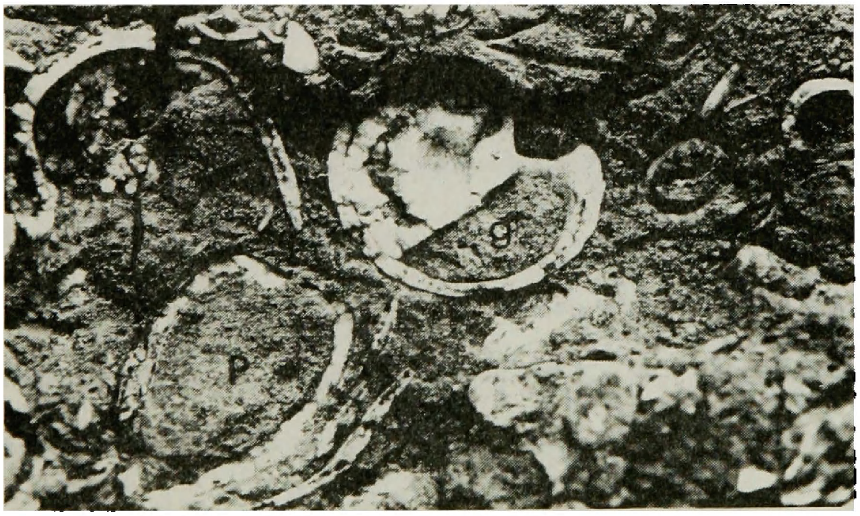


Fig. 19. Bellerophontacean gastropod with geopetal filling (g). Geode-type silica cement fills the shell mold and the void above the geopetal sand. Note an articulated pelecypod (p) in the lower left corner and cross sections of scaphopod shells in the upper right (s). Horizontal field of view is about 11 cm.

fossils with their beds is difficult to ascertain where gastropods dominate, but scaphopods roughly parallel the bedding and in many lenses they are telescoped and/or directionally alligned. Disarticulated pelecypod shells are concave-up and nested in some lenses or chaotically disturbed in others. Tabular, horizontally laminated shelly layers up to 10 cm thick are a rare variation; these contain concave-down shells characteristic of sheet flow (Clifton, 1976). Articulated pelecypods (Fig. 19) occur much less commonly than disarticulated ones in fossiliferous lenses and very rarely as isolated shells in interbedded sandstones.

Although most of the fossil lenses are poorly sorted, size and perhaps shape sorting produced a few deposits of uniform-sized gastropods and scaphopods and what is probably their hydrodynamic equivalent in pelecypod shells. Fossils in many lenses are in grain contact and some have geopetal fillings (Fig. 19) implying that the shells were originally deposited with little or no matrix. Shells and shell debris are sparsely intermixed with sandy, spiculitic carbonate mudstone intraclasts in the vicinity of sections 1 and 2 and the same material appears inside some fossil cavities and adheres to some outer edges. Uneven cherty patches of silica replacement are localized within the mudstone. Replacement may have occurred in the environment from which the shells and pebbles were ripped up, before they were deposited with the sands, since there is no other evidence of carbonate replaced by silica in the rest of the rock.

Sandstone included in this unit thickens markedly from less than 1 m at section 1 to about 6 m at section 2; equivalent, mostly unfossiliferous, sands at sections 3 and 4 are up to 8.5 m thick (Fig. 15a). The unit thins again and becomes cherty farther eastward (no sections measured). Mollusc fossil lenses appear in the eastern extension of section 1, become dominant in the sands at section 2, and then lens out eastward to unfossiliferous, massive sandstone.

Bioturbated Marker Zone and Burrowed, Interbedded Sandstone and Chert. The upper marker zone was recognized at each sub-station by the abrupt appearance of large vertical cherty burrows, smaller vertically and horizontally branching burrows and yellowish gray-weathering, usually siliceous dolomite. Small-scale bioturbation is most intense on upper bed surfaces, while larger burrows penetrate through one or more beds. Bedded and nodular chert reappears above the marker zone after an absence throughout the fossiliferous sand unit and occurs with interbedded sandstone and dolomite. Fossil molluscs are absent in the beds above the marker zone.

b. Interpretation of rock types:

Tosi Chert and Silicified Dolomite Marker Zone. Lithologic similarities in the chert underlying this partial section and that at Cedar Creek suggest similarities in origin. Both are interpreted as probable shallow submarine spiculites winnowed from the living community and transported by waves or currents.

Rock in the marker zone compares closely to subaerial laminated crusts on carbonate rocks in the Florida Keys (Multer and Hoffmeister, 1968; Fobbin and Stipp, 1979), and is inferred to be a similar subaerially exposed surface. The thin, patchy, eroded distribution of the rock supports that conclusion.

Crossbedded, Conglomeratic Sandstone. Bedding and well preserved sedimentary structures in this rock unit resemble the Interbedded Lenticular Sandstone and Chert unit at Cedar Creek. Most crossbeds are similarly interpreted as deposits of migrating megaripples and at least some of the planar beds were deposited during sheet flow. They were produced by currents or shoaling waves in a sand bar and channel system. At Sappington Canyon the sandstone also contains dolomite intraclasts which probably originated nearby in an intertidal lime mud environment (Ginsburg, 1957). Lenticular and channel-shaped beds with erosional basal surfaces overlain by lag deposits of tidal flat mud intraclasts probably accumulated in tidal or storm channels (Shinn *et al*., 1969; Reineck and Singh, 1975, p. 366, 327; Friedman, 1977).

Interbedded Lensy Molluscan Bioclastic Conglomerate and Sandstone. The molluscan conglomerates were probably deposited by storm currents in rip channels of the bar system. The large number of unbroken fossils and the articulated pelecypods indicate a rapid depositional process like storms which could remove animals from living communities and deposit them quickly and permanently. Some of the more worn and broken shells probably came from the back-barrier lagoon or tidal flat. They retain some spiculitic carbonate mud or are deposited with mud intraclasts from the tidal flat. Lenses characterized by geopetal fossil filling and grain-supported fabric were originally deposited without matrix, as lag deposits during high energy flow. Most mollusc fossil lenses are localized in the vicinity of section 2, perhaps the site of a large channel that breached the bar.

<u>Bioturbated Marker Zone and Burrowed Interbedded Sandstone and Chert</u>. Perhaps shifting channel and bar patterns or changing sea level temporarily terminated sand deposition in the Sappington Canyon area and a thin zone of bioturbated, locally siliceous, dolomite was deposited rather uniformly over the sea. Abundant small burrows on upper bed surfaces probably record intervals of non-deposition as at Cedar Creek. Sediments overlying that horizon represent a combination of alternating traction load (sand) and bed load (dolomite mud) deposition in an environment that was probably normally quiet but subject to high energy storm bursts.

c. Summary and environmental interpretation:

Shedhorn Sandstone in the Sappington Canyon area belongs to a larger barrier bar system recognized in this area by Shepherd (1971). There is probably not enough data to tell if this sequence records regressive or transgressive facies. Because prograding barrier bar systems are more likely to be preserved than retrograding systems (Reinson, 1979) and because the diagenetic record suggests early subaerial exposure (Chapter 3), these rocks are tentatively interpreted as progradational.

4. Devils Slide

The Devils Slide locality was the only one of this study which contained members of the molluscan assemblage in more than one stratigraphic horizon (Fig. 20 and Appendix Id), so almost the entire exposed section was measured. Although the Permian rocks are thin (less than 20 m), they include an astounding variety of lithologies and generally good exposure

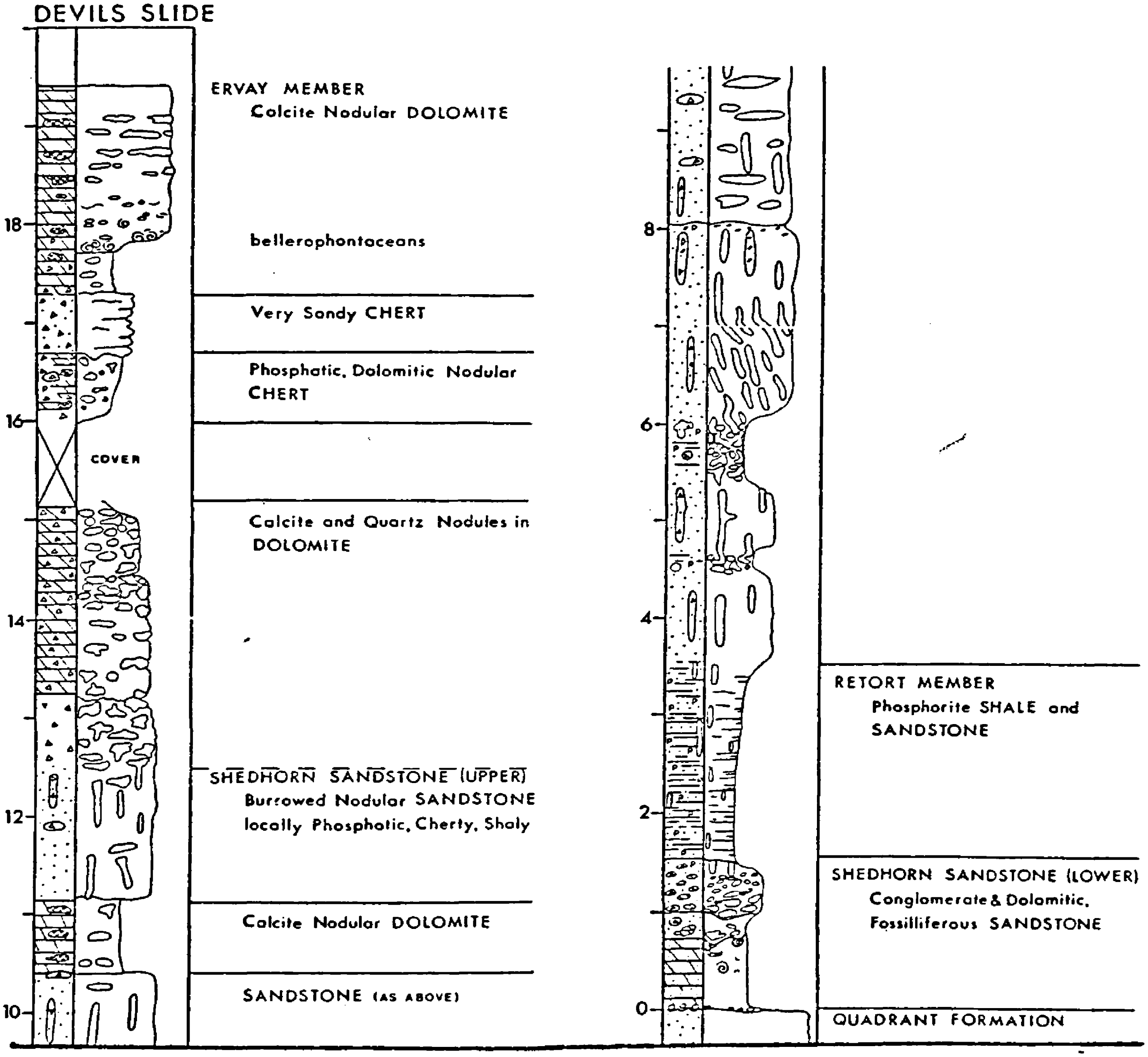


Fig. 20 . Partial stratigraphic section showing the mollusc-bearing rocks and related strata, Devils Slide (generalized from Appendix Id)

makes this an excellent place to observe stratigraphic relationships near the edge of the Phosphoria Sea.

a. Rock descriptions:

Conglomerate and Dolomitic, Fossiliferous Sandstone. The base of the Permian section at Devils Slide is marked by thin patches of grain-supported conglomerate which fill slightly undulating topography on the Pennsylvanian Quadrant Sandstone (Fig. 20, and Appendix Id). This basal Lower Shedhorn Sandstone conglomerate grades upward to sandy dolomite and dolomitic sandstone with calcite-filled fossil molds toward the center of the bed and sand-filled molds at the top. Sand molds are truncated by another conglomerate that includes unsorted, rounded to very angular dolomite and chert clasts with blackened, iron stained and phosphatic (?) rinds, that are supported in a matrix of dolomitic quartz sandstone. A very uneven contact separates the second conglomerate from the overlying pebble-to-boulder conglomerate. The base of this bed contains rounded chert and more angular sandy dolomite clasts up to 10 cm diameter, dominantly matrix supported in dolomitic quartz sandstone. Average clast size decreases upward in this bed, which suggests subaqueous gravitational settling and sorting. The upper 10 cm is fine to coarse quartz sand and sand- to elongated pebble-sized phosphatic fossil hash and contains a few large cherty columnar burrow structures similar to those at Sappington Canyon. None of the beds in this unit show internal stratification.

Phosphorite Shale and Sandstone. Phosphatic components increase upward throughout the conglomeratic sequence; gravely and very coarse-grained phosphorite skeletal sandstone that caps the conglomerate unit is more than 50 percent worn and fragmented inarticulate brachiopod shell hash. The overlying impure phosphorite mudstone and pelletal and skeletal sandstone of the Retort Member (Fig. 20) is high- to medium-grade phosphorite up to 23.4 percent P_2O_5 (Cressman and Swanson, 1964, p. 548). Very thin laminations in the finer grained lenses provide the only observed primary sedimentary structures. Mudstone and phosphatic fossil hash dominates the unit and must have been deposited in a moderately quiet environment which was periodically interrupted by higher energy events. Much of the coarser phosphatic shell debris appears in abundant, identical, large vertical burrows which are bent and squeezed, recording deformation during sediment compaction.

Burrowed Nodular Sandstone. Upper Shedhorn Sandstone beds above the phosphorite record dramatically increased clastic sedimentation. Fine- to very fine-grained phosphatic and cherty quartz sandstone is thick bedded and contains few sedimentary structures besides large vertical burrows like those in the phosphorite. Probably the activity of these burrowers, whose traces locally comprise greater than 50 percent of the rock, obliterated other structures. The borrows bend uniformly at about 7 m in the measured section (Fig. 20), accenting soft-sediment deformation within the sand bed. The sandstone unit includes some chert nodules apparently unrelated to burrows, and locally coarse pebbly chert and phosphorite as well as a few thin interbeds of phosphorite sandstone and mudstone. The tongue of calcite nodular dolomite (at about 10.3 m to 11.1 m in the section) is similar to the rock at the top of the section (above 18.3 m) which is described below. The sandstone is therefore in gradational contact with both the overlying nodular carbonate and underlying phosphorite, making it a transitional facies between the two.

Calcite and Quartz Nodules in Dolomite. Most of the Ervay Member dolomite rocks above about 12.5 m in the measured section are riddled with quartz and calcite nodules (Fig. 21) as isolated masses, lensoid concentrations and densely packed beds. They are rounded to elongate and are usually a few cm in diameter, although they range from less than 1.0 cm to more than 10 cm. Surfaces, best seen where the nodules weather out of the rock and form lose geodes, are bulbous and cauliflower textured. Most of the dolomite matrix is microcrystalline except for larger euhedral rhombs which commonly float in cherty zones. Locally distorted laminations in the matrix indicate that nodules grew by displacement of the soft host sediment. Near the nodules, elongate grains in the sediment lie tangential to nodule surfaces which suggests that they were realligned during nodule growth.

Nodules are filled with a variety of silica and carbonate cements and replacement minerals. Silica phases include microcrystalline quartz, quartzine, leutecite and chalcedonite. Euhedral, doubly-terminated quartz crystals (Fig. 22) grew in the nodules and occupy unfilled centers of some nodules or are overgrown by calcite cement which fills the centers of many nodules. Pyrite is a common constituent of cherty nodule rims. Although mineralogical composition of the nodules is mixed, it varies from primarily silica in beds below the fossil horizon to primarily calcite in and above the fossil zone. This difference is interpreted to be the result of uneven distribution of sponge spicules which probably provided the source of dissolved silica for nodule filling. Siliceous matrix in the lower beds retains some recognizable recrystallized spicules and their

Figure 21. Cherty (dark) nodules and dolomite matrix (light) from 14.8 m in the measured section, calcite and quartz nodules in dolomite rock type.

Fig. 22. Two almost-coalescing elongated nodules (enclosed in dashed lines) with a doubly-terminated quartz crystal (arrow) from the phosphatic, dolomitic nodular chert rock type at about 16.3 meters in the section). recessively weathering matrix immediately surrounding the nodules is unsilicified. Approx. actual size.

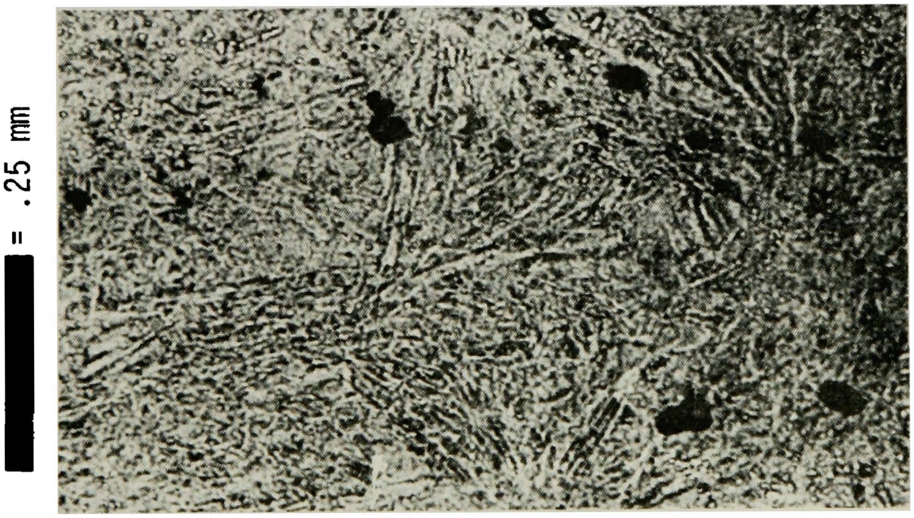


Fig. 23. Felted texture in microcrystalline quartz, possibly relict evaporites.

phosphatic canals, which are apparent even when the spicule itself has dissolved. Matrix immediately surrounding the nodules tends to be unsilicified (Fig. 22).

The lower nodular part of the section begins with about 0.7 meters of vuggy rock supported by an open framework of chert and calcite nodules, lenses and irregular masses (about 12.5 m to 13.2 m, see Fig. 20 and Appendix Id). A residue of unconsolidated reddish calcareous silt in the middle of the bed is almost all that remains of the matrix. Some nodules protrude into underlying sandstone, producing a gradational lower boundary. The upper contact is sharp and very rough.

Overlying rocks are densely nodular and create a remarkable outcrop of up to 50 percent dark bluish-gray to brownish-gray chert nodules in a light tan-weathering, silty, cherty dolomite matrix (Fig. 21). Preservation of matrix is the major difference between these nodular rocks and the underlying ones.

Phosphatic, Dolomitic Nodular Chert. This rock is a very dark bluish gray, phosphatic, silicified dolomite with abundant fossil sponge spicules, phosphatic shell fragments, small gastropod steinkerns and pellets, silicified phylloid algal (?) fragments, and nodules. Most of the nodules are zoned with dolomitic, spiculitic, phosphatic chert grading inward to a thin (mm to cm scale) uneven rind of iron-oxide stained phosphatic microdolomite that surrounds blocky calcite cement. The calcite contains no intracrystalline inclusions or relict textures and appears black because of abundant amorphous intercrystalline organic (?) residue, probably dead oil.

Very Sandy Chert. This poorly-exposed, dark gray rock has nearly horizontal, very sinuous partings less than 1 cm thick. It contacts the chaotic, nodular cherty rock below along a very uneven, possibly erosional boundary. Relict sponge spicules and quartz sand grains in a microcrystalline quartz, chalcedony and megaquartz matrix comprise most of the rock.

Calcite Nodular Dolomite. Nodules are variable in this unit. Within the recessive rock below the fossil bed (Fig. 20) they contain spherulitic chalcedony, including leutecite and quartzine locally retaining a relict felted texture (Fig. 23), tiny, rectangular (anhydrite?) inclusions (Fig. 24), and one example of a relict bladed crystal that is probably gypsum (Fig. 25).

Nodule centers in and above the fossil zone are mostly coarse blocky calcite with common black intercrystalline organic residue. They form aggregates up to 10 by 20 cm in size in discontinuous lenses along bedding planes (18.5 m to 19.1 m in the measured section). They are much smaller (mm to cm scale) above and below that zone and tend to be more randomly scattered. Siliceous rinds around calcite in the nodules contain euhedral quartz and spherulitic chancedony like that described above. Vaguely pelletal, silty, pyritic matrix dolomite is rather uniformly microcrystalline (.001 to .02 mm) and sponge spicules are rare to absent. No internal stratification was observed but the dolomite has a mottled appearance and a few recognizable burrow structures. The rock contains matrix- and grain-supported silica molds of bellerophontacean gastropods in thin lenses along a single bedding plane (17.7 to 17.8 m in the measured section). Microsphorite intraclasts and steinkerns (Fig. 26) are abundant

Fig. 24. Portion of a quartz and calcite nodule from about 18 m in the measured section at Devils Slide. Euhedral quartz crystals contain rectangular inclusions (eg. arrow) which may be anhydrite. Center of this nodule is blocky calcite.

Fig. 25. Relict balded crystal in chert nodule, possibly gypsum.

Fig. 26. Abundant microsphorite intraclasts (light gray, eg., P) and a nearly complete small silty microsphorite gastropod steinkern (G) in silty dolomite of the calcite nodular dolomite rock type.

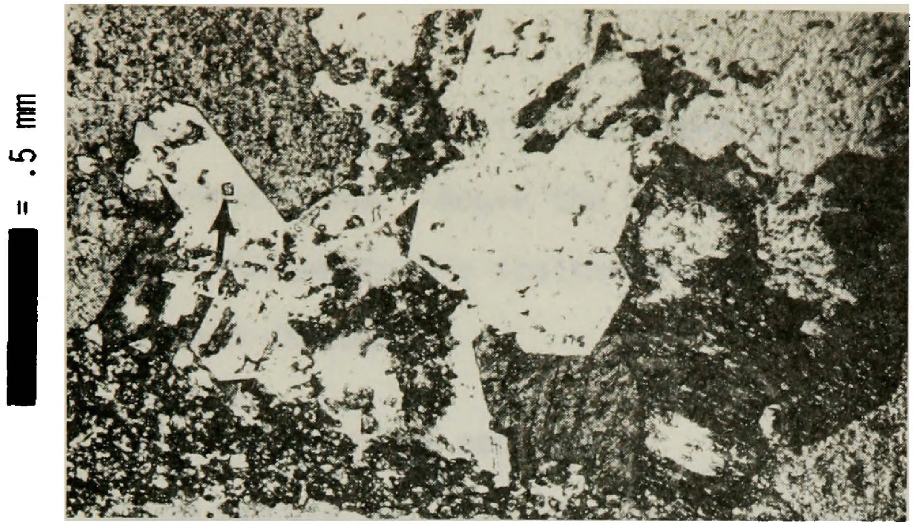


Fig. 24

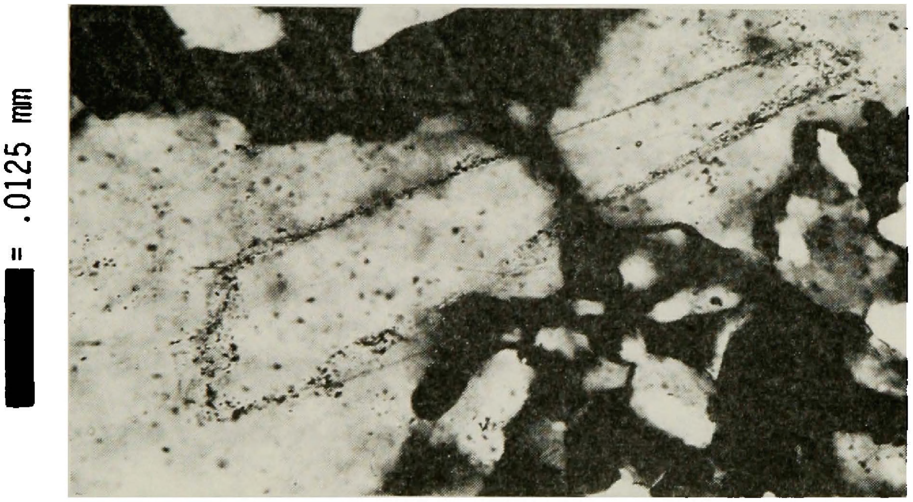


Fig. 25

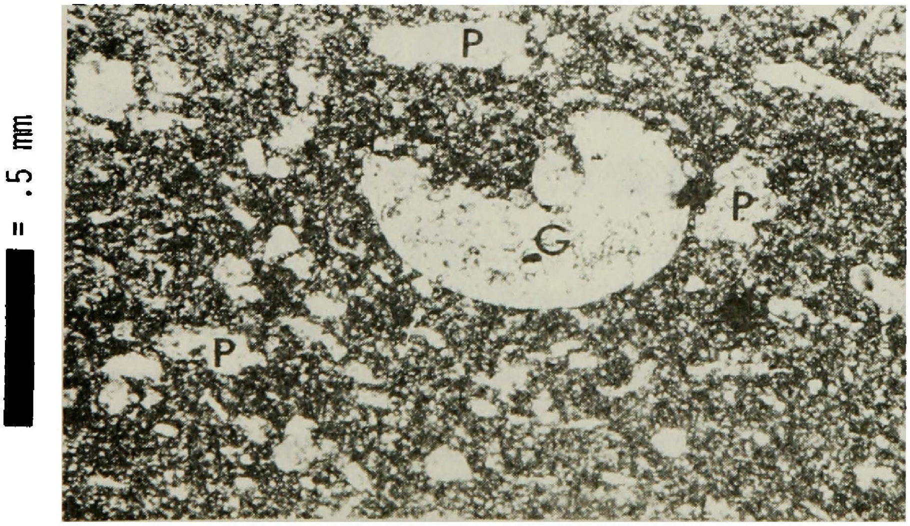


Fig. 26

from the base of the fossil lens to about 18.2 m, and continue above that as a trace constituent. Above the bellerophontacean packstone/wackestone lenses fossil fragments are scattered through the mudstone matrix to about 18.2 m and then disappear.

b. Interpretation of rock types:

Conglomerate and Dolomitic Fossiliferous Sandstone. This sequence is the preserved record of high-energy conditions that repeatedly eroded underlying strata and deposited very coarse sediments. Truncated, sand-filled molds of molluscs at the top of the lower conglomeratic bed suggest that a significant period of nondeposition and erosion separated it from the overlying conglomerate. It could be all that remains of the first marine transgression that reached this area during the Permian. The upper two conglomerates below the Retort Member phosphorite are probably the earliest deposits of the final and most extensive Permian transgression in the region (see Peterson, 1980b). Phosphorite clasts and rounded chert and dolomite clasts coated with black phosphatic (?) rinds probably are similar to phosphate nodules and coated particles that form during long exposure of sediments in upwelling areas of modern shallow shelf environments. (eg. Baturin et al., 1974; Veeh et al., 1973; Burnett, 1977; Birch, 1979).

Phosphorite Shale and Sandstone. The Retort Member here is the northeasternmost extension of a huge phosphorite accumulation that centered in southwestern Montana but is also represented in correlative rocks of Idaho, Wyoming and Utah (eg. McKelvey et al., 1959, Cressman and Swanson, 1964; Wardlaw, 1979). Major phosphogenic environments like this one are rare in the geologic record, requiring a peculiar set of circumstances. They appear to develop: 1) in low-latitude locations during early stages of marine transgressive episodes, 2) in areas of locally restricted circulation; 3) created by moderate tectonic highs and lows; 4) where there is a large available source of P_2O_5 (Cook and McElhinny, 1979; Peterson, 1977, 1980b; Riggs, 1979a, 1979b, 1980; Sheldon, 1964, 1981; Arthur and Jenkyns, 1981).

This deposit correlates with transgressive Retort Member phosphorites elsewhere (see esp. Peterson, 1980b), and independent evidence from the limited fauna and nodular dolomite in the overlying rocks indicates that circulation was restricted in this area during the Permian. The combination of mud- and sand-sized phosphorite reflects alternating fair weather suspension-load deposition and stormy weather winnowing and traction-load deposition (see eg., Specht and Brenner, 1979). That sequence indicates that the water was shallow enough for storm waves or currents to effect the bottom.

Accumulation of high grade phosphorite also demands an anomalous environment where phosphate production either simply overwhelms or actually inhibits other types of deposits. Shallow, low latitude seas normally support a large calcium carbonate-producing population if terrigenous influx is not too high. However, there is abundant evidence that major phosphogenic environments are inherently biologically stressed. They have generally low-diversity/high-density populations of animals such as phosphatic brachiopods, non-shelly burrowers and phosphate-producing microorganisms (Riggs, 1979b). High phosphate waters commonly develop euxenic conditions which are stressful to most higher life forms

(McNaughton and Wolf, 1973). Phosphate compounds may also act as inhibitors of calcification (Rhodes and Bloxam, 1969), thus restricting calcareous-shelled animals. Phosphate deposits commonly contain anomalous concentrations of fluorine and vanadium (Gulbrandson, 1977), uranium (Cressman and Swanson, 1964; Kolodny and Kaplan, 1970) and other elements, which were concentrated in the sediments concurrently with the phosphate (Riggs, 1979b) at levels toxic to many organisms (Table 1).

Table 1. Heavy metal concentrations in phosphorites. Adapted by Riggs (1979b) from Tooms et al. (1969) and Turkian (1968).

Metal	Concentration in phosphorites (Range in ppm)	Concentration in sea water (avg. in ppb)
Mercury	10-1.00	0.15
Zinc	4-345	11.00
Copper	0.6-394	23.00
Lead	0-100	0.03
Arsenic	0.4-188	2.60
Cadmium	1-10	0.11
Chromium	7-1600	0.20
Titanium	100-3000	1.00

The possibility that this strange and toxic environment was a neighbor to the molluscan habitat might help explain the low diversity of that assemblage, especially if the phosphogenic system was a barrier to faunal migration positioned seaward of the carbonate facies. Microsphorite pellets and intraclasts are present almost throughout the whole section in at least trace amounts, suggesting that the primary phosphorite environment which passed through this location may have continued as an active adjacent facies, or at least an exposed and unlithified nearby sediment for most of Permian depositional history. La Marche Gulch carbonates containing phosphorite algal mat chips and pellets and absent to very restricted macro fauna perhaps also reflect the influence of a nearby toxic phosphogenic facies.

Burrowed, Nodular Sandstone. Eventually, clastic sedimentation overwhelmed or replaced phosphorite. Without internal structures the sandstones are difficult to interpret. They are generally coarser grained than the phosphorites and represent higher energy deposition. Soft-sediment deformation may reflect accumulation on an unstable slope.

Nodular Rocks (including Calcite and Quartz Nodules in Dolomite, Phosphatic Dolomitic Nodular Chert and Calcite Nodular Dolomite). Although quartz and calcite nodules at Devils Slide differ in form from those at La Marche Gulch North, they are also interpreted to be replaced evaporites on the basis of similar mineralogies, textures and occurrence. At Devils Slide the nodules are much more abundant, and generally larger, creating an outcrop reminiscent of chicken wire anhydrite texture locally (Maiklem et al., 1969). They are mineralogically more complex, with zoned quartz forms and calcite (see Milliken, 1979, for a summary of zoned mineralogies in replaced evaporite nodules), and they contain more convincing relict evaporite inclusions. Cement textures indicate that at least some of the space that the nodules now occupy was once open and relict inclusions and textures retain evidence of the anhydrite and gypsum that were removed.

In addition to very fine-grained, burrowed, locally spiculitic dolomite, which was probably a shallow subtidal carbonate mud, the matrix contains terrigenous clastic sand and silt grains which may be windblown. The biological component reflects restricted conditions probably caused by very shallow, abnormally saline water. Some of the phosphorite pellets and intraclasts resemble the algal mat material at La Marche Gulch North.

These sediments are therefore interpreted to have accumulated in shallow, restricted coastal basins, probably as a series of progradational units which were interrupted by periods of exposure and sabkha diagenesis. The situation was perhaps analogous to the modern Trucial Coast embayment in the southern Persian Gulf (see Kendall, 1979, for a summary of this modern sabkha). Pyrite in the sediments may have formed during early diagenesis since microbial sulfate reduction and generation of H_2S is common in recent sabkha sediments (Butler _et al_., 1973).

Very Sandy Chert. Fine quartz sand and relict sponge spicules in this rock suggest that the original siliceous deposit was dominantly fine-sand sized. The placement of a spiculitic chert bed between two very shallow water, supratidally-altered dolomite units suggests that the chert was originally a shoreline spiculite sand (see Chowns and Elkins, 1974).

c. Summary and environmental interpretation:

The sequence of rocks at Devils Slide (Fig. 20) records a transgressive - regressive cycle in an area that probably never attained very deep water or normal marine circulation. Three basal conglomeratic units are early failed attempt by the sea to cover this area. Phosphorites here, as elsewhere (eg. Peterson, 1980b; Riggs, 1980; Sheldon, 1981), represent abnormal transgressive marine sedimentation at the shallow onlapping edge where normal marine circulation was probably obstructed by local topography. The sandstone, which is stratigraphically situated between two finer grained deposits, might be the remains of a sand bar that formed when clastic sediment influx increased, perhaps at the inflection point between transgression of the sea and progradation of landward facies (regression). Carbonate mud formed in quite shallow water and experienced early diagenesis under hypersaline conditions as the sea level continued to fall. This cycle corresponds to the last and highest marine transgression-regression event observed in correlative Permian rocks of southeastern Idaho, Wyoming, and Utah (eg. Peterson, 1980; Wardlaw, 1979).

5. Boulder River

This section was too poorly exposed to allow detailed environmental interpretation but is included here because it provides some interesting additional data, especially on faunal relationships.

a. Rock descriptions:

Conglomeratic, Dolomitic Sandstone. The easternmost Permian section of the study (Fig. 27 and Appendix Ie) begins above a poorly exposed, undulating erosional surface on the Pennsylvanian Tensleep Sandstone. The overlying conglomerate contains spiculitic chert clasts

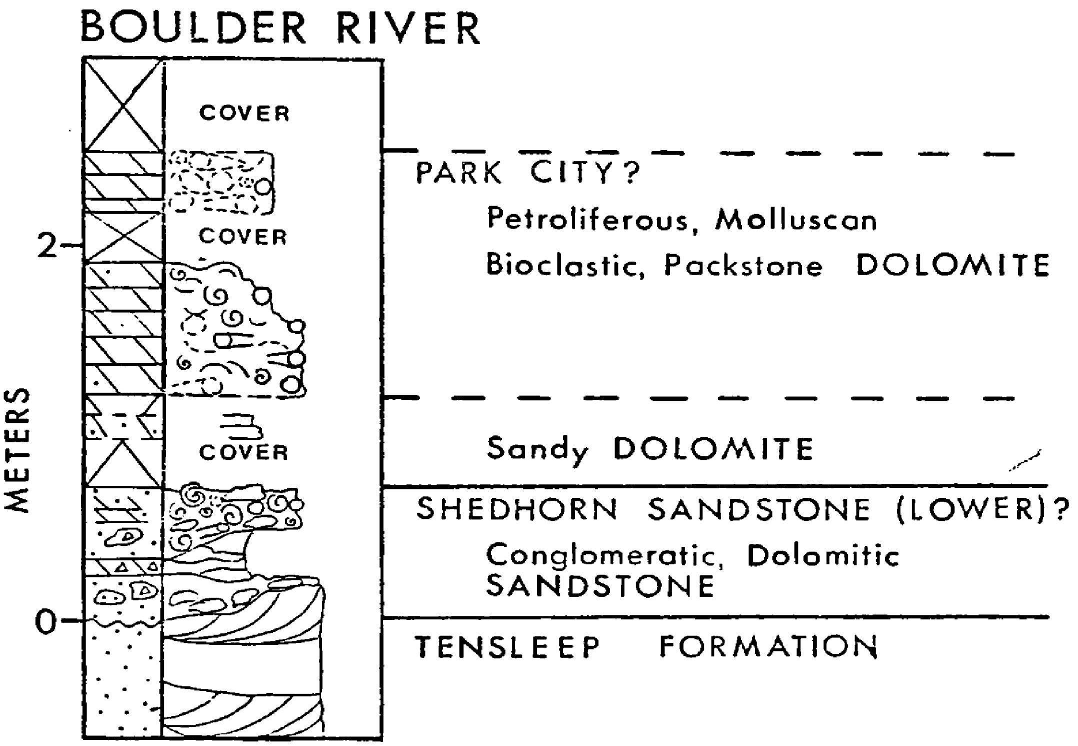


Fig. 27. Partial stratigraphic section showing the mollusc-bearing rocks and related strata, Boulder River (generalized from Appendix Ie).

up to 10 cm in diameter. There boulders lie in both matrix and grain support, locally creating a lag deposit in the sand and indicating very high-energy conditions. Matrix is well-sorted, medium-grained quartz sandstone with a brittle black organic material (dead oil?) filling much of the intergranular pore space and dolomite and calcite cement. A very discontinuous zone of large angular chert clasts (up to several tens of cm) in dolomite matrix caps the sandstone conglomerate. R. C. Douglas, U. S. Geological Survey, examined chert boulders I sampled which contained relict algae and fululinids and he assigned the fossils a Middle Pennsylvanian, probably Desmionesian, age (written communication, 1979).

A third conglomerate contains molluscs and chert clasts in mottled, pinkish-tan dolomitic sandstone and sandy dolomite matrix (Fig. 28). Fossils and other clasts lie in both grain and matrix support. The fauna is dominantly molluscan; bellerophontacean gastropods are the most abundant large fossil, but scaphopods and pelecypods are also common and large ramose bryzoan fragments (greater than 1 cm long) occur in local concentrations as well as a few randomly scattered, silicified internal molds of bellerphontacean gastropods and scaphopods.

Sandy Phosphatic Dolomite. Above the conglomerates is a covered zone with float and one small outcrop of very sandy, very phosphatic, burrowed dolomite (Fig. 27). Angular fragments of microsphorite and small (1.0 to 2.0 mm basal diameter) stubby conical paleoniscoid fish teeth occur in all beds, but here they comprise up to 10 percent of the rock locally. Fine- to medium-grained quartz sandstone with a trace of chert and rare

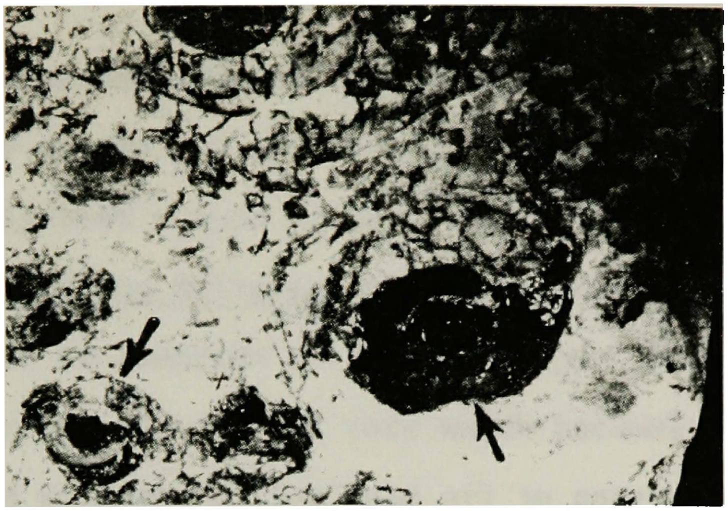


Fig. 28. Conglomeratic dolomitic sandstone rock type showing poorly-preserved bellerophontacean fossils (arrows) and other fossils. Actual size.

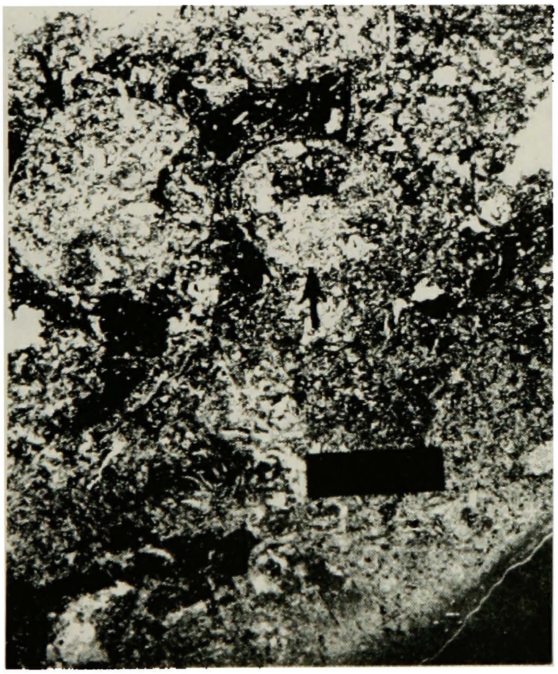


Fig. 29. Petroliferous molluscan packstone dolomite rock type showing internal molds of two large scaphopods (arrows) with collapsed shell walls and packstone texture of fossils. Scale bar = .5 cm.

larger chert granules comprise up to 40 percent of the rock, but grains are chemically eroded and replaced by dolomite at the surfaces and may have originally been a much larger fraction.

Petroliferous Molluscan Packstone Dolomite. About half of the exposed section is composed of this rock type (Fig. 27). The light gray weathering surface disguises a rock which becomes progressively darker colored upward with increasing dead oil in pore spaces. Large bellerophontaceans, which dominate the molluscan fauna in the conglomerates and in the lower part of the packstone, are replaced upward by large scaphopods although very small gastropods continue to be present in about the same numbers throughout. In contrast to lower beds, pebbles and other lithoclasts disappear here and quartz sand becomes a minor constituent. Matrix dolomite is finely crystalline and larger euhedral crystals line pore spaces. Fossils are preserved as molds, nearly all of which are broken and deformed, but the altered remains are abundant enough to create a packstone texture (Fig. 29). The top of this bed is poorly exposed and stratigraphically overlain by a broad swale with no exposures.

b. Interpretation of rock types:

Absence of sedimentary structures, poor quality of exposures and extensive diagenetic alteration make interpretation of these rocks difficult.

Conglomeratic Dolomitic Sandstone. This coarsely conglomeratic zone lies at the base of Permian rocks dominated by a restricted marine molluscan fauna and is the initial deposit of a marginal marine sequence.

Clasts and well-sorted quartz sand came from erosion of Pennsylvanian and perhaps earlier strata as the sea transgressed.

Sandy Phosphatic Dolomite. Moderately well-sorted fish teeth and quartz sand encourage speculation that the carbonate portion of this rock was also originally deposited as sand-sized grains which were obliterated during diagenesis. In near-shore marine environments such sands are most common in beach or bar sediments.

Petroliferous Molluscan Packstone Dolomite. This rock type may represent *in situ* accumulation with continuous partial winnowing of finer grained matrix or a transported deposit of grain-supported fossils. It could be a storm deposit similar to the one at Cedar Creek or channel lag--evidence is simply insufficient to determine the depositional environment.

c. Summary and environmental interpretation:

This locality lies in an environmental transition zone between western marine-dominated and eastern continental-dominated sediments. Less than 30 km to the southeast, in the Nye area, Vhay (1934) noted redbeds and preserved anhydrite, which have not been described in Permian rocks in Montana west of the area. Sediments at the Boulder River locality contain coarse clastic and biologic components with minimal finer matrix, and mostly record fairly high energy deposition. This marine-marginal area would have been covered by only the highest stands of the Middle Permian sea and may correlate with the highest recorded transgression, making these rocks facies of Upper Shedhorn Sandstone and Ervay carbonate in Montana and Wyoming.

Summary and Conclusions

Rock unit characteristics and interpretations for the five localities are summarized in Tables 2 through 6. The relationships between depositional environments and fossil mollusc deposits are varied:

Cedar Creek partial section records a prograding, shallow marine, mixed-lithology system with a spiculitic outer facies, terrigenous higher energy sand facies and mixed terrigenous sand and carbonate mud tidal flat. The mollusc fossils were incorporated into a storm coquina deposited on the tidal flat.

La Marche Gulch North partial section contains several shallowing-upward (prograding) carbonate sequences with the fossil mollusc deposit occurring as channel or storm lag deposits in a normally quiet, restricted carbonate lagoon or shallow basin.

Sappington Canyon partial section appears to be a prograding (?) barrier bar system heavily dominated by terrigenous clastic sedimentation. Fossil mollusc conglomerates are probably tidal channel lag deposits.

Devils Slide section is a complete transgressive-regressive sequence with molluscs appearing in a transgressive (?) sandstone and conglomerate at the base and a (regressive) progradational, shallow restricted carbonate deposit at the top. The upper shell deposit may be *in situ*.

Boulder River environment is unknown except that it was fairly high energy and very near the highest recorded stand of the Permian sea in this area. Molluscs appear abundantly in a conglomerate and packstone dolomite of undetermined origins.

DATA				INTERPRETATIONS		
UNIT	BEDFORMS	INTRABED STRUCTURES	TEXTURES/COMPOSITION	TYPE OF FLOW	PROCESSES	DEPOSITIONAL ENVIRONMENT
Chert	v thin, planar, wavy, discontinuous	thin horizontal lam, massive or mottled	relict sponge spicules,slt, cly, f sand & authigenic silica	uncertain	poss. storm-deposited spiculite layers	shallow submarine
Interbedded Lenticular Sandstone and Chert	trough & lens-shaped beds w/ erosional bottoms, some planar beds	dom massive. rare low- to moderate-angle megaripple crosslam, sm ripple crosslam, planar lam, burrowed upper bed surfaces	2'sand types (sources) vf-crs sand, section coarsens upward crudely, rare mud intraclasts	upper lower-flow regime, poss. local upper flow regime	episodic unidirectional currents or v assymetric waves	shallow-water sand body (bar and/or channels)
Burrowed, Finely Interbedded Sandstone and Dolomite	v discontinuous, thin beds	sm ripple crosslam, scour channels, flaser beds, graded beds, flame structures, burrows	f-crs terrigenous sand and slty dolomite mdst	lower-flow regime and no flow	intermittent waves or currents and suspension settling	mixed sand-mud tidal flat or poss. lagoon, tidal delta
Molluscan Packstone Dolomite	tk bed, poss. lenticular on several-meter scale	not evident except for locally directionally oriented shells,bed-parallel shells, rare bifurcating shell lenses	poorly srtd shell hash, grain and matrix support w/ slty (cly) dolomdst matrix. worn, broken & fresh fossil shells	turbulent, high energy	single, gen non-sorting depositional event w/ local reworking	storm coquina
Sandy Burrowed Dolomite & Chert and Sandstone	v thin-tk beds, lenticular and planar	abundant burrows esp. in f seds, rare planar lam	f-m sand, slty calc chert and sdy or cherty dolomdst	variable	alternating current or wave conditions and slack water	semi-protected shallow subtidal

Table 2. Rock unit characteristics and interpretations, Cedar Creek.

DATA				INTERPRETATIONS		
UNIT	BEDFORMS	INTRABED STRUCTURES	TEXTURES/COMPOSITION	TYPE OF FLOW	PROCESSES	DEPOSITIONAL ENVIRONMENT
Conglomeratic Sandstone & Dolomite	med-tk bedded, crudely planar, some truncating lower contacts	mottles, horizontal to vertical branching burrows	pebble to boulder congl at base of beds w/finer sed overlying	sporadically turbulent & energetic	episodic erosion & transport of crs sed followed by lower energy deposition	submarine
Pelletal Wackestone Dolomite 1) dolomite 2)sltst partings w/ chert nodules	1) tk planar beds. 2)v thin-med beds, crudely planar	1)burrows, stylolites 2)wavy planar lam & stylolites, poss. birdseye structure,	1)impure pelletal wackestone dolomite 2)slt w/vf sand,chert nodules,pellets & ang phos frags	suspension settling w/ poss. some lower-flow regime	1)organic production of carbonate mud & pellets. 2)wind and/or water-deposited clastics, sabkha diagenesis, solution	v shallow-water restricted carbonate lagoon or shelf, shallowing upward cycles
1) Brecciated Dolomite and 2)Stromatolite(?) Zone	1)thin, discontinuous. 2)med, discontinuous	1)breccia 2)wavy planar lam grading upward to prob. laterally-linked hemispheroids, stylolites	1) unsrtd ang clasts in grain and matrix support. 2) slt & dolomite mudst w/mnr sand and clay	1)------ 2) some lower-flow regime	1)autobrecciation, prob. solution collapse. 2) organic-related accumulation, prob. algal	shallow subtidal to supratidal
Bioclastic Wackestone Dolomite	tk beds, planar	bioturbation, stylolites esp. near bed surfaces	bioclastic wackestone w/ v sm fossils,slty, pelletal	suspension settling	<u>in situ</u> production of carbonate mud & shells	shallow, semi-restricted carbonate shelf or lagoon
Silty Black Chert	tk, lumpy bed	faintly to distinctly nodular,brecciated, stylolitic	chaotic qtz textures, self-healed fractures, mottles, tiny inclusions in authigenic silica	----------	inferred dissolution and replacement of evaporites by silica, brecciation and collapse	silcrete developed on exposed dolomite-evaporite surface
Molluscan Packstone Dolomite	tk, planar beds	bioturbation, local grain-supported lenses of large molluscs	molluscan packstone in bioclastic pelletal wackestone dolomite, mnr f clastics	intermittently quiet and turbulent	<u>in situ</u> production of carbonate mud and shells w/stronger energy transport of larger shells	semi-protected, semi-restricted shelf or lagoon subject to episodic storms

Table 3. Rock unit characteristics and interpretations, La Marche Gulch North.

DATA				INTERPRETATIONS		
UNIT	BEDFORMS	INTRABED STRUCTURES	TEXTURES/COMPOSITION	TYPE OF FLOW	PROCESSES	DEPOSITIONAL ENVIRONMENT
Silicified Dolomite Marker Zone	thin, discontinuous beds	poss. thin planar sed. lam w/lam of oxides and organic residue, non-tectonic fractures	dark mottles, f lam, relict sponge spicules, authigenic chert, dolo rhombs	---------	subaerial exposure of siliceous dolomite sediment, formation of silcrete crust	--------
Crossbedded Conglomeratic Sandstone	med trough- & lens-shaped beds w/erosional boundaries, rare planar beds	low- to mod-angled multi-directional crosslam, some v low- to planar-lam	f-m sand,w/dolomdst intraclasts and chert pebbles in bottom sets & along crosslam, rare discontinuous dolomdst beds	upper lower-flow regime, poss. upper-flow regime locally	intermittently migrating lunate megaripples, poss. local sheet flow	channels in sand bar system, poss. some bar crest seds and beach sands
Interbedded Lensy Molluscan Bioclastic Conglomerate & Sandstone	m-tk beds, dom lens & trough shaped, planar beds	dom massive, rare low- to mod-angle crosslam outlined by pebble or fossil lag, some oriented shells, troughs multidirectional	fossiliferous lenses unsrtd to bimodal, usu. grain support, geopetal matrix rare, f-m sand, some mud intraclasts, chert pebbles	turbulent, high energy, upper lower- to upper-flow regime	intermittently migrating lunate megaripples, sheet flow, poss. debris flow	tidal or longshore channels in barrier bar system
Bioturbated Marker Zone & Burrowed, Interbedded Sandstone & Chert	thin-med beds, discontinuous planar-wavy	rare planar & crosslam intense burrowing in marker zone	cherty dolomdst, well-srtd sands, sdy slty dolomitic chert	variable--lower-flow regime and suspension settling	alternating sediment sources and processes	semi-protected shoreface or lagoon

Table 4. Rock unit characteristics and interpretations, Sappington Canyon.

DATA				INTERPRETATIONS		
UNIT	BEDFORMS	INTRABED STRUCTURES	TEXTURES/COMPOSITION	TYPE OF FLOW	PROCESSES	DEPOSITIONAL ENVIRONMENT
Conglomeratic and Dolomitic Fossiliferous Sandstone	med-tk beds, crudely planar	erosional bases, massive except for some grading in upper conglomerate	pebble-cobble lag in lowest bed w/finer overlying seds, other beds poorly srtd, pebble-boulder clasts, rnd in upper bed, intraclasts in middle bed	episodic, turbulent & energetic	intermittent erosion and deposition	channel deposit? debris flow? proximal tubidite?
Phosphorite Shale and Sandstone	thin beds, discontinuous to planar	thin horizontal lam, lg vertical burrows	impure pelletal mdst, pelletal and fossil-fragmental sandstone	lower-flow regime and suspension settling	episodic sand transport or winnowing by currents or waves, otherwise quiet	protected, restricted subtidal w/crs storm? deposits
Burrowed Nodular Sandstone	tk beds, planar?	lg vertical burrows, soft-sed folding	crs-vf sand, mod well srtd w/ thin chert & phosphate pebble beds	evidence destroyed	?	poss. submarine bar or channel sands
Calcite and Quartz Nodules in Dolomite & Phosphatic Dolomitic Nodular Chert	tk beds	nodular, chaotic, rare thin lam in dolomite	massively nodular, locally chicken-wire texture, dolomdst matrix	suspension settling of carbonate mud	organic accumulation of carbonate mud followed by sabkha diagenesis	restricted lagoon or shallow carbonate shelf to supratidal
Very Sandy Chert	poorly exposed poss. thin beds	?	relict sponge spicules & authigenic silica w/slt, sd	?	?	shoreline spiculite?
Calcite Nodular Dolomite	tk beds	nodular zones parallel to bedding, bioturbation	impure pelletal? wackestone, horizon of lg gastropod shells, phosphorite frags	evidence destroyed	organic accumulation of carbonate mud & shells, in situ, sabkha diagenesis	shallow restricted lagoon or shelf to supratidal

Table 5. Rock unit characteristics and interpretations, Devils Slide.

DATA				INTERPRETATIONS		
UNIT	BEDFORMS	INTRABED STRUCTURES	TEXTURES/COMPOSITION	TYPE OF FLOW	PROCESSES	DEPOSITIONAL ENVIRONMENT
Conglomeratic, Dolomitic Sandstone	poorly exposed discontinuous	truncating lower boundaries, burrows, no internal sed structures	pebble-boulder sized clasts of mixed lithologies & large fossil molluscs in grain & matrix support	turbulent & energetic, sporadic	intermittent erosion and deposition of crs sediment, non-sorting	storm deposits? debris flows?
Sandy Dolomite	?too poorly exposed	bioturbated	sdy dolomite, sm fish teeth	? not enough data to interpret?		
Petroliferous Molluscan Packstone Dolomite	tk-med beds, poorly exposed	mottles, massive	packstone, molluscs of all sizes w/dolomdst matrix, mnr slt & sand, collapsed fossil molds	turbulent & energetic	non-sorting	storm deposits? insufficient data

Table 6. Rock unit characteristics and interpretations, Boulder River.

Wherever they lived, the molluscs' habitats were definitely subject to violent erosive forces and the community must have had to survive this disruptive activity or become reestablished fairly quickly. This was not the only problem imposed by their physical environment; waters were very shallow and may have had variable and/or higher than normal salinity. It is possible, but not proven, that toxic phosphogenic systems sometimes created seaward barriers to faunal migration. Apparently the molluscs could survive and sometimes even flourish under these conditions, occupying both dominantly clastic and dominantly carbonate sedimentary environments.

CHAPTER 2

THE MOLLUSCAN ASSOCIATION AND OTHER FOSSILS

Introduction

Giant scaphopods and bellerophontacean gastropods were recognized as a recurring low-diversity fossil group in Permian rocks of the western phosphate field by Yochelson (1968) whose fossil category number six (p. 592) includes:

> Plagioglypta, bellerophontacean gastropods, and Schizodus, or rarely Plagioglypta and (or) bellerophontaceans alone, commonly associated with pectenoid pelecypods and pleurophorid pelecypods, and rarely associated with orbiculoid brachiopods, Composita, nuculoid pelecypods, and (or) myalinid pelecypods.

The most common scaphopod of these collections, identified by Yochelson as Plagioglypta canna, was reassigned to Prodentalium canna by Yancey (1973). Yochelson inferred from the available biological, paleogeographic and stratigraphic evidence that the molluscs lived in very shallow, possibly hypersaline water. Table 7 summarizes Yochelson's (1960, 1963, 1968) and many other authors' conclusions about the life styles, preferred substrates and biological and environmental associations of ancient scaphopods and bellerophontaceans. They appear to have had a strong affinity for rigorous nearshore environments which were uninhabitable by more normal Paleozoic marine faunas. In this study I chose localities where scaphopods and bellerophontaceans were the most abundant

	SCAPHOPODS	BELLEROPHONTACEANS
Life Style	Shallow infaunal burrowers, microcarnivores and/or detritus feeders. Move horizontally through the sediment with long muscuar foot.	Epifaunal, benthonic active grazers or detritus feeders, possibly shallow burrowers.
Preferred Substrate	Fine-grained sandstone and carbonates (usually dolomite, calcareous mudstone, often phosphatic, organic rich, pyritic.	Fine-grained clastics, sometimes phosphatic and organic rich, notably bioturbated, firm bottom.
Habitat	Modern are wide ranging. Ancient show affinities for restricted marine, possibly hypersaline or fluctuating salinity, nearshore, shallow, moderately quiet water.	Restricted by aspidobranch gill to clear water (tolerated brackish and hypersaline as well as normal marine). Intertidal to nearshore platform areas.
Biological Associates	Epifaunal and infaunal bivalves esp. nuculoids and pectinoids, *Schizodus*, *Lingula*, *Orbiculoidea*, bellerophontaceans. Very abundant locally with molluscan-dominated near shore benthic community.	Lagoonal and offbeach algal stands, low-diversity, epifaunal and infaunal detritus feeding bivalves and molluscs, esp. nuculoids, linguloids, locally found with scaphopods.
References	Barnes,1968; Bretsky and Bermingham, 1970; Donahue and Rollins, 1974; Ludbrook 1960; Morton, 1959; Nassichuk and Hodgkinson, 1976; Rollins and Donahue, 1975; Trueman, 1968; Yochelson, 1963, 1968.	Bretsky, 1969; Linsley, 1978; Rollins and Donahue, 1975; Sutton, Bowen and McAlester, 1970; Yochelson, 1960, 1968.

Table 7. Life styles and physical and biological associations of scaphopods and bellerophontacean gastropods.

and obvious biotic elements in the rocks, hoping that they would lead me to some detailed conclusions about nearshore Permian paleoenvironments in southwestern Montana and the physical, and perhaps biological conditions that constrained them. This section introduces the biological component of the rocks. Appendix II provides a list of fossils found at the five localities.

The Molluscs

1. Scaphopods

Throughout their history, from Early Ordovician to Recent (Bretsky and Birmingham, 1970), scaphopods have exhibited remarkable evolutionary stability, conserving a basic conical shell form which puts taxonomists to task finding significant variations in ornamentation, curvature and size for classification. Their lack of ctenidia (gills) and heart, coupled with a very primitive circulatory system and unique feeding apparatus (Ludbrook, 1960) apparently place severe restrictions on the variety of habitats scaphopods can occupy and contribute to their evolutionary stability (Bretsky and Birmingham, 1970). All representatives of Carboniferous and Permian scaphopods in North America are accommodated within only four or five genera (Nassichuk and Hodgkinson, 1976), a fact which further emphasizes their conservatism.

The cosmopolitan genus, Prodentalium ranges from Lower Devonian to Upper Permian (Emerson, 1962). At Cedar Creek, silica molds faithfully preserved the subtle outer longitudinal shell ornamentation that is the primary distinguishing characteristic of Prodentalium canna (White).

At the other localities scaphopods are similarly large and thick shelled and are probably the same species, although the actual fossil material is not usually identifiable to the specific or even generic level. During a Permo-Carboniferous acme Prodentalium became the largest member of its class ever reported, with shell thicknesses up to 8 mm and lengths over 200 mm. Giant Permian scaphopod shells in southwestern Montana are characteristically 2 to 7 mm thick and many had original lengths of 200mm or more. Modern scaphopod shells are composed of two layers of aragonite (Majewske, 1969). Ancient ones had two layers of aragonite (Orlov, 1960, in Bretsky and Birmingham, 1970) or three calcareous layers (Emerson, 1962; Nassichuk and Hodgkinson, 1976).

Modern scaphopods live partially buried in fine-grained, organic-rich sediment. They collect food particles with specially adapted tentacles called captacula and pull themselves forward with a strong foot. The posterior end projects above the sediment surface for inhaling and exhaling water (Fig. 30) (Morton, 1959; Yonge, 1960; Trueman, 1968; Barnes, 1968). Scaphopods appear in the rocks of this study in dolomite and sandstone which originally ranged in grain size from mud to fine sand. During their lives, water movement must have been normally less than that required to move the substrate and dislodge them.

Most scaphopod fossils in this study are oriented parallel or subparallel to bedding. This could be a life position very slightly altered by winnowing or settling, but it is probably the result of stronger wave and current activity since most shells occur in large but broken sections, commonly directionally alligned and frequently in grain support. Curiously,

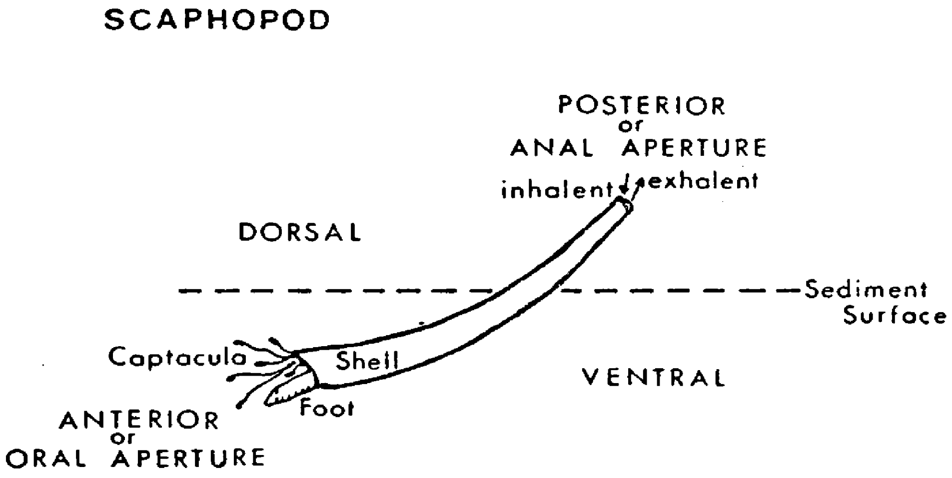


Fig. 30. Orientation and morphological features of a scaphopod, from Emerson (1962) and Bretsky and Birmingham (1970).

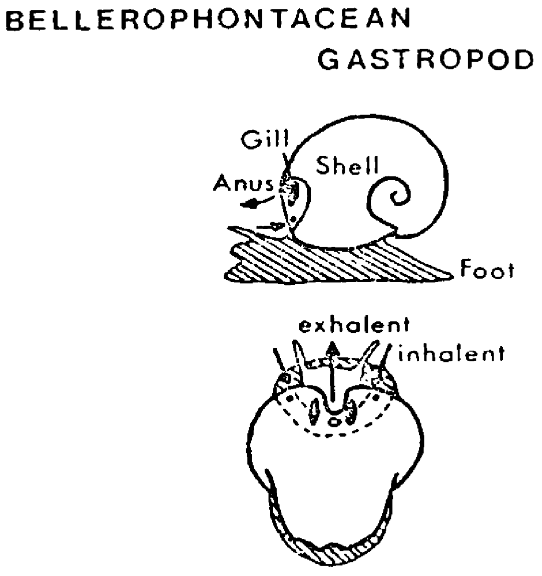


Fig. 31. Morphological features of a bellerophontacean gastropod, from Linsley (1978).

at Sappington Canyon and La Marche Gulch, scaphopod shells are telescopically nested inside each other (Fig. 14). Yochelson and Fraser (1973) observed similarly nested scaphopods in a beach deposit in the Permian Plympton Formation of Nevada and suggested that the nesting is a feature of current deposition. Alternatively, the back-and-forth motion of waves might be responsible. Given sufficient shell density, arcs circumscribed by oscillating conical shells could intersect, occasionally allowing larger shells to "capture" smaller ones and creating the nested effect. Because the orientation occurs at only two localities it is probably not related to life habits of the animal.

Abundant borings on specimens at Cedar Creek, La Marche Gulch and Sappington Canyon are roughly the same size and shape at all localities and resemble acrothoracican barnacle borings (Tomlinson, 1963, 1969; Yochelson, 1968; Seilacher, 1969). Borings are preferentially located along grooves in the posterior ends, along a single side of the shell length, or around worn and broken ends. Posterior borings were probably acquired during the animals' lives when that was the only exposed portion of the shells and when water currents created by the living scaphopods may have created favorable conditions for the filter feeding barnacles. Other borings (eg. those located on worn ends of broken shells) were obviously made when the shell lay immobilized and partially buried in the substrate. Borings rarely penetrate the whole shell and there is no reason to suspect a parasitic relationship. Tomlinson (1969) notes that, "the cirriped can at most be considered a very modest shell weakening pest, and in general does little if any harm to the host."

2. Bellerophontaceans:

The superfamily Bellerophontacea (Upper Cambrian to Lower Triassic) (Cox, 1960) encompasses most of the gastropod fossils in these rocks. These shells are characterized by a high degree of bilateral symmetry, lack of septae, and an anal slit that aided in separating exhalent and inhalent water currents (Fig. 31) (Linsley, 1978). Shells were probably originally aragonite (Cox, 1960). A primitive, easily fouled aspidobranch gill structure probably restricted them to relatively clear water and firm bottoms (Yonge, 1947 and Yonge *in* Yochelson, 1960). They were a diverse group with adaptations primarily for active grazing but also perhaps for burrowing and even for preying upon other animals (Linsley, 1978).

Four genera of bellerophontaceans are distinguishable at the five localities of this study (Appendix II). At Cedar Creek many specimens can be identified to species level but elsewhere inferior preservation usually only allows recognition of the bilateral symmetry of the superfamily. Their maximum size at all localities is about 4 cm wide. As Yochelson and Fraser (1973) note, these adults were probably too big to live on algal fronds and may have grazed shoreline algal mats. They may also have fed on seafloor algae or detritus.

Bellerophontacean shells are preserved in the same sandstones and dolomites as the scaphopods, but their spherical shapes preclude preferential orientation. Although there are some nearly perfect specimens, they are commonly worn, broken and extensively bored. Barnacle borings like those on the scaphopods are sometimes locallized on positive surfaces and within grooves of shell ornamentation (see also Seilacher, 1969). Some of the shells are abraded in a manner characteristic of beach shells, especially at Cedar Creek.

Tiny gastropods 1.0 to 2.0 mm wide form a significant microfauna at all localities and are interpreted to be juveniles (or perhaps very stunted adults). Their shell shapes show affinities with high, medium and low spired asymmetrical gastropods in addition to bellerophontaceans and they appear to represent a more diverse group than the larger shells. The bellerophontaceans are specifically interpreted to be juveniles on the basis of their small number of whorls (all those counted had less than 4) (see Tasch, 1953).

Preserved shells in the upper fossil zone at Devils Slide are almost entirely two species of bellerophontaceans (Appendix II) plus a pelecypod, Schizodus, identified by Yochelson (1968), and some unidentifiable fragments. Many of the best preserved bellerophontacean shells appear to have been originally fresh and unworm. Most of them are about the same size (3 to 4 cm wide) and they occur concentrated at one stratigraphic level as discontinuous lenses one or a few shells thick. The striking lack of diversity is probably not simply a matter of selective preservation or hydrodynamic selection since unidentified fossil fragments in the bed are identically preserved as authigenic silica mold fillings. Perhaps the bellerophontaceans were transported from a place where they were the only large shelled animal living, or perhaps they lived more or less where they are deposited and represent a "flash in the pan" colonization event by a generation of opportunistic gastropods. The later might explain why they are all the same size. Either way, the deposit records a remarkably non-diversified shelly community and this non-diversification must have been the result of very rigorous physical or chemical restriction. The gastropods might have thrived on an intertidal algal mat for a brief time when the water was not too salty. A modern analog could be the browsing cirithid gastropods and their faecal pellets which make up most of the intertidal belt faunal remains around hypersaline lagoons in the southwestern Persian Gulf (Illing, _et al_., 1965).

The only other whole fossils at Devils Slide are the small gastropod steinkerns which are distributed throughout much of the section and are possibly juveniles killed by the same conditions which excluded other animals. These microsphorite steinkerns are also uniform sized (1.0 to 2.0 mm). Perhaps at that size the gastropods changed life styles, for example by moving from hospitable surface waters to anoxic or above-normally saline bottom waters. Diagenetically-replaced evaporite nodules in the sediments record hypersaline conditions and authigenic pyrite and microsphorite indicate low oxygen levels. If these conditions also affected the depositional environment they would have had powerful restrictive influence on the diversity of life forms. Alternatively, the micro-gastropods might have occupied a subtidal algal mat which was a phosphogenic system at least periodically. Bathurst (1976, p. 123) describes a fauna including micromolluscs which he found in modern subtidal mats in the Bahamas. Since it is best developed in very shallow water, the mat is subject to storm disruption, possibly explaining why the steinkerns and phosphorite fragments at Devils Slide are scattered through the carbonate rocks.

3. Pelecypods:

Six genera of pelecypods were identified in this study (Appendix II). All are cosmopolitan and except for *Polidevcia* (Devonian to Lower Triassic) their common range is Carboniferous to Permian. All or most of these shells were originally aragonite (Cox, 1969). The protobranchs (*Nuculopsis*, *Polidevcia*) are very primitive bivalves whose modern representatives make their livings as shallow infaunal detritus feeders (Yonge, 1939). They are most abundant in extremely shallow water, organic-rich sediments where they use proboscis-like extensions of the labial palps to gather food particles. The other most common bivalves, *Schizodus*, *Permophorus* and *Pseudopermophorus* are all shallow-burrowing, infaunal filter feeders (Yochelson, 1968). *Schizodus* and the nuculids appear in other faunal associations noted by Yochelson and individually as the dominant genera of very near shore, perhaps hypersaline environments especially in the Franson Member (Yochelson, 1968).

In the rocks of this study pelecypod shells are usually disarticulated and preferentially oriented. A few *Schizodus* at Sappington Canyon Canyon and *Pseudopermophorus* at Cedar Creek were preserved as articulated individuals. At Cedar Creek articulated pelecypod shells are also the only ones found in a vertical (life) orientation. Perhaps they lived in the sediments after they were deposited or are preserved in an attempt to reorient themselves and escape after they were incorporated into the sediment. Some articulated Pseudopermophorus shells never filled with sediment and were crushed during early compaction of the sediment.

Barnacles bored surfaces of the stouter shells and shell fragments. Pseudopermophorus shells at Cedar Creek are characteristically most intensely bored at the posterior tips (Fig. 32), suggesting that, like the scaphopods, they were bored during life, when only the posterior tips of the shells were exposed. Coarse surface ornamentation of Pseudopermophorus shells indicates that they were designed for stability in a substrate that may have been regularly reworked by wave and current action (Kauffman, 1969). At Cedar Creek, interior surfaces of bivalve shells occasionally contain silicified tubes of worms which inhabited the dead animals' shells.

Miscellaneous Animals

Tiny, very poorly preserved shells of creatures which might have been ostracods were noted at all localities, especially at La Marche Gulch and Boulder River. The fragile nature of these shells suggests that they were not transported very far and their presence indicates the possibility of abnormal salinities (Benson, 1961; Walker and LaPorte, 1970).

Most of the other animal fossils were probably only peripherally related to the molluscan fauna, or are totally exotic to it. Ramose bryzoan fragments, locally large and abundant at Cedar Creek, are very minor constituents elsewhere. Disarticulated crinoid ossicles were seen only at Cedar Creek, where they are a common constituent of the gravel-sized shell debris. Bryzoans and crinoids both require more normal

Scale 3 cm.

Fig. 32. Silica mold of Pseudopermophorus annettae with barnacle-bored posterior tip (arrow).

marine waters than the molluscs. They may have lived in carbonate bioherms a little farther to the west and south (Mclellan, 1973; Brittenham, 1976). Their rarity in the rocks, worn and fragmented condition and stenohaline restriction all suggest that they were not part of the living scaphopod-bellerophontacean community. The fossil deposit at Cedar Creek with its mixture of members from different communities, wide range of highly abraded to unworn shells and unsorted to moderately sorted texture strongly support the interpretation that it is a beach coquina.

Siliceous sponge spicules in the Phosphoria and related rocks are of the class Desmospongia, a shallow-water form that thrives within the photic zone in areas of clear, normal marine water, moderate currents and firm substrates (Cressman and Swanson, 1964; de Laubenfels, 1955). Sponge spicules are extremely rare in mollusc-bearing rocks although spiculitic dolomite and chert interfinger with those sediments. Spiculitic mud adhered to shells and formed intraclasts in some of the sandstones at Sappington Canyon. No whole sponges were observed and the spicules probably came from outside the mollusc community.

Phosphatic fish teeth, bone fragments and scales, and fragmented phosphatic brachiopods are found locally in trace amounts in the fossiliferous sediments or as more concentrated deposits. Lingula and Orbiculoidea fragments are a major constituent of some phosphorite beds at Devils Slide and they appear as whole fossil impressions on bed surfaces of sandstones underlying the molluscan horizon at Sappington Canyon along with rare Acanthopecten and Schizodus.

Plants

Surprisingly, some identifiable plant remains are preserved in these very altered rocks. Dasycladacean (green) algal fragments are rare in the fossiliferous rocks at Cedar Creek and fairly common in the siliceous dolomite intraclastic sandstone at Sappington Canyon where many have a little siliceous dolomite adhering to them. Modern Dasyclads grow in warm, extremely shallow water, just below low tide to about 15 m depth, especially in protected lagoonal environments where they are major contributers to calcareous mud sedimentation. They can tolerate water salinity of 50 to 60 0/00 (Wray, 1969; Ginsburg _et al_., 1971; Wilson, 1975). Also at Sappington Canyon, an impression in sandstone of a large, heavily ribbed leaf suggests the presence of terrestrial plants nearby. Small fragments of what appears to be phylloid (Codiacean?) algae are preserved in silicified dolomite below the fossil-bearing horizon at Devils Slide. They appear in rocks which probably hosted diagenetic growth of evaporites and are also considered to be shallow water plants which are tolerant of slightly increased salinity (Ginsburg, _et al_., 1971; Wilson, 1975). Their presence helps substantiate the theory that the sediments formed in a restricted shallow shelf or carbonate lagoon. Both of these algal types grew as erect plants and could have acted as sediment baffles and also dissipated wave energy, reducing water circulation in a manner analogous to modern seagrasses (see, eg., carbonate banks of Shark Bay, Australia, Davies, 1970). Fossil blue-green algae cannot be directly identified in these rocks, but wavy linear structures in the dolomite at La Marche Gulch and stromatolite-shaped structures might record their former presence. Also at that locality, angular fragments of phosphorite are tentatively identified as algal mat chips.

Trace Fossils

Besides barnacle borings on shells (described above) a variety of burrows (Appendix II) record the activity of living creatures. These trace fossils, generally not a major element of the fossiliferous beds, are frequently abundant in adjacent strata.

The most conspicuous burrows are large (up to 7 cm diameter by 1.5 m long), columnar-shaped (and very rarely branched) structures noted primarily in sandstones but also observed in sandy dolomite and phosphorite. They have been previously described and discussed (Cressman and Swanson, 1964; Yochelson, 1968; Peterson, 1972; Young, 1973) and are found throughout the Permian rocks in southwestern Montana, and in northeastern Idaho and northwestern Wyoming, mostly in the Shedhorn Sandstone. Gutschick and Suttner (1975) summarized previous studies and compiled new information about these structures, concluding that they are feeding or escape burrows, created perhaps by infaunal siphon-feeding clams or decapod crustaceans. No fossil animal capable of creating the burrows has ever been discovered in one.

Diplocraterion, Skolithos, Planolites, Thalassinoides and escape burrows, all of which occur in the bioturbated strata directly above fossil beds at Sappington Canyon (Appendix II), were identified in the protected-shoreface environment of Permian rocks in Australia, with the last three exclusive to that environment (McCarthy, 1979). By analogy, these trace fossils contribute to the interpretation of the Sappington

Canyon rocks as a quiet, protected shallow-water facies, which in this case was probably situated behind a fossiliferous sand bar and channel facies (Chapter 1). The fossil bed at Cedar Creek overlies beds which contain possible Thalassinoides burrows (Appendix II). Their protected-soreface affinity (McCarthy, 1979) strengthens the independent evidence suggesting that those rocks also formed in a protected shallow-water setting.

Knut Andersson (University of Wyoming) is conducting an extensive study of Permian trace fossils in the western phosphate field which includes some of the localities of this study.

Summary and Conclusions

Statistical comparisons of faunal diversity at the five southwestern Montana localities were impractical because quality of preservation varied too widely between localities. Table 8 shows the dominant faunal elements and gives an approximate idea of relative diversity. In a semi-quantitative manner the localities can be listed in order of decreasing diversity: 1) Cedar Creek, 2) Sappington Canyon, 3) Boulder River, 4) La Marche Gulch and 5) Devils Slide. Cedar Creek almost certainly preserves a death assemblage of mixed living groups and diversity is also highest there because of the good preservation. The Devils Slide locality is definitely the least diverse of the five.

The apparent low diversity and absence of more normal Paleozoic marine life indicates some biologically restrictive influence. Although diversity is a complex community property, responsive to many parameters besides physical habitat structures (eg. Terborgh, 1977), most preserved members of this fauna were reportedly tolerant of rigorous physical conditions, specifically variable salinity. A molluscan-dominated fauna is by itself indicative of shallow water (eg. Bretsky, 1969; Stevens, 1971). The distribution and size of fossils, especially at Devils Slide, suggests that animal populations fluctuated rapidly, probably within the lifetime of a single generation. Except for microgastropods, molluscs at all sites tend to be either absent altogether or large and abundant. While this might be partially the result of physical processes during sedimentation or diagenetic processes effecting preservation, most localities show only minor effects of sorting and also contain minor non-molluscan fossils. More likely, the rocks preserve a history of creatures who lived on the borderline of physically tolerable marine conditions that fluctuated between extremely inhospitable and restrictively hospitable to tolerant opportunistic organisms. Enough time elapsed between disruptive events to allow for gigantic growth of scaphopods.

Inferred life habits of the molluscs as well as evidence from these rocks indicates a very low degree of biological interaction. They probably comprise a non-dependent association as defined by Kauffman and Scott (1976, p. 20). A low level of biological interaction provides circumstantial evidence in favor of interpreting them as members of a physically controlled community.

Although bellerophontaceans and scaphopods were often deposited together, their habits probably did not precisely overlap but were close enough for shells to mix during deposition. This suggestion is supported by the occurrence of bellerophontaceans without scaphopods at Devils Slide and by the dominance of bellerophontaceans in the lower fossiliferous zone at Boulder River and scaphopods in the upper zone (p.71). That these are not results of hydrodynamic selectivity is supported by the fact that the two animals occur together in other deposits of this study and elsewhere, where current and wave sorting did occur at least to a minor degree. Grazing bellerophontaceans might have survived better in firmer bottomed (subtidal or intertidal algal mat) zones while shallow-burrowing scaphopods preferred a slightly softer (shallow subtidal) substrate.

LOCALITY	SCAPHOPODS	BELLEROPHONTACEANS	PELECYPODS
CC	*Prodentalium*	*Knightities* *Bellerophon*	*Nuculopsis* *Pseudopermophorous* *Schizodus*
LG	Scaphopod (indet.)	Bellerophontacean (indet.)	Pelecypod (indet.)
SC	Scaphopod (indet.)	Bellerophontacean (indet.)	*Schizodus*
DS		*Bellerophon* *Euphemitopsis*	
BR	Scaphopod (indet.)	Bellerophontacean (indet.)	Pelecypod (indet.)

Table 8. Dominant fauna in the fossil-bearing rocks, determined semi-quantitatively. Information from Yochelson (1968) and this study.

CHAPTER 3

DIAGENESIS IN THE FOSSILIFEROUS ROCKS

After sediments are deposited, diagenesis usually alters or obliterates some of the original characteristics. As the sediments alter toward equilibrium with changing physical and chemical conditions, clues reflecting the depositional environment are overprinted by new textures and mineralogies. Although diagenesis is primarily postdepositional, it can proceed at normal surface temperatures and pressures so that very early diagenesis is common, especially in carbonate rocks. In this case, alteration will reflect conditions inherent in, or at least related to, the original sedimentary environment. I investigated the types and sequences of diagenetic events recorded in the Permian rocks primarily to discover what environments produced the earliest changes in the sediments and were therefore most closely related to depositional conditions.

This chapter describes and interprets the observed effects of diagenesis in the fossiliferous zones, where carbonate was an important component of the original sediments at all localities. Fossils are especially useful indexes of change because, where remains are identifiable, original shapes, textures and mineralogies can be determined with relative certainty. A summary and environmental interpretation follows a locality-by-locality description of diagenetic events and their relative timing.

Descriptions and Interpretations by Locality

1. Cedar Creek

a. Description:

At Cedar Creek, fossils occur in a 0.5 m to 1 m thick, poorly sorted, impure packstone dolomite. The fossil component is dominated by scaphopods, bellerophontacean gastropods and pelecypods and also contains crinoid, bryzoan, brachiopod and probably algal debris. The original carbonate mineralogy was therefore aragonite with minor high- and low-Mg calcite. The silty, sandy microcrystalline matrix was probably impure lime mud before diagenesis.

Fossil content throughout the bed is fairly consistent, but differences in preservation give it a very heterogeneous appearance; diagenesis has produced a curious three-tiered vertical zonation of fossils (Fig. 33). Weathered surfaces on the unresistent upper part of the bed, Zone A, display sandy concentrations which, on closer scrutiny, turn out to be sand-filled molds of dissolved mollusc shells. In the middle, Zone B, the same kinds of fossil molds are filled with authigenic silica. These fossils, and some locally chert-replaced matrix, make this part of the bed more resistent. At the base, in Zone C, most of the larger mollusc fossil molds collapsed, leaving only their impressions which appear subtley on freshly broken rock surfaces.

Zone A. The upper zone contains thin lenses and stringers of sand which stand out in moderate relief on weathered surfaces (Fig. 34). Many sand concentrations have the shapes of gastropods, scaphopods and

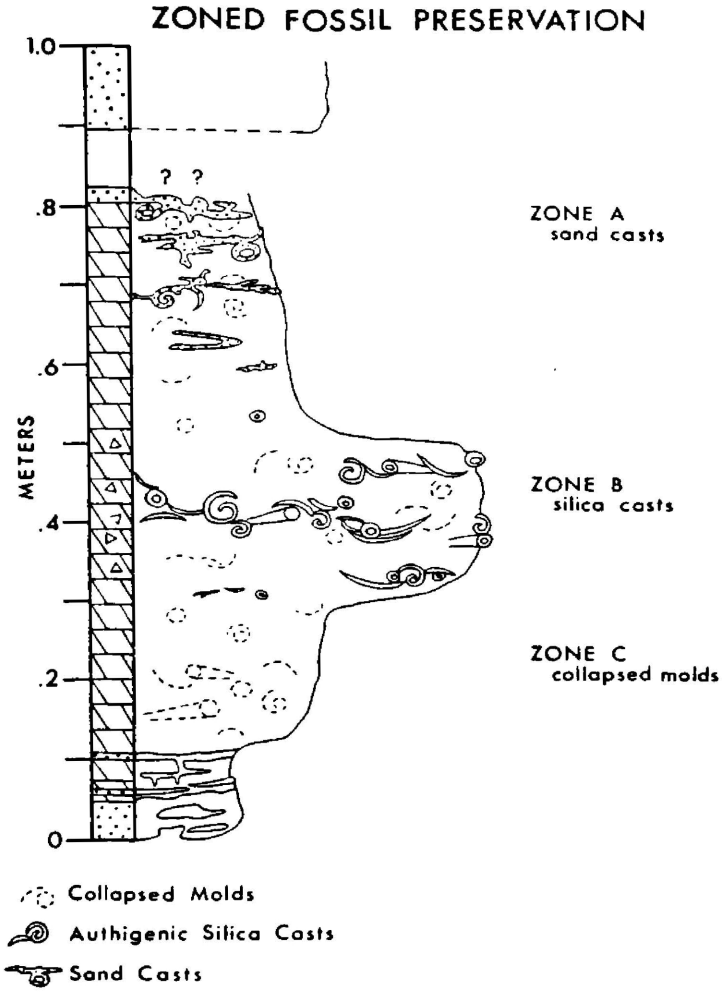


Fig. 33. Diagrammatic representation of the mollusc fossil bed at Cedar Creek, showing the zonation of three different types of shell preservation.

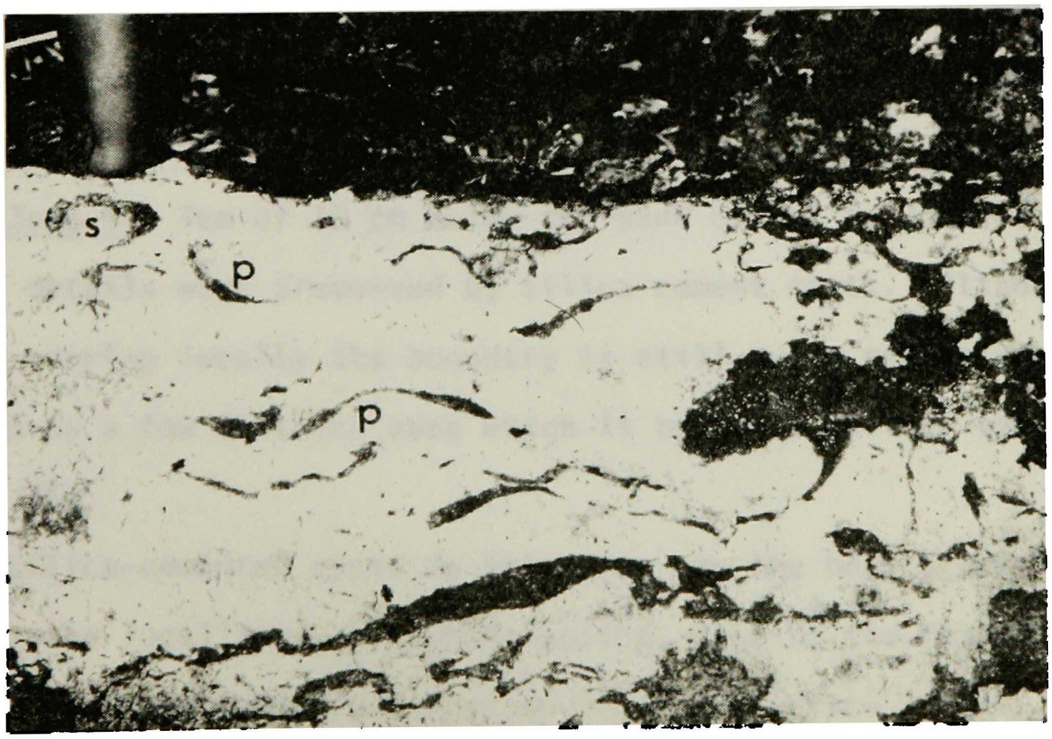


Fig. 34. Sand fossils in Zone A including pelecypods (p) and partially collapsed scaphopod (s). Finger for scale.

pelecypods. Some fossil molds are completely filled by sand but others were distorted during partial collapse (Fig. 34) and in some places by shearing, which demonstrate that the sediment was still soft when the molds formed and filled. Most sand pockets and lenses are only vaguely suggestive of fossils, burrows or solution cavities. Density of sand-fossil casts, lenses and stringers generally increases upward in the zone, but may be locally very erratically distributed. Sand structures commonly form connected networks, but these could not always be observed.

Thin sections show that mold filling is fine-grained carbonate-phosphate-chert-quartz sandstone cemented by sparse quartz overgrowths and dolomite (Fig. 35). Matrix micritic carbonate at mold surfaces deformed plastically around sand grains, destroying shell detail. No carbonate or silica cement lines the walls of these sand-filled molds and dolomite texture is unchanged from the matrix to the cement of sand fillings, suggesting that dolomitization accompanied or postdated mold formation and filling.

Zone B. Ten or 15 cm below the sand casts, in Zone B, the finest shell details were preserved by silica cement casts. Although the two zones overlap locally the boundary is still quite recognizable, locally marked by a few cm-thick zone which is barren of either type of fossil (Fig. 36).

Silica-cemented casts in this zone are the best preserved fossils of all the localities. In thin section, most of the fossil fillings show geode-type cement growth from the mold surface inward. Many of them are identical to textures described by Schmitt (1979) and Schmitt

Fig. 35. Photomicrograph of part of a sand-filled pelecypod mold, Zone A. Note well-sorted quartz and chert grains and collapsed matrix around them.

Fig. 36. Zonation of fossil preservation: silica molds of pelecypods and scaphopods at the base (Zone B), sand molds at the top (Zone A) and an area of mostly collapsed molds between them.

Fig. 37. Typical open space-filling quartz textures in a silica-filled fossil mold, Zone B. A microcrystalline quartz rind (m) was overgrown by chalcedonite (c) which grades inward to blocky megaquartz (q).

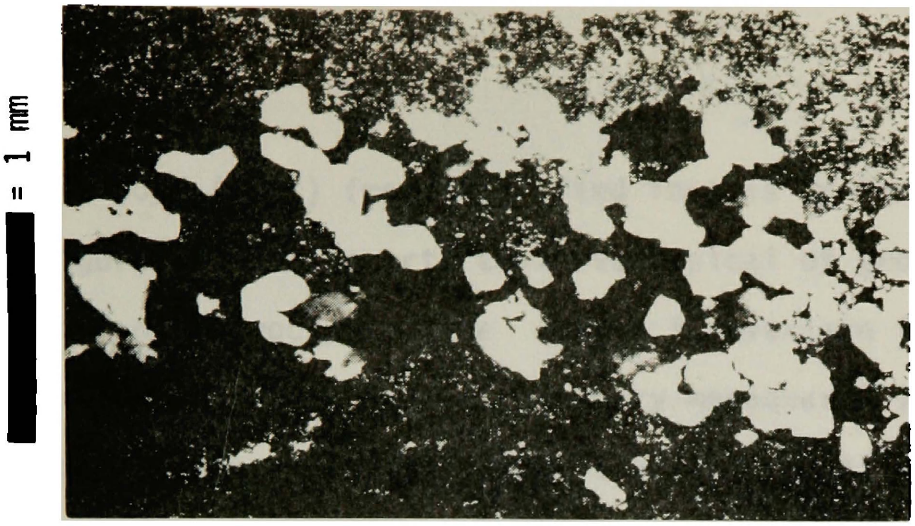
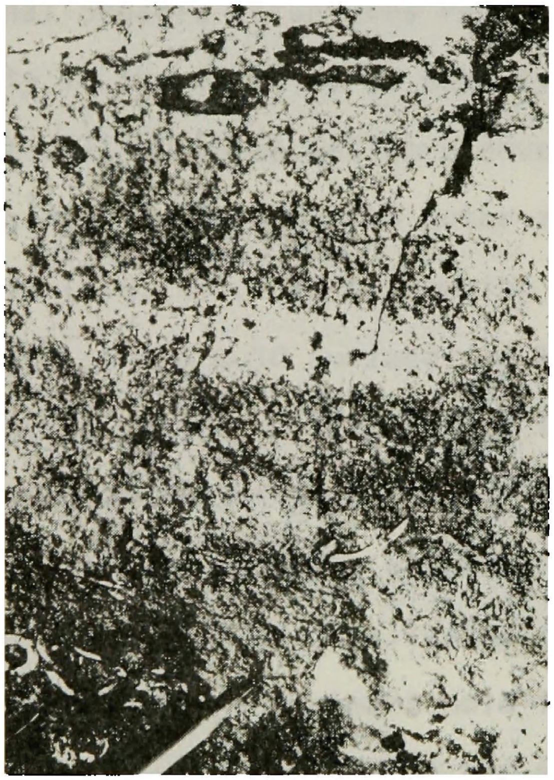


Fig. 35



Sand Fossils

Collapse Zone

Silica Fossils

Fig. 36

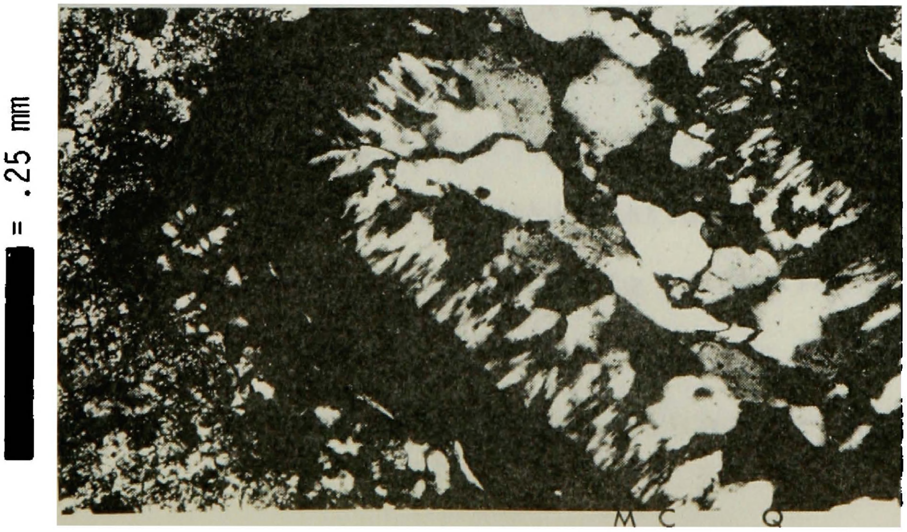


Fig. 37

and Boyd (1981) from silicified fossils in Permian rocks of Wyoming. Figure 37 shows quartz textures typical of growth into a void; a thin rind of microcrystalline quartz is overlain inward by chalcedonic megaquartz which grades to blocky megaquartz in the center. A few of the fossils are entirely microcrystalline quartz and it is possible that this texture is direct replacement of shell material (Schmitt, 1979) although no original organic structures remain. Chert replaced carbonate matrix very locally in the vicinity of densely fossiliferous lenses.

Many, but not all, of these well-preserved fossils have a dark, extremely fine-grained, inclusion-rich outer zone that is probably a remnant micrite rim (Fig. 38). Fossils which had micrite rims tend to have dolomite cement at the mold surface. A few shell molds are lined by dolomite displaying relict calcite cement textures (Fig. 38). Locally quartz replaces dolomite rhombs in both mold fillings and matrix, showing that quartz growth followed dolomite growth in those molds.

In addition to localized mold collapse, many shells in Zone B were fractured before dissolution and cement mold filling. Most offset is only a few millimeters and silica cement has mended the breaks showing that breakage occurred before silica cementation. Angular fractures offset otherwise undeformed fossils and are not visibly propagated into the surrounding matrix, indicating that breakage preceded shell dissolution and matrix lithification. Fractures are generally perpendicular to bedding and appear to be the result of compaction deformation.

Zone C. The large fossil molluscs in Zone C are very subtley preserved. The same size fossils which have shell walls several millimeters

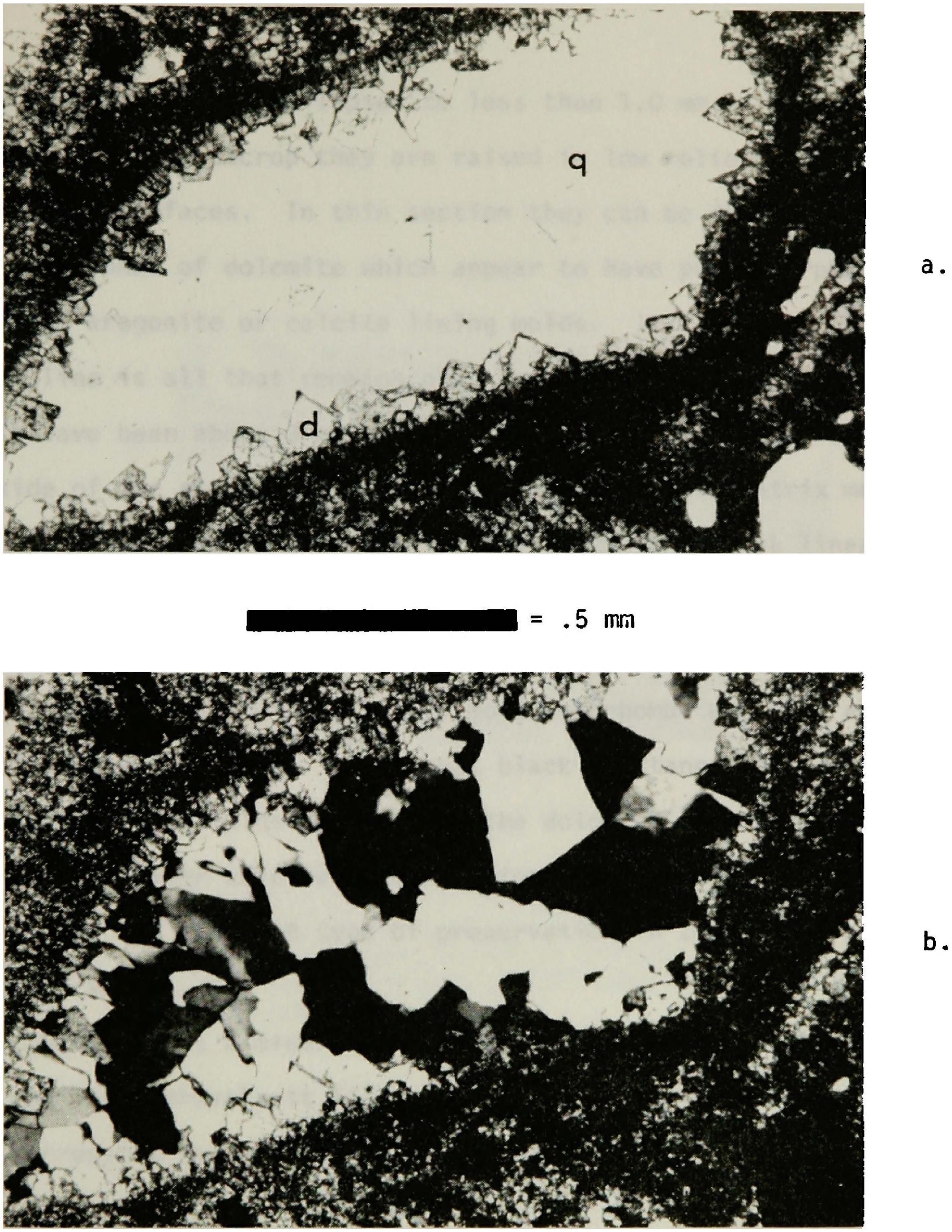


Fig. 38. Plane light (a) and crossed polarizers (b) photomicrographs of a fossil fragment in Zone B. Note dark relict micrite rim (m), radial fibrous calcite cement (c), cavity-lining dolomite rhombs (d), and blocky megaquartz filling (g).

thick in Zone B are collapsed to less than 1.0 mm of filled or open mold space. On the outcrop they are raised in low relief on broken and weathered surfaces. In thin section they can be distinguished sometimes by thin zones of dolomite which appear to have pseudomorphously replaced fibrous aragonite or calcite lining molds. In Figure 39 the thin dolomite line is all that remains of a scaphopod shell wall which originally must have been about 3 mm thick. Material to the right was originally inside of the shell and is denser and sandier than matrix material to the left. The matrix is characterized by a jumble of dark linear zones. Some of these are micrite rims which have collapsed into open molds and can be traced into dolomite-filled fossil molds. Partially open molds are commonly lined with euhedral dolomite rhombs and some are filled with blocky calcite cement. An opaque, black substance (dead oil?) coats the insides of some molds inward from the dolomite and appears to have locally obstructed later calcite precipitation. Collapsed or partially filled molds are the dominant type of preservation in Zone C but also occur in Zones A and B.

Dolomite is a minor cement in all three zones. Coarse, blocky calcite is the last arrival; it filled a few remaining voids and some fractures that crosscut the earlier cements.

b. Discussion:

Crosscutting relationships of shell and mold deformation and successive cement growth as well as local mineralogical replacement help define the sequence of events. This sequence is clear except for timing of dolomite growth which overlaps some of the other events:

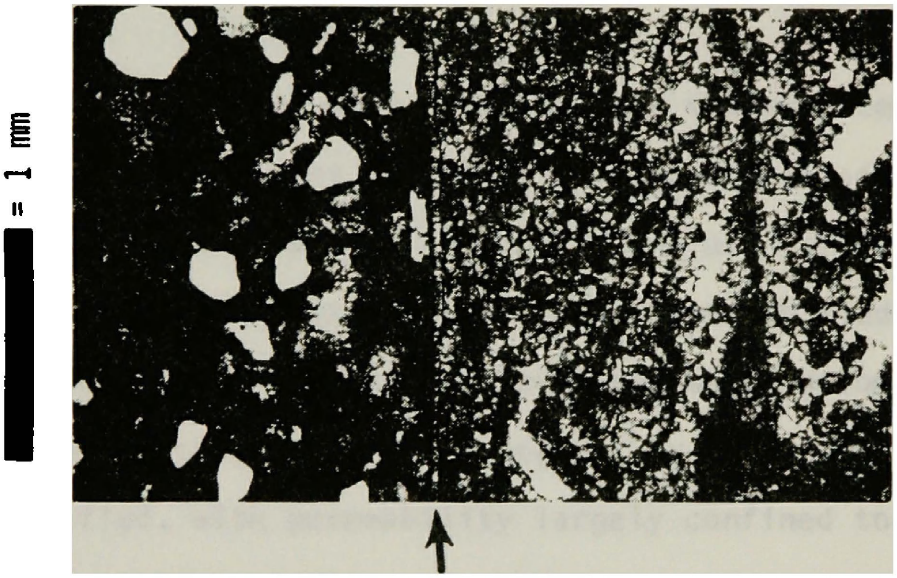


Fig. 39. The thin dolomite line (arrow) in this picture is a collapsed mold in Zone C. It separates the interior of a large scaphopod (left) from the porous dolomite matrix (right) which contains more collapsed molds, seen as dark linear structures.

1) Soon after deposition, aragonite fossils and some of the matrix dissolved and minor calcite cement precipitated.

2) Dolomitization probably began during mold formation or shortly afterward. Newly forming moldic porosity probably enhanced movement of dolomitizing fluids through the sediment, which was still mostly unlithified.

3) Except where they were propped up by dolomite cement, most of the molds in Zone C and many elsewhere collapsed soon after they formed.

4) Molds in Zone A were filled with sand and deformed plastically while the surrounding matrix was still mostly unlithified.

5) Although there may be minor overlap, major dolomitization stopped before silica precipitation began. By this time the rock was becoming lithified, with permeability largely confined to connected moldic porosity in the middle zone which had escaped sand filling and collapse. The most permeable region would be the natural path for silica-bearing solutions, and that is where most of the authigenic silica grew. Some carbonate matrix was replaced and sands in Zone A were partially cemented by quartz overgrowths.

6) Finally, minor blocky calcite grew as the last cement.

2. La March Gulch North

a. Description:

Fossil molluscs at this locality lie in an impure pelletal wackestone dolomite at the top of a series of dolomite-to-siltstone units (Fig. 8). Recognizable fossils are dominantly gastropods and scaphopods; original shell material, which was mostly aragonite, has vanished along with shell textures and structures. The very fine-grained dolomite matrix was probably micrite mud before diagenesis.

Two types of preservation emphasized (or possibly created) an apparent bimodal size distribution of fossils (Fig. 40). Most of the larger fossils are part of a connected network of molds in grain-supported lenses which are filled with fine-grained, light gray dolomite. Smaller fossil molds (less than about 0.5 cm largest dimension) are lined with coarse euhedral dolomite and filled with blocky calcite.

Large Fossils. Dolomite filling the larger fossils and connecting vuggy pore spaces in the matrix is equigranular and anhedral to subhedral with crystal diameters usually between 0.02 mm and 0.05 mm. Crystal fabric of the fossil-filling dolomite grades into matrix dolomite, sometimes across a dark relict micrite rim, but the boundary between fossils and matrix is easily distinguishable because of the darker color of the matrix which contains finely disseminated organic material, pyrite, quartz sand and silt, phosphorite grains and small fossils. These materials are absent in the fossil dolomite except where they occur in angular, 0.1 mm to 1.0 mm sized, floating fragments of matrix-type dolomite (Fig. 41).

The clean dolomite fills large fossils and some adjacent pores and, very rarely, occurs above geopetal, matrix-type dolomite filling primary void spaces. It is never found in small fossils and does not form beds or other primary sedimentary packages in the surrounding rocks.

Small Fossils. Well-formed, rhombohedal dolomite cement crystals (commonly 0.05 mm to 0.1 mm in diameter) line the walls of most small fossils and a few larger ones which are not filled with the dolomite discussed above (Fig. 42). Many of the smaller molds have relict micrite

Fig. 40. Large thin section showing bimodal fossil size distribution at La March Gulch North. A large broken scaphopod in the lower right corner contrasts with smaller fossils and fossil hash in most of the slide. Scale = .5 cm.

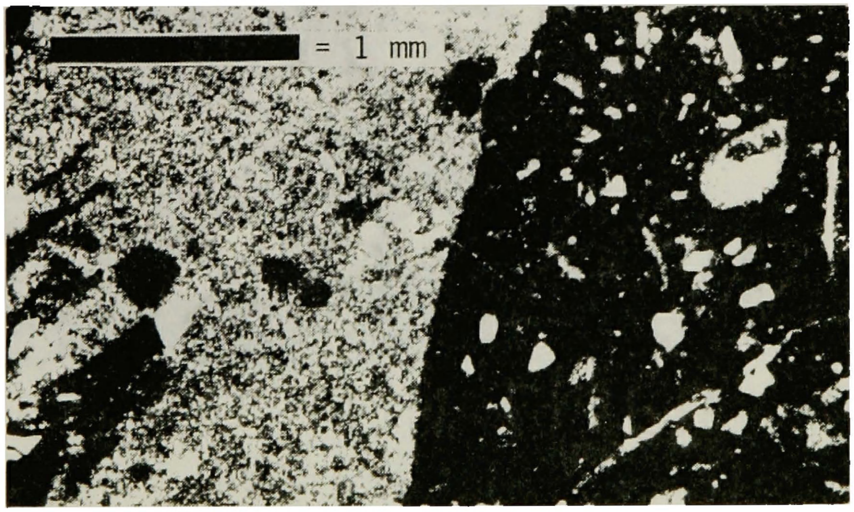


Fig. 41. Photomicrograph showing mold filling of a large scaphopod on the left (light color) and dolomite matrix on the right. Pieces of matrix-type dolomite and detrital quartz grains float in the mold filling.

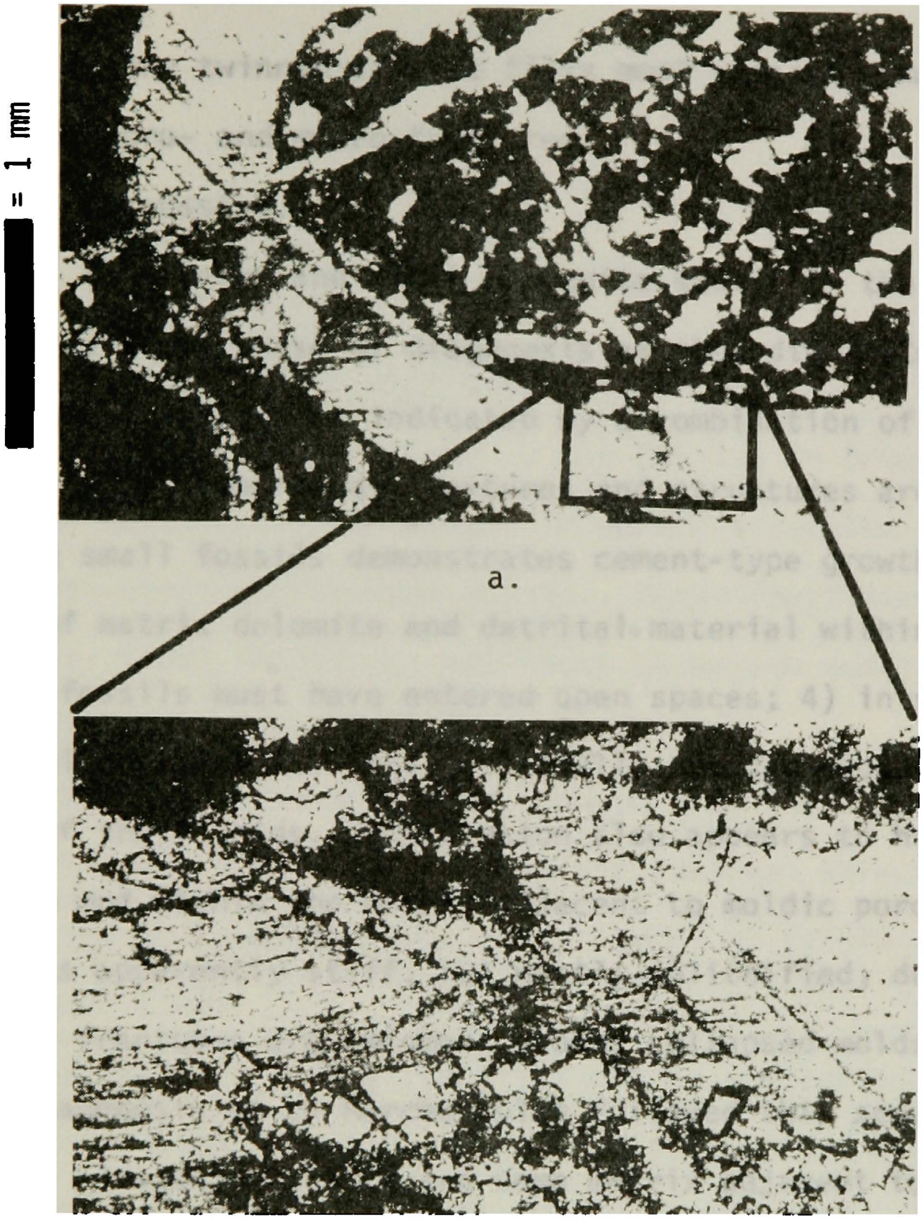


Fig. 42. Photomicrograph of one of the fossils with dolomite and calcite cement filling typical of small fossils at La Marche Gulch North. Expanded view (b) shows details of dolomite lining and twinned calcite fill.

rims. Blocky twinned calcite fills most remaining mold space and extensive macro- and micro-fractures.

b. Discussion:

Both large and small aragonite shells in the sediment dissolved in a very early phase of diagenesis as they did at Cedar Creek. Dissolution of fossils is indicated by a combination of factors: 1) original mollusc shell mineralogy, textures and structures are absent; 2) material filling small fossils demonstrates cement-type growth; 3) angular fragments of matrix dolomite and detrital material within shell walls of larger fossils must have entered open spaces; 4) in some places collapsed internal sediment fillings, especially of scaphopods, lie touching outer walls of shell molds. Dissolution also appears to have locally affected micrite mud within the matrix adjacent to moldic porosity. The sediment was apparently stiff, but mostly unlithified, during this stage because fractures are uncommon around collapsed molds.

Diagenesis at La Marche Gulch followed this sequence:

1) Aragonite shells and some matrix adjacent to the shells dissolved, possibly accompanied by partial calcite cementation of the matrix. The sediment was stiff enough to maintain many open molds but as moldic porosity increased, it became locally unstable and collapsed into open spaces.

2) Carbonate silt or sand containing some angular fragments of matrix completely filled large connected moldic porosity.

3) Dolomitization altered the matrix and mold-filling carbonate and large euhedral dolomite crystals grew at the surfaces of small molds and other voids.

4) After lithification, blocky calcite entered remaining spaces through a fine fracture system.

3. Sappington Canyon

a. Description:

Cliff faces at Sappington Canyon display strikingly weathered outcrops of white calcite and silica fossils in brown sandstone. The original sediment was a mixture of mostly aragonite shells in a carbonate-phosphate-chert-quartz sand matrix. Minor constituents include algae and other plant fragments, siliceous carbonate mud intraclasts, scattered ooids and rare siliceous sponge spicules.

Aragonite dissolution occurred at this locality also; fossils lack original shell mineralogy and organic internal structures and material inside the shell walls consists of layers of varying cement mineralogies and growth forms.

The outer surface of many fossils is a dolomitized relict micrite rim. In addition, or alternately, a single layer of carbonate cement crystals evenly lines many of the mold walls (Fig. 43). Long axes (0.1 mm to 0.3 mm) of these crystals fan out slightly and become thicker away from the wall. Crystal length:breadth ratio is up to 5:1. Terminations are slightly flattened. Under crossed polarizers, thin sections of this material extinguish radially but the "crystals" have a fuzzy composite appearance. This cement is most likely a pseudomorphously dolomitized, coarse, radial-fibrous calcite cement. Carbonate inclusions at the boundaries between sand grains and silica overgrowth or calcite cement may be remmants of another early calcite cement.

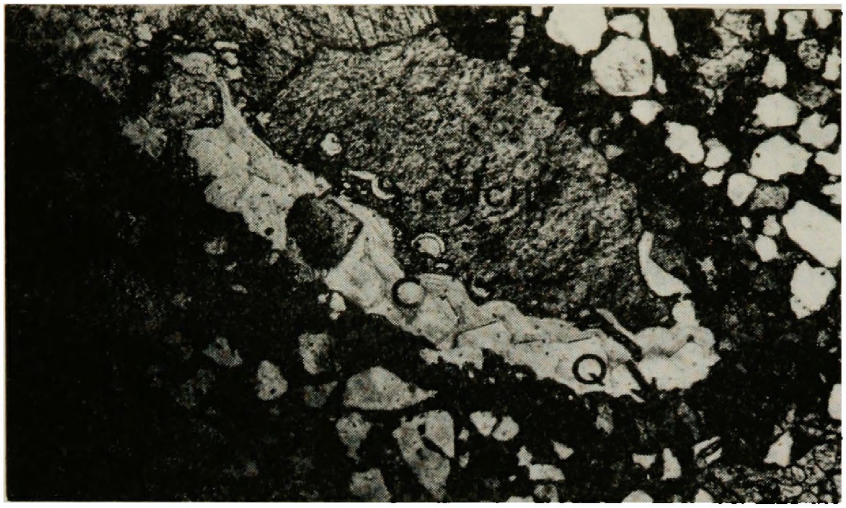


Fig. 43. Plane-light photomicrograph showing a complete sequence of cements filling fossil mold at Sappington Canyon. Dolomitized radial fibrous calcite cement lining (arrow) was overgrown by pseudocubically-terminated quartz crystals(Q) and chalcedonite(C). The remainder of the mold is filled with blocky calcite.

= 1 mm

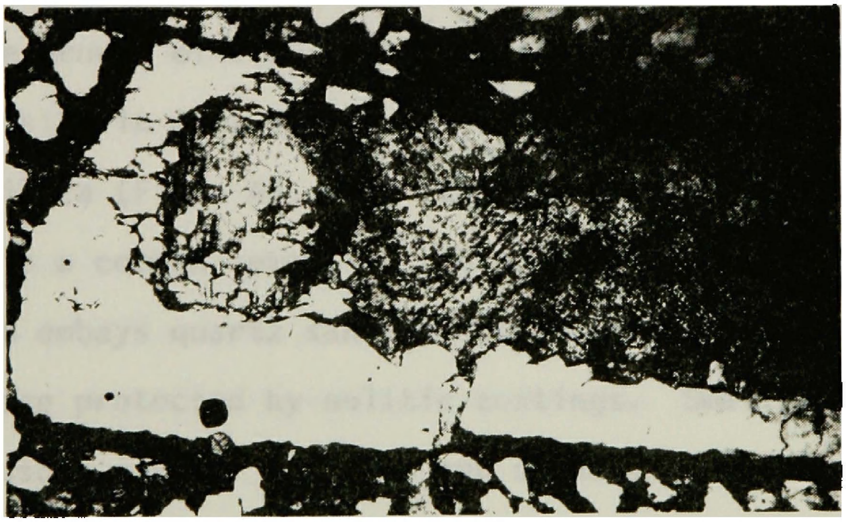


Fig. 44. Plane-light photomicrograph of fossil mold filling similar to Fig. 43. Note the distribution of quartz filling (white) in both figures along part of the wall surface, thickening in corners in a manner analogous to vadose calcite cement.

Silica precipitated as syntaxial overgrowths on quartz grains in the matrix sand and as cement in fossil molds. It is difficult to determine the original extent of cement around quartz grains because of widespread embayment by later calcite cement. Within fossil molds, silica, in the form of chalcedonic and blocky megaquartz and minor chert, grew unevenly, and did not generally fill the cavities completely. It appears that silica-precipitating fluids dripped along a few walls or concentrated in corners (Fig. 44). Silica forms and textures vary systematically from the edge of the cemented mold surface inward (Figs. 43, 44). Very locally, chert replaces some of the carbonate cement rim described above. Inward, megaquartz with euhedral, often pseudocubic terminations (Figs. 43, 44) is overlain by chalcedonic megaquartz which fills many cavities or grades inward to blocky megaquartz.

Extensive growth of very coarse blocky, twinned calcite cement fills remaining porosity in most fossil molds and is a much more abundant cement than silica (Figs. 43, 44). Calcite fills spaces above geopetal fillings and is a common cement in the sand matrix where it is locally poikilitic and embays quartz sand grains and overgrowth cement except where grains are protected by oolitic coatings. Small, calcite-filled fractures crosscut earlier textures and structures and appear to have provided access for the calcite-precipitating fluids into an already-indurated rock.

Some fossils display the complete sequence of cements described above but most lack one or more phases. Silica is a major constituent of fossil molds at only one horizon, which is no more than a few meters thick (Fig. 15). Locally in this zone, fossils with dominantly silica cement sit adjacent to others with dominantly calcite, or mixed cements (Fig. 45). There are also tabular areas of silicified fossils surrounded by calcite fossils. Capricious movement of silica-cementing groundwater through connected openings in a partially cemented sandstone might account for this distribution. More commonly, very large blocky calcite is the only cement.

These rocks appear to lack primary dolomite cement but a later dolomitization event replaced all carbonate in the rock except the blocky calcite cement, sometimes preserving original textures of rare ooids (Fig. 46), micritic rims, carbonate sand grains and early calcite cement.

Several deformation events can be distinguished. Some fossils were broken and extensively bored before deposition. More minor breakage occurred after aragonite dissolution, as unsupported micrite rims collapsed into newly created molds (Fig. 47). The rock was not yet completely indurated because fractures in the fossils do not extend into the matrix. After silica cementation and dolomitization, fractures in a lithified sediment cut across both fossils and matrix.

b. Discussion:

Early diagenesis of this fossiliferous sandstone was characterized by a scarcity of cementing material. Locally derived carbonate from dissolving shells did not completely indurate the sands and minor compaction and collapse continued. Silica cement was rarely sufficient to fill cavities even in the zone where it is most abundant. Prior to

Fig. 45. Mixed cement types at Sappington Canyon. Recessively weathering fossils are calcite filled (eg. the bellerophon, B, at upper left); silica-filled fossils are raised in relief (eg. pelecypods, P, and scaphopods, S, at bottom center). Approximately one half actual size.

Fig. 46. Photomicrograph of sandstone matrix at Sappington Canyon showing a rare well-preserved dolomitized ooid (arrow).

Fig. 47. Photomicrograph of a fossil mold from Sappington Canyon. The right side collapsed (arrow) after the radial fibrous cement rim formed but before lithification and blocky calcite cementation.

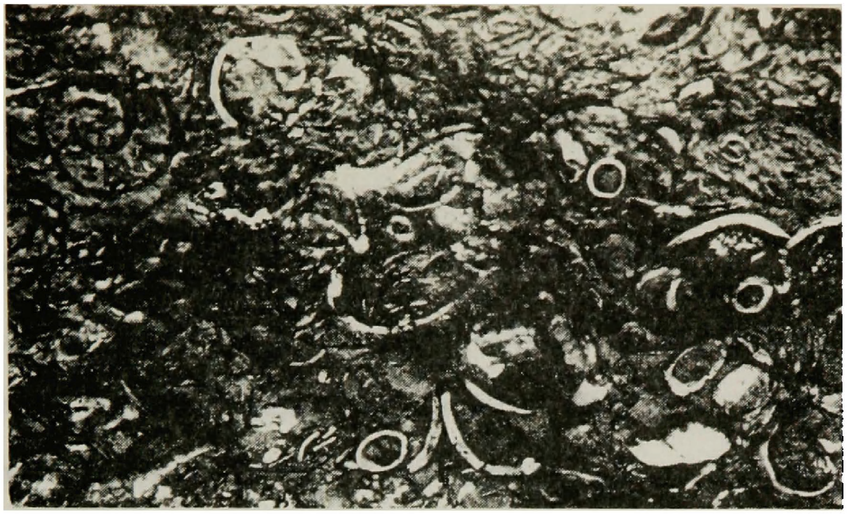


Fig. 45

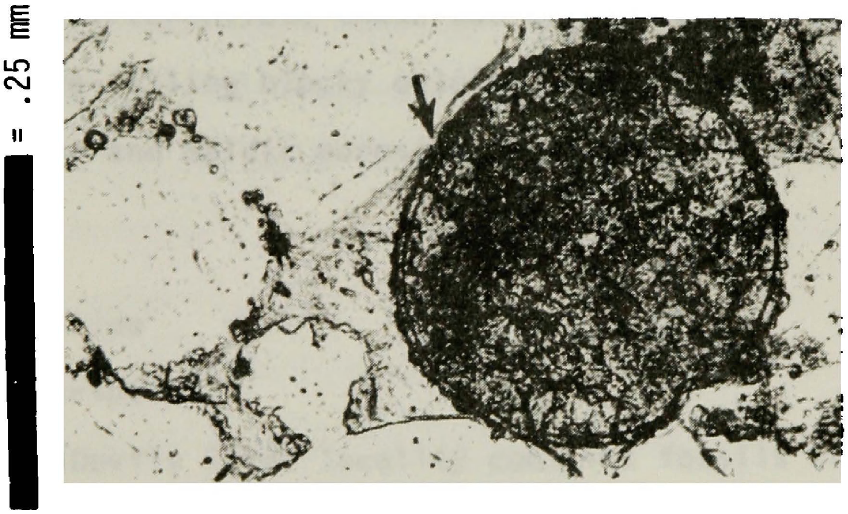


Fig. 46

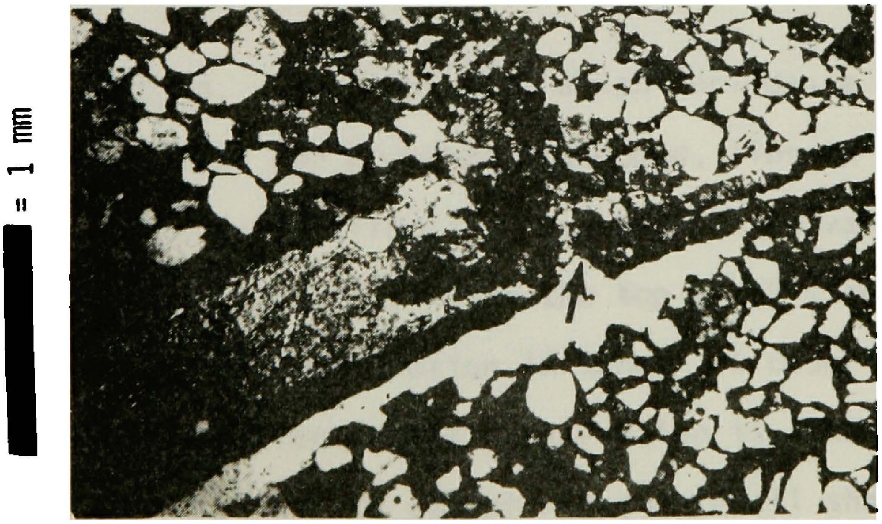


Fig. 47

blocky calcite cementation the rock had very high moldic porisity and locally high intergranular porosity.

This sequence of diagenetic events emerges:

1) Mollusc shells were selectively leached and the dissolved carbonate was partially reprecipitated as calcite around sand grains and around the interior walls of some molds.

2) Silica cementation and dolomitization followed.
Evidence to differentiate these two events sequentially is inconclusive.

3) Pore-filling blocky calcite cement developed in remaining intergranular and moldic porosity after the rock was indurated and fractured.

4. Devils Slide

a. Description:

The Devils Slide locality contains fossils of the molluscan assemblage in two beds which are widely separated stratigraphically (Fig. 20).

Lower Fossils. The lower bed, which includes a few bellerophontaceans and at least one probable scaphopod, lies in the conglomeratic, dolomitic sandstone bed directly above the Pennsylvanian sandstone and below a scour surface. Fossils at the top of this bed are filled with sand, similar to the preservation in Zone A at Cedar Creek. Toward the middle of the fossiliferous bed preservation is like that at Sappington Canyon where blocky calcite cement retains fossil shapes, but no internal shell details.

Upper Fossils. Near the top of the Permian deposit at Devils Slide a tongue of dolomite contains abundant bellerophontacean gastropods in a thin zone near its base. Fossils are preserved as open or silica-filled molds. Sparse chalcedony spherules with separate layers of both length-fast and length-slow chalcedony nucleated and grew on the interior walls of molds (Fig. 48). Pyrite crystals formed at boundaries between chalcedony layers, within length-fast layers and also in the surrounding carbonate. Strongly undulose blocky megaquartz grades inward from the chalcedony and fills most of the remaining space. These silica-cemented molds apparently lacked micrite rims and quartz and chalcedony fillings are in very uneven contact with the surrounding sediment.

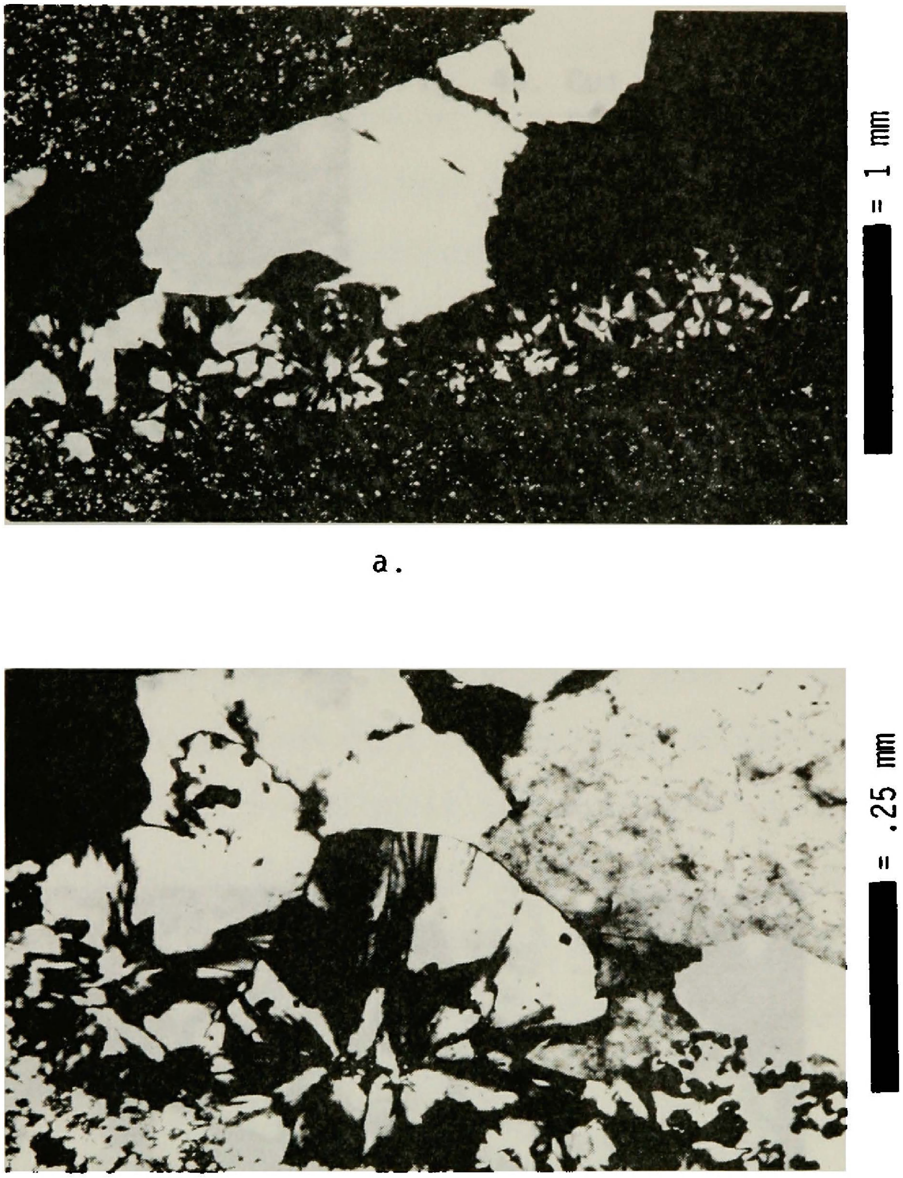
Sandy dolomitic phosphorite fills body cavities in some shells. In places molds collapsed leaving the phosphorite steinkern in direct contact with the dolomite matrix (Fig. 49). Elsewhere phosphatic steinkerns survive with open mold space around them.

Some molds survived with reasonable good detail, but others are greatly deformed by collapse and shearing. One gastropod shell appears to have been partly uncoiled during compaction, apparently by shearing within the sediment (Fig. 49).

Very minor blocky calcite cemented some of the remaining open space in the fossil molds.

b. Discussion:

In the upper fossiliferous zone at Devils Slide aragonite shells dissolved before the sediment was very well indurated. Molds were



a.

b.

Fig. 48. Photomicrograph (a) and expanded view (b) of bellerophontacean mold filling at Devils Slide, upper fossil zone (crossed polarizers with quartz plate). Layered quartz spherules contain both length-slow and length-fast chalcedony with pyrite concentrated at some layer boundaries. These chalcedony spherules are sparsely distributed along one wall of the mold (a) and blocky megaquartz fills the rest of the cavity.

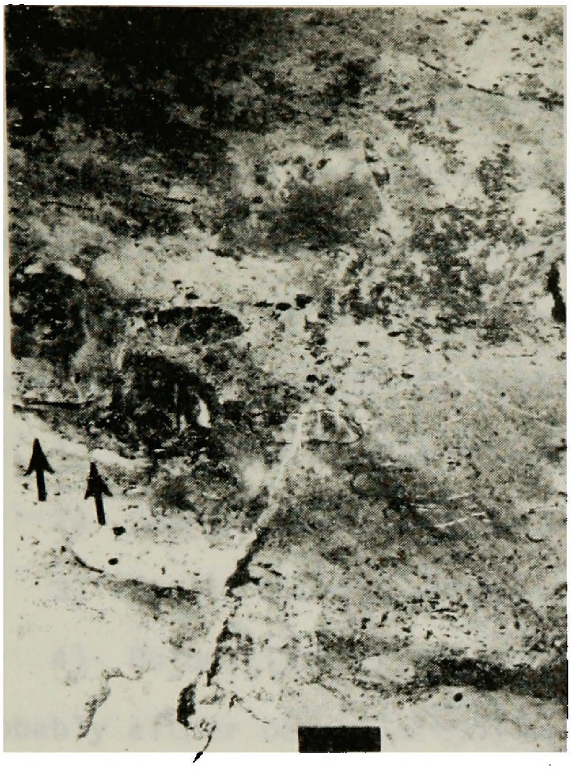


Fig. 49. Cut slab, mottled dolomite of the upper bellerophontacean zone (about 17.9 m in the measured section), showing fossil molds that are partially filled with silica and partially collapsed (left center). The lower fossil appears to have been unrolled and shows tensional fractures (arrows). Many of the black specks are fragments or cut slices of small phosphatized gastropod steinkerns. Scale = 1 cm.

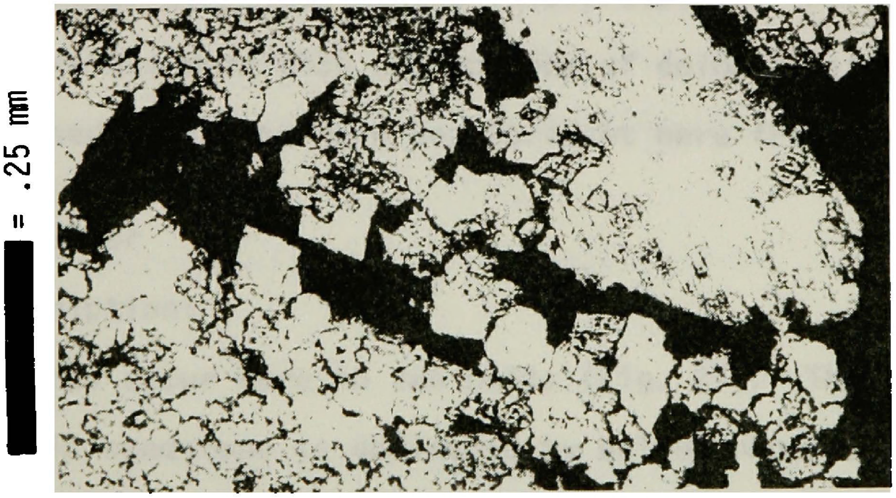


Fig. 50. Photomicrograph of dolomite textures and residual petroleum (black), Boulder River.

deformed by settling of unstable sediments and the uneven boundary between mold cement and matrix indicates that crystals either grew into the soft matrix or it deformed around them during collapse.

Diagenesis at Devils Slide includes these events, which are in sequential order except for number 4:

1) Aragonite shells dissolved.

2) Quartz cement grew in fossil molds.

3) Blocky calcite filled the few remaining spaces in molds.

4) Dolomitization is difficult to place in the sequence; it was probably either before aragonite dissolution or after silica cementation since these molds are not lined with rhombohedral dolomite cement. Individual dolomite rhombs are common in the phosphate mud and also occur in chert, further complicating the interpretation. Perhaps at this locality there was more than one episode of dolomitization or previously dolomitized sediments may have been brought here from other environments.

5. Boulder River

a. Description:

Fossils occur here in two units (Fig. 27). The lower conglomeratic, dolomitic sandstone is dominated by bellerophontaceans and the upper impure, packstone dolomite is dominated by scaphopods, although both units contain bellerophontaceans, scaphopods and a few pelecypods. Diagenesis at this easternmost locality is another version of the now-familiar theme.

Early dissolution and collapse of the originally aragonite-shelled fossils is evidenced by absence of internal shell structures, distortion of shell forms, attentuation of some shell walls (Fig. 29) and broken relict micrite rims. Mold collapse does not appear to have fractured the matrix which must have been quite plastic during this event. Much of the fossil material is unidentifiable; except for a few silicified molluscs none of the larger fossils are well-preserved. The silicified fossils are worn and scattered about in a conglomeratic zone and were probably reworked from earlier rocks or sediments.

Dolomite lined the fossil molds and formed throughout the rock in crystals of micron scale to more than 1.0 mm diameter. Crystals are largest and best developed where they grew into open pore spaces (Fig. 50).

In the upper bed a brittle, black material which is probably petroleum residue fills pores inward from the dolomite cement (Fig. 50). The same material is present in the lower bed, but less abundantly. Some broken rock surfaces separate along these hydrocarbon boundaries, producing relief faces of fossil forms.

Coarsely crystalline, blocky, twinned calcite is the latest major cement addition.

b. Discussion:

At Boulder River the diagenetic sequence was:

1) Aragonite shells dissolved, followed or accompanied by dolomitization of matrix carbonate and growth of euhedral dolomite cement lining mold walls; most molds collapsed.

2) Petroleum flowed through the rock and left a residue in many pore spaces.

3) Calcite was introduced as a last event and fills some remaining voids.

Summary and Interpretation

The sequence of diagenetic events is similar at all localities (Table 9):

1) Early and ubiquitous dissolution of aragonite shells formed molds within a stiffened or partially cemented sediment.

2) Molds were partially or completely filled with cement and/or detrital material with variations that characterize the individual localities.

3) Carbonate in the rocks was dolomitized and euhedral dolomite grew around open spaces in an event that followed and/or accompanied mold formation and filling.

4) Blocky, twinned, usually coarse-grained calcite cement was introduced after lithification.

The repetition of this diagenetic sequence at the five localities is particularly striking because of the differences in original sediments and inferred depositional environments. A closer look at some of these events helps explain the common diagenetic overprint as well as some of its variations.

1. Mold Formation

Shell molds present two questions: Why did the original shells dissolve and how did the molds remain open in unlithified sediments long enough for the various fillings to preserve their details?

SUMMARY OF DIAGENETIC EVENTS

Locality	Fossil Mold Formation	Early Calcite Cement	Silt or Sand Casts	Silica Cement	Dolomite	Petrol. Migration	Blocky Calcite Cement
CC	X	X	X	X	X	X	X
SC	X	X		X	X		X
LG	X	?	X		X		X
DS	X	?	X	X	X		X
BR	X	?			X	X	X

Table 9. Summary of diagenetic events at individual localities, listed in interpreted chronological order from left to right, except timing of dolomite growth, which is ambiguous at most localities and probably multiphase at some.

The original carbonate in these rocks was undoubtedly a combination of aragonite mollusc shells, algal fragments and mud; high-Mg calcite and/or aragonite bryzoans; high-Mg echinoderm shells and low-Mg calcite. This mineral assemblage is meta-stable in warm shallow sea water which is supersaturated for all three forms. With time, aragonite and high-Mg calcite in marine sediments normally revert to low-Mg calcite (Stehli and Hower, 1961), often preserving internal shell structures by direct replacement. However, in these Permian rocks, cement textures, collapsed shell forms and loss of internal shell structures demonstrate that aragonite shell material was completely dissolved very early in the diagenetic sequence. Therefore the relevant questions are, "what diagenetic environments are characterized by $CaCO_3$ undersaturated waters which would dissolve aragonite, and which one operated here?

Whereas warm shallow marine waters are $CaCO_3$ saturated, cold shallow seas may not be. Alexandersson (1978) documented dissolution textures on carbonate grains in the North Sea, but his example of marine dissolution cannot apply to the rocks of this study because: 1) Alexandersson noted dissolution textures on <u>all</u> carbonate grains regardless of phase and 2) paleogeographic reconstructions based on faunal and paleomagnetic data indicate that this area occupied a warm, low-latitude position during the Permian (Fig. 2).

Undersaturated meteoric waters also dissolve carbonate. According to a model first developed by Land (1966) and Land, Mackenzie and Gould (1967), during fresh water diagenesis of a lime sediment aragonite is selectively leached and low-Mg calcite precipitated contemporaneously.

In a rock composed of both aragonite and calcite polymorphs, solutions tend toward saturation for the more soluble aragonite and become supersaturated for the less soluble calcite, thus dissolving aragonite and precipitating calcite (see work by Garrels _et al_, 1949 ; Garrels and Dreyer, 1952). Sometimes most of the dissolved carbonate is precipitated locally (Harris and Matthews, 1968) quickly developing a rigid framework that prevents mold collapse (Matthews, 1968; Semeniuk, 1971). In other cases molds collapse either because there is not enough aragonite originally present to provide sufficient carbonate for lithification, or because carbonate is washed out of the system. Although later dolomitization makes this event difficult to trace, at least two localities contain remnant evidence of minor early calcite cementation. Exposure to meteoric water could therefore both explain the preferential dissolution of aragonite shells and partially account for mold stability.

Micrite envelopes, which survive aragonite shell dissolution and have enough mechanical strength to hold molds open in an unlithified sediment (Barthurst, 1964), also must have contributed to mold stability. Bathurst (1976) summarized research which shows that micrite rims result from tiny dense borings of endolithic algae, fungi and perhaps bacteria. Since algal borings are restricted to the photic zone, and since the abundance of micrite-rimmed shells has been seen to reduce with depth (Swinchatt, 1969), these rims have been used as indicators of shallow, sediment-water interface alteration. However, non-algal endolithic activity has now been documented to as much as 160 cm below the sediment surface (May and Perkins, 1979). Since it is impossible to identify the type of borings in these recrystallized Permian rocks, micrite rims can be used as suggestive, but not conclusive evidence that the shells spent some time in shallow water.

2. Mold Filling

Once open molds formed, the spaces were available to be filled by clastic material and various cements. Fillings at each locality provide a unique detailed account of changing chemical and physical conditions within the sediments and further refinement of environmental interpretations.

Sandstone casts of aragonite shells like those at Cedar Creek and Devils Slide have been identified in Permian carbonates in Wyoming (Boyd and Newell, 1972) and in Ordovician rocks of Norway (Hanken, 1979). This apparently rare (or perhaps unrecognized) form of preservation is a strong indicator of early diagenesis in the meteoric vadose zone (Hanken, 1979). Shells which were originally in grain support formed a connected network of open molds during aragonite dissolution. Burrows, borings and local matrix dissolution also contributed to the network. Where open vugs were exposed at the bed surface they trapped well-sorted fine sand, and the sand gradually filled up all of the connected spaces. Only downward-percolating water currents in the vadose zone would have been forceful enough to move sand grains laterally through rock porosity into the molds, often completely filling them (Dunham, 1969; Hanken, 1979). At Devils Slide, truncated sand casts at the bed surface provide additional evidence of exposure.

At La Marche Gulch North, clean equigranular dolomite, or the carbonate it replaced, selectively fills only large pore spaces. It must have arrived after shell dissolution and before the dolomitization event that left rhombohedral cement linings on remaining cacities. There is no textural evidence that the uniform dolomite grew as a cement and it cannot have formed by direct replacement of shell material since it contains floating fragments of matrix-type dolomite. Probably the dolomite entered connected secondary pore spaces as silt- or sand-sized carbonate grains which were too large to move into the smaller voids. Dunham (1969) described an internal calcite silt in a Permian carbonate reef which could be analogous, although the material he described is undolomitized. He assigned a vadose origin to the silt filling partly because of the need for an energetic transport mechanism as discussed above. Dunham (1969) believed that the silt he studied formed internally by mechanical and chemical action of vadose water on the primary sediment. Since the type of dolomite which fills the large pores at La Marche Gulch occurs nowhere else in surrounding and nearby rocks, it was probably also derived internally. Recrystallization apparently obliterated original detrital textures. Smaller molds were filled later with a fine dolomite crystal lining and blocky calcite cement.

All the mineral cements could be interpreted as meteoric or mixed marine-meteoric precipitates. At Sappington Canyon and Devils Slide silica cement in the fossils appears to reflect precipitation in the vadose zone, where cavities were not water-filled at all times. This is particularly obvious at Sappington Canyon where silica fills the small ends of fossils, only one or two sides, or a corner (Figs. 43, 44), leaving the impression of meniscus cement (Dunham, in Bathurst, 1975, p. 326, described similar meniscus textures in calcite cement). The very sporadic distribution of chalcedony-nodule cement in molds at Devils Slide also suggests uneven distribution of the fluids.

The type of coarsely crystalline, euhedral dolomite that lines molds at these localities has been linked by many authors to slow growth in dilute meteoric-influenced waters (eg. Land et al., 1975).

Coarsely crystalline, twinned, sometimes poikolitic blocky calcite with straight intracrystalline boundaries is interpreted to have formed in a meteoric phreatic environment (Folk and Siedlecka, 1974; Land, 1970; Randazzo et al., 1977; Longeman, 1980). Because this calcite postdates all other diagenetic events including complete lithification, the environment in which it formed is not relevant to the early history of the rock.

3. Shell Deformation

Although shell deformation is not strictly part of diagenesis, cross-cutting relationships with diagenetic events helped reveal relative timing of both types of alteration episodes. Prelithification compaction breakage, documented at most localities, is rare in carbonate rocks (Pray, 1960; Zankle, 1969) and its presence is significant. Sarker, Bhattacharyya and Chanda (1980) have recently recognized deformed allochems in carbonate rocks as a signal for the presence of hardgrounds or emersion surfaces. They suggest that cemented surfaces and nodules created during early partial lithification of the sediment could amplify stresses during compaction, locally reaching the yield point of allochems and causing characteristic early breakage. Hanken (1979) cites fractured fossils in Norwegian limestones as evidence of subaerial exposure, suggesting that differential compaction of sediments or gravitational instability of a semi-consolidated exposed sediment could have caused breakage.

4. Dolomitization

Except for late-stage blocky calcite cement, dolomite is virtually the only carbonate in the rocks at all localities. Recrystallization textures ranging from the well-preserved ooids at Sappington Canyon to the ghostly remains of pellets and fossils at other localities show that much of the dolomite originated by replacement of calcite or aragonite. Euhedral dolomite cement lining cavity walls is the other important occurrence and it is also clearly post-depositional. There are at least two models for the formation of sedimentary dolomite by replacement of primary carbonate.

1) Evaporative Reflux (Adams and Rhodes, 1960; Deffeyes *et al.*, 1969; Murray, 1969).

2) Dorag dolomitization (Hanshaw, 1971; Land, 1973; Badiozamani, 1973; Land *et al.*, 1971).

Suggestions of relict evaporites in the strata at La Marche Gulch North and Devils Slide make these two localities likely candidates for dolomitization by hypersaline brines *via* the evaporative reflux model. Meteoric waters influenced diagenesis at all localities and the absence of evaporites and evaporite-related facies at Cedar Creek, Sappington Canyon and Boulder River makes them possible candidates for Dorag dolomitization.

Environmental Summary

Subaerial exposure and alteration by meteoric or mixed marine-meteoric water can explain many of the diagenetic events recorded in the fossiliferous zones. The best evidence for early non-marine diagenesis includes:

1) Selective dissolution of aragonite shells;
2) Mold fillings characteristic of the meteoric vadose zone;
3) Pre-dissolution breakage of shells in carbonate sediments.

Early fresh-water diagenesis very conveniently compliments the developing interpretation of these rocks which contain independent evidence of deposition near shoreline, including a shallow-water molluscan fauna, coastal sedimentary facies and relict evaporites. It is very likely that even slight sea level changes would have exposed the sediments to subaerial conditions, or that some deposits, especially the fossil coquina at Cedar Creek, were originally deposited subaerially.

SUMMARY OF CONCLUSIONS

Table 10 summarizes some of the key relationships between the stratigraphic, petrographic and paleontological data. This study makes the following contributions toward understanding the scaphopod-bellerophontacean gastropod fossils and the strata in which they are found:

1) The mollusc fossils cannot be studied as an in situ community in these southwestern Montana deposits because current- and wave-formed structures in the enclosing sediments and wear, breakage and preferential orientation of shells indicate an undetermined amount of transport before deposition.

2) The fossils can be studied in the context of their depositional settings. Combined stratigraphic, petrologic and paleontologic data reinforce previous suggestions that the environments where the moluscs lived and were deposited were characterized by physically restrictive conditions. These include susceptibility to storm disruption, shallow water, possible increased water salinity and perhaps even poisonous water in adjacent phosphogenic systems.

3) The specific paleoenvironments of deposition interpreted in this study are generally consistent with previous broader-scaled interpretations of the area. New, detailed data presented here helps better define some major coastal environments preserved in Permian rocks of this area: shallow submarine terrigenous sand bars and tidal channels; lagoonal or shallow shelf carbonate environments which display variations on a common shallowing-upward progradational theme; intertidal and

SITE	MAJOR MOLLUSCS	FOSSIL-BEARING STRATIGRAPHIC INTERVAL	ENCLOSING LITHOLOGY	MECHANISM OF DEPOSITION	POSTULATED DEPOSITIONAL ENVIRONMENT	FOSSIL MOLD FILLINGS
CC	P,B,S	Franson Mbr.	Molluscan Packstone Dolomite	Storm wave transport and mixing	Storm beach	Collapsed or filled with vadose sand or silica, dolomite and/or calcite cement
LG	P,B,S	Park City carbonate, (Franson Mbr ?)	Molluscan Packstone Dolomite	Current and/or wave transport	Tidal channels or storm lag in a carbonate lagoon	Vadose silt; dolomite and calcite cement
SC	P,B,S	U. Shedhorn Sandstone	Molluscan Sandstone Conglomerate	Transported	Barrier bar system, channel lag	Dolomite, vadose silica cement, calcite cement
DS	1) B 2) B, rare P,S	1)Ervay Mbr? 2) L. Shedhorn Sandstone	1)Calcite & Quartz Nodular Dolomite 2) Congl. Sandstone	1)*In situ*? 2)Transported	1)Intertidal zone 2) ?	1)Vadose silica cement 2)Vadose sand fill, calcite cement
BR	B,S,P	? in and above basal Permian conglomerate	Conglom.& Molluscan Packstone Dolomite	Transported	?	Most molds collapsed, some dolomite & calcite cement

Table 10. Summary of Rock-fossil Relationships

P=Pelecypods
B=Belerophontaceans
S=Scaphopods

supratidal flats which locally developed into coastal sabhkas.

4) This study extends the areal distribution of Permian evaporitic sediments in the carbonates westward to include the Devils Slide and La Marche Gulch North localities where evaporites were replaced by silica and calcite. Similar silica and calcite nodules reported by other workers in this region may also be replaced evaporites.

5) Early diagenesis in the meteoric or mixed marine-meteoric vadose zone is primarily responsible for the form of preservation of mollusc fossils. Although the sediments which enclosed the mollusc shells were originally very diverse, ranging from nearly pure carbonate mud and shells to nearly pure terrigenous sandstone, the powerful vadose diagenetic environment overprinted a very similar series of events at all localities.

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APPENDIX I, MEASURED SECTIONS

All locations are in southwestern Montana.

a. Cedar Creek
attitude: north section - N25W, 55W, middle and south sections-N15E, 45W
location: natural exposures on the east limb of Cedar Creek syncline, sec. 26-T9S-R11W. Location in Cressman and Swanson (1964, p. 470) which contains a measured section of the Retort phosphatic shale beds only.

b. LaMarche Gulch North
attitude: varies from N30W, 35S to N55W, 55S
location: composite section measured at the extreme NE corner sec. 31 and NW corner sec. 32-T1S-R9W, natural exposures west of the Big Hole River. Location and section probably measured south of mine in Cressman and Swanson (1964, p. 553-555).

c. Sappington Canyon
attitude: (section 1) N80E, 52N
location: 4 sections measured along strike on ridge east of Jefferson River, sec. 25-T1N-R2W. Location and original measured section in Cressman and Swanson (1964, p. 534-537).

d. Devils Slide
attitude: N50W, 75S
location: excellent hogback exposures east of Cinnabar Mountain, NE¼, SW¼, sec. 32-T8S-R8E. Location and measured section near mine called Cinnabar Mountain in Cressman and Swanson (1964, p. 547-547).

e. Boulder River
attitude: N55E, 18W
location: exposures NW of the road, center S½, sec. 23 and NE¼, NW¼, sec. 26-T3S-R12E. Permian fossil locality originally noted in Yochelson (1968, p. 648) as an unmeasured Big Timber locality.

KEY TO ALL MEASURED SECTIONS

LITHOLOGIES

- Sandstone
- Dolomite
- Shale/Siltstone
- Chert
- Breccia
- Conglomerate

P Phosphatic

C Calcite

Pebbles, usually chert and/or phosphorite

STRUCTURES

- Small-scale burrows, usually less than 1 cm. diameter
- Large burrows, usually greater than 4 cm, mostly vertical
- Ripple-scale crossbeds
- Large-scale crossbeds
- Horizontal beds or laminations
- Intraclasts
- Nodules, mineralogy or lithology shown inside
- Stylolites

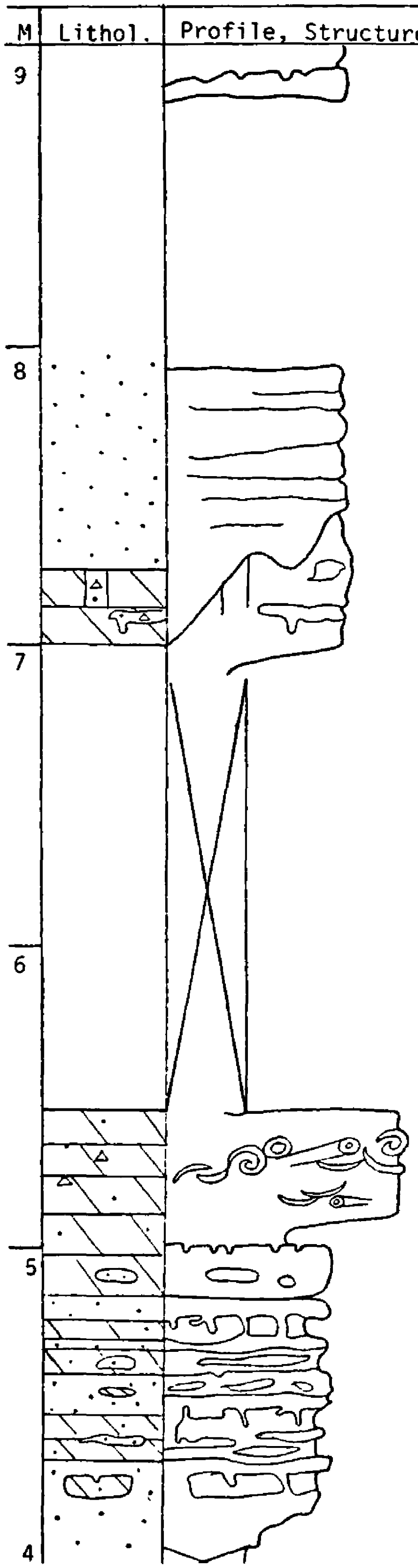
FOSSILS

- Scaphopods
- Bellerophontacean gastropods
- Small gastropods and gastropod steinkerns
- Pelecypods

Types of Preservation

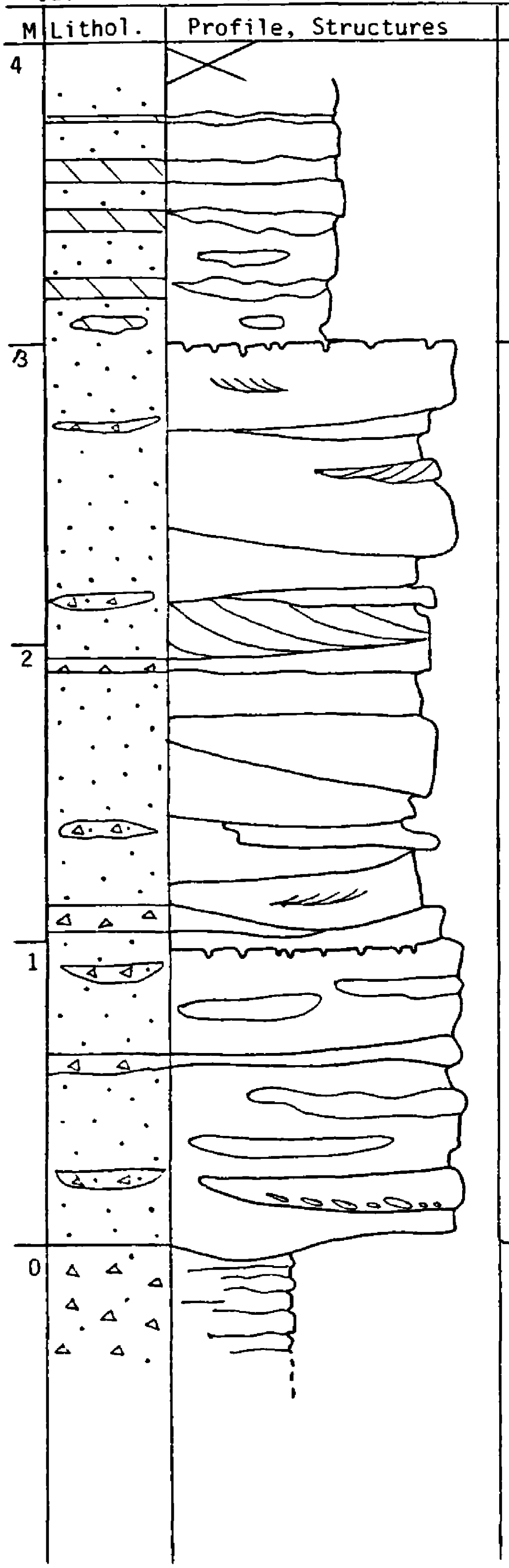
- Sand-filled molds
- Calcite, silica or dolomite-filled molds
- Collapsed molds

Ia. CEDAR CREEK, North Section



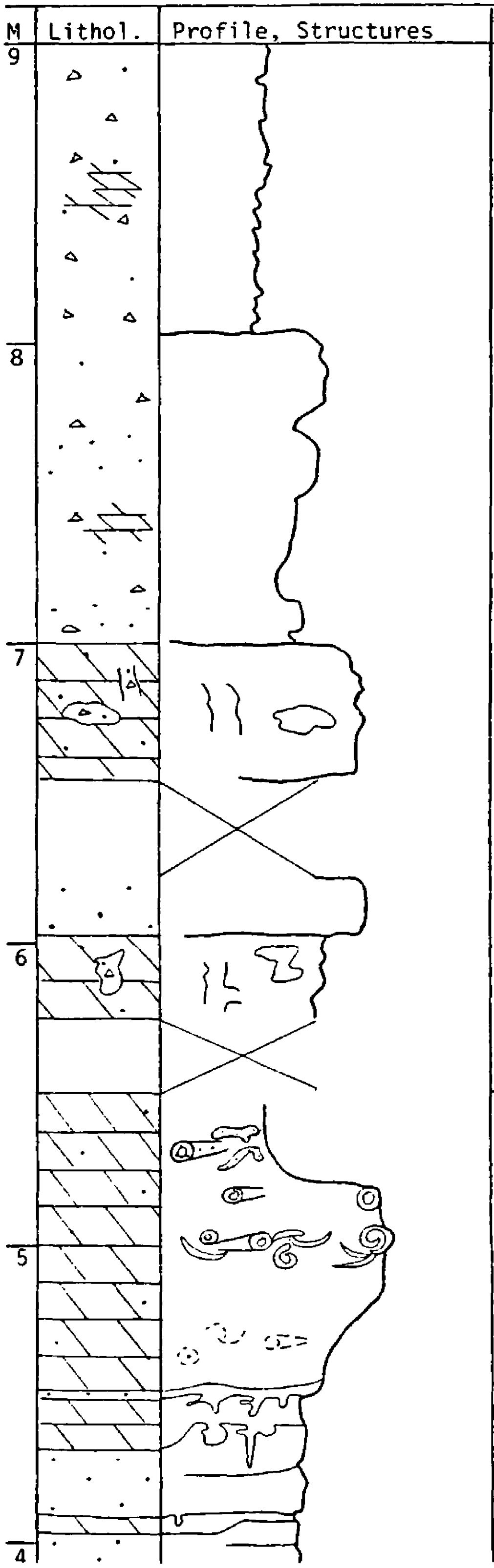
Description	Sample #
	8-29-4,5
Phosphatic chert-qtz SANDSTONE, lt (gy)tan, f grn, well srtd, qtz about 90%, calc cmt, wthrs in plates a few cm thick, pocky surfaces	8-3-9-1
Cherty, sdy DOLOMITE similar to south section 7.7-8m and 4-4.8m.	
Float includes: DOLOMITE, lt gy-buff, aphanitic, w/ sm sand-filled burrows;Dolomite, lt brn, sdy, w/lg mollusc fossils as sand molds and also silica-filled molds as below	Float: 8-3-9-2,3, 4,5,
Molluscan Packstone DOLOMITE, sdy lt brn-lt gy vf xline matrix w/discontinuous lenses of molluscs (whole shells and shell debris), mostly grain supported, silica-filled molds, matrix locally silicified, no silica fossils in lower 10 cm	8-3-9-7
Burrowed, Finely Interbedded SANDSTONE and DOLOMITE Sandstone:lt-med brn, f-crs, sorting good-poor,about 30% chert, 5% phos, 65% qtz, calc & qtz cmt; occurs in thin stringers (few mm), beds (less than 10 cm), burrow fillings (.5cm diam, vert. & horiz.), some ripple x-beds, rare graded beds. Dolomite:lt-med (brn) gy, slty-sdy, aphanitic, prob. v bioturbated, v rare f lam, burrows as above, occurs as v thin discontinuous beds	8-2-9-3 8-2-9-2 8-2-9-1

Ia. CEDAR CREEK, North Section



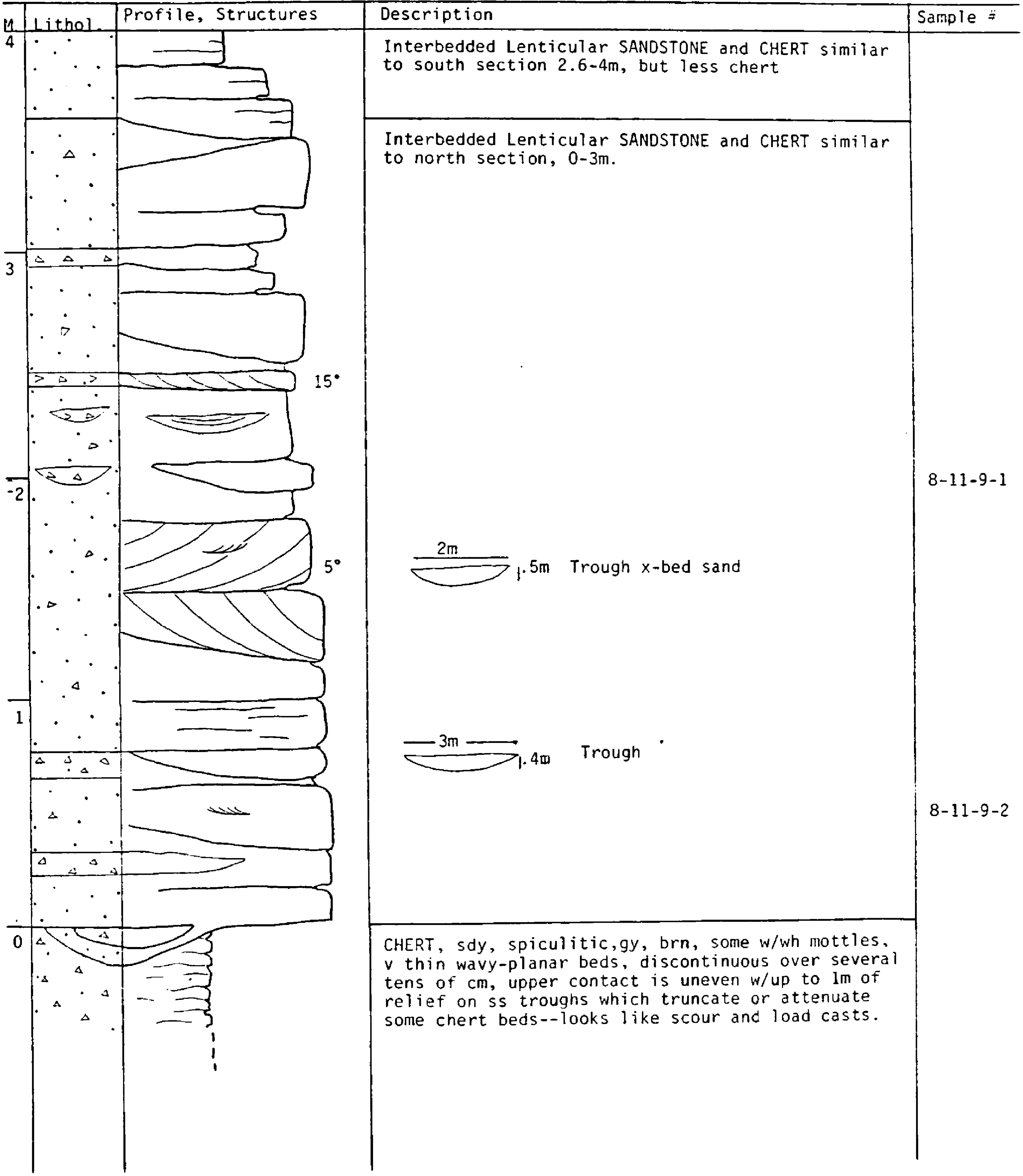
Description	Sample #
As Above. Sed Structures include sm ripple x-lam in ss, sand-filled scour structures into dolom (2-8cm wide), graded beds less than 10cm thick w/crs ss-dolomdst variation, flaser beds, wavy and planar beds, prob. flame structures.	
Interbedded Lenticular SANDSTONE and CHERT Sandstone: lt-med brn, about 70-90% qtz, 10-25% chert, 5% phos, varies from f-med grn & well srtd to f-crs grn & poorly srtd, crs grains becoming more common upward in section, phos also inc upward, cmt dom siliceous, w/ some ss-chert lens contacts gradational, lensoid beds 2-20cm thick & a few m long, ripple & med-scale x-beds appear faintly on some surfaces, some trough x-beds dip 12-20 degrees, best preserved where cherty, bed tops commonly v uneven burrowed (?) surfaces Chert: a) lt (brn) gy-med (bl)gy, sdy & b)wh-carmel, fairly pure. sdy cherts frequently preserve sed. structures including horiz. lam, x-beds, burrows, gen occur as discontinuous lenses w/in ss 2-10cm thick, 30-300cm long, contacts w/ss often wavy, poss load structures. also occurs as silicified(?) carbonate mud intraclasts.	8-1-9-5 8-1-9-4 Several Cherts: 8-4-9-1 8-1-9-3 8-1-9-1
Thin bedded CHERT similar to middle section.	8-1-9-2

Ia. CEDAR CREEK, Middle Section



Description	Sample #
Sdy, dolo CHERT, grading laterally to sdy, siliceous DOLOMITE, fractured	8-11-9-10
As above w/ss interbeds	
Sdy, cherty bioturbated DOLOMITE	8-11-9-9 8-11-9-8
SS, f grn, sorted, calc cmt, lt-med brn	8-12-9-1
Molluscan Packstone DOLOMITE, similar to north and south sections; zonation of fossil mollusc-mold fillings evident here with sand-filled molds in upper recessive part of bed, silica-filled molds in middle of bed w/local silicification of matrix near some fossil lenses,prob. some moldic porosity near base of bed, but also collapsed molds can be seen there. Rock is very poorly sorted, chaotic mixture of shells and shell hash, dom grain support where preservation of shells is good--some better sorting locally in lenses	8-11-9-7 8-11-9-6 8-11-9-5
Burrowed, Finely Interbedded SANDSTONE and DOLOMITE as in north section 4-5m	8-11-9-3 8-11-9-4

Ia. CEDAR CREEK, Middle Section



Interbedded Lenticular SANDSTONE and CHERT similar to south section 2.6-4m, but less chert

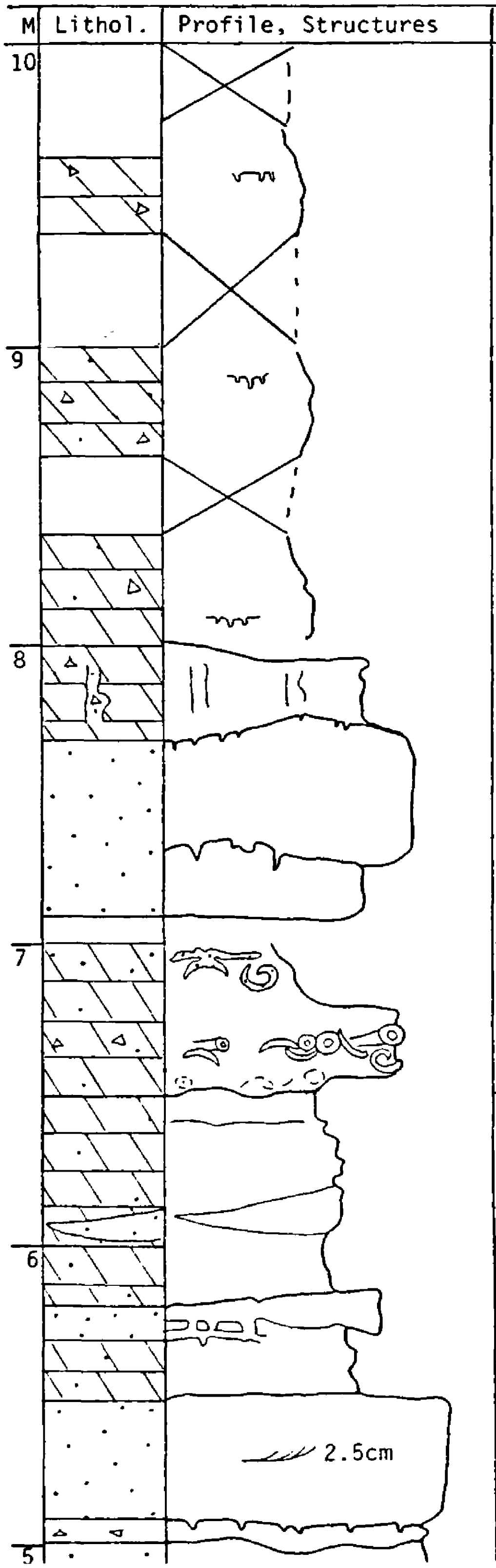
Interbedded Lenticular SANDSTONE and CHERT similar to north section, 0-3m.

8-11-9-1

8-11-9-2

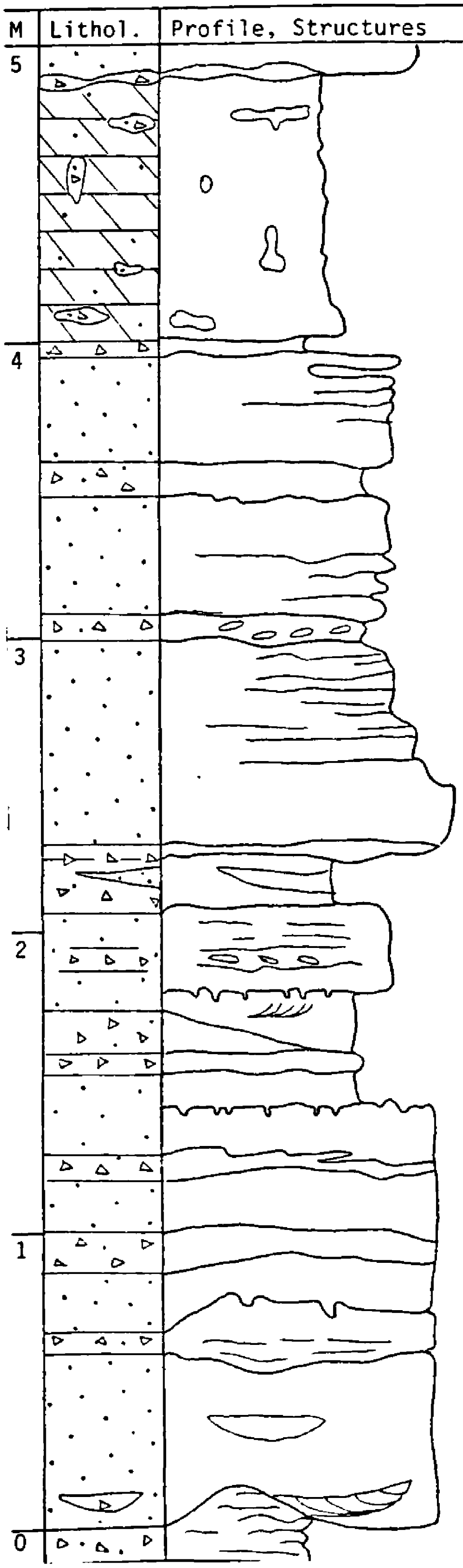
CHERT, sdy, spiculitic, gy, brn, some w/wh mottles, v thin wavy-planar beds, discontinuous over several tens of cm, upper contact is uneven w/up to 1m of relief on ss troughs which truncate or attenuate some chert beds--looks like scour and load casts.

Ia. CEDAR CREEK, South Section



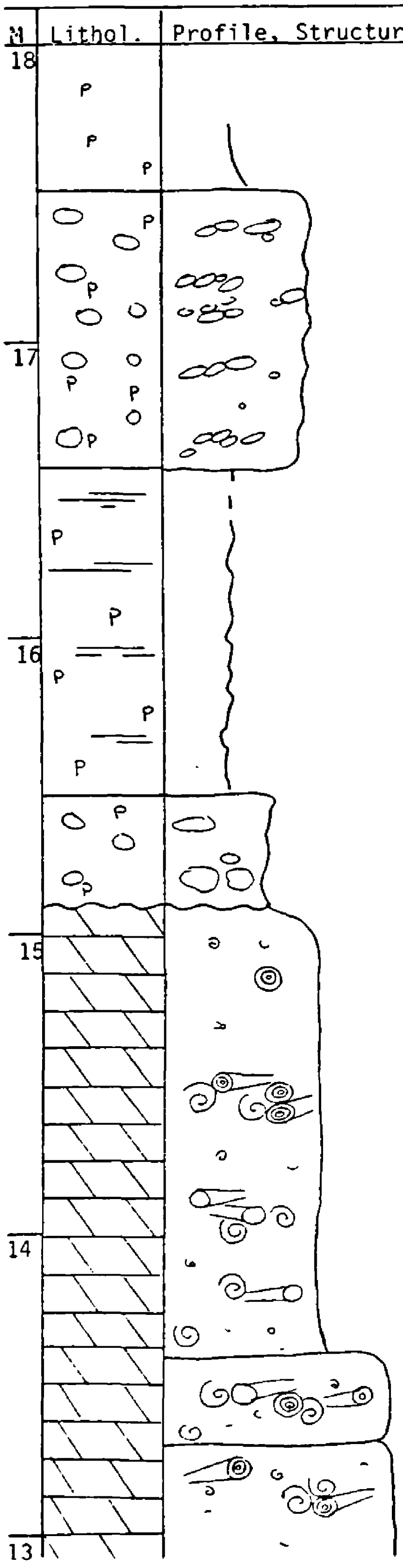
Description	Sample #
Sdy, cherty DOLOMITE; aphanitic lt tan-gy DOLOMITE which locally grades(?) to dolomitic CHERT, v thin bedded, burrowed	8-29-9-9
SANDSTONE, dom qtz w/chert & phos, med brn, massive, burrowed (?) surface includes a few v-shaped burrows(?) up to 8cm deep, 6cm max diam.	
Molluscan Packstone DOLOMITE as in middle and north sections, sand fossil-silica fossil transition well exposed near gully	v lg block
Burrowed, Finely Interbedded SANDSTONE and Dolomite as in north section 4-5m. some platy bedding (about 5cm), a few ss lenses up to 10 cm thick, gen v thin beds.	9-25-9-6,7
SANDSTONE, f grn, well srtd, calc cmt, faint ripple x-beds, otherwise massive	
Chert as below 0-4 m	

Ia. CEDAR CREEK, South Section



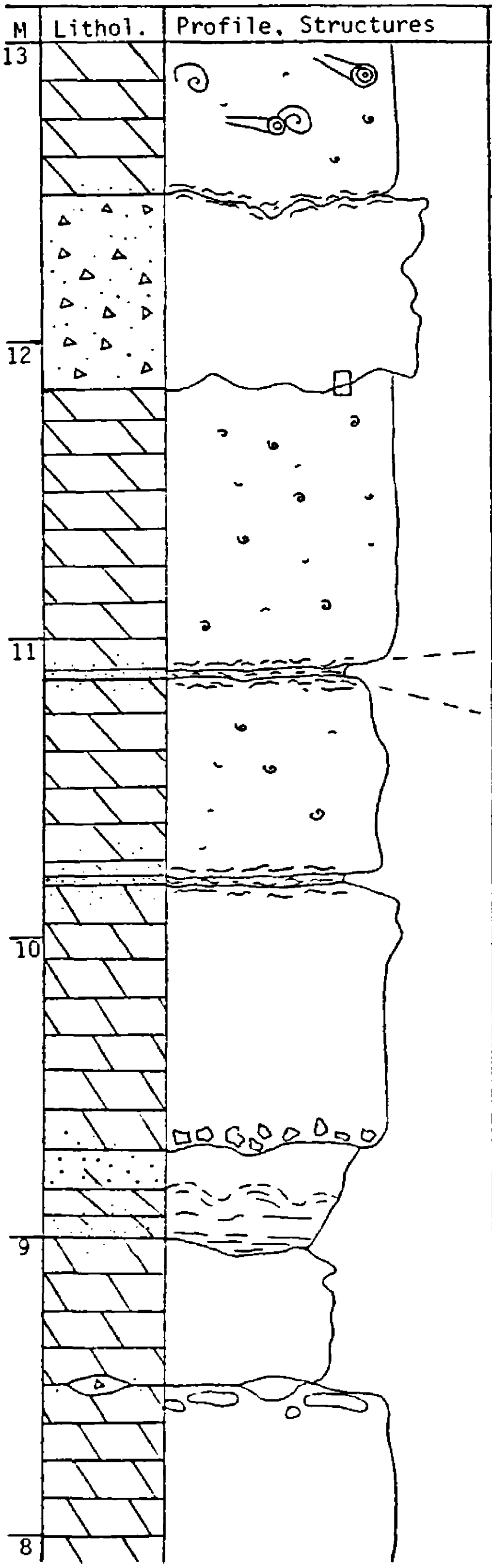
Description	Sample #
V sdy, cherty DOLOMITE, uneven, knobby-shaped sdy-cherty masses wthr out in relief, burrowed	9-25-9-6 9-29-9-5
Interbedded, Lenticular SANDSTONE and CHERT similar to north section. Cmt is mostly calc, wthrs punky & platy where calc cmt dom over qtz, poorly-preserved low-angle x-beds (about 5 degrees).	
CHERT w/lt (yel) gy silicified dolomite? intraclasts	9-29-9-4 9-29-9-3
Chert lens w/imbricated intraclasts 1-2.5cm long in cherty ss bed	
Ripple x-beds 3cm high	
horiz. and vert. burrows about .5cm diam, seen on bed surface	
Sdy CHERT, sd in whispy lam (less than .5cm) and burrows	9-29-9-1,2
Chert	

Ib. LA MARCHE GULCH NORTH



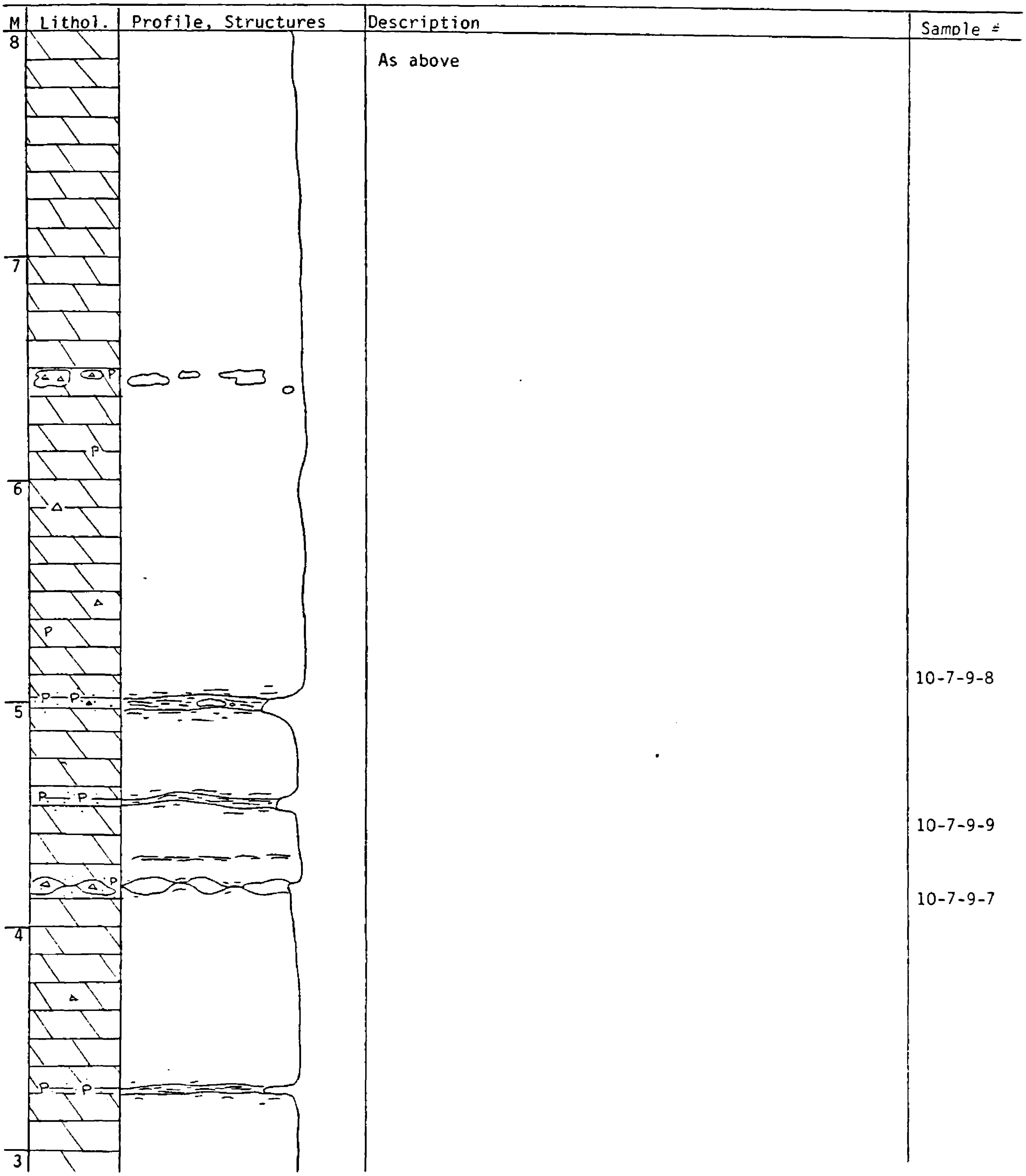
Description	Sample #
PHOSPHORITE sands and mudstones	
Qtz sdy, slty, (mic), (arg), phosphorite pelletal & intraclastic CONGLOMERATE. intraclasts dom pelletal phosphorite & qtz ss, phos & chert cmt, blk, rnd-(ang), flattened, up to several cm diam, locally imbricated, float in matrix or define grn-to-grn contact lenses. matrix srtd qtz ss and phos pellets. some graded bedding, shaley layers	LG17-2 LG17-1
Qtz and pelletal phosphorite SANDSTONE. blk-dk brn, mic, srtd, vf-f grn, qtz 30%, phos. 70%, phos & chert cmt, v thin beds, wavy-horizontal, fossil frags also v wthrd thin interbeds of mic, slty, sdy, phos MUDSTONE.	LG15.6
CONGLOMERATE. clasts dolo and pelletal, fossil frag, qtz sdy phosphorite to 10 cm, most 1cm, ang- (rnd). matrix qtz ss, phos pellets, fossil frags, spines.	
Molluscan bioclastic packstone DOLOMITE and wackestone DOLOMITE.(dk) med gy, thick bedded-massive, dense, hard, mnr qtz ss & slt. lg (to several cm diam)fossils dom scaphopods, gastropods, pelecypods occur in grn-supported lenses .25m-.5m long & float in matrix, Scaphs alligned parallel to beds, commonly nested, preserved lt gy microXline dolo (wthrs wh). sm fossils (less than .5cm) molluscs, ostracods (?), frags, preserved Xline dolo & calcite. tr blk petrol (?).	
As above	
As above	

Ib. LA MARCHE GULCH NORTH

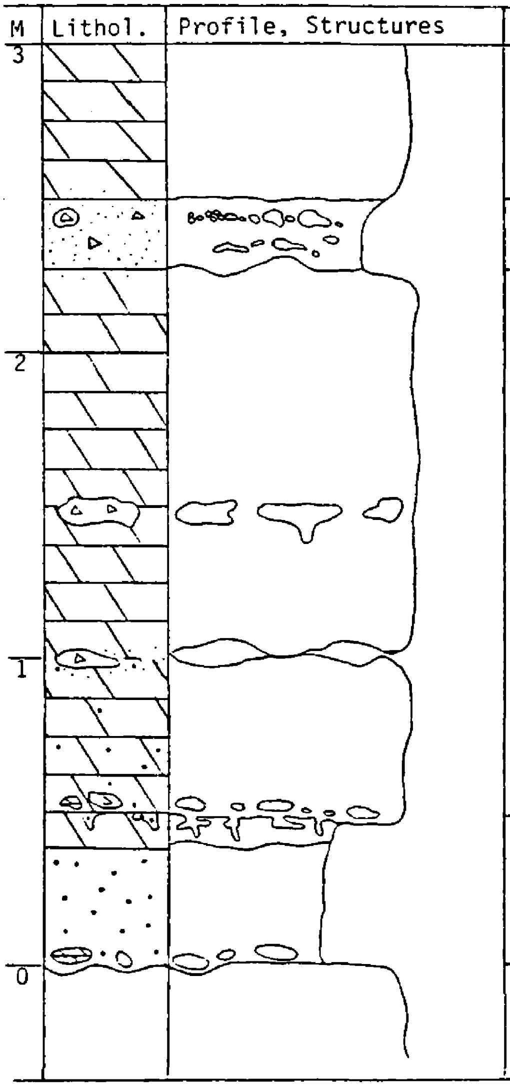


Description	Sample #
As Above	10-7-9-23
Silty black CHERT, v tk lumpy bed, curdled, mottled blk-wh texture, fractured, qtz veins	5-8-80-3
Bioclastic wackestone DOLOMITE as above but mostly med gy wackestone & some packstone, fossils v sm (less than .5 cm)	10-7-9-19
SILTSTONE, sdy, mic, pyr, dom qtz. blk when fresh, crudely planar lam less than 1 mm, wavy anastomosing stylolites	LG 10.85
DOLOMITE as above	
SILTSTONE w/blk chert nodules less than .5cm diam	10-7-9-17
Pelletal wackestone DOLOMITE, sdy-slty, mic, pry, mottled (lt) med gy w/(orng) red wavy digitate stylolites, non-fossiliferous, sltier upper 10 cm.	10-7-9-16 10-7-9-15
BRECCIA, lt gy, ang dol clasts, dom grain support in slty, f grn calc qtz ss	10-7-9-13 10-7-9-12
Stromatolite(?) zone, (yel) gy vf ss caps slty-sdy dolomite w/hemispheroidal shapes, stylolites, basal gy cacl-dolomitic ss-sltst	10-7-9-14 10-7-9-11 10-7-9-18
Brecciated DOLOMITE, slty, v sparsely fossil frag, dk gy, massive w/ fine qtz & calcite-filled fract.	10-7-9-10
Pelletal wackestone DOLOMITE, mottled lt-dk gy, qtz slty, massive, phos intraclasts and pellets scattered throughout and concentrated in slty zones separating beds, elongate chert nodules esp in slty bed partings, no fossils observed.	

Ib. LA MARCHE GULCH NORTH (cont.)

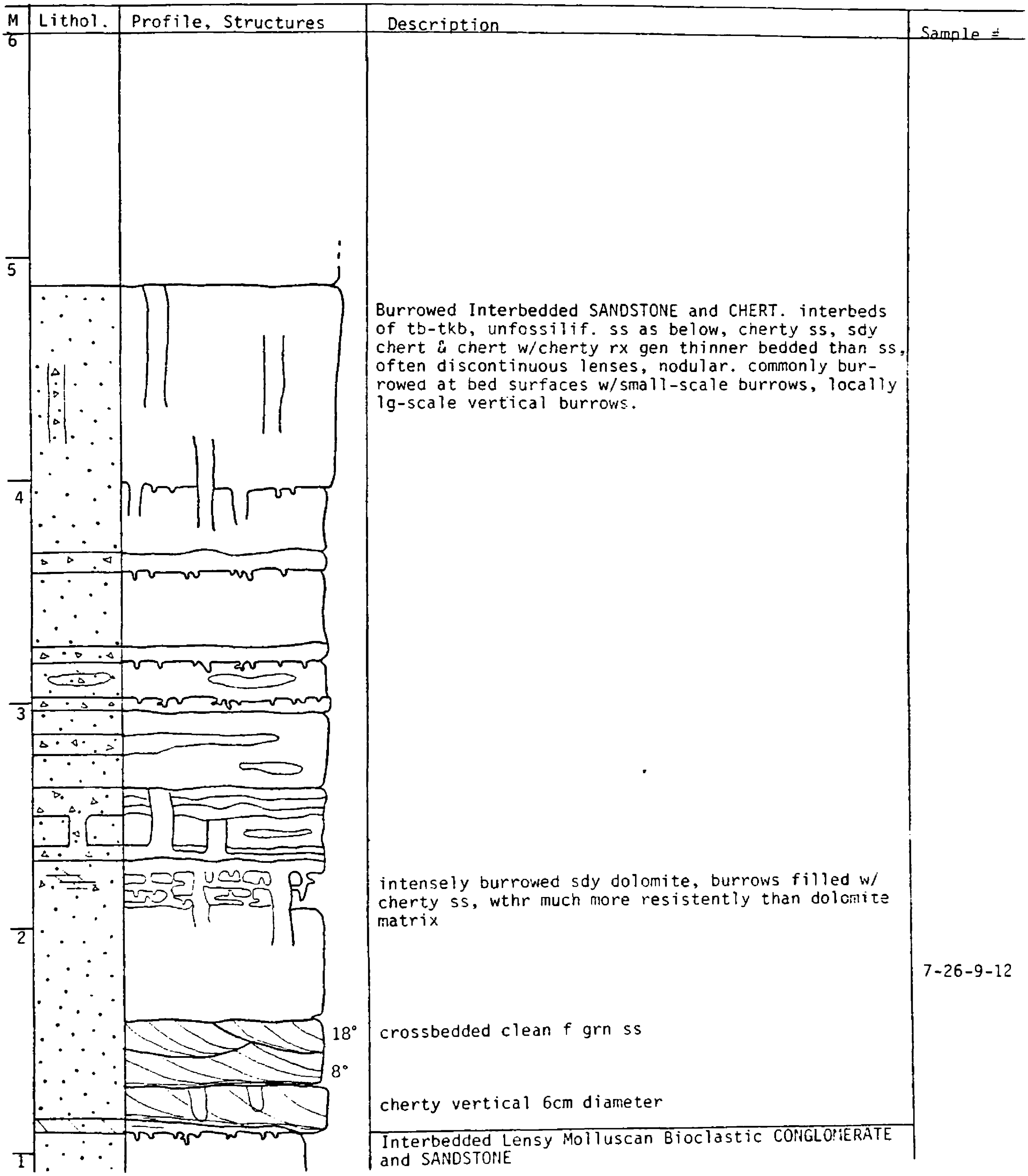


Ib. LA MARCHE GULCH NORTH



Description	Sample #
As Above	10-7-9-6
SILTSTONE, dolo, sdy, pyr, cherty, phos, mic,chert nodules lm-lcm in lenses bed-parallel, stylolites	5-8-80-2
DOLOMITE as above, phos content increases in lower 2 m. CHERT blk, mottled gy-wh-blk, nodular (up to 10x25cm) many brecciated w/qtz veins, assoc w/concentrations of pyr, stylolites, phos frags	5-8-80-1 10-7-9-5
DOLOMITE as above but w/sm burrows, grades downward to dolo ss and congl.	10-7-9-3 10-7-9-2
Conglomeratic SANDSTONE & DOLOMITE; clasts blk,phos, spiculitic, chert and gy dolo, ang, max 5 cm; matrix pyr, phos qtz ss. Burrowed sdy dolomdst w/ burrows .5cm diam, sd-filled. Sandstone qtz, chert, f grn	10-7-9-1
Nodular silicified DOLOMITE, lt gy w/mottled dk gy silicified zones, spicular, stylolitic, pyr	10-7-9-0

Ic. SAPPINGTON CANYON, Section 1



Burrowed Interbedded SANDSTONE and CHERT. interbeds of tb-tkb, unfossilif. ss as below, cherty ss, sdy chert & chert w/cherty rx gen thinner bedded than ss, often discontinuous lenses, nodular. commonly burrowed at bed surfaces w/small-scale burrows, locally lg-scale vertical burrows.

intensely burrowed sdy dolomite, burrows filled w/ cherty ss, wthr much more resistently than dolomite matrix

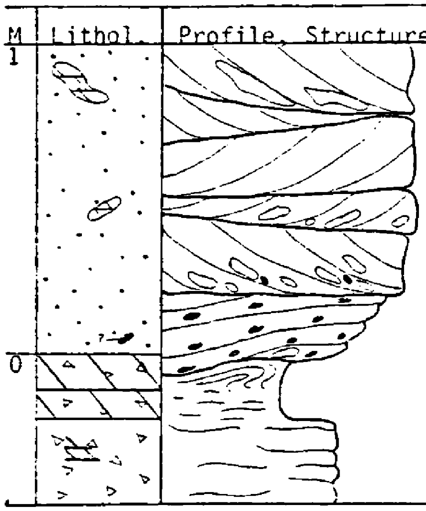
7-26-9-12

crossbedded clean f grn ss

cherty vertical 6cm diameter

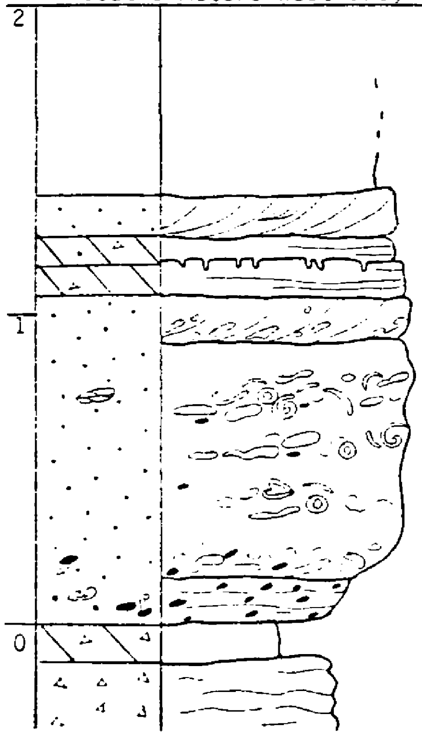
Interbedded Lensy Molluscan Bioclastic CONGLOMERATE and SANDSTONE

Ic. SAPPINGTON CANYON, Section 1



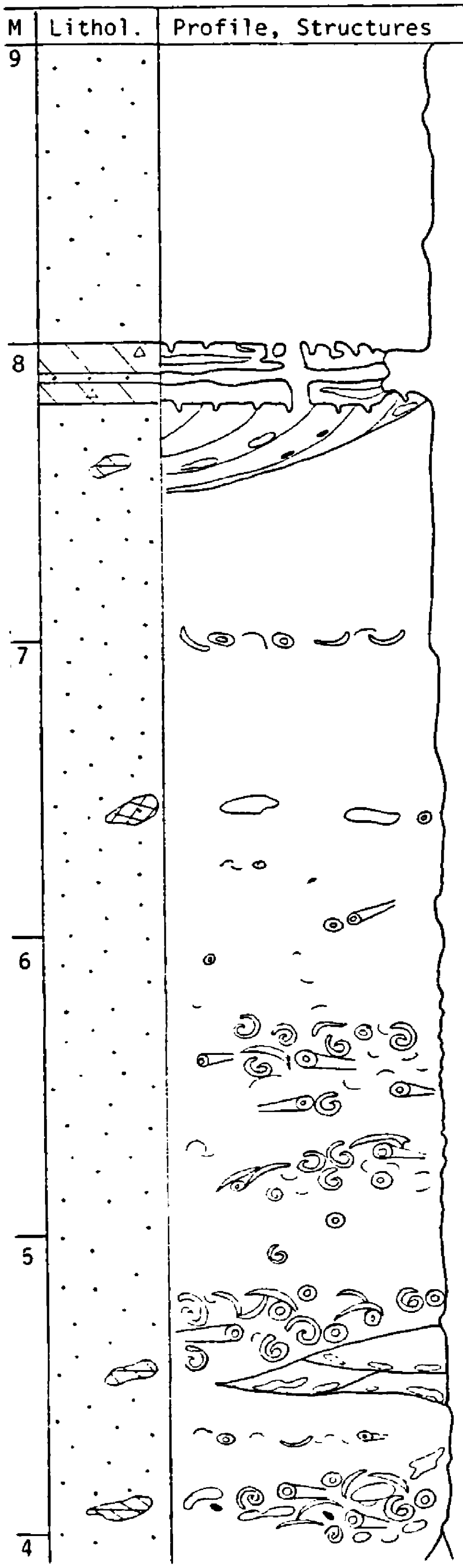
Description	Sample #
As above. Sandstone:vf-m grn, lt brn, wthrs m brn, well srtd, dom qtz + 5-10% chert & Phos, calc cmt. truncating trough-shaped beds often defined by basal lag of dolomite intraclasts (mm-9cm long), low-mod angle x-beds, bed thickness 10-40 cm, chert & phos pbls in lower 20 cm , rare fossil frags.	
Crossbedded Conglomeratic SANDSTONE as below 0-.1m (Sec. 1 horizontal beds to low angle x-beds)	7-26-9-10
Marker Zone. 0-18cm vf lam, yel wthr, aphanitic, siliceous dolomite, gradational lower contact	
Tosi Chert. vtb-discontinuous bedded, gy-brn chert, some horiz lam, rare ripple x-beds, mnr lensy siliceous dolomite	

About 5 meters westward, lower sands become fossiliferous:



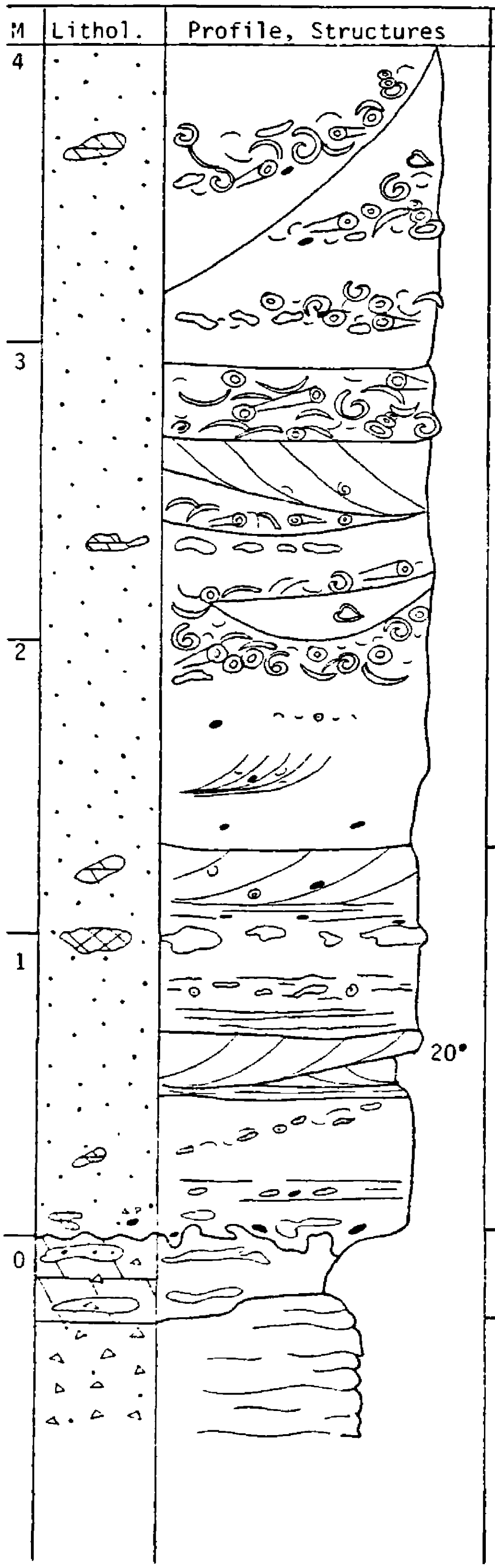
Burrowed Interbedded SANDSTONE and CHERT as above ripple-scale x-beds, 15cm scale x-beds.	SC2.1
Interbedded Lensy Molluscan Bioclastic CONGLOMERATE and SANDSTONE. Conglomerate lenses gen 20cm-1m tk, contain partly-silicified flat dolo intraclasts,phos pbls, chert lithoclasts to 1cm diam, fossils & foss. frags of scaphopods, pelecypods, bellerophontaceans, bryzoans (mostly as calcite-filled molds) lower 10cm fossil hash, bottom surface of bed shows molds of pectins, orbiculoidea(?), other pelecypods	SC1.9
X-Bed. Congl. SS, vtb-tb, vf-f grn ss, chert-phos pbl	SC1.2
Marker Zone	
Tosi Chert as above, red-stn upper surface	

Ic. SAPPINGTON CANYON, Section 2



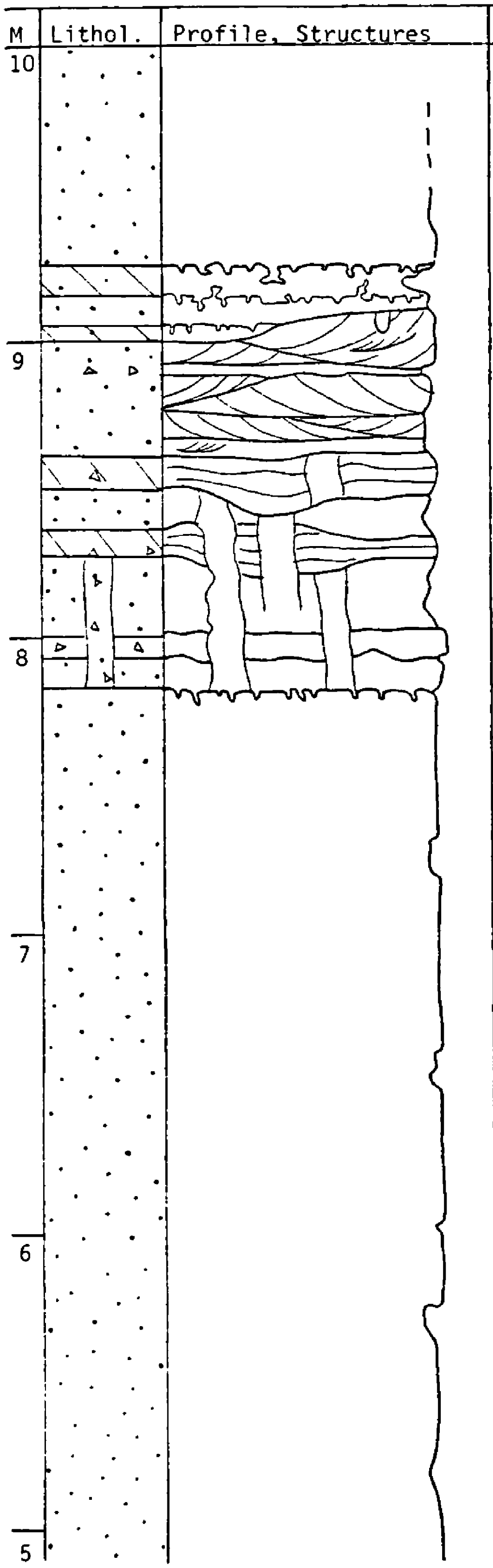
Description	Sample #
Burrowed Interbedded SANDSTONE and CHERT as in Section 1	
Bioturbated Marker Zone, as Sec. 1	7-25-9-8 7-25-9-9
Interbedded Lensy Molluscan Bioclastic CONGLOMERATE and SANDSTONE.	
massive, brn wthr, vf-m grn qtz + mnr chert & phos ss, a few thin lenses of v poorly preserved mollusc fossils, crs blocky calcite pods	
Pocky wthr ss, (yel) gy-(brn) gy, as above w/more abundant calcite casts of molluscs, gen poor preservation	
Sandstone w/interbedded lenses (few cm-1m x 10cm-few m) of silica and/or calcite-filled mollusc molds, grain-supported in sandstone, locally abundant dolomite flat mud intraclasts, pbls.	7-25-9-10

Ic. SAPPINGTON CANYON, Section 2



Description	Sample #
As above, wthr color becomes more (red) brn	
	7-25-9-11
borings preserved on some shells, occasional articulated pelecypod	7-25-9-12
	7-25-9-7
becomes sparsely fossiliferous, pbly	7-25-9-6
Crossbedded Conglomeratic SANDSTONE. f grn, qtz 95%, 5% blk & red chert & phos grns, crs calcite pods to several cm diam	
15 cm-high x-beds	7-25-9-5
	7-25-9-4
Marker Zone, as in Sec. 1, erosional upper contact, contains ripped-up clasts.	7-25-9-3 7-25-9-2
	7-25-9-1
Tosi Chert. wavy-planar, discontinuous vtb, (brn) gy-lt (pk) gy, mottled-vf lam, most beds have lt-color wth rind	

Ic. SAPPINGTON CANYON, Section 3



Description

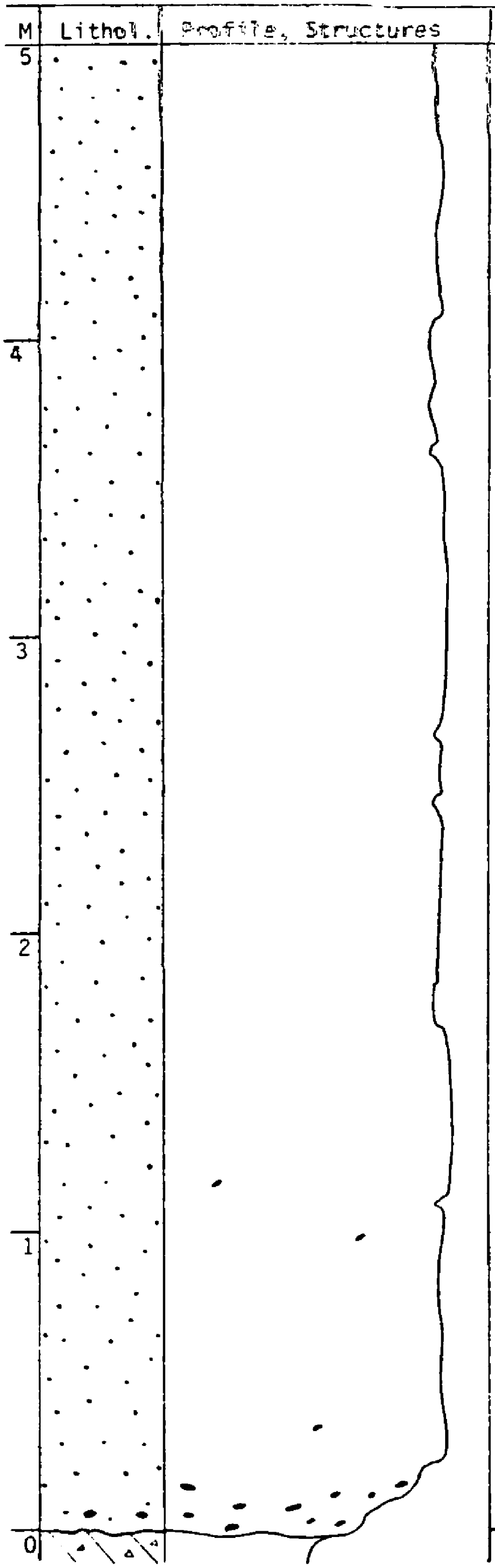
Burrowed, Interbedded SANDSTONE and CHERT. interbed sandstone,chert, dolomite. SS dom: brn, vf-f grn, rare carbonate mud intraclasts, ripple and larger x-beds locally + massive or horiz lam beds. Chert: brn-gy, usu sdy, vtb-tb. Dolomite: yel wthr, burrowed, laced w/sand that is prob. also burrow traces, siliceous, sometimes vtb. Truncating or undulating bed surfaces common, locally crossed by lg cherty vertical burrows.

Bioturbated Marker Zone

Interbedded Lensy Molluscan Bioclastic CONGLOMERATE and SANDSTONE. Here only sandstone: brn wthr, massive, vf-f grn, well srtd except for rare local pbly zones, bedding indistinct

Sample #

Ic. SAPPINGTON CANYON. Section 3



Description | Sample =

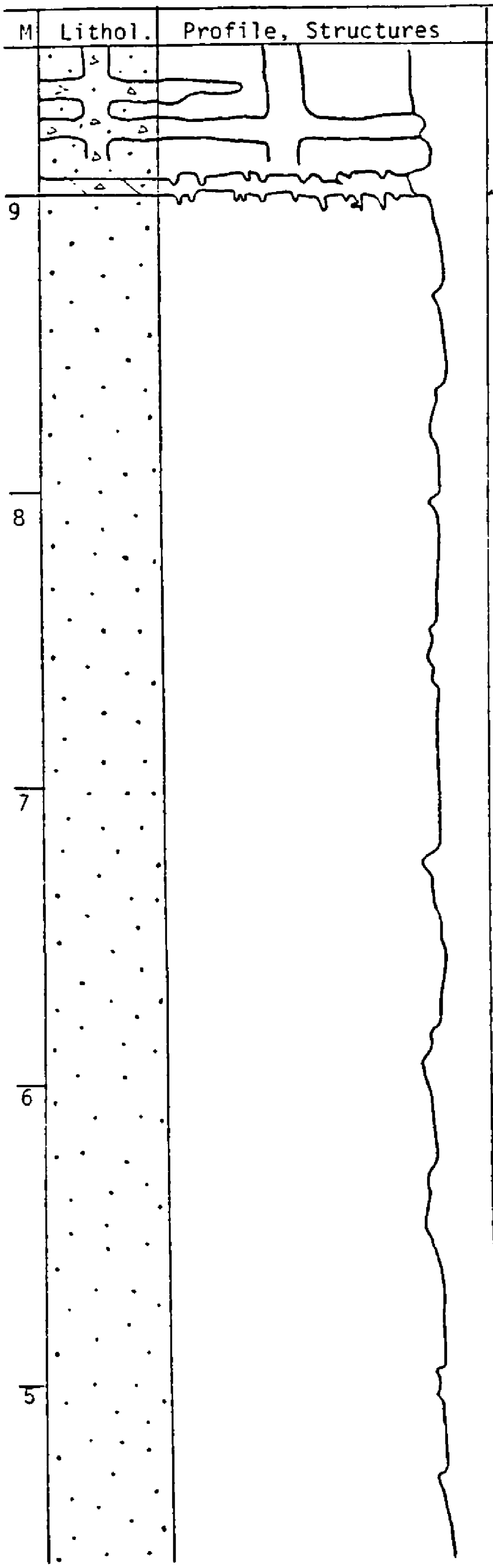
Sandstone as above

7-26-9-1

lowest 20cm contains scattered chert and phos pbls

Marker Zone

Ic. SAPPINGTON CANYON, Section 4



Description

Sample #

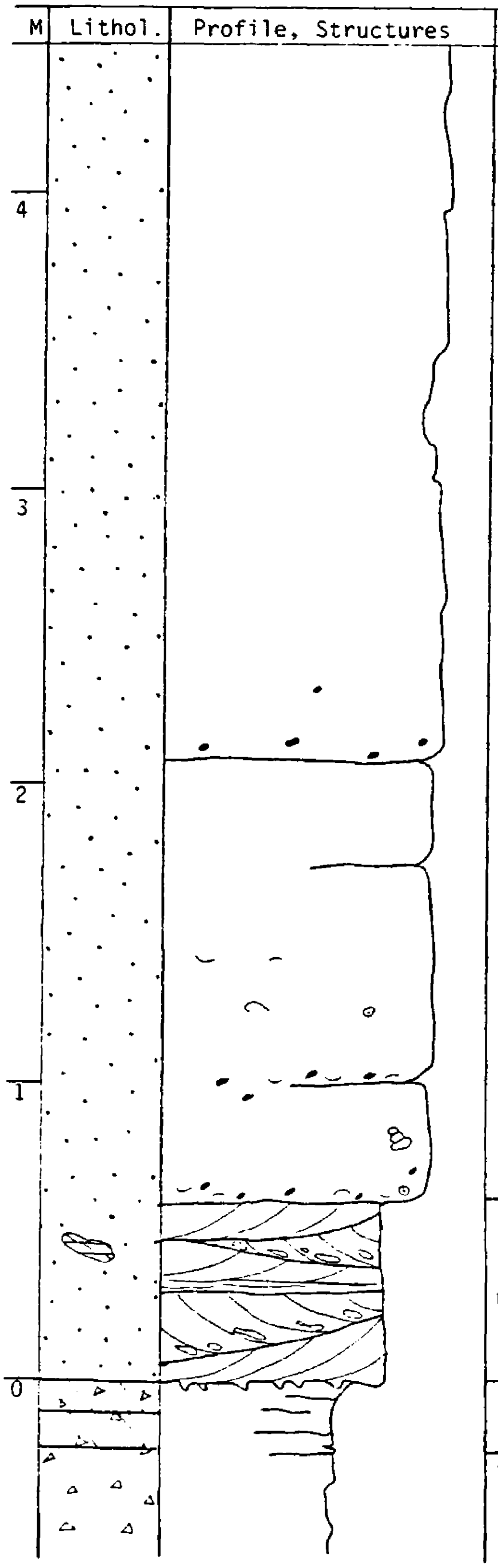
Burrowed Interbedded SANDSTONE and CHERT

Bioturbated Marker Zone

Interbedded Lensy Molluscan Bioclastic CONGLOMERATE and SANDSTONE.

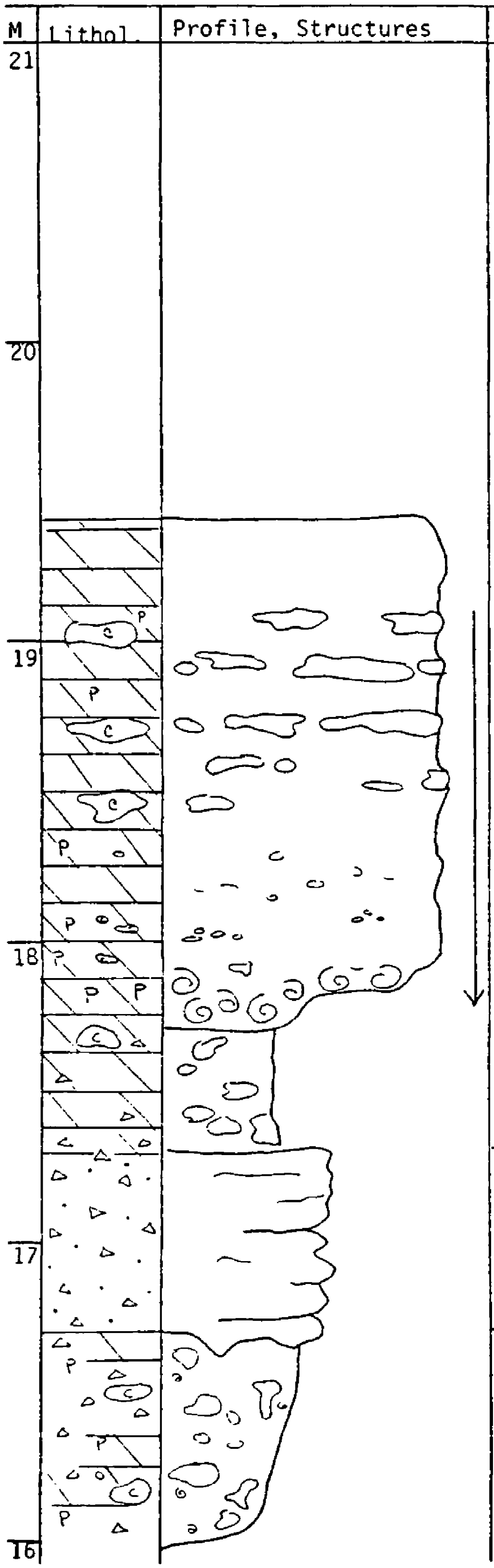
Sandstone, brn, massive vf-m grn

Ic. SAPPINGTON CANYON, Section 4



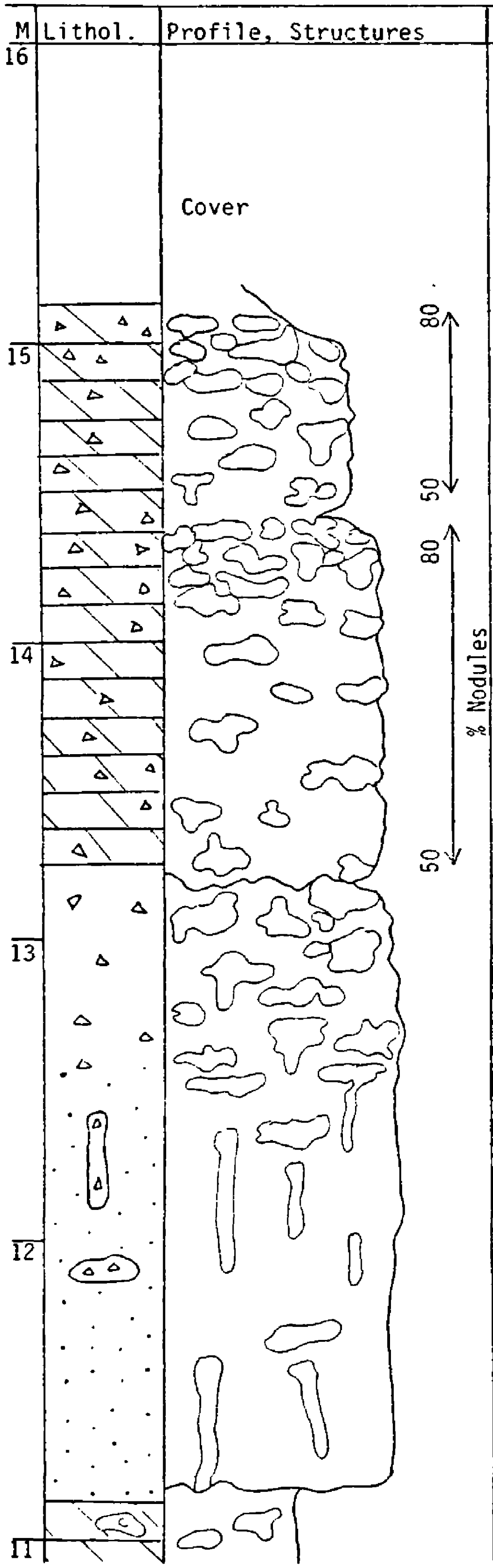
Description	Sample #
Massive brn Sandstone as above	
Pocky wthr SS, crs pbl lag locally, gen poorly srtd, some v indistinct probable x-beds, bed surfaces display imprints of *Schizodus*, *Nucula*, *Lingula*, *Orbiculoidea*, mnr gastropods and scaphopods which are only rarely seen as calcite-filled molds	7-26-9-3,4 7-26-9-2 8-26-9-4
Crossbedded Conglomeratic SANDSTONE. brn-gy, calc & silica cmt, well srtd, f-m grn w/flat carb mud pbls to 6cm long, dk chert & phos pbls locally, festooned, multi-directional crossbeds 10-20cm thick and some horizontal lam beds, some fossil imprints as above.	7-26-9-5
Marker Zone of yel wthr siliceous dolomite and bedded chert	
Tosi Chert	

Id. DEVILS SLIDE



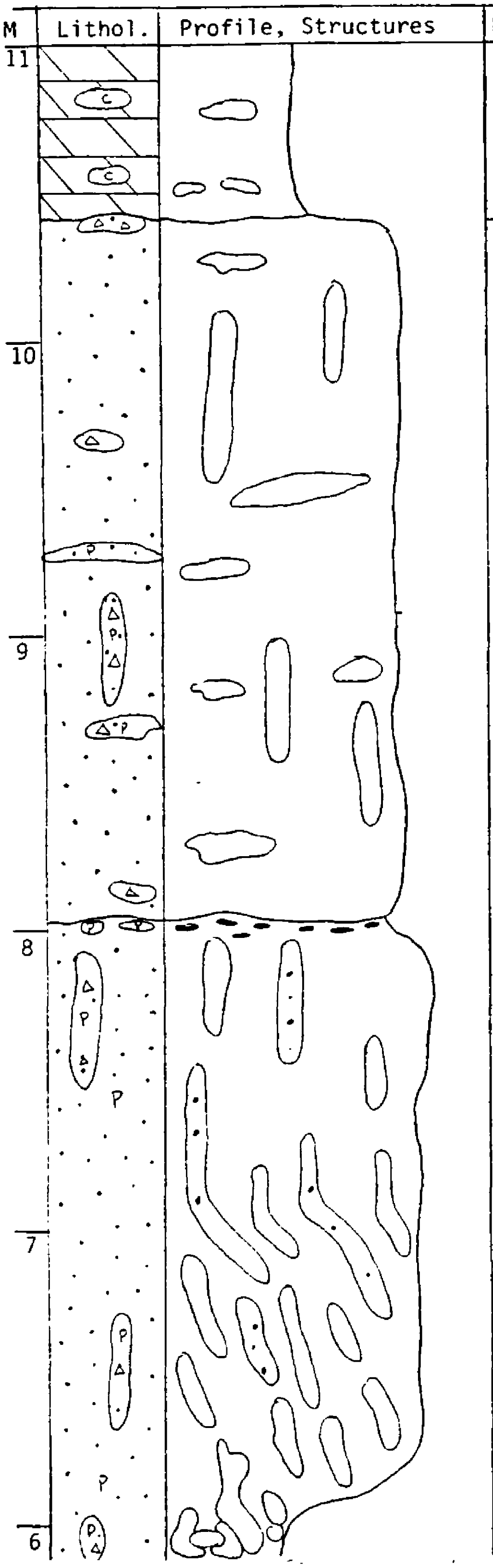
Description	Sample #
Calcite-nodular DOLOMITE, lt-med gy, microcrystalline to silt-sized crystals, mottled & burrowed, qtz slty, pyr, phos; nodules dom calcite w/mnr qtz, less than 1mm to greater than 20 cm, tend to occur in concentrations parallel to bedding, crs, twinned calcite, some euhedral qtz xls, nodules wh-blk.	DS19.3 DS18.7 DS18.5
Calcite nodules fewer & smaller than above, scattered qtz-filled fossil frag molds, ang phos intraclasts to 1cm, gen less than 1mm, phos microgastropod molds.	DS18.3 DS18.1 DS18 DS17.9
Silica-filled molds of bellerophontacean gastropods, phos microgastropod molds, dolo as above	DS17.8 DS17.7 DS17.6
Calcite nodular DOLOMITE grading downward to dolomitic chert.	DS17.5 DS17.4
Very sdy CHERT, w/chert sandstone, wthrs to poorly-exposed low jagged ridge, prob. v thin bedded	DS17
Phos, dolo, nodular CHERT. DK (bl)gy chert, nodules dom blky calcite w/ blk interxline mat, local euhedral qtz, chaotic texture. dk (red) brn-blk phos frags & microgastropod steinkerns occur in dolomite	DS16.3

Id. DEVILS SLIDE (cont.)



Description	Sample #
Calcite and qtz nodules in DOLOMITE. dolo "matrix" lt gn-gy tan, microXline occurs in thin layers and stringers between nodules and chert, grades locally to chert. chert, bl-gn gy, carmel, rough nodules and cylindrical shapes (1-10 cm) intergrown to massive chaotic texture, riddled w/few cm diam qtz-calcite geodes.	DS14
Calcite and qtz nodules and chert as above, but w/out matrix, which has apparently weathered away. center 40cm contains (yel) gy- (red) brn, slty, calc unconsol. mat. between cherty masses. upper and lower zones contain open vugs. gradational lower contact, sharp uneven upper contact.	
Phosphate qtz SANDSTONE, med gy-lt (gy) brn, srtd, f-vf, calc, locally cherty. 30-50% phos. cherty ss columns and nodules. phos. in ss 10%.	
Calcite nodular DOLOMITE, (yel) gy, massive. crs calcite nodules are dk, oily-smelling	DS11

Id. DEVILS SLIDE (cont.)



Description

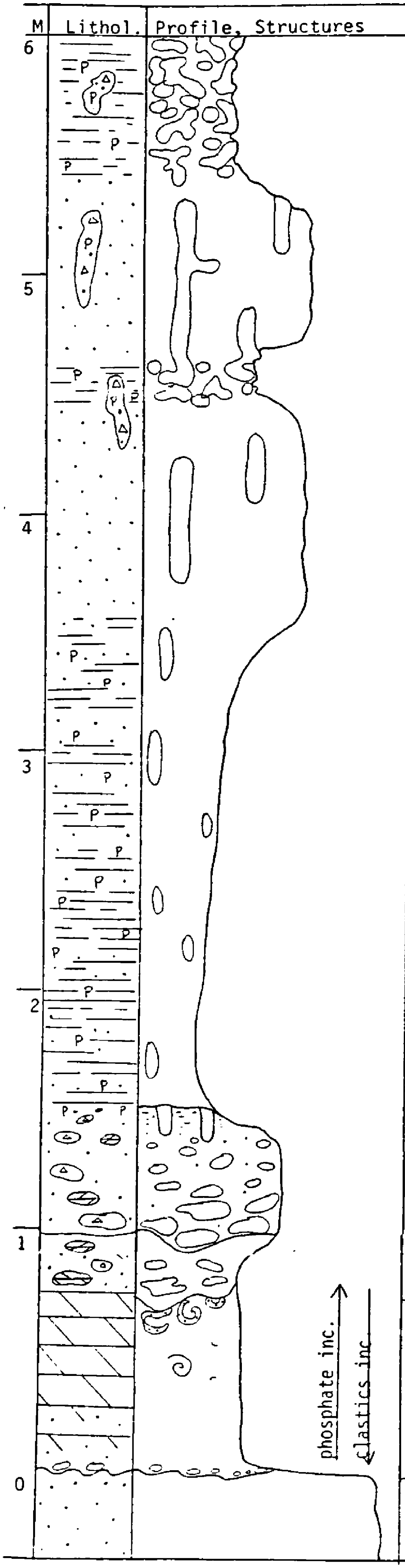
Sample #

As Above

Qtz SANDSTONE, lt (brn) gy, vf grn, srtd, w/cherty columnar structures & interb thin discontinuous lenses of v poorly srtd phos fossil frags & qtz pbls (gen 2-5mm).

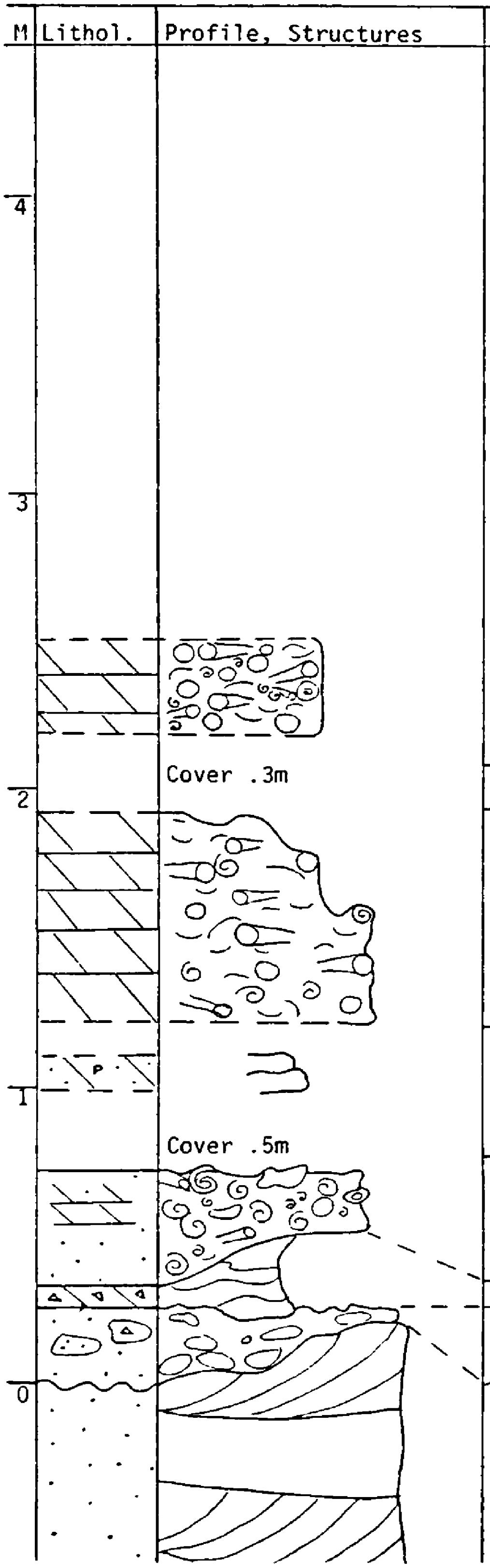
Phos fossil frag and chert pbl CONGLOMERATE SANDSTONE,lt (gy) brn, f-med grn, dom qtz w/ locally significant chert pbls & sm phos fossil frags. CHERT columns, sdy, phos in upper bed esp, med gy, 3-6cm diam, up to 1m or more long. at about 7m in section culumns bend and increase from less than 40% to more than 60% of rock.

Id. DEVILS SLIDE (cont.)



Description	Sample #
Sdy, phos, CHERT columns and phos MUDSTONE. contorted blk chert columns (almost 90% of rock) in matrix of dk brn-blk sdy, phos mudstone, columns are several cm diam, prob tens of m long.	
SANDSTONE, lt (gy) brn, f-crs qtz ss w/local phos fossil frag congl lenses, contains cherty, sdy, phos column as above, gradational upper and lower contacts.	DS4
Interbedded phos SANDSTONE and MUDSTONE, w/ cherty columns locally, much of phos is shell frags, wthrs recessively.	
CONGLOMERATE, crs ss-pbl sized phos shell hash and qtz ss, lg columnar chert-phos structures CONGLOMERATE, chert & dolo clasts up to 10 cm in dolo-qtz ss matrix at base grades up to smaller clasts (less than 1 cm) in phos-qtz ss matrix, scattered fossil frags.	
CONGLOMERATE intraclastic sdy dolo, chert pbls & boulders, fossil frags (phos. & calcite), matrix (yel) gy dolo qtz ss.	DS.9 DS.8 DS.7
Dolo qtz SANDSTONE grading (?) upward to sdy DOLOMITE. sand-filled fossil molds at upper erosional boundary (gastropod, scaphopod(?), frags). calcite-filled bellerophontacean and frags in mid-bed.	DS.6 DS.5 DS.4 DS.3 DS.2 DS.1 DS0
CONGLOMERATE 5cm, qtz, chert, dolo clasts to 2cm	
SANDSTONE f grn, srtd, qtz	

Ie. BOULDER RIVER



Description	Sample #
Covered swale bottom	
Petroliferous molluscan bioclastic packstone DOLOMITE mottled med-dk gy & blk w/ scattered wh calcite-filled vugs <cm diam, whtrs lt gy-wh. dom. fossils lg scaphopods (5cm), sm gastropods (2mm) also ostracods, pelecypods, fish teeth, most deformed. much BPM	BR4-1 BR4-2
As above. intensely altered & reXlized, mottled tan, lt-dk gy, lt (pk) gy, darkest where black petroliferous material (BPM) lines pores, wthrs lt gy. fossils dom. lg scaphopods w/ some lg bellerophontaceans, pelecypods, sm gastropods, fish teeth. most fossils in both beds collapsed, deformed molds partially filled w/dolomite rim cmt and calcite & BPM.	BR3-1 BR3-2
Phos., v qtz sdy, burrowed DOLOMITE. phos. up to 10% clean ang (yel) brn frags & paleaoniscoid fish teeth. sand f-med grn to 40%.	BR2-1
CONGLOMERATE. matrix dolo ss-sdy dolo.chert clasts ang-(rnd) av .5cm (to 2cm). bioclasts dom. bellerophontaceans, scaphopods, pelecypods w/ramose bryzoans & fish teeth, scattered sil. internal molds.lt (pk) tan w/ local concentrations of BPM.	BR1-6,a-e BR1-5 BR1-4
Conglomeratic SANDSTONE, chert clasts to 40cm.	BR1-3
CONGLOMERATE and Conglomeratic SANDSTONE. SS med grn, srtd, calc cmt w/BPM. clasts microfossiliferous chert and (dolo) f grn qtz ss.	BR1-2,1-1
UNCONFORMITY SANDSTONE, f gr, srtd, qtz sand w/ dolo cmt, some v sdy dolo, well-developed x-beds.	

APPENDIX II. Faunal Lists by Locality

Location	Cedar Creek	Sappington Canyon	La Marche Gulch N.	Devils Slide	Boulder River
Taxon					
Mollusca					
Pelecypoda					
Schizodus	x	x		x	x
Pseudopermophorus	x				
Permophorous	x?				
Nuculopsis	x	x			
Polidevcia	x				
Acanthopecten		x			
Pelecypod indet.	x	x	x	x	x
Permophorid indet	x				
Nucula		x			
Scaphopoda					
Prodentalium canna	x				
scaphopod indet.	x	x	x	x	x
Gastropoda					
Bellerophon deflectus	x			x	
Bellerophon indet.	x	x	x	x	x
Knightites eximia	x				
Euphemitopsis				x	
Euphemites crenulatus	x				x
Wothenia	x	x?		x	
Bellerophontacean indet.	x	x	x	x	x
Microgastropods	x	x	x	x	x
Gastropod indet.	x	x	x	x	x
Brachiopoda					
Inarticulata					
Lingula		x		x	
Orbiculoidea		x		x	x
Articulata					
Chonetes					x
Wellerella					x
Bryzoa					
Fenestrate	x				
Ramose	x	x		x	
Porifera					
Sponge spicules	x	x		x	
Echinodermata					
Crinoid ossicles	x				
Vertebrata					
Palaeoniscoid fish teeth	x	x		x	x
bone fragments	x	x	x	x	x
Trace Fossils					
Thalassinoides	x	x			
Planolites		x			
Skolithos	x	x			
Diplocraterion		x			
Large vertical burrows	x	x	x	x	
Barnacle borings	x	x	x		
Plants					
Algae					
Dasycladacean	x	x			
Phylloid			x		
Algal mat chips (?)			x	x	
Stromatolites (?)			x		
Other					
Ribbed leaf		x			

This list was compiled from a list used in the publication of Yochelson (1968) and from my own observations. It was not intended to be an exhaustive final study but is suggestive of the types and variablity of fossils at these localities. Systematic sampling was not employed in this study.