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DEPOSITIONAL ENVIRONMENTS AND DIAGENESIS OF THE MADISON LIMESTONE, NORTHERN MEDICINE BOW MOUNTAINS, WYOMING

by

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ABSTRACT

Mississippian strata of southeast Wyoming provide new insight into regional Mississippian stratigraphy. The Madison Limestone along the west and northwest flanks of the Medicine Bow Mountains is approximately 10 m thick. The Madison is conformably underlain by a Mississippian sandstone, and disconformably overlain by redbeds which represent a Mississippian terra rossa. Stratigraphic correlation and scanty fossil evidence suggest that the Madison is Osagean, probably correlative with Sando's (1968) unnamed member of the Madison Limestone in central Wyoming.

The Madison within the field area consists mainly of pelsparite and oopelsparite. Oolitic intervals have been correlated and are more abundant to the south near Coad Mountain. Subordinate beds of micrite, biopelsparite, and bio-oopelsparite are also laterally persistent. A section at the north end of the field area consists of extensive neomorphic calcite and silicified limestone beds.

Cross-bedding is very common. Cross-bedded units range in geometry from tabular to wedge-shaped, and foreset dip directions indicate a predominantly south-southwest current direction. Post depositional deformation of beds by slumping is also common.

A marine depositional model is proposed which consists of a carbonate sand belt composed of individual subparallel bars. This belt, lying only a few kilometers offshore, paralleled the northeast-trending Mississippian shoreline and aggraded south-southwest as a result of longshore drift.

Diagenetic alteration of the Madison Limestone has been minimal. Diagenetic changes seem related to times of deep burial, Laramide deformation, and subaerial exposure. At least two generations of cementation are recognized. Liesegang banding originated prior to second generation cementation. Stylolitization occurred during times of deep burial and Laramide deformation. Similarly, calcite-filled fractures and neomorphic spar patches originated during deformation. Late Cenozoic regional uplift and exhumation have resulted in sub-aerial diagenesis. Copper mineralization, silicification, and massive recrystallization, all at the north end of the field area, are thought to be late in the diagenetic sequence.

INTRODUCTION

This study was undertaken to determine the depositional environment and diagenetic chronology of the Mississippian Madison Limestone in the Elk Mountain area of the northern Medicine Bow Mountains. Other objectives include placement of the Madison Limestone of the field area within the Mississippian biostratigraphic framework of Wyoming.

This area was chosen because the Madison Limestone is excellently exposed and exhibits interesting sedimentary structures. In particular, Oberg Pass, situated between Coad and Pennock Mountains, offers excellent flatiron exposures of the Madison Limestone.

The field area for this study occupies part of eastern Carbon County, Wyoming. Madison Limestone outcrops extend from T17N to T20N and from R81W to R82W. The Kennaday Peak, Coad Mountain, Rattlesnake Pass and Coal Bank Basin 7.5 minute U.S. Geological Survey quadrangle maps provide topographic control for the area. The field area is a northern extension of the Medicine Bow Range. Pennock, Coad and Elk Mountains extend to the north of the main range as progressively semi-isolated masses.

METHODS OF INVESTIGATION

Field work for this study was undertaken during the months of July and August, 1976. Six major sections through the Madison Limestone were measured, and numerous minor sections were measured through parts of the formation where special features warranted detailed inspection. All major stratigraphic sections were thoroughly sampled and described in detail. Fig. 1 shows the locations of measured sections.

The petrographic microscope was the primary laboratory tool. Approximately 200 standard size thin sections (26mm x 46mm) were cut and mounted on glass slides with cover slips.

Hand samples from which thin sections were made were polished for hand lens examination. Approximately 20 polished slabs were selected for staining (potassium ferricyanide and Alizarin red-S) and acetate peels. In addition, acetate peels were made of small-scale cross-bed sets.

Additional equipment utilized includes the microprobe and scanning electron microscope.

STRATIGRAPHY

Mississippian strata of Kinderhookian and Osagean age nonconformably overlie Precambrian granites and gneisses in the northern Medicine Bow Mountains (Houston and others, 1968). The Mississippian strata may be subdivided into three lithologically distinct units. These are, in ascending order, a basal arkose, a cross-stratified oopelsparite limestone, and a red siltstone and shale containing abundant chert pebbles and concretions (Fig. 2). The three-part division of Mississippian strata is readily observable on outcrop, although the basal arkose is often covered with talus. Good exposures of all three units may be found on the southwest flank of Coad Mountain.

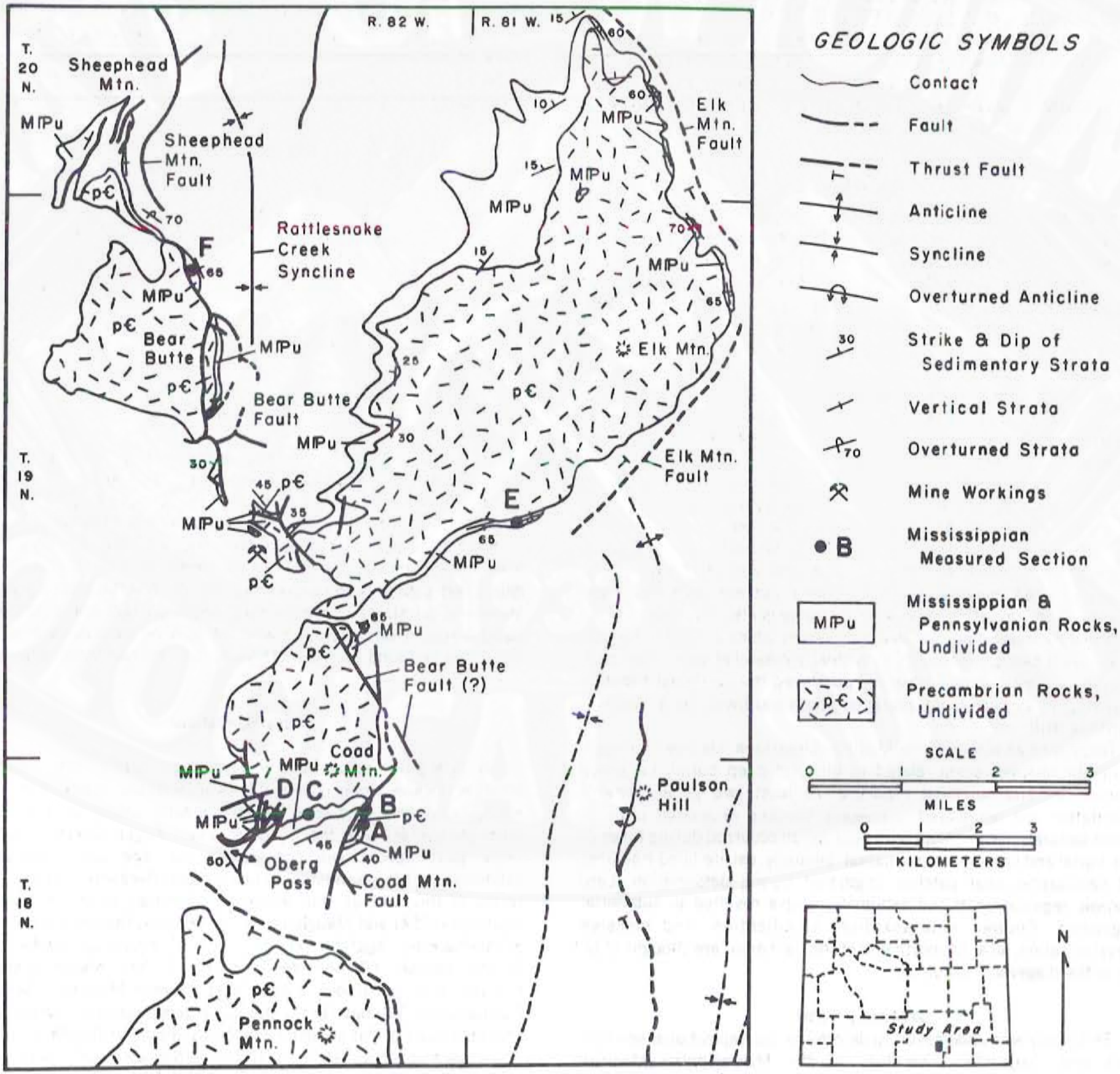
Basal Sandstone

A dark pink, yellow, and white mottled poorly sorted arkose of variable thickness nonconformably overlies Precambrian rocks. Good exposures of this sandstone, which are rare, clearly show a nonconformable contact with the Coad Mountain Augen Gneiss. There has been past speculation concerning the age and stratigraphic relationship of this sandstone. For example, Beckwith (1941, p. 1451) refers to this unit as thin lenses of Cambrian quartzite. However, Agatston (1954) and Maughan (1963) proposed that this sandstone is Kinderhookian. Agatston (1954, p. 514) collected Kinderhookian fossils, notably *Chonopectus fisheri*, 13 feet above granite at the top of a calcareous arkose east of Iron Mountain, Wyoming. Furthermore, Thomas (1951) provided paleontological evidence that the upper part of this sandstone is Mississippian at the Rawlins Uplift.

Craig and others (1972, p. 100) question a Kinderhookian age for this basal arkose and include it with beds of Osagean age because of variable thickness and unknown limits. Although fossils were sought in the basal sandstone by the author, none were found to verify the age at Coad Mountain. However, there can be little doubt that the sandstone is Mississippian (probably Kinderhookian) on the basis of conformable relationships and fossil identification at other localities. Maughan (1963, p. C24) has suggested that the basal Mississippian sandstone in the Laramie Range is correlative, at least in a genetic sense, with other Mississippian sandstones such as the Gilman Sandstone Member of the Leadville Limestone of central Colorado.

According to Maughan (1963), the unit commonly grades upward into moderately well-sorted quartzose sandstone which becomes increasingly calcareous and grades into the overlying unit. Several trenches extending from well-exposed basal arkose into overlying Madison Limestone were dug during the present investigation on the southeast side of Coad Mountain. In some cases, the gradation from arkose to limestone characterizes an interval of a few centimeters. In other cases, the contact appears to be very abrupt. An increase in calcite cement, presumably leached from the overlying limestone, was noted in all cases as the upper contact was approached. In addition, thickness of the basal unit varies from zero to several meters along strike in many outcrops, indicating that deposition was probably on an

DISTRIBUTION OF CARBONIFEROUS OUTCROPS AND LOCATIONS OF MEASURED SECTIONS, NORTHERN MEDICINE BOW MOUNTAINS, WYOMING



(modified from Houston and others, 1968)

FIGURE 1. Index map, distribution of Carboniferous outcrops, and locations of measured sections, northern Medicine Bow Mountains, Wyoming.

irregular, channeled Precambrian terrain.

The simplest explanation for the stratigraphic position of this sandstone involves a Mississippian arkosic regolith which was partially reworked by the encroaching Mississippian shelf sea. This is preferable to postulating a major hiatus between Cambrian and Mississippian strata, with preservation of 1 or 2 meters of relatively friable Cambrian sandstone conformably overlain by Mississippian limestone. There seems little justification in calling any sandstone "Cambrian" simply because it was deposited on a Precambrian terrain.

Madison Limestone

The Madison Limestone was originally named by Peale (1893, p. 32) for lower Carboniferous limestones underlain by the Devonian Three Forks Shale and overlain by the Upper Carboniferous Quadrant Formation in the "... region immediately adjacent to Three Forks ...", Montana. Peale divided the Madison Limestone into basal laminated limestones, middle massive limestones, and upper "jaspery" or cherty limestones. Maughan (1963, p. C26) recognized the upper chert unit of the Madison Limestone in the southern Laramie Range. This unit may be correlative with a chert interval observed by the author south of Sheephead Mountain.

The Madison Limestone of southeast Wyoming was deposited during "cycle 1" of Sando's (1976) outline of Mississippian history. This cycle spans the time from early Kinderhookian through early Meramecian. Sando has divided cycle 1 into seven "phases." Phase 1 represents the initial transgressive sediments (early Kinderhookian)

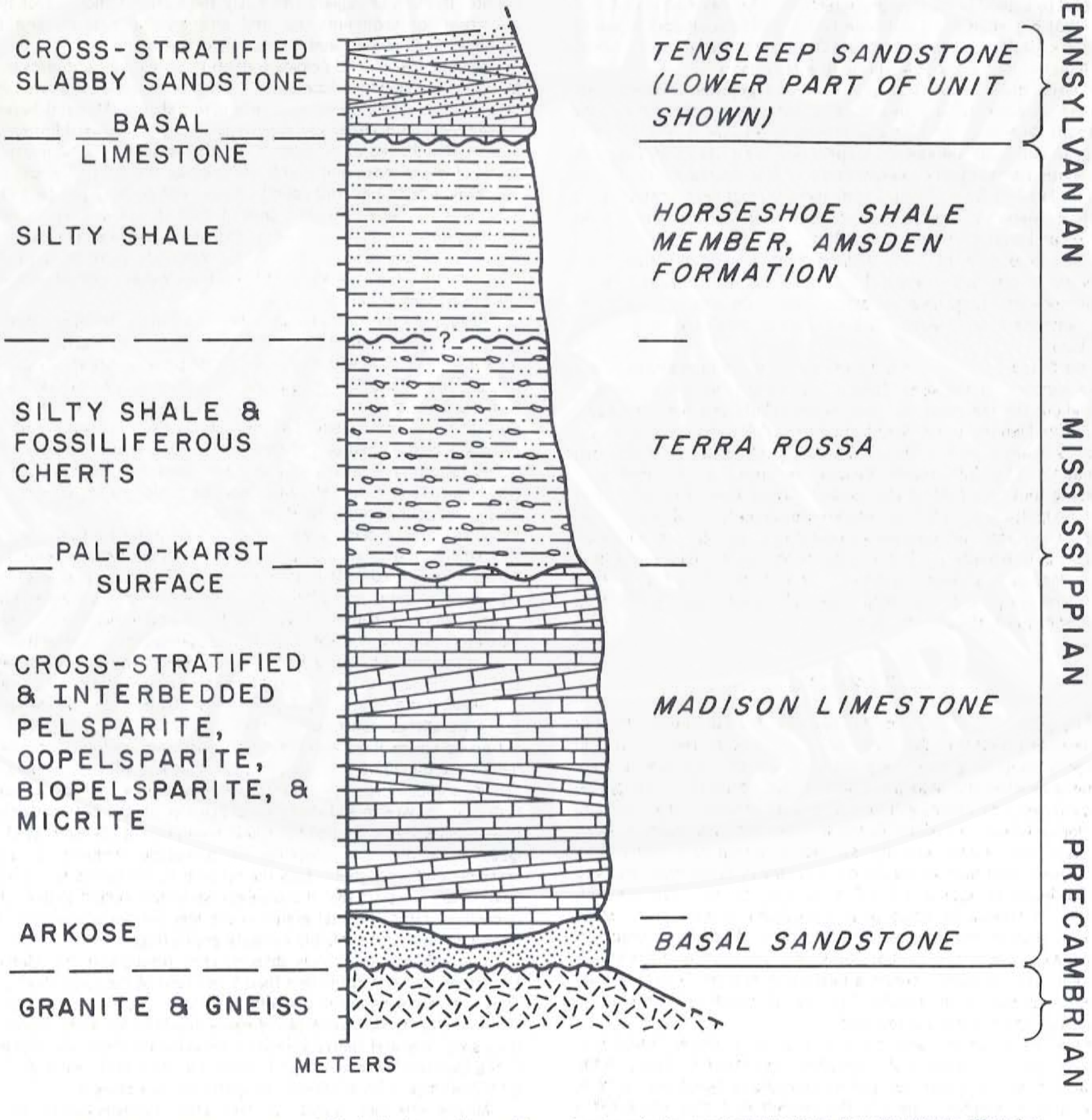


FIGURE 2. Columnar section of Mississippian and lower Pennsylvanian strata, northern Medicine Bow Mountains, Wyoming.

deposited as the Mississippian sea spread over the cratonic margin. The basal sandstone of the field area may be related to this phase of deposition. During phase 2 (late Kinderhookian), subtidal carbonate deposition began throughout the northwest Wyoming Province.

Phase 3 (latest Kinderhookian) was the time of maximum transgression. Deposition of the Madison Limestone in the northern Medicine Bow area was probably initiated during this time. Sando (1976, p. 323) states that the shelf margin shifted landward, probably because of a rise in sea level. This would help explain pervasive large-scale cross-stratification in the Madison Limestone, in terms of providing a high energy environment across southeast Wyoming. Cross-stratification, from small to large scale, was found throughout the field area.

Phase 4 (early Osagean) of Sando's sequence was the "turning point" of the cycle in that the shelf margin began to migrate seaward. However, carbonate deposition still occurred on the shelf, flanked to the east by a band of subtidal and intertidal dolomites. Sando (1973, p. 328-330) has shown this dolomite belt covering southeast Wyoming from late Kinderhookian through late Osagean. However, dolomite was not found in the northern Medicine Bow Mountains.

During phase 5 (late Osagean) regional regression resulted in restricted circulation and evaporite sedimentation throughout the northern Wyoming and Montana Provinces. Phases 6 and 7, latest Osagean and early Meracecian respectively, were times of additional carbonate sedimentation, dolomitization, and restricted circulation (Sando, 1976, p. 324). Phase 7 sediments are not represented in the northern Medicine Bow Mountains due to latest early Meramecian erosion and truncation (Sando, 1976, p. 330).

Thus, the main body of Madison Limestone in the field area, according to Sando's stratigraphic scheme, range in age from latest Kinderhookian through latest Osagean. This agrees with conclusions by other workers, such as Maughan (1963, p. C26) and Craig (1972, p. 101 and 105).

Sando (1975, p. A17), in a discussion of pre-Amsden strata, refers to two members of the upper Madison Limestone which are widespread throughout the Wyoming Province. Sando (1968) proposed the name Bull Ridge Member of the Madison Limestone for the upper member which is overlain by the Darwin Sandstone Member of the Amsden Formation. The Bull Ridge Member outcrops across northwest Wyoming, but is absent in the southern Wind River Mountains and Rawlins Uplift due to post-Madison, Pre-Amsden erosion (Sando, 1968, p. 1856). An unnamed member conformably underlies the Bull Ridge Member and extends southeast of the stratigraphic limits of the Bull Ridge Member. Osagean strata of the northern Medicine Bow Mountains are probably correlative with all, or part, of the unnamed member of the Madison Limestone.

Redbed Unit

The upper unit of the tripartite division of Mississippian strata of the northern Medicine Bow Mountains consists of red shales and siltstones containing chert nodules and cobbles. This unit disconformably overlies the Madison Limestone and typically forms gentle slopes, traversed by many gullies, between the Madison Limestone and the Pennsylvanian Tensleep Formation. On the west side of Coad Mountain, the contact with the Madison is sharp and planar. This contrasts with the highly irregular nature of the disconformity observed at other localities, such as Wind River Canyon (Mallory, 1967, p. G6). However, evidence of paleo-karst topography is evident at some localities such as the extreme south end of the Madison outcrop belt along the Coad Mountain fault at Oberg Pass. Here, vertically oriented, irregular, breccia zones contain a mixture of angular limestone fragments in a red sandy matrix. The matrix closely resembles the mineralogy of the overlying red unit.

Fossiliferous chert nodules and cobbles in the upper redbed unit have importance relative to stratigraphic interpretation. Based on the presence of Mississippian (Osagean?) brachiopod molds and casts in the cherts, a significant part of the redbed unit may represent a residual lag concentrate derived from an upper cherty member of the Madison. Significantly, the upper Madison contains fossiliferous cherts in the northern Laramie Range (Maughan, 1963). The upper part of the redbed unit may correlate with the Horseshoe Shale Member of the Amsden Formation.

DESCRIPTIVE PETROGRAPHY

Folk's (1959) classification of limestones has been used throughout the course of this investigation. It should be stressed, at the beginning of this section, that adequate description of Madison hand samples requires, at the minimum acetate peels or polished slabs. Due to the aphanitic texture of the Madison Limestone, it is impossible, even with a hand lens, to distinguish an oolitic limestone from a peloidal limestone in the field. Most hand samples would be called "unfossiliferous micrite" by many geologists. Obviously, the discrimination of rock types is critical for sedimentologic and stratigraphic studies, and thin sections have been utilized extensively in this study.

Oolites, fossils, and peloids constitute primary constituents of the Madison Limestone. Accessory components include proto-ooids, calcispheres, micrite, and non-carbonate detritus. Material between these allochems is either void-filling sparry calcite (radiaxial fibrous and equant rhombohedral cement) or microcrystalline calcite matrix. In terms of whole-rock point counts, an average thin section would yield approximately 45 per cent peloids, 3 per cent ooids, 2 per cent other allochems, 35 per cent sparry cement, and 15 per cent vein spar or neomorphic spar. However, when allochems are recalculated to 100 per cent, ooids form as much as 90 per cent of the point count in some thin sections. Thus, the Madison Limestone is a well-sorted carbonate sand composed of peloids and ooids.

Peloids are the most abundant allochems in the Madison. Most are small (0.1 - 0.2 mm in length), oval grains of micrite. At high magnification (300X) with plane light, most peloids appear as light gray masses, with sharp boundaries, and a clotted or lumpy texture (Fig. 3). Some peloids are probably micritized skeletal grains, but most are thought to be fecal pellets. The distinction of fecal pellets from other peloids is best judged on the basis of size and shape. Those micritic peloids within the length and breadth limits reported by Bathurst (1971, p. 84) and, at the same time, ellipsoidal to subspherical in shape, are considered to be fecal pellets.

Ooids are associated with peloids, cemented by sparry calcite, throughout the Madison Limestone. Intervals characterized by abundance of ooids occur throughout the Madison (Figure 4). The admixture of ooids and peloids presents a bimodal size distribution. Ooids commonly contain peloid nuclei. Ooids average 0.5 mm in diameter, and many show excellent preservation of concentric and radial fiber microstructure (fig. 5). Proto-ooids have one-layer cortices, and typically occur in intervals gradational between oolitic and peloidal.

Skeletal grains are uncommon in the Madison. Ostracode valves are generally concentrated in thin, sparry beds (Fig. 6). Madison ostracode valves have well preserved prismatic shell microstructure. Valves are thin (0.03 mm average thickness) and show no evidence of ornamentation (i.e., the valves are smoothly concavo-convex). Ostracode valve size and shape are suggestive of near bottom dwellers in a stabilized, fine-grained carbonate environment (Benson, 1961, p. Q58). However, the presence of ostracode coquina in small cross-bedded laminations, plus the occurrence of ostracode valves as ooid nuclei, suggests that these valves were transported to the site of deposition. Other skeletal grains in the Madison include echinoderm fragments and unidentifiable elongate grains (Fig. 7).

Calcispheres are widely disseminated throughout the Madison Limestone, but constitute less than 1 per cent of the total allochems. They are very constant in diameter (averaging 0.07 mm) and high in spericity (Fig. 3). Calcispheres are easily mistaken for ooids. However, their small size and sparry appearance distinguish them. Calcispheres in the Madison Limestone tend to have thin, dark outer walls (0.01 to 0.02 mm thick) with an interior of sparry calcaite cement.

Micrite intervals consist of dark gray cryptocrystalline calcite speckled with small spar patches, sparry skeletal fragments, and

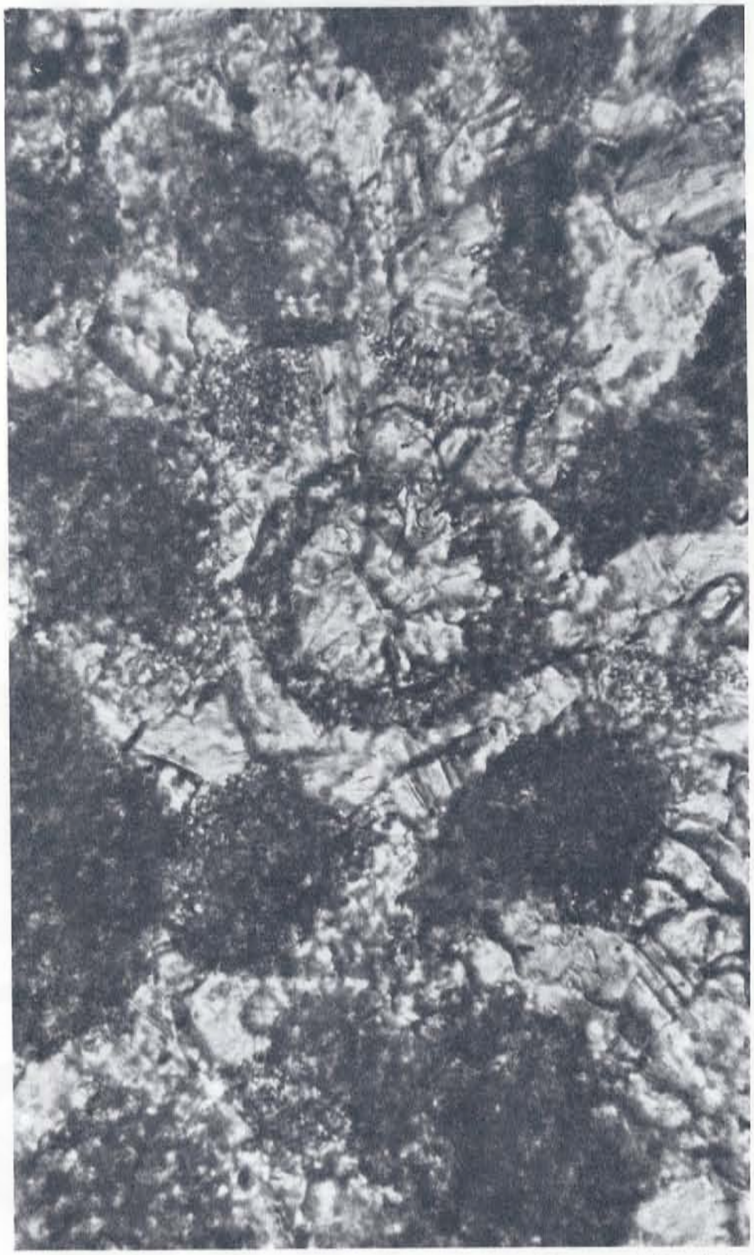


FIGURE 3. Photomicrograph of peloids cemented by equant rhombohedral calcite. Large oval grain in center is a calcisphere consisting of a 3-layer wall surrounding sparry calcite. 300 X.

0.1 mm

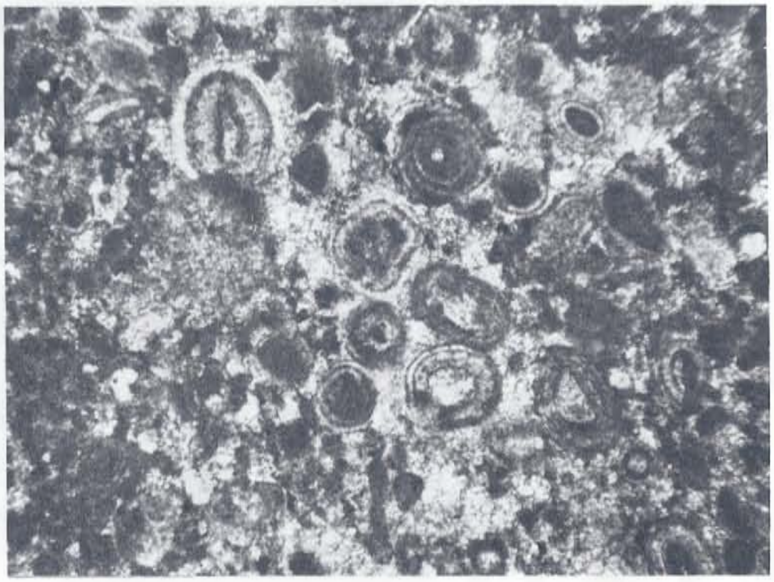


FIGURE 4. Photomicrograph of oopelsparite. 30 X.

0.5 mm

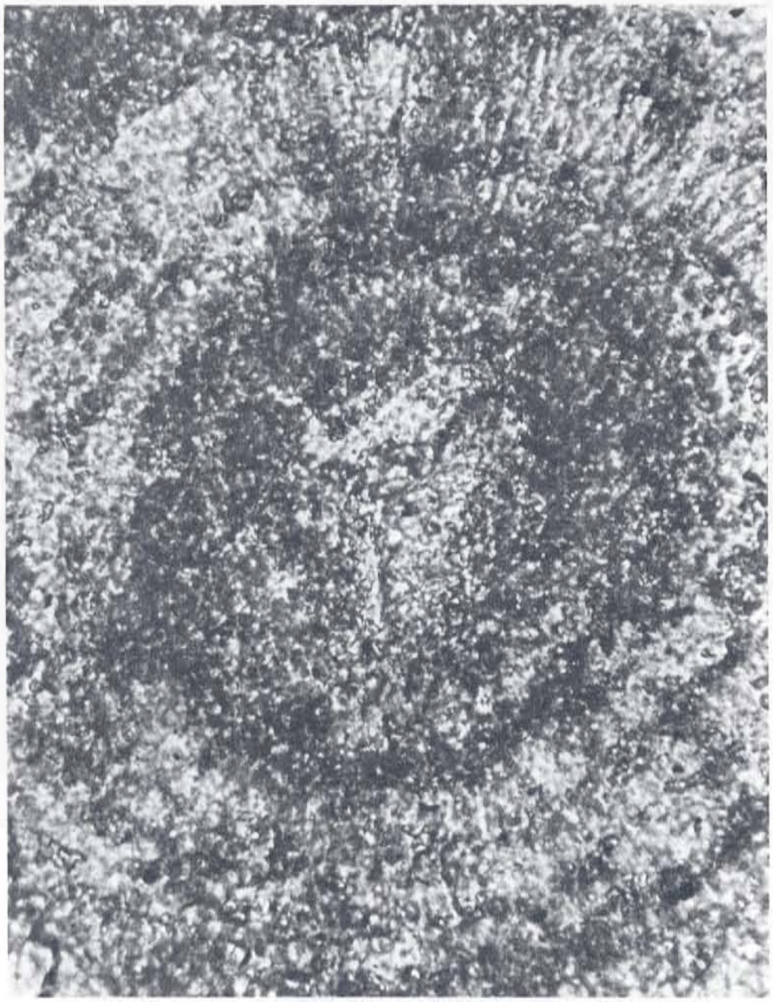


FIGURE 5. Photomicrograph of ooid. Note concentric microstructure and radial arrangement of fibers. Nucleus recrystallized. 300 X.

0.1 mm

calcispheres. Such intervals are suggestive of the pellet-mud lithofacies of the Bahamas (Bathurst, 1971, p. 136).

Non-carbonate grains include quartz, ferromagnesian minerals, and rare feldspars, micas, and amphiboles. Replacement textures around quartz grains are common. Non-carbonate grains were derived from the underlying basal sandstone and/or Precambrian rocks.

Neomorphic alteration of the Madison Limestone, although minimal, may be recognized by irregular intercrystalline boundaries, embayments into primary allochems, overgrowths on cement crystals, and non-systematic crystal size (Fig. 8). Measured sections "A" through "E" show surprisingly little neomorphic alteration. For example, the upper part of section "C" is characterized by small, irregular neomorphic spar patches. Measured section "F", however, is pervasively neomorphosed and silicified, except for the bottom 2.5 meters.

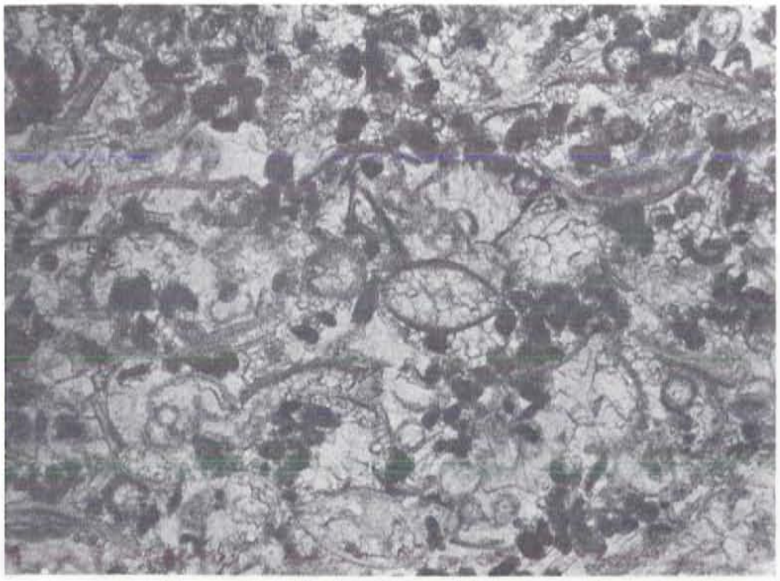


FIGURE 6. Photomicrograph of ostracode valves and peloids cemented with sparry calcite. Note articulated valves in center of photograph with cement centripetally filling the interior. Long axes of ostracode valves are aligned parallel to foreset bedding. 30 X.

0.5 mm

SEDIMENTARY STRUCTURES

Bedding in the Madison Limestone is controlled by an anastomotic network of styloites. Present bedding surfaces are approximately 2 cm apart. The small beds are set apart in groups by more distinct bedding surfaces approximately 10 cm apart. Thus, what superficially seems to be a uniform bed several centimeters thick actually consists of several small, stylolite-bounded beds.

Ripple marks were identified near the base of Madison Limestone at measured section "E", on the south side of Elk Mountain. The ripples have broad troughs and sharp, symmetrical crests. Ripple wavelengths average 4 to 5 centimeters. No ripple marks were observed at other measured sections.

Cross-bedding in carbonate sequences has not been a commonly reported phenonmenon. However, a few important contributions have been made on the subject (e.g., McKee and Gutschick, 1969, p. 111; MacKenzie, 1964, p. 1449; Swinchatt, 1967, p. 93; Imbrie and Buchanan, 1965, p. 149; and Bathurst, 1971, p. 121).

Cross-bedding in the Madison Limestone varies widely in scale, ranging in foreset length from a few centimeters to 10 meters. Following the geometric classification presented by Blatt and others (1972, p. 113), Madison cross-beds range from tabular to wedge-shaped; no trough-shaped or festoon cross-bedding was observed. The majority of larger cross-beds are wedgeshaped (Fig. 9), whereas most smaller cross-beds (hand-sample scale) are tabular (fig. 10).

A scale classification of cross-bedding based on foreset length was empirically developed during field work. Foreset dip angles are reasonably constant. Small scale cross-bedding ranges from 10 to 50 centimeters in foreset length, medium scale ranges from 50 centimeters to 5 meters, and large scale ranges over 5 meters. Medium scale, wedge-shaped cross-bedding is the most abundant and occurs throughout the Madison Limestone.

Foreset bedding, like normal bedding, is marked by stylolites. Stylolites typically form the upper and lower bounding surfaces of tabular sets, which can produce false angles of foreset bedding. The angle between foreset beds and the lower bounding surface of the set averages 20 degrees. In some cases, stylolites deflect downward and follow foreset bedding. This produces the illusion of preserved topset beds. In addition, foreset beds in the Madison taper and show an asymptotic relation to the base of the set. Thus, the foreset beds have an overall concave-upward shape. Tapering is the result of suspended sediment settling from the zone of mixing and free turbulence at the base of the foreset beds (Blatt and others, 1972, p. 128). Textural analysis suggests that rates of bedload movement may have varied between high and low during the formation of cross-bedding.

Fig. 11 shows the compass direction of foreset dip of 57 cross-bed sets. Tectonic dip and strike were substracted on a stereonet, and resultant primary dip directions are grouped in 10 degree intervals for plotting. The predominant dip direction is south-southwest, ranging from 180 degrees to 230 degrees. The dominant dip direction is between 180 and 190 degrees. Although the majority of foresets dip

FIGURE 7. Photomicrograph of oolitically coated skeletal fragment. Sequential history of the ooid includes abrasion during transport, external micritization, oolite coating, external micritization of oolite cortex, dissolution of internal skeletal fragment, and internal cementation by calcite. 300 X.

0.1 mm

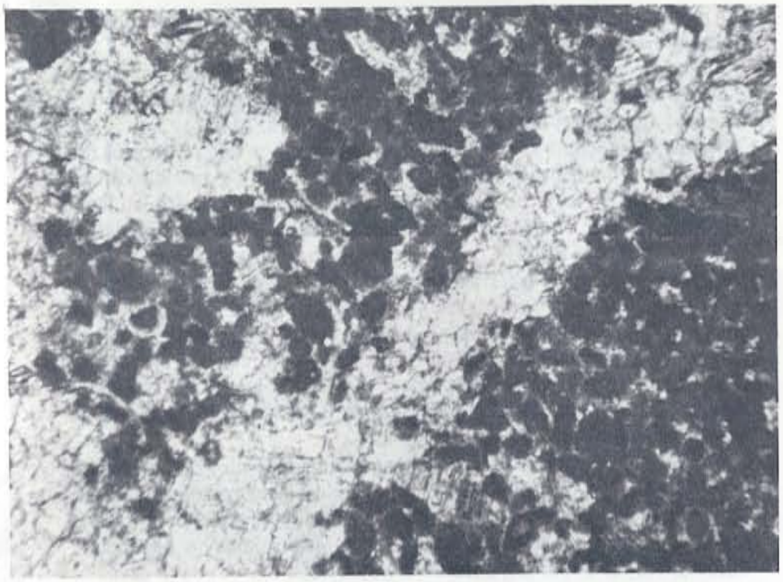


FIGURE 8. Photomicrograph of neomorphic spar replacing pelsparite. 30X.

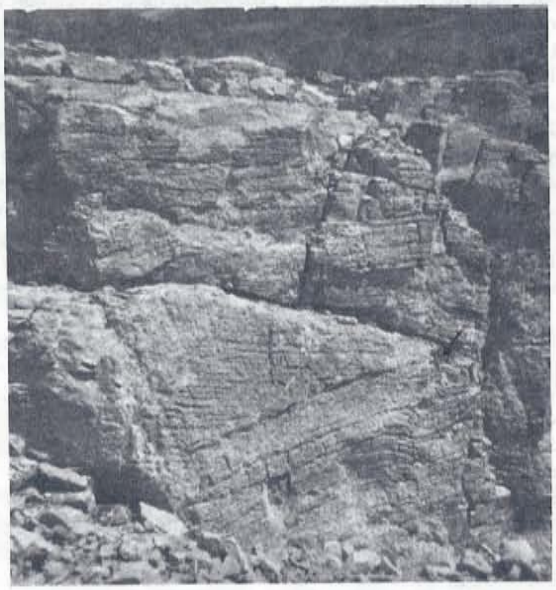


FIGURE 9. Large-scale cross-bedding. Excellent example of wedge geometry. Rock hammer gives scale [arrow]. Southwest corner of Coad Mountain.

southwest, there is strong bimodality. For example, dip directions between 200 and 230 degrees have an equally strong counterpart of dip between 50 and 60 degrees. Bimodality is best developed with the less dominant groups (e.g. 330-335 degrees and 150-155 degrees), suggesting secondary current systems with alternate directions of flow. It seems, however, that the main current and sediment transport direction was to the southwest.

Dip directions of foresets in medium to large-scale cross-bedding exposed on the south side of Sheephead Mountain are consistently west. No indication of bimodality is observed. This suggests a change in current direction from southwest to west at the north end of the field area. The rock type is the same as found at Oberg Pass.

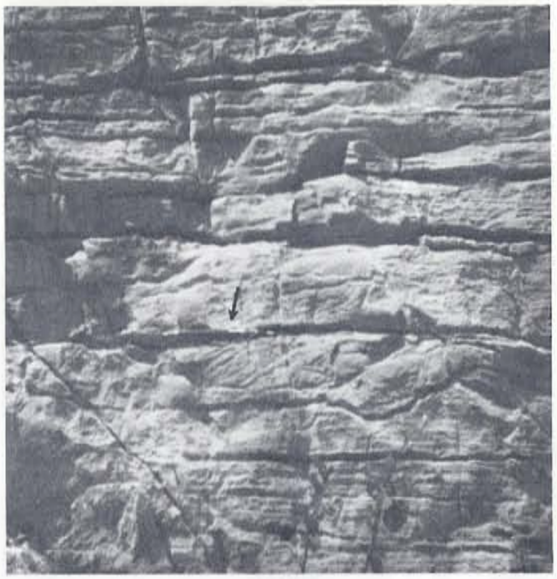


FIGURE 10. Small-scale, tabular cross-bedding. Pencil on upper contact of foresets gives scale [arrow]. West side of Coad Mountain.

Deformed bedding is exposed at Oberg Pass. The deformation assumes various forms, ranging from subtle folds to recumbent folds. in some cases, deformation seems to be genetically associated with cross-bedding. For example, oversteepened foresets might be caused by differential compaction of soft, subjacent sediment following rapid deposition of a thick set of cross-beds (Fig. 12).

Folded beds also exist in front of some cross-bed sets. The folds are asymmetrical with the steep limb on the side nearest the cross-beds. Axes trend parallel to the front of cross-bedding, which is perpendicular to the inferred current direction. It is difficult to understand the origin of these folds, but they may be related to soft-sediment deformation by lateral flowage in front of an advancing sheet of cross-bedded, oolitic and peloidal sand.

Other examples of deformed bedding not associated with cross-beds are in the form of wave-like undulations of bedding. These waves are not current formed because they lack internal cross-stratification. They seem to be the result in situ sagging and warping of sediment. Such an effect could be the result of static or differential superjacent sediment weight. Sea floor topography during Madison deposition can be visualized as irregular with mounds of carbonate sediment, channels, and intervening flat areas. Such differential accumulation of sediment could cause contortion in subjacent sediment due to unequal loading.

Small open folds were observed in the lower Madison Limestone adjacent to the Coad Mountain Fault. These folds are not the result of either soft sediment deformation or stylolitization, but rather are the product of detachment and readjustment across the Madison-Precambrian nonconformity. During progressive deformation, anisotropy across the nonconformity must result in different modes of deformation. As Stearns (1971) pointed out, crystalline Precambrian rocks responded to Laramide stress by fracturing while overlying strata deformed by both folding and fracturing. The small folds along the Coad Mountain Fault are adjacent to small faults displacing the Precambrian.

Depositional Model

The Madison Limestone in southeastern Wyoming was deposited on the flanks of an uplift which formed in Devonian time, in the eastern part of a broad, shallow, epeiric sea which deepened to the west. The transcontinental arch was an emergent landmass to the east of Wyoming, and the Medicine Bow Mountains were an arm of this arch (Sando, 1975, p. 657).

Marine transgression over southeast Wyoming probably occurred during latest Kinderhookian time. The sea partially reworked an arkosic

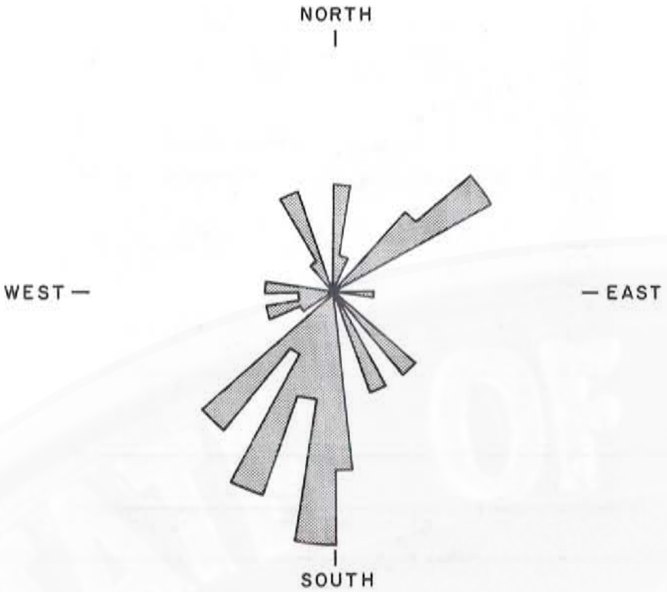


FIGURE 11. Directions of foreset dip in the Madison Limestone, northern Medicine Bow Mountains, Wyoming. Diagram is based on 57 field measurements. Directions are grouped in 10 degree intervals.

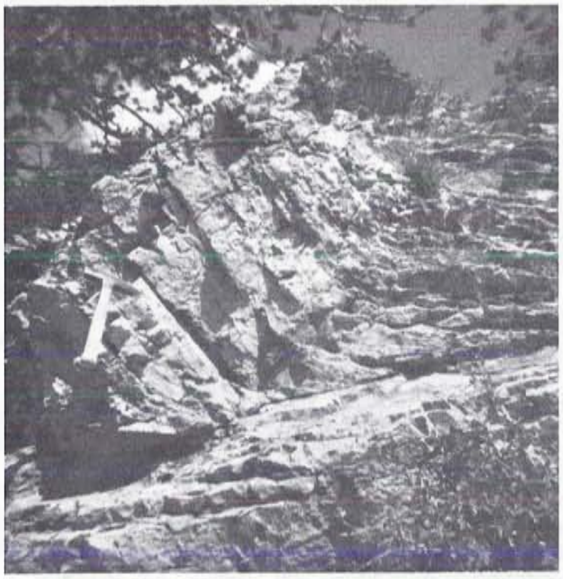


FIGURE 12. Medium-scale, over-steepened foreset beds. Individual foresets asymptotically approach lower bedding contact, producing concave-up geometry. Over-steepening is due to post-depositional slumpage. Rock hammer gives scale. West side of Coad Mountain.

regolith covering Precambrian rocks. Transgression must have been quite rapid, because features suggestive of intertidal environments (e.g., stromatolites, mud balls, edgewise conglomerates, mud cracks, rill marks, dolomitic crusts) are not preserved. In fact, at measured section "A", the vertical transition from arkosic sandstone to cross-bedded, subtidal, carbonate takes place within a few centimeters.

Basal micrites at measured sections "B" and "E" are suggestive of local bays or lagoons where fine carbonate muds accumulated. Lower Madison beds consist of pelsparite, representing a well-sorted accumulation of fecal pellets and other peloids. Tidal currents were probably responsible for sorting of the sediment. Cloud (1962, p. 47) observed that small fecal pellets of invertebrates (0.05-0.1 mm range) are more common toward shore than their large counterparts, substantiating a near-shore interpretation for the Madison.

Micritization and hardening must have been important processes due to the abundance of non-descript, irregular peloids reminiscent of the mud aggregates described by Bathurst (1971, p. 131).

Oolitic limestone is encountered within one or two meters of the base at most measured sections. Several bar or shoal models can be proposed to explain the oolitic limestone, and all require at least moderate current energy. A model involving oolite shoals accumulating leeward of barrier reefs is rejected due to the great distance of reefs from southeast Wyoming. However, Ahr (1973, p. 221) has proposed a carbonate ramp model which results in high-energy environments near shore. In this model, the ramp is a uniformly sloping surface. Oolitic and pelletal calcarenites are deposited near shore, while calcilutites are deposited in deeper water. Ahr refers to the western Trucial Coast of the Persian Gulf and the Campeche Bank of the Yucatan Peninsula as modern examples of a carbonate ramp.

Thus, oolitic intervals in the Madison Limestone may be envisioned as near-shore, low profile shoals. These shoals were probably stabilized most of the year, but shifted during times of very high tides or storms. It seems quite probable that, like modern megaripples in the oolitic lithofaces of the Bahamas, shoals were stabilized by subtidal algal mats (Bathurst, 1971, p. 122).

However, problems arise when trying to interpret Mississippian carbonate sand bodies in terms of modern environments of small, shallow banks. However, after consideration of the available data, a reasonable interpretation can be proposed. Two important factors in this model include the direction of cross-bedding and position of the shoreline. Foreset dips (Fig. 11) show a predominantly southwest current trend. This could represent a net sediment transport towards shore. However, longshore currents could also produce a strong, unidirectional trend. Mississippian paleotectonic maps (Craig and others, 1972; Sando, 1975) suggest the shoreline may have trended northeast-southwest across the field area. Thus, longshore drift appears to be a likely cause for the cross-bedding. A carbonate sand belt, composed of individual bars parallel to the belt, is envisioned offshore in the Mississippian sea. This belt, parallel to the ancient shoreline, aggraded to the south-southwest. Dominant current flow was parallel to the trend of the belt, although bimodal trends on the rose diagram are suggestive of tidal currents perpendicular to the sand belt.

Water depth was probably greater than two meters over most of the bars. Newell and others (1960) noted a decrease in percentage of ooids below that depth, suggesting that ooids begin to grow in deeper water and move towards shoal crests as they become larger.

The majority of Madison ooid nuclei are peloids. Due to the abundance of peloids in the Madison, this suggests a local origin for the ooids. Bathurst (1971, p. 312) noted that ooids are not forming on Bahamian megaripples, but were transported there from mobile shoals in the oolite lithofacies. Such transport seems unlikely for Madison ooids. High-energy conditions appear to have been located close to shore, and water depth probably increased to the west and north.

Flat areas of peloidal sand separated oolitic, megaripple shoals. The substrate consisted of fecal pellets, micritized shell fragments, and mud aggregates (irregular peloids). Current action was sufficient to sort, abrade, and winnow the sand, thus removing micritic mud and producing cross-bedding. Bioturbation was not a significant factor. Most Madison Limestone exposures are finely bedded and show no evidence of burrowing.

The relative positions of transgressing, near shore oolite shoals and intervening areas of peloid sands shifted laterally with time. As a result, a vertical section shows intervals of oolite alternating with those of peloidal sand. It should be stressed that the oolitic shoals were not composed solely of ooids. Even the most oolitic intervals of the Madison Limestone include an admixture of peloids. During times of maximum current action (e.g., storms), peloid sand was transported and incorporated into cross-bedded shoals.

Due to poor outcrop exposure in the southern part of the field area, the former shoreline position is difficult to determine. It undoubtedly shifted back and forth with time. Barton (1974) noted that Madison exposures at the south end of Kennaday Peak are sandier (quartz sand) than exposures to the west of the peak; this was substantiated by the present author. Perhaps the shoreline during Madison deposition was somewhere in the Kennaday Peak area, trending northeast.

Diagenetic Chronology

Diagenetic modification of the Madison Limestone began as soon as transport processes no longer affected the sediment. It is likely that a subtidal algal mat or organic film (Bathurst, 1971, p. 122) helped immobilize the sediment. Micrite envelopes developed on skeletal fragments and many peloids were completely micritized. By analogy with modern carbonate sediments, endolithic algae and fungi were probably responsible for creating tubular voids which subsequently filled with micrite (Bathurst, 1971, p. 381). Bathurst (1971, p. 385) notes a reduction in micritization with water depth. Due to the dependence of algae on light for photosynthesis, most micritization takes place at water depths less than 15 - 18 meters. Fungi, however, do not need light for life processes, and are not depth restricted.

The next diagenetic events involved loss of magnesium from high-magnesian skeletal calcites, and transformation of skeletal aragonite to calcite. High-magnesian calcite and aragonite are unstable minerals of calcium carbonate, and tend to change with time to cemented limestones of low-magnesian calcite (Bathurst, 1971, p. 231). The condition of skeletal fragments in the Madison Limestone suggests that these changes commonly occurred via a cavity stage. First-generation radiaxial fibrous cement and micrite envelopes of skeletal grains remained intact around voids created by dissolution of grains of high-magnesian calcite or aragonite. Partial filling of such voids with low-magnesian calcite probably occurred during second generation cementation (pl. 6). This void-filling interpretation is based on the large number of enfacial junctions observed in sparry skeletal fragments (Bathurst, 1971, p. 423).

The Madison Limestone was subaerially exposed during an Osagean-Meramecian regression. Regional erosion and truncation occurred with development of a karst terrain. This event was responsible for second-generation cementation of intergranular voids in the lower Madison. Bathurst (1971, p. 325-330) described the diagenetic chronology of recent carbonates in the fresh water environment. These stages include the first cementation (low-magnesian calcite meniscus), loss of magnesium, dissolution of aragonite, and culmination in low-magnesian calcite. The last-mentioned stage does not imply that the entire limestone is cemented; as much as 20% porosity may be left.

Bathurst (1971, p. 346) pointed out that replacement of aragonite by low-magnesian calcite can occur both by formation of cavities and calcitization. Calcitization involves in situ, wet, polymorphic transformation which obscures or completely destroys skeletal microstructure. During calcitization of carbonate mud, primary textures may also be changed to coarse mosaics of clear calcite. By this process, interstitial carbonate mud in the Madison Limestone may have been neomorphosed to coarse calcite, artifically enhancing the pelsparite aspect. Similarly, calcitization could begin around a skeletal fragment, and grow outward in lattice continuity producing an irregular patch of neomorphic spar. Scattered neomorphic patches in the upper part of section "C" may have originated in this manner.

The Madison Limestone was buried by progressive development of a terra rossa during subaerial exposure. Late Paleozoic orogeny produced the Ancestral Rocky Mountains, again uplifting the Medicine Bow Mountains area as part of the front-range uplift (Mallory, 1972, p. 131). Subsequent marine transgressions buried the Madison under a substantial thickness of clastic sediments. Formation of iron oxide color banding in the Madison occurred prior to complete cementation, possibly as early as late Mississippian. However, asymmetry encountered in some color banding may reflect tectonic dip produced by late Paleozoic deformation, thus dating color banding as Pennsylvanian. Overlying red beds provided iron which was emplaced in the Madison by ground waters.

Deep burial of the Madison Limestone during the Mesozoic brought about stylolitization and some recrystallization in response to lithostatic loading. Stylolites developed along primary discontinuities such as bedding planes, offsetting earlier diagenetic features such as color banding. Recrystallization of strained crystals produced spar patches adjacent to stylolites.

During early Cenozoic Laramide deformation, tectonically oriented stylolites formed perpendicular to local stress fields. Tensional stresses, as on the crests of anticlines, produced fractures which were subsequently filled with sparry calcite; calcite was provided by stylolitic dissolution. Progressive deformation resulted in superimposed fracture orientations, cross-cutting previous textures and structures. Shear fractures developed in the Madison on the limbs of anticlines.

Brittle deformation of the Madison, due to extensive folding and faulting, resulted in formation of breccia zones. These zones, several centimeters wide, consist of cataclastic fragments of limestone in a red, sandy matrix.

At measured section "E" southeast of Elk Mountain, there is evidence for three episodes of recrystallization during progressive Laramide deformation. First, the relationship of calcite veins which transect neomorphic spar suggests pre-deformation recrystallization. Second, lateral gradation of pelsparite into neomorphic spar, which in turn grades into calcite veins suggests syn-deformational recrystallization. Third, the existence of relic veins in neomorphic spar suggests post-deformation recrystallization.

Late Tertiary and Quarternary regional uplift and exhumation have resulted in subaerial diagenesis. Final cementation and recrystallization have reduced porosity in the Madison Limestone to zero. Ground water dissolution and precipitation have altered all primary textures and structures in places. Silicification at measured section "F" was post-deformation, possibly being the result of waters moving along the north end of the Bear Butte Fault. The occurrence of unsilicified limestone adjacent to calcite veins suggests the rigid, interlocking vein cement was impermeable to silica solutions, thus shielding the limestone from silicification.

Copper mineralization and accompanying alteration at the south end of Elk Mountain were late in the diagenetic sequence, being a product of cold, ion-charged waters percolating up basement fractures formed during Laramide deformation.

Currently, significant quantities of $CaCO_3$ are being removed from outcrops by growth of lichen. This process results in a very irregular pitted outcrop surface.

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