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Petrography of a Cyclical Sequence, Upper Madera Limestone, Sandia Mountains, New Mexico

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PETROGRAPHY OF A CYCLICAL SEQUENCE UPPER MADERA LIMESTONE, SANDIA MOUNTAINS, NEW MEXICO

By

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ABSTRACT

Chemical determinations of calcium and magnesium carbonates, iron, Kjeldahl nitrogen, and sulfate with supplementary petrographic thin-section and insoluble-residue studies and differential thermal analyses were used to study a Virgilian sedimentary cycle in the upper Madera Limestone of New Mexico. In 120 meters of section 4 cycles were recognized; one of these was studied in detail.

Cyclic subsidence and subsequent basin filling produced a sequence of gross environmental changes accompanied by organisms in a definite ecological succession. Biologic communities were progressively modified by the changing marine sedimentary cycle. The cycles of the upper Madera Limestone begin with a lower fusulinid claystone, followed by massive limestone that is fusulinid-bearing in the basal part. Upward, the fusulinids are succeeded by a brachiopod-bryozoan fossil assemblage. Overlying the brachiopod-bryozoan assemblage is nodular claystone and the cycle is terminated with nodular red claystone.

The various fossil assemblages within the cycle are not simply depth indicators, but have a more consanguineous relationship to the variables of wave base, clastic material, distance from shore, and the phase of the marine sedimentary cycle.

INTRODUCTION

The upper Pennsylvanian Missourian and Virgilian series of northern New Mexico display a sequence of interesting sedimentary cycles. This paper is the report of a petrographic study of one of these cycles.

The outcrop studied is approximately 15 miles east of Albuquerque, New Mexico in a road-cut along U. S. Highway 66 (Fig. 1). Four sedimentary cycles were recognized within 120 meters of section. The third cycle from the base, because it was complete and well exposed, was selected for detailed field and laboratory study. This third cycle lies within the Virgilian series and is approximately 40 meters below the uppermost limestone bed in the Madera Limestone at this locality.

ACKNOWLEDGMENTS

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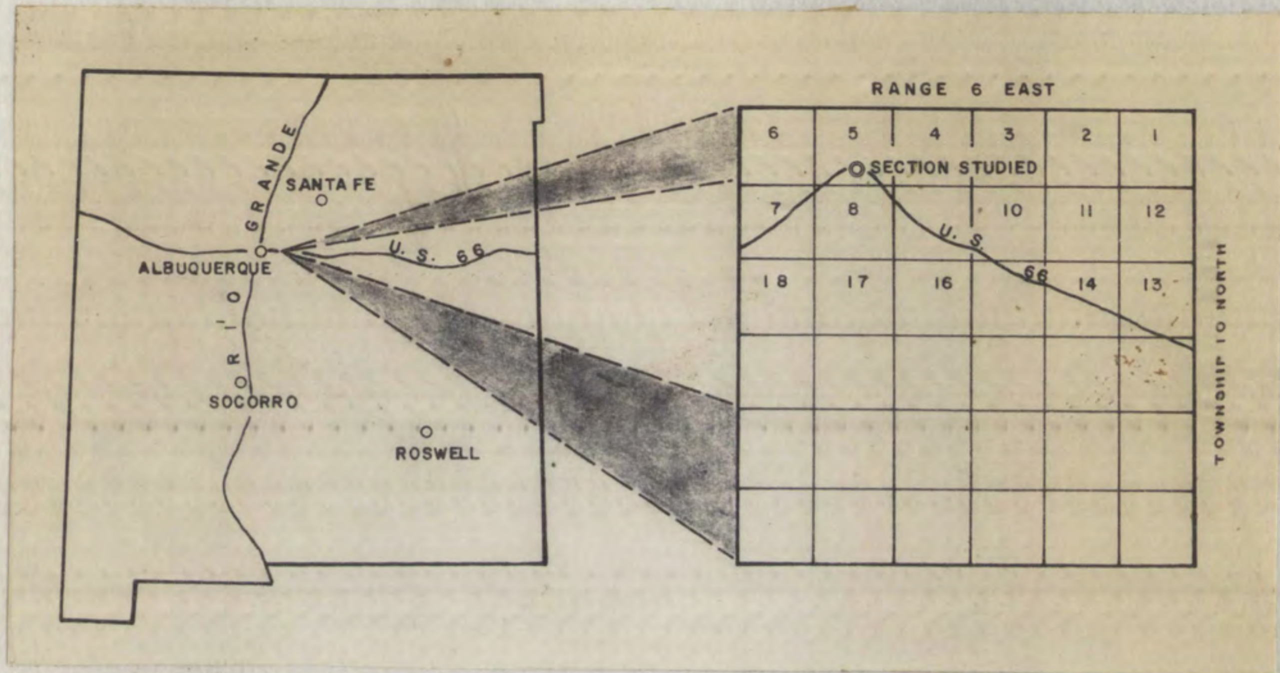


Figure 1. Index map of New Mexico and an exploded view of the township in which the studied section is located.

PALEOGEOGRAPHY AND PROVENANCE

During Pennsylvanian and Permian times certain northwesterly trending positive areas of the Ancestral Rockies became strongly developed (Kelley, 1955, p. 112). Kelley considered the three large positive trends of the Colorado Plateau to have been: (1) the Front Range, (2) the Uncompahgre-San Juan positive, and (3) the Zuni positive. The southern extension of the Uncompahgre-San Juan axis into north-central New Mexico has been designated as the Lamy axis (Kelley, 1955, figure 3, p. 114). The sediments discussed in this report were deposited west of the Lamy axis in the Sandia basin (Fig. 2). Terrains contributing sediment to this basin were the

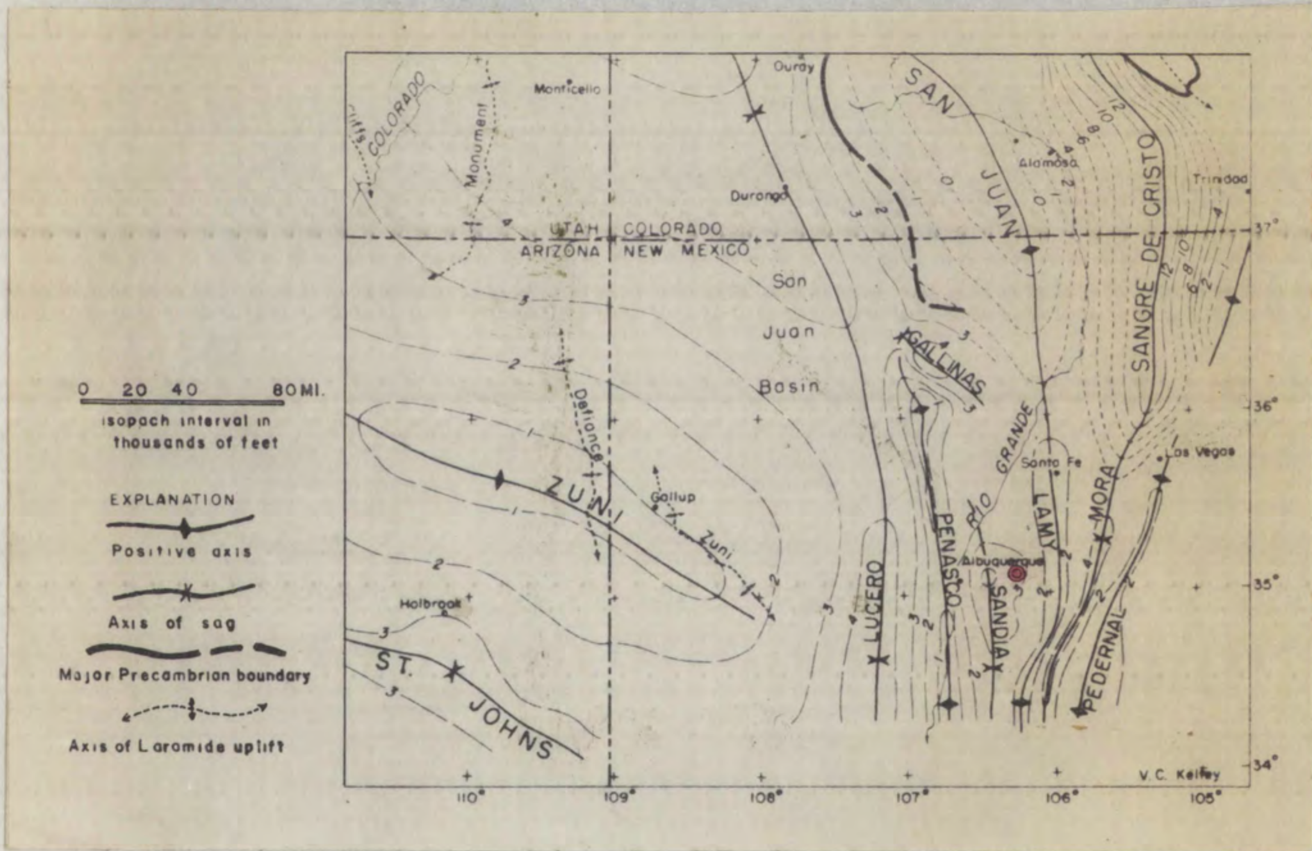


Figure 2. Permo-Pennsylvanian isopach and structural map of northwestern and north-central New Mexico showing the principal source areas and position of the Sandia basin. The studied section is designated by the red circle. Reproduced, in part, after V. C. Kelley, 1955, figure 3, p. 114.

Lamy and Penasco positives. The mineralogic composition of the coarser clastic sediment indicates that they were probably derived from metamorphic and granitic terranes; some of the clastic material may be a second-cycle sediment derived from the Sandia Formation.

MADERA LIMESTONE AND ITS CYCLES

The Pennsylvanian and Permian of New Mexico represent two dominant phases of deposition; marine and continental respectively. The Magdalena group was deposited during the Pennsylvanian marine phase and its upper boundary represents the limit of marine sedimentation. The continental red beds above the Magdalena group constitute the Permian Abo Formation. Read and Wood (1947), subdivided the Pennsylvanian system of northern New Mexico on the basis of lithologic features, but the resulting boundaries are transitional. In the area of this study the Magdalena group is about 365 meters (1,200 feet) thick and has been subdivided on the basis of lithology into a basal Sandia Formation and an upper Madera Limestone. The Madera Limestone is Atokan through Virgilian in age and most of it represents the regressive marine phase of Pennsylvanian sedimentation. East of the Rio Grande the Madera Limestone is further divided into a basal gray limestone member and an upper arkosic limestone member (Read and Wood, 1947).

The lower gray limestone member of the Madera Limestone consists of massive and thinly bedded cherty limestone and interbedded shale (Read and Wood, 1947). The upper arkosic limestone member of the Madera Limestone is massive and thinly bedded limestone interbedded with dark shale, red claystone, and micaceous and arkosic sandstone. The upper arkosic limestone member contains the sedimentary cycles discussed in this report.

Four sedimentary cycles were observed within the investigated section; for convenience they have been numbered 1, 2, 3, and 4 in ascending order (Fig. 3). These four cycles are all completely

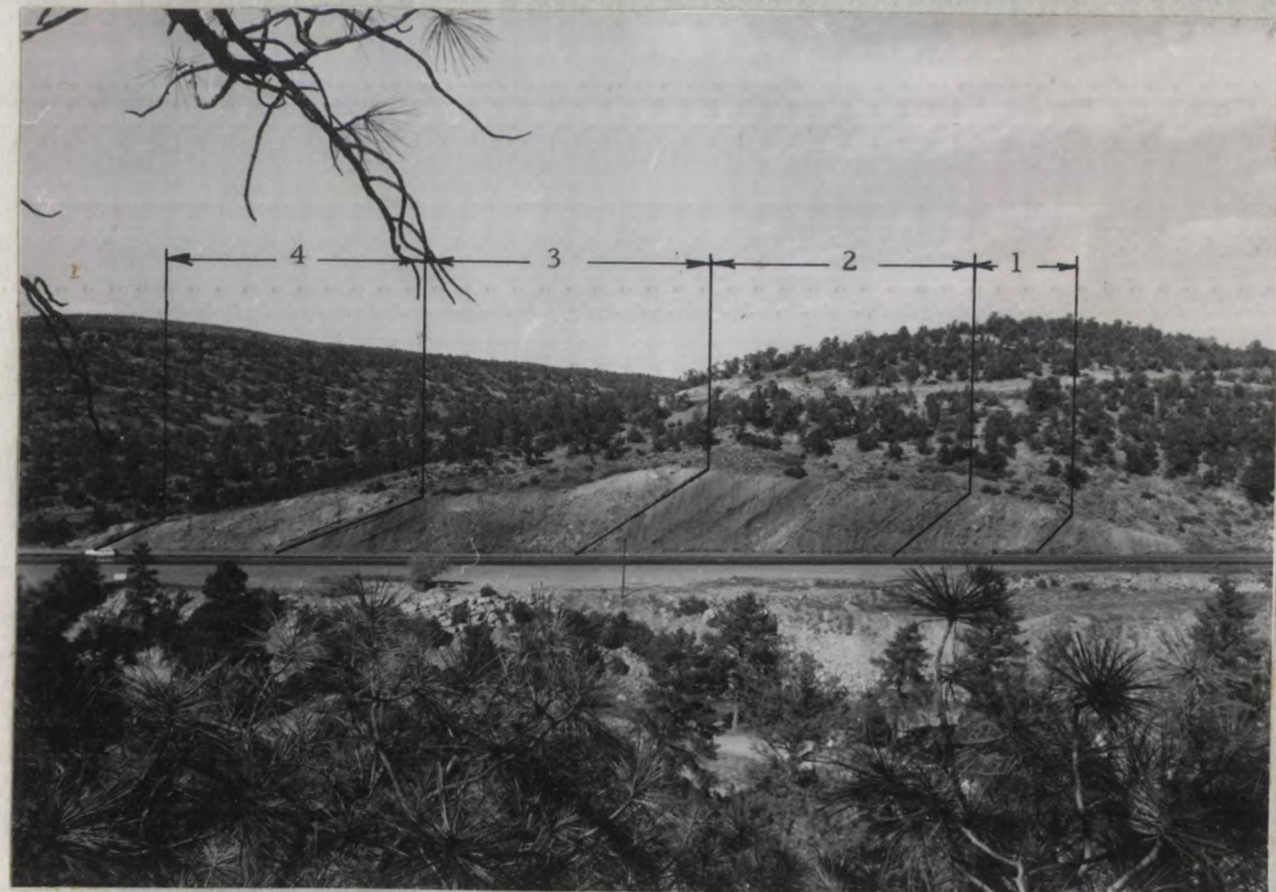


Figure 3. Cyclic Pennsylvanian sequence showing the positions of cycles 1 through 4. The view is north; Albuquerque is situated about 15 miles to the west.

within the upper arkosic limestone member of the Madera Limestone. The top of cycle 4, considered the last marine Pennsylvanian sedimentation, lies near or within the Virgilian-Wolfcampian transition zone. The limestone above the top of cycle 4 (Fig. 4) may be the beginning of an abbreviated fifth cycle, but exposures are too poor for study. The Missourian-Virgilian boundary (Fig. 4) in cycle 2 conforms to the placement recommended by Werrell (1961) on the basis of ostracods and fusulinids.

In the upper arkosic limestone member of the Madera Limestone a sedimentary cycle is considered as that sequence of rocks lying between disconformities and representing both an initial transgressive and a succeeding regressive phase of marine sedimentation.

Cycle 1

Cycle 1, at the base of the sequence, is 18.1 meters thick and consists of 37.0 percent limestone, 16.6 percent claystone, 12.7 percent siltstone, 33.1 percent sandstone, and 0.6 percent lignite. This cycle ranks fourth in thickness and contains the only lignite in the entire section examined. Micaceous claystone, siltstone, and sandstone are abundant; red claystone, nodular claystone, and arkosic sandstone, present in the other cycles, are absent. This cycle, with its coal and sandstone, is somewhat similar to the cycles of the

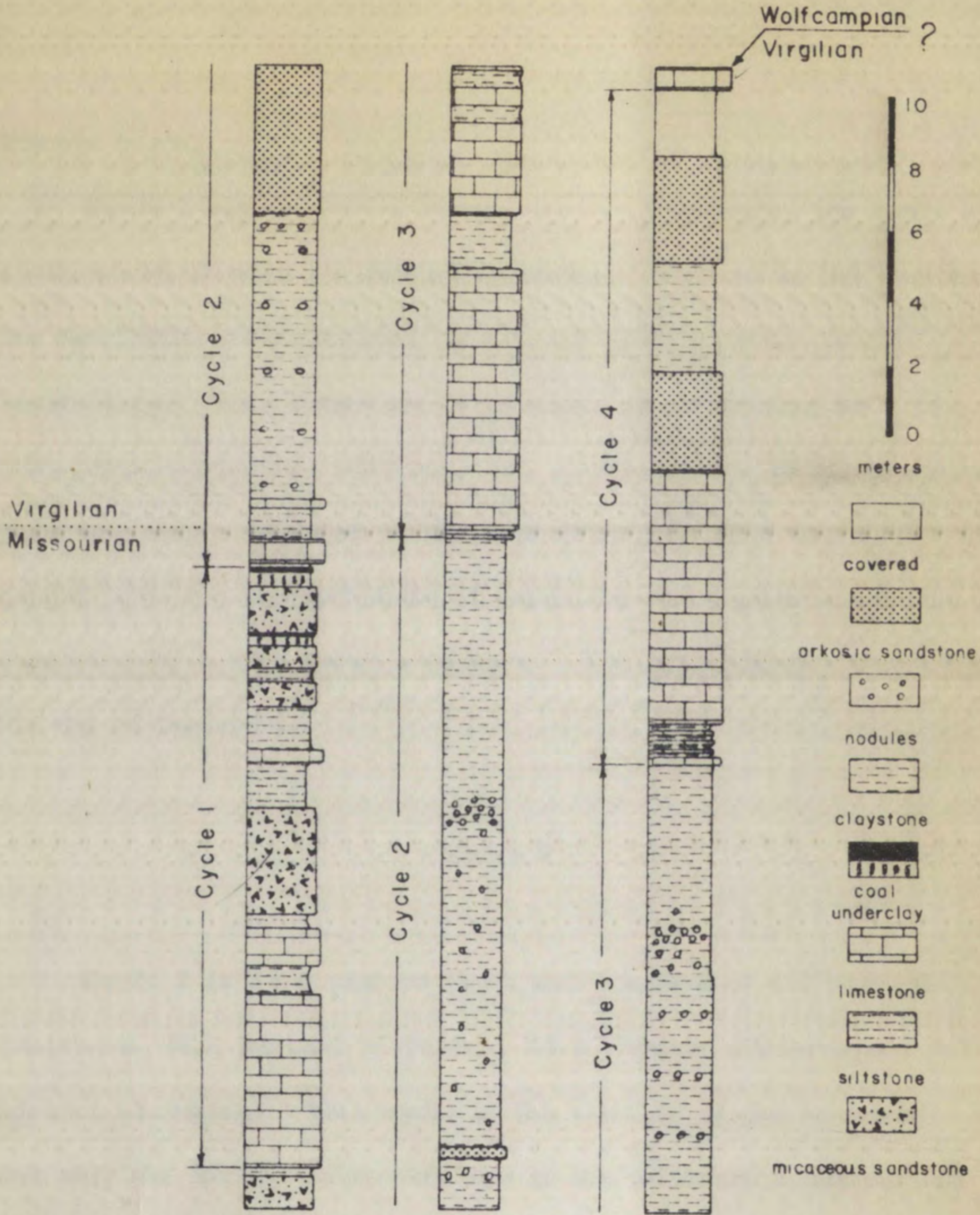


Figure 4. Stratigraphic section of the cyclic sequence in the upper arkosic member of the Madera Limestone.

Illinois basin.

Cycle 1 begins with a lower massive limestone, the basal 20 centimeters of which is fusulinid-bearing. Upward in the section the fusulinids are succeeded by a brachiopod-bryozoan fossil assemblage. This limestone is overlain by alternating beds of micaceous sandstone, siltstone, and claystone; two minor limestone beds are also associated in this unit (Fig. 4). The cycle is capped with two distinct units of underclay and lignite which are separated by a micaceous sandstone. The upper lignite is considered the top of the cycle.

Cycle 2

Cycle 2 is 34.0 meters thick and consists of 4.1 percent limestone, 41.2 percent claystone, 45.0 percent siltstone, and 9.7 percent sandstone. This cycle is the thickest of the sequence and only the lower two meters are in the Missourian series; the remainder, according to Werrell (1961), are in the Virgilian series.

Cycle 2 begins with a lower fusulinid-bearing claystone followed by a massive limestone that contains fusulinids in the basal 10 centimeters. Upward the fusulinids are succeeded by a brachiopod-bryozoan fossil assemblage. This limestone is overlain by a nodular claystone unit (Fig. 4) and an arkosic sandstone. The cycle is capped by a red claystone unit that contains abundant rounded algal carbonate nodules. This cycle is very similar to the succeeding cycles and represents a major change in cycle type when compared with the preceding cycle 1. Lignite and micaceous claystone, siltstone, and sandstone, as observed in cycle 1, are absent; nodular claystone, arkosic sandstone, and red claystone constitute a major part of this cycle. Cycles 2, 3, and 4 resemble closely the Permian cycles of Kansas as described by Elias (1937), and those of the southwestern United States Pennsylvanian system as described by Wanless and Patterson (1951).

Cycle 3

Cycle 3 is 27.5 meters thick and consists of 41.9 percent limestone, 46.5 percent claystone, 11.6 percent siltstone, and no sandstone. The cycle is unusually well exposed and is typical of the Pennsylvanian cycles of the southwestern United States described by Wanless and Patterson (1951). Cycle 3 will be presented in detail in the next section of this report.

Cycle 4

Cycle 4 is 20.4 meters thick and consists of 44.0 percent limestone, 3.4 percent claystone, 23.1 percent siltstone, and 29.5 percent sandstone. This cycle is the thinnest of the sequence and represents the last marine phase of Pennsylvanian sedimentation in this area.

Cycle 4 begins with a series of alternating, thinly bedded fusulinid-bearing limestones and claystones (Fig. 4) followed by a massive limestone containing a brachiopod-bryozoan fossil assemblage. Overlying this limestone are two units of massive arkosic sandstone separated by a shaly red and green siltstone. Above the upper arkosic sandstone the section is covered and the top of the cycle has not been observed. A polished slab of a thin overlying limestone bed revealed only *Triticites* sp.; no *Pseudoschwagerina* or other Permian genera were observed. Immediately above this limestone bed is the red siltstone and sandstone of the Permian Abo Formation.

PETROGRAPHY OF CYCLE 3

Cycle 3 has been studied in greater detail than the other cycles described above. Spot samples were collected at all observable lithologic and paleontologic changes. Massive units of homogeneous lithology and paleontology were generally sampled at the bottom, middle, and top. Thin sections of 48 samples representing the upper 5.2 meters of cycle 2, all of cycle 3, and the lower 3.1 meters of cycle 4 were examined for texture and fossil content. Chemical analyses for calcium and magnesium carbonate, iron, and Kjeldahl nitrogen were made on representative samples. Insoluble residues, thermal properties of the clays, and sulfate content were studied for fewer samples.

Cycle Succession

Cycle 3 has been subdivided into seven units (Fig. 5). In ascending order they are as follows: lower fusulinid claystone, lower fusulinid limestone, brachiopod-bryozoan limestone, upper fusulinid claystone, upper fusulinid limestone, nodular claystone, and red claystone. The following paragraphs describe these units, in ascending stratigraphic succession, with respect to their petrographic and paleontologic characteristics. The underlying red claystone unit of cycle 2 is very similar to the same unit in cycle 3 and will not be considered here.

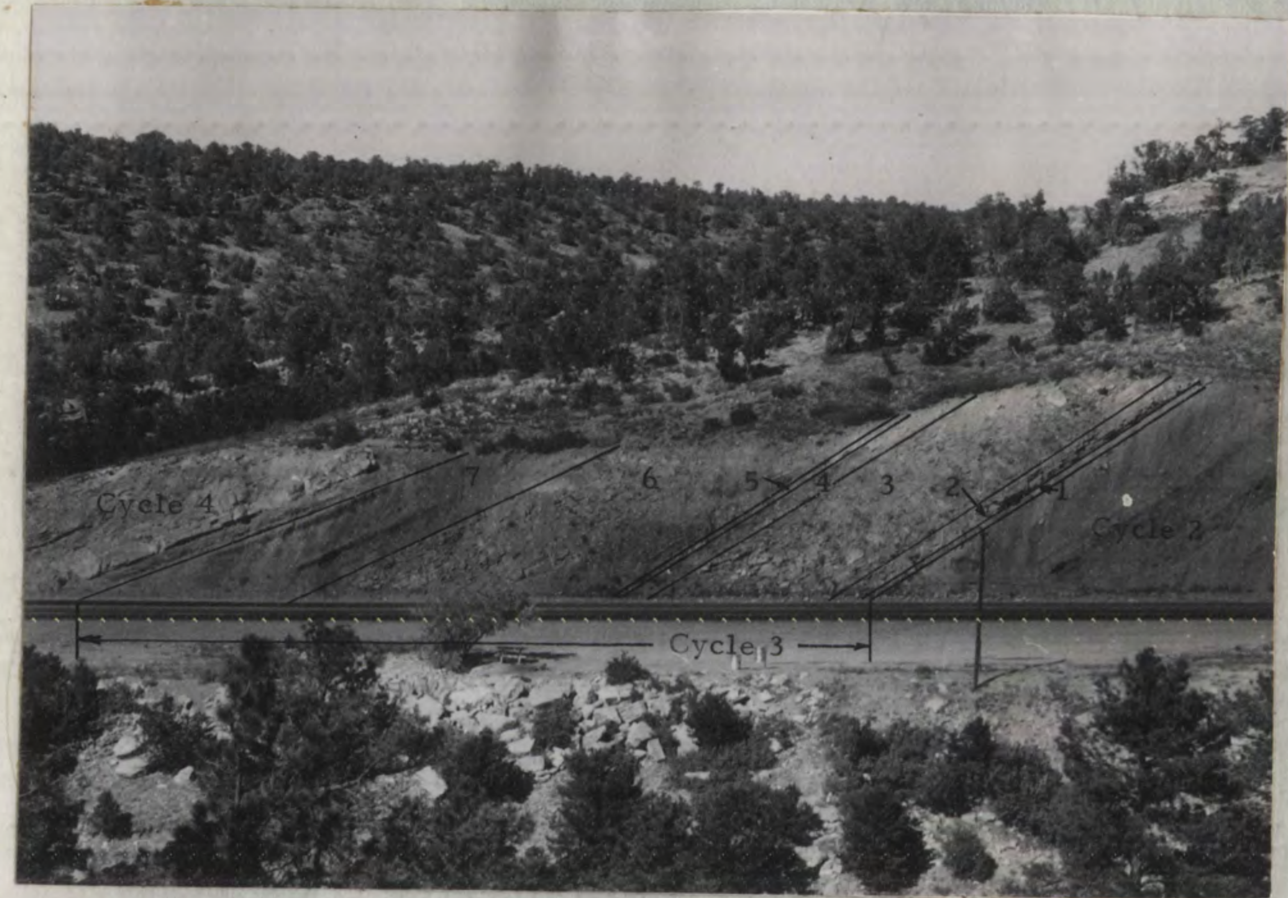


Figure 5. Cycle 3 showing the position and relationship of the principal stratigraphic units: (1) lower fusulinid claystone, (2) lower fusulinid limestone, (3) brachiopod-bryozoan limestone, (4) upper fusulinid claystone, (5) upper fusulinid limestone, (6) nodular claystone, (7) red claystone. The red claystone unit of cycle 2 is present below cycle 3 and the lower fusulinid units and brachiopod-bryozoan unit of cycle 4 are present above cycle 3.

Lower fusulinid claystone unit

The lower fusulinid claystone unit is 25 centimeters thick and rests disconformably, with marked contrast in color, composition, and fossil content, on the underlying red claystone of cycle 2. This unit consists of a basal medium-gray thinly bedded clayey fusulinid-bearing intrabiosparrudite (Fig. 6) overlain by 15 centimeters of

Figure 6. Fusulinid intrabiosparrudite which forms the basal 10 centimeters of the lower fusulinid claystone unit. Crossed nicols, X 22.

greenish-gray thinly laminated silty calcareous fusulinid-bearing claystone.

Within this claystone, carbonate nodules constitute between 15 to 25 percent of the total volume. The nodules are greenish-gray, clayey, fusulinid-bearing biosparites, 2 to 6 centimeters in diameter. The total carbonate content of the basal intrabiosparrudite and the biosparite nodules is 66 and 75 percent respectively (Fig. 7). The

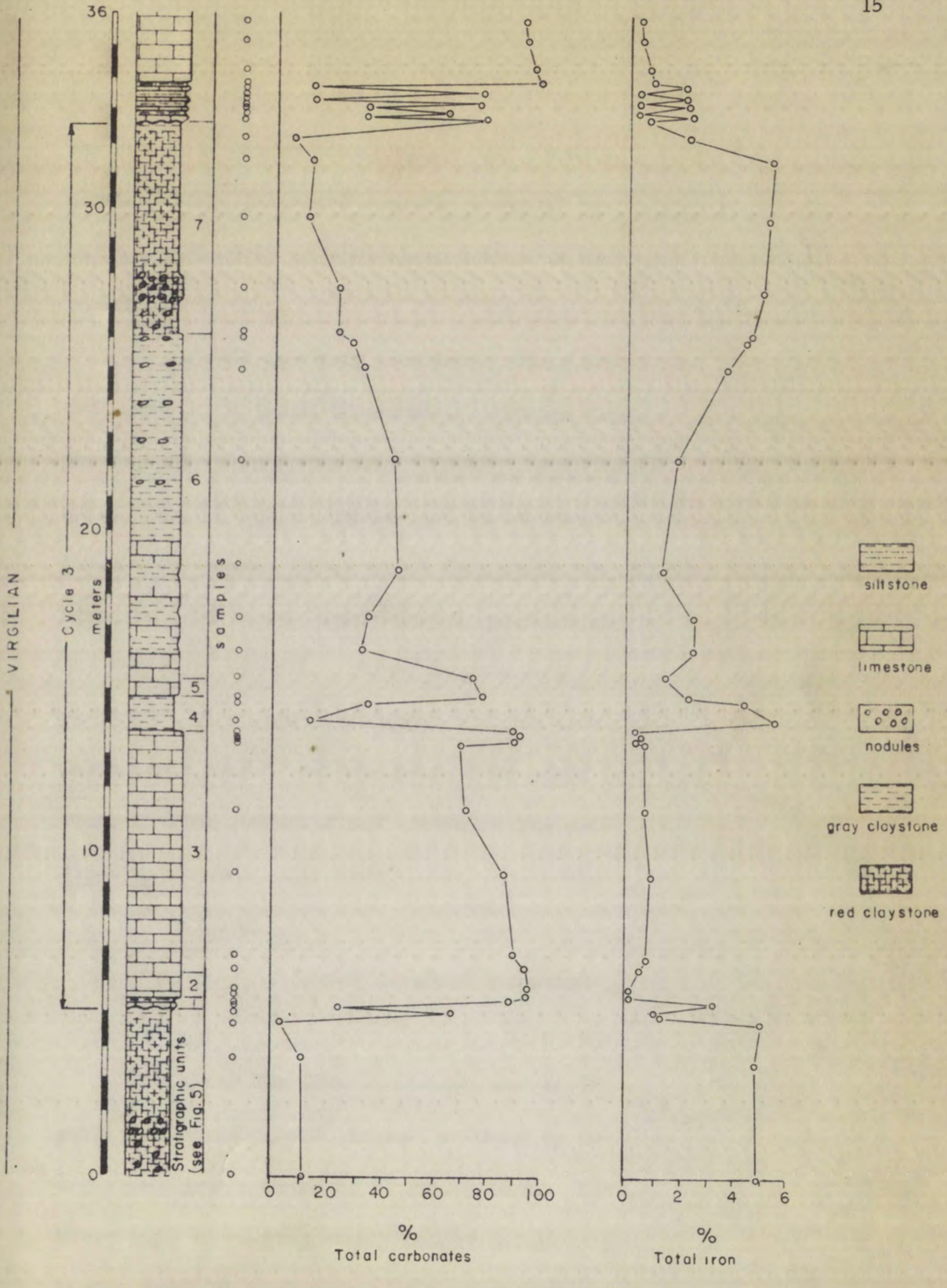


Figure 7. Stratigraphic section of cycle 3 and graphical presentation of the calcium-magnesium carbonate and iron content of the samples analyzed.

remainder is predominantly clay; silt constitutes less than 5 percent. The claystone contains about 23 percent total carbonate and approximately an equivalent content of angular quartz silt; the remainder is clay.

Fusulinids are very abundant. They are probably indigenous and occur as a fossil biocoenose, although there is no method of proving this interpretation. Triticites ventricosus is the dominant form (Fig. 6) and is represented in all stages of development from juvenile to adult. Other fossil fragments are present in minor amounts. Of these, brachiopods, bryozoans, gastropods, and crinoids are the most evident. These fragmentary remains are probably not part of the fusulinid community, but are undoubtedly the products of posthumous mixing and transport from other biotopes farther landward. Werrell (1961) collected and identified the ostracods Bairdia and Amphissites from this unit.

Lower fusulinid limestone unit

The lower fusulinid limestone unit is 95 centimeters thick and rests conformably with marked contrast in composition on the underlying lower fusulinid claystone unit. This unit consists of a lower light olive-gray thinly bedded fusulinid-bearing biomicrite. In the upper 10 centimeters of the unit the biomicrite is succeeded by a light olive-gray thinly bedded fusulinid-bearing intrabiosparrudite (Fig. 8). Calcareous fossiliferous claystone intraclasts form

Figure 8. Fusulinid-bearing intrabiosparrudite which forms the upper 10 centimeters of the lower fusulinid limestone unit. The black objects are calcareous claystone intraclasts. Crossed nicols, X 30.

approximately 10 to 15 percent of the upper zone. The average total carbonate content of the lower biomicrite and the upper intrabiosparrudite is 87 and 89 percent respectively (Fig. 7). This unit, when compared with other units of the cycle, contains considerable magnesium carbonate (3.4 percent). The significance of this magnesium carbonate will be considered later. The remainder of the unit is predominantly clay, however, diagenetic euhedral quartz silt and detrital subrounded quartz silt is present in the insoluble residue.

Fusulinids are very abundant. Triticites ventricosus is the dominant form and is represented in all stages of development from juvenile to adult. The tests are whole, and probably represent a fossil biocoenose as in the lower claystone. In the lower 85 centimeters of biomicrite the fusulinids comprise between 35 and 50 percent of the rock; in the upper 10 centimeters of intrabiosparrudite the fusulinids constitute between 50 and 75 percent of the rock (Fig. 9). As in the lower claystone, other fossil fragments are

Figure 9. Upper intrabiosparrudite as observed in outcrop. The fusulinids are in relief due to weathering of the limestone. Natural size.

present in minor amounts. Of these fragments, brachiopods, bryozoans gastropods, and crinoids are the most abundant; echinoid spines and endothyroid-type Foraminifera are present in some samples.

Brachiopod-bryozoan limestone unit

The brachiopod-bryozoan limestone unit is 7.40 meters thick and rests conformably with no observable break in color, lithology, or weathering characteristics on the underlying lower fusulinid limestone unit. This unit consists of light gray, massive, in places clayey, mixed fossil biomicrite. The total carbonate content of this unit is highly variable, ranging from 87 percent near the base to 69 percent in the center and to 91 percent near the upper boundary (Fig. 7). In the central zone, where the carbonate content is lowest, angular quartz silt grains are observed in the insoluble residue, however, clay is the dominant residue and probably forms as much as 25 to 30 percent of the rock. In the lower and upper regions of high carbonate content, euhedral diagenetic quartz silt is observed in the insoluble residue. In these zones clay forms approximately 5 to 10 percent of the rock. In all the samples representing this unit the rocks were cemented with carbonate ooze.

Brachiopods and bryozoans of the following genera are the dominant unbroken fossil forms: <u>Linoproductus</u>, <u>Derbyia</u>, <u>Wellerella</u>, Antiquatonia, Polypora, and Septopora. Other recognizable groups of invertebrates abundantly present are the crinoids, echinoids, gastropods, and corals. These remains are fragmental, comprise approximately 20 to 30 percent of the limestone, and are probably indigenous to the brachiopod-bryozoan biotope. Houbolt (1957), in his work on modern sediments of the Persian Gulf, concluded that the occurrence of angular shell remains was hard to account for by the slow movements of offshore currents over the bottom. Houbolt considered that current-transported shell fragments would be rounded and the currents would also remove the mud content; such is not the case and the angular remains are considered to be the result of scavenger activity. There is a marked similarity in Houbolt's photographs of the Persian Gulf sediments and the brachiopod-bryozoan unit in this cycle. The fossil fragments of this unit show some rounding in the upper zone, whereas those fragments in the lower zone are generally quite angular (Fig. 10). Houbolt noted a similar effect with increasing depths in the Persian Gulf and concluded the rounding was due to oscillating water movements caused by the waves in the shallower parts of the sea. The rounding of fossil fragments in this unit is only slight, but it may indicate shallowing.

A B

Figure 10. Biomicrites from the brachiopod-bryozoan limestone unit as observed in (A) the lower angular fossil fragment zone, and (B) the upper rounded fossil fragment zone. Crossed nicols, X 22.

Upper fusulinid claystone unit

The upper fusulinid claystone unit is 1.10 meters thick and rests conformably with marked contrast in color, composition, paleontology, and weathering characteristics on the underlying brachiopod-bryozoan limestone unit. This unit consists of a lower olive-gray, thinly laminated, silty, slightly fossiliferous claystone and an upper dark greenish-gray, thinly laminated, silty, calcareous, highly fossiliferous claystone. The total carbonate content of the lower slightly fossiliferous zone and the upper highly fossiliferous zone is 13 and 37 percent respectively (Fig. 7). This change in carbonate percentage is probably a result of the increase in fossil content in the upper zone. Angular and rounded quartz silt and sand grains constitute approximately 10 to 15 percent of this unit. Iron is observed as limonite stains and fossil replacements; clay forms the remainder of the rock.

The upper 50 centimeters contains abundant brachiopods, pelecypods, and bryozoans (Fig. 11); fusulinids are present, but not abundant. These fossil remains are fragmental and aligned parallel

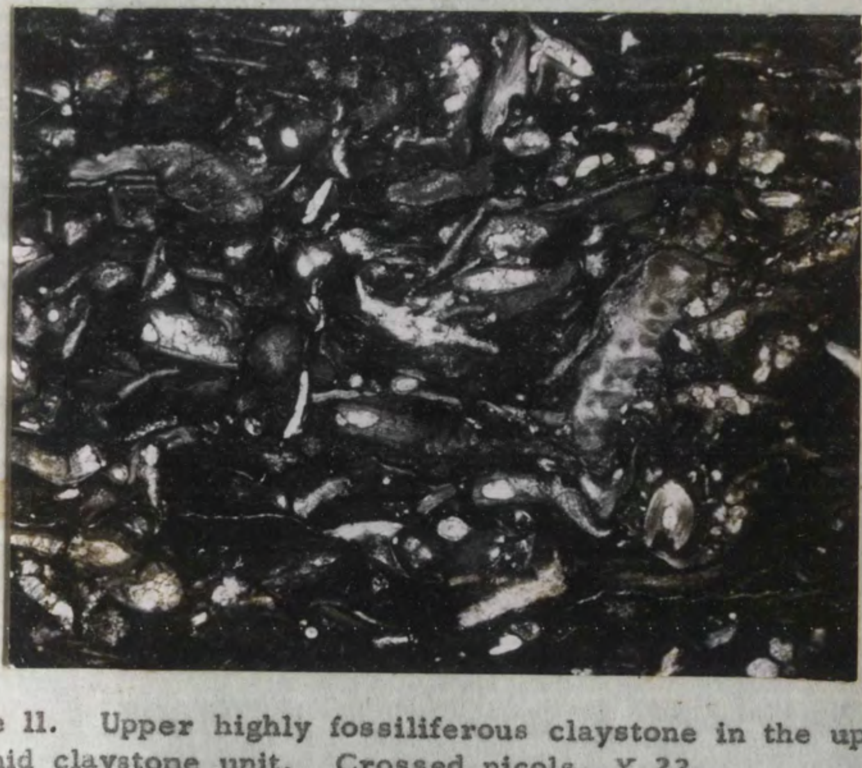


Figure 11. Upper highly fossiliferous claystone in the upper fusulinid claystone unit. Crossed nicols, X 22.

with the bedding. The following genera of invertebrate fossils have been collected and identified: Derbyia, Composita, Chonetes, Aviculopecten, Wilkingia, Bairdia, Bythocypris, Silenites, Amphissites, Cytherella, and Triticites. One shark tooth of the genus Orodus was also collected.

Upper fusulinid limestone unit

The upper fusulinid limestone unit is 40 centimeters thick and rests conformably with marked contrast in composition and weathering characteristics on the underlying upper fusulinid claystone unit. This unit consists of medium gray, thinly bedded, clayey, fusulinid-bearing biomicrite. The total carbonate content of a sample from this unit is 77 percent (Fig. 7). Carbonate is present mainly as ooze, homogeneously mixed with clay, but approximately 20 to 25 percent of the total carbonate is derived from the fossil fragments. Angular quartz silt grains were observed in the insoluble residue, but clay is the dominant residue and forms approximately 20 percent of the rock.

This unit is sparsely fossiliferous (Fig. 12), containing scattered broken fusulinids and some fragmental remains of brachiopods and bryozoans. Triticites ventricosus has been identified; other invertebrates are poorly preserved and rare.

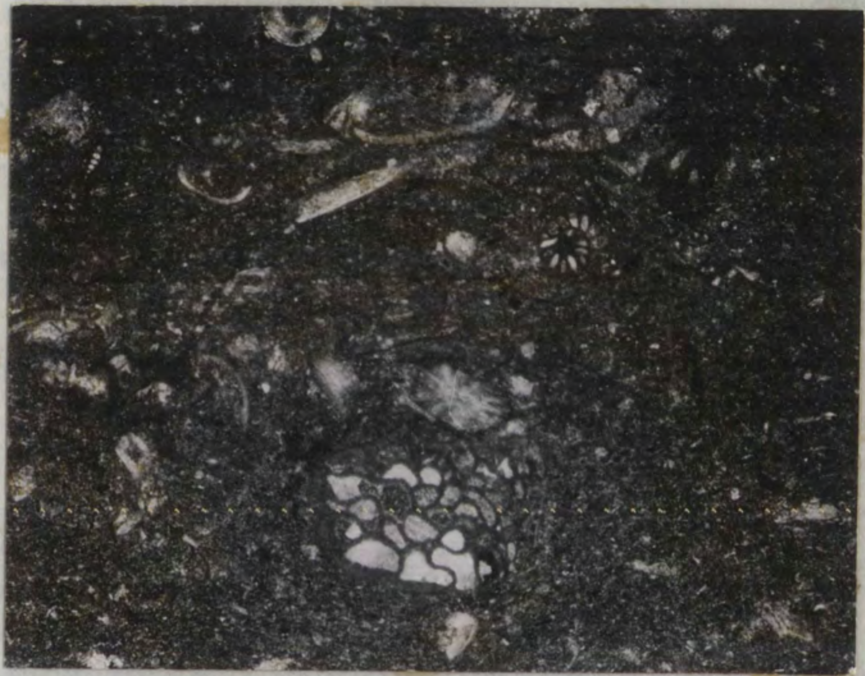


Figure 12. Clayey biomicrite from the upper fusulinid limestone unit. Fossils are sparse and generally fragmental. The rock is cemented with carbonate ooze and clay. Crossed nicols, X 28.

Nodular claystone unit

The nodular claystone unit is approximately 10 meters thick and rests conformably with a gradational contact on the underlying upper fusulinid limestone unit. The upper limit of the nodular claystone unit is transitional as the nodules continue into the overlying red claystone unit. It is within the upper 5 meters of this unit that the nodules first appear, the lower 5 meters is a series of dark gray, thinly bedded clayey sparites alternating with dark gray, laminated calcareous claystone and siltstone.

The sparite examined contains 73 percent total carbonate (Fig. 7), it is barren of fossils and the carbonate content is in the form of fine-grained sparry calcite (Fig. 13). Angular quartz silt

Figure 13. Clayey non-fossiliferous sparite from the lower zone of the nodular claystone unit. Crossed nicols, X 10.

was observed in the insoluble residue, but clay is the dominant residue and forms approximately 20 percent of the rock. The claystones examined contain between 34 and 43 percent total carbonate (Fig. 7). Angular quartz silt is present in minor amounts (Fig. 14), but the predominant constituent is clay and it forms between 45 and 60 percent of the rock. The siltstone examined contains 31 percent

Figure 14. Claystone from the lower zone of the nodular claystone unit. Crossed nicols, X 30.

total carbonate (Fig. 7), 20 to 30 percent clay, and the remainder is composed of quartz and plagioclase silt and iron oxide. No fossil remains were observed in the lower 5 meters of the unit.

The upper 5 meters of the nodular claystone unit consists of medium gray, thinly bedded, silty calcareous claystone with zones of calcareous algal nodules. The claystones examined contain between 31 and 44 percent total carbonate. Minor amounts of angular quartz silt is present, but the predominant constituent, comprising between 50 and 65 percent of the rock, is clay.

Unidentified organic structures (Fig. 15) probably of algal origin are very common in these claystones. Brachiopods, of the

Figure 15. Calcareous claystone from the upper zone of the nodular claystone unit. Arrows point to structures considered to be of algal origin. Crossed nicols, X 30.

genus Linoproductus are scattered throughout the upper 5 meters of the unit and unidentified branching bryozoa are also observed in some samples.

The nodules in this unit are probably algal in origin. They are micritic in texture and distributed in definite zones (Fig. 16). They are lenticular masses seldom exceeding a thickness of 4 centimeters and a length of 15 centimeters. In the 2 nodules examined the total carbonate content is 65 and 77 percent. Magnesium

Figure 16. Nodular claystone unit showing a zone of algal carbonate nodules. Arrows point to the nodules.

carbonate in both samples is less than 1 percent. Angular quartz silt is present in amounts not exceeding 1 or 2 percent and the remainder of the nodule appears to be clay. Minor quantities of fragmental brachiopod remains are generally associated with the nodules. Similar nodules are encountered in the upper limestone member of the composite Illinois "cyclothem", but according to Weller (1957), their origin and significance is unknown. Wanless and Patterson (1951) and others consider them of definite algal origin.

Red claystone unit

The red claystone unit is approximately 8 meters thick and rests conformably with a transitional contact on the underlying nodular claystone unit. The red claystone unit is terminated at the top by a leached zone and the disconformity that ends the cycle.

The unit consists of 3 zones: (1) a basal nodular zone, (2) a medial zone, and (3) an upper leached zone. The lower 3.5 meters is grayish-red, laminated, silty, calcareous claystone which contains abundant subround to round algal carbonate nodules. The total carbonate, excluding the nodules, of this zone ranges from 23 to 28 percent (Fig. 7). Most of this carbonate is in the form of micritic textured granules (Fig. 17). Angular quartz silt constitutes approximately 25 to 30 percent of the rock and the remainder is clay, deeply stained with hematite.

The carbonate nodules of this lower zone are definitely of algal origin. A thin section of one of these nodules has been identified by J. Harlan Johnson (written communication, October 16, 1963) as "an algal felt made by blue-green algae" (Fig. 18B). These nodules are micritic in texture and profusely distributed throughout the zone (Fig. 18A). They are generally subspherical in shape, less then 6 centimeters in diameter, and commonly agglutinated with clay and carbonate cements into larger nodular aggregates. The nodules are grayish red in color and contain

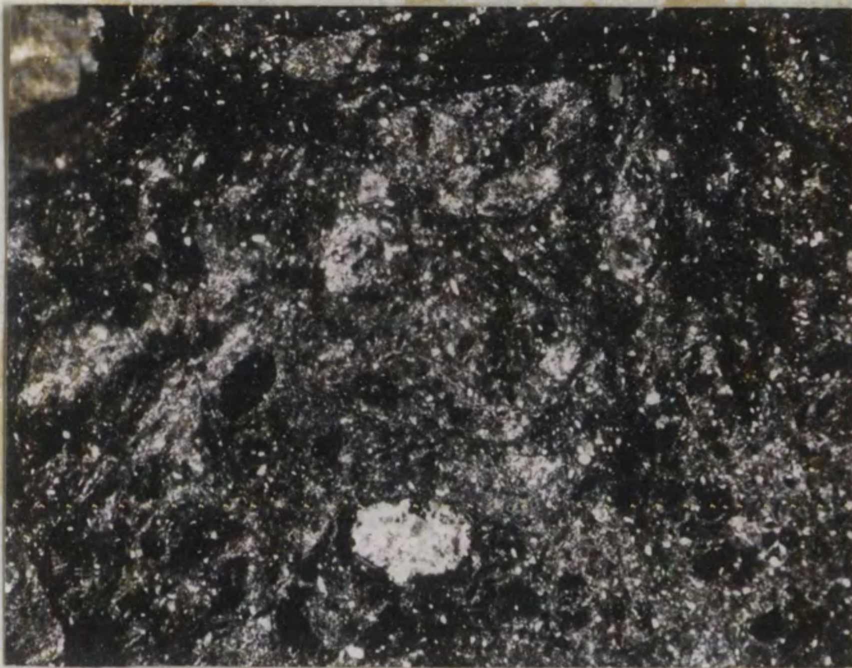


Figure 17. Silty calcareous claystone from the basal zone of the red claystone unit. The black areas are hematite-stained clay. Carbonate granules are in the upper left corner and the lower center. The smaller white particles are quartz silt grains. Crossed nicols, X 10.

between 20 and 25 percent clay, approximately 1 or 2 percent angular quartz silt and average 77 percent in total carbonate. Magnesium carbonate was less than 0.5 percent in each of the nodules analyzed. Brachiopods of the genus Linoproductus are scattered throughout the claystone and are often observed as an integral part of the nodule.

The medial zone is approximately 4 meters thick and consists of reddish-brown, thinly bedded, silty claystone (Fig. 19). There are only trace amounts of small (less than 1 centimeter in diameter)

A

B

Figure 18. Algal nodules from the lower zone of the red claystone unit as observed in (A) outcrop, and (B) in thin section. (A) The nodules are in relief due to weathering of the claystone. (B) This particular thin section has been identified by J. Harlan Johnson as "an algal felt made by the blue-green algae", and was collected from the same stratigraphic horizon as seen in (A). Crossed nicols, X 25.

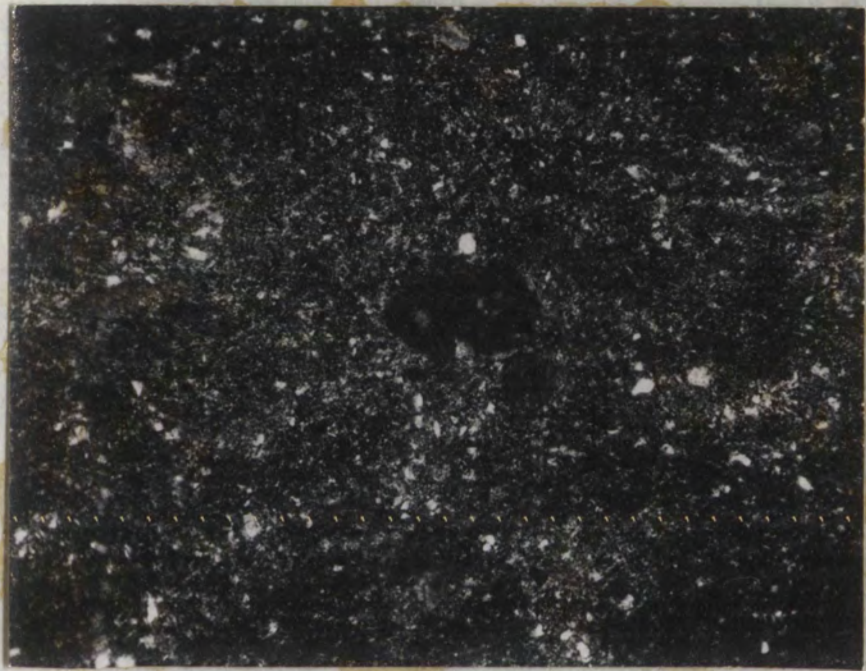


Figure 19. Silty claystone from the medial zone of the red claystone unit. White particles are quartz silt. Crossed nicols, X 18.

carbonate granules in this zone. Total carbonate ranges from 10 to 13 percent (Fig. 7). Subrounded quartz silt forms approximately 30 to 35 percent of the rock and the remainder is clay which is deeply stained with hematite. There are no fossils in this zone.

The upper leached zone is approximately 50 centimeters thick and consists of medium olive-gray, thinly bedded, sandy claystone. The total carbonate content in a sample from this zone is 5.6 percent. Rounded quartz grains (Fig. 20) form approximately 30 to 40 percent of the rock and the remainder is limonite-stained clay.

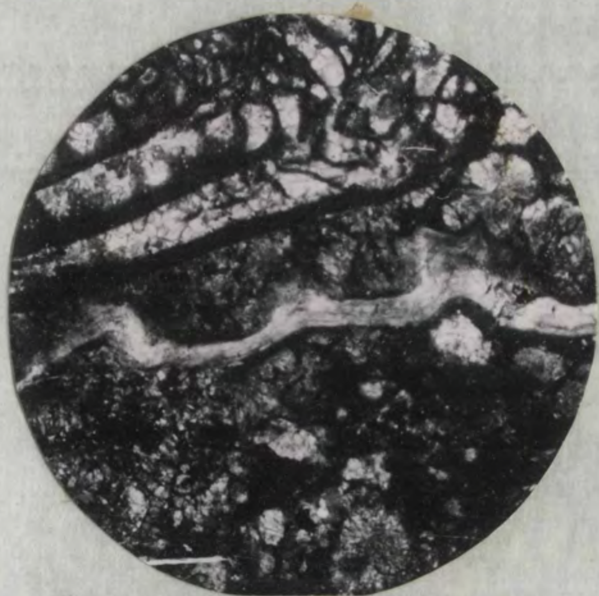
Figure 20. Sandy claystone from the upper leached zone of the red claystone unit. White particles are rounded quartz grains. Crossed nicols, X 10.

Lower fusulinid claystone unit of cycle 4

Above the disconformity terminating cycle 3, is a series of alternating claystones and limestones that are very similar in lithology and paleontology to the lower fusulinid claystone unit of cycle 3. This unit is much thicker and more complex than its equivalent in cycle 3. The lower fusulinid claystone unit of cycle 4 is 1.18 meters thick and rests disconformably with marked contrast in color, lithology, and paleontology on the underlying red claystone unit of cycle 3.

This unit consists of a basal medium gray, thinly bedded, fusulinid-bearing intrabiosparrudite followed by a series of alternating dark gray, thinly bedded, clayey, fusulinid-bearing biomicrites (Fig. 21A) and olive-gray, laminated, calcareous, fusulinid-bearing claystones (Fig. 21B). Total carbonate content of the limestone examined ranges from 71 to 76 percent (Fig. 7), quartz silt is present in quantities to 5 percent and the remainder is clay. The claystone analyzed contains between 12 and 32 percent total carbonate,

A
(X 25)



B
(X 40)

Figure 21. (A) Fusulinid-bearing biomicrite, and (B) fusulinid-bearing calcareous claystone from the lower fusulinid claystone unit of cycle 4. Crossed nicols.

approximately 10 to 30 percent quartz silt, and the remainder is clay.

Both the claystone and the limestone are highly fossiliferous. Fusulinids are the dominant fossil forms; however, brachiopods, bryozoans, gastropods, crinoids, corals, and ostracods have been collected. Above this unit is the massive brachiopod-bryozoan limestone unit of cycle 4. The lower fusulinid limestone unit of cycle 4 is missing.

CHEMICAL ANALYSES

In the following discussions the individual units are not considered separately; rather, general results are presented for the entire cycle.

Calcium and magnesium carbonate

The quantity of calcium and magnesium in a known sample was determined by titration using a modified EDTA method. The results of these titrations are reported as calcium and magnesium carbonate (Fig. 7). Because some calcium and magnesium was probably extracted from clay minerals, these results were qualified by quantitative carbon dioxide determinations on 15 samples of various clay content. The results of the two methods agreed within 5 percent; the method of titration was faster and these figures have been used exclusively.

Generally the percentage of magnesium carbonate in the samples is quite insignificant with respect to dolomitization. However, it does show some correlation with the different organic zones of the cycle. Revelle and Fairbridge (1957) have shown that the magnesium content of marine organisms tends to increase with the more highly evolved forms. The magnesium carbonate constitutes approximately 3 to 4 percent of the fusulinid limestone whereas the algal limestone nodules contain only trace amounts of magnesium carbonate. Revelle and Fairbridge (1957) stated that most marine carbonate deposits are the result of organic activity as the greater percentage of the deposits are in the form of recognizable skeletal material; the surrounding ooze, because of similar calcium-magnesium and calcite-aragonite ratios, is considered to be derived from the same source.

Magnesium carbonate is more soluble in marine water than calcium carbonate and its direct precipitation by physical processes is possible only in highly saline waters. Inorganically precipitated calcium carbonate never contains more than about 2 percent magnesium carbonate (Revelle and Fairbridge, 1957, p. 259) unless the magnesium carbonate was introduced during some other stage of petrogenesis. Because the non-algal limestone of cycle 3 contains abundant skeletal remains and magnesium carbonate in excess of 2 percent it is almost entirely the accumulation of fossil invertebrates.

Iron

The quantity of iron in a known sample was determined colorimetrically by the phenanthroline method; these results are reported as Fe_2O_3 (Fig. 7).

Within the cycle, iron is present in all samples, but in none is it abundant, ranging from nearly 6 percent in the upper fusulinid claystone unit to a minimum of 0.4 percent in the limestone. Iron has been observed as hematite and limonite stain and in some samples as rhombs of siderite.

Total iron and total carbonate content are in direct opposition (Fig. 7). This effect indicates that iron is associated with the terrigenous fraction and is probably a function of the amount of clay in the sample. Iron is generally a uniform 5 percent within the red claystone unit; as the upper boundary of this unit is approached the iron abruptly decreases to approximately 2 percent.

Kjeldahl nitrogen

The organic content of cycle 3 was determined by the Kjeldahl nitrogen analysis of 33 samples. Nitrogen determinations range from 0.0001 percent in the algal nodules to a maximum of 0.0029 percent in the lower fusulinid claystone unit (Fig. 22). It appears that the units of the cycle high in carbonate are low in nitrogen and those of low carbonate content contain the higher nitrogen values, but all values are low. This associates the nitrogen with the iron and both were probably brought in with the terrigenous fraction, suggesting that the organic matter may be in the form of minute plant fragments. Swain (1963) considered the organic content of La Casita black shales (Jurassic) of Mexico to be of similar origin.

Sulfate

The quantity of sulfate was determined on selected samples by the turibidimetric method. The significance of sulfate is questionable as of the 20 samples analyzed none contains more than 0.8 percent sulfate.

INSOLUBLE RESIDUE

Insoluble residues were prepared by the method of McQueen (1931) and studied with a binocular microscope. The dominant mineral, found in all residues, is clay. Much of the clay is fossomoldic, showing casts of fusulinids, crinoid columnals, and

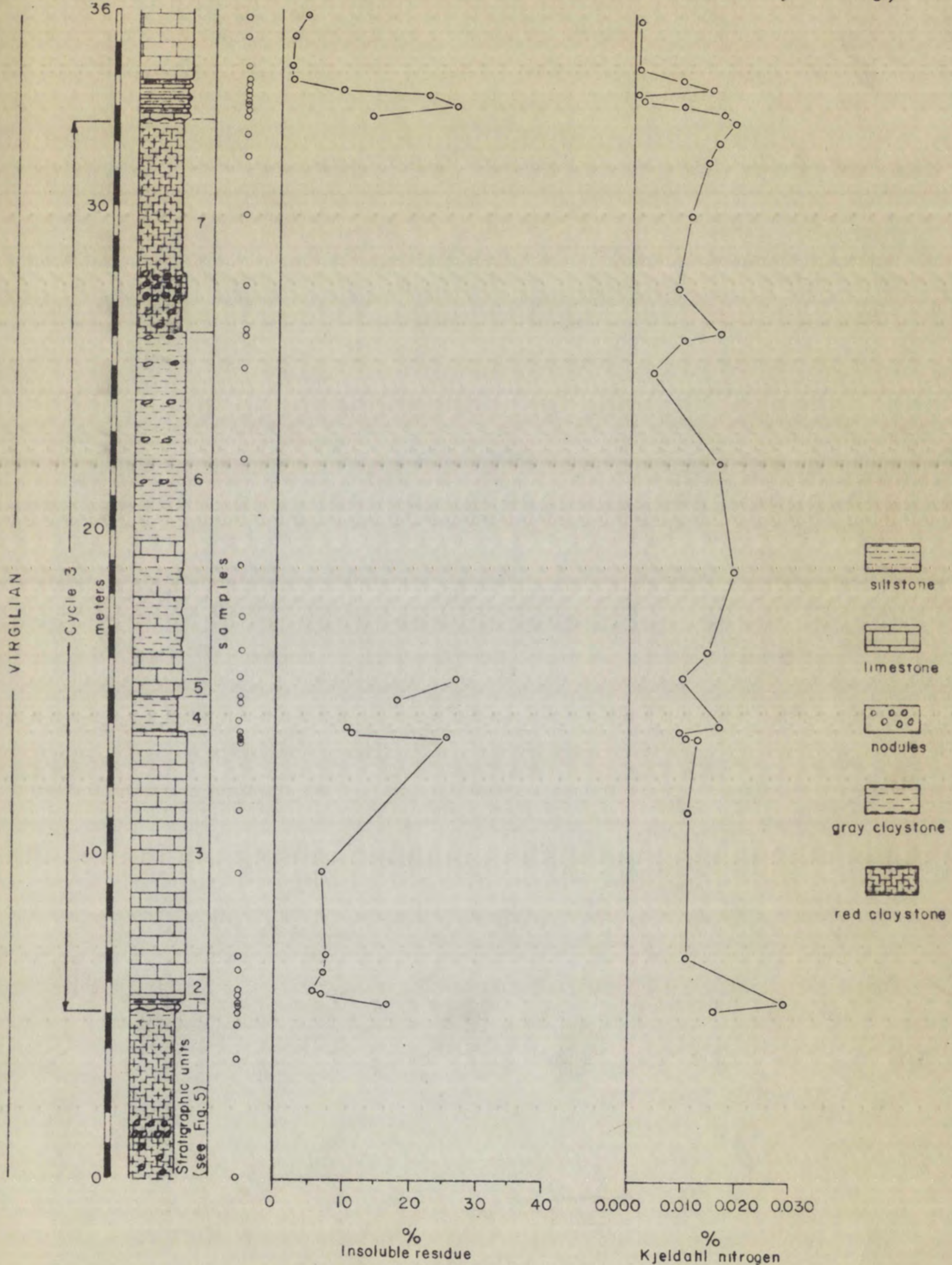


Figure 22. Stratigraphic section of cycle 3 and graphic presentation of the Kjeldahl nitrogen and insoluble residue of the samples analyzed.

bryozoans. In some samples, undissolved limestone granules are found in clay sheaths. The clay in high-carbonate limestone is yellowish-white whereas that associated with the clayey limestone is dark gray. Euhedral diagenetic quartz silt is present in the high-carbonate limestone. The graphical presentation of insoluble residue percentages (Fig. 22) resembles approximately that of iron and Kjeldahl nitrogen.

DIFFERENTIAL THERMAL ANALYSES

Differential thermal analyses were conducted on a majority of the samples to detect variations in clay composition. In all instances the thermograms resembled those of illite.

STRATIGRAPHIC-ECOLOGIC SUCCESSION

In cycle 3, as in other Virgilian strata of New Mexico, vertical changes in the fossil assemblage accompany the stratigraphic changes. Cline (1954) noted similar changes as stratigraphic units were traced laterally to the Pedernal positive area. From the base of the cycle upward the gross changes in fossil assemblage are: fusulinids, brachiopods and bryozoans, and algae. It is likely that these vertical and lateral changes have resulted from a complex of environmental changes associated with the sedimentary cycle or created by the organisms themselves.

Sedimentary cycles

Cyclic Pennsylvanian sedimentary sequences were recognized by Udden (1912) in the Peoria Quadrangle, Illinois. Udden grouped the Pennsylvanian of this region into four major, almost perfectly repetitious cycles each of which contains four distinctive stages; (1) accumulation of vegetation, (2) deposition of calcareous material, (3) sand importation, and (4) aggradation to sea level and soil making.

Since Udden's early work on cyclic sedimentation the concept has become greatly modified. Wanless and Weller (1932) proposed the term "cyclothem" for a series of beds deposited during a single sedimentary cycle of the type that prevailed during the Pennsylvanian period. As defined by Weller (1957), the typical "cyclothem" of western Illinois consists of 10 members as follows: a basal sandstone followed by sandy shale, lower limestone, underclay, coal, lower shale, middle limestone, middle shale, upper limestone, and an upper shale.

In many Pennsylvanian sections of the New Mexico region the cyclic sequence is as follows: basal disconformity followed by marine claystone, marine limestone, nodular claystone, red claystone, and an upper disconformity.

The causes of cyclic Pennsylvanian sedimentation have been ascribed, by various authors, to a diversity of geologic processes, the most worthy of mention being:

1 Alternating subsidence and uplift, (Weller, 1930).

2 Glaciation, (Wanless and Shepard, 1931).

3 Periodic subsidence and basin filling, (Stout, 1931; and Cady, 1933).

Any of the above processes will explain cyclic sedimentation, but the upper Madera cycles are most easily explained by the processes suggested by Stout (1931) and Cady (1933) and by the concepts of Barrell (1917). Barrell (1917) considered erosion and sedimentation to be pulsatory processes with smaller oscillations imposed on larger geologic rhythms of uplift and subsidence. The rate of sedimentation depends largely on the rate of subsidence to make sedimentational space. If the rate of subsidence is less than the rate of supply the excess will be carried elsewhere. In an epeiric sea the supply of sediment may be greater than the rate of subsidence. Eventually, waves and currents cannot carry away all of the excess material and this results in the seaward migration of the shoreline and filling of the basin. If another subsidence does not lower the bottom, the marine realm will eventually be replaced by the continental environment. As discussed earlier in this paper, cycle 1 contains continental members, but cycles 2, 3, and 4 were interrupted by subsidence, or the upper continental parts were later removed by erosion.

Stratigraphic-ecologic succession in cycle 3

Observations on the distribution of living organisms have shown that in given biotopes certain communities tend to succeed one another. These changes in the communities are created by external causes and the actions of the community itself. These two processes are generally working together, as is observed in the replacement of a pond community by a marsh community and eventually by a land community. The filling of a pond is caused by both deposition of transported material and deposition of organic remains of the successive communities (Buchsbaum, 1937). In the marine realm the changes within a community are determined more by the physical factors of the environment than by the community (Hedgpeth, 1957). Within the marine environment the type of community that dominates any particular biotope is determined by the nature of the bottom and the physical and chemical properties of the water; since these variables are subject to cyclic change so is the community. If periodic subsidence and subsequent basin filling are accepted as the cause for the Virgilian cycles of the Pennsylvanian system in New Mexico, then the observed vertical changes in the fossil assemblage can be explained as a stratigraphic-ecologic succession of organisms.

In cycle 3 time, subsidence initiated a marine transgression. This transgression created new areas to be inhabited by marine biota. Apparently the organisms were very sensitive to their surroundings and transgression was slow enough so that population of new areas was coincident with the transgression. Near culmination of transgression, the various marine biotopes were occupied and climax communities developed. The organic sediment produced by these communities and the clastic detritus of terrestrial origin accumulated and the basin became shallower, resulting in the initiation of regression. The communities, restricted to their critical environments, migrated with the sea. In cycle 3 the succession of organisms was initiated with an offshore fusulinid community and terminated with a near-shore algal community; the brachiopod-bryozoan community was intermediate. Ideally, the cycle should be symmetrical, but moderately rapid subsidence followed by slow basin filling has produced asymmetry.

During the deposition of cycle 3 the following events may have occurred. The fusulinids entered the environment in the early transgressive phase during the deposition of the lower marine claystone, persisted through the claystone phase, and continued to thrive during the initial stage of carbonate deposition. Then for some unknown reason they disappeared and were succeeded by a brachiopod-bryozoan community and associated fragments. However, in cycle 4 fusulinids and entire brachiopods are found together (Fig. 21A). This significant biologic change occurs in only a few centimeters stratigraphically and it seems unlikely that depth was the critical factor as suggested by Elias (1937). For some reason, perhaps competition for food, type of bottom, currents, or temperature the fusulinids favored the newly transgressed marine areas. As these new environments changed the fusulinids were succeeded by the brachiopods and bryozoans.

The succeeding community of brachiopods and bryozoans persisted for a long time, until approximately 4 meters of angular and 3.5 meters of slightly rounded fossil fragment limestone had accumulated. Shallowing of the sea was accomplished by the action of the organisms contributing organic waste and by an increase in fine clastic material.

The brachiopod-bryozoan climax community was ended by a minor subsidence and another transgression. Fusulinids returned, but, because of the continued influx of terrestrial material, were soon overwhelmed and replaced by the algae and linoproductoid community. This community persisted, possibly until the ultimate phase of marine sedimentation. The algal nodules and linoproductoid brachiopods continue into the overlying red claystone unit, and at least this part of the red claystone unit is of marine origin.

Field studies and chemical analyses have provided information for establishing a significant disconformity above the red claystone units of cycles 2 and 3. In the outcrop the lower zones of these units are grayish red, but approximately 50 centimeters below the disconformity the color becomes a mottled grayish-red and pale olive. At the top of the unit the red color is completely absent and it is pale olive. Within the lower nodular zone the carbonate and iron content is uniform in all samples; 24 and 5 percent respectively (Fig. 7). However, in the pale-olive zone carbonate and iron content drop significantly. It is possible that cycle 3 went all the way through the continental phase as did cycle 1. The red color of the red claystone unit is due to the oxidized state of the iron minerals rather than the amount of iron (Fig. 7) suggesting that the red color is a superimposed feature; the oxidation could have taken place during subaerial exposure. The low carbonate and iron content of the uppermost zone may be the result of leaching and reduction after burial by the succeeding submergence.

CONCLUSIONS

In the cycles of the upper Madera Limestone, changes in the fossil assemblage accompany the vertical lithologic changes. From the base of a typical cycle upward these gross changes in paleontology and lithology are: fusulinid-bearing claystone, followed by fusulinid-bearing limestone, brachiopod and bryozoan-bearing limestone, algal-nodule claystone, and red claystone. The changes in fossil assemblage are probably a stratigraphic-ecologic succession created by the marine sedimentary cycle and the organisms themselves. The lithologic changes have resulted from periodic subsidence and subsequent basin filling.

Elias (1937) considered the fusulinid-bearing strata of the Big Blue series to represent depths of deposition between 49 and 55 meters, and similarly considered other fossil assemblages to be indicative of particular depths of deposition. To differentiate the various organic communities of the Virgilian cycles in New Mexico in terms of depth alone seems hardly possible, as it appears that the variables of wave base, clastic material, distance from shore, and phase of the marine sedimentary cycle are more significant.

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APPENDICES

APPENDIX 1

Laboratory Analyses

Sample number	Rock type	% Calcium carbonate	% Magnesium carbonate	% Fe_2O_3	% Kjeldahl nitrogen
		Cycle 4			
		Brachiopod-bryozoan unit			
45	biomicrite	89.4	1.2	0.7	0.0001
44	biomicrite	91.4	1.4	0.4	
43	biomicrite	95.4	0.2	0.9	0.0001
42	biomicrite	94.4	0.4	0.9	0.0009
41	biomicrite	94.3	0.6	0.3	
		Lower fusulinid claystone unit			
40	siltstone	12.1	0.8	2.6	0.0015
39	biomicrite	75.4	0.4	0.4	0.0001
38	claystone	10.7	1.7	2.0	0.0002
37	biomicrite	71.0	3.0	0.4	0.0009
36	claystone	20.9	3.2	2.3	
35	biosparite	60.9	1.8	0.7	
34	claystone	30.9	1.5	1.7	0.0017
33	intrabiosparrudite	76.4	0.1	0.9	0.0019

Sample number	Rock type	% Calcium carbonate	% Magnesium carbonate	% Fe_2O_3	% Kjeldahl nitrogen
		Disconformity			
		Cycle 3			
		Red claystone unit			
32	claystone	4.2	1.4	2.3	0.0017
31	claystone	10.8	1.7	5.4	0.0014
30	claystone	9.6	0.5	5.3	0.0012
29	claystone	22.1	1.1	5.1	0.0008
29 n	algal nodule	76.1	0.2	2.0	0.0001
28	claystone	18.9	2.2	4.7	0.0016
27	claystone	28.1	0.3	4.7	0.0010
27 n	algal nodule	78.4	0.1	0.5	0.0002
		Nodular claystone unit			
26	claystone	31.0	0.2	3.6	0.0004
26 n	algal nodule	76.3	0.8	1.0	
25 n	algal nodule	64.2	0.8	1.4	0.0001
24	claystone	41.6	1.4	1.9	0.0016
23	claystone	42.1	1.3	1.4	0.0019
22	claystone	32.5	1.0	2.7	0.0020
21	siltstone	31.4	0.2	2.7	0.0014
20	sparite	71.0	2.4	1.4	0.0010

Sample number	Rock type	% Calcium carbonate	% Magnesium carbonate	% Fe_2O_3	% Kjeldahl nitrogen
	Upper fusulinid limestone unit				
19	biomicrite	75.7	1.7	2.6	
	Upper fusulinid claystone unit				
18	claystone	27.4	9.4	4.6	
17	claystone	12.5	0.7	5.6	0.0016
	Brachiopod-bryozoan limestone unit				
16	biomicrite	88.1	0.5	0.4	0.0009
15	biomicrite	90.3	0.4	0.5	0.0010
14	biomicrite	84.7	3.5	0.4	0.0012
13	biomicrite	68.2	1.0	0.7	
12	biomicrite	71.3	1.0	0.9	0.0011
11	biomicrite	84.6	2.1	1.0	
	Lower fusulinid limestone unit				
10	intrabiosparrudite	86.0	3.4	0.7	0.0010
9	biomicrite	89.8	3.0	0.6	
8	biomicrite	89.5	3.8	0.3	
7	biomicrite	84.2	2.9	0.4	
	Lower fusulinid claystone unit				
6	claystone	19.8	2.8	3.3	0.0029
6 n	carbonate nodule	72.6	2.8	1.1	0.0022
5	intrabiosparrudite	61.3	4.9	1.0	0.0016

Sample number	Rock type	% Calcium carbonate	% Magnesium carbonate	% Fe_2O_3	% Kjeldahl nitrogen
		Disconformity			
		Cycle 2			
		Red claystone unit			
4	claystone	1.5	0.5	1.3	
3	claystone	2.2	1.0	5.0	
2	claystone	8.3	1.3	4.9	
1	claystone	8.5	1.1	4.8	

APPENDIX 2

Terminology used in stratigraphic-petrographic descriptions (app. 3).

Stratification:

thick-bedded	over 50 centimeters
thinly bedded	1 to 50 centimeters
laminated	2 to 10 millimeters
thinly laminated	less than 2 millimeters

Quantities:

abundant	more than 50 percent
some	25 to 50 percent
trace	less than 25 percent

Form:

euhedral	showing well-developed crystal faces
flaky	small thin mass
granule	arenite size carbonate particle
nodule	rudite size carbonate particle
saccharoidal	fine granular
tabular	flattened

Roundness:

angular	corners and edges sharp
subrounded	corners and edges curved
rounded	corners and edges absent

Adjectives:

calcareous	containing more than 20% carbonate minerals
clayey	containing more than 20% clay particles
earthy	having a dull appearance
fossiliferous	containing more than 20% fossil material
greasy	having a greasy appearance
intraclast	an allochem in a carbonate rock
silty	containing more than 20% silt particles

Rock names:

biomicrite	a carbonate rock consisting of more than 25% fossil material with carbonate ooze cement
biosparite	a carbonate rock consisting of more than 25% fossil material with sparry calcite cement
claystone	an indurated rock formed from clay size particles
intrabiosparrudite	a carbonate rock consisting of more than 25% rudite intraclasts and 25% fossil material with sparry calcite cement
siltstone	an indurated rock formed from silt size particles
sparite	a carbonate rock consisting of more than 50% sparry calcite and less than 20% fossil material

APPENDIX 3

Stratigraphic-petrographic descriptions

(descending order)

Cycle 4

Brachiopod-bryozoan unit

Biomicrite No. 45 35.93 meters

Description:

Light gray, thick-bedded, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly brachiopods, bryozoans, productoid spines, and echinoid spines. Minor quantities fusulinids. Fossil material fragmental, rounded.

Insoluble residue:

4.4%: white, earthy, saccharoidal clay. Transparent, euhedral, diagenetic, quartz silt.

Other:

Some sparry calcite pore filling. Brachiopod remains recrystallized to sparry calcite.

Biomicrite No. 44 35.43 meters

Description:

Greenish-gray, thick-bedded, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly brachiopods, bryozoans, crinoids, echinoid spines, and productoid spines. Minor quantities fusulinids, Endothyra sp., and gastropods. Fossil material fragmental, rounded.

Insoluble residue:

2.0%: white, earthy, saccharoidal clay. Transparent, euhedral, diagenetic, quartz silt.

Other:

Trace sparry calcite pore filling. Brachiopod remains recrystallized to sparry calcite. Typical "Fossil Hash" limestone. Trace epigenetic sparry calcite veins.

Biomicrite No. 43 34.48 meters

Description:

Light gray, thinly bedded, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly brachiopods and bryozoans. Minor quantities echinoid spines, productoid spines, crinoids, Endothyra sp., gastropods, and fusulinids. Fossil material fragmental, angular.

Insoluble residue:

1.2%: white, earthy, saccharoidal clay. Transparent, euhedral, diagenetic, quartz silt. Clay fossomoldic after crinoid columnals and bryozoans.

Other:

Trace sparry calcite pore filling. Brachiopod remains recrystallized to sparry calcite.

Biomicrite No. 42 34.10 meters

Description:

Light gray, thinly bedded, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly brachiopods, bryozoans, and productoid spines. Minor quantities crinoids and fusulinids. Fossil material fragmental, angular.

Insoluble residue:

0.9%: white, earthy, saccharoidal clay. Transparent, euhedral, diagenetic, quartz silt.

Other:

Trace sparry calcite pore filling. Brachiopod remains recrystallized to sparry calcite. Typical "Fossil Hash" limestone.

Biomicrite No. 41 33.93 meters

Description:

Light brownish-gray, thinly bedded, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly brachiopods, bryozoans, crinoids, and productoid spines. Minor quantities fusulinids and Endothyra sp. Fossil material fragmental, angular.

Insoluble residue:

1.2%: white, earthy, saccharoidal clay. Transparent, euhedral, diagenetic, quartz silt. Clay fossomoldic after crinoid columnals and bryozoans.

Other:

Trace sparry calcite pore filling. Brachiopod remains recrystallized to sparry calcite. Typical "Fossil Hash" limestone.

Lower fusulinid claystone unit

Siltstone No. 40 33.90 meters

Description:

Yellowish-gray, laminated, clayey, fossiliferous.

Recognizable organic remains:

Some fossil material, predominantly fusulinids, minor quantities crinoids, brachiopods, bryozoans, corals, and echinoid spines.

Fusulinids unabraded; others fragmental, rounded.

Other:

Abundant limonite-stained clay. Trace angular quartz and magnetite silt.

Biomicrite No. 39 33.80 meters

Description:

Pale olive, laminated, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly pelecypods, brachiopods, and bryozoans. Minor quantities echinoid spines and productoid spines. Fossil material fragmental, angular.

Insoluble residue:

12.2%: yellowish-white, greasy, flaky, limonite-stained clay.

Other:

Brachiopods and pelecypods recrystallized to sparry calcite. Trace limonite stains outlining some fossil forms. Trace epigenetic sparry calcite veins.

Claystone No. 38 33.68 meters

Description:

Grayish-olive, laminated, silty, fossiliferous.

Recognizable organic remains:

Moderate fossil material, predominantly fusulinids. Minor quantities bryozoans, brachiopods, corals, and crinoids. Fusulinids unabraded; others fragmental, angular.

Other:

Abundant hematite-stained clay. Angular quartz and magnetite silt.

Biomicrite No. 37 33.48 meters

(Figure 21A)

Description:

Olive-gray, thinly bedded, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly fusulinids. Minor quantities brachiopods, gastropods, and productoid spines. Fusulinids unabraded; others fragmental, rounded.

Insoluble residue:

8.2%: yellow, earthy, flaky, limonite-stained clay. Subrounded quartz sand.

Other:

Brachiopods and gastropods recrystallized to sparry calcite. Trace hematite stains.

Claystone No. 36 33.32 meters

(Figure 21B)

Description:

Olive-gray, laminated, silty, calcareous, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly fusulinids. Minor quantities brachiopods, bryozoans, and productoid spines. Fusulinids unabraded; others fragmental, angular.

Other:

Abundant hematite-stained clay. Some angular sparry calcite intraclasts.

Biosparite No. 35 33.18 meters

Description:

Medium dark gray, thinly bedded, clayey, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly brachiopods and bryozoans. Minor quantities fusulinids and crinoids. Fossil material fragmental, angular.

Insoluble residue:

26.1%: yellowish-gray, greasy, flaky, limonite-stained clay. Angular, quartz sand.

Other:

Fossil material recrystallized to sparry calcite, very difficult to recognize.

Claystone No. 34 33.03 meters

Description:

Dusky yellow, laminated, calcareous, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly brachiopods. Minor quantities bryozoans and productoid spines. Fossil material fragmental, angular.

Other:

Abundant hematite-stained clay. Fossil material recrystallized to sparry calcite. Trace angular quartz silt.

Intrabiosparrudite No. 33 32.80 meters

Description:

Medium gray, thinly bedded, quartz-bearing.

Recognizable organic remains:

Trace fossil material, predominantly fusulinids, brachiopods, and bryozoans. Fossil material fragmental, angular.

Insoluble residue:

13.5%: yellowish-brown, earthy, saccharoidal clay. Subrounded, quartz sand.

Other:

Abundant rounded micrite carbonate intraclasts. Sparry calcite cement. Trace hematite stains. Brachiopod remains recrystallized to sparry calcite.

Disconformity

Cycle 3

Red claystone unit

Claystone	No. 32	32.28 meters

(Figure 20)

Description:

Medium olive-gray, thinly bedded, sandy.

Other:

Abundant limonite-stained clay. Some angular quartz silt and rounded quartz sand. Mass parallel extinction.

Claystone	No. 31	31.58 meters

Description:

Reddish-brown, thinly bedded, silty.

Other:

Abundant hematite-stained clay. Trace rounded micrite carbonate granules. Moderate angular quartz silt.

Claystone No. 30 29.75 meters

(Figure 19)

Description:

Reddish-brown, thinly bedded, silty.

Other:

Abundant hematite-stained clay. Moderate subrounded quartz silt. Trace rounded micrite carbonate granules.

Claystone No. 29 27.58 meters

Description:

Reddish-brown, thinly laminated, silty, calcareous.

Recognizable organic remains:

Some fossil material, consisting of micrite carbonate algal nodules and brachiopods.

Other:

Abundant hematite-stained clay. Trace angular quartz silt.

Biomicrite No. 29 nodule 27.58 meters

(Figure 18B)

Description:

Grayish-red, nodular, clayey, algal.

Recognizable organic remains:

This nodule has been identified as an "algal felt made by the blue-green algae", by J. Harlan Johnson. Trace brachiopod remains.

Insoluble residue:

Abundant rounded micrite algal granules aggregated into nodule with micrite and sparite cements. Trace angular quartz silt. Trace hematite stain.

Claystone No. 28 26.23 meters

(Figure 17)

Description:

Reddish-brown, thinly bedded, silty, calcareous.

Recognizable organic remains:

Some fossil material, predominantly micrite algal granules. Minor quantities brachiopods.

Other:

Abundant hematite-stained clay. Moderate angular quartz silt.

Claystone No. 27 26.13 meters

Description:

Grayish-red, laminated, silty, calcareous.

Recognizable organic remains:

Some fossil material, predominantly micrite algal granules aggregated with clay and micrite cement. Minor quantities recrystallized brachiopod fragments.

Other:

Abundant hematite-stained clay. Moderate angular quartz silt.

Biomicrite No. 27 nodule 26.13 meters

Description:

Medium dark gray, nodular, clayey, algal.

Recognizable organic remains:

Abundant fossil material, predominantly micrite algal granules and brachiopod remains aggregated with micrite and clay cements.

Insoluble residue:

15.2%: white, earthy, saccharoidal clay. Clay fossomoldic after bryozoans. Bryozoans not observed in thin section.

Other:

Trace hematite-stained clay veins in nodule.

Nodular claystone unit

Claystone No. 26 25.10 meters

(Figure 15)

Description:

Light brownish-gray, thinly bedded, calcareous.

Recognizable organic remains:

Fossil fragments skeletal and identification uncertain. Possibly algae, brachiopods, and bryozoans.

Other:

Abundant clay. Trace angular quartz silt.

Biomicrite No. 26 nodule 25.10 meters

Description:

Medium gray, nodular, clayey, algal.

Recognizable organic remains:

Abundant fossil material, predominantly micrite algal granules. Minor quantities of brachiopod remains.

Insoluble residue:

5.9%: white, earthy, saccharoidal clay. Angular quartz silt.

Other:

Trace hematite-stained clay veins in nodule.

Biomicrite No. 25 nodule 24.10 meters

Description:

Medium gray, nodular, clayey, algal.

Recognizable organic remains:

Abundant fossil material, predominantly algal remains. Minor quantities brachiopods.

Insoluble residue:

29.2%: white, earthy, tabular clay. Angular quartz silt.

Claystone | No. 24 | 22.30 meters

Description:

Medium gray, thinly bedded, silty, calcareous.

Other:

Abundant limonite-stained clay. Trace angular quartz silt. Mass parallel extinction.

Claystone | No. 23 | 19.10 meters

(Figure 14)

Description:

Medium gray, thinly bedded, silty, calcareous.

Other:

Abundant clay. Trace angular quartz silt. Trace carbonate granules. Mass parallel extinction.

Claystone | No. 22 | 17.40 meters

Description:

Medium dark gray, laminated, calcareous.

Other:

Abundant clay. Mass parallel extinction.

Description:

Dark gray, laminated, clayey, calcareous.

Other:

Unidentified fossil fragments. Abundant limonite-stained clay. Moderate angular quartz and plagioclase silt.

Sparite No. 20 15.58 meters

(Figure 13)

Description:

Dark gray, thinly bedded, clayey.

Insoluble residue:

26.0%: light gray, earthy, limonite-stained, tabular clay. Angular, quartz silt.

Other:

Very fine sparry calcite texture.

Upper fusulinid limestone unit

Biomicrite No. 19 14.90 meters

(Figure 12)

Description:

Medium gray, thinly bedded, clayey, fossiliferous.

Recognizable organic remains:

Moderate fossil material, predominantly fusulinids. Minor quantities brachiopods, bryozoans, and productoid spines. Fossil material fragmental, angular.

Insoluble residue:

17.4%: gray, earthy, limonite-stained, tabular clay. Trace angular quartz silt. Clay fossomoldic after fusulinids and bryozoans.

Other:

Trace epigenetic sparry calcite veins. Fossil material and clay aligned with the bedding. Mass parallel extinction.

Upper fusulinid claystone unit

Claystone No. 18 14.83 meters

(Figure 11)

Description:

Dark greenish-gray, thinly laminated, silty, calcareous, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly brachiopods, pelecypods, bryozoans, fusulinids, gastropods, ostracods, and crinoids. All fossil material fragmental, angular, and strongly compressed.

Other:

Abundant limonite-stained clay. Trace angular quartz silt.

Fossil material aligned with the bedding.

Claystone No. 17 14.18 meters

Description:

Olive-gray, thinly laminated, silty.

Recognizable organic remains:

Trace recrystallized brachiopod fragments.

Other:

Abundant limonite-stained clay. Trace subrounded quartz sand.

Brachiopod-bryozoan limestone unit

Biomicrite No. 16 13.80 meters

Description:

Dark gray, thick-bedded, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly brachiopods, bryozoans, and gastropods. Minor amounts echinoid spines, productoid spines, and *Endothyra* sp. Fossil material fragmental, rounded.

Insoluble residue:

10.0%: light gray, earthy, limonite-stained, saccharoidal clay. Angular, quartz silt.

Other:

Brachiopod remains recrystallized to sparry calcite. Trace epigenetic sparry calcite veins. Typical "Fossil Hash" limestone.

Biomicrite No. 15 13.70 meters

Description:

Medium gray, thick-bedded, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly brachiopods, bryozoans, and crinoids. Fossil material fragmental, rounded. Brachiopod remains stained with limonite.

Insoluble residue:

9.5%: white, earthy, saccharoidal clay. Transparent, euhedral, diagenetic quartz silt.

Other:

Trace epigenetic sparry calcite veins. Trace rounded micrite carbonate intraclasts.

Biomicrite No. 14 13.45 meters

(Figure 10B)

Description:

Medium gray, thick-bedded, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly brachiopods and bryozoans, other remains unidentified. Fossil material fragmental, rounded.

Insoluble residue:

10.0%: white, earthy, saccharoidal clay. Angular, quartz silt.

Other:

Trace epigenetic sparry calcite veins. Trace sparry calcite pore filling.

Biomicrite No. 13 11.45 meters

Description:

Light brownish-gray, thick-bedded, clayey, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly brachiopods and bryozoans. Minor quantities crinoids, fusulinids, and echinoid spines. Fossil material fragmental, angular.

Insoluble residue:

25.2%: white, earthy, tabular clay. Angular, quartz silt. Clay fossomoldic after bryozoans and brachiopods.

Other:

Trace epigenetic sparry calcite veins. Typical "Fossil Hash" limestone.

Biomicrite No. 12 9.45 meters

Description:

Light olive-gray, thick-bedded, clayey, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly bryozoans and brachiopods. Minor quantities productoid spines. Fossil material fragmental, angular.

Insoluble residue:

30.1%: white, earthy, tabular clay. Angular, quartz silt. Clay fossomoldic after bryozoans.

Other:

Trace epigenetic sparry calcite veins.

Biomicrite No. 11 7.45 meters

(Figure 10A)

Description:

Light olive-gray, thick-bedded, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly brachiopods, bryozoans, and crinoids. Minor quantities productoid spines, fusulinids, and other Foraminifera. Fossil material fragmental, angular.

Insoluble residue:

5.6%: white, earthy, saccharoidal clay. Transparent, silt size, euhedral, diagenetic, quartz crystals.

Other:

Typical "Fossil Hash" limestone.

Lower fusulinid limestone unit

Intrabiosparrudite No. 10 6.45 meters

(Figure 8)

Description:

Light olive-gray, thinly bedded, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly fusulinids. Minor quantities brachiopods and bryozoans. Fusulinids unabraded; others fragmental, angular.

Insoluble residue:

6.8%: dark gray, earthy, limonite-stained, tabular clay. Subrounded quartz sand. Clay fossomoldic after fusulinids.

Other:

Trace black angular claystone intraclasts bearing fragmental angular crinoids, fusulinids, productoid spines, and echinoid spines with angular quartz sand. Trace epigenetic sparry calcite veins. Sparry calcite cement.

Biomicrite No. 9 5.85 meters

Description:

Light gray, thinly bedded, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly fusulinids. Minor quantities brachiopods, bryozoans, gastropods, crinoids, productoid spines, and Endothyra sp. Fusulinids unabraded; others fragmental, rounded.

Insoluble residue:

6.3%: white, earthy, saccharoidal clay. Transparent, euhedral, diagenetic, quartz silt.

Other:

Trace epigenetic sparry calcite veins. Brachiopods recrystallized to sparry calcite. Trace hematite stains.

Biomicrite No. 8 5.61 meters

Description:

Light olive-gray, thinly bedded, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly fusulinids. Minor quantities bryozoans, crinoids, gastropods, brachiopods, echinoid spines, and productoid spines. Fusulinids unabraded; others fragmental, subrounded.

Insoluble residue:

5.3%: white, earthy, saccharoidal clay. Transparent, euhedral, diagenetic, quartz silt.

Other:

Trace epigenetic sparry calcite veins. Brachiopod remains recrystallized to sparry calcite. Typical "Fossil Hash" limestone.

Biomicrite No. 7 5.45 meters

Description:

Light olive-gray, thinly bedded, fossiliferous.

Recognizalbe organic remains:

Abundant fossil material, predominantly fusulinids. Minor quantities brachiopods, bryozoans, and productoid spines. Fusulinids unabraded; others fragmental, rounded.

Insoluble residue:

5.7%: white, earthy, saccharoidal clay. Transparent, euhedral. diagenetic, quartz silt.

Other:

Trace sparry calcite pore filling. Brachiopod remains recrystallized to sparry calcite.

Lower fusulinid claystone unit

Claystone No. 6 5.33 meters

Description:

Greenish-gray, thinly laminated, silty, calcareous, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly fusulinids. Minor quantities brachiopods, crinoids, and bryozoans. Fusulinids unabraded; others fragmental, rounded.

Other:

Abundant limonite-stained clay. Trace angular quartz silt.

Biosparite No. 6 nodule 5.33 meters

Description:

Greenish-gray, nodular, clayey, fossiliferous.

Recognizable organic remains:

Abundant fossil material, predominantly fusulinids. Minor quantities brachiopods, crinoids, productoid spines, and bryozoans. Fusulinids unabraded; others fragmental, rounded.

Insoluble residue:

11.8%: brownish-gray, earthy, tabular clay. Angular, quartz silt.

Other:

Sparry calcite cement. Trace limonite stains outlining intraclasts. Veins of clay penetrating nodule.

Intrabiosparrudite No. 5 5.26 meters

(Figure 6)

Description:

Medium gray, thinly bedded, clayey, fossiliferous.

Recognizable organic remains:

Some fossil material, predominantly fusulinids. Minor quantities brachiopods, bryozoans, and crinoids. Fusulinids unabraded; others fragmental, rounded.

Insoluble residue:

16.4%: light green, greasy, saccharoidal clay. Angular quartz silt. Clay fossomoldic after fusulinids.

Other:

Abundant rounded sparite carbonate intraclasts. Brachiopod remains recrystallized to sparry calcite. Trace limonite stains.

Disconformity

Cycle 2

Red claystone unit

Claystone No. 4 5.13 meters

Description:

Pale olive, thinly bedded, silty.

Other:

Abundant limonite-stained clay. Trace angular quartz silt.

Mass parallel extinction.

Claystone No. 3 4.70 meters

Description:

Grayish-red, thinly bedded, silty.

Other:

Abundant hematite-stained clay. Trace angular quartz silt.

Mass parallel extinction.

Claystone No. 2 3.70 meters

Description:

Grayish-red, thinly bedded, silty.

Other:

Abundant hematite-stained clay. Trace angular quartz silt.

Claystone No. 1 0.00 meters

Description:

Grayish-red, thinly bedded, silty.

Recognizable organic remains:

Trace fossil material, predominantly algal carbonate granules.

Minor quantities brachiopod remains.

Other:

Abundant hematite-stained clay. Trace angular quartz silt.