Petrography and Environmental Analysis of Some Pennsylvanian Limestones from Central Texas

GEOLOGICAL SURVEY PROFESSIONAL PAPER 315-E

Prepared in cooperation with the
Bureau of Economic Geology
The University of Texas

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By ROBERT T. TERRIERE

PENNSYLVANIAN AND LOWER PERMIAN ROCKS OF PARTS OF WEST AND CENTRAL TEXAS

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PETROGRAPHY AND ENVIRONMENTAL ANALYSIS OF SOME PENNSYLVANIAN LIMESTONES FROM CENTRAL TEXAS

By Robert T. Terriere

ABSTRACT

Limestone units form a small part of the dominantly shale sequence that constitutes the Upper Pennsylvanian section of central Texas; they are important and distinctive marker beds for distinguishing and correlating stratigraphic units.

Seven limestone units in the lower part of the Cisco group, which seemed from field examination to be representative of the Upper Pennsylvanian limestone strata, were selected for detailed study. These limestone units are within the Bluff Creek shale member and the Gunsight limestone member of the Graham formation. Each limestone unit is 1 to 10 feet thick. For reference in this report the units are designated by letters, unit *A* being stratigraphically the lowest limestone unit in a member and unit *D* the highest. The study was restricted to the Grosvenor quadrangle, Brown and Coleman Counties, in which the limestone units are comparatively well exposed and have been carefully mapped.

The limestone units were studied megascopically in the field and microscopically by use of smoothed and etched surfaces, insoluble residues, and thin sections in the laboratory. Point counts were made of the thin sections to determine the abundance of the organic and inorganic components. Shale and sandstone associated with the limestone were studied in less detail.

The limestone is composed of (1) microcrystalline calcite and sparry-calcite cement; (2) carbonate grains or aggregates, including fossils, ooliths, pellets, and reworked limestone fragments; (3) terrigenous sand, silt, and clay; and (4) authigenic minerals.

Microcrystalline calcite appears dusty or imperfectly translucent in thin section because it is composed of small crystals 1 to 4 microns in diameter. Part of this material has been recrystallized to slightly larger crystals (microspar). The calcite is intermixed with very small poorly preserved remnants, or "ghosts," of clastic calcite debris. Sparry calcite consists of clear crystals larger than 0.02 mm and occurs as cement, vein fillings, recrystallized or replaced fossil fragments, and recrystallized microcrystalline calcite. Sparry-calcite cement is most abundant in limestone containing sorted and rounded clastic debris, which shows that it is cement rather than recrystallized calcite.

Fossils are the most abundant and varied of the carbonate grains. Fossils identified in thin-section study include (1) algae, further subdivided into recrystallized coralline algae, dasycladaceans, and oncolites, (2) smaller Foraminifera, (3) fusulinids, (4) horn corals and colonial corals, (5) bryozoans, (6) brachiopods, (7) mollusks, (8) echinoderms, and (9) other fossils.

The ooliths have both radial and concentric structure. They seem to have been especially susceptible to later replacement by barite. Pellets are ovoid aggregates of microcrystalline calcite that may be mostly fecal pellets of invertebrates. Limestone fragments seem to consist of locally reworked pieces only slightly older than the rocks in which they occur. Some of the fossils and ooliths show evidence of reworking and may also be considered rock fragments.

Terrigenous sand and silt consist of quartz and very small amounts of chert, feldspar, and heavy minerals. The ultimate source rocks seem to have been largely metamorphic, but the immediate source rocks were probably sedimentary. Clay minerals, as determined by X-ray, are chiefly kaolin and mixed-layer illite. The ratio of kaolin to illite is higher in the insoluble residues of limestone than in the shale associated with the limestone, presumably because clay minerals in the limestone were protected from postdeposition changes.

Authigenic constituents in the limestone consist of chert, barite, pyrite, ankerite, hematite, limonite, and psilomelane(?).

The constituents found to be most diagnostic of certain units are fusulinids, algae, corals, and insoluble residue. These constituents, together with texture and field appearance, can be used to divide the limestone into four types.

Type 1 is unsorted, unwinnowed limestone with many fusulinids; it is dark gray where fresh but weathers orange. This type of limestone commonly is thick bedded, resistant to erosion, and uniform in thickness and lithology along the strike. Type 1 limestone is also characterized by finely disseminated pyrite, suggesting poor water circulation. It is characteristic of unit *D* of the Bluff Creek and also composes much of unit *B* of the Bluff Creek.

Type 2 limestone is microcrystalline and has many recrystallized algae and veinlets of sparry calcite. Locally it contains many horn corals. It is light gray and weathers to nodular rubble. Units composed of type 2 limestone tend to thin along the strike because of gradation of the limestone to shale. Probably type 2 limestone was deposited in extremely shallow water on a broad shelf where waves were small and conditions were most favorable for chemical precipitation. Lack of water circulation in the shallowest areas may have prevented growth of horn corals that are elsewhere abundant in type 2 limestone. Unit *A* of the Gunsight consists primarily of type 2 limestone with many corals, and unit *C* of the Gunsight of type 2 limestone with few corals.

Type 3 limestone contains abundant evidence of strong wave action: well-sorted and well-rounded particles, reworked fossils and fragments of limestone, ooliths, and relatively large amounts of terrigenous sand. Type 3 limestone probably origi-

nated on offshore bars. Erratic distribution and rapid lateral changes support this hypothesis. Unit *B* of the Gunsight is the best example of type 3 limestone studied, but units *A* and *B* of the Bluff Creek also locally are type 3.

Type 4 is light-gray microcrystalline limestone and contains few fusulinids or algae but much poorly sorted and poorly preserved fine fossil debris, especially smaller Foraminifera, and pellets. It tends to be nodular where weathered and to persist laterally, although differing in thickness from place to place. Of the beds studied, unit *C* of the Bluff Creek is the best example of type 4 limestone. This unit merges southwestward with the overlying type 1 limestone of unit *D* of the Bluff Creek and seems, from these field relations, to be a regressive phase of the transgressive type 1 limestone.

INTRODUCTION

PURPOSE OF THE STUDY

Limestone beds of Pennsylvanian and early Permian age in central Texas are of particular interest because they constitute distinctive marker beds for distinguishing and correlating stratigraphic units. Interpretation of their environment of deposition may be helpful in interpreting the origin and distribution of other limestone units, including much thicker limestone units of the same age that are important oil and gas reservoirs in western Texas. The limestone units are part of a sequence of shale, sandstone, and limestone that crop out in central Texas in a band extending northward and northeastward from the Llano uplift (fig. 13).

In terms of gross lithology, the Upper Pennsylvanian and Lower Permian succession is an alternation of limestone and shale that contains a recurrence of channel-fill deposits in some parts of the section. In detail, however, there is much less repetition of rock types; individual limestone units have lithologic characteristics that are not repeated in most of the other limestones. Recent emphasis in many areas on the the origin of limestone has stressed the importance of describing various limestone types and of attempting to understand the differences in their depositional environment.

The area chosen for this study is the Grosvenor quadrangle (fig. 13), and the samples were collected in conjunction with detailed geologic mapping (Terriere, 1960). From the more than 30 individual limestone units cropping out in the Grosvenor quadrangle, 7 units in the lower part of the Graham formation were chosen for detailed study. These units contain a variety of lithologic types and have very different faunas and textures that seem to reflect different environments of deposition. The 7 limestone units chosen for detailed study are locally exposed over almost the entire length of the quadrangle, a distance of more than 16 miles, and reentrants and outliners along their outcrop give them a more nearly three-dimensional outcrop distribution than most of the other limestone units in the quadrangle.

The investigation on which this report is based was made as a part of a U.S. Geological Survey study of the lithology, distribution, stratigraphic relations, and conditions of deposition of the Pennsylvanian and Lower Permian strata of central and western Texas. Some of the results of that more general study have been presented in papers by Bergenback and Terriere (1953), Myers, Stafford, and Burnside (1956) Eargle (1960), Terriere (1960), and Myers (1960). The project was carried on in cooperation with the Bureau of Economic Geology, The University of Texas.

The fossils were studied by Mackenzie Gordon, Jr., Helen Duncan, Ellis Yochelson, and I. G. Sohn. Corals and bryozoans were given preliminary identification by Duncan, primarily to establish general generic relations. Gastropods were identified as completely as possible by Yochelson. Sohn identified the ostracodes. All other fossils shown in the checklist (table 1) were identified by Gordon.

This paper is part of a dissertation submitted to the Department of Geology, The University of Texas, as a partial requirement for the Ph. D. degree.

GEOLOGIC SETTING

The Grosvenor quadrangle is underlain by sedimentary rocks of Pennsylvanian and Permian ages that dip gently west-northwestward and are locally overlain by patches of rocks of early Cretaceous age that dip slightly southeastward. The Pennsylvanian and Permian rocks consist mainly of gray shale but also include limestone, siltstone, sandstone, conglomerate, and red shale. Most of the sandstone and conglomerate occupies broad, shallow channels cut into the shale and limestone. Shale and siltstone also fill parts of some channels. In general, red shale and channel-fill material are more abundant upward in the section.

The rocks belong to the Canyon and Cisco groups of Late Pennsylvanian age, and to the Wichita group of Permian age. The Canyon group consists of alternating gray limestone and shale and includes smaller amounts of very fine to fine-grained sandstone. Only 1 channel-fill deposit was found in the Canyon group within the quadrangle, although 2 others have been reported in nearby areas.

The Cisco group also consists of alternate limestone and shale, and contains small amounts of sandstone and conglomerate in lenticular beds. In the Cisco group, however, the limestone beds are thinner than those in the Canyon group and channel-fill deposits are more numerous. The Wichita group is similar to the Cisco

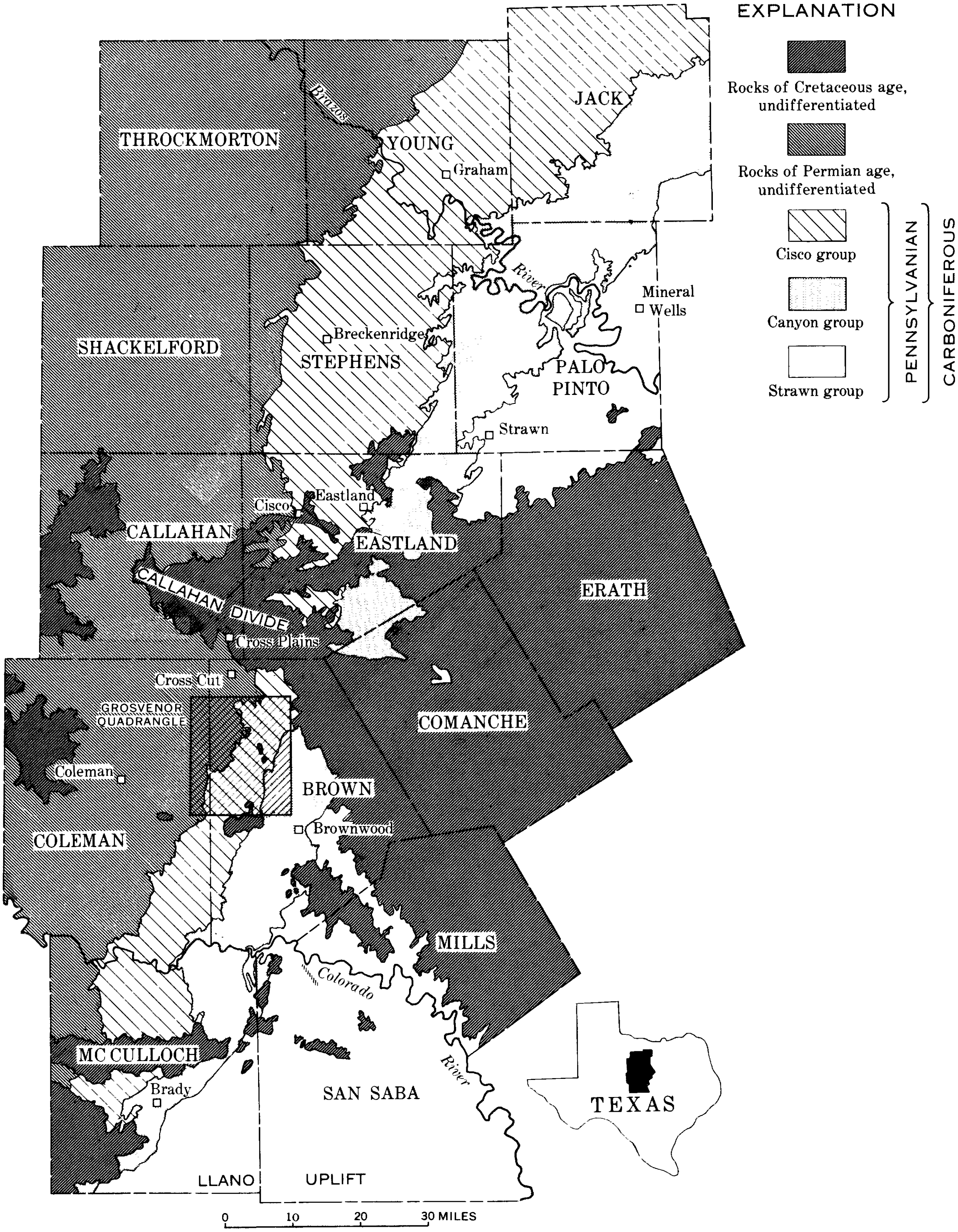

FIGURE 13.—Index map of central Texas showing the location of the Grosvenor quadrangle in relation to outcropping rocks.

but contains a larger percentage of channel-fill material and of red beds. Channel deposits are especially numerous in the lower part of the Wichita group, where three or more channel deposits are superimposed on one another.

The limestone units chosen for detailed study are in the lower part of the Graham formation, the lower of two formations in the Cisco group (fig. 14). The Graham formation is about 300 feet thick and has been divided into 5 members, in descending order: an unnamed shale unit, the Ivan limestone, Wayland shale, Gunsight limestone, and Bluff Creek shale. The limestone units studied for this report lie within the Bluff Creek shale and the Gunsight limestone members of the

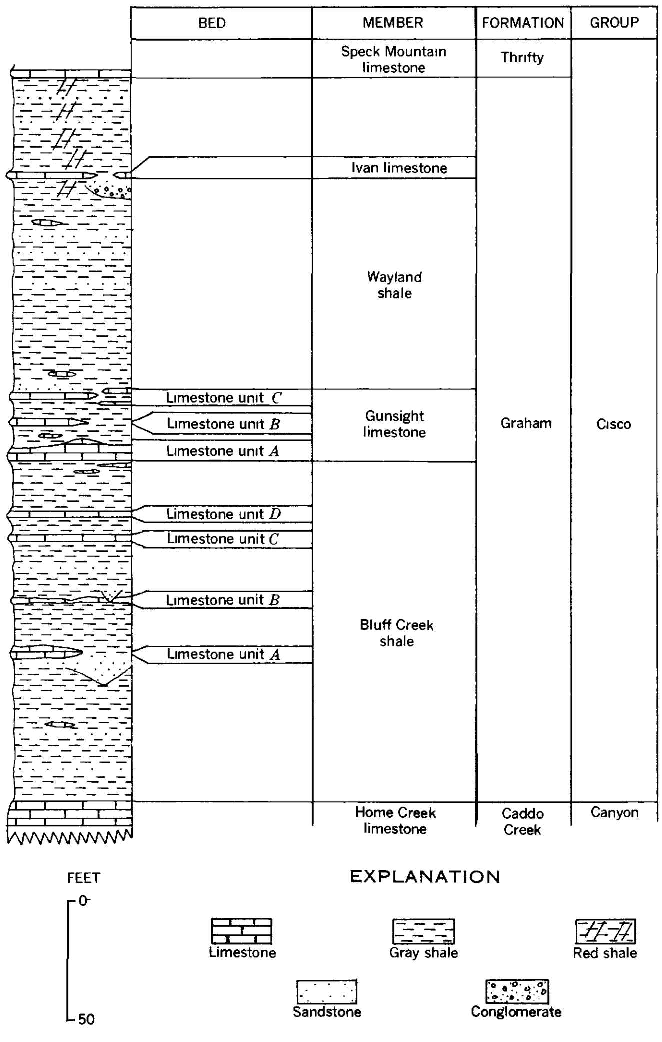

FIGURE 14.—Composite stratigraphic section of the Graham formation in the Grosvenor quadrangle, Texas.

Graham formation. The Graham formation is overlain by the Spect Mountain limestone member of the Thrifty formation and is underlain by the Home Creek limestone member of the Caddo Creek formation of the Canyon group.

The Bluff Creek shale member is composed of approximately 140 feet of gray shale that contains lenticular sandstone and thin limestone beds. The shale is poorly exposed, especially that in the lower part of the member. It is nonfissile to fissile and nonsilty to very silty. Its color ranges from very light to medium gray, locally mottled with purple or red. Most of the shale is light gray, silty, slightly fissile, and unfossiliferous, except for scattered plant fragments. At several localities the uppermost 10 to 20 feet of the shale contains many marine fossils, including fusulinids, brachiopods, gastropods, and cephalopods (table 1, collection 15098). A sparse fauna of gastropods, pelecypods, brochiopods, crinoids, and ostracodes is present in the lower part of the Bluff Creek at a few places (table 1, collections 16011 and 16012).

Most sandstone beds in the Bluff Creek shale member are thin and very fine grained. Two sandstone units near the middle of the member thicken locally in such a manner as to suggest that they are channel-fill deposits.

Three limestone beds within the Bluff Creek shale member of the Grosvenor quadrangle were assigned formal names (Cheney and Eargle, 1951) by extension into this area of beds originating in the Brazos River drainage area to the north. (See fig. 13.) More recently Eargle (1960, p. 69) has concluded that the correlation of these beds with beds of the type localities is too questionable to justify the use of these formal names in the Grosvenor quadrangle. The limestone beds seem to be too thin and too discontinuous to justify use of formal names; therefore, for this report, letters have been assigned to the beds.

The lowest limestone bed in the Bluff Creek member, referred to here as unit *A*, was called the Gonzales limestone by Cheney and Eargle (1951). Unit *A* is a discontinuous and poorly exposed bed slightly below the middle of the Bluff Creek shale member (fig. 14). It differs considerably from place to place along the strike but is mostly light-gray sandy clastic limestone. Unit *B* is about 20 feet above unit *A*, approximately at the middle of the member (fig. 14). It was correlated by Cheney and Eargle with the North Leon limestone member. Unit *B* is most commonly about 1½ feet thick and is composed of dark-gray limestone that weathers yellowish orange.

TABLE 1.—*Check list of megafossils and ostrocodes collected from the Graham formation in the Grosvenor quadrangle*

[Query (?) indicates the occurrence of a specimen that has been questionably identified as the genus or species. Numbers are U.S. Geological Survey collection numbers (localities shown on figure 15)]

	Bluff Creek shale member			Gunsight limestone member				Wayland shale member		
	16011	16012	15098	16014	16015	16016	16017	16019	16020	16021
Wewokella solida Girty							×			
sp										×
Conularia sp			×							
Lophophyllidium cf. *L. plummeri* Jeffords			×							×
cf. *L. radicosum* (Girty)										×
sp				×						
Dibunophyllid coral									×	
Caninia sp				×	×		×			
Aulopora sp				×	×					
Auloporoid coral									×	
Syringoporoid coral			×							
Fistuliporoid bryozoans			×				×			
Stenoporoid bryozoans						×		×		
Fenestella sp							×		×	
Polypora sp							×	×		
Penniretepora sp							×			
Rhomboporoid bryozoans						×		×		
Orbiculoidea spp										×
Derbyia plattsmouthensis Dunbar and Condra			×							
sp						×				
Isogramma millepunctata (Meek and Worthen)?										×
Chonetes geinitzianus plattsmouthensis (Dunbar and Condra)			×							×
geinitzianus geronticus Dunbar and Condra									×	
granulifer Owen								×		
Marginifera wabashensis (Norwood and Pratten)			×							
lasallensis (Worthen)			×							×
Juresania nebrascensis (Owen)			×			×		×		×
Echinoconchus moorei Dunbar and Condra			×							
sp							×			
Dictyoclostus huecoensis King										(?)
(*Pinguis*) n. sp			×							
(*Antiquatonia*) sp								×		
Linoproductus meniscus Dunbar and Condra			×							
prattenianus (Norwood and Pratten)			(?)					(?)		×
Productid indet		×	×							
Wellerella osagensis (Swallow)			×							×
cf. *W. dekalbensis* Dunbar and Condra										×
Spirifer n. sp			×							
sp			×							
Neospirifer dunbari King			×		(?)	×	×	×	×	
texanus (Meek)			×							
sp						(?)				(?)
Phricodothyris perplexa (McChesney)			×							
Crurithyris planoconvexa (Shumard)			×						×	×
Composita subtilita (Hall)			×		(?)	×	×	×		
sp										×
Spiriferoid indet., fragment									×	
Hustedia mormoni (Marcou)			×							
n. sp			×							
Rhynchopora illinoisensis (Worthen)			×							
Dielasma sp			×							
Paleoneilo sp										×
Nucula sp			×							×
Nuculopsis girtyi Schenck			×							
cf. *N. girtyi* Schenck										×
Nuculana bellastriata (Stevens)			×							
sp										×
Yoldia sp			×							×
Schizodus sp			×							×
Myalina (*Orthomyalina*) *slocumi* Sayre	×					(?)				
Septimyalina sp									×	
Acanthopecten sp								×		
Astartella concentrica (Conrad)			×							
sp									×	×
Allorisma sp										(?)
Edmondia sp			(?)							×
Pelecypods indet						×		×		×
Scaphopod indet										×
Euphemites vittatus (McChesney)			×							×
Bellerophon sp			(?)						×	

TABLE 1.—*Check list of megafossils and ostrocodes collected from the Graham formation in the Grosvenor quadrangle*—Continued

[Query (?) indicates the occurrence of a specimen that has been questionably identified as the genus or species. Numbers are U.S. Geological Survey collection numbers (localities shown on figure 15)]

	Bluff Creek shale member			Gunsight limestone member				Wayland shale member		
	16011	16012	15098	16014	16015	16016	16017	16019	16020	16021
Knightites (*Retispira*) sp										X
Bellerophontid steinkerns indet								X		
Amphiscapha muricata (Knight)										X
Amphiscapha? sp. indet									X	
Amaurotoma? sp									X	
Trepospira depressa (Cox)			X							X
Glabrocingulum grayvillense (Norwood and Pratten)			X							
sp										X
Ananias or *Glabrocingulum* sp. indet									X	
Ananias cf. *A. marcouianus* (Geinitz)										X
Cf. *Peruvispira* sp										X
Worthenia tabulata (Conrad)			X							
sp										X
Phymatopleura brazoensis (Shumard)			X							X
Pleurotomariacean steinkern									X	X
Neritacea? sp							X			
Goniasma? sp		X								
Stegocoelia (*Hypergonia*)? sp		X								
Murchisoniid, genus and species indet										X
Meekospira peracuta (Meek and Worthen)			X							
Ianthinopsis cf. *I. paludinaeforme* (Hall)			X							
Gastropods indet			X			X				X
Cycloceras sp			X							
Mooreoceras sp			X			X				X
Pseudorthoceras? sp										X
Euloxoceras milleri Flower			X							
Bactrites sp			X							
Liroceras aff. *L. liratum* (Girty)			X							
Metacoceras sp										X
Neoaganides grahamense Plummer and Scott			X							
Shumardites cuyleri Plummer and Scott			X							
Gonioloboceras goniolobum (Meek)			X							
Glaphyrites cf. *G. millsi* Miller and Cline			X							
cf. *G. clinei wari* Miller and Owen			X							
Schistoceras missouriensis (Miller and Faber)			X							
hildrethi (Morton)			X							
Neodimorphoceras texanum (Smith)			X							
Prothalassoceras caddoense Plummer and Scott			X							
Uddenites oweni Miller and Furnish			X							
Cavellina spp	(?)	(?)				X	X			
"*Bairdia*" cf. *B. texana* Harlton							(?)		X	
Bairdia cf. *B. beedi* Ulrich and Bassler									X	
spp	X			X	X		X		X	
Bairdiacypris cf. *B.? trojana* (Wilson)					X					
Bairdiacypris? sp							X			
Fabalicypris sp	X									
Healdia spp		(?)					X			
Kirkbya sp	X			(?)	X					
Amphissites sp., one valve									X	
Kegelites dattonensis (Harlton)							X			
Glyptopleura cf. *G. coryelli* Harlton	X									
Ostracode fragments, indet	X			X						X
Delocrinus? sp			X							
Crinoid spines										X
Crinoid columnals and plates	X		X			X	X	X	X	X
Echinocrinus spines						X	X	X		X
Fish fragment			X							

In the southern part of the Grosvenor quadrangle, the next higher limestone bed in the Bluff Creek is a bed of dark-gray ferruginous limestone, 1½ feet thick, that has been called the Bunger limestone (Cheney and Eargle, 1951). In the northern part of the quadrangle this bed is represented by two limestone units separated by shale (fig. 14). These limestone units are referred to here as units *C* and *D* of the Bluff Creek, and where they merge in the southern part of the area the single limestone is called unit *CD*. Unit *D* strongly resembles unit *CD*. Unit *C* is light-gray and locally nodular limestone that is less constant in lithology along the strike than unit *D*.

The Gunsight limestone member consists of several thin limestone units separated by shale (fig. 14). In most parts of the area two of these units can be mapped separately. The lower unit called unit *A* of the Gunsight in this report, is composed of light-gray limestone containing large numbers of horn corals. It has an average thickness of about 4 feet, but it ranges in thickness from 2 to 10 feet. The differences in thickness seem to be a result of lateral transitions into calcareous shale, much of which contains horn corals. Locally, unit *A* of the Gunsight is divided by several beds of calcareous shale.

The limestone bed called unit *B* of the Gunsight in this report is one of several discontinuous thin limestone beds near the middle of the Gunsight member, but it is distinctive in that it is clastic and at many places oolitic. Unit *B* has a maximum thickness of about 4 feet.

Unit *C* of the Gunsight is at the top of the member. Because of poor exposures, the stratigraphic relations and lateral variations of unit *C* are obscure. Apparently the unit is absent near the north boundary of the area studied. In the southern part of the Grosvenor quadrangle, 2 limestone units separated by 6 to 8 feet of shale are present at about the position of unit *C* of the Gunsight. At its most typical exposures north and west of Lake Brownwood, unit *C* is light olive gray and about 2 feet thick.

METHODS OF STUDY

The limestone units in the lower part of the Graham formation were examined by several techniques, partly to describe these beds themselves and partly to evaluate the usefulness of different methods and degrees of detail of study. The techniques included: (1) careful application of standard field methods, the detailed description of many outcrops, and measurements of many stratigraphic sections; (2) examination of freshly broken, polished, and acid-etched surfaces under a binocular microscope; (3) examination of thin sections under the petrographic microscope, with emphasis on texture and faunal content and a point count of the various constituents of more than 100 thin sections; and (4) study of insoluble residues, including X-ray-diffraction investigation of clay minerals in the residues.

Sampling was done in the field on the basis of megascopic appearance. At outcrops where a limestone unit appeared homogenous, a single sample was taken. Where a unit differed from place to place within an outcrop, two or more grab samples were collected to include conspicuous varieties of limestone within the outcrop. In all, about 225 samples of limestone representing about 170 outcrops of the lower part of the Graham were collected. Of these, 100 samples were selected for more detailed study in the laboratory on the basis of areal and stratigraphic distribution, certainty of correlation, and freshness of the sample.

In the laboratory, the samples were first examined under the binocular microscope to study features too large to be seen in thin sections, to determine the distribution of insoluble residue, and to select both typical and unusual parts of the samples for thin sections. This step was also useful in preparing for future fieldwork; features that had passed unnoticed in preliminary fieldwork were later seen in the field after noting them in the laboratory. A smoothed surface, about half of it etched with acid, was used for each binocular-microscope examination.

For point counts of the thin sections, fossil fragments were divided into general groups, such as brachiopods, fusulinids, or Foraminifera other than fusulinids, but no attempt was made to identify the fossil constituents as to genus or species. About eight categories of constituents were set up for most samples, but some of these, such as several types of fossils that had been grouped together, were subdivided by estimation after the count was completed. Experience showed that counting 200 points gave reasonably reproducible percentages.

The many possible sources of error involved in the counts of constituents have not been statistically evaluated. However, an estimate of the amount of error can be made from point counts of limestone unit *B* of the Gunsight member from locality 828. At this locality unit *B* contains a large variety of constituents and has variations in lithology that are readily observable in the field. On the basis of cursory field examination three unit *B* samples were taken, Nos. 828–17, 828–18, and 828–19, each representing a different part of the unit and each composed of chips that seem to include all variations of lithology within that part of unit *B*. Two thin sections were made from each sample. Each thin section was described and point counted and then put aside for more than a year before being point counted again.

These 12 point counts are summarized in table 2. They are considered to show maximum differences between two counts of the same thin section, because the counts were made at widely different times on thin sections that are difficult to count. They are considered to show maximum differences between thin sections of the same sample, because they represent the samples that more than any others show obvious intra-sample diversity under megascopic examination. The samples represent parts of a limestone unit with differences that can be seen in the field; other units should give much better reproducibility.

TABLE 2.—*Percentage composition of unit B of the Gunsight limestone member of the Graham formation from point counts of three samples from locality 828*

[Samples 828-17, -18, and -19 were taken near the bottom, middle, and top, respectively, of a 2½-ft limestone unit. For each sample, thin-sections 1 and 2 were ground from chips chosen to show the variation within each sample. Count B of each thin section was made more than a year later than count A]

Constituent	Sample 828-17				Sample 828-18				Sample 828-19			
	1		2		1		2		1		2	
	A	B	A	B	A	B	A	B	A	B	A	B
Clear calcite cement	45	45	35	45	55	55	60	60	55	50	45	40
Calcite matrix	17	12	30	22	----	----	----	----	----	----	----	----
Unidentified fragments composed of calcite mosaics	15	12	15	12	----	----	----	----	----	----	----	----
Reworked limestone fragments	7	10	5	5	13	16	12	10	20	25	30	30
Foraminifera	4	3	2	2	2	2	1	2	1	2	1	2
Dasycladacean algae	1	2	2	2	5	3	2	2	1	1	3	4
Echinoderm fragments	3	3	3	2	3	5	4	5	12	10	4	4
Other fossils	8	13	8	10	15	15	10	6	8	7	12	10
Oolites	----	----	----	----	7	4	3	5	3	5	5	10
Quartz silt	----	----	----	----	----	----	8	10	----	----	----	----

Despite these handicaps, the data in table 2 show that differences between 2 point counts of the same thin section are small and that, in general, differences between 2 chips from the same sample are only slightly greater. However, differences between samples are greater still and may be large. Rocks that appear similar in the field prove to be very similar in thin section, and rocks that appear different in the field prove to be different in thin section.

In addition to differences between thin sections and errors inherent in point counts, table 2 indicates differences that can be attributed to procedure and identification. Many of the percentages of the more abundant constituents were rounded to the nearest 5 percent. This procedure increases apparent differences in some counts and reduces it in others. Some particles are difficult to identify, especially in poorly preserved parts of the slide. On the basis of the operator's judgment, others could be assigned to more than one category; for example a reworked fossil could be assigned to "fossils" or to "rock fragments."

Because mistakes in identification are undoubtedly present, statistical analysis of errors is impossible (Chayes, 1956, p. 51-53). Although the potential errors in the point counts may be large from the viewpoint of the statistician, the results should be considerably more accurate than the qualitative descriptions or visual estimates commonly used in carbonate studies. The point counts have all been made by the same operator using the same method; therefore, differences between beds and between samples should be more accurately represented than the absolute composition of individual samples.

Another source of sampling error perhaps should also be mentioned at this time, although its importance cannot be evaluated. Whether or not a bed crops out at a given place is in part dependent on its resistance to erosion. Thus the distribution of outcrops, as well as the selection of samples from these outcrops, may introduce errors. Argillaceous limestone seems to be less resistant to erosion than sandy or relatively pure limestone and may not be represented adequately either by samples or in outcrops.

Insoluble residues were obtained from chips of the same pieces of rock from which the thin sections were ground. After removal of all weathered material, the sample was crushed and dissolved in about 10 percent hydrochloric acid. The sample was kept in the acid until well after the effervescence had stopped, usually about 24 hours, and the strength of the acid was maintained by adding concentrated acid. Some of the insoluble residues were stored in glass vials and examined later, but those examined while still on the filter paper were easier to describe and better retained such delicate structures as partially silicified Foraminifera. The insoluble residues were examined with the aid of the binocular microscope, except for occasional checks of individual constituents with the petrographic microscope. The abundance of various constituents was estimated but not measured.

Insoluble residues of some typical samples were studied by X-ray diffraction methods. The X-ray procedure used in described on page 107.

An additional technique that has been used in making detailed studies of limestone samples is the preparation of acetate peels or replicas. This technique produces an impression of the slightly etched limestone surface on a clear sheet of cellulose acetate (Sternberg and Belding, 1942). Acetate replicas were made for only a few of the samples because the additional information gained did not seem to justify making peels for all of them.

The relative merit of the various methods of carbonate study varies, of course, for different types of carbonates, different areas, and different objectives and training of the worker. From the present study, however, field studies and qualitative examination of thin sections seem still to be the most important techniques. The types of limestone distinguished on the basis of detailed laboratory study are essentially the same as would have been set up by field methods alone, and the interpretation of these types is the same as would have been reached by a combination of field methods and qualitative thin-section study. Other methods proved to be very valuable for limited numbers of samples or for special problems but were unnecessary as part of a standard procedure for all samples.

Point counts of thin sections are valuable in two respects. First, they give quantitative percentages of constituents, and a few point counts of a suite of thin sections quickly emphasizes how inaccurate visual estimates can be. Second, they are valuable in forcing the observer to make at least some sort of an interpretation of every point on the thin section that falls beneath the cross hairs during the count. Some objects, of course, must be counted as unknown, but the effect of forcing even this decision from the petrographer is very effective in combating the tendency to ignore the unrecognized particles or postpone their identification. Point counting every slide can be very time consuming, however, and does not seem to be necessary. Probably counting a few slides from each unit is all that is worth the time spent, except for special cases.

The qualitative examination of many more thin sections seems profitable. Commonly, all the important evidence obtained from a thin-section study can be demonstrated from relatively few slides, but equally commonly many slides must be carefully examined before one containing critical evidence is found. Many problems of genesis of constituents and of sequence of events can be solved only by thin-section studies.

Acetate replicas require less time to prepare than thin sections and can be easily made for large surfaces. In some types of limestone, textures are more easily seen in replicas than in thin sections because thin sections are thick enough to contain several superimposed layers of the finest particles. The replicas are not a satisfactory substitute for thin sections, however, because mineral identifications are more difficult, or even impossible, and because certain types of textures are shown best by color differences not transferred to the acetate.

The preparation of insoluble residues has proven very valuable in carbonate study, although the number of residues needed differs for different types of investigations. Insoluble residue is not only a feature of the rock that can be easily obtained quantitatively, but it gives a concentration of material that may be overlooked in thin section.

The study of clays from the insoluble residues by X-ray techniques is time consuming and the results difficult to interpret. Until more basic information is acquired by specialists, clay-mineral studies do not seem to be of value as a standard procedure in carbonate investigations. Study of a few samples from each suite may prove of value and, at present, adds basic data about clay minerals that may eventually be important.

Mechanical analysis of insoluble residues also seems to be too time consuming in terms of the value of the data obtained. Study of heavy minerals of a few samples is of great value in determining source area, if sufficient sand is present in the residues. The light minerals also are well worth study for some samples.

Insoluble-residue studies are incomplete without examination of etched hand specimens under the binocular microscope to see the distribution of the residue in the rock. Study of etched hand specimens is also valuable (1) for recognizing different types of carbonate, such as dolomite in a calcitic limestone, and seeing their distribution; (2) for seeing the three-dimensional shape of features that are puzzling in thin section; (3) for becoming familiar with the rocks to prepare for additional fieldwork; and (4) for selecting chips for thin sectioning. Minerals that are difficult to identify can be picked free from the etched surface and identified with a petrographic microscope and index oils.

CONSTITUENTS OF THE LIMESTONE

The limestone in the lower part of the Graham formation is composed of various combinations of the following constituents: Microcrystalline-calcite ooze; sparry-calcite cement; fossils; ooliths; pellets; reworked limestone fragments; terrigenous sand, silt, and clay; and authigenic minerals. This terminology is used throughout the report and is, in general the terminology first defined by Folk (1959) in his practical petrographic classification of limestone.

The calcite of the limestone is of two main types: (1) Calcite in discrete aggregates that existed as such even before formation of the rock, and (2) calcite of probable chemical origin that fills the space between the aggregates. These two categories have been respectively termed allochemical constituents and orthochemical constituents by Folk (1959, p. 4, 7). By analogy with noncarbonate sandstone, the aggregates may be considered as grains and the rest of the calcite as matrix or cement. The aggregates, or "grains," may be fossils that have been moved or have grown in place, reworked fragments of older limestone (intraclasts of Folk), or any other type of aggregate of carbonate crystals that occurs as a particle distinguishable from the surrounding carbonate. The matrix of the limestone consists of microcrystalline calcite ooze of uncertain and probably complex origin that, like the clay matrix of noncarbonate sandstones, can form the entire rock if no aggregate particles are present. The cement of the limestone is clear, or "sparry," calcite that is not only analagous to the calcite cement in noncarbonate sandstone but is virtually identical to it. Sparry calcite can also form as a void filling or as a product of recrystallization.

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CALCITE OOZE

Calcite ooze, as the term is used herein, refers to microcrystalline calcite that appears dusty or imperfectly translucent in thin section because of its fine particle size. Ooze is described by Folk (1959, p. 8) as having grains 1 to 4 microns in diameter.

Slightly coarser (5 to 15 microns) and slightly clearer calcite, apparently formed by slight recrystallization of ooze, is called microspar by Folk (1959, p. 32). Many samples of limestone from the Graham formation contain some microspar, part of which has crystals larger than the 5- to 15-micron size given by Folk. This microspar is intermixed with ooze and is difficult to differentiate from it because of intergradation.

Much of the ooze is intermixed with very fine poorly preserved remnants, or "ghosts," of carbonate fragments whose outlines are too vague to differentiate them from ooze in point counts. Percentages of matrix given in the descriptions of limestone therefore include an unknown amount of coarser particles in addition to ooze.

Many possible modes of origin of ooze have been suggested and discussed (Cloud and Barnes, 1948, p. 84–89). It seems certain that ooze forms in several ways, but exactly how and in what relative amounts is still unsolved. The most recent suggestion was by Lowenstam (1955), who called attention to widely distributed calcareous algae that are weakly calcified with tiny aragonite needles that dissociate after the death of the plants. Lowenstam and Epstein (1957) reinforced this possibility with determinations of isotope ratios of carbon and oxygen from several types of carbonate sediment from the Bahama Bank. The ratios for sedimentary aragonite needles correspond more closely to the ratios for needles from algae than to those from inorganic sediment.

Quantitative study of the composition of limestone emphasizes the large amount of ooze in carbonate rocks and emphasizes the importance of determining its mode of formation if the origin of limestone is to be understood.

SPARRY CALCITE

Sparry calcite, as the term is used herein, is composed of crystals coarser than 0.02 mm that appear in thin section as clear mosaics. Sparry calcite occurs as (1) cement, (2) vein filling, (3) recrystallized or replaced fossil fragments, and (4) recrystallized ooze. Not all sparry calcite can be definitely interpreted as to origin.

Sparry cement is generally found in samples that contain little fine clastic material. These samples are characterized by relatively good sorting and rounding of sand-size calcareous fragments and by the presence of ooliths and quartz sand. In other samples, small areas of cement are localized near the coarsest fossil fragments, where bridging of relatively coarse debris left voids not filled with ooze. Sparry calcite has filled most hollow fossils, but carbonate mud has sifted into some of them.

Sparry-calcite vein fillings occur largely in what appear to have been shrinkage cracks, although some may be later features formed by compaction or by minor structural movements. In general, the veinlets are short and discontinuous, indicating an orgin in unconsolidated or incompletely consolidated sediment. Some veinlets in limestone unit *C* of the Gunsight member seem to have been filled in two stages, and in the last stage calcite did not completely fill all the openings. The first stage of filling is represented by a relatively finely crystalline drusy fringe radiating into the veinlets from the sides. The second stage is represented by coarse anhedral calcite in the center of the veinlets. In one slide barite has partially replaced calcite filling of the second stage. In some veinlets in other limestone samples the sparry calcite may have been introduced in two stages, but the two generations of calcite are not as distinctive as in unit *C* of the Gunsight.

Many recrystallized or replaced fossil fragments belong to groups believed to have had shells composed largely of aragonite, such as gastropods and pelecypods. Nevertheless, some coralline algae have been recrystallized, and modern coralline algae precipitate only calcite. Perhaps some early coralline algae were aragonitic or perhaps their recrystallization was caused by high initial porosity or other factors. That they were recrystallized rather than leached and refilled is shown by the fact that some of them retain ghosts of cell structure crossed randomly by the anhedral sparry calcite of which the fossils are now composed (pl. 33, fig. 2).

Recrystallization of ooze seems to have formed only insignificant amounts of sparry calcite. Small poorly defined patches of sparry calcite in ooze have been tentatively identified as recrystallized ooze, but such patches are scarce. Other areas in the matrix may have been recrystallized but remain too finely crystalline to be called sparry.

FOSSILS

Fossils are by far the most abundant and varied of the aggregate particles. They hold great promise as indicators of environment, although too little is known at present of the ecology of many organisms to allow complete interpretation of their environment significance. For the purpose of this report, fossils have been subdivided into groups that are practical for thin-section identification rather than a strictly biologic classification. Thus the phylum Brachiopoda is not subdivided, whereas the family Fusulinidae is considered separately from all other Foraminifera. This method of grouping is far from ideal because different species of fossils—different brachiopods, for example—may characterize very different environments. Its use is necessitated by the difficulty of making more detailed identifications in randomly oriented thin sections and by the poor preservation of many fossils.

A general idea of the fossils that have been grouped into these broad subdivisions can be obtained from table 1, although most of the collections represented in table 1 were taken from shale and thus may show a somewhat different fauna than that in the limestone. Fusulinids from the area were included in a study by D. A. Myers (1960) that gives the identifications of genera and species of fusulinids found in the limestone.

In making point counts of the constituents of the limestone samples, material within a fossil was considered to be a part of that fossil. This procedure slightly distorted the relative contribution of such hollow fossils as Foraminifera as contrasted with echinoderms (mostly crinoid columnals), but greatly simplified the process of point counting and allowed these data to be compared with information obtained megascopically or with the aid of a binocular microscope.

ALGAE

Algal fossils seen in the samples have been divided into three groups: Coralline and recrystallized algae, dasycladaceans, and oncolites.

Coralline and recrystallized algae.—Wavy stringers of sparry calcite are a common constituent of some of the limestone, especially in units *A* and *C* of the Gunsight (pl. 37, fig. 4). These stringers range in length from a few millimeters to 4 cm and average 1 to 2 mm in width. They actually are plates rather than rods but are characteristically seen as stringers both in hand specimen and in thin section.

In a few thin sections the stringers contain remnants of the cell structure of coralline algae (pl. 33, figs. 1, 2). These specimens were identified as the genus *Archeolithophyllum* by Richard Rezak (oral communication, 1957). Other sparry stringers contain no organic structure but are also considered to be coralline algae, because they are otherwise identical with better preserved algae. Within a single thin section there is a gradation from well-preserved algae to stringers with no trace of internal structure.

The algae seem to have grown primarily as crusts on a soft calcareous seabottom rather than as erect or branching forms. Most of the algae are in the samples which show no evidence of winnowing, but many probably have been moved slightly from their original position.

The destruction of the internal structure was caused by recrystallization rather than by leaching and refilling. Several specimens retain brownish ghosts of algal cell structure randomly crossed by mosaics of anhedral sparry calcite (pl. 33, fig. 2).

Dasycladaceae.—Green algae belonging to the family Dasycladaceae are present in some of the limestone samples (pl. 33, fig. 3). All of these algae seem to belong to the genus *Epimastropora* and probably are related to species from the Pennsylvanian of Kansas described by Johnson (1946). More than one species is present, but no attempt at identification was made.

Only small disk-shaped fragments averaging about 1 to 2 mm in diameter and 0.2 mm in thickness are present. The size of the fragments as well as the size of the "pores" seems to be related to species differences as well as to preservation. Internal structure is well preserved in nearly all the dasycladacean fragments; "pores" filled with ooze are clearly distinguishable, although the remainder of the fragments now consist only of sparry calcite. The dasycladaceans, unlike the other algal types, are most numerous in samples that are winnowed and sorted. They seem to have been largely restricted to areas of relatively strong currents or wave action.

Oncolites.—The term "oncolite," a modification of Pia's (1927) term "Oncolithi," has been used for laminated algal masses, commonly with no preserved cell structure, that originated as colonies not attached to an extensive hard substratum (Rezak, 1956; Maslov, 1956). Recent oncolites contain unicellular blue-green and green algae and commonly include nonagal material. The calcite of an oncolite may be merely entrapped sediment or may have been directly precipitated by the algae themselves, or they may be a mixture of the two.

Bodies from the Graham formation that have been called oncolites consist of masses of fine calcite as much as 4 mm in diameter, much smaller than such oncolites as the "algal biscuits" of modern reefs. Their distinguishing features are (1) the very fine crystal size of the calcite, making them white in reflected light and very dark gray (nearly opaque) in transmitted light; and (2) the wavy to smooth microscopic internal banding, expressed by differences in color or grain size. They have no characteristic shape; many are encrusting masses on clastic fragments and others appear to have been separate colonies. Oncolites are believed to have been formed primarily by primitive blue-green algae, but they also contain other algal forms resembling *Gir-*

vanella, irregular porcelaneous Foraminifera, and enmeshed clastic debris.

The relative amounts of the various constituents differ widely between oncolites. Some seem to have been composed almost entirely of blue-green algae and are characterized by very fine and relatively continuous banding (pl. 33, fig. 4). The porcelaneous nature of the calcite, as contrasted with a much coarser crystal size in the surrounding rock, suggests that the algae precipitated calcium carbonate themselves rather than merely enmeshing other sediment.

Some oncolites contain dark tubes similar to *Girvanella* and resemble *osagia* (pl. 33, fig. 5), as described by Johnson (1946). Johnson concluded that *Osagia* is a form genus composed of different algae and of Foraminifera and is to be distinguished only by its characteristic external form. Oncolites from the Graham formation do not have the shape or the regularity of shape needed to classify them as *Osagia*, but some seem to contain essentially the same faunal and floral elements.

Other oncolites consist of a combination of presumed blue-green algae and irregular porcelaneous Foraminifera (pl. 33, fig. 6), an association considered by Johnson (1950) to be symbiotic rather than fortuitous and referred to by him as an algal-foraminiferal consortium. The Foraminifera in consortia described by Johnson (1946, 1950) belong to the genus *Nubecularia*. The Foraminifera in oncolites from the Graham formation have not been identified. Some closely resemble *Nubecularia* as illustrated by Johnson; others represent other genera of the family Ophthalmidiidae, such as *Calcitornella*, *Orthovertella*, or *Calcivertella*.

Foraminifera of this same type also occur as separate fossils associated with little or no algal material. In descriptions of samples from the Graham formation these fossils have been included under the category "Foraminifera." The dividing line between specimens called oncolites and considered "algae" and specimens containing little algal material and included under "Foraminifera" is an arbitrary one based on the dominant type of fossil.

The oncolites also contain enmeshed clastic debris, but in most of them the volume of this enmeshed debris is small.

SMALLER FORAMINIFERA

A variety of Foraminifera are present in the lower limestone units of the Graham formation. Fusulinids are the most numerous and the most easily recognized, and they have been considered separately from the smaller Foraminifera.

Many of the Foraminifera, especially the porcelaneous irregular and encrusting forms mentioned under the discussion of oncolites, are silicified. The silicification is incomplete, however; the silicified Foraminifera have very fragile and incomplete skeletons of microcrystalline quartz. Other types of Foraminifera observed include uniserial and biserial forms; several coiled types, one of which resembles *Tetrataxis*; and single-chambered Foraminifera some of which are hat- or bell-shaped and others spherical and filled with fine radiating calcite crystals.

Smaller Foraminifera are the most widely distributed of the fossils, and almost every sample from every unit contains some. This is probably partly because the Foraminifera are so diversified and partly because unattached forms were transported after death. The attached and irregular forms are in almost every limestone sample and seem to have been adapted to a variety of environments.

FUSULINIDS

Fusulinids are numerous in many of the samples studied and are among the most readily recognizable types of fossils because of their good preservation and distinctive external and internal structure. D. A. Myers (1960) has included fusulinids from the Graham formation in his study of Pennsylvanian Fusulinidae from Brown and Coleman Counties. He reports the genera *Triticites*, *Dunbarinella*, and *Staffella* from both the Bluff Creek and the Gunsight members of the Graham formation and the genus *Millerella*? from the Bluff Creek member. *Triticites* is by far the most common genus, both in number of species and in number of individuals.

With some exceptions, fusulinids seem to be most concentrated in limestone containing the smallest number of smaller Foraminifera. They are most abundant in dark-colored, brownish-weathering limestone.

CORALS

The limestone units contain both horn corals and small colonial corals. Horn corals, most of them belonging to the genus *Caninia*, are extremely abundant within the Gunsight member, especially in limestone unit *A* of the Gunsight and in shale associated with it. Most commonly, the horn corals lie on their sides within the rock, but locally they are upright in their position of growth.

Colonial corals related to *Aulopora* are locally abundant and seem to have been less restricted by environment than the horn corals.

Although fragments of coral are present in a few thin sections, most corals occur as individuals or in colonies too large to be studied quantitatively in thin section, so percentages of corals were largely determined by estimation at the outcrop.

BRYOZOANS

Bryozoans are present in almost every limestone sample studied, but they rarely compose as much as 5 percent of the rock. At one locality, No. 835, tremendous numbers of bryozoans weather from a thin shale bed in the Gunsight member, probably between units *B* and *C*. This seems to be a unique locality in this area; no other shale exposure contains such a concentration of bryozoans.

The bryozoans are preserved mostly as small fragments representing fragile fronds or branches. Even small shreds of bryozoans can be easily recognized in thin section by their fibrous structure and brownish color.

BRACHIOPODS

Brachiopods are represented in the limestone mostly by fragments, but they can be recognized by the preserved fibrous internal structure of their shells and spines. Small numbers of brachipod fragments are in many of the samples. Because of the relatively large size of some fragments, the percentage of brachiopod material reported in each limestone sample may have an appreciable error, but most of the fragments are small enough and widely scattered enough to be counted reasonably accurately in thin section.

MOLLUSKS

Mollusks also are represented in the limestone mostly by fragments, although some small gastropods are preserved nearly intact. Most fragments cannot be identified as to biologic class from thin-section studies, but essentially all mollusks seen are presumed to be pelecypods and gastropods by analogy with the best preserved specimens seen on the outcrop. Many species of cephalopods and a few scaphopods have been collected from shale (table 1), but none have been observed in the limestone.

The internal structure of mollusk shells is not preserved, a fact attributable to inversion of aragonite in the original shell to calcite (Stehli, 1956). Mollusk fragments consist of mosaics of sparry calcite, and those having no distinctive outline are difficult to differentiate from fragments of recrystallized algae. Some of the fragments with no distinctive outlines can be tentatively identified as algae or mollusks, on the basis of their association with better preserved fragments.

ECHINODERMS

Echinoderms are represented by disarticulated fragments but are easily identified because they consist of single large calcite crystals penetrated by a well-preserved internal network. Nearly all the echinoderm fragments consist of crinoid columnals, but spines and plates of crinoids and echinoids are also present. Most echinoid and crinoid fragments could not be differentiated.

Echinoderm fragments are widely distributed in the limestone studied, probably representing both a tendency for the original animals to be widely distributed and for the disarticulated fragments to be moved locally after the death of the animal.

OTHER FOSSILS

The only recognizable fossils not included in the point counts are ostracodes. Many samples contain very small numbers of ostracodes, but they rarely constitute as much as 1 percent of the limestone.

Every sample contained fragments of probable organic origin that could not be identified because of poor preservation. Whenever possible, doubtful fragments were tentatively identified to make the percentages as complete as possible.

Some samples contain isolated fragments with organic structure that could not be identified. Many of these fragments probably are unusual sections of fossils that would have been identified in different orientations or with better preservation. Some may belong to groups not otherwise observed, such as sponges, conularids, or stromatoporoids. Well-preserved but unidentified fossils constitute less than 1 percent of the limestone and are not an important element in any of the samples.

Many samples contain round mosaics of sparry calcite averaging about 0.25 mm in diameter. These "balls" seem to be truly spherical but are difficult to observe in three dimensions because of their size. Some have a faint indication of an outer wall; others end abruptly against surrounding ooze. Probably the balls are organic in origin, but they have not been definitely identified. Perhaps they are parts of coralline algae. Their relation to the algae is suggested by their greater abundance in samples containing many coralline algae and by at least two occurrences of balls which are adjacent to and perhaps a part of algal fragments (pl. 34, figs. 1, 2). However, no unequivocal example of a ball connected to an algal fragment could be found. If the balls of sparry calcite are not parts of algae, their size and shape suggest that they may be Foraminifera.

OOLITHS

Volumetrically, ooliths constitute a minor element in the limestone, but they seem to be important as an environmental indicator. Nearly all the ooliths are in limestone unit *B* of the Gunsight member and are associated with comparatively well-sorted and well-rounded fossil fragments and with sparry-calcite cement (pl. 33, fig. 3; pl. 34, fig. 4).

The ooliths commonly have a well-developed radial structure and a faint concentric structure. The rind (nonnucleus part) of most ooliths is moderately thin, constituting on the average, about one-third of the radius of the oolith. The nuclei consist of fossil fragments, including bryozoans, crinoids, Foraminifera, brachiopods(?), and oncolites, and of microcrystalline ooze that probably represents reworked limestone fragments. At least one oolith has a quartz grain for a nucleus. For point counts, oolith nuclei were considered as part of the oolith, even if they were recognizable fossils. Most ooliths are well preserved, but in a few, ooze nuclei or the edges of the rind are slightly recrystallized into or replaced by sparry calcite. Rinds of ooliths seem to have been especially susceptible to replacement by barite, as is discussed on page 93.

In most samples, ooliths average about 0.25 mm in diameter; they are larger than most of the quartz-sand grains but smaller than many of the associated fossil fragments. Ooliths are better sorted than other clastic debris. The finest and coarsest debris have no oolitic rinds, which shows that the ooliths were formed elsewhere and mixed before final deposition with particles that were less well sorted.

Four types of evidence show that some of the ooliths have been reworked: (1) Worn ooliths; (2) fragments of oolitic limestone; (3) complete inter-mixing of ooliths with clastic debris having no trace of oolitic coating; and (4) a few two-generation ooliths, in which the original rind has been slightly worn, partly coated by probable blue-green algae, and then covered by a new rind. Although some ooliths have obviously been reworked from at least partly consolidated limestone, the reworking seems to have been local and penecontemporaneous. None of the ooliths seem to have been derived from limestone beds appreciably older than the bed in which they now occur. There are two reasons for this conclusion: (1) Ooliths are almost entirely restricted to unit *B* of the Gunsight and seem to have no adequate source in older rocks, and (2) obviously reworked ooliths are associated with virtually identical ooliths that show no indication of having been part of a consolidated rock or of having undergone more than local transportation.

PELLETS

Pellets are aggregates of microcrystalline calcite (pl. 34, fig. 3) that are characteristically ovoid. They have been interpreted as fecal pellets of invertebrates, although the term "pellet" seems used best in only a purely descriptive sense.

Pellets in the limestone of the lower part of the Graham formation constitute a very minor element of the rock, but vague relic(?) structures in the matrix of some samples suggest that they may have been more abundant before diagenetic changes. Pellets surrounded by ooze can be distinguished only by their slightly darker color. Most of the recognizable pellets have rather indistinct boundaries. The average size of the pellets is about 0.06 mm; but in some samples, such as No. 1012a, it averages as large as 0.18 mm. Most pellets are ovoid, but others are elongate or slightly irregular.

LIMESTONE FRAGMENTS

Limestone fragments in the limestone appear to consist of locally reworked pieces only slightly older than the rocks in which they occur (intraclasts, in the terminology of Folk, 1959, p. 4). Although they constitute only a minor part of the limestone volumetrically, they include a variety of rock types (pl. 34, fig. 5). The most common variety consists of sand-size fragments of microcrystalline limestone. Commonly these appear not to have been entirely lithified at the time of reworking. Many of them may have been derived from upturned edges of layers previously broken along shrinkage cracks. Small rounded fragments of microcrystalline limestone can be easily confused with pellets, but they usually can be recognized by poorer sorting as to size and shape. Like pellets, they are difficult to distinguish where surrounded by a matrix of microcrystalline calcite.

Another variety of limestone fragments is reworked fossils. Fossils that have been deposited, eroded, and redeposited obviously have little more environmental significance for the rock in which they are now found than any other rock fragment. Criteria used for recognizing reworked fossils include (1) ooze-filled chambers (as in fusulinids) or patches of ooze sticking to the sides of organisms, especially when the patch of ooze is rounded, in a rock with sparry cement (pl. 35, fig. 1), (2) rounding of the fossil, (3) broken or very poorly preserved fossils of a type commonly unbroken and well preserved, and (4) association with limestone fragments containing similar fossils. Probably all the fossils are penecontemporaneous with the limestone in which they now occur and have been moved only short distances. The dividing line between fossils considered to be virtually in place and those called reworked is an arbitrary one. Undoubtedly many of the fossils considered indigenous to the limestone have been moved slightly after death, but they are considered to be virtually in place unless they show definite evidence of reworking.

Ooliths have also been moved and some have been reworked. They are considered as reworked or not on much the same basis as fossils.

TERRIGENOUS CONSTITUENTS

Terrigenous sand and silt in the limestone consist of quartz and very small amounts of chert, feldspar, and heavy minerals. This sand appears to be identical with the sand in calcareous sandstone locally associated with the limestone, and it is described with the sandstone on page 105.

Clay minerals in the limestone cannot be adequately studied in thin section and have been examined by use of X-ray techniques. The clay mineralogy of the limestone and associated shale is discussed on page 107.

The terrigenous constituents tend to be evenly disseminated throughout the limestone, although a few samples have concentrations of silt or sand in poorly defined beds.

AUTHIGENIC CONSTITUENTS

CHERT

Authigenic chert in the limestone consists of small masses of microcrystalline quartz, most of it replacing fossil debris. The replacement of individual fragments has been very incomplete, producing lacy or spongy masses that etch out of the limestone as white very friable, commonly incomplete, replicas of the original debris. Foraminifera, especially encrusting and irregular types, are the fossils most commonly replaced.

BARITE

Barite forms small secondary masses in the limestone, most commonly replacing the rinds of ooliths (pl. 34, fig. 4) but also replacing or partly replacing fossil fragments or sparry-calcite veins (pl. 35, fig. 2). Barite occurs in all the beds studied but is most abundant in limestone beds of the Gunsight, especially unit *B*. In none of the samples, however, does barite constitute as much as 1 percent of the rock by volume, and no barite was found in many of the samples.

Barite tends to occur in scattered patches; thin sections or parts of thin sections containing a small isolated mass of barite commonly contain other masses nearby. Barite masses could not be related to joints or unusually porous parts of the limestone.

One of the most interesting barite occurrences is in sample 721, from an outcrop of unit *B* of the Gunsight not otherwise studied in detail because exposures are much less complete than at locality 828 about 0.3 mile to the southwest. This oolitic sample contains barite within irregular patches a few millimeters in diameter (pl. 34, fig. 3). All the barite within each of these patches is in optical continuity, although it constitutes only a small percentage of the rock within the patch. The optical continuity within these patches is particularly striking, because barite is largely limited to rinds of ooliths, most of which are not in contact with the plane of the thin section. However, by dissolving the limestone in dilute hydrochloric acid, it was found that all the barite in each patch is interconnected in three dimensions. The barite residue of the dissolved limestone resembles a loosely connected pile of hollow BB shot. This strong crystallizing power of barite is also shown by the fact that a single barite crystal replaces a sparry-calcite veinlet (pl. 35, fig. 2).

IRON MINERALS

Iron-bearing minerals in the limestone, including limonite, hematite, pyrite, and ankerite, are closely interrelated. Probably most, if not all, of the iron was an original constituent of the limestone and has been moved only locally to form the present authigenic minerals.

Ankerite is a very minor constituent of the limestone (pl. 35, fig. 3). Rhombs about 0.06 mm long were etched free from a smoothed surface of one sample (No. 828–11) and were checked in an index oil under the petrographic microscope. In these rhombs the ordinary ray had an index of about 1.71, which corresponds to the index of ankerite containing about 20 to 25 percent iron. The ankerite rhombs occur within sparry calcite in recrystallized fragments of probable coralline algae. The presence of a small amount of ankerite in sample 839–3 was confirmed by scanning a chip of the sample in an X-ray spectrometer. Similar rhombs in other samples are probably ankerite also, although some may be dolomite. In only one sample was ankerite (or dolomite) present in more than trace amounts.

Some of the ankerite rhombs are fresh, but others have weathered to a friable skeleton of limonite. In some samples, weathering to limonite indicates that the rhombs are zoned (pl. 35, fig. 5). Many weathered rhombs contain considerable amounts of limonite in their centers and in their outer edges but only little limonite in an intermediate zone. The concentration of limonite in the outer edges may be due entirely to weathering, but limonite centers in weathered crystals indicate that the rhombs were more ferruginous at their centers.

Pyrite has been observed in only a few samples, but it probably is a very finely disseminated constituent in all the dark-gray limestone. No other iron mineral has been observed in many unweathered dark-colored limestone beds, but they characteristically weather to a limonite-stained surface. Light-gray limestone beds have very little limonite on weathered surfaces.

Although much of the pyrite may be finely disseminated, crystals are visible (cubes, pyritohedra, and octahedra) and partly replace some fossils. Most pyrite crystals are 2 to 5 microns across, but a few are as large as 20 microns.

Hematite occurs as an alteration product of pyrite, some of it as pseudomorphic cubes. Locally hematite is slightly concentrated near weathered surfaces, so at least part of the pyrite-to-hematite alteration is probably due to modern weathering. More severe weathering has altered both hematite and pyrite to limonite.

Hematite also occurs as diamond-shaped crystals (pl. 35, fig. 4), averaging about 0.08 mm long by 0.03 mm wide. These crystals replace grains, matrix, and sparry cement.

Limonite is by far the most abundant iron mineral in the limestone. Actual amounts of limonite are difficult to estimate in many samples because small amounts of limonite stain much larger quantities of other mineral. This effect is especially troublesome in estimating the amounts of clay versus limonite in insoluble residues. All the limonite seems to have formed by alteration of other iron minerals mostly during modern weathering.

OTHER MINERALS

Some samples contain traces of psilomelane(?) as tiny feathery masses. The psilomelane is closely associated with some of the limonite and seems to be a product of modern weathering.

Collophane occurs as a very few grains in only a few thin sections. Most of the collophane appears to be primary and clastic and probably represents pieces of small phosphatic shell fragments.

DESCRIPTION OF LIMESTONE UNITS OF THE GRAHAM FORMATION

The following descriptions will treat each limestone unit with respect to outcrop distribution, description of a representative thin section, variation between samples, and types and amounts of insoluble residue.

Data on the distribution of fossils and insoluble residues as determined from thin-section point counts are summarized on plate 31. Diagrams representing individual samples are arranged to show both bed-to-bed and areal variations. Where more than one sample of a bed was taken at an outcrop, the results of point counts were averaged to represent that bed at that outcrop. A separate diagram (pl. 32) is given to summarize the point-count data of the many individual samples of unit *A* of the Gunsight that were averaged in compiling plate 31.

LIMESTONE UNIT A OF THE BLUFF CREEK SHALE MEMBER

Unit *A* of the Bluff Creek is the least well exposed and the least persistent of the limestone units studied in the lower part of the Graham, so its precise areal extent and, to some extent, its stratigraphic relations are very difficult to determine. The unit is exposed in four separate parts of the Grosvenor quadrangle: (1) On the north and south shores of Lake Brownwood, just east of the bridge of State Highway 279 (fig. 15); (2) north of Park Road 15, 4 miles east of State Highway 279; (3) in the vicinity of the town of Byrds; and (4) about 2.5 miles south of the northeast corner of the quadrangle.

The separation of the outcrop pattern of unit *A* appears to be the result of lack of outcrops, original lack of continuity of the bed along the present line of outcrop, and channel cutting. The importance of channel cutting is difficult to evaluate. Channel-fill sandstone beds are present in the lower part of the Bluff Creek shale member in several parts of the quadrangle, but nowhere can they be seen to relace limestone unit *A*. Rocks in the lower part of the Bluff Creek member in other parts of the quadrangle differ from place to place along the strike and may be, in part, additional channel-fill deposits. In general, however, the present lack of continuity of unit *A* seems to reflect lack of continuity of the bed at the time of deposition.

Limestone unit *A* of the Bluff Creek is about 5 feet thick where it is well developed. It is typically medium to thick bedded, although in a few highly weathered exposures it seems thin bedded. At one outcrop in the northern part of the quadrangle, the unit is crossbedded with an amplitude of as much as one foot. The limestone is fragmental, commonly coarse grained, and contains fine-grained quartz sand. It overlies a sandstone bed that is calcareous at most outcrops. Both the sandstone and the limestone are more calcareous toward their tops, although at many outcrops the contact between calcareous sandstone and sandy limestone is marked by a bedding plane and a discontinuity in the relative amounts of quartz and calcite.

Unit *A* is light gray and weathers medium gray or light brown. It contains considerable finely broken fossil debris, most of which could not be identified, and locally contains fusulinids, encrusting Foraminifera, and fragments of crinoids, brachiopods, and bryozoans (pl. 31). Some fossil fragments show evidence of reworking, perhaps from older limestone beds but more probably from locally reworked penecontemporaneous parts of the unit.

Because the unit is very different petrographically in different places, no one thin section can be considered entirely typical of the unit, but the following thin-section description of 1 of 2 samples of unit *A* from locality 1012 is reasonably typical (pl. 36, fig. 1). Information on the amounts of various organic and insoluble constituents in other thin sections can be seen on plate 31.

Sample 1012-2, limestone unit A of the Bluff Creek member

Texture

Comparatively well sorted organic carbonate debris, averaging about 0.3 in diameter, in a matrix of calcite ooze and finely crystalline cement. Fragments have only a slight tendency for preferred orientation parallel to the bedding: there is no microbedding or lamination. Shows evidence of the following five-stage depositional history of leaching and filling:

1. Leaching of part of the coarse clastic debris, matrix virtually unaffected. Much of leaching occurred in the fragments that were originally at least partly aragonite (mollusks particularly), as evidenced by distinctive outlines of the leached grains.
2. Calcite deposited as a very fine druse lining pores.
3. Complete filling of remaining voids by very coarse calcite. Some voids were filled by a single crystal that is in optical continuity with similar crystals filling adjacent voids not touching them in the plane of the thin section. Thus a single crystal extends through more than one void in a way comparable to "luster mottling" in sandstone.
4. Replacement of some coarse sparry calcite by a few thin scattered rhombs of ankerite.
5. Leaching, again largely restricted to coarse clastic grains rather than to matrix. This last stage of leaching seems to have occurred very late in the limestone's history (no sign of druse lining pores) and probably was caused by Recent weathering. Slight limonite stain lining some of the pores shows that the pores were not formed by "plucking" during preparation of the thin section.

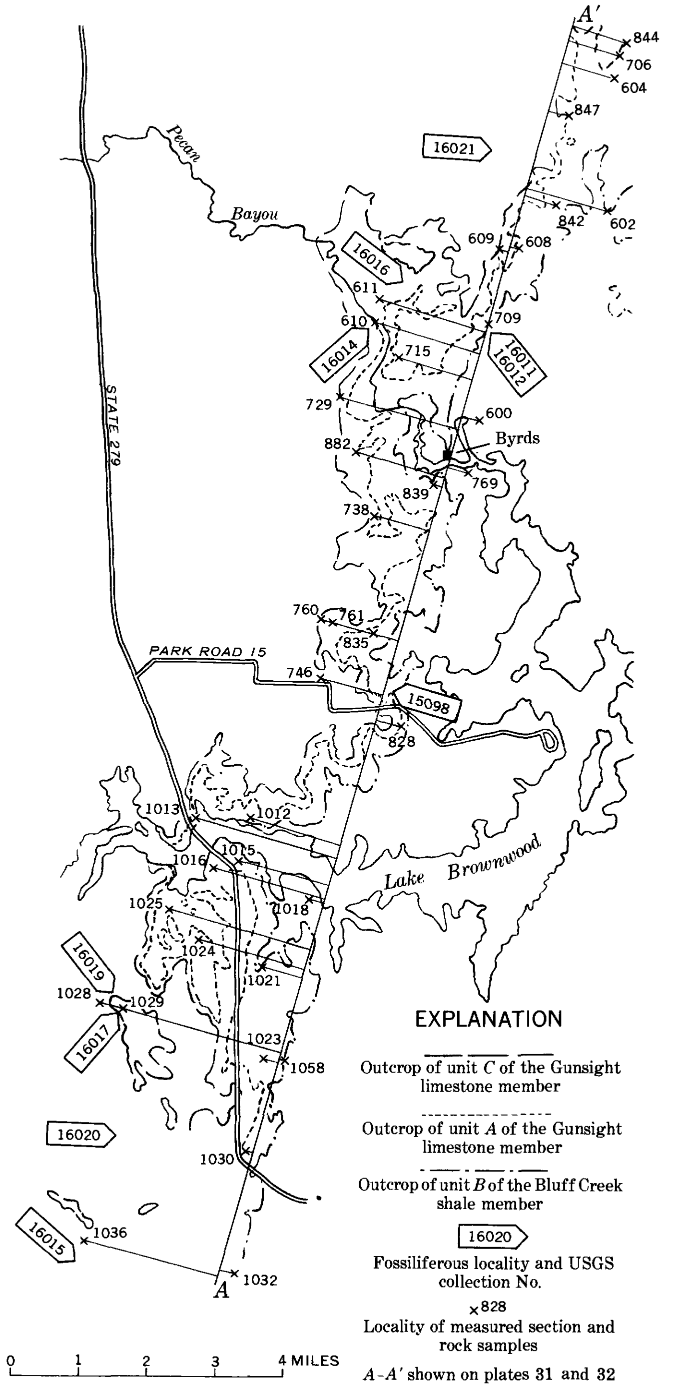

FIGURE 15.—Map of the eastern part of the Grosvenor quadrangle showing location of sample localities in relation to the generalized outcrop of limestone unit *B* of the Bluff Creek shale member of the Graham formation, and limestone units *A* and *C* of the Gunsight limestone member of the Graham formation.

Composition (from point count of 200 points)

	Percent
Matrix	52
Calcite mosaics (replaced fragments)	15
Unidentified dark fragments (reworked limestone(?))	5
Smaller Foraminifera	2
Bryozoans (fragments)	12
Echinoderms (fragments)	10
Other fossils	3
Porosity	1
Secondary chert	Trace
Barite	Trace
Hematite and limonite	Trace
Psilomeane(?)	Trace

Description of constituents

Matrix: Mixture of cement (crystal size averaging about 0.02 mm) and ooze except in small areas that contain only ooze—this suggests that part of the "cement" is recrystallized ooze. Contains a few "ghosts" of unidentifiable clastic debris.

Sparry-calcite mosaics: About one-third of the leached and refilled fragments have outlines suggesting small pelecypod and gastropod shells. The others have no distinctive outlines and remain unidentified.

Unidentified dark fragments: Very finely crystalline fragments, some of which probably are fragments of reworked limestone and others are poorly preserved fossils.

Smaller Foraminifera: A variety of types; most are poorly preserved; includes two small fusulinids.

Bryozoans: Broken and slightly rounded fragments of fenestellid types.

Echinoderms: Fragments, some of which have ragged edges due to solution; others have overgrowths in optical continuity.

Other fossils: Included are very small amounts of very small gastropods, coral fragments (*Aulopora*-like), ostracodes, and Dasycladacean algae resembling *Epimastopora*. Many are broken and some are rounded. Several have a filling of ooze that seems to have been in fossils before transportation.

Porosity: See "Texture".

Secondary chert: Microcrystalline quartz replaces a foraminiferal shell and also probably fills a small pore.
Barite: Replaces a single foraminiferal shell.
Hematite and limonite: Scattered very small secondary grains.
Psilomelane(?): Small feathery secondary patches of material that is dull dark gray to black in reflected light and opaque to transmitted light.

Other thin sections of unit *A* are similar to the one described previously (sample 1012–2), but they contain very fine quartz sand. Binocular-microscope examination of etched surfaces many times the size of a thin section revealed that sample 1012-2 also contains traces of very fine sand. Each of the unit *A* samples studied in thin section have (1) a matrix of ooze intermixed with coarser calcite; (2) fossils of the types described previously, in which many individuals are broken and abraded; (3) fragments representing probable reworked limestone, (4) at least suggestions of slight post-deposition solution; and (5) various degrees of preferred orientation of larger fragments parallel to the bedding. In one thin section quartz sand was seen within a reworked limestone fragment. The percentage of sand in this fragment was much greater than in the surrounding rock. In one sample a few rhomb-shaped "ghosts," probably of ankerite, are represented by limonite with calcite centers. The original rhombs replaced part of the matrix.

Insoluble residues of samples from unit *A* of the Bluff Creek ranged from 1.3 to 7.2 percent of the rock with a median of 4.7 percent. One insoluble residue contains a fragment of well-sorted fine-grained sandstone. The other residues consist mostly of clay, small spongy masses of limonite and hematite, and very fine grained sand. The residues contain traces of secondary chert, mostly in the form of fragile incompletely replaced Foraminifera, and a few small flakes of detrital mica.

LIMESTONE UNIT B OF THE BLUFF CREEK SHALE MEMBER

Limestone unit *B* of the Bluff Creek is better exposed and more persistent than unit *A*. However, outcrops are too scattered and lithologic characteristics and stratigraphic intervals are too inconsistent to map the bed accurately without very careful and detailed fieldwork. Even then, it is possible that several limestone lenses in about the same part of the section, rather than a single bed, constitute unit *B* of the Bluff Creek.

The unit can be traced over most of the Grosvenor quadrangle with a reasonable degree of assurance, but north from the northernmost tip of Lake Brownwood, mapping and definite correlation of unit *B* is more tenuous. In part of this area, near the east edge of the quadrangle, unit *B* has been removed by erosion.

At many places, especially in the northern part of the quadrangle, unit *B* is underlain by sandstone; elsewhere it is underlain by gray silty to sandy shale. The most typical lithology of the unit is dark-gray limestone weathering yellowish brown and containing many fusulinids. It is thick bedded at most outcrops and commonly is a single bed about 1½ feet thick.

A typical thin section of unit *B* of the Bluff Creek is difficult to choose because the samples differ widely. Sample 1012-3 (pl. 36, fig. 2) is described below as an example which is believed to be reasonably representative.

Sample 1012-3, limestone unit B of the Bluff Creek member

Texture

A jumble of unsorted organic debris and scattered very fine quartz sand in a matrix of ooze and fine-grained cement. Larger particles have only a suggestion of preferred orientation parallel to the bedding; there is no microbedding. Quartz sand is evenly distributed through the slide.

Composition (from point count of 200 points)

	Percent
Matrix	65
Sparry-calcite mosaics	4
Fusulinids	5
Echinoderms (fragments)	7
Other fossils	17
Quartz sand	1
Secondary chert	Trace
Limonite	1
Rhombic pseudomorphs	Trace
Collophane	Trace

Description of constituents

Matrix: Granular-appearing limonite-strained ooze intimately mixed with finely crystalline cement and fine fossil debris.
Sperry-calcite mosiacs: Circular and elliptical patches of clear calcite; probably recrystallized fossils. Percentage does not include patches of cement or mosaics with distinctive outlines that allow them to be identified definitely as fossils.
Fusulinids: Mostly well preserved, but a few are broken and others partly replaced by fine calcite.
Echinoderm: Fragmented, not badly—few overgrowths.
Other fossils: Include many smaller Foraminifera and unidentified shell fragments (each estimated to compose roughly 5 percent of the slide), brachiopods and bryozoans (each estimated to compose about 3 percent of the slide), and a few ostracodes.
Quartz sand: Average grain size about 0.15 mm, fairly well sorted, subangular. Most of the quartz has only slight strain shadows; some is strongly strained quartz of probable metamorphic origin. Includes a trace of detrital chert.
Secondary chert: Small masses of microcrystalline quartz replace clastic debris.
Limonite: Occurs partly as stain on other minerals, partly as disseminated hematite and limonite grains. Widespread stain on other constituents makes the amount of limonite appear much larger than it really is.

Rhombic pseudomorphs: "Ghosts" of ankerite(?) composed of limonite and carbonate with limonite rims; carbonate is in optical continuity with surrounding calcite. Some rhombs have been leached to hollow limonite pseudomorphs.

Collophane: Scattered small shell fragments(?).

Amounts of sand, clay, and the various organic constituents in samples studied of the unit *B* of the Bluff Creek are shown on plate 31. Most of the samples have similar texture, but samples 709–3 and 600–2, both unusually sandy, and sample 1032, which contains a sandy-limestone fragment, contain sparry-calcite cement with little or no admixed matrix of ooze. All the samples contain clastic quartz, most of it as fine to very fine sand. Several samples contain clots of ooze that may be of organic origin but probably are pieces of inorganic sediment reworked from the sea-bottom before lithification. Reworked fusulinids are present in samples 1018–2 and 1058–1. Sand is most abundant in the northern part of the area, but intraclasts and reworked fossils are numerous in the southern part.

Some of the quartz grains in sample 839–2 have a thin coat of calcite ooze (pl. 36, fig. 3). These coats have a vague concentric structure and appear to have formed by rolling about of the grains in carbonate mud.

Insoluble residues of unit *B* range from 2.1 percent of the rock in sample 1032 to 37 percent in sample 709–3, with a median of 10.0 percent. They consist of sand, silt, clay, and limonite with smaller amounts of hematite, pyrite, and authigenic chert. The sand consists almost entirely of quartz but also contains traces of orthoclase, sodic plagioclase (almost completely unweathered), muscovite, and tourmaline. Most of the quartz has nearly straight extinction, but some of it has moderate to extreme undulose extinction. Quartz grains in several of the samples have prominent overgrowths, and in two of the samples the overgrowths seem to have been slightly abraded. The abraded overgrowths must have been reworked, but most of the overgrowths appear to have formed in place. Hematite occurs as tiny subsequent masses and as small disseminated rhombic crystals. Pyrite occurs as scattered small cubes and, in sample 1018–2, as replacement of an encrusting foraminifer and a bryozoan fragment. The chert has imperfectly replaced Foraminifera and other small clastic grains to form lacy or spongy masses.

LIMESTONE UNIT C OF THE BLUFF CREEK SHALE MEMBER

Limestone unit *C* of the Bluff Creek is exposed in many places, because overlying unit *D* is a resistant bed that forms the top of a bench. Unit *C* itself is not as resistant to erosion and so its many exposures characteristically show only part of the bed. The exposed thickness ranges from 1 to 7 feet, but the total thickness may be as much as 10 feet in some places.

At many places, especially near the middle of the area mapped, unit *C* has wavy bedding planes and weathers to nodules 1 to 3 inches in diameter. The limestone is light gray except at locality 604, where it is medium dark gray, and at locality 835, where the upper part of the unit is medium gray and strikingly mottled with dark yellowish orange. Under the hand lens, the texture is difficult to interpret, but the limestone appears to be finely clastic, containing ooze and finely ground fossil debris mixed with poorly preserved small fossil fragments. Fusulinids are distributed erratically in unit *C* of the Bluff Creek and are much less prominent than in the underlying unit *B* or the overlying unit *D*, but smaller Foraminifera are present in virtually every outcrop of unit *C*.

The thin section of sample 1013–1 (pl. 37, fig. 1) is typical of the unit *C* samples studied.

Sample 1013-1, limestone unit C of the Bluff Creek member

Texture

Ooze containing many smaller Foraminifera and recrystallized shell fragments. Has only a suggestion of preferred orientation of clastic particles parallel to the bedding and no microbedding.

Composition (from point count of 200 points)

	Percent
Matrix	70
Sparry-calcite mosaics	14
Smaller Foraminifera	5
Fusulinids	2
Echinoderms (fragments)	2
Other fossils	7

Description of constituents

Matrix: Ooze partly recrystallized to microspar and contains poorly defined pellets and finely broken and poorly preserved fossil debris. In one place only, very fine dusty-appearing calcite has banding and slightly wavy structure visible only under a high-power microscope; this suggests that sediment-binding algae coated the seabottom rather than only a particular fragment. The wavy bands contain some enmeshed fine clastic debris.

Sparry-calcite mosaics: Probably most are recrystallized fossil fragments (predominantly mollusks?), but some mosaics are irregular in outline and discontinuous. These mosaics are probably inorganic and perhaps filled the shrinkage cracks. Average crystal size is about 0.15 mm.

Smaller Foraminifera: Most are porcelaneous encrusting and irregular forms; a few small uniserial Foraminifera and a very few coiled forms are included.

Fusulinids: Slightly broken, with alveolar structure of the walls replaced by microcrystalline calcite.

Echinoderms: Small fragments of crinoids and echinoid spines.

Other fossils: Include mostly small fragments of bryozoans, but also a few brachiopod spines and a few ostracodes and small gastropods.

Differences between samples of unit *C* of the Bluff Creek, in addition to those shown on plate 31, include variations in texture and in amounts of unidentified sparry-calcite mosaics and of minor mineral constituents, such as hematite and limonite. The texture of most samples, like sample 1013–1 described above, is that of unsorted debris with only a suggestion of preferred orientation in a matrix of calcite ooze. Samples from four localities, Nos. 715, 828, 1018, and 1021, have a matrix containing both ooze and sparry-calcite cement. In samples 828, 1018, and 1021 the ooze and cement are somewhat segregated into poorly defined microbeds about 2 to 3 mm thick. Parts of the thin sections containing relatively large amounts of clear cement in relation to ooze have better sorting and orientation than areas containing only ooze. This indicates that the clear cement originated by filling open pores rather than by recrystallization of ooze.

Nearly all samples of unit *C* are characterized by poor preservation of most fossil constituents and by indistinct texture in their finest grained parts. Several samples contain poorly defined pellets and at least one had a suggestion of small borings. Perhaps at least part of the relative lack of preservation of the smallest constituents was caused by reworking of the sediment by scavenging organisms. Other types of post-deposition alteration are evidenced by calcite veins, some suggesting shrinkage cracks, by considerable replacement and recrystallization of larger shell fragments, and by numerous narrow idiomorphic rhombs of hematite. Some samples contain a trace of ankerite and rhombic pseudomorphs of limonite. The parts of the thin sections containing the largest amounts of ooze in relation to sparry cement seem to have the largest amounts of sparry-calcite mosaics and to contain the greatest number of calcite veins.

Insoluble residues are small in most samples of unit *C* of the Bluff Creek, the amounts ranging from 1 to 5.4 percent of the rock, with a median of 3.0 percent. All the residues contain clay and at least a trace of very fine sand (31). Nearly all contain small irregular masses of limonite, hematite, and secondary chert. Some also contain traces of psilomelane and barite. Sample 847–1 contains small aggregates of very fine pyrite crystals and sample 715 contains tiny diamond-shaped hematite crystals and a few scattered rhombs of ankerite(?).

The sand grains of the insoluble residues are well sorted and subrounded in every sample. The average size of the sand grains is about 0.07 mm. In one of the sandiest samples, sand grains are locally clustered and seem to represent reworked calcareous-sandstone fragments. Another sample contains small angular chips of hard gray shale.

LIMESTONE UNIT D OF THE BLUFF CREEK SHALE MEMBER

Limestone unit *D* of the Bluff Creek is the most persistent unit along the strike and the most consistent in appearance of any of the beds studied. It caps a topographic bench at many places and commonly is exposed as large blocks or slabs 1 to 1½ feet thick lying atop or on the edge of the bench. Rocks above and below unit *D* are rarely well exposed, but seem to consist of gray shale and some siltstone, sandstone, and mottled red shale below and of gray shale containing pelecypods and gastropods above.

The limestone seems to range in thickness from about 1½ to 3 feet. It is thick bedded and dark gray and weathers dark yellowish orange. Fusulinids are the dominant faunal element and are clearly observable in the field.

The thin section of sample 1018–4 is representative of unit *D* of the Bluff Creek thin sections studied and is described below as a typical example.

Sample 1018–4, limestone unit D of the Bluff Creek member

Texture

Unsorted fossil debris in calcite ooze with patches of fine cement. Crystals in the cement are coated with a thin film of limonite. Random orientation of particles; no microbedding.

Composition (from point count of 200 points)

	Percent
Matrix	56
Recrystallized matrix(?)	10
Fusulinids	15
Echinoderms (fragments)	2
Other fossils	15
Secondary chert	Trace
Pyrite	Trace
Limonite	2

Description of constituents

Matrix: Ooze containing small areas of cement (mostly adjacent to and near relatively coarse fossil debris) and poorly preserved and finely broken clastic debris.

Recrystallized matrix(?): Patches of unusually equicrystalline calcite with an average crystal size of about 0.03 mm. Contacts between crystals have a brown stain, probably limonite. Crystals are anhedral, with no rhombs or other suggestions of dolomite. The patches of calcite crystals differ greatly in size and seem to represent areas of recrystallization or replacement of matrix.

Fusulinids: Some are broken, at least partly by crushing in place, but many are fairly well preserved.

Echinoderms: Some fragments are well preserved; others are very poorly preserved, at least in part because of postdeposition changes.

Other fossils (estimated percentages of the rock): Smaller Foraminifera, 4 percent; bryozoan fragments, 2 percent; mollusks, 3 percent; brachiopods, 1 percent; and unidentifiable shell fragments, 5 percent.

Secondary chert: Only one small irregular patch in matrix was noted.

Pyrite: Mass of very tiny crystals replaces a foraminifer.

Limonite: Thin film coats crystals in cement.

Textures of unit *D* of the Bluff Creek in other thin sections are very similar to that of the sample described above (pl. 37, fig. 2). The particles are unsorted and unoriented or with only slight preferred orientation. Most of the slides show considerable limonite replacement and stain, making it very difficult to interpret the finer constituents of the rock included under the term "matrix." The matrix of each sample consists mostly of ooze but contains suggestions of finely broken clastic debris and of pellets. Two thin sections contain 5 to 10 percent of more distinct pelletlike structures about 0.07 mm in diameter. Most of the ooze is composed of crystals estimated to range from about 0.005 to 0.01 mm in diameter, but the crystal size differs so much and is so obscured by stain and possible recrystallization that estimation of its crystal size is difficult. Several slides contain a few small patches of clear calcite that is probably primary cement.

Some samples contain rhombs, suggesting dolomite or ankerite, now completely or largely replaced by limonite. Rhombs partly replaced by limonite seem to have been zoned crystals and now consist of calcite except where replaced by limonite. In sample 835 limonite occurs as both rhombic and cubic pseudomorphs after carbonate and pyrite. Most of the limonite in unit *D* occurs as irregular masses associated locally with a small amount of psilomelane. Barite occurs in sample 835 in a patch about 4 mm in diameter; all the barite is in optical continuity despite the fact that it has replaced fragments constituting less than half the material within the patch. This type of barite replacement is more common in the oolitic limestone of unit *B* of the Gunsight member.

Calcite seems to have filled fusulinid tests after compaction began. Fusulinid tests in several slides are slightly crushed and seem obviously to have been hollow during early stages of compaction. Other fusulinids, perhaps cracked or weakened by compaction, have septa broken apparently from the force of crystallization of calcite filling the chambers (pl. 37, fig. 3). Such a relation fixes the time of calcite deposition in fusulinids, and presumably in other fossils, as occurring after shallow burial but before deep burial and complete compaction.

Fusulinid walls in some slides are replaced by calcite with an average crystal size of about 0.003 mm. This replacement destroys the wall structure of the fusulinid, but the resulting calcite is as finely crystalline as the surrounding matrix, or even finer, in contrast to the more coarsely crystalline calcite that commonly replaces fossil debris.

Insoluble residues of unit *D* of the Bluff Creek range in amount from 1.9 to 5.9 percent of the rock with a median of 3.6 percent. They consist of clay and limonite with only a small amount of silt and sand, and traces of hematite, authigenic chert, and barite. Three samples contain a brown, nearly isotropic mineral that is probably collophane. Coarse sand and granule-size clay chips are present in two samples. Sample 1013–2 contains a flake of coal.

Limonite and clay are so intermingled in several of the samples that estimation of their relative amounts is very difficult. Silt is present in most of the samples, but sand occurs in only a few. In the samples containing both sand and silt the distribution seems to be bimodal with maxima at about 0.10 to 0.15 mm and 0.02 to 0.05 mm. This grain-size distribution probably reflects sorting of sedimentary source rocks.

LIMESTONE UNIT CD OF THE BLUFF CREEK SHALE MEMBER

Near the south shore of Lake Brownwood units *C* and *D* of the Bluff Creek diverge to the northeast and in the extreme northeast corner of the Grosvenor quadrangle are approximately 20 feet apart. The two limestone units differ in lithology where they are separated. South of the point of divergence in the southern part of the quadrangle, a single limestone unit, here called limestone unit *CD* of the Bluff Creek, resembles unit *D* more than unit *C*.

Only two samples of limestone unit *CD* were studied in detail because good exposures are very scarce. Both, samples 1030 and 1058–3, are somewhat weathered and both were taken from outcrops where rocks immediately above and below unit *CD* are concealed.

The thin section of sample 1058–3 is shown on plate 36, figure 4, and described below.

Sample 1058–3, limestone unit CD of the Bluff Creek member

Texture

Much relatively coarse fossil debris in a matrix of irregularly intermixed ooze and cement. Sample is stained with limonite and cut by several microstylolites. The largest and most elongate fragments have a preferred orientation parallel to the bedding.

Composition (from point count of 200 points)

	Percent
Matrix	50
Smaller Foraminifera	4
Fusulinids	13
Bryozoans	3
Echinoderms (fragments)	11
Other fossils	19
Limonite	Trace

Description of constituents

Matrix: Ooze and cement in about equal amounts and contain a few "ghosts" of fine clastic debris and some tiny shell fragments and poorly defined dark pellets.

Smaller Foraminifera: Several types: coiled forms are most abundant.

Fusulinids: Many have edges removed along microstylolites, but they seem to have been whole and unabraded before compaction.

Bryozoans: Mostly small shreds of fenestrate types.

Echinoderms: Unabraded fragments with large overgrowths. Include some probable crinoid calyx plates in addition to columnals and spines.

Other fossils: Include many fragments difficult to identify. Many seem to be coral and brachiopod fragments (each composes perhaps 5 percent of the rock). Small gastropods, probable pelecypod fragments, and a few ostracodes are also included.

Limonite: Occurs as stain on other constituents: concentrated along microstylolites.

As shown on plate 31, sample 1030 contains a smaller amount of fossil debris than sample 1058–3. Part of this difference may be due to poorer preservation of fossils, but the large difference in numbers of such fossils as fusulinids and echinoderm fragments, which are normally well preserved and are easily recognizable even when poorly preserved, suggests that most of the difference is real. The smaller number of fossil fragments in sample 1030 is reflected by an increased percentage of matrix. In other respects sample 1030 is very similar to sample 1058–3.

Insoluble residues of both samples of unit *CD* of the Bluff Creek consist of clay, limonite, and traces of fine sand to silt and lacy secondary chert. Sample 1058–3 contains 1.2 percent insoluble residue and sample 1030, 3.9 percent. On an etched surface of sample 1058–3 clay and limonite were seen to be concentrated along incipient stylolites that parallel the bedding and have a maximum amplitude of 3 mm. The insoluble residue of sample 1030 contains a sandstone fragment consisting of two fine grains of quartz sand with a clay matrix, showing that the source of the sand and silt was older sedimentary rock. Sample 1058–3 contains a trace of muscovite.

LIMESTONE UNIT A OF THE GUNSIGHT LIMESTONE MEMBER

Limestone unit *A* of the Gunsight is about 4 to 60 feet thick over most of the area studied. It is characterized in the field by the presence of many large horn corals in float. Some of the corals weather from poorly consolidated marllike beds immediately below unit *A*, or, less commonly, above it, but most outcrops of the limestone itself also contain many horn corals. Most of the horn corals, especially where they are most numerous, lie parallel to the bedding, but some are upright in the limestone. Those lying on their sides seem to have no preferred horizontal orientation.

Limestone unit *A* of the Gunsight seems to be more closely related to shale than to beds lower in the Graham formation. Individual parts of the unit grade to shale along the strike, causing considerable differences in thickness of limestone from place to place. Unit *A* is overlain and underlain by shale except at locality 610, where it is overlain by siltsone containing limestone pebbles. At many places the shale contains thin discontinuous limestone beds or layers of limestone nodules.

Unit *A* of the Gunsight is light gray to light olive gray and characteristically weathers to nodular rubble. It is relatively nonresistant to erosion and is incompletely exposed at most outcrops. At its freshest outcrops in stream beds, the limestone is thin to medium bedded and has weathered surfaces that are smooth but lumpy or, rarely, rough and irregular.

Most of the limestone is very finely crystalline. It contains many coarsely recrystallized algae and subequant masses of sparry calcite of unknown origin 0.5 to 2 mm in diameter. At many outcrops the limestone also contains veinlets of coarsely crystalline calcite, some of them in patterns that suggest shrinkage cracks.

Although the typical unit *A*, as described above, is present over most of the quadrangle with few variations in lithology, the facies differs in both the extreme northeast corner and the southern part of the Grosvenor quadrangle. Limestone unit *A* in the northeast corner of the quadrangle differs from the most common facies of the unit by the absence or near absence of corals, by greater numbers of calcite veinlets, and by slight limonite stain. In the south, at locality 1029 (fig. 15), limestone unit *A* is considerably stained with limonite, is thicker bedded and more resistant to erosion than elsewhere, and contains larger numbers of fusulinids and other fine fossil material than most limestone of unit *A*. At locality 1029 this limestone is similar in general appearance to limestone unit CD of the Bluff Creek, but its correlation with unit *A* of the Gunsight has been confirmed by fusulinid identifications by D. A. Myers (oral communication, 1955). Both of the unusual facies in the northern and southern parts of the quadrangle seem to be local and do not persist beyond areas of Cretaceous cover bounding the area studied (fig. 13).

From thin-section study, sample 882–4 (pl. 37, fig. 4) was selected as the most representative sample of unit *A* of the Gunsight in the central part of the quadrangle.

Sample 882–4, Limestone unit A of the Gunsight member

Texture

Unsorted and unoriented fossil debris in a matrix of calcite ooze.

Composition (from point count of 200 points)

[Corrected to allow for about 10 percent of the bed constituted by horn corals not represented in thin section]

	Percent
Matrix	60
Unidentified calcite mosaics	6
Algae (coralline)	15
Algae (oncolites)	2
Horn corals (percent estimated from field notes)	10
Other fossils	7
Limonite	Trace

Description of constituents

Matrix: Calcite ooze, about one-quarter of which has been recrystallized to a fine interlocking mosaic of crystals averaging about 0.008 mm (microspar); possibly includes a trace of dolomite. Shows other evidence of recrystallization; fine crystals of the matrix encroach slightly upon the borders of clastic fragments, and the matrix itself has slight color variations that suggest fine clastic debris.

Unidentified calcite mosaics: Subequant areas of calcite mosaics, in which the crystal size averages about 0.06 mm. Some are roughly circular in outline, but most are angular or irregular. Many are probably recrystallized shell fragments or parts of algae.

Algae (coralline): A few of the very elongate stringers contain remnants of internal cell structure, but most are completely recrystallized and are recognized only by their external shape and association with fragments containing algal structure.

Algae (oncolites): Small masses encrusting other algae and a few small separate fragments of colonies.

Horn corals: Too large to be properly represented in a thin section, although a few tiny fragments of broken septa were noted in thin section.

Other fossils: Include bryozoans (constitutes about 3 percent of the rock), Foraminifera (about 1 percent), echinoderm fragments (about 1 percent), traces of ostracode fragments and mollusks, and numerous unidentified fossil fragments (about 2 percent of rock).

Limonite: Scattered tiny grains locally somewhat concentrated along coralline and recrystallized algae.

Differences in amounts of recognizable organic debris and of insoluble residue for samples of limestone unit *A* of the Gunsight are shown on plates 31 and 32. Plate 32 includes individual samples of unit *A* located stratigraphically on measured sections. In plate 31 all the samples from each individual outcrop have been averaged to show more general lateral variations and to emphasize differences and similarities between limestone units in the Graham formation.

In general, thin sections of unit *A* show few differences in texture and composition not shown on plate 32. Thin section 882–4, described above, is typical of almost all thin sections of the *A* unit of the Gunsight. Most unit *A* samples contain a high percentage of ooze with average crystal size between 0.002 and 0.008 mm. In many thin sections the matrix contains suggestions of fine clastic debris and has definite indications of at least incipient recrystallization in the form of very vague borders on many clastic fragments. Some parts of the matrix contain vague structures, some of which suggest borings of small organisms, and other parts have wavy banding perhaps due to sediment-binding algae. In many of the slides, ooze is cut by veinlets that probably formed before lithification of the sediment and resemble shrinkage cracks. A few thin sections contain clear calcite cement, some of which is probably due to recrystallization of ooze and some of which, especially near large fragments, is primary cement.

Atypical features found only in one or a few samples of the unit *A* include small amounts of pyrite, some of it partly altered to hematite; pellets; algal(?)-coated pebbles; reworked fusulinids; small scattered patches of secondary chert and barite; and slight sorting and preferred orientation of clastic constituents.

Samples of unit *A* of the Gunsight contain from 1.6 to 19.3 percent insoluble residue with a median of 5.4 percent. The insoluble residues of samples of unit *A* consist of clay and small amounts of sand, silt, secondary chert, barite, pyrite, hematite, limonite, psilomelane(?), and collophane(?). The clay is micaceous and evenly scattered through the rock, except for slight concentrations in areas of ooze, as contrasted with more highly clastic parts of the rock or areas of clear calcite cement. Barite and chert occur as small scattered irregular masses or crusts, and the chert also occurs as a replacement of Foraminifera and other small fossils. Hematite and limonite occur as alteration products of pyrite, which itself is, at least in part, secondary. Psilomelane(?) as tiny dendrites is associated with limonite in a few slides. Collophane apparently is primary and represents clastic fragments of phosphatic shells.

Silt with an average grain size of about 0.02 mm is associated with clay in almost all the samples. Sand occurs in fewer samples and has an average grain size of about 0.2 mm. Both the sand and the silt are well sorted; they seem to represent a strongly bimodal grain-size distribution.

LIMESTONE UNIT B OF THE GUNSIGHT LIMESTONE MEMBER

Limestone unit *B* of the Gunsight is characterized in the field by ooliths and other comparatively well sorted and cleanly winnowed debris. The limestone is light gray on fresh surfaces and medium gray to medium dark gray where weathered, except for scattered localities where it is slightly stained by limonite. In general, unit *B* is the lightest colored of the units studied. It appears medium- to thick-bedded on fresh surfaces but is thin-bedded at most of its highly weathered outcrops.

Unit *B* of the Gunsight seems to be discontinuous along the strike, although lack of exposures in many areas make its exact extent doubtful. The bed has been mapped from a point just north of the western arm of Lake Brownwood (fig. 15) northward to a point about 1½ miles northwest of the town of Byrds, with one possible break in continuity. About 1 mile north of the northernmost extent of unit *B*, a calcareous siltstone bed containing brachiopod and mollusk fragments occupies the approximate stratigraphic position of unit *B*. At locality 847, near the northeastern corner of the quadrangle, this stratigraphic position is occupied by a well-winnowed but poorly sorted nonoolitic limestone that contains considerable shell debris and may represent a local lens of unit *B*. The rocks overlying and underlying unit *B* are exposed in only a few places but seem to consist almost entirely of shale.

Sample 738 is typical of the samples from the main area of outcrop of unit *B* of the Gunsight, and its thin-section description is given as representative of the bed (also pl. 38, fig. 1, and pl. 34, fig. 4).

Sample 738, limestone unit B of the Gunsight member

Texture

Thoroughly winnowed calcarenite composed of ooliths and a wide variety of fossil fragments and reworked limestone fragments in clear cement. Sample contains numerous reworked fossils and other limestone fragments. Bedding, about 2 cm as seen in hand specimen, reflects different sizes of fragments and proportions of grains to cement. Elongate fragments have a well-developed preferred orientation parallel to the bedding. Average grain size is approximately 0.4 mm and ranges from 0.03 to 2 mm; grains are well sorted for a clastic limestone. The large proportion of cement causes many grains to apparently "float." It is surprising that this slide contains no quartz.

Composition (from point count of 200 points)

	Percent
Cement	40
Limestone fragments	24
Reworked fossils	20
Fossils, perhaps not reworked	6
Ooliths	10

Description of constituents

Cement: "Comb structure" of radiating crystals around fragments is evidence of primary origin as are the sorted and rounded grains. Includes large overgrowths around some fossils and fillings of small cracks, such as those in broken fossils. Contains a few small masses of secondary hematite and limonite. May contain a small amount of recrystallized fossil debris.

Limestone fragments: Grade into reworked fossils as the amount of ooze around fossils decreases. Include fragments of calcilutite, irregular chunks of fine calcite that may represent organic colonies, and fragments of fossiliferous limestone containing encrusting Foraminifera, echinoderm fragments, and recrystallized algal fragments.

Fossils reworked: Include fusulinids, echinoderms, bryozoans, and brachiopods.

Fossils, perhaps not reworked: Some may be reworked but there is no definite evidence of reworking. Include echinoderm fragments and dasycladacean algae (each estimated to compose about 2 percent of the rock) and very small amounts of Foraminifera, bryozoans, tiny fragments of horn corals, brachiopods, and gastropods.

Ooliths: Better sorted than the total clastic fraction; the largest and smallest fragments have no oolitic coating. Average size about 0.25 mm. Thickness of rind constitutes about one-quarter of the radius of many of the ooliths. The rinds have both radial and concentric structure. Nuclei consist of limestone fragments and fossils; some ooliths are elongate, partly reflecting the shapes of their nuclei. Ooliths presumably were transported to have become mixed so completely with nonoolith fragments, but there is no evidence that they were reworked from older oolitic limestone nor are they abraded to indicate prolonged reworking or much transportation. Some have been slightly flattened in place, suggesting that they were slightly soft at the time of deposition. A few have been attacked by cement: that is, part of their rind has been replaced by or recrystallized into clear calcite.

Most of the fossils and fossil fragments in sample 738, described previously, show specific evidence of reworking and have not been tabulated with unreworked fossils in the thin-section description and on plate 31. For this reason, sample 738 appears atypical of unit *B* of the Gunsight in terms of fossil content. Other unit *B* samples may also contain many reworked fossils, but fossils without specific evidence of reworking have been assumed to be unreworked.

In other respects, sample 738 is typical of unit *B* of the Gunsight. In general the unit is characterized by comparatively good sorting, relatively large amounts of sparry-calcite cement, reworked limestone fragments, and ooliths (pl. 38, fig. 1). Most samples are well winnowed and contain large proportions of sparry cement, which constitutes nearly half the volume of the rock. Other samples are less cleanly winnowed and contain a mixture of slightly finer sparry cement with calcite ooze matrix. Cement in unit *B* sample from locality 835 is partly in the form of a drusy coating around clastic fragments. The drusy coating may represent a separate stage of cementation from that of anhedral, unoriented calcite crystals in the middle of interstices, but there is no marked difference in crystal size or clarity to substantiate this.

Reworked limestone fragments are also present in nearly all unit *B* samples. Some of these limestone fragments consist entirely of finely crystalline calcite and may be organic, but others show evidence of abrasion, contain considerably more silt and sand than the surrounding rock (samples 729–1 and 882–8), or are associated with undisputed limestone fragments. The shapes of some of the more questionable limestone fragments suggest that they were soft partly consolidated calcite mud at the time of reworking.

Many, but not all, of the samples of unit *B* of the Gunsight contain ooliths, but ooliths compose no more than about 20 percent of any sample. The rinds of the ooliths were particularly susceptible to replacement by barite, although the replacement was not entirely restricted to ooliths.

At locality 882, where the top of unit *B* is exposed in the bed of a stream, the upper surface of the unit has smooth irregular mounds as much as 1 foot high and as much as 4 feet across at the base (pl. 38, fig. 2). The slopes on these mounds are as steep as 45°. Richard Rezak (oral communication, 1957) has seen similar mounds on the Bahama Banks that were formed by burrowing organisms, presumably crabs or worms. His suggestion that the mounds on unit *B* might also have been built by burrowing organisms fits the field evidence very well, inasmuch as the mounds do not suggest wave-built or erosional forms by their shape and distribution, seem to contain no megascopic sedimentary structures, and are composed of poorly sorted and unwinnowed debris.

Thin-section study also indicates that the mounds were built by organisms (pl. 38, fig. 3). The thin section contains many small calcite veins, which seem to be cracks resulting from slight slumping while the sediment was unconsolidated. The cracks show that the mounds are not recent erosional remnants. Roughly 10 percent of the rock is comprised of dark pellets of ooze about 0.06 mm in diameter and elliptical to slightly irregular and equant. The pellets have rather vague outlines and locally are slightly recrystallized but, in general, strongly resemble fecal pellets. The rock, however, contains considerable debris coarser than the pellets. Thus, if the mounds were formed by the organisms that produced the pellets, the organisms must have piled up much additional debris besides that which passed through their digestive tracts.

One thin section from locality 729 contains a considerable number of oncolites (pl. 33, fig. 5). The rock is a coarse, cleanly winnowed calcarenite. The algal material forms separate sand-sized colonies and coats almost all other fragments. The algal material in this slide more closely resembles the *Osagia* found in limestones of Pennsylvanian age, in Kansas by Johnson (1946) than that of any other slide, although the algal coatings are much thinner than those of *Osagia* from Kansas.

Insoluble residues from unit *B* of the Gunsight constitute from 3.2 to 15.6 percent of the rock, with a median of 5.0 percent. They consist of secondary chert, barite, clay, silt, and sand. Chert is present in almost all unit *B* samples and is more abundant than in any of the other limestone units studied. Much of the chert occurs as a friable partial replacement of encrusting and irregular Foraminifera, but in some samples other Foraminifera, other types of fossil debris, and, locally, the outer parts of ooliths are also partly replaced.

Barite most commonly replaces the rinds of ooliths, but also replaces other clastic particles and occurs as irregular small masses not specifically related to any recognizable primary constituents. Barite is present in about one-third of the samples of unit *B* studied.

The sand-and-silt fraction of the insoluble residues commonly appears to be bimodal. The average diameter of the silt mode most commonly is about 0.03 to 0.04 mm. The average diameter of the sand differs considerably between samples, but ranges mostly from very fine to fine. Most of the silt is angular, but some shows definite signs of slight rounding. Probably the silt, and perhaps the sand, was derived from older sedimentary rocks.

LIMESTONE UNIT C OF THE GUNSIGHT LIMESTONE MEMBER

Limestone unit *C* of the Gunsight has been recognized over a large area in Brown and Coleman Counties (Eargle, 1960), but seems to be less persistent within the Grosvenor quadrangle than units such as unit *D* of the Bluff Creek, whose lateral continuity and correlations are more in doubt.

The limestone units of the lower part of the Graham formation collectively form a broad bench over wide areas, individual units forming subsidiary benches. Limestone unit *C* of the Gunsight is the uppermost of this group of limestone beds and many of its outcrops consist only of rubble on the bench of the lower part of the Graham or of the weathered basal part of the unit. Rocks immediately overlying unit *C* are concealed over most of the area.

Unit *C* seems to undergo facies changes along the strike and may be discontinuous in the northern part of the area. Locally it may have been removed by channel erosion.

Over about the middle three-quarters of the quadrangle in a north-south direction, the unit *C* of the Gunsight seems to be continuous, or nearly so, and to undergo little facies change. In this area the unit is about 2 to 4 feet thick and consists of light-olive-gray and microcrystalline limestone with coarse stringers of recrystallized algae. Locally it contains scattered fusulinids, horn corals, and brachiopods.

North of this area of relative lithologic uniformity, unit *C* seems to change to a calcareous sandstone, although this can not be proved with certainty because of the lack of exposures. Limestone unit *C* seems to be completely absent near the north boundary of the Grosvenor quadrangle.

In the extreme southern part of the quadrangle, the approximate position of unit *C*, is occupied by two limestone beds separated by 3 to 7 feet of shale. These two limestone beds are lithologically very similar to each other and to the single unit *C* in the central part of the Grosvenor quadrangle. The upper bed has a maximum thickness of about 3 feet and the lower bed, about 4 feet, but in many places each bed seems to be only about 1 foot thick. The upper bed contains horn corals at most outcrops, whereas the lower bed contains none, a feature that helps in distinguishing them.

The description of the thin section of sample 1012a is typical of descriptions of unit *C* of the Gunsight from the central part of the Grosvenor quadrangle (pl. 38, fig. 4).

Sample 1012a, limestone unit C of the Gunsight member

Texture

Ooze containing algal(?) debris, small amounts of other fine fossil debris, pellets, indistinct probably clastic fragments, and a few small patches of cement. Sample is cut by a few calcite veinlets. Pellets are concentrated in certain poorly defined parts of the slide. The limestone contains one microstylolite that dies out within the thin section. Along the stylolite are concentrated a small amount of limonite and traces of psilomelane(?) and pyrite.

Composition (from point count of 200 points)

	Percent
Matrix	65
Sparry-calcite mosaics	12
Algae(?)	12
Other fossils	6
Pellets	3
Vein-filling calcite	2

Description of constituents

Matrix: Ooze, partly recrystallized to crystals averaging about 0.008 mm in diameter and containing vague relics of probable pellets and fossil debris and scattered patches of coarser grained calcite.

Sparry-calcite mosaics: Distinct to poorly defined patches of sparry calcite, possibly of organic (algal or shell fragment) origin. Part of this calcite may be cement.

Algae(?): Very poorly perserved and badly broken stringers of sparry calcite that are considered algal only because of analogy with algal material in other slides.

Other fossils: Poorly preserved fragments of bryozoans, Foraminifera (mostly irregular forms), ostracodes, echinoderm spines, and unidentified shells.

Pellets: Ovoid particles of very fine calcite, well sorted, averaging about 0.18 mm in diameter (pl. 34, fig. 3).

Vein-filling calcite: Sparry calcite filling narrow, sharp-walled veinlets, some of which can be traced across recrystallized fragments and seem to be younger than the recrystallization.

Although unit *C* of the Gunsight may not be persistent along the outcrop, petrographically it differs only moderately from place to place in areas where it can be definitely identified. The unit is characterized by microcrystalline calcite containing many recrystallized algae. The microcrystalline matrix of several of the slides contains suggestions of "ghosts" of clastic debris but little material than can be definitely identified as clastic. Unit *C* contains considerable microspar that in its general appearance suggests recrystallized ooze more than does the matrix of any of the other limestone units studied.

The sparry-calcite areas are of four types. The first consists of recrystallized algae, some of them dasycladaceans, probably *Epimastopora*, but most of them coralline algae. A few samples contain fragments of coralline algae with some microstructure preserved. The second consists of more equant mosaics, which may be largely fragments of considerably broken algae. Also included in this category are nearly spherical mosaics of clear calcite whose original nature is not yet understood.

The third type of sparry-calcite area consists of veinlets filled with clear calcite. In general, the veinlets are short and discontinuous and seem to represent shrinkage cracks. Some veinlets seem to have been filled in two stages: The first produced a drusy fringe of finely crystalline calcite radiating into the veinlets from the sides, and the second produced coarse anhedral calcite in the centers of the veinlets but did not completely fill all voids. In one slide barite partly replaced the second-stage calcite but did not fill the remaining voids.

The fourth type of sparry-calcite area in unit *C* of the Gunsight is considered primary cement because it is concentrated near the coarsest clastic constituents where prelithification voids were most likely to have been present. Some areas may be recrystallized clastic fragments or patches of recrystallized ooze.

In general, samples of unit *C* seem to have original textures less well preserved than the other limestones.

This is shown by the recrystallized appearance of the ooze, the lack of internal structure in probable algae, and the poor preservation of many other clastic constituents.

Replacement by noncarbonate material, however, has been relatively slight in unit *C*, probably because of small porosity and permeability of the unit from very early in its history. Barite and chert are present in many samples, but generally in smaller quantities than in other limestone samples from the lower part of the Graham. Limonite and hematite occur chiefly as stain or very small and scattered masses along tiny stylolites or veins.

Some samples of the unit *C*, notably sample 746, seem to be limestone breccia, in which the brecciation occurred in place, probably because of shrinkage. The shrinkage cracks were filled with carbonate mud rather than with clear calcite because they were relatively large and fine ooze was available.

Practically none of the unit *C* samples suggest evidence of appreciable wave or current action. They are almost completely unsorted and contain larger, though rather fragile, pieces of algae and bryozoans than the other beds.

Insoluble residue constitutes 1.2 to 10.0 percent of the unit *C* samples, with a median of only 2.3 percent. It is characterized by the relative scarcity of authigenic minerals like chert and barite and of sand and silt. Limonite and hematite are present in some samples as small scattered irregular masses, somewhat concentrated in and near the calcite veinlets.

Most of the chert replaces porcelaneous Foraminifera and other fine fossil debris. Barite occurs as impure crusts and irregular masses not related to any recognizable primary constitutent and as a replacement of calcite filling veins.

Some unit *C* samples have a small amount of silt averaging from about 0.01 to 0.04 mm in diameter. In no sample does the amount of silt exceed an estimated 5 percent of the insoluble residue, or roughly 0.3 percent of the total rock. Three samples contained sand about 0.15 mm in diameter but none contained more than a few grains in the insoluble residue of about 20 grams of rock.

SANDSTONE AND SAND FRACTION OF THE LIMESTONE

Brief studies of calcareous sandstone and very sandy limestone associated with the lower limestone beds of the Graham formation serve the dual purpose of providing information about the sandstone and of giving a more detailed picture of the noncarbonate sand present in the limestone. Visual examination of thin sections did not suggest that the noncalcareous sand of the limestone is significantly different from the sand of the associated sandstone. Sandstone samples studied represent local sandstone bodies 12 feet below unit *A* of the Bluff Creek, 8 feet below unit *B* of the Bluff Creek, immediately below unit *B* of the Bluff Creek, immediately below unit *C* of the Bluff Creek, at the approximate position of unit *B* of the Gunsight, and 5 feet above unit *C* of the Gunsight. Only one sample was studied from most of these statigraphic positions, because the sandstone bodies are very local in their distribution and because they were not the primary object of the study. Three samples were studied, however, from the sandstone immediately below unit *B* of the Bluff Creek.

The samples studied contain 18 to nearly 55 percent carbonate by weight. The insoluble residues of the samples were sieved, using sieves graduated according to the Wentworth size scales. Every sample is fine grained or very fine grained, with 78 to 97 percent of the noncarbonate fraction falling in these two size classes of Wentworth. Only 4 of 8 samples studied contained sand coarser than 0.25 mm; and in 3 of these, this medium-grained sand constituted no more than 1 percent of the noncarbonate fraction. The fourth sample, from a sandstone above unit *C* of the Gunsight which perhaps is a channel-fill sandstone, contained 16 percent medium sand. Comparison of the size distribution with carbonate content indicates that finer grained samples tend to contain more carbonate (fig. 16).

The sand is subangular to subrounded on the basis of the subdivisions of Powers (1953). Many quartz grains have tiny overgrowths. Some grains have been slightly replaced along their edges by calcite cement.

The sorting of the noncarbonate constituents is indicated by the phi-scale standard deviation (σ_G), obtained using the formula $\sigma_G = \frac{\phi 84 - \phi 16}{2}$, where $\phi 84$ and $\phi 16$ are the diameters, in phi units, corresponding to the 84 and 16 percent points on the cumulative curve (Folk, 1957, p. GS–H–2). Most samples have standard deviations of 0.4 to 0.65 and are therefore well to moderately sorted. One of the samples from immediately below unit *B* of the Bluff Creek has a standard deviation of 0.9 and is only moderately sorted. The standard deviation and the graphic mean, Mz, (obtained from $Mz = \frac{\phi 16 + \phi 50 + \phi 84}{3}$, where $\phi 16$, $\phi 50$, and $\phi 84$ are the 16, 50, and 84 percentiles from the cumulative curve) are shown on table 3.

The sand grains consist mostly of quartz, with less than 1 percent feldspar and commonly less than 1 percent heavy minerals by volume. They are classified

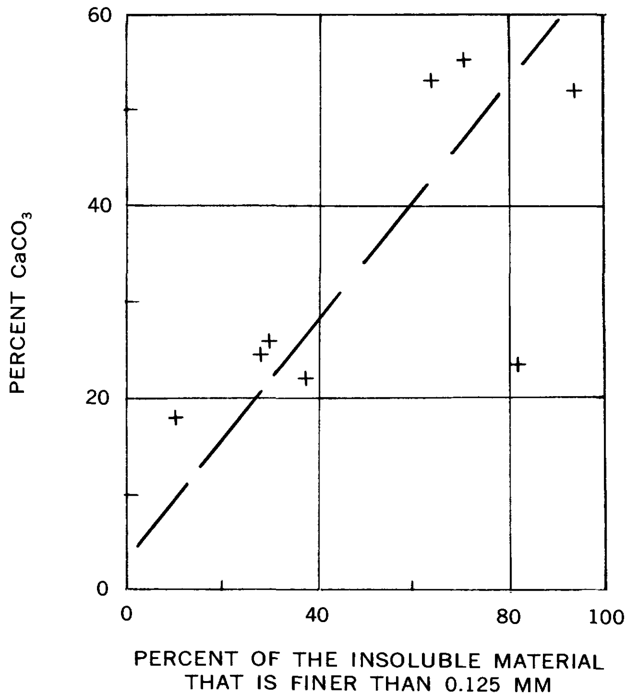

FIGURE 16.—Scatter diagram of percentage of carbonate cement versus grain size of insoluble constituents in calcareous sandstone and very sandy limestone.

TABLE 3.—*Graphic mean (Mz) and graphic standard deviation (σ_G) of grain sizes of calcareous sandstone and very sandy limestone associated with the limestone units of the Bluff Creek shale and Gunsight limestone members of the Graham formation*

Sample	Stratigraphic position	*Mz*	σ_G
1014-1	12 ft below unit *A* of the Bluff Creek	3.5	0.65
829-1	8 feet below unit *B* of the Bluff Creek	3.3	.55
709-2	Immediately below unit *B* of the Bluff Creek	2.8	.5
828-4	do	3.4	.9
837-2	do	2.9	.4
839-5	Immediately below unit *C* of the Bluff Creek	2.8	.45
832-2	Near position of unit *B* of the Gunsight	3.5	.4
882A-2	About 5 feet above unit *C* of the Gunsight	2.4	.4

as quartzose subgraywacke (Folk, 1957). A count of 600 grains from three samples gave the following approximate composition of the noncarbonate sand grains: quartz with straight or nearly straight extinction, 65 percent; quartz with undulose extinction, 15 percent; composite metamorphic quartz, 10 percent; fragments of orthoquartzite, 2 percent; semicomposite grains (made up of two or more subindividuals with separate but very close optical orientation), 7 percent; feldspar (orthoclase slightly predominating over plagioclase), 1 percent; detrital chert, 1 percent. Some of the finer sands contain quartz splinters that are very angular and at least twice as long as they are wide. These distinctive grains are probably fragments of more equant semicomposite grains. Other grains have a typical subequant shape.

The relative amounts of the various types of quartz suggest that the ultimate source area contained metamorphic rocks (undulose and composite metamorphic quartz), quartz veins (semicomposite grains), and granitic rocks (quartz with straight to slightly undulose extinction). Probably, however, the immediate source consisted mainly of older sedimentary rocks. This would account in part for the good sorting, the complete intermixing of quartz from different types of source rock, sandstone fragments in the sands, the presence of detrital chert, and the scarcity of feldspar.

Heavy minerals were examined briefly and constitute a suite dominated by tourmaline but also containing garnet, zircon, rutile, and traces of hypersthene and hornblende. Authigenic barite and limonite are also present in the heavy-mineral suite. Tourmaline occurs in great abundance in the heavy-mineral separates. Most of the tourmaline grains are well rounded, but some seem to have small overgrowths. Common brown tourmaline is by far the most abundant variety, but green, blue, and pink varieties are present in small amounts. The garnet is pink and very angular. Grains of zircon and rutile are rounded, but many grains show remnants of euhedral crystal shapes. Hypersthene and hornblende are present only in trace amounts, and their identification is tentative. They are surrounded to rounded. The suite, as a whole, is a stable one and substantiates other lines of evidence that the immediate source rocks were sedimentary and that the ultimate source was probably a mixture of igneous and metamorphic rocks.

Several of the sandstone bodies are cemented by coarse calcite crystals, each of which encloses many sand grains (luster mottling). The calcite crystals are irregular in outline and some are complexly intergrown. Their average size is difficult to estimate, because the crystals differ considerably in size and shape. Most of them are about 3 or 4 mm in diameter, but some are more than 15 mm long. The most elongate crystals tend to parallel the direction of bedding, probably owing to slight original differences in porosity and permeability. The luster mottling seems to be a secondary feature caused by replacement or recrystallization, as suggested both by the wide spacing of quartz grains and by a few vague "ghosts" of sand-size grains in the large calcite crystals.

SHALE AND THE CLAY FRACTION OF THE LIMESTONE

Insoluble residues of the limestone samples were studied by X-ray diffraction to identify the clay minerals present and to check for differences in clay mineralogy between beds. Samples of the shale beds that are interbedded with the limestone units were studied in the same manner to compare the clay mineralogy of the insoluble residues from the limestone with that of the shale.

Two techniques were tried to determine, or avoid, the effect on the clay of the acid treatment used in obtaining the insoluble residues. An attempt was made to use an ultrasonic separator to disaggregate the limestone in order to study the clay minerals in the limestone without first subjecting them to acid. This was unsuccessful because the amount of clay minerals in the finely separated material was too small to be studied satisfactorily by X-ray. A more successful method was to X-ray shale samples both before and after acid treatment, as is done in the method used to obtain insoluble residues from limestone. By this method the effect of the acid treatment could be determined.

Techniques used in conjunction with the X-ray unit to confirm the identification of peaks include ethylene glycol solvation, differential cation treatment, and heating. Several samples were tested for expansible material by glycol saturation. Two shale samples were subjected to differential cation treatment to confirm the presence of hydrous mica (Rolfe and Jeffries, 1953, p. 86). This technique consisted of X-raying the samples after saturation with 1*N* potassium acetate and again after saturation with 1*N* calcium acetate. Five samples were heated to 600°C for one-half hour to confirm that 7 A maxima on their X-ray patterns were due to a kaolinite-type material rather than a chlorite-type. The disappearance of the 7 A maxima tends to confirm the identification as a kaolinite-type mineral (Brindley and Robinson, 1951).

The X-ray patterns were made using a Geiger counter X-ray spectrometer with copper radiation and a nickel filter. All the samples were prepared by sedimenting the material on a slide to obtain a preferred orientation. Two patterns each were made for most of the samples, one for the insoluble residue, or shale, as a whole, and the other only for material finer than 2 microns that was separated by settling the sample in water. The last groups of patterns made, those for calcium- and potassium-saturated clay and acid-treated shale, were made only on material representing the entire sample, because earlier runs had shown no differences in the amounts and types of clay minerals in the two size distributions.

CLAY MINERALS IN THE INSOLUBLE RESIDUES OF LIMESTONE

Insoluble residues of 13 limestone samples representing limestone of various colors, textures, faunas, and degrees of purity were studied. Two clay minerals were found in each of the samples: kaolin and mica.

The principal kaolin peak at about 7 A was absent on samples that had been heated to 600°C for one-half hour. Most, if not all, varieties of chlorite resist this type of heat treatment, so the disappearance of the 7–A peak is additional evidence for the presence of kaolin rather than a 7–A chlorite.

The mica produces a 10–A peak tailing off irregularly toward higher spacings, the higher spacings representing mixed-layered material. One sample showed a trace of some nonexpansible 14–A material, interpreted as chlorite.

Quartz was present in large amounts in all the samples, in most of them even in the fraction smaller than 2 microns. One sample gave a very small peak that suggests a trace of feldspar.

CLAY MINERALS IN SHALE

Studies were made of seven shale samples representing beds below unit *B* of the Bluff Creek, between units *B* and *C* of the Bluff Creek, between unit *D* of the Bluff Creek and unit *A* of the Gunsight, and overlying unit *C* of the Gunsight. Samples that appeared to be entirely free from the effects of Recent weathering were difficult to obtain because most of the shale is poorly exposed. Samples of both unweathered and weathered shale were studied from an unusually good shale outcrop above the Gunsight member to evaluate the effects of Recent weathering on the shale.

All the samples studied contain the same clay minerals that were found in the limestone. In addition to kaolin, mica (and hydrous mica), and quartz, small amounts of ankerite, calcite, and feldspar(?) were present in a few slides. Three samples contain small amounts of chlorite.

Differential cation treatment resulted in contraction of spacings in the 10– to 14–A region toward 10 A during saturation with potassium. Saturation with calcium expanded the material toward 14 A. This type of reaction to differential cation treatment has been used by Rolfe and Jeffries (1952) to confirm the presence of hydrous mica.

Each sample was again X-rayed after immersion for about 24 hours in 10 percent HCl at room temperature, the same process by which clay had been removed from the limestone. Comparison with patterns of unacidized shale revealed no important change in the type of clay minerals present. Apparently the acid treatment used in obtaining insoluble residues from the limestone introduced no serious error in the study of the clay mineralogy.

Four types of minor changes were produced by the acid, however: (1) The apparent amount of hydrous mica, relative to mica, increased. Typically, this increased "weathering" of the micas was shown by a higher and broader shoulder on the low-angle side of the 10-A peak. (2) The background angle (degrees

2θ) in the 2° to 3° area of the pattern was sharply reduced. B. N. Rolfe (oral communication, 1956) expressed the opinion that this was due to removal of very fine particles by the acid, with a consequent reduction of low-angle scattering. He has found this reduction of low-angle background to be a common result of acid treatment of clays. E. J. Weiss of The University of Texas Ceramic Engineering Department (oral communication, 1956) pointed out that removal of iron also reduces low-angle background. (3) Acid treatment emphasized indefinite peaks representing spacings of 20 to 40 A. This probably was at least partly due to the lowering of background in and adjacent to that part of the patterns. (4) On most of the patterns the 10 A mica peak was sharpened appreciably on the high-angle side.

Comparison of weathered and unweathered shale from the same outcrop revealed only minor differences. The amount of hydration of the mica seemed to be slightly larger. This was especially obvious when comparing the two patterns run after acid treatment. Whereas the unweathered shale sample gave a mica peak with a definite shoulder to about 11.7 A after acid treatment, the weathered sample after acidization gave a secondary peak extending to 12.6 A. Patterns of the less-than-2-micron fraction of the weathered shale have an unidentified peak at about 7.55 A that is not present on the corresponding pattern of the unweathered shale. Possibly this unidentified peak represents a small amount of gypsum.

QUANTITATIVE STUDY OF HEIGHTS OF 10–A AND 7–A PEAKS

Despite the similarities of the patterns made from all samples, there were indications of some differences in the relative amounts of mica and kaolin. No attempt was made to study the absolute amounts of these minerals in the samples, but a rough check was made on the relative amounts present by a comparison of heights of first-order peaks. Absolute-peak heights were not compared because different settings of the X-ray machine were used on different samples. Instead, a ratio, *Ik/Im*, was determined by dividing the height above background of the 7–A kaolin peak on each pattern by the height above background of the 10–A mica peak. This ratio gives an objective measure of differences in patterns, and it was averaged for various groupings of samples with the following results:

Type of sample	Number of patterns	Average *Ik/Im*	Standard deviation
Bulk sample	23	1.6	0.6
<2-micron fraction	20	1.4	.4
Shale	18	1.0	.5
Limestone	25	1.8	1.0
Shale bulk sample, not acid treated	8	1.2	.6
Same shale, acid-treated	8	1.0	.4
Samples not treated with glycol	3	1.1	.4
Same samples treated with glycol	3	0.9	.1

The difference between the shale and limestone samples is statistically significant at the 99-percent level, but the differences within the other pairs of means are not significant at the 95-percent level.

This significantly greater ratio of kaolinite to mica in the limestone than in the shale might be interpreted in several ways: (1) A difference in source area, (2) a difference in size and, hence, hydraulic properties of the two minerals influencing their proportions in different depositional environments, (3) difference in treatment of the samples, and (4) post-deposition changes. The first possibility seems to be very remote. It is extremely unlikely that there was such a rapid alternation of source areas that interbedded rocks would have different source areas. The second possibility seems to have been disproved by the lack of significant difference between the patterns of unfractionated samples and those containing only material finer than 2 microns. However, it is conceivable that a size difference might be present only in sizes smaller than 2 microns, or that the original effective size of the particles was affected by flocculation not reproduced by settling the material in distilled water. The third possibility can be ruled out because of the lack of significant difference between the acid-treated and the untreated shale samples. In other respects the shale and limestone samples were treated identically.

The fourth possibility seems to be the most likely. Clay minerals in the limestone were protected chemically and physically by encasement in the limestone, but those in the shale were not.

SUMMARY OF CONCLUSIONS

The conclusions resulting from this study may be summarized as follows: (1) The insoluble residues from limestone studied contain mica, kaolin, quartz, and traces of probable feldspar. (2) No variations in clay mineralogy were determined that would be useful in correlation of limestone beds. (3) The clay minerals have undergone no obvious diagenetic changes that reflect differences in environments of limestone deposition. (4) The shale samples studied contain the same clay minerals as the limestone, but the ratio of kaolin to mica is smaller for the shale than for the limestone, presumably as the result of changes during accumulation and compaction. (5) The ratio of kaolin to mica for the fraction smaller than 2 microns is not significantly different from the ratio for the entire sample. (6) Acid treatment of shale does not change the clay mineralogy appreciably, except to increase the apparent amount of weathering of the mica. This increase in the amount and degree of hydration of hydrous mica produced no statistically significant difference in the height of the 10 A peak as compared to the height of the 7 A peak. (7) Recent weathering seems to have produced no appreciable changes in the shale.

The significance of the clay minerals in these sedimentary rocks is not well understood. Illite can be easily explained as having come from metamorphic rocks indicated in the source area by straining in quartz grains. Kaolin is believed to be produced only by weathering and implies weathering in a warm humid climate.

DISTRIBUTION AND INTERRELATIONS OF CONSTITUENTS

INSOLUBLE RESIDUES

For each unit studied, the percentages of insoluble residue were listed in order and their logarithms plotted as a cumulative curve on probability paper (figs. 17, 18). Two few points are present on each curve to be expected to approximate a straight line, but most of the curves are straight enough in general trend to suggest a log normal distribution, so the logarithms of the insoluble residues can be examined by the usual statistical procedures.

From these curves (figs. 17, 18), various values were read or calculated, using the logarithms of the percentages and the methods suggested by Folk (1957). The values calculated for each limestone unit include the graphic mean

$$\left(Mz = \frac{P_{16}+P_{50}+P_{84}}{3}\right)$$

where P is the indicated percentile, read from the graph); the confidence limits of the graphic mean; and the inclusive graphic standard deviation

$$\left(\sigma_G = \frac{P_{84}-P_{16}}{4} + \frac{P_{95}-P_5}{6.6}\right)$$

(Folk, 1957, p. GS-H-2, 51-4).

Figure 19 shows the average (mean) amount of insoluble residue found in each limestone unit, based on the number of samples shown. The arrows show the standard deviation, which is determined by the amount of variation among insoluble residues of different samples of a unit. The shaded bar shows the 95-per-

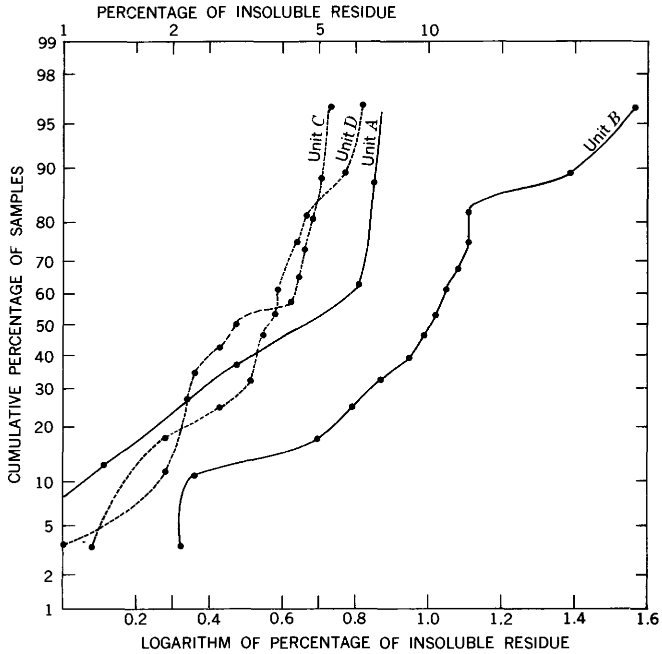

FIGURE 17.—Cumulative curves of amounts of insoluble residue in each limestone unit in the Bluff Creek shale member of the Graham formation. Each point on a curve shows the percentage of the unit that contains insoluble residue equal to or less than the amount indicated.

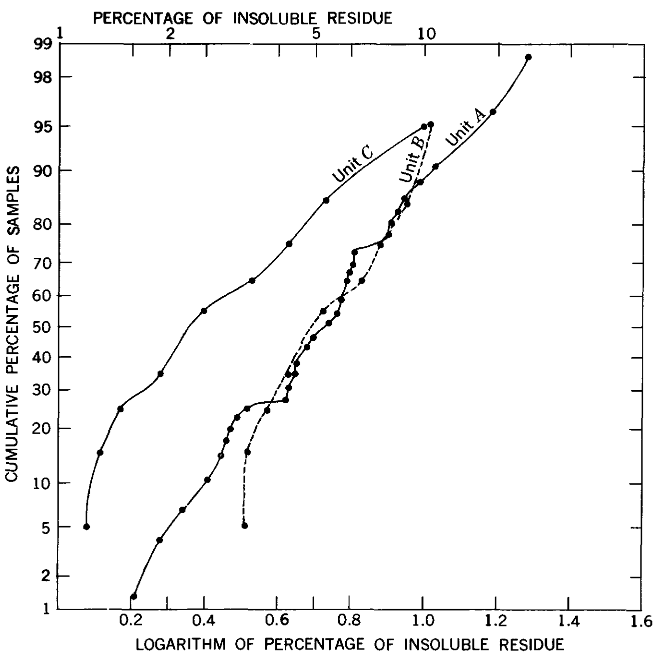

FIGURE 18.—Cumulative curves of amounts of insoluble residue in each limestone unit in the Gunsight limestone member of the Graham formation. Each point on a curve shows the percentage of the unit that contains insoluble residue equal to or less than the amount indicated.

cent-confidence limit of the average; in other words, a statement that the true average for the unit falls within these limits would be right 95 percent of the time. In general, the range of the confidence limits is smaller for units with larger numbers of samples because the chance of error decreases as more samples are studied. The range of the confidence limits is also related to the standard deviation, being smaller if most of the samples have about the same amount of insoluble residue and larger if the samples differ widely in the amount of residue.

Comparison of the mean insoluble residues by the "t" test (Davies, 1954, p. 58) confirms statistically the qualitative impressions given by figure 17. Limestone unit *A* of the Bluff Creek is represented by too few samples and has too scattered values to show significant differences from other units. Among the other limestone units, unit *B* of the Bluff Creek has the highest content of insoluble residue. The differences between unit *B* of the Bluff Creek and the other beds are statistically significant at the 95-percent level, except for the difference between unit *B* of the Bluff Creek and unit *B* of the Gunsight which is significant at barely below the 95-percent level. Units *A* and *B* of the Gunsight have the next highest content of insoluble residue, significantly higher than units *C* and *D* of the Bluff Creek and unit *C* of the Gunsight, which have the lowest amounts of residue.

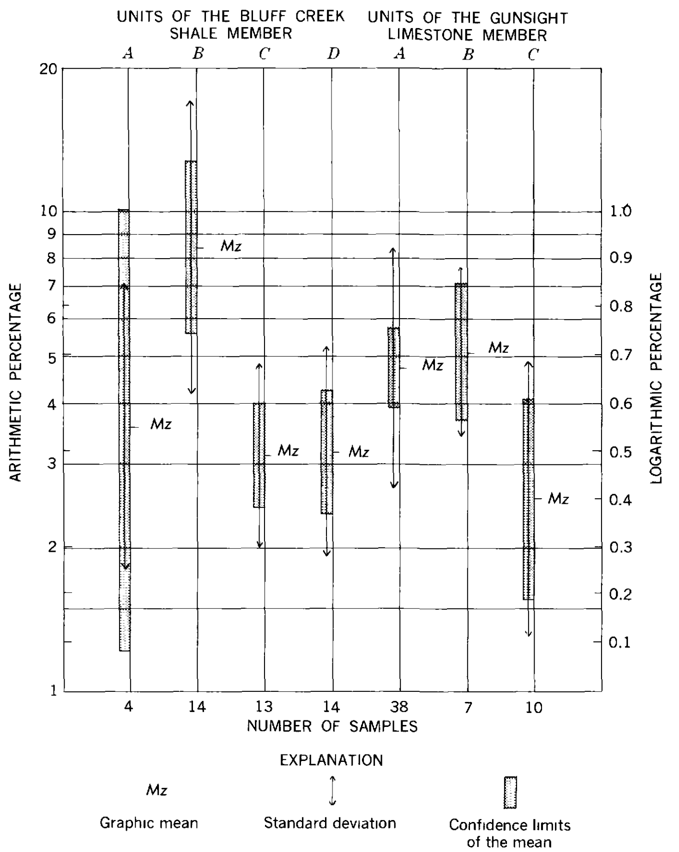

FIGURE 19.—Average amounts of insoluble residue in each limestone unit.

Several facts should be mentioned concerning these results and the data from which they are derived: (1) The two samples of limestone unit *CD* of the Bluff Creek from the southern part of the quadrangle were included with samples of unit *D* of the Bluff Creek because they seem closely related. (2) A sample of sandstone from locality 611, considered to be the possible equivalent of limestone unit *B* of the Gunsight because of its stratigraphic position, was not included with the samples of limestone unit *B* of the Gunsight. (3) It seems especially important to note that the general results may not apply to a specific part of the area because areal variations in the amounts of residue are masked by averaging. For example, the statistically valid difference in amount of insoluble residues in unit *B* of the Bluff Creek and unit *A* of the Gunsight would be even more striking by use of samples from only localities in the northern part of the quadrangle, but the difference would be nonexistent by use of samples from only the southern part (pl. 31). (4) The measurements used include all insoluble constituents, whether primary, such as sand and clay, or secondary, such as limonite and barite.

Figure 20 is a scatter diagram of the total percentage of sand plus silt plus clay in the insoluble residue versus the percentage of sand and silt divided by sand plus silt plus clay. The percentage of sand plus silt plus clay is the total terrigenous insoluble residue, as contrasted with the authigenic components of the residue, such as chert or barite, so figure 20 is a plot of the amount of terrigenous residue versus the proportion of that residue that consists of sand and slit. The graph shows no clear trend, but it does indicate that among the samples studied those with the highest amount of terrigenous insoluble residue have an insoluble residue composed mostly of silt and sand. Conversely no sample had more than 20 percent insoluble residue consisting mostly of clay. This is a logical result, because areas into which considerable terrigenous sediment was being carried might be expected to have currents strong enough to carry in coarser sediment and to winnow out part of the clay. However, too few samples with high contents of insoluble residues were studied to show a conclusive relation. The most argillaceous limestone beds may weather rapidly and perhaps were not sampled adequately.

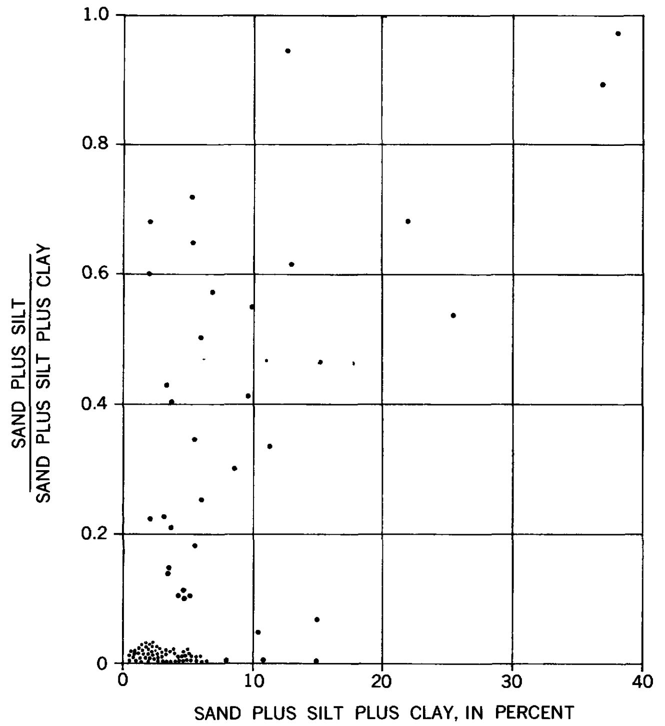

FIGURE 20.—Scatter diagram of the percentage of the terrigenous insoluble residue of sand and silt size versus the total percentage of terrigenous insoluble residue.

ASSOCIATIONS OF CONSTITUENTS

Before attempting to interpret the environmental significance of various primary rock-forming constituents, it seems valuable to try to group types of constituents according to their associations or antipathies. One of the simplest ways of doing this is to plot pairs of constituents on scatter diagrams, each point on a diagram representing a single sample plotted to show its content of each of two constituents.

Figures 21–30 are scatter diagrams of various pairs of constituents. Groupings of the points are partly artificial because percentages of organic constituents were rounded off to whole numbers or, for large percentages, to the nearest 5 percent. Some points are slightly misplotted to avoid having them overlap the axes or other points.

Correlations between constituents can also be tested mathematically and expressed by various coefficients, but the nature of the data seriously complicates the use of such coefficients. William Connor and Churchill Eisenhart of the National Bureau of Standards and the Geological Survey advisory committee on statistics examined the data and advised against attempting rigorous mathematical correlations. The percentages of any pair of constituents tend to follow an inverse relation because the part of the rock composed wholly of one constituent cannot be composed of the other. Another complicating factor is that the distribution of each of the constituents may approximate a Poisson distribution, which could cause a correlation between two constituents that had no genetic connection whatsoever. These factors may be unimportant in terms of the present data, but they cast doubt on the mathematical validity of the standard correlation coefficients for this data. Connor advised the writer that time-consuming calculations would not be worthwhile without basic statistical research on the implications of using this type of data.

Visual examination of scatter diagrams suggests inverse relations for figures 21–24, and perhaps for figures 26 and 29. Figure 30 shows a direct relation and figure 25 suggests one. From these impressions, one concludes that fusulinids and coralline algae are most abundant in relatively pure limestone (figs. 21, 23) and especially avoid waters containing relatively coarse terrigenous material (figs. 22, 26). Fusulinids tend to occur in different rocks than the smaller Foraminifera (fig. 24), but are commonly associated with echinoderms (fig. 25). As would be expected from these relations, smaller Foraminifera seem to be fairly abundant in rocks containing relatively larger amounts of insoluble residue (fig. 27). Perhaps the smaller Foraminifera are concentrated by currents and deposited with terrigenous material. Echinoderms show no marked tendency to avoid insoluble residue (fig. 28), despite their frequent association with fusulinids.

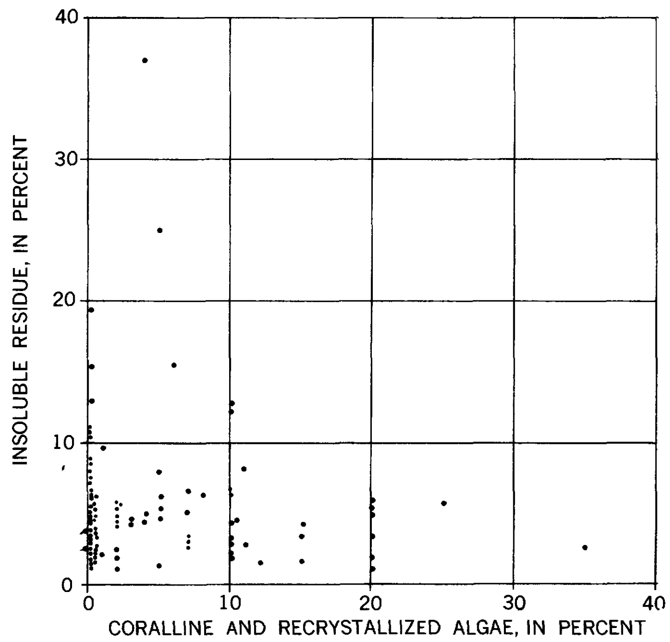

FIGURE 21.—Scatter diagram of percentage of insoluble residue versus percentage of coralline and recrystallized algae for all limestone samples studied. Dots to left of vertical axis represent points moved slightly to avoid overlapping.

Bryozoans seem to avoid the environment of the coralline algae (fig. 29). Brachiopods and mollusks occur together (fig. 30) and occur in some rocks containing few or no other fossils, such as the calcareous sandstone at the position of unit *B* of the Gunsight at locality 611 (pl. 31). The associations of constituents in individual samples can be observed on plates 31 and 32, as can differences in abundances of constituents in different beds and different areas.

Lack of more definite relations between various pairs of constituents on the diagrams may be caused in part by a greater complexity in the relations than can be shown by such a simple method, as well as by actual

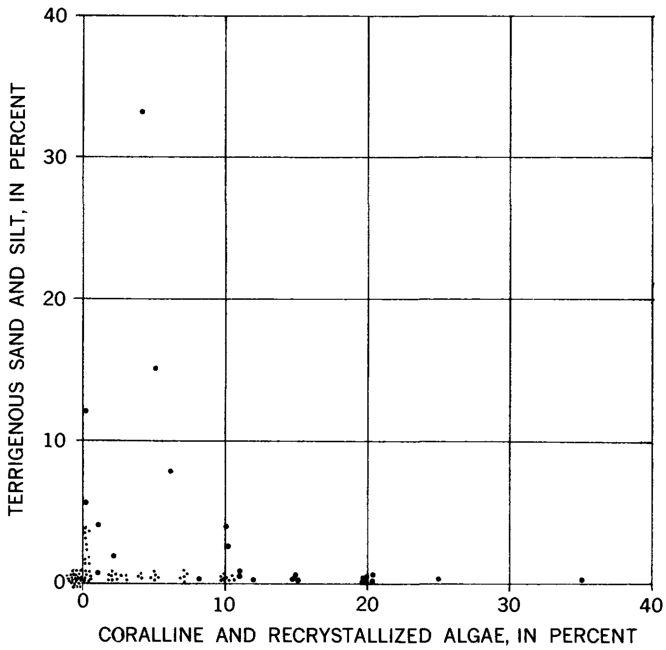

Figure 22.—Scatter diagram of percentage of sand and silt versus percentage of coralline and recrystallized algae for all limestone samples studied. Dots to left of vertical axis represent points moved slightly to avoid overlapping.

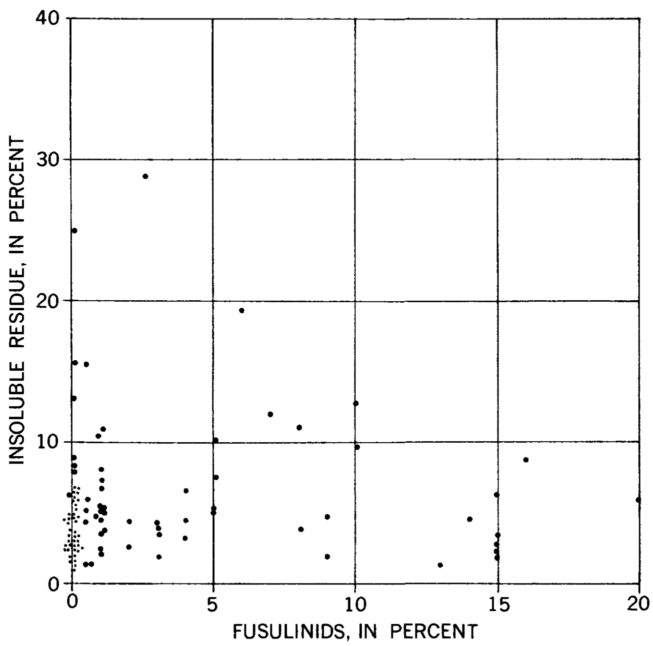

Figure 23.—Scatter diagram of percentage of insoluble residue versus percentage of fusulinids for all limestone samples studied. Dots to left of vertical axis represent points moved slightly to avoid overlapping.

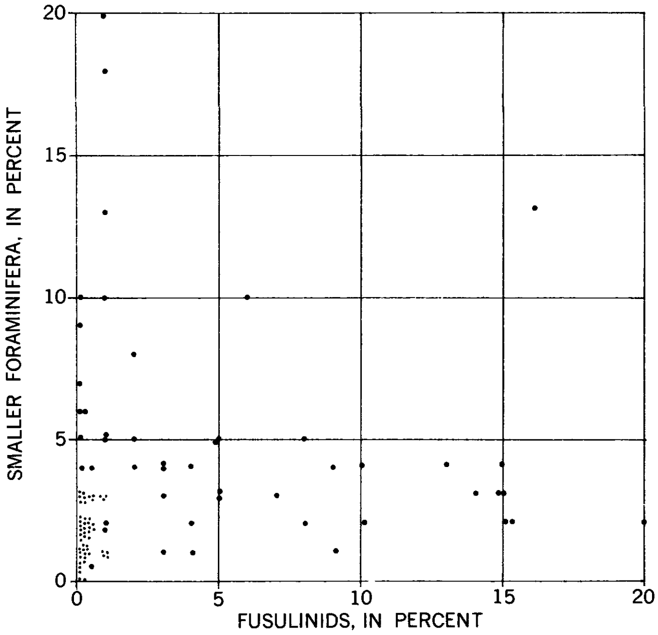

Figure 24.—Scatter diagram of percentage of smaller Foraminifera versus percentage of fusulinids for all limestone samples studied.

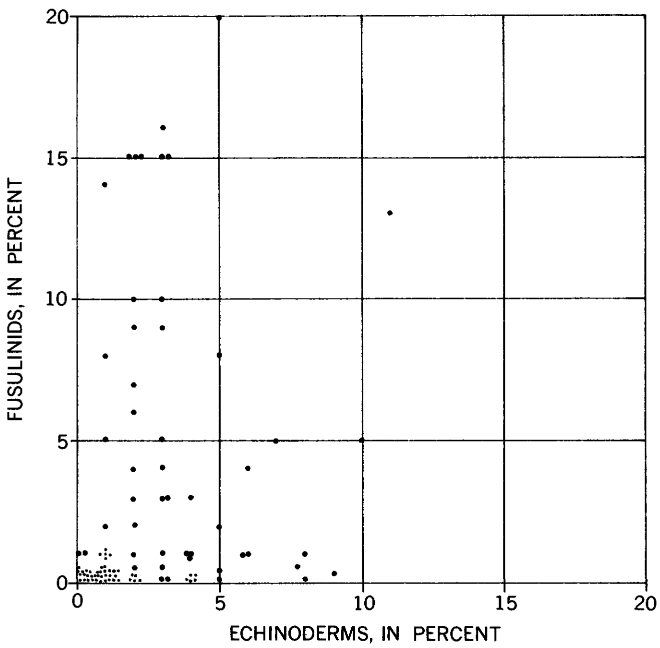

Figure 25.—Scatter diagram of percentage of fusulinids versus percentage of echinoderms for all limestone samples studied.

absence of relations. Perhaps also, the units studied are too much alike for threshold values to be reached or at least for relations to be made clear.

The composition of the limestone in terms of calcite ooze versus sparry cement versus fragmental constituents is shown on figures 31–33. On these triangular diagrams the clastic component was determined by subtracting the percentage of ooze plus sparry cement from 100 percent; the top pole of each diagram represents not only fossil fragments and other carbonate particles, but also silt and sand and minor amounts of some secondary constituents. The data were determined from thin-section point counts, so clay was undoubtedly counted as ooze. Most of the limonite was included with the calcite ooze because it seems to replace or stain mostly areas that were originally ooze.

The data on which figures 31–33 were based are undoubtedly inaccurate. Some finely crystalline sparry calcite counted as cement is probably recrystallized ooze and some of the finer clastic particles were included as ooze. The distribution of the points is intended to reasonably indicate the overall composition of the limestone units rather than to represent individual samples with absolute accuracy.

Samples of limestone units *A* and *B* of the Bluff Creek are plotted on figure 31. All samples contain appreciable clastic debris, but they differ widely in amounts of ooze and sparry calcite. This wide variation is in accord with other observations of the two units. On figures 31–33 the large amounts of sparry calcite in some samples indicate formation of sparry calcite by recrystallization of ooze or from clastic or organic components.

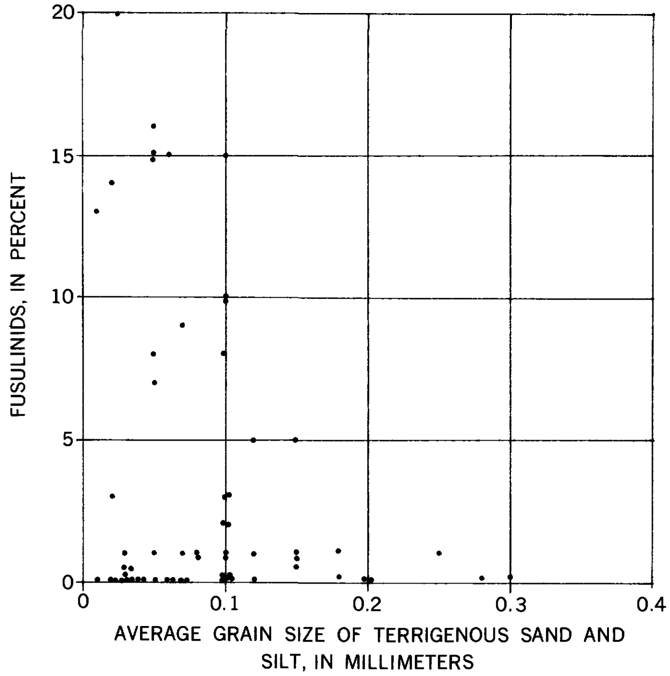

FIGURE 26.—Scatter diagram of percentage of fusulinids versus average grain size of terrigenous sand and silt for all limestone samples studied.

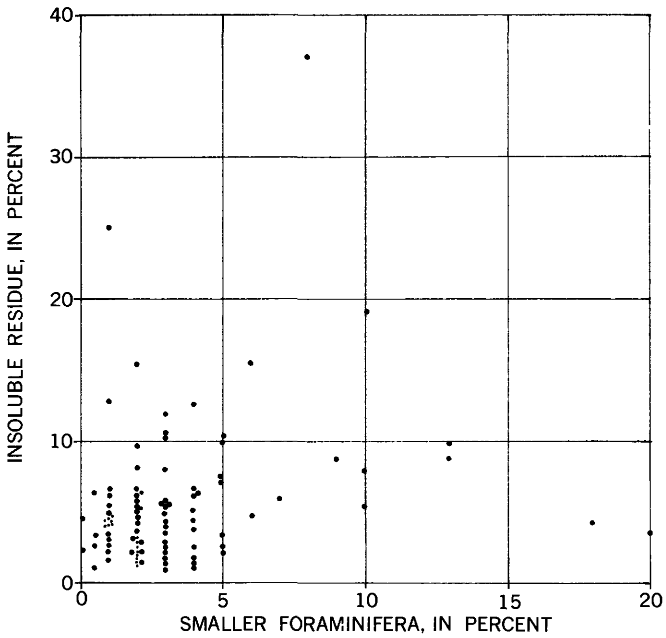

FIGURE 27.—Scatter diagram of percentage of insoluble residue versus percentage of smaller Foraminifera for all limestone samples studied.

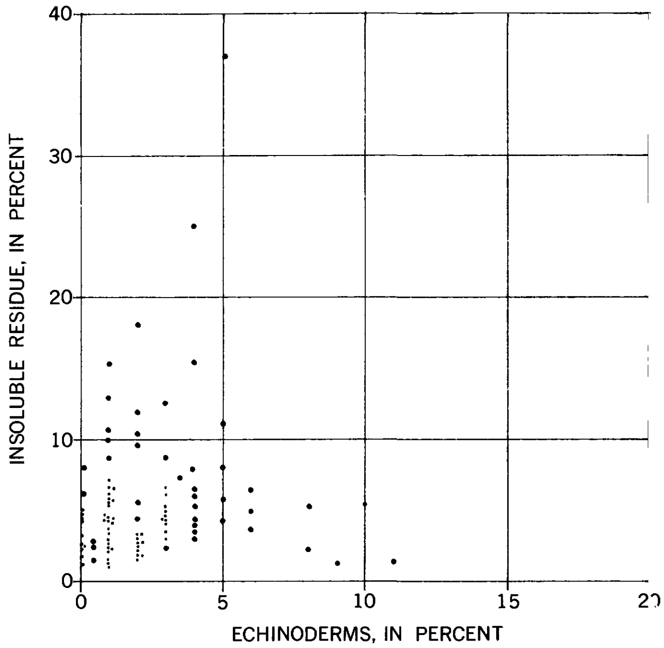

FIGURE 28.—Scatter diagram of percentage of insoluble residue versus percentage of echinoderms for all limestone samples studied.

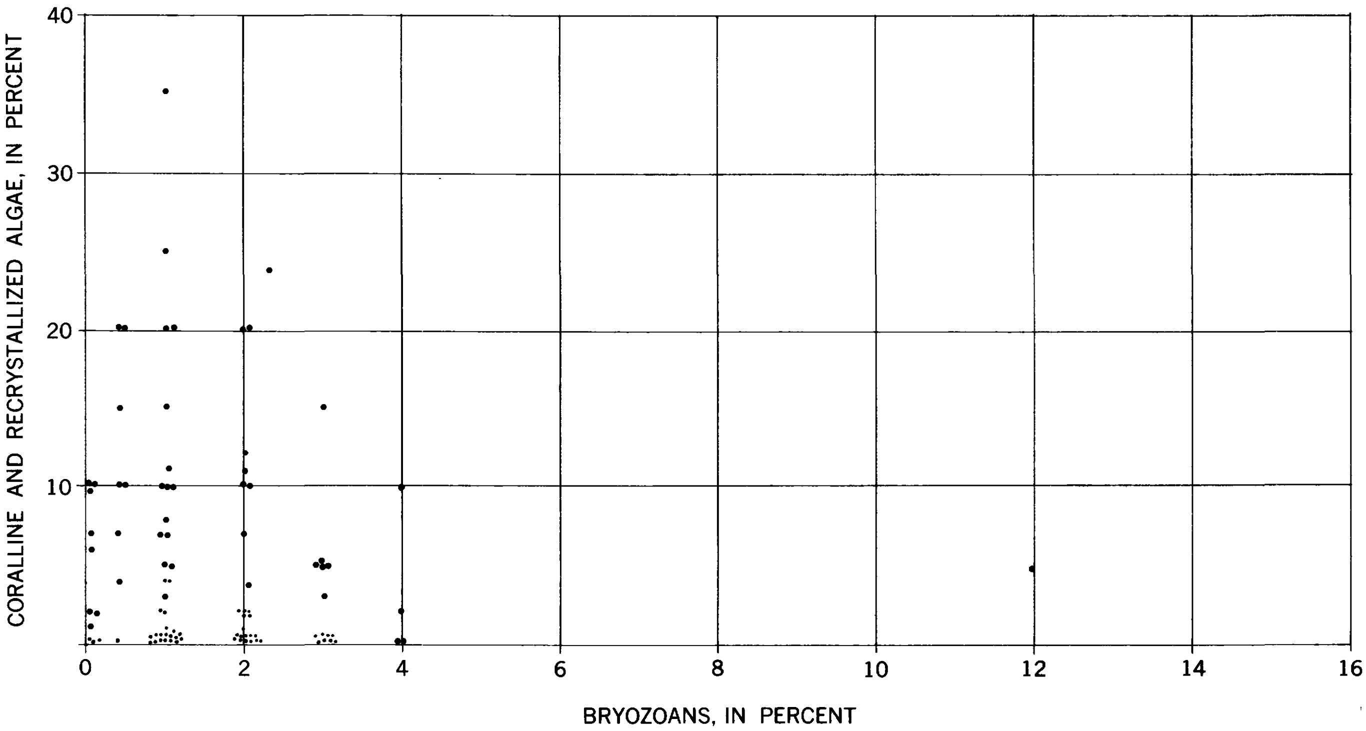

FIGURE 29.—Scatter diagram of percentage of coralline and recrystallized algae versus percentage of bryozoans for all limestone sample studied.

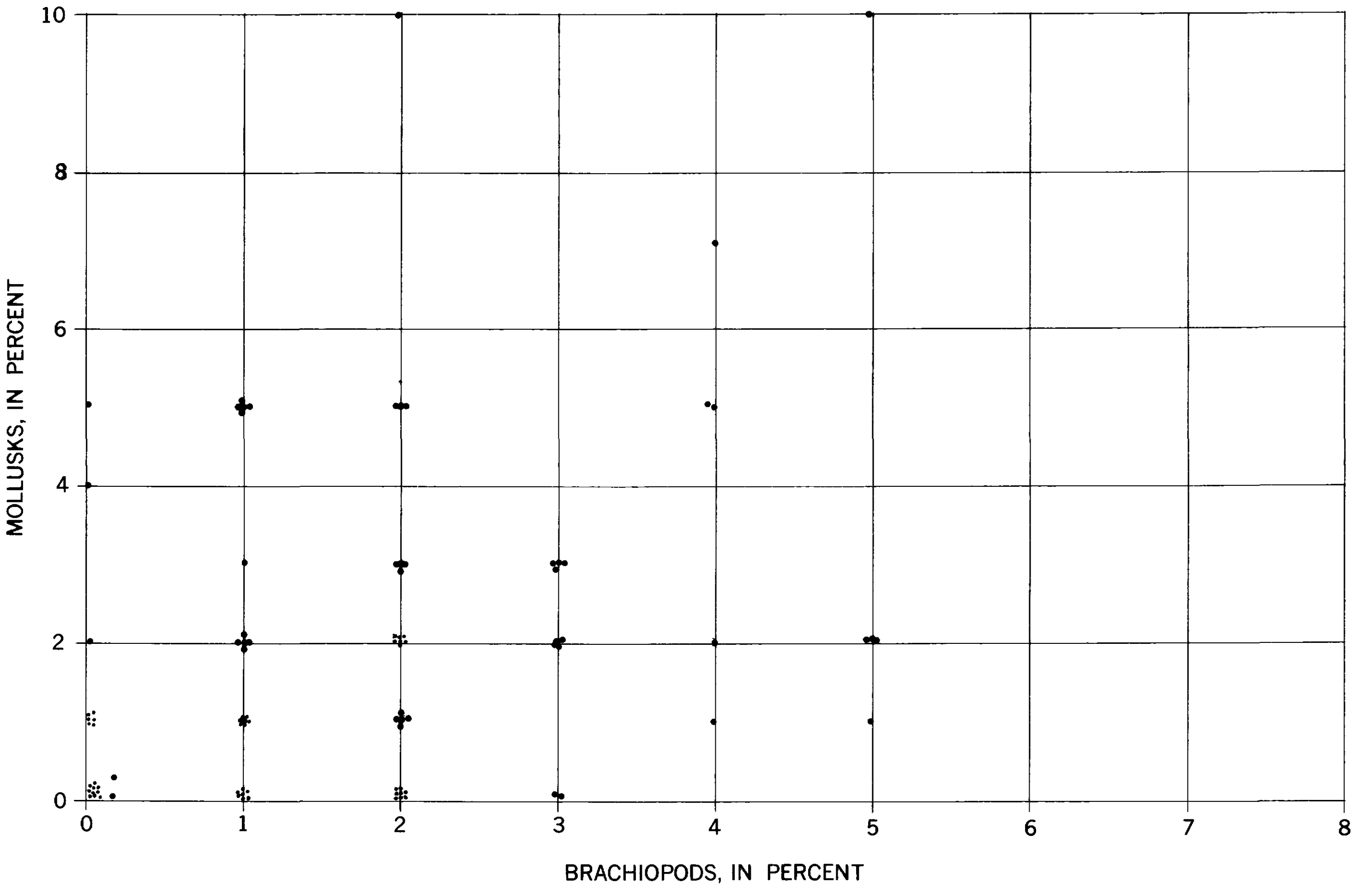

FIGURE 30.—Scatter diagram of percentage of mollusks versus percentage of brachiopods for all limestone samples studied.

Figure 32 shows the composition of samples from units *C*, *D*, and *CD* of the Bluff Creek. With a few exceptions, probably resulting from formation of microspar by recrystallization of ooze, these samples are clustered on the diagram. They are roughly two-thirds ooze (including as ooze some of the finest clastic particles), and one-third allochemical particles, with only small amounts of sparry calcite, quartz sand, and other components. Unit *D* has only one sample outside the cluster, reflecting the greater uniformity of the bed than unit *C*.

Samples from units *A*, *B*, and *C* of the Gunsight are represented on figure 33. The samples of units *A* and *C* are clustered on much the same part of the diagram as were the samples of units *C* and *D* of the Bluff Creek, although the samples from the Gunsight tend to have slightly larger amounts of ooze and less clastic material. The samples of the unit *B* of the Gunsight are less tightly clustered but tend to have very little ooze. This grouping to represent more cleanly washed limestone is also merely a reemphasis of characteristics mentioned previously.

The composition of the organic fraction of the limestone is shown on figures 34 and 35 in terms of relative amounts of fusulinids, smaller Foraminifera, and coralline algae and oncolites. These triangular dia-

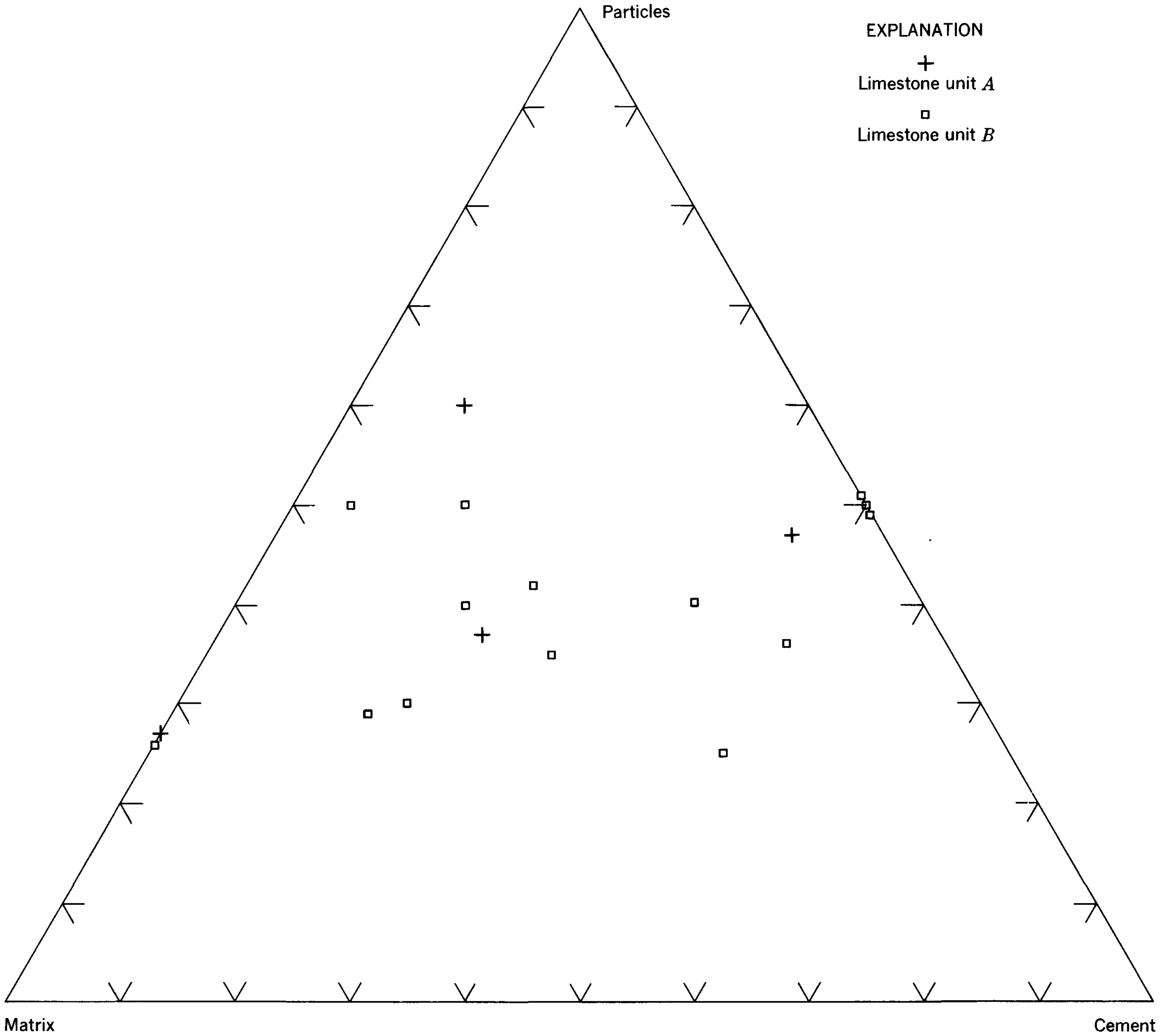

FIGURE 31.—Composition of limestone samples from units *A* and *B* of the Bluff Creek shale member of the Graham formation in terms of cement, microcrystalline-calcite matrix (ooze), and particles (allochems).

grams emphasize some of the differences between limestone units that can be seen on plate 31. The most striking difference is between the limestone units of the Bluff Creek as a whole and those of the Gunsight. Limestone units of the Bluff Creek contain relatively little algal material, but many samples contain large numbers of fusulinids. Samples from the Gunsight member contain considerable algae but few fusulinids. The nature of figures 34 and 35 is such that the position of a sample is determined by relative amounts of the three constituents rather than absolute amounts. From figure 35 it might appear that smaller Foraminifera are rather uncommon in samples from the Gunsight member, but reference to plate 31 shows that this impression is largely due to great numbers of algae in the Gunsight member, making the amount of smaller Foraminifera seem small.

Detailed examination of figure 34 for differences between the individual limestone units of the Bluff Creek member also shows that unit *D* of the Bluff Creek is primarily a fusulinid containing limestone. Every sample of unit *D* contains fusulinids and every sample but one contains at least as much fusulinid material as smaller foraminiferal and algal material combined. Unit *C* of the Bluff Creek contains more smaller Foraminifera; 8 of 12 samples of unit *C* contain

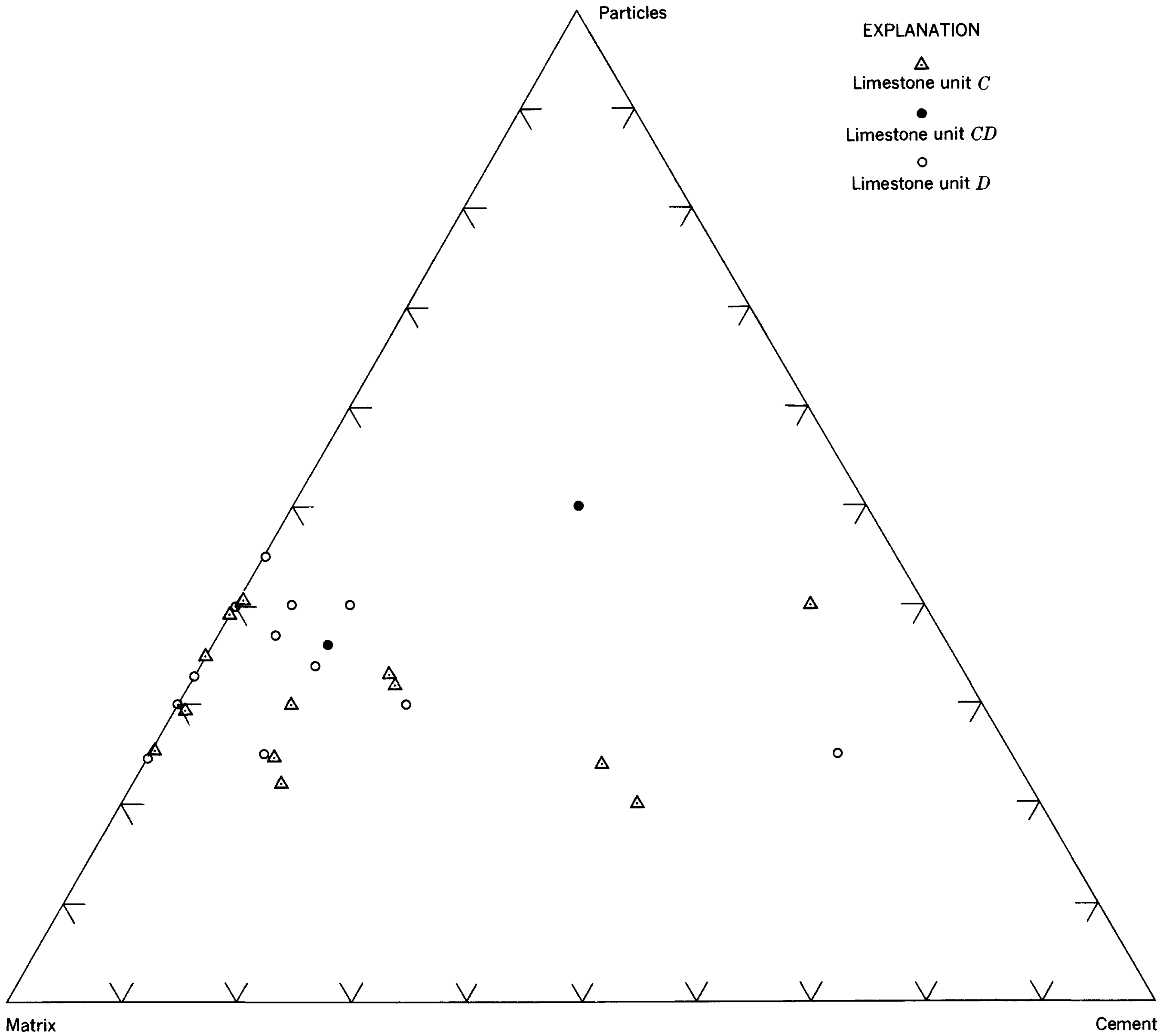

FIGURE 32.—Composition of limestone samples from *C*, *CD*, and *D* of the Bluff Creek shale member of the Graham formation in terms of cement, microcrystalline-calcite matrix (ooze), and particles (allochems).

greater amounts of material from smaller Foraminifera than from fusulinids and algae combined. Units *A* and *B* of the Bluff Creek show no consistent pattern and here, as elsewhere, are best characterized by their lack of uniformity.

No obvious differences between individual units of the Gunsight can be seen on figure 35, although unit *B* shows less uniformity than unit *A* or unit *C*.

LIMESTONE VARIETIES AND THEIR DEPOSITIONAL ENVIRONMENTS

Most constituents of the limestone are too widely and uniformly spread to be considered distinctive in formulating a classification of the limestone. The constituents most diagnostic of certain beds are fusulinids, algae, corals, and insoluble residue. These constituents, together with sorting, proportion of cement to ooze, and the field characteristics of color and bedding, can be used to divide the limestones into 4 types:

1. Unsorted unwinnowed limestone with many fusulinids; it is dark gray where fresh but weathers yellowish orange. This type of limestone is commonly thick bedded, resistant to erosion, and uniform in thickness and lithology along the strike. Transported particles are randomly oriented and poorly sorted.

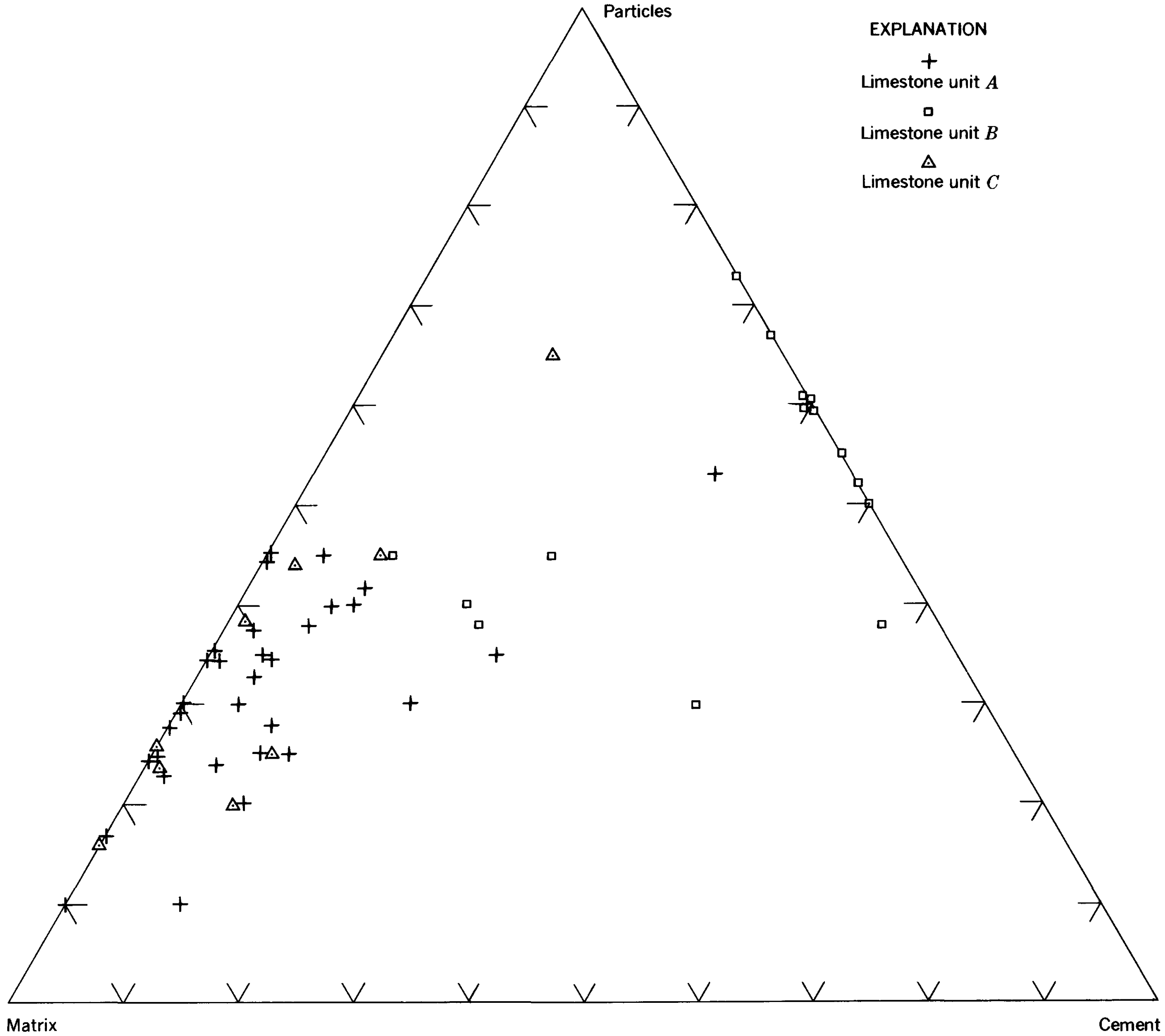

FIGURE 33.—Composition of limestone samples from the Gunsight limestone member of the Graham formation in terms of cement, microcrystalline-calcite matrix (ooze), and particles (allochems).

2. Microcrystalline limestone with many recrystallized algae and veinlets of sparry calcite and locally many horn corals. This type of limestone is light gray and weathers to gray nodular rubble. It commonly changes in thickness along the strike, owing to gradation between limestone and shale.
3. Relatively well sorted and cleanly winnowed calcarenite with sparry cement predominating over ooze. Much of this type of limestone contains ooliths and reworked fossils and limestone fragments; some contains quartz sand. Most commonly it is very light gray to yellowish gray and weathers medium gray. It tends to be thin to medium bedded and is characteristically discontinuous laterally.
4. Light-gray microcrystalline limestone containing few fusulinids or algae but commonly with poorly sorted and poorly preserved fine fossil debris, especially Foraminifera, and pellets. It tends to be nodular where weathered. Limestone beds of this type differ in thickness from place to place but are fairly continuous.

The environments of deposition of these four types of limestone are not fully understood. Tentatively, type 1 limestone is considered to have formed in deeper water than the others. Elias (1937), in his study of

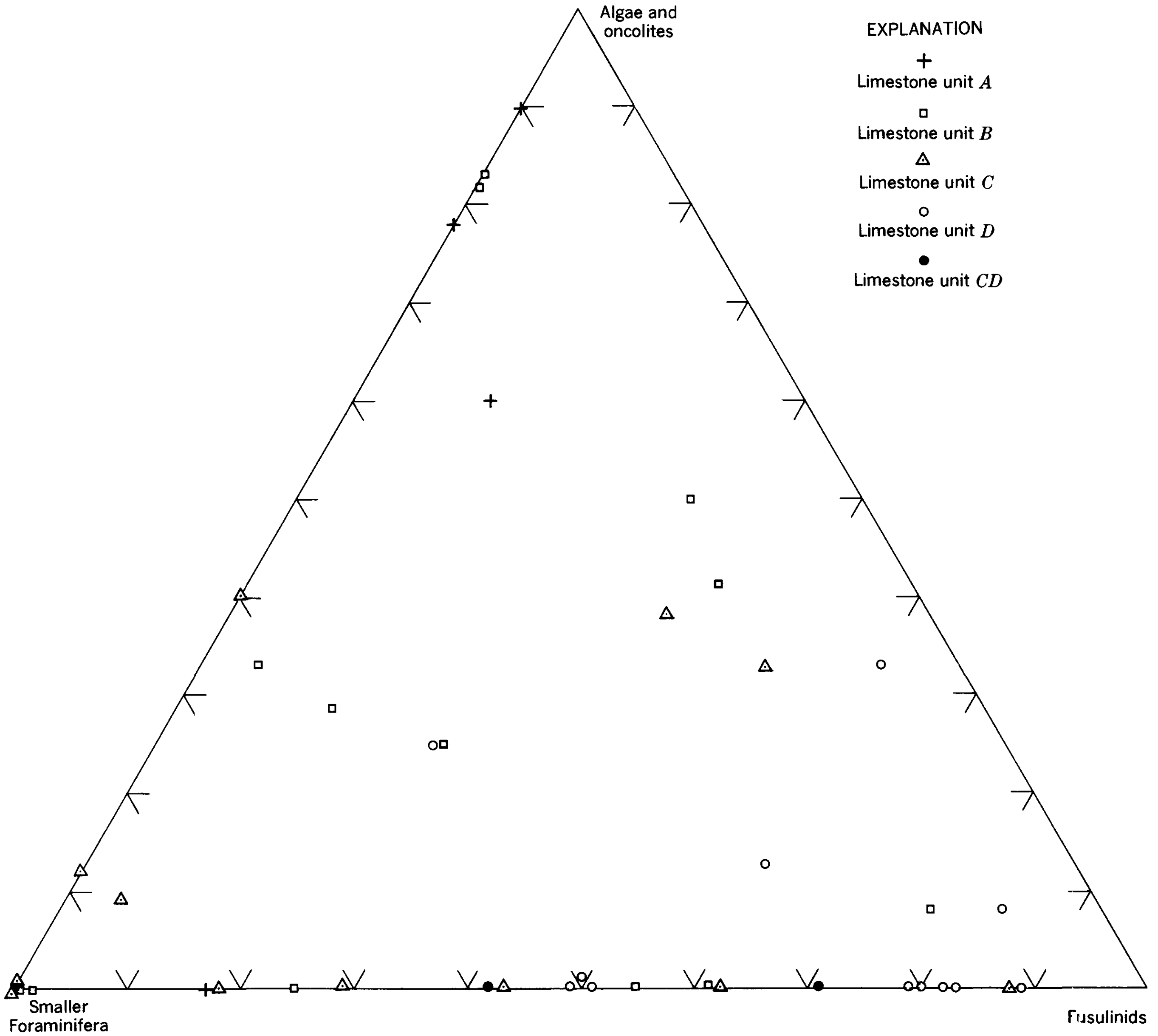

FIGURE 34.—Relative proportions of fusulinids, smaller Foraminifera, and coralline algae and oncolites in samples from the Bluff Creek shale member of the Graham formation.

the cyclothems of the Big Blue series of Kansas, concluded that fusulinid-bearing limestone was deposited in deeper water than any of his other types of limestone. This conclusion was based upon analogy between fusulinids and modern large benthonic Foraminifera and upon the position of the fusulinid limestone in the cyclothems. According to Elias' interpretation, fusulinids in the Big Blue series lived in water between 160 and 180 feet deep.

Type 1 limestone of central Texas is characterized by pyrite and other iron minerals, as well as by fusulinids and so, presumably, was deposited in more stagnant water than the other types of limestone. This could be attributed either to deposition below wave base or to a lagoonal environment. The "normal-marine" aspect of the fauna and the lateral uniformity of this type of limestone indicate that the deeper water interpretation is much more tenable. There is no suggestion, however, that the water was deeper than the 160- to 180-foot depth suggested by Elias for Kansas sediments.

Type 2 limestone is especially difficult to interpret. The association of calcareous algae and corals fits only the mixed-fauna phase of Elias, believed to represent deposition in water ranging in depth from 90 to 110 feet, but the types of calcareous algae observed by Elias

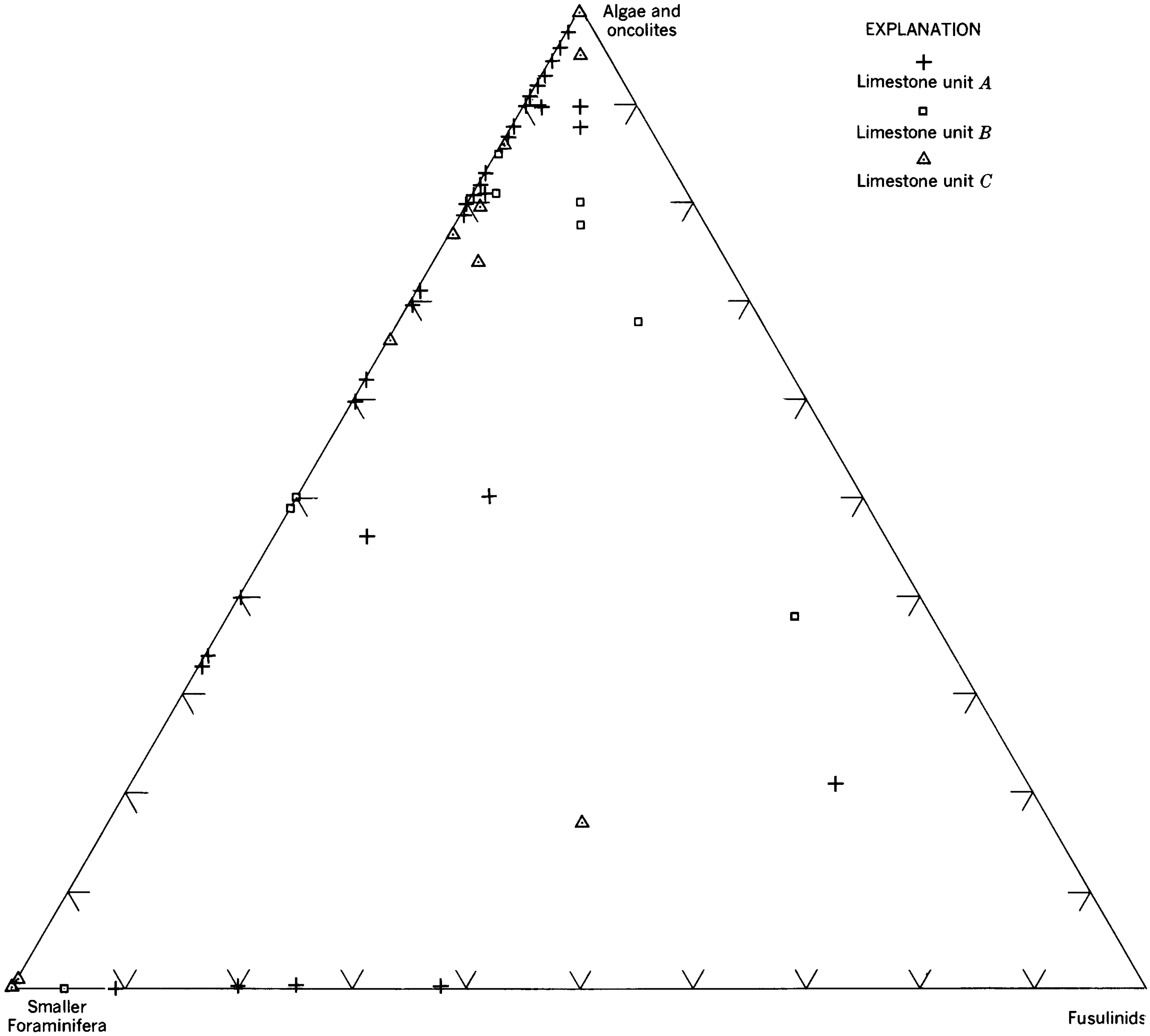

FIGURE 35.—Relative proportions of fusulinids, smaller Foraminifera, and coralline algae and oncolites in samples from the Gunsight limestone member of the Graham formation.

are not the same as the coralline algae characteristic of type 2 limestone. Johnson (1954, p. 40) and Ginsburg (1956, fig. 9) indicate that coralline algae can withstand violent wave action and are most abundant where waves are strong. Corals also grow well where wave action is vigorous. Type 2 limestone, however, seems to have been deposited in very quiet water, as indicated by its large percentage of unwinnowed microcrystalline ooze and by almost unbroken fragile algae. Shrinkage cracks and pseudobreccias suggest very shallow water, although they do not necessarily indicate subaerial exposure. Perhaps type 2 limestone was deposited in a broad area of extremely shallow water protected from strong waves by its breadth and shallowness, similar to the Florida Bay area studied by Ginsburg (1956) but with slightly better water circulation promoting more coral and algal growth. Johnson (1954) describes in detail how coralline algae grow very near or even slightly above sea level, so that deeper water is not necessary.

On a broad flat shelf area with very shallow water, waves are small and conditions are most favorable for chemical precipitation of carbonate ooze. Water deeper than the zone of wave action may also be very calm, but probably fragments of organisms broken elsewhere would be carried in, as indeed they seem to have been during deposition of type 1 limestone.

Over most of the area studied, unit *A* of the Gunsight is type 2 limestone associated with many horn corals. To the northeast the limestone is thinner and corals are almost absent. Near the south boundary of the Grosvenor quadrangle, part of unit *A* of the Gunsight contains fusulinids and is iron stained, thus resembling type 1 limestone. If the land is assumed to have been more to the northeast than to the southwest and if the unit is everywhere contemporaneous, this distribution would show that type 1 limestone represents deposition farthest from shore; type 2 limestone with horn corals, deposition in an intermediate area; and type 1 limestone with no corals, deposition nearest shore.

Type 3 limestone shows abundant evidence of strong wave action: Sorting and rounding of constituent particles, reworked fossils and fragments of limestone, transported ooliths, and relatively large amounts of terrigenous sand. Dasycladacean algae are present in many samples, but otherwise the faunas of type 3 limestone are not diagnostic and may be largely reworked. Type 3 limestone probably originated on offshore bars. Some may also have originated as beach deposits, but in a broad flat area wave action on beaches probably was weak and less effective for winnowing than on bars. Erratic distribution and rapid lateral changes support the hypothesis of deposition on bars.

Type 4 limestone is less distinctive than the other three types, although many beds of light-gray microcrystalline limestone with few fusulinids or algae occur throughout the Upper Pennsylvanian section of central Texas. Perhaps type 4 limestone would require subdivision into several subtypes if this study were extended to other parts of the section.

Unit *C* of the Bluff Creek is the only unit characterized by type 4 limestone. Units *C* and *D* of the Bluff Creek are believed to be regressive and transgressive phases of the same limestone because the two units merge to the southwest. Apparently unit *C* is regressive and unit *D* transgressive. Unit *D* of the Bluff Creek is type 1 limestone previously concluded to have been deposited in water more than 160 feet deep. If this is correct, the regressive equivalent was also deposited at that depth. The differences in depositional conditions during transgression and regression that account for the differences between type 1 and type 4 limestones are not understood. The single limestone unit *CD* of the Bluff Creek southwest of the junction of units *C* and *D* of the Bluff Creek closely resembles unit *D*, so type 1 limestone must be more characteristic of the combined environments.

The paleoecologic and paleogeographic significance of the shale is not entirely clear. The Pennsylvanian rocks of central Texas include many different types of shale that undoubtedly represent many different environments. The diversity of shale types and the dominance of shale in the section suggest that shale be considered the normal rock type of the area and that limestone and sandstone be explained in terms of the absence of clay. In other words, clay seems to have composed most of the sediment being brought into the area and to have been deposited in every depositional environment except those where unusual conditions prevented its deposition. These unusual conditions could have been caused by (1) clay failing to reach an area because of distance from the mouths of streams, (2) protection of the area from influx of clay by bars or other obstructions, (3) bypassing of the clay because of the winnowing action of currents, or (4) by masking deposition of the clay through extremely rapid deposition of carbonate.

The first of these possibilities probably was important for the formation of type 1 and type 4 limestones. The large areal extent of the many thin rock units indicates that the region was extremely flat, so the shoreline must have been a considerable distance away when the water was deepest. At those times most of the clay could be expected to have flocculated and settled out before reaching the area. The second possibility may account for the deposition of type 2 limestone. If type 2 limestone was deposited on flat extremely shallow areas, away from the mouths of streams and perhaps protected from waves and marine currents by offshore bars, little clay could reach the area. The close association between unit *A* of the Gunsight (type 2 limestone) and the underlying, overlying, and interbedded shale supports this hypothesis. At times when the shallow areas were best interconnected with the open sea, greater water circulation could have brought in clay that masked the carbonate precipitation and at the same time encouraged more prolific growth of horn corals, which are indeed most abundant in marly clay associated with unit *A* of the Gunsight rather than in unit *A* itself.

The winnowing action of currents best accounts for the lack of clay in type 3 limestone and also in the sandstone beds of the area. The clear evidence of wave or current action in type 3 limestone makes this seem fairly certain.

A fourth possible reason for deposition of limestone instead of shale at a particular place and time would be an extremely high rate of carbonate deposition that would mask clay deposition. However, several lines of evidence seem to refute this possibility. First, the amount of clay in most of the limestone is fairly small and most of the shale beds are noncalcareous. If it is assumed that the terrigenous content of a limestone is 5 percent, carbonate would have to be deposited 20 times as fast as terrigenous material. This is an unlikely possibility, considering the fact that the shale above and below most limestone units contains virtually no carbonate.

Another reason for believing that the rate of carbonate deposition was not extremely high lies in the relations between the calcite ooze and sparry cement in the limestone. R. L. Folk (oral communication, 1956) pointed out to the writer that it is very unusual for calcite ooze and sparry cement to be so closely intermixed as in the limestone units of the Bluff Creek and Gunsight members. Normally, a limestone will have either a matrix of ooze or sparry cement, but seldom appreciable quantities of both. Folk observed also that the unusual proportions within the limestone units of the Bluff Creek and Gunsight may be due either to gentle currents that washed away part but not all the calcite ooze or to the fact that ooze was being precipitated too slowly to fill all interstices between the accumulating intraclasts. The near absence of sorting, rounding, and especially microbedding in most of the samples makes the first of these choices hard to accept. Moreover, the intermixing of calcite ooze and sparry cement is most apparent in the limestone units of the Bluff Creek, which are believed to have been deposited in relatively deep water where chemical precipitation of ooze would be expected to be slower than in shallower water. Units *A* and *C* of the Gunsight contain microspar, probably formed by recrystallization of material that was originally ooze, but contain relatively little sparry cement, showing that chemical precipitation was relatively rapid in these extremely shallow and presumably unusually warm waters.

GEOLOGIC HISTORY

The Upper Pennsylvanian rocks of central Texas are believed to have been deposited on a shallow shelf area lying between land to the east and northeast and a deeper basin to the west. The land area furnished sediments of both igneous and metamorphic origin and probably consisted of a part of the Ouachita fold belt. Because of tectonic activity in the source area and fluctuations of sea level in the basin, some sediments along the edge of the basin were reworked, cutting channels into slightly older rocks and providing sedimentary source rocks for sediments deposited farther seaward.

The Cisco group was deposited during a time of sedimentary instability marked by alternations of thin widespread units and channel-fill deposits, of red beds and marine limestone. The lowest part of the group, the basal part of the Graham formation, is very poorly exposed in the Grosvenor quadrangle but is marked farther north by a deep channel (Lee, Nickell, Williams, and Henbest, 1938). There is some suggestion that channel cutting may have taken place at this same time in the Grosvenor quadrangle.

The lowest of the limestone beds studied, unit *A* of the Bluff Creek, is less persistent laterally than most of the other limestone beds, apparently reflecting deposition on a slightly irregular surface inherited from the period of channel cutting. Although unit *A* of the Bluff Creek is exposed in only a few places, limestone at least approximating each of the four main types described above have been observed. Probably variation in the depth of water was a major factor in causing this erratic lithology, but location in relation to mouths of streams and the nature of the sea bottom inherited from earlier deposition may have been important. Deposition of calcium carbonate took place by chemical precipitation of fine ooze, by accumulation of organic fragments (both whole and finely comminuted), and by slightly later precipitation of sparry calcite in voids within the sediment. No one type or organism predominated in the accumulating organic debris, but crinoids, bryozoans, and mollusks were relatively abundant. The end of deposition unit *A* of the Bluff Creek probably was caused by further influx of terrigenous materials.

Limestone unit *B* of the Bluff Creek was deposited on a slightly more even seabottom than unit *A*. Some irregularities in the topography had been partially leveled by deposition of terrigenous sediments between the deposition of units *A* and *B* of the Bluff Creek. In the northern part of the area studied, unit *B* of the Bluff Creek was transgressive onto a sandstone bottom, and the deposition of unit *B* itself was strongly influenced by an influx of terrigenous sand. In this region currents were active, and the limestone most commonly resembles type 3 limestone, or at least a lithology intermediate between types 1 and 3. Farther south the water was deeper, currents less active, and the source of terrigenous sediments more distant. Most of the limestone deposited in this area is type 1. During this time fusulinids were the dominant fossil-forming organism.

After deposition of unit *B* of the Bluff Creek, the water again became more shallow. In the northern part of the area, shallow channels that were soon filled with sand cut into unit *B*. Probably this part of the area was a few feet to a few tens of feet above sea level. Neither channel cutting nor sand filling seem to have occurred in the southern part of the area where the end of unit *B* deposition was accompanied by an influx of terrigenous mud.

It is difficult to interpret the conditions immediately after deposition of unit *B* of the Bluff Creek. Perhaps the sea deepened, but terrigenous mud and not carbonate was deposited. The next carbonate deposition resulted in limestone unit *C* of the Bluff Creek, which is believed to represent carbonate deposition in relatively deep water during a regression of the sea. In part of the area unit *C* is type 1 limestone, but elsewhere it is type 4, perhaps because regression was accompanied by currents that kept the water circulating.

During subsequent transgression of the sea limestone unit *D* of the Bluff Creek was deposited. By this time, irregularities in the seabottom had been almost entirely smoothed out, so unit *D* was deposited with nearly uniform thickness over a wide area. The lithology also is uniform laterally, as type 1 limestone represents deposition in waters with poor circulation and presumably of greater depth than usual.

After deposition of unit *D* of the Bluff Creek, slight shallowing of the water caused encroachment of terrigenous clay. As the area was extremely flat, almost no sand accompanied the clay. Thin nodular beds of limestone were formed by chemical precipitation in this broad region except where masked by terrigenous clay.

When terrigenous material became less abundant and chemical precipitation increased, owing to further shallowing and consequent warming of the water, deposition of unit *A* of the Gunsight began, presaged and accompanied by abundant growth of horn corals in many parts of the area. Wherever and whenever the water became too shallow and too restricted in circulation to support corals, coralline algae became the principal agents of chemical precipitation in the formation of limestone. In many parts of the area, deposition of type 2 limestone was interrupted frequently by influxes of terrigenous clay.

Precipitation of carbonate, interrupted by influxes of clay, continued through the time of deposition of unit *C* of the Gunsight, except for a brief interval during which unit *B* of the Gunsight formed. Unit *B* seems to have formed as an offshore bar in response to slightly deeper water and an alongshore current that carried sand from delta areas and winnowed out much of the finest carbonate ooze.

After deposition of unit *B* of the Gunsight as a discontinuous and local offshore bar, the previous conditions returned. During part of the time, terrigenous mud was carried into the area and deposited as shale, and at other times precipitation of carbonate resulted in limestone. The water was extremely shallow during deposition of unit *C* of the Gunsight limestone; perhaps the northeast corner of the quadrangle was above sea level. The shallowing and warming of the water may have caused precipitation of barite, accounting for the greater abundance of this mineral in beds of the Gunsight member than in beds of the Bluff Creek.

After deposition of unit *C* of the Gunsight, channel erosion removed part of the unit and increased amounts of sand were carried into the area. Larger quantities of terrigenous material continued to be carried in; and, except for local and impure beds, no additional limestone was deposited until the Speck Mountain limestone member of the Thrifty formation.

During and after deposition of each limestone unit, other processes led to the formation of shrinkage cracks, to precipitation of sparry calcite within voids, to the recrystallization of some constituents, and to the formation of chert, barite, and the various iron minerals.

Several types of evidence have been used to determine the sequence of these processes.

a. Pyrite is most characteristic of certain beds and seems to be mainly primary.
b. Foraminifera are silicified in every bed and at many many localities. The complete absence of a relation between the silicification and joints, veins, or bedding planes suggests that this silica is also mainly primary.
c. Some calcite fills veinlets that were probably shrinkage cracks formed while the sediment was soft.

d. The shrinkage of the carbonate mud may have accompanied expulsion of water during an inversion of aragonite to calcite.

e. In some thin sections of limestone unit *D* of the Bluff Creek, calcite in veinlets are continuous with calcite inside fusulinids. Some of these fusulinids have been slightly crushed during compaction, but others seem to have been expanded by the force of crystallization of the calcite fill. This fixes the time of filling of the fusulinids and presumably of the veinlets as occurring after the start of compaction but before complete lithification.

f. Calcite filling veinlets that cross algae seems to be younger than the coarser grained calcite of recrystallized algae.

g. In some samples ankerite rhombs occur within coarse-grained calcite of leached and refilled fragments, indicating that the ankerite formed after secondary sparry calcite.

h. Zoned rhombs of ankerite may have been deposited from solutions varying in iron content, but the concentration of iron in their centers suggests that they more likely had pyrite nuclei. If so, they are younger than the pyrite and logically seem to be contemporaneous with unzoned ankerite.

i. In some slides, rhombs of limonite after ankerite occur in both calcite and barite as crystals of about the same size. The rhombs would probably have preferentially replaced the calcite if they had been deposited after the barite. Probably they replaced only calcite and some of them were later isolated by barite replacement of calcite.

j. Barite fills voids left by the last stage of sparry calcite and in one slide seems to replace it.

These observations combine information from all the limestone units studied and assume from the many similarities that the units have had similar petrographic histories. From these observations can be synthesized the following sequence of events.

1. Deposition of clastic sediment and ooze.
2. Formation of pyrite. Precipitation of sparry calcite in primary voids. Silification of smaller Foraminifera.
3. Inversion of aragonite in organic fragments to calcite. Inversion of aragonite ooze to microspar, accompanied by formation of shrinkage cracks.
4. Precipitation of sparry calcite in shrinkage cracks and other secondary voids. This occurred actually in two stages which may have been widely separated in time.
5. Ankerite rhombs replaced calcite, some rhombs originating about pyrite nuclei. Diamond-shaped crystals of hematite replaced carbonate and some hematite replaced pyrite cubes.
6. Deposition of barite as a vein filling and a replacement of sparry calcite and clastic fragments.
7. Recent weathering produced hematite from some pyrite, and limonite from both hematite and pyrite.

Events listed under each number were probably nearly simultaneous or, at least, cannot be placed at specifically different times. The actual timing of the events was that events 1 through 4 and, at least part of 5, occurred very early, probably before burial under more than a few feet of sediments. Deposition of barite in event 6 cannot be dated more closely than between event 5 and Recent weathering.

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[Major references are in italic]

Pennsylvanian and Lower Permian Rocks of Parts of West and Central Texas

GEOLOGICAL SURVEY PROFESSIONAL PAPER 315

This professional paper was published as separate chapters A–E

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

CONTENTS

[The letters in parentheses preceding the titles designate separately published chapters]

PLATES 33–38

PLATE 33

FIGURE 1. Coralline algae of the genus *Archeolithophyllum* showing cell structure and conceptacle. The walls of the dome-shaped conceptacle (upper center) are recrystallized to a sparry-calcite mosaic. × 33. Upper part of limestone unit *A* of the Gunsight limestone member of the Graham formation, locality 1029.

2. Fragment of recrystallized coralline algae retaining cell structure as "ghosts" in a mosaic of sparry calcite. × 33. Sample same as that shown on figure 1.

3. Fragments of dasycladacean algae, probably *Epimastopora*, in cleanly winnowed and oolitic limestone. The two dasycladacean fragments (*d*) show two views of particles of about the same shape. × 33. Limestone unit *B* of the Gunsight limestone member of the Graham formation, locality 738.

4. Oncolite composed primarily of blue-green algae. × 33. Limestone unit *A* of the Gunsight limestone member of the Graham formation, locality 835.

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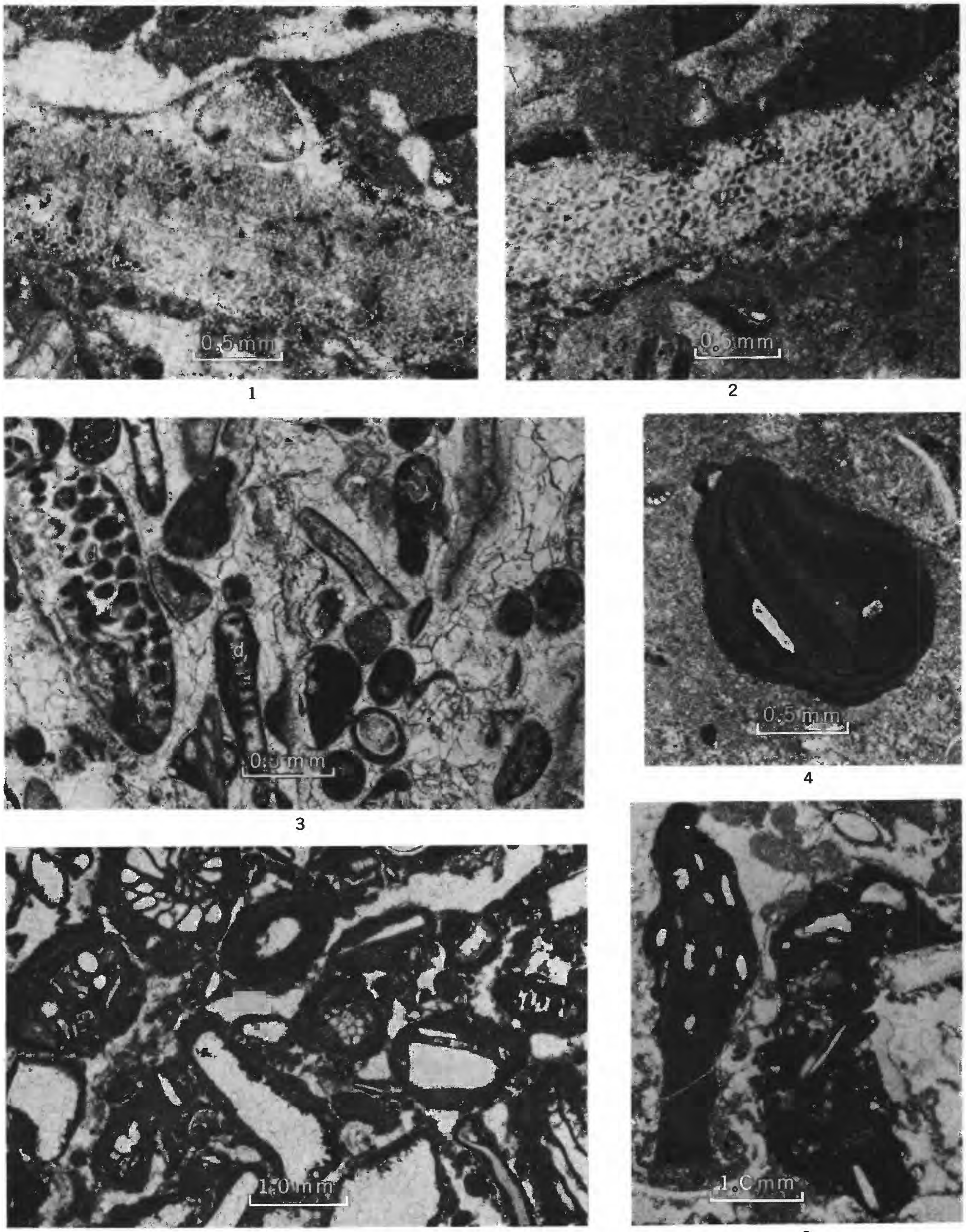
6. Oncolites, held together by blue-green algae, contain Foraminifera and enmeshed clastic debris as well as algae. × 18. Basal part of limestone unit *A* of the Gunsight limestone member of the Graham formation locality 828.



ALGAL TYPES SEEN IN THIN SECTION

PLATE 34

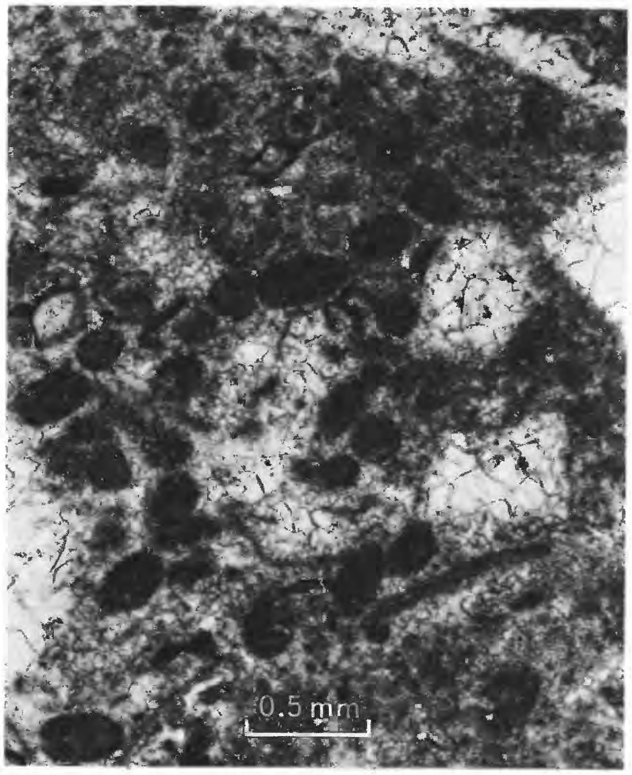
FIGURE 1. "Ball" of sparry calcite adjacent to recrystallized fragment of coralline algae. × 33. Limestone unit *A* of the Gunsight, locality 828.

2. "Ball" of sparry calcite apparently connected to sparry-calcite mosaic of probable recrystallized coralline algae. × 55. Limestone unit *A* of the Gunsight, locality 738.

3. Pellets in limestone. Pellets are far more abundant and more distinct in the area of this photograph than in other parts of the slide. Notice places, especially near right margin, where dark spots that seem originally to have been pellets have almost lost their identity in surrounding ooze. × 33. Limestone unit *C* of the Gunsight limestone member of the Graham formation, locality 1012a.

4. Oolitic limestone. Black patches at center and extending to upper right are barite (*B*) replacing calcite. All the barite that is black in this picture (at extinction position under crossed nicols) is in optical continuity and is interconnected in three dimensions. × 33. Limestone unit *B* of the Gunsight limestone member of the Graham formation, 1,200 feet northwest of locality 828.

5. Reworked limestone fragments. Fragment slightly left of center contains quartz silt (*Q*). × 25. Limestone unit *A* of the Bluff Creek shale member of the Graham formation, locality 602.



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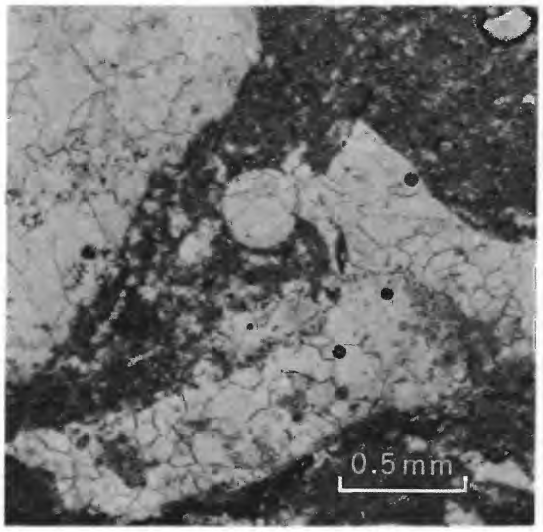

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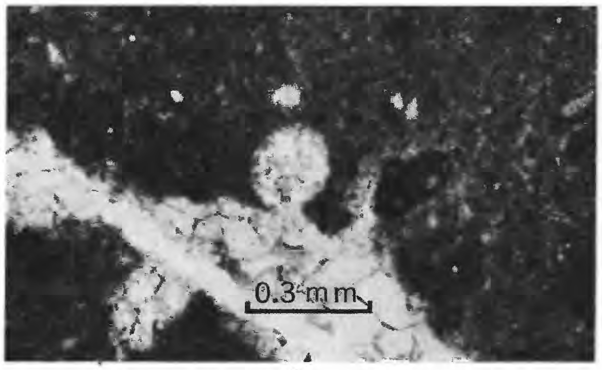

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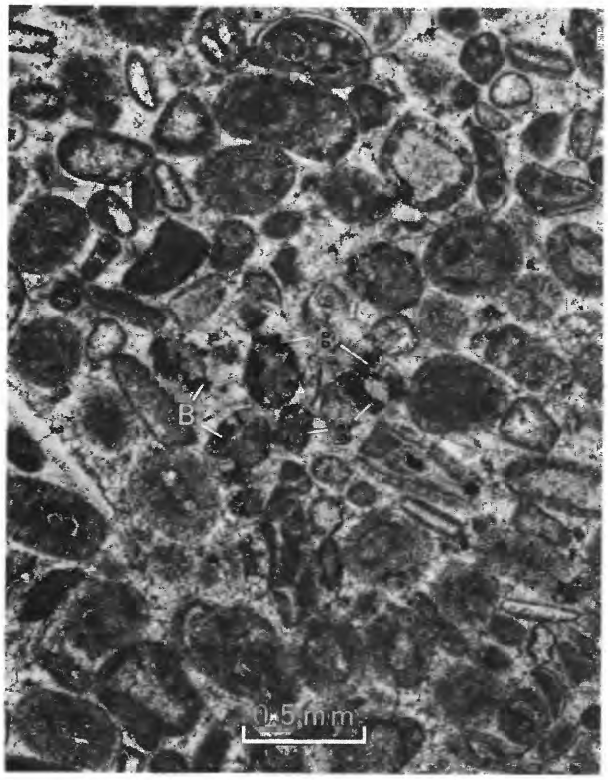

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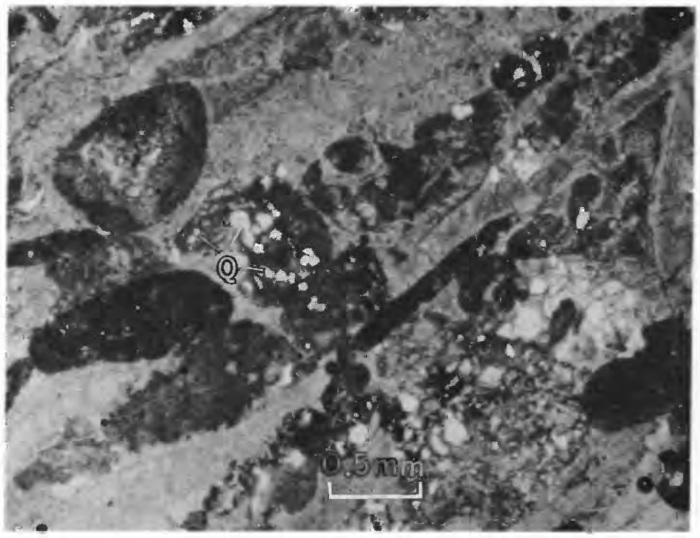

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SPARRY CALCITE BALLS, PELLETS, AND REWORKED LIMESTONE FRAGMENTS

PLATE 35

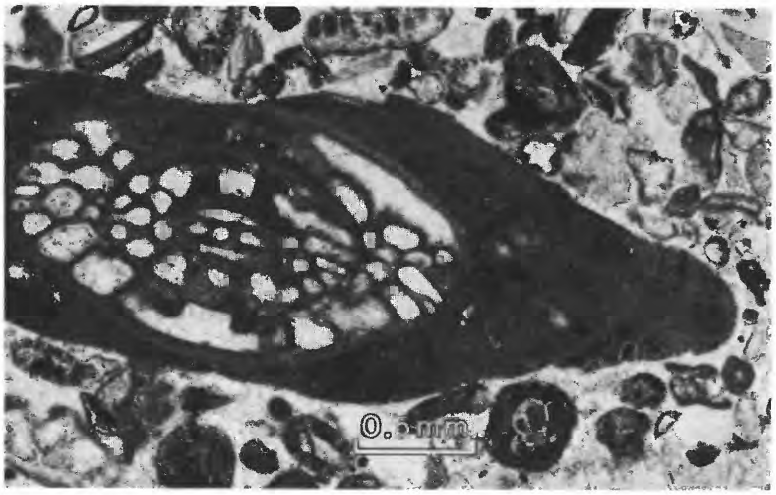
FIGURE 1. Reworked fusulinid. During original burial of fusulinid outer whorls were filled with ooze and inner whorls with sparry calcite. During later reworking outer part of fusulinid has been worn away and part of ooze filling abraded. × 33. Limestone unit *B* of the Gunsight limestone member of the Graham formation, locality 828.

2. Vein of barite replacing sparry calcite. A few small remnants of calcite remain in the vein. A second vein of ankerite, mostly altered to limonite, extends from the center of the photograph to the bottom. Note also the many sparry-calcite "balls" in the limestone. × 15. Limestone unit *C* of Gunsight limestone member of the Graham formation, locality 706.

3. Rhombs of ankerite replacing calcite. The ankerite has been largely altered to limonite. × 65. Limestone unit *A* of the Gunsight limestone member of the Graham formation, locality 828.

4. Diamond-shaped crystals of hematite in limestone. × 80. Limestone unit *C* of the Gunsight limestone member of the Graham formation, locality 715.

5. Zoned rhombs of ankerite now partly altered to limonite. Most rhombs have a center of limonite, probably representing an iron-rich core, and a border in which limonite is concentrated. × 75. Limestone unit *B* of the Bluff Creek shale member of the Graham formation, locality 604.



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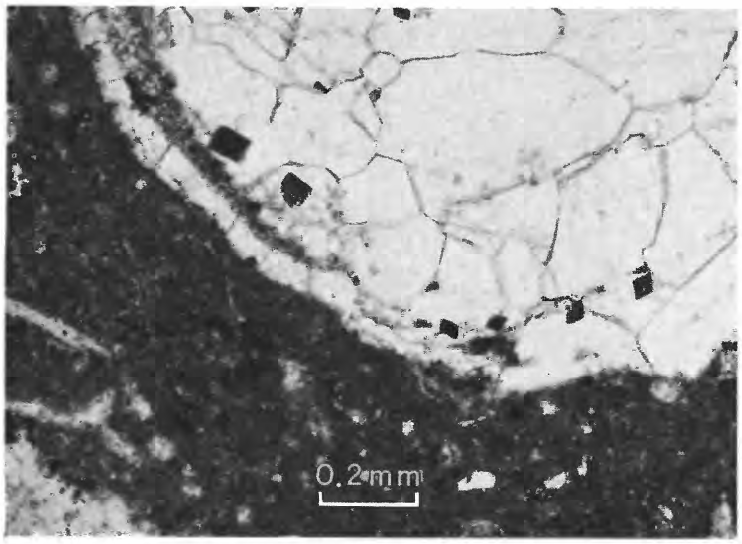

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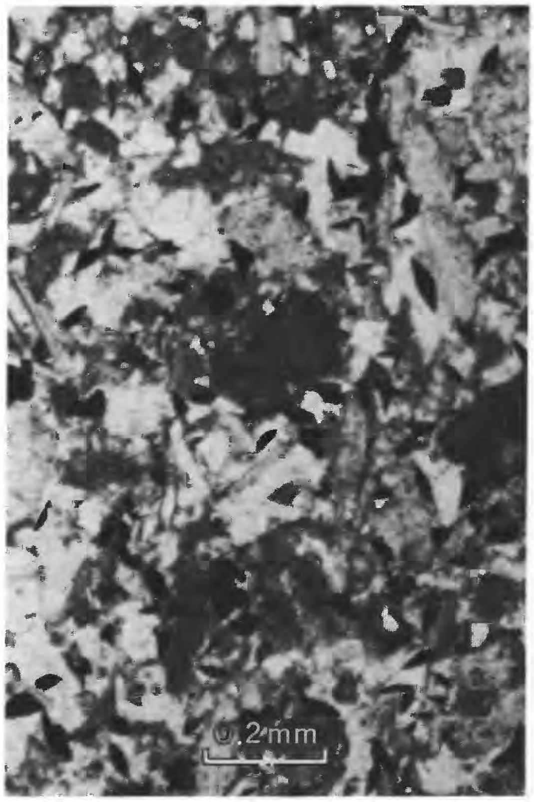

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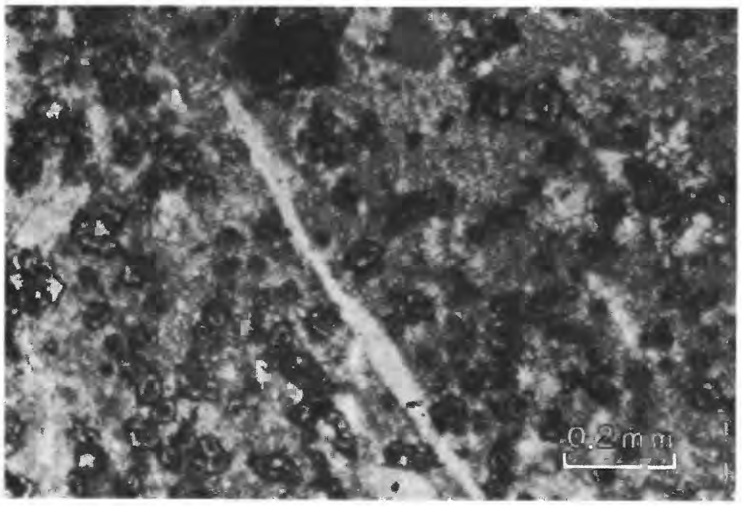

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REWORKED FUSULINID AND AUTHIGENIC MINERALS

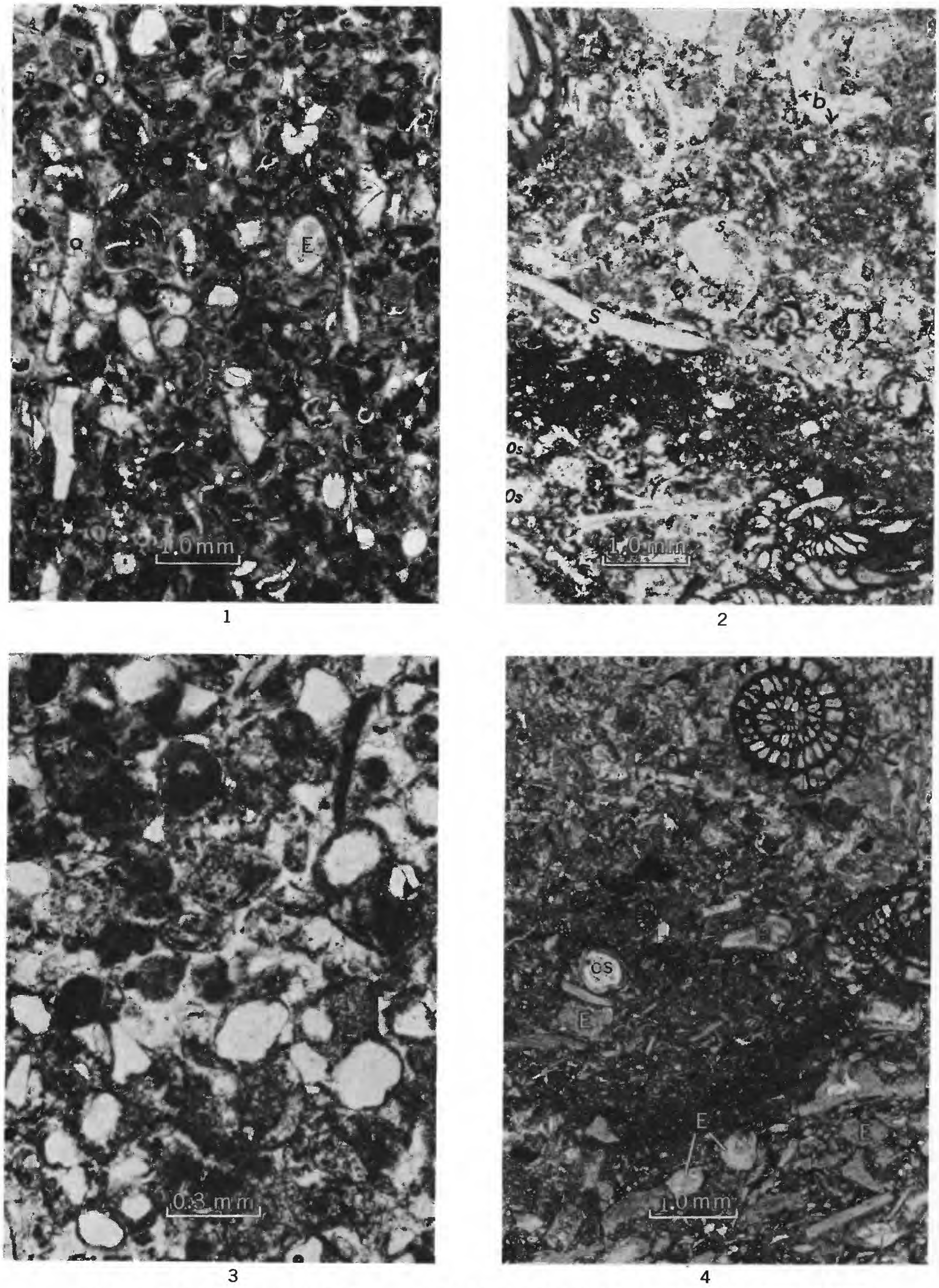
PLATE 36

FIGURE 1. Typical limestone unit *A*. Dark particles consist of fossil fragments coated wtih calcite ooze (bryozoan shreds are among the most abundant), limonite-stained fossils, and unidentified particles that probably include reworked limestone fragments. Light-colored particles are predominently echinoderm fragment (*E*) and recrystallized or replaced shell fragments. × 15. Locality 1012.

2. Typical limestone unit *B*. Black band just below center and most pronounced at left margin is an area of limonite stain. Fossils and fossil fragments include fusulinids (extreme upper left and lower right corners); smaller Foraminifera (scattered through upper half but most abundant near right center); recrystallized shell fragments (*S*), probably mollusks; ostracodes (*Os*); and a thin-shelled brachiopod (*b*) lined with sparry calcite. × 15. locality 1012.

3. An unusually sandy sample of unit *B*. Many of the quartz grains (white) are coated with dark-appearing calcite ooze, probably from having been rolled about on a carbonate-mud seabottom. × 55. Locality 839.

4. Typical limestone unit *CD*. Dark areas are limonite stained. Fossils and fossil fragments include fusulinids (top and right margins); smaller Foraminifera (scattered, most abundant in upper half); echinoderm fragments (*E*, and others); fragments of brachiopods (*B* is one of several probable brachiopod fragments); and many unidentified fragments. × 15. Locality 1058.



THIN SECTION FEATURES OF *A*, B, AND *CD* LIMESTONE UNITS OF THE BLUFF CREEK SHALE MEMBER OF THE GRAHAM FORMATION

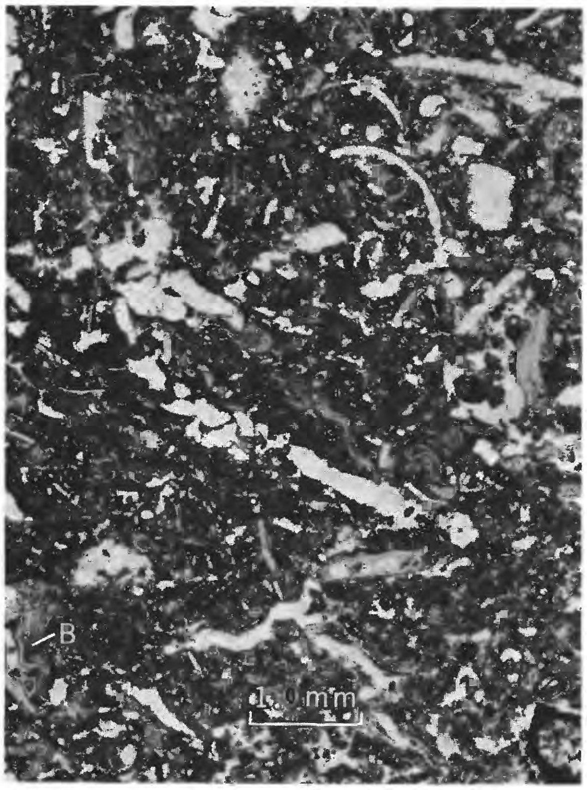
PLATE 37

FIGURE 1. Typical limestone unit *C* of the Bluff Creek. Many smaller Foraminifera are present. One bryozoan shred (*B*) is at lower left. Many of the irregular white areas (sparry calcite) seem to have been voids rather than fossils. Those just to the left of center may have been in part, small borings; others perhaps were caused by slight slumping. × 15. Locality 1013.

2. Typical limestone unit *D* of the Bluff Creek. Matrix darkened with limonite stain. Fossils and fossil fragments include fusulinids (at top), a few smaller Foraminifera, and echinoderm fragments (*E*). Most of the elongate fragments are parts of brachiopod shells. One oblique section of a brachiopod spine (*sp*) can be seen at lower left. × 15. Locality 709.

3. Vein and fusulinid filled with sparry calcite. The fusulinid test seems to have been pushed apart by the growth of sparry calcite within, and thus the sparry calcite seems to have been deposited before the surrounding rock was lithified × 33. Limestone unit *D* of the Bluff Creek. Locality 1025.

4. Typical limestone unit *A* of the Gunsight. Large fragments composed of sparry calcite are mostly pieces of recrystallized coralline algae. Dark material just below center and coating coralline algae at lower right was formed by blue-green algae. Matrix is lighter colored toward lower right because ooze has been largely converted to microspar. × 15. Locality 884.



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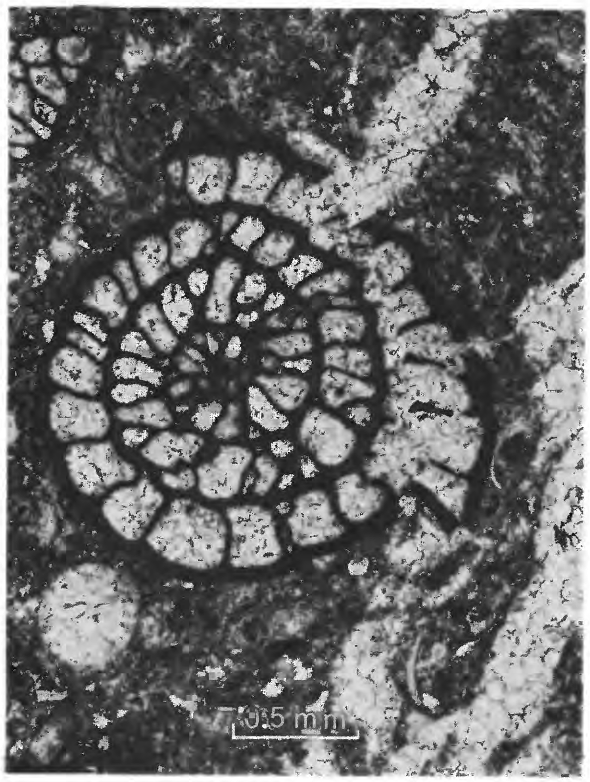

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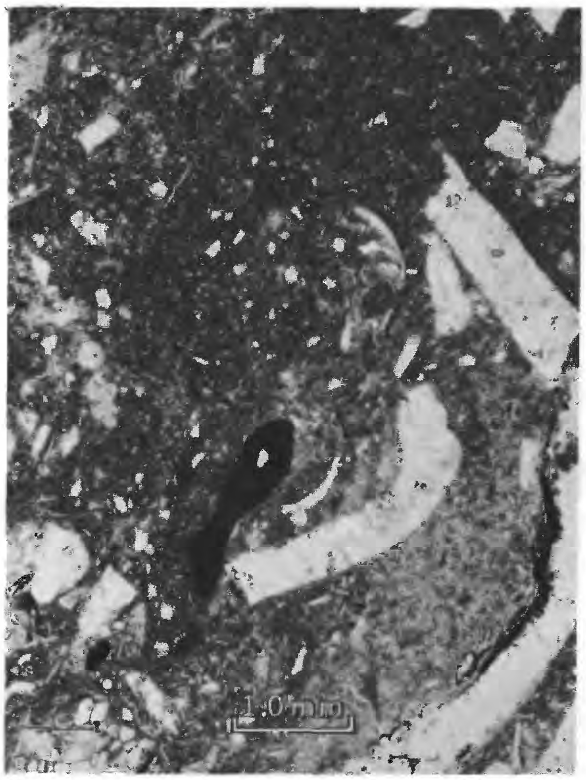

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THIN SECTION FEATURES *C* AND *D* LIMESTONE UNITS OF THE BLUFF CREEK SHALE MEMBER AND LIMESTONE UNIT *A* OF THE GUNSIGHT MEMBER OF THE GRAHAM FORMATION

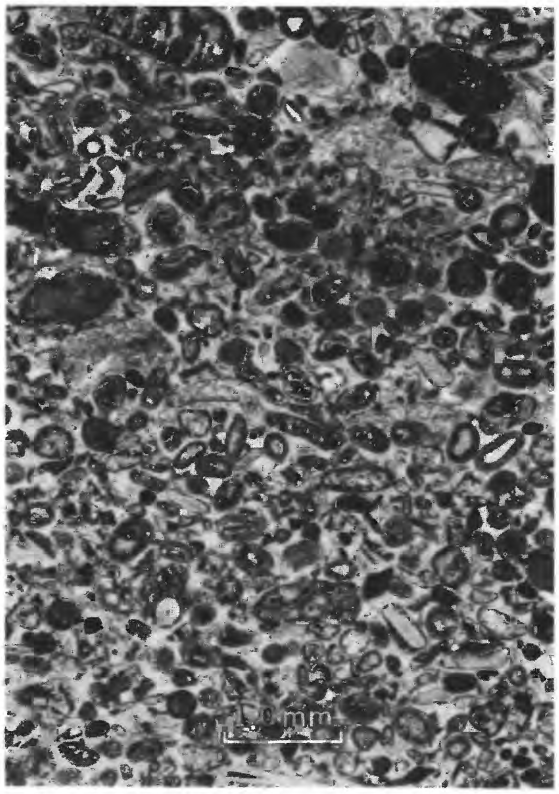
PLATE 38

FIGURE 1. Typical limestone unit *B*. × 15. 1,200 feet northwest of locality 828 (same section, at smaller scale, as that shown on pl. 34, fig. 4, to show overall texture).

2. Mounds rising from the top of limestone unit *B* where exposed on a bare dip slope at locality 882.

3. Thin section of limestone from mounds shown in fig. 2. Irregular cracks (top of photograph), now filled with sparry calcite, seem to have been caused by slight slumping, which would indicate that the mounds are primary structures and not formed later by erosion. × 33.

4. Typical limestone unit *C*. The large fragment of sparry calcite extending downward and right from the upper left corner, as well as several smaller fragments, is recrystallized coralline algae. A microstylolite, black because of limonite and psilomelane(?) stain, extends from the left margin and follows the lower edge of the large algal fragment a short distance before dying out. × 15. Locality 1012a.



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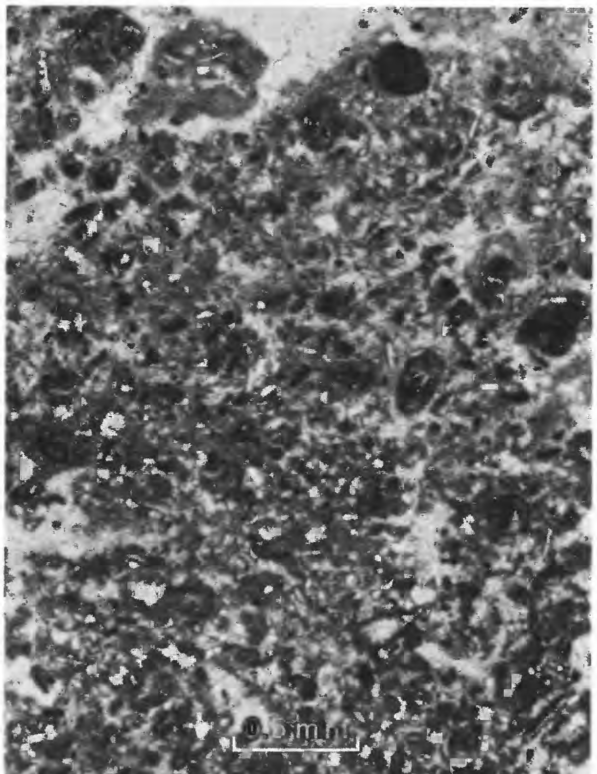

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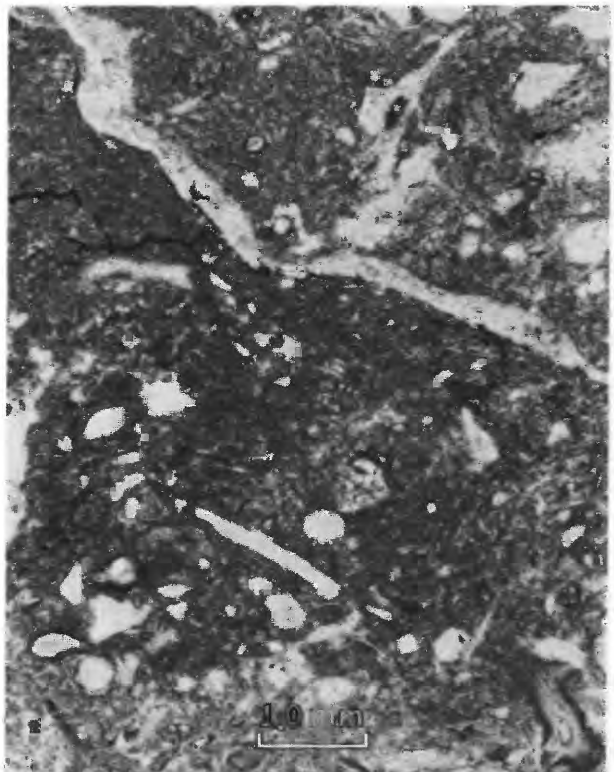

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FEATURES OF LIMESTONE UNITS *B* AND *C* OF THE GUNSIGHT LIMESTONE MEMBER OF THE GRAHAM FORMATION

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