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CONICAL STRUCTURES IN THE MIDDLE PRECAMBRIAN
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CONICAL STRUCTURES IN THE MIDDLE PRECAMBRIAN MICHIGAMME FORMATION

By

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ABSTRACT

CONICAL STRUCTURES IN THE MIDDLE PRECAMBRIAN MICHIGAMME FORMATION

By

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Small conical structures that were tentatively considered to be algal stromatolites, a shallow water sedimentary feature, are found in black slates and graywackes, interpreted as deep water turbidity current deposits. The inconsistency of how an organosedimentary structure which depends on light for its existence could form in the non-illuminated depths of a marine basin was finally dismissed, because the structures showed a greater resemblance to cone-in-cone structure, a post-depositional feature that does not require light to form. Examination of core segments and thin sections proved that the structures could neither be stromatolites in growth position, nor stromatolites transported as clastic debris.

The methods used in this study involved petrographic analysis of core segments and thin sections, staining, and microprobe analysis.

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INTRODUCTION

STATEMENT OF THE PROBLEM

In the Baraga Basin of Baraga County, Michigan, Mancuso, Lougheed, and Shaw (1975) strongly suggest the presence of columnar branching algal stromatolites in cherty carbonate iron-formation of the Marquette Range Supergroup of Middle Precambrian age. Eastward along strike in this basin and in other portions of northern Marquette County, the immediately overlying Upper Slate Member of the Michigamme Formation consists of gray to black graywacke, argillite, and slate, containing thin layers of small conical laminate structures, tentatively considered to be Conophyton-type stromatolites when view macroscopically in diamond-drill cores (Trow, 1979). However, these graded-bedded clastics appear to be Bouma-type turbidite sequences deposited in a reducing, deep-water environment as suggested by sedimentary type and by the presence of present-day abundant pyrite and graphite. Such a sedimentary setting traditionally is not considered to be favorable for the growth of stromatolite-producing algae, which presumably could not grow at such light-free depths. Several questions arise: 1) Are these small cones paleobiologically significant Conophyton-type stromatolites which grew *in situ* at hitherto unrecognized depths in a relatively light-free reducing environment? 2) Are these layers of small cones clastic fragments of stromatolites deposited as rip-up clasts by turbidites, shifted basinward to deep water from shallow platform growth area, and hence are of no paleobiological *in situ* significance? 3) Are these small cones something else, such as cone-in-cone structures, as suggested by A. T. Cross (1980, personal communication)?

4) What is the origin of these cone-bearing layers and their laminations? 5) When were they formed? 6) Do they have any stratigraphic significance that could be useful in correlating strata of the Michigamme Formation of the Marquette Range Supergroup, which is dated between 1900 and 2000 Ma (Van Schmus, 1976).

LOCATION

Samples used in this study were taken from four of the six drill cores obtained during the DOE--Bendix--Michigan Geological Survey Upper Peninsula Precambrian Project (Fig. 1), which are now stored at the Michigan Department of Natural Resources #1 Regional Headquarters, Marquette, Michigan. Sites selected for those four Precambrian Project drill holes were section 5, T. 50 N., R. 28 W. for drill core 1; section 2, T. 48 N., R. 28 W. for drill core 4; section 16, T. 49 N., R.27 W. for drill core 5; and section 4, T. 50 N., R. 28 W. for drill hole 7 in Marquette County, Michigan. Samples from drill hole 5 were not included in this study after preliminary investigation revealed a lack of possible algal structure. Of significance to this study are the locations of drill holes 1 and 7 in the East Baraga Basin, and the location of drill hole 4 in the Dead River Basin.

GEOLOGY OF THE STUDY AREA

Both the Baraga Basin in northwestern Marquette County and the Dead River Basin in north-central Marquette County are located north of the Marquette Synclinorium. They are sedimentary basins containing Middle Precambrian Baraga Group "metasediments... of quartzite, cherty iron-formation, graywacke, slate, and argillite" (p. 7, Burns), and

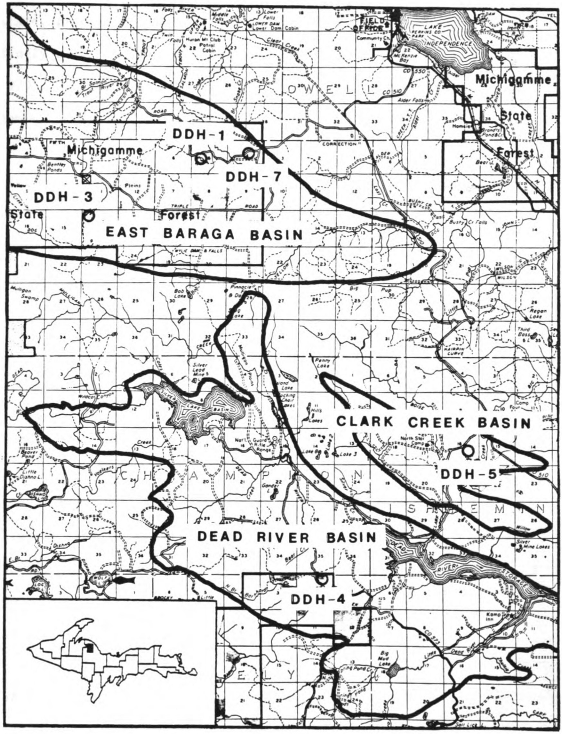

Figure 1. Index map of the East Baraga, Clark Creek, and Dead River Basins (after Trow, 1979). This map shows the sites of diamond drill holes 1, 3, 4, 5, and 7; and the inset shows the location of the map in the Upper Peninsula of Michigan.

slate, respectively (Seaman, 1910; Burns, 1975), which behaved independently until Bijiki time when seas inundated the entire area (Trow, 1979). The sediments in each are believed to correlate with the Michigamme Formation (Van Hise and Leith, 1911; Burns, 1975).

Drill core 1 penetrated glacial overburden and the Upper Slate Member of the Michigamme Formation, while drill core 7 penetrated overburden, the Upper Slate Member, Bijiki Iron Formation Member, and Precambrian W granite. Drill core 4 was drilled through overburden, Precambrian Y diabase, Upper Slate and Bijiki Iron Formation Members of the Michigamme Formation, Goodrich Quartzite, and Precambrian W tonalite (Trow, 1979). The stratigraphic column of the Marquette District is provided as a reference (Fig. 2).

The Bijiki and Upper and Lower Slate Members intercepted by drilling contrast with the Michigamme Formation of the Marquette Synclinorium, which contains the Clarksburg Volcanics Member and the Greenwood Iron Formation Member in addition to these three members (Cannon and Klasner, 1975). In contrast to the more varied lithology of the Marquette Trough, (Boyum, 1975), macroscopic examination showed pertinent core segments to be composed primarily of argillite and graywacke assigned to the chlorite zone of metamorphism (James, 1955).

One final item that deserves mention is the stratigraphic horizon of the conical structures, which seems to be the lower part of the Upper Slate Member of the Michigamme Formation (Trow, 1979).

TERMINOLOGY

Because revisions of terminology by other researchers have led to the use of "Michigamme Formation", "Upper Slate Member", "Precambrian W, X, and Y", and "argillite" in this study, a brief discussion of that

Precambrian Y	Keweenawan		diabase dikes and plugs
Precambrian X	Marquette Range Supergroup	Baraga Group	Michigamme Formation Upper Slate Member -- metagraywacke, schist, and slate Bijiki Iron Formation Member -- cherty silicate iron formation Lower Slate Member -- black slate, quartzite, argillite Clarksburg Volcanics Member -- mafic to intermediate pyroclastics Greenwood Iron Formation Member -- magnetic silicate iron formation Goodrich Quartzite -- quartzite, conglomerates, argillite
			UNCONFORMITY
		Menominee Group	Negaunee Iron Formation -- carbonate, silicate, and oxide iron formation Siamo Slate -- argillite, slate, graywacke Ajibik Quartzite -- quartzite, local conglomerate beds
			UNCONFORMITY
		Chocolay Group	Wewe Slate -- gray sericitic and quartz-sericite slate Kona Dolomite -- various colored massive dolomite and cherty dolomite Mesnard Quartzite -- vitreous white quartzite Enchantment Lake Formation -- Reany Creek Formation metasediments
			UNCONFORMITY
Precambrian W			gneiss and schist

Figure 2. Stratigraphic column of the Marquette District. (Cannon and Gair, 1970; Boyum, 1975; Cannon and Klasner, 1975).

history is in order. James (1958) subdivided the Precambrian rocks of northern Michigan into Lower Precambrian rocks corresponding to the Archean-type, and Middle and Upper Precambrian rocks corresponding to the Algonkian-type of the older literature (Leith, Lund, and Leith, 1935). He also revised "Huronian" to "Animikie Series", because of a lack of correlation of the Huronian type section with other districts in the Lake Superior region (Figure 3). Cannon and Gair (1970) replaced "Animikie Series" with "Marquette Range Supergroup", which encompasses James's Chocolay, Menóminee, Baraga, and Paint River Groups, the last of which is now recognized by some researchers (Cambray, 1978; Trow, personal communication) as equivalent to the Menominee and Baraga Groups. As a replacement of "Michigamme Slate", which they considered to be a misnomer, Cannon and Klasner (1975) resurrected Van Hise's terminology (1897) "Michigamme Formation" to include an Upper Slate Member, the Bijiki Iron Formation Member, a Lower Slate Member, the Clarksburg Volcanics Member, and the Greenwood Iron Formation Member. Cannon (1974) combined the Marquette Range Supergroup with James's interim scheme (1972), resulting in the classification of the Michigamme Formation and the Baraga Group as Precambrian X rock units.

As a final point, the term "argillite" is restricted to a low rank metamorphosed shale without slaty cleavage, while slate refers to a metamorphosed shale possessing slaty cleavage (Flawn, 1953; Moorehouse, 1959).

SAMPLE COLLECTION, PREPARATION, AND EXAMINATION

SAMPLE COLLECTION

Drill cores obtained from DOE--bendix--Michigan Geological Survey Precambrian Project which presently are stored at the Department of Natural Resources Headquarters in Marquette, Michigan, were used for this study. Appropriate samples were selected by consulting the Engineering Reports which denoted footages of algal-bearing core. Drill core extending fifteen feet both above and below each algal-appearing section was sampled to determine the lithology in which the structures were embedded. With the aid of a 13 W 4000 Rock Trimmer, the cores were split and half was left in the storage boxes, at the request of Jack van Alstine.

The samples and thin sections are identified by a five-digit hyphenated number. The first four digits refer to the depth cored, and the fifth digit refers to drill core 1, 4, 5, or 7. Letters refer to multiple samples from a single foot of core: 2761A-4 is stratigraphically above 2761B-4, which is above 2761C-4, and so on; all are from a depth of 2761 feet in drill core 4. "Top" and "bottom" also refer to relative positions within a designated footage. The letters M, N, O, P, W, X, Y, Z, K, and L indicate the thin section is a replacement of one that was damaged. A sixth number, such as in 2769-4 #4 indicates the thin sections is one of four taken from that depth. Thin sections are often more precisely identified than core segments.

THIN SECTION PREPARATION

Sixty-seven thin sections were originally prepared from the samples collected, but more slides were necessary because of damage, or incomplete coverage of a structure. Thin sections were to have been made parallel or perpendicular to bedding planes, but they would have represented too small a surface area. Instead, orientations were chosen to record as large a sample as possible on the slide. Bedding, therefore, shows only an apparent and not a true thickness.

The thin sections were chosen to illustrate possible algal structures, the contacts between the structures and the adjacent lithology, and the adjacent lithology, to determine if they were perhaps clasts of the Bouma sequence. At depths of 2039 feet in drill core 1, and 2769, 2774, and 2861 feet in drill core 4, pieces of drill core were missing at the DNR; consequently only the lower contact of the upper layer of structures and the upper contact of the lower layer of core segment 2774-4 are preserved. There are gaps in core segments 2039-1, 2769-4, and 2861-4, because these footages were previously sampled for DNR thin sections; and not all the structure can be said to have been documented with certainty. A sample taken from 2856 feet in drill core 4 made reconstruction of the core somewhat uncertain, but the most logical sequence downward stratigraphically is 2856-4 K, 2856-4 L, 2856-4 M, and 2856-4 N. At 2774-4, the proper sequence proceeding downward is 2861-M, 2861-NO, 2861-4 O, and 2861-4 P; at 2907 feet in drill core 4 the sequence is 2907-4 X, 2907A-4, and 2907B-4, proceeding downward.

The aim of documenting the top and bottom of the algal structures was not reached with segment 2861-4, because what was preserved in the core was a side of the structure. It is assumed that the entirety of the structure was represented in all other segments.

THIN SECTION EXAMINATION

Thin sections were examined petrographically at the following magnifications: 40, 100, 200, and 400, and their descriptions are included in Appendix A.

Samples once thought to contain structures, from 1992 feet in drill core 1, and from 682-683 feet in drill core 5, are believed to lack conical structures and were not used for further study.

Point counts were made of all slides, except those of primarily carbonate lithology. Rock fragments were counted as such, and not as constituent minerals. Because of the fine-grained nature of the samples, it was often difficult to determine what constituted a rock fragment; and in such cases individual minerals were counted. Different point totals resulted from the samples' unequal surface areas. When the cross hairs fell on grain boundaries, the point was assigned to one of the two lithologies, and was not discounted.

Concerning 2867-4, the percentage of pyrite depended on the position of the slide in the point counter, but actually it appears to be bedded pyrite within the argillite, and a larger sample is needed for a more accurate point count.

Measurements of the apparent angle between the axis of symmetry of the conical structure and the bedding planes in the argillite were taken from thin sections (Table 1). The reading may appear greater than the actual angle, because of the orientation of the axes and the bedding planes in thin section. The purpose of the measurements is to help determine if the structures are in growth position (approximately 90°) or if they were brought in from another source (all orientations ranging from 0°, where one axis is parallel to bedding, to 90°, where structures are both right-side up and upside down).

Table 1. Measurements of orientation, size and apical angle of conical structures.

SAMPLE NUMBER	ORIENTATION TO BEDDING	SIZE RANGE (mm.) WIDTH	HEIGHT	SHAPE	OBSERVED NUMBER OF CONICAL STRUCTURES	APICAL ANGLE
2039-1 DNR small sample	90°	2.3 (actual) to 3.0[1]	5	conical	at least one	indeterminate
2039-1 DNR large sample	indeterminate	2.25, diameter		rosettes	at least two	none
2039-1	indeterminate	2.0 to 7.5	1.2 to 2.5	parts of cones	3 or more	41° - 42°
2039c-1 top	52°	1.0 to 2.25	2.0 to 2+ cm.	conical	many	15° - 18°
2039c-1 bottom	indeterminate	indeterminate		obliterated	many (?)	indeterminate
2761A-4	upside-down[2] 75°	0.5 to 3.5	0.5 to 5.5	conical	many	36° - 50°
2761C-4	right-side up 78°	1.5 to 3.5	2 to 7	conical	many	35° - 62°

Table 1. (continued)

SAMPLE NUMBER	ORIENTATION TO BEDDING	SIZE RANGE (mm.) WIDTH	HEIGHT	SHAPE	OBSERVED NUMBER OF CONICAL STRUCTURES	APICAL ANGLE
2769-4	upside-down, right-side up; 62° - 72°	0.75 to 2.5	1.25[3] to 2.75	conical, some fragments; commonly obliterated	many	40° - 45°
2774-4 #1	assumed parallel to bedding	2 - 7, diameter		rosettes	many	none
2774-4 #2	upside-down, nearly 90°; some can't be oriented	2.0 to 3.5 fragments: 0.23	6 0.23	conical, and parts of cones	many	35° - 63°
2774a-4 bottom	right-side up	at least 3	0.3 to 10	conical, and truncated pieces	many	22° - 47°
2774B-4 #3	upside-down	3.4 to 5	1.6 to 5	truncated cones	several (?)	no apex present
2769-4 #1-3	upside-down 70° - 90°	0.5 to 4	0.75 to 8	conical, some truncated	many	21° - 38°

Table 1. (continued)

SAMPLE NUMBER	ORIENTATION TO BEDDING	SIZE RANGE (mm.) WIDTH	HEIGHT	SHAPE	OBSERVED NUMBER OF CONICAL STRUCTURES	APICAL ANGLE
2856-4	upside-down 76° - 81°; indeterminate for oblique views	2.5[4]	5.5	conical	many	9° - 36°
2861-4 M	upside-down	?	1 to 9	bottoms of cones	3 or more	no apex present
2861B-4	indeterminate	2.25	6.5 to at least 7.25	conical	many	19° - 35°
2861-4 O	apparently up-side down; approx-imately 45°	3.5 (maximum values)	10	conical, some obliteration	many	36° - 55°
2907A-4	apparently right-side up; some in-determinate	4[5] to 8	6 to 11	conical, much obliteration	many	45° - 57°
2907B-4	upside-down	1.5 to 3	2 to 8	conical	many	33° - 60°

Table 1. (continued)

SAMPLE NUMBER	ORIENTATION TO BEDDING	SIZE RANGE (mm.) WIDTH	HEIGHT	SHAPE	OBSERVED NUMBER OF CONICAL STRUCTURES	APICAL ANGLE
483-7	upside-down	0.2 to 0.25	0.2 to 0.75	conical, much oblit-eration	many	22^{o} - 34^{o}

1, 3, 4, and 5. This is not the skewed reading which would result from measurements taken from the middle of a side to the base, but what would be the result if the interconical clay layers were extended so that measurements were obtained from a theoretical base.

2. Upside-down and right-side up directions are given in relation to the downhole direction.

Apical angles were also determined from thin section by rotation of the stage.

STRATIGRAPHIC HEIGHT COMPUTATIONS

Stratigraphic height or thickness above the top of the Bijiki Iron Formation Member was computed by multiplying the cosine of the angle between the bedding and a plane perpendicular to the core axis, by the difference in depths between the top of the Bijiki Iron Formation Member and the particular occurrence of conical structures.

The angles between the core axis and bedding, obtained by measureing core segments with a protractor, yielded angles of 34° for segment 2761-4, 32° for 2769-4, 17° for 2861-4, 31° for 2039-1, and 36° for 483-7. Obliterated bedding prevented such measurements in 2774-4, 2856-4, and 2907-4, In the first two cases, the values for the angles in core segments 2769-4 and 2861-4 were used (32° and 17°, respectively) because of proximity. 17° was also used for 2907-4, because bedding was assumed to have a constant dip to the base of the Upper Slate Member.

In Table 2, 2507 feet is a theoretical depth computed from the assumption that Precambrian W rocks would be intercepted at 2599 ft. (Trow, 1979).

IDENTIFICATION OF CARBONATE BY MICROPROBE AND STAIN

Thin sections 2039-1, 2761C-4, 2769-4 #1, 2774-4 Y, 2856-4B (borrowed from the DNR), 2861B-4 (transverse section, not previously listed), 2907A-4, and 483-7 were analyzed for magnesium, manganese, calcium, zinc, and iron by Tom Taylor with an ARL electron microprobe using an accelerating potential of 10 kv. and 0.05 milliamperes beam current. Percentages of $CaCO_3$, $MgCO_3$, and $FeCO_3$ that he computed are given in

Table 2. Stratigraphic height of conical structures.

	DDH-1	DDH-4	DDH-7
Stratigraphic height of conical structures above the top of the Bijiki Iron Formation Member, in feet	401	170	70
		167	
		162	
		105	
		100	
		56	
Depth to the top of the Bijiki Iron Formation Member, in feet	2507	2966	569

Table 3.

All samples containing the structures were tested in at least one thin section for calcite with alizarin red stain.

Table 3. Percentages of $CaCO_3$, $MgCO_3$, and $FeCO_3$ in conical structures.

SAMPLE	% $CaCO_3$	% $FeCO_3$	% $FeCO_3$
2039-1	52	40	8
	49	42	9
	47	34	19
	43	38	19
2761-4	53	41	6
	52	41	7
2769-4	47	38	15
	96	2	2
	45	10	10
2774-4	57	37	6
	55	38	7
	53	35	12
2856-4	56	26	18
	55	27	18
2861-4	45	31	24
	46	40	14
2907-4	50	37	13
483-7	49	49	2
	57	41	2
	51	41	8

ENVIRONMENT OF DEPOSITION OF THE UPPER SLATE MEMBER

Environmental conditions suitable for the deposition of black muds and their preservation as black shales have been discussed by numerous researchers (Strøm, 1939; Twenhofel, 1939; James, 1951; Krumbein and Garrels, 1952; Pettijohn, 1957). The sequence involves organic matter preserved in the bottom of a sedimentary basin as a result of toxic, oxygen-depleted water. This reducing environment, illustrated by the Black Sea and Norwegian fjords, is brought about by restricted circulation of bottom water and bacteria that reduce sulfate to sulfide and generate H_2S in the process. Otherwise known as an euxinic environment and characterized by a low oxidation-reduction potential or Eh, (Pettijohn, 1957), it is believed to be the environment of deposition of black graphitic slate (low-grade metamorphic counterpart) of the Michigamme Formation in Iron, Baraga, and Marquette Counties (James, 1951; Pettijohn, 1957; Olmsted, 1962; Burns, 1975).

The alternation of great thicknesses of black shales, argillites, and slates, with graywackes (Tyler and Twenhofel, 1952) has led to the interpretation of the Michigamme Formation's Upper Slate Member as a product of turbidity currents (Cannon and Klasner, 1977; Trow, 1979; Larue and Sloss, 1980). Samples from a depth of 2761 feet from drill core 4 contain such features as rock and argillite fragments, which may be rip-up clasts, and reinforce this interpretation (Stanley, 1963). Thin sections are too small to permit observation of grading, elsewhere suggested as evidence for the turbidity current origin of the Michigamme Formation (Hase, 1957; Cannon and Klasner, 1977). Trow's suggestion (1979), that the clastic source for turbidites during deposition of the Upper Slate Member was from the south because there is a northwardfining of grain sizes, is consistent with Alwin's conclusion (1979) that paleocurrent indicators of the Tyler Formation in Wisconsin and Michigan, of which the upper lithology is correlative with the Michigamme Formation (Leith, Lund, and Leith, 1935; Sims, 1976), imply movement of turbidity currents "toward the west-northwest....from a single source area for all of Tyler time" (p. 225).

The Baraga Group has been attributed to primarily geosynclinal (James, 1954; Hase, 1957, Pettijohn, 1957) and more specifically, eugeosynclinal sedimentation (Cannon, 1973). Proceeding to a more inclusive view, Pettijohn (1957) integrated the depositional environments of black shales and geosynclinal graywacke into one model:

> The clastic facies recognized are an expression of the tectonic stability or instability of the site of deposition.... Rapid subsidence carries the site below the wave base. If ample clastic materials are available they will consist of muds, settled from above, and immature sands introduced by turbidity underflows. The result is a rhythmically interlayered and even-bedded accumulation of graywackes and shales (p. 631).

More recently, Van Schmus (1976), Cambray (1978), and Larue and Sloss (1980) have interpreted the data in the light of plate tectonic theory, where sedimentary basins were simultaneously filling and subsiding into passive continental crust, later to be structurally deformed into the Marquette, Felch, and Menominee Synclines by a continental collision. This theory may be extended upon further investigation to the East Baraga, Dead River, and Clark Creek Basins.

If the conical structures found in the Michigamme Formation are stromatolites, then one of two issues is raised:

1) If the structures are in growth position, how did photosynthetic algae flourish in a toxic, reducing environment to form stromatolites?

2) If the structures are not in growth position, were they transported into the basin as rip-up clasts by turbidity currents?

DESCRIPTION OF STRUCTURES

Structures anticipated in the Upper Slate Member are turbidites Conophyton, which may be confused with cone-in-cone structure. Descriptions are provided to facilitate identification in thin section.

TURBIDITES

For this study the concept of turbidity current deposits as defined by Walker and Mutti (1978) will be used:

> Collectively, a group of turbidites in outcrop will be very regularly bedded, and consist of alternating coarse and fine beds.... The coarse layers are normally sandstones.... The fine layers are shales.... Individually, each coarse layer has a sharp or erosive base with an assemblage of sole marks.... Internally the sandstone is commonly graded.... (p. 120).

Several salient points indicate why the Bouma Sequence is in fact considered a turbidity current deposit:

1) The Bouma sequence contains graded bedding, which has been argued (Kuenen and Migliorini, 1950) and experimentally demonstrated (Kuenen and Menard, 1952; Kuenen, 1953; and Middleton, 1967) to be a product of turbidity currents.

2) Both "convolute ripple lamination and convolute lamination" are included within the current ripple interval of the Bouma Sequence (Bouma, 1962). Dzulynski and Walton (1965) produced convolute laminations with small-scale turbidity currents; and from observations of a fluvial environment, Harms and Fahnestock (1965) theorized current ripple lamination to result from the decreasing flow regime of a turbidity current.

3) Sole marks such as flute casts and tool marks, that are now included in a modified version of the Bouma Sequence (Stanley, 1963), were produced experimentally by turbidity currents in glass tanks

(Dzulynski and Walton, 1965).

4) The actual sequence of intervals in the Bouma Sequence (Middleton and Hampton, 1973) could result from bedforms produced by a waning turbidity current (p. 109, Harms and Fahnestock, 1965).

Stanley (1963) modified the original Bouma Sequence to include rip-up clasts that "represent non-consolidated muds....ripped off the floor of the basin and transported and redeposited downslope by the passing current" (p.787). Bouma (1962) also described sequences where the bases and upper layers were absent.

STROMATOLITES

Walter (1972) describes stromatolites as "layered organosedimentary structures", formed when microbial communities trap and bind sediment in order to survive (Golubic, 1976; Awramik, Margulis, and Barghoorn, 1976). Once preserved in the sediments, these algal mats consist of layers of the organic remains of algae and bacteria (Monty, 1976) alternating with layers of detrital and chemically precipitated carbonate. Cyanophytes or blue-green algae, eucaryotic algae, photosynthetic bacteria, and various heterotrophic bacteria (Golubic, 1976) are present-day stromatolite-building organisms, which may include the microboring alga Plectonema terebrans (Smith, 1951; Drouet, 1968), which has been collected from depths of 370 meters (Lukas, 1978).

Stromatolites are currently forming in subtidal and intertidal environments (Gebelein, 1976; Playford and Cockbain, 1976), freshwater marshes (Eggleston and Dean, 1976), hot springs (Walter, 1976), and sabkhas (Kinsman and Park, 1976). Furthermore, the fossil record documents shallow water forms (Playford et. al., 1976; Haslett, 1976; Horodyski, 1976). Hoffman (1976), however, has argued on the basis of stratigraphic analysis for the existence of deep-water forms, reporting that Conophyton-like columns...grew in foreshelf basins of water tens or even humdreds of meters deep" (p. 611).

Hoffman's findings are controversial when data regarding the lower limit of light necessary for the growth of algae and bacteria are considered. Brock (1976) reported 2100 - 2800 lux as the minimum for blue-green algae and eucaryotic algae to flourish, but Sverdrup's calculations (1942) show that light diminishes to 2500 lux in the clearest ocean water (p. 776) at 100 meters (Brock, 1976). The difficulty of how algae survive at depths below 100 meters, or the equivalent in normal ocean water which is 50 meters, when there is not enough light for photosynthesis is not explained.

The classification of stromatolites is not only confused because of uncertainty of the "nature of the material classified" (p. 33, Krylov), but usage of the Linnean system of nomenclature is also debated (Logan et. al., 1964), because entities that are not entirely organic are being classified with a system developed for biological forms. Nevertheless, the term "conophyton" is understood to mean "columnar and pseudocolumnar stromatolites characterized by conical laminations....with a distinctive axial zone" (p. 523, Donaldson; p. 34, Krylov). Conophyton in the generic sense used by Maslov is italicized and capitalized (Cloud and Semikhatov, 1969), and refers to a group ("genus") subdivided into forms ("species") on the basis of differences in the axial zone. This paper uses the term in the more general sense, unless specifically indicated.

Figure 4 shows alternating carbonate and organic laminae of Conophyton.

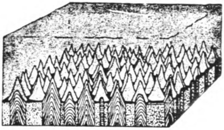

Figure 4. Alternating carbonate and organic laminae of Conophyton (after Walter, 1977).

CONE-IN-CONE STRUCTURES

Cone-in-cone structures, a sedimentary feature composed of layers of circular concentric cones separated by thin films of intercone clay, are presumably due to pressure-solution (Tarr, 1932; Pettijohn, 1957), although a few questions regarding their origin still remain. They have been observed in radial arrangements with apices pointing inward (Harker, 1892; Garwood, 1898), in double-layered lenses where apices point toward each other, and at the ends of lenses pointin in all directions. Values for apical angles range between 15° and 100°, while height normally varies from 1 to 200 millimeters (Tarr, 1932).

Cone-in-cone structures have been reported in coal beds, underclays, shales, slates, and limestones (Bartrum, 1941; Cole, 1892; Garwood, 1892; Gresley, 1892). They have been reported with fossil fish, bivalves, and trilobites (Newberry, 1885; Gresley, 1887; Brown, 1954), but are primarily associated with concretions (Hall, 1843; Gresley, 1894), and concretions are found in the Michigamme Formation (James, 1955; James, Clark, Lamey, and Pettijohn, 1961; James, Dutton, Pettijohn and Wier, 1968). Composition ranges from calcium carbonate, magnesium limestone, and siderite, to gypsum and coal (Cole, 1893; Grimsley, 1903-04; Tarr, 1932; Hendricks, 1937; Bartrum, 1941). Occurences range from the Cambrian (Utah) to the Tertiary (Tarr, 1932).

A comparison of Conophyton and cone-in-cone structure reveals they are composed primarily of carbonate, and due to the continuity of layers of adjacent columns, apices point both up and down (Cloud and Semikhatov, 1969; Hill, 1963). They differ in their associations: cone-in-cone structures are found associated with concretions, and stromatolites are found associated with other stromatolites or bioherms (Krylov, 1976).

Cone-in-cone structures are frequently found in double-layered lenses, with apices pointing toward the opposite layer, while columnar Conophyton frequently grade into other stromatolitic forms (Donaldson, 1976, Hoffman, 1976; and Serebryakov, 1976).. Also, epigenetic (Tarr, 1932) cone-in-cone structures contain layers exhibiting transverse ribs (Dawson, 1868; Gresley, 1894) presumably due to pressure - solution (Tarr, 1932), whereas the laminae of Conophyton, a morphologically-related structure that forms in place, are merely thicker in the axial zone (Walter, 1976).

IDENTIFICATION OF CONICAL STRUCTURES

IDENTIFICATION OF CARBONATE IN CONICAL STRUCTURES

Microprobe analysis revealed a close relation of 2039-1 to the dolomite standard (Appendix B) plus a high iron content, suggesting ferroan dolomite. Staining thin sections 2039-1 bottom, 2039-1 top, 2039-1, and 2039a-1 with alizarin red dye revealed no calcite.

Staining thin sections 2761A-4, 2761B-4, 2761C-4, 2761D-4, and 2761E-4 proved the absence of calcite. Microprobe analysis of 2761C-4 showed high iron content with small amounts (much less than 1%) of zinc and manganese, and values of calcium and magnesium similar to the dolomite standard, indicating the mineral is probably ferroan dolomite.

2769-4 #2, 2769-4 #3, and 2769-4 #4 were stained and revealed the presence of calcite. 2769-4 #1 was subjected to microprobe analysis and values were obtained similar to those of the calcite standard, confirming the results of the stain test. A small amount of iron was found.

2774-4 #1, 2774B-4, and 2774-4 #2 revealed the presence of calcite after they were stained with alizarin red dye. Results of microprobe analysis of 2774-4B were mixed: values for calcium were low but were very high for magnesium and high for iron compared to the calcite standard. This means that it could be considered dolomite with a low content of magnesium and high amounts of calcium. Much less than 1% zinc and manganese are present,

2856-4 revealed no calcite after being stained with alizarin red dye. 2856-4 was analyzed by microprobe, revealing values comparable for dolomite, except the iron content is very high and the magnesium content very low. Perhaps this is ferroan dolomite.

Alizarin red did not reveal calcite in slides 2861B-4 and 2861C-4. Microprobe results for 2861B-4 showed values for calcium and magnesium comparable to dolomite, but values for iron were much in excess of those of the dolomite standard. This suggests very iron-rich dolomite.

2907A-4 and 2907-4 Y were stained for calcite with alizarin red, but the test proved negative. Values for calcium and magnesium in 2907A-4 are low, but high for iron in comparison with the dolomite standard, so the sample may be closer to iron-rich dolomite than to any other carbonate.

483-7 was stained with alizarin red but revealed no calcite. Microprobe results of 483-7 showed values comparable to calcium and magnesium of the dolomite standard, but values for iron were high. This implies the presence of iron-rich dolomite.

STROMATOLITES IN GROWTH POSITION

Do the samples contain stromatolites in growth position? Core segments from drill core 4 at depths of 2761 and 2774 feet each preserve two sets of conical structures with apices pointing toward each other. Consideration of growing conical stromatolites in Yellowstone National Park (Walter, Bauld, and Brock, 1976) implies that the bases of Conophyton occur on the stratigraphically lower side. This is in contrast to the samples, where the bases occur on the lower side of the lower set of structures, and on the upper side of the upper set. The asymmetric nature of grain sizes in the intervening clastics precludes the possibility of isoclinal folding, so the structures cannot be a single layer of stromatolites doubled back on itself after the stromatolites had grown with their apices pointing in one direction. The forms are not stromatolites in growth position. (Figures 5 and 6).

Figure 3. Evolution of terminology in the Marquette District. The sixth and seventh columns show stratigraphic sections of the Minnesota Gunflint and Mesabi Ranges.

	Mesabi Range		
	Morey (1972)		
'itary and ıs rocks	Upper Precambrian	Keweenawan	Sedimentary and igneous rocks
rmation	Middle Precambrian	Animikie Group	Virginia Formation
t Iron Formation			Biwabik Iron Formation
ı Quartzite			Pokegama Quartzite
ONFORMITY			UNCONFORMITY
ONFORMITY			UNCONFORMITY
and metamorphic rocks	Lower Precambrian		igneous and metamorphic rocks

Figure 5. Photograph of core segment 2774-4. The diameter of the segment is 1.9 inches.

Figure 6. Photograph of core segment 2761-4. The arrow is approximately 1.2 inches.

STROMATOLITES AS CLASTIC DEBRIS

Do the samples contain stromatolitic clastic debris transported from growth positions? Structures in samples from drill core 4 at depths of 2761, 2774, 2856, 2861, and 2907 feet, from drill core 1 at 2039 feet, and from drill core 7 at 483 feet form an abrupt contact with argillite, but scattered debris is not present in the argillite. Deformation and secondary mineralization have obliterated much sedimentary structure at a depth of 2856 feet in drill core 4, but an abrupt contact between argillite and conical structures is preserved. Structures from core segments 2761-4 and 2774-4 grade through argillite and graywacke to structures at the opposite ends.. Proving the presence of stromatolitic rip-up clasts in these two segments requires that pieces of stromatolites occur in all orientations, similar to those in Figure 7, as part of the lowermost interval of the Bouma Sequence (Bouma, 1962; Stanley, 1963). They are not, therefore, randomly oriented.

Macroscopic examination shows that segments 2761-4 and 2774-4 do not contain clasts of conical stromatolites (Fig. 5 and 6).

The absence of rip-up clasts and the current ripple and convolute lamination interval suggests that the sedimentary sequence observed in these two core segments does not match with the Bouma Sequence, and that the structures are not clastic debris transported from growth positions by turbidity currents.

ARE THESE CONE-IN-CONE STRUCTURES?

Conical structures are composed in part of black graphitic or carbonaceous opaque layers arranged in short (several millimeters in height) conical stacks (2039c-1 top), which have both smooth and serrated appear-

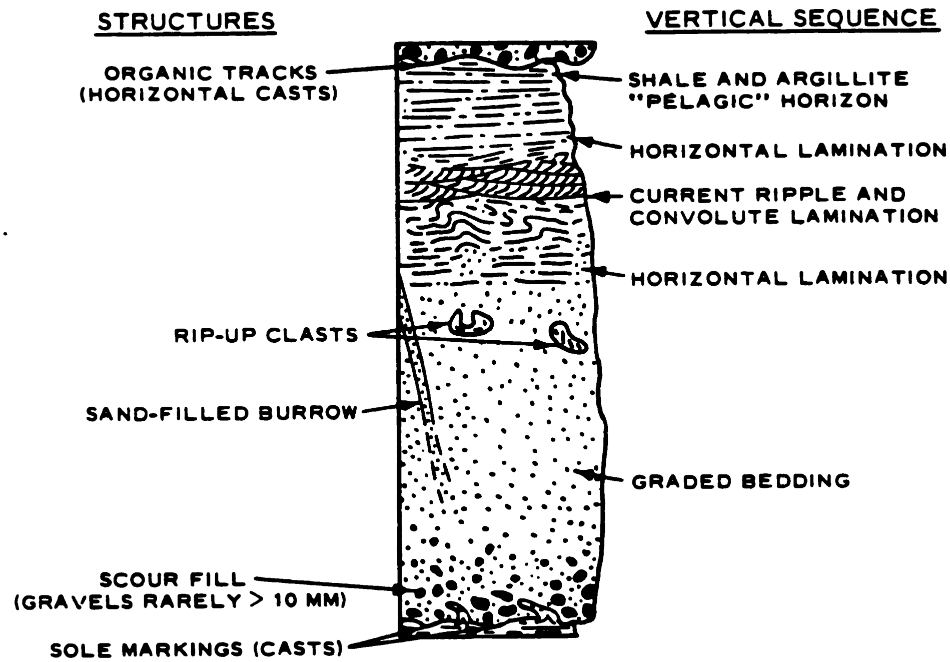

Figure 7. Modified Bouma Sequence (after Stanley, 1963).

ances (Fig. 8). Layers of stacks are superpositioned on other layers as in 2774-4 #2, 2761C-4, and 2907-4 X, but their axes are not necessarily aligned from layer to layer. Discontinuities in or the absence of graphitic layers are partly due to replacement of graphite or carbonaceous matter by quartz and chlorite (2856-4). Actual widths of layers vary between 0.01 and 0.25 mm., and apical angles range from 10^{o} to 63^{o}, while structures as a whole at their bases range in size from 0.5 - 6 mm., and from 0.2 - 11 mm. in height.

Opaque layers in cone-in-cone structure (Fig. 9) have been described as muddy, clayey material, and as clay consisting of illite, chlorite, and a mixed layer mineral; and have been shown to display both smooth and corrugated surfaces (Gresley, 1887; Gresley, 1894; Cole, 1892; Tarr, 1932; Gilman and Metzger, 1967). The layers are frequently superpositioned, but stacks of conical layers have also been reported (Dawson, 1868; Gresley, 1887; Cole, 1892). Cone-in-cone structures range in height from less than 1 mm. to 20 cm., with apical angles commonly varying between 30^{o} and 60^{o} (Tarr, 1932).

The non-opaque portions of the conical structures are composed primarily of anhedral grains of carbonate. Calcite was found at depths of 2769 and 2774 feet in drill core 4, and ferroan dolomite was found in all other samples. Quartz exhibiting replacement texture is found along contacts between conical structures and argillite in drill core 4 at depths of 2761, 2769, and 2774 feet, while chlorite is found along contacts at 2856 and 2861 feet in the same drill core. Quartz frequently replaces portions of carbonate in the structures (2761A-4, 2774-4 #1, 2856-4 #1, 2861-4 M, 2907-4 X, 2039a-1, and 483-7).

Although gypsum (Grimsley, 1903-04) and coal (Young, 1886;

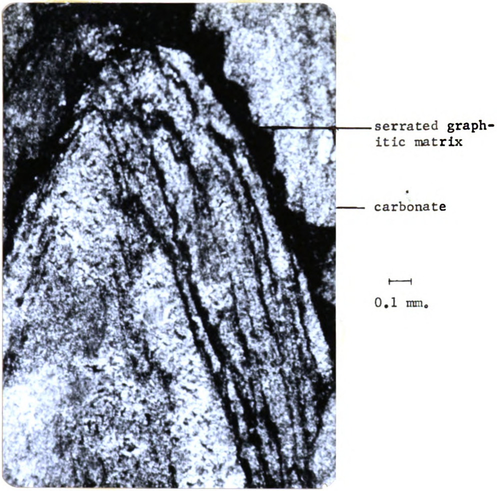

Figure 8. Profile of conical structure in 2039c-1 top.

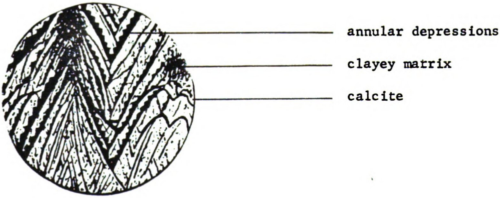

Figure 9. Profile of cone-in-cone structure (after Cole, 1892). X 8.

Bartrum, 1941) cone-in-cone structures have been reported, the prevailing composition is calcite (Tarr, 1932), in some cases with traces of iron carbonate (Cole, 1892). Outer surfaces show annular grooves, the nature of which is made distinct by thin films of opaque matrix adhering between crystalline surfaces of adjacent cones (Cole, 1892; Tarr, 1932).

Transverse sections of conical structures and cone-in-cone structures (Figs. 10 and 11) are inserted to display the similarity in form from another view.

Other comparisons to be made are optical continuity, dispensation of structures in double layers, contact, and surrounding strata. Sweeping extinction under crossed nicols of carbonate is observed in some conical structures (2039-1 DNR large, 2039-1 DNR small, 2774a-4), and is reported in some cone-in-cone structures (Cole, 1892; Gilman and Metzger, 1967). Core segments from depths of 2861 and 2774 feet from drill core 4 display two sets of conical structures with apices pointing toward each other, separated by argillite and graywacke (Figs. 5 and 6). Cone-in-cone structures have been associated with concretions (Tarr, 1932; Gilman and Metzger, 1967) with apices pointing toward each other, the area between the layers being filled by argillite or siltstone (Fig. 12). A core segment from drill core 4 from 2761 feet where part of the structure appears bifurcated and infilled by argillite invites comparison with "tongues or offshoots" (Gresley, 1894) of a layer of cone-in-cone structure (Figs. 13 and 14). The contact between argillite and conical structure observed in samples 2039a-1, 2761A-4, 2769-4 #1, 2856-4 M, and 2861-4 M (Fig. 15) is similar to the contact between some cone-in-cone structure embedded in argillaceous matrix

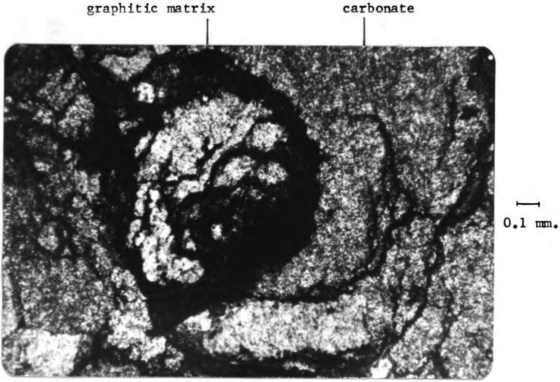

Figure 10. Transverse section of conical structure, from 2774-4 #1.

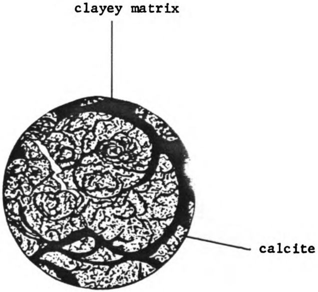

Figure 11. Transverse section of cone-in-cone structure (after Cole, 1892). X 12.

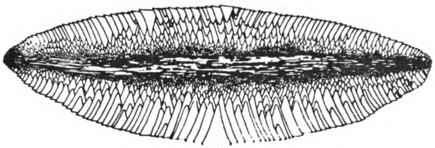

Figure 12. The diagram depicts two layers of cone-in-cone in a concretion. The apices point in the direction of the opposite layer (after Gilman and Metzger, 1967).

Figure 13. Core segment 2761-4 exhibiting a possible offshoot from the primary layer to the right. Core diameter is 1.9 inches.

Figure 14. Offshoots from the primary cone-in-cone layer (after Gresley, 1894). 1/8.

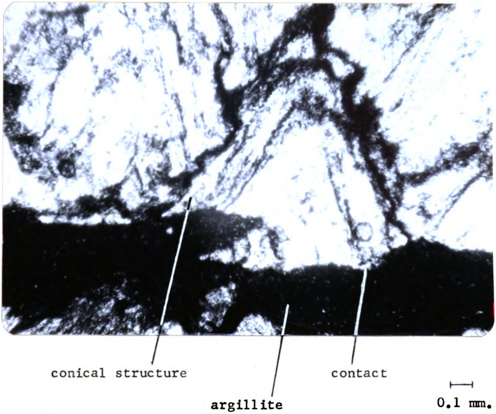

Figure 15. Photograph of 2861-4 M illustrating the contact between the conical structures and the argillite.

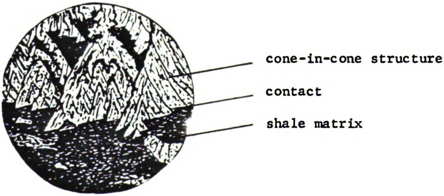

Figure 16. Diagram showing cone-in-cone structure developed in argillaceous matrix (after Cole, 1892). X 18.

(Cole, 1892), which is abrupt, well-defined, and uneven due to the multiplicity of levels of the various bases (Fig. 16).

Cone-in-cone structures are found primarily in shales and marls (Tarr, 1932) and all occurrences of the conical structures are present in argillite, the metamorphic equivalent of shale. Slide 2761C-4 reveals apices of conical structure pointing in the direction of the adjacent graywacke, as cone-in -cone structures pointed to a medial siltstone or sandstone layer in some concretions (Gresley, 1894; Gilman and Metzger, 1967).

Conical structures bear a superficial resemblance to <u>Conophytons</u> in gross morphology (Fig. 17), yet comparisons concerning laminae are hard to draw because of diagenetic effects (Fig. 18; Donaldson, 1976). The similarity ends, however, because bases of <u>Conophyton</u> occur only on the lower surface; and <u>Conophytons</u> which are postulated to have a subtidal origin because of associations with such sedimentary features as oolites, intraformational conglomerates, cross bedding and ripple marks, grade into other stromatolitic forms (Donaldson, 1976). A consideration of form, composition, and associations with other lithologic types and sedimentary features leads to the belief that there is a greater resemblance between conical structures of the Michigamme Formation and cone-in-cone structures.

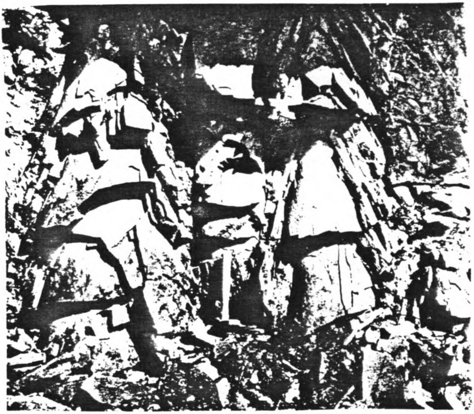

Figure 17. Conophytons from the Dismal Lakes Group. The hammer in the lower center provides a scale (after Donaldson, 1976).

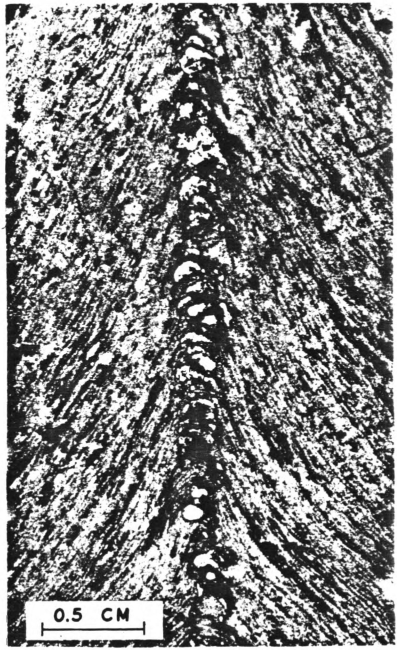

Figure 18. Laminae of the Conophyton from the Dismal Lakes Group (after Donaldson, 1976).

ORIGIN OF CONE-IN-CONE STRUCTURES

FORMATION OF CONE-IN-CONE STRUCTURES AND STYLOLITES

Gilman and Metzger (1967) use the continuity of the medial siltstone layer into a concretion as proof of its "syngenetic character", while Pettijohn argues the presence of this layer implies epigenetic formation of concretions (1957). If the graywacke and argillite in footages 2761 and 2774 of drill core 4 are medial layers of concretionary cone-in-cone structures, this continuity has a bearing on their formation. Bilateral symmetry of concretionary cone-in-cone structures does not suggest, contrary to Gilman and Metzger's conclusion, that "sedimentation of clay was going on at the time the carbonate concretion was developing" (p. 94), but implies that deposition had ended. One would expect differences between the upper and lower layers if concretions were syngenetic (Pantin, 1957).

A syngenetic origin (Shaub, 1937) which requires a continuation of sedimentary processes (deposition) for the formation of cone-in-cone structures where the apices are necessarily directed downward is inadequate to explain the occurrence of cone-in-cone structures in the Michigamme Formation. Shaub studied the molds of the conical structures preserved in unconsolidated sediments, and not the actual cones or casts of the molds. He concluded that the preservation of cones would require filling these conical molds with sediment that would later convert to carbonate, and which would be overlain by a second layer of mudstone or siltstone. The samples from the Michigamme Formation are believed to be turbidites, and it is not understandable how cone-in-cone structures could be preserved by Shaub's method and still be turbidites.

Other theories of the origin of cone-in-cone structures include

1) the gaseous theory, 2) the crystallization theory, and 3) the pressure - solution theory as developed by Tarr, although debate regarding the source of the pressure continues (Tarr, 1932). Present-day researchers with few exceptions favor the pressure - solution theory. Carbonate was reorganized into layers along bedding planes, and pressure from the weight of overlying beds caused fractures in the recrystallized carbonate. Either a second or a continuation of the first episode of pressure-solution caused more dissolution of carbonate, resulting in the clayey residues left as intercone clay and stylolites.

Whether the origin of intercone clay is entirely by pressure-solution (Tarr, 1932; Pettijohn, 1957) or by pressure pushing semi-consolidated shale into conical fractures (Gilman and Metzger, 1967) is debated, but pressure forcing shale along the entire length of the conical fractures isn't believable. Stylolites observed in slides 2039-1, 2039c-1 and 483-7 indicate pressure-solution has been active in the rock (Stockdale, 1922), and the fact that they grade into intercone clay in some instances implies the simultaneous formation of stylolites and intercone clay.(Tarr, 1932).

Thin sections 2039-1 top, 2761A-4, 2761 c-4, 2769-4 #1, 2769-4 #3, 2774a-4 top, and 2856-4 exhibit argillite continuing into the interconical clay; 2761A-4, 2761C-4, 2774a-4 top, and 2774a-4 bottom, contain fragmented cone-in-cone structures embedded in argillite; and graphitic and argillitic conical laminae are present in 2774-4 X. These three observations are essentially the same as those made by Gilman and Metzger (1967), which they interpreted as the soft, plastic shale being deformed by solid cone-in-cone structures.

Layers of cone-in-cone structures appear conformable with bedding in segments 2039-1, 483-7, 2769-4, and 2774-4, which do not possess slaty cleavage. In segment 2761-4, bedding is deformed, and the relationship of cone-in-cone structures to bedding or slaty cleavage is equivocal, as it is in segment 2856-4. Layers of cone-in-cone structure don't appear to follow either bedding or slaty cleavage in 2861-4, where structures appear to deflect bedding. Layers of cone-in-cone structure apparently are unrelated to slaty cleavage in 2907-4.

Parallelism of layers of conical structures with slaty cleavage would imply that slaty cleavage formed prior to the cone-in-cone structures, which it would have guided. The significance of layers parallel to bedding may indicate that cone-in-cone structure formed under the weight of overlying strata before the onset of deformation and metamorphism of the Penokean Orogeny during an episode(s?) of pressure-solution responsible for the stylolites. Whether they are diagenetically formed while shales were relatively unindurated, or epigenetic as Tarr thinks (1932), is unresolved but the fact that stylolites transect cone-in-cone structures (2039-1 top) implies that stylolites continued to form after the construction of cone-in-cone structure had ceased.

PARAGENESIS

The origin of the carbonate in the cone-in-cone structures is probably not a sedimentary lamination of micrite (Burns, 1975), but from recrystallization of interstitial carbonate present in the argillite (Trow, personal communication), which dissolved and reprecipitated as carbonate during diagenesis before the metamorphic peak of the Penokean Orogeny, Carbonate veins in the cores show that carbonate was in solution after lithification of sediments.

Although cone-in-cone structure is found in concretions, (Gresley, 1894; Gilman and Metzger, 1967) and calcareous concretions have been reported in the Michigamme Formation (James, 1955; James, Clark, Lamey, and Pettijohn, 1961; James, Dutton, Pettijohn, and Wier, 1968), the cone-in-cone structures found in the Upper Slate Member samples have not been proved concretionary. If these samples are part of concretions, Klasner's belief (1978) that calc-silicate concretions were "originally calcareous" (p. 716) strengthens the observation that cone-in-cone structures were originally carbonate, because at depths of 2761, 2769, and 2774 feet in drill core 4, the amount of silica is very small in fairly-well preserved carbonate cone-in-cone structures, while at all other depths of cone-in-cone structures, carbonate is present with recrystallized quartz which obliterates much of the structures.

Cone-in-cone fragments do not represent a reorganization of argillite by pressure-solution into carbonate, because this process produces rhombs. The formation of the layers of carbonate prior to the formation of cone-in-cone structures is not questioned in this study. Argillite in slide 2769-4 exhibits carbonate rhombs whose upper and lower edges are defined by thin carbonaceous layers, and whose lateral edges grade into the surrounding argillite. The carbonaceous layers may be an insoluble residue formed as carbonate crystallizes at the expense of argillite. Indicative of their secondary origin is the observation that bedding appears to pinch out above and below these rhombs, which could have formed synchronously with the carbonate of the structures.

A small amount of pyrite present as irregular grains in the Michigamme Formation argillite (slides 2856-4 and 2911-4) is presumably of diagenetic origin (James, 1966; Curtis and Spears, ;968). Forming prior to the lithification of sediments at or below the sediment - water interface in a reducing environment of low Eh values (Krumbein and Garrels, 1952; Pettijohn, 1957; Curtis and Spears, 1968; Berner, 1970), it probably formed as FeS and later converted to pyrite. Pyrite transected by stylolites (2039-1, 2907-4, and 2856-4) obviously antedates pressure-solution.

A second episode of pyrite formation during Keweenawan time (Trow, personal communication) is implied by pyrite grains replacing carbonate, recrystallized quartz, and cone-in-cone structure (2774a-4, 2774b-4, 2856-4 M, and 2907-4 X) and stylolites (2856-4, 2861-4, 2907-4, 483-7, and 2039-1), and pyrite aggregates injected into slaty cleavage formed during the Penokean Orogeny and along Keweenawan faults.

Chert is present as clastic grains in argillite and graywacke in samples from all three drill cores, presumably from the Bijiki Iron Formation Member. An episode of grain growth for quartz in slide 2039c-1 top is indicated where finer-grained quartz does not obliterate structure, but the coarser-grained quartz does eradicate structure. Silica may have been present or introduced from another source during Keweenawan time, but an episode of quartz recrystallization possibly during the Penokean Orogeny postdates the formation of cone-in-cone structure.

The formation of chlorite along contacts between cone-in-cone structure and argillite, and as a replacement of the intercone clay (2856-4 M) occurred after the formation of cone-in-cone, probably during the metamorphism of the Penokean Orogeny.

CONCLUSION

SUMMARY AND CONCLUSION

Structures once thought to be stromatolites of questionable shallow water origin are believed to be cone-in-cone structures. The idea that they were stromatolites in growth position was ruled out by the fact that within two core segments, the apices pointed toward each other, but in the absence of isoclinal folding.

The pieces of cone-in-cone structure do not necessarily have a clastic origin, for these fragments may be explainable as normal outgrowths of the formative processes of cone-in-cone structure. More evidence is accumulated in favor of their identity as _in situ_ cones, such as carbonate cones with serrated layers of intercone clay and graphite, sweeping extinction of some structures under crossed nicols, apices of double layers found associated with calcareous argillite, and the nature of the contacts with the argillite.

Because these forms are probably not stromatolitic, the question of a deep water origin for algal stromatolites together with the implications for photosynthesis is dismissed. However, stromatolites of bacterial origin are known to exist and it is not inconceivable that such could exist in a deep water environment (Hoffman, 1976).

RECOMMENDATIONS FOR FURTHER STUDY

Further study should extend to the conical structures of the Bijiki Iron Formation Member, to gauge any similarities with the Upper Slate Member. Problems remaining to be solved are: 1) Was the shale plastic or indurated at the time of origin of the cone-in-cone structures? 2) Why is calcite present in the cone-in-cone structures at depths of 2769 and 2774 feet in drill core 4, but ferroan dolomite present in the other structures? Paragenesis of minerals and their relationships to orogeny and deformation may yield a more precise time of formation of these cone-in-cone structures.

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APPENDIX A

THIN SECTION DESCRIPTIONS

THIN SECTION DESCRIPTIONS

2031-1

Argillite, laminate, gray. This sample contains quartz, anhedral grains, 0.5 mm. maximum dimension, approximately 5%; graphite, matrix, approximately 43%; sericite, 50%; plagioclase, clastic, exhibiting polysynthetic twinning, alteration, and graphite inclusions, 0.1 mm. maximum dimension, less that 1%, dolomite, subhedral to anhedral crystals, 0.06 mm. maximum dimension, less than 1%; calcite, anhedral crystals, 0.05 mm. maximum dimension, less that 1%; chlorite, anhedral, 0.13 mm. maximum dimension, less that 1%. rock fragments, rounded, 0.23 mm. maximum dimension, composed of quartz, carbonate, sericite, plagioclase, and graphite, less than 1%. Sericite-rich layers alternate with thicker graphite-rich layers.

2039-1 DNR small sample

This slide contains carbonate, with conical structure and stylolites, and argillite. The carbonate in the column of conical structure exhibits sweeping extinction under crossed nicols, embayed boundaries with quartz (chalcedony) forming a cement on pyrite. Pyrite occurs as irregular grains, attains 0.87 mm. maximum size, and exhibits boundaries embayed by quartz. Graphite occurs as stylolitic seams and as part of the conical structure in the form of conical laminae, with an irregularly shaped "v" appearance in thin section. Chlorite is associated with graphite in stylolites. Quartz is pseudomorphous after pyrite, and obliterates conical structure.

The argillite consists of a graphite matrix in which are embedded carbonate, sericite, and quartz grains. Bedding, defined by elongated grains, appears compressed where argillite thins.

2039-1 DNR large sample

This slide exhibits conical structure and stylolites. Carbonate comprises the greater part of the conical structure, and exhibits sweeping extinction under crossed nicols in some structures, and displays embayed boundaries. Graphite occurs as stylolites, seams in conical structures, and smaller irregular grains, 0.75 mm. maximum dimension. Chlorite, usually in patches, is associated with stylolitic graphite. Pyrite is uncommon, but occurs as irregular grains, 0.75 mm. maximum dimension.

Shapes and orientations of conical structure vary within the slide. Graphite in coaxial "v" shapes 3.5 mm. in height suggest profiles, while 2.5 mm. diameter rosette-shaped graphite indicates transverse sections. Penetration through successively higher and higher layers of one structure is implied by progression from the innermost center ring to the outermost ring.

2039a-1

This slide contains argillite and conical structure. Argillite is composed of graphite as matrix, approximately 75%, quartz, angular to subrounded anhedral grains, 0.21 mm. maximum size, 10%; sericite, laths, 0.7 mm. maximum size, 1%; carbonate, irregular grains, 0.1 mm. maximum dimension, 23%; and rock fragments, rounded, 0.16 mm. maximum dimension; composed of chert, graphite, and carbonate. The bedding is defined by long axes of muscovite grains, and streaks of quartz and carbonate grains, and exhibits deformation.

The conical structure is composed primarily of quartz, carbonate, and pyrite. Quartz (60%) is partly a replacement of carbonate and pyrite, since it exhibits embayed boundaries, and masses of quartz interrupt conical structure. It is also a cement on pyrite. Anhedral plagioclase grains, displaying polysynthetic twinning, are angular to rounded, and reach a maximum size of 0.65 mm. Pyrite (1%) occurs as cubes and irregular grains with 1.75 mm. as a maximum dimension. Carbonate occurs as rhombs and anhedra, and constitutes 26%. Sericite is present as laths, and chlorite occurs as aggregates; both add up to less than 1%. Graphite is present as stylolites (13%).

The contact is well-defined at magnifications of 40, 100, and 200. Graphite matrix is in contact with the carbonate or quartz at a fairly sharp planar boundary.

2039c-1 top

This slide of conical structure is composed of carbonate, quartz, graphite, and pyrite. Quartz, from 0.025 mm. to 0.25 mm., is bimodal in size distribution, and larger recrystallized textures of quartz obliterate and replace conical structure. Pyrite occurs as irregular grains, 1 mm. maximum dimension; and graphite composes stylolites and the conical layers of the structures. In addition to graphite, fragments of carbonate not yet removed by pressure-solution are present in some of the thicker stylolites.

The argillite at the top of the slide is composed of graphite, quartz, sericite, and carbonate. Quartz grains are anhedral; the largest measures 0.05 mm. Carbonate occurs as irregular grains, with a 0.05 mm. maximum dimension. Bedding defined by long axes of sericite and quartz grains, exhibits deformation due to the carbonate lithology that pushed into it. The deformed zone is 3mm. in length. Dark, carbonaceous matter of the argillite grades into stylolites of the conical structures, whose boundaries are cross-cut by stylolites.

The contact between argillite and conical structure is sharp and well-defined, and nearly planar.

Conical structures measure from 1 to 2.25 mm. at their bases, and individual columns of "coaxial v's" range from 2 mm. to more than 2 cm. in height. Structures are obliterated in the 1 - 3 mm. wide zone adjacent to the largest seam, but it is not clear whether they belong to the same column. While defining the conical structure in thin section, some of these graphitic "coaxial v's" appear serrated or jagged on one side. "Coaxial v's" grade into stylolites and larger seams.

A twenty-two millimeters thickness of a stylolite from 0.5 to 2 mm. wide is represented on the slide, and appears to separate portions of conical structure. The seam is composed of amorphous masses of graphite ranging in size form 0.13 X 0.25 mm. to 1.3 X 2.0 mm., appearing as if they were laid end-to-end in thin section. A twelve millimeters thickness of a second seam occurs in another zone of obliteration of structure from 7-10 mm. in a downhole direction from the first. It appears as amorphous masses of graphite on the sides and apices of the structures that grade into stylolites and layers of the conical structure.

Stylolites are abundant, but generally do not exceed 0.25 mm. in width, or 10 mm. in length.

2039c-1 bottom

This graphitic carbonate is largely a transition from the carbonate above; the stylolitic zone shows vague definition of "coaxial v" shapes, but instead of conical structure the graphite forms parallel anastomosing seams with 0.02 mm. maximum width below the stylolites. Quartz is present in patches; as a replacement of carbonate, it exhibits embayed boundaries. It comprises 6.7%, compared to carbonate which makes up 50%. Graphite (42%) is present as amorphous masses and seams, which cross-cut veins of calcite and quartz. Muscovite comprises less than 1%, and attains 0.04 mm. maximum size. Carbonate is present as anhedral grains.

2043-1

Argillite, laminated, gray. It contains graphite as matrix, approximately 70%; muscovite, 24%, 0.03-0.6 mm. long laths; plagioclase, less than 1%, anhedral, twinned, altered, angular to rounded, 0.1 mm. maximum dimension; chlorite, irregular grains, θ.5 mm. maximum dimension, less than 1%; quartz, anhedral grains, angular to subangular, 0.25 mm. maximum dimension, 1.5%; carbonate, rhombs and irregular grains, 0.45 mm. maximum dimension, less than 1%; rock fragments, angular to rounded, 0.6 mm. maximum dimension, 4%, composed of chlorite, sericite, graphite, chert, and carbonate.

Bedding is defined in thin section by linear arrangement of grains of quartz, carbonate, and rock fragments. Sericite-rich layers alternate with graphite-rich layers.

2750-4

Argillite, gray, bedded. This sample contains quartz, angular to subrounded, anhedral, 0.4 mm. maximum size, 2.5%; muscovite, laths, 0.1 mm. maximum length, and flakes; graphite, irregular grains, 0.05 mm. maximum dimension, 0.1%; pyrite, irregular grains, less than 1%; carbonate, 2.3%, rhombic, 0.38 mm. maximum dimension, and irregular grains, partially replaced by quartz; chlorite, irregular grains, 1.8%, 0.15 mm. maximum dimension; plagioclase, 0.25 mm. maximum dimension, angular to subrounded, anhedral to subhedral, polysynthetic twinning, altered to sericite, 0.5%; rock fragments, rounded, 0.4 mm. maximum dimension, composed of muscovite, quartz, graphite, and chlorite, less than 1%.

Clastic laminae of coarser-grained quartz, plagioclase, rock fragments, and carbonate are present in a quartzose, sericitic matrix.

2761A-4

The rock contains graywacke, carbonate, and argillite. The graywacke is composed of quartz, 0.4 mm. maximum dimension, 21%; carbonate, rhombs to irregular grains, 0.4 mm. maximum dimension, partly replaced by quartz, 23%; rock fragments, rounded, 0.5 mm. maximum dimension, composed of chert, carbonate, and graphite, 0.6%; chlorite, irregular grains, and laths, 0.75 mm. maximum diemsnion, 4%; plagioclase, partly replaced by carbonate, anhedral, 0.3%, twinned, 0.05 mm. maximum dimension; graphite, stringers, 0.5 mm. maximum length, and irregular grains, 0.2 mm. maximum dimension, 15%; The smaller grains serve as the matrix in this graywacke. Graphite defines conical structures, layers of which are embedded in this siltstone; the apices point in a downhole direction.

Argillite, laminated and massive, is composed of graphite, stringers, 2.5 mm. maximum length, and irregular grains, 0.11 mm. maximum length, 38%; sericite, 50%; quartz, 4%, 0.03 mm. maximum dimension, anhedral, angular. Laminated argillite associated with the conical structures shows graphite stringers alternating with layers of quartz, sericite, and graphite grains.

The conical structures are composed of carbonate which is being replaced by quartz. Pyrite is present as irregular grains, 0.3 mm. maximum dimension, and is being replaced by quartz. Graphite layers defining the structures have been replaced to a large extent by chlorite. Apices point in a downhole direction.

The contact between argillite and conical structure is well-defined and consists of irregular grains of carbonate bordering the argillite. Some 0.005mm. to 0.01 mm. wide graphitic stringers are present between the carbonate and the argillite.

The contact between conical structure and graywacke is distinct. Conical structures are outlined by argillite, or else the carbonate of the conical structures makes a sharp contrast under crossed polars with the graywacke.

The contact between the argillite and graywacke is obvious at 40 magnification, but is less distinct at 100 and 400 magnification, it is remarkably planar considering the small grain size.

2761B-4

The two lithologies represented are graywacke and graphitic carbonate. The carbonate consists of a graphite-sericite-carbonate matrix with an anastomosing network of veins containing sericite, quartz, and chlorite.

The graywacke is composed of quartz, anhedral, angular, to subrounded, 0.15 mm. maximum dimension, 2%; rock fragments, rounded, 0.25 mm. maximum dimension, containing chert, plagioclase, carbonate, and sericite, less than 1%; chlorite, elongated irregular grains, 0.15 mm. maximum dimension, 40%1 sericite, laths, 0.2 mm. maximum length, and flakes, 8%; graphite, irregular grains and stringers constituting the matrix.

2761C-4

Argillite is composed of graphite, quartz, carbonate, and sericite. Carbonate occurs as rhombs, less than 1%, 0.25 mm. maximum dimension, and irregular grains. Quartz is present as angular anhedra, 0.05 mm. maximum dimension. Graphite, 52%, occurs as irregular grains, 0.08 mm. maximum dimension, and tiny stringers, 0.15 mm. maximum length, that define either foliation or bedding planes by parallel alignment of long axes. Sericite, 49%, and elongated quartz grains also help define this foliation. Quartz is present in the 0.04 mm. size range along the contact, possible as a replacement mineral.

The conical structures consist of carbonate and layers of graphite and chlorite. In some, the graphite layers have a serrated appearance, and measure 5 mm. in length. Apices point in an uphole direction.

The argillite pinches out into graywacke. This is composed of quartz grains, angular to subrounded, with some recrystallization texture, 0.32 mm. maximum length; chlorite, laths and irregular grains; carbonate, anhedral crystals, 0.63 mm. maximum dimension; graphite, irregular grains and clots; and plagioclase, subhedral, polysynthetically twinned, 0.05 mm. maximum dimension.

The contact between argillite and conical structure is frequently a graphite stringer, from 1 mm. in length to individual grains. Where no graphite is present, fine grains (0.025 mm. maximum dimension) of anhedral quartz occur. At 40 magnification the resolution is very indistinct for this fine-grained rock's contacts and grain boundaries.

The contact between conical structure and graywacke is a well-defined break that grades into a ¼ mm. wide zone of carbonate.

2761D-4

Argillite, laminated, gray. This sample is mineralogically composed of quartz, angular to rounded, 0.20 mm. maximum dimension, anhedral to elongated grains, also as a cement on carbonate grains, 13%; carbonate, rhombs, 19%, 0.3 mm. maximum dimension, partial replacement by quartz, present in all laminae; sericite, 0.18 mm. maximum length, 30%, laths and flakes; graphite, irregular grains, 37%, 0.09 mm. maximum dimension, and stringers, 2.5 mm. maximum length; chlorite, laths and aggregates, 0.25 mm. maximum dimension, less than 1%; plagioclase, incipient alteration to sericite, polysynthetic twinning, 0.25 mm. maximum dimension, less than 1%; rock fragments, composed of quartz, carbonate, graphite, and are rounded, with a 0.25 mm. maximum dimension.

Clastic beds of silt size quartz and plagioclase alternate with laminae that are finer grained. Quartz veins are also present in the argillite.

2761E-4

Argillite with graywacke. Argillite is composed of graphite, irregular grains, 0.075 mm. maximum dimension, 40%; sericite, 36%; quartz, angular, anhedral grains, 0.03 mm. maximum dimension, 3.5%; chlorite, laths, 0.025 mm. maximum length, and irregular grains, 0.4%; carbonate, rhombs and irregular grains, 0.2 mm. maximum dimension, 19%.

The graywacke contains rock fragments, less than 1%, rounded, 0.2 mm. maximum size, composed of chert and sericite; plagioclase, polysynthetically twinned, 0.18 mm. maximum dimension, 3.4%; carbonate, rhombs, 0.35 mm. greatest dimension, 9.5%; sericite, shreds, I.1 mm. maximum length; 22%; pyrite, irregular grains, 0.6 mm. maximum dimension, 2%; graphite, irregular grains, 0.08 mm. maximum dimension, 12%; chlorite, irregular grains and laths, 0.5 mm. maximum dimension, 3.2%; and quartz, also in the form of chert, angular to subrounded grains, 0.58 mm. maximum dimension, also a replacement of carbonate, 47%.

2764-4

Argillite, gray. It consists of graphite, irregular grains, 0.1 mm. maximum, some stringers, 60%; carbonate, rhombs, 0.2 mm. maximum dimension, 18%; quartz, anhedral, anhedral grains, 0.01 mm. maximum dimension, less than 1%, sericite, 20.5%, pyrite, irregular grains, less than 1%.

A quartz vein, approximately 0.01 mm. wide, and a carbonate vein, approximately 0.125 mm. wide, are present.

2769-4 #1

This slide contains conical structure and argillite. Mineralogically it consists of carbonate in the conical structure, rhombs and parts of rhombs in the argillite, 0.075 mm. maximum dimension, 18%; graphite, composing layers of conical structure, and laminae in the argillite, 10 mm. maximum length X 0.1 mm. maximum width, irregular grains in argillite, 0.075 mm. maximum dimension, 64%; chlorite, aggregates, associated with and partially replacing graphite in stylolites and layers in conical structures, less than 1%; pyrite, in irregular grains, 0.25 mm. maximum dimension, associated with the contact, 0.5%; chalcopyrite, irregular grains, associated with the contact, 0.125 mm. maximum dimension, less than 1%; and quartz, associated with the contact, and with pyrite in the argillite, 3.4%, with embayed boundaries.

Conical structures are defined by graphitic layers, frequently with a serrated appearance, or straight appearance, from 0.075 mm. to 2.5 mm. in length. The bases range from 0.5 mm. to 4 mm. and heights vary from 0.75 mm. to 8 mm. The shape in thin section is a "coaxial v", with a rounded apex, which is expected in an oblique section intermediate between a transverse section and a profile. Some fragments are embedded in the argillite and point in the uphole direction.

The basal contact between the bases of the conical structures and argillite is clearly-defined, planar, and jagged due to the protrusion of structures. At 400 magnification, the resolution isn't great enough to see grain boundaries.

2769-4 #4

Argillite is composed of quartz, 5%, angular anhedra, 0.25 mm. maximum dimension; carbonate, rhombs, 18%, 0.275 mm. maximum dimension; graphite, irregular grains 0.07 mm. maximum dimension, and layers at least 1 mm. long, 40%; sericite, laths, 36%, 0.1 mm. maximum length; chlorite, laths, 0.2 mm. maximum length, less than 1%. The bedding is defined by long axes of phyllosilicate grains and graphite stringers. Some pyrite is being replaced by quartz and carbonate.

Argillite is contained in the coaxial cones that define the conical structures. They are smaller and more fragmented compared to those in sample 2769-4 #1, although both exhibit some obliteration of fine structure, indicated by faint, diffuse layers. Apices point in a downhole direction, and vary in size from 0.2 mm. to 2.5 mm. in height, and from 0.3 mm. to approximately 2.5 mm. in width. Structures are also composed of carbonate.

The third lithology is graphitic carbonate containing carbonate as irregular grains, 46%, 0.12 mm. maximum dimension; sericite, laths, 0.08 mm. maximum length, 1.1%; and graphite, 54%, in seams, layers, and irregular grains.

Fragmentary conical structures are obliterated and grade downward into graphitic carbonate with much less carbonate, where they are no longer discernable. The upper contact can be considered a 2 mm. wide zone where discrete and commonly obliterated structures are embedded in argillite.

2773-4

Argillite, gray. This is composed of a fine-grained matrix of quartz, sericite, and graphite, with larger grains of carbonate and graphite. Quartz occurs as angular anhedra, 0.02 mm. maximum dimension, 1%; sericite, comprises 38%, and graphite, 45%. Carbonate occurs as rhombs and irregular grains, 0.23 mm. maximum dimension, 17%. Bedding is defined by parallel arrangement of long axes of sericite grains, 0.125 mm. maximum length.

2774-4 #1

This transverse section of conical structure consists of carbonate, graphite in rosette-shaped arrangements, 2-7 mm. in diameter; pyrite, 1 mm. maximum dimension, irregular grains; chlorite, irregular grains, 0.1 mm. maximum dimension, also as a replacement of graphite; and quartz, exhibiting embayed boundaries and recrystallization texture.

2774-4 W

This slide is composed of conical structure and fragments of conical structure that grade downward into argillite. Structures contain carbonate; chlorite, in irregular grains and aggregates commonly replacing graphite; and graphite, forming conical laminae. The largest structures measure 2-5 mm. at their base, and 6 mm. in height; while the smallest fragments' dimensions are 0.23 mm X 0.23 mm. The largest structures' apices point down.

Argillite is composed of graphite, irregular grains, 0.1 mm. maximum dimension, and stringers; carbonate, generally in the form of anhedral grains, but rhombs are also present; and phyllosilicate in the forms of sericite and chlorite.

2774-4 X

Conical structures with apices pointing upward gradually diminish in size so that in a ½ cm. wide zone, structures grade into carbonate-rich argillite. At the base of the slide conical structures range from 7 mm. high to a few millimeters wide at the distance of greatest separation of graphitic conical laminae, where bases are not present. These grade upward to fragments measuring 0.125 mm. (base) X 0.15 mm. high. Graphite and argillite define conical structures, and some of these have a serrated appearance. A single axis common to multiple conical structures is found and the structures form a column. In other cases, graphite layers serve as a common side to adjacent conical structures, and nested structures without a single axis of symmetry prevail. At the base of the slide, graphite layers fade into carbonate.

2774-4 Y

This profile of conical structures consists mainly of carbonate that includes a few layers of graphite grading into stylolites of graphite and phyllosilicate. Pyrite occurs as irregular grains measuring 0.4 mm. as a maximum dimension. Orientation and other measurements can not be determined from this thin section due to a lack of defining layers.

2774-4 #3

Conical structure consists of carbonate, graphite, and layers of phyllosilicate, both sericite and chlorite. Pyrite is present as irregular grains, cubes, and aggregates. Quartz occurs as cement on some pyrite grains, and replaces carbonate and pyrite, as indicated by embayed boundaries and recrystallization texture.

Argillite consists of quartz, angular anhedra, 5%, 0.05 mm. maximum dimension; carbonate, 8%, as irregular grains and rhombs, 0.23 mm. maximum dimension; graphite, 22%, irregular grains and layers, 0.75 mm. maximum dimension; muscovite, laths, 65%, 0.125 mm. maximum length; and chlorite, 0.43 mm. maximum length, less than 1%.

Pyrite and recrystallized quartz are present along the abrupt and well-defined contact between argillite and conical structures. The zone of quartz and pyrite ranges between ¼ mm. and 2 mm. wide, and obscures the original contact.

2778-4

Argillite, gray, composed of larger irregular grains of pyrite and carbonate. Pyrite attains 1.25 mm. maximum dimension, and carbonate rhombs reach 0.125 mm. maximum dimension, and comprise 7%. The matrix is composed of quartz, 0.015 mm. maximum, 0.3%; graphite comprises 38%, and is present as irregular grains and stringers; and sericite totals 55%.

2844-4

Argillite, gray, massive. This is composed of a graphite matrix, 81%; in which are embedded quartz grains, 0.05 mm. maximum dimension, 13%, anhedral, angular; carbonate, rhombs, 1.4%; sericite, 6%; rock fragments, containing chert, sericite, and graphite, rounded, 1.75 mm.

maximum dimension, less than 1%.

2856-4 K

Conical structures consist of crystalline carbonate, in irregular grains, 0.05 mm. maximum dimension; quartz, which obliterates conical structure; graphite, as irregular grains, 0.05 mm. maximum, and stringers, distinct to diffuse, serrated and smooth, 5.75 mm. long X 0.12 mm. wide maximum, and stylolites. Pyrite is present as irregular grains and aggregates several millimeters in diameter, and its embayed boundaries show it is being replaced by quartz and carbonate. Chlorite occurs in aggregates at the base of the structures, and in layers of conical graphite. Apices of structures point down, and in place of discrete symmetric structures are multiple structures, possibly a result of joining at the sides of two or more single structures. This is indicated by the multiple occurrence of apices without the graphite layers defining the individual sides of structures. Lower layers fade into carbonate, and upper layers define several apices.

Laminated and crenulated argillite consists of graphite, 69%, alternating with patches of recrystallized quartz, 20%; sericite, 11%, and graphite grains. Quartz is present as angular, anhedral grains, 0.05 mm. maximum dimension, and disrupts the lamination of the argillite where it occurs as a replacement. Graphite occurs in irregular grains, 0.1 mm. maximum dimension.

The generally rounded but smooth contact consists of chlorite aggregates adjacent to graphitic laminae of the argillite. One relatively defined structure is oriented so its axis does not form a right angle with the bedding. The contact's jagged appearance in places is due to this fact and also to stylolites or graphite that define the conical layers grading into the argillite.

2856-4 L

Semi-preserved conical structure is composed of graphite, quartz, and carbonate. Graphite layers appear serrated, and the recrystallization of quartz has obliterated conical structure. Graphite is also present as stylolites. Irregular pyrite grains measuring several millimeters in diameter are present.

2856-4 M

Both obliterated and preserved conical structures are present. The largest bases measure 0.75 mm. - 1 mm. across, and some columns appear to reach 2 mm. in height; apices point upward.

A six to eight millimeter wide zone of interbedded argillite with which the structures form a contact is composed of graphite, matrix, 76%; quartz, angular anhedra, 16%, 0.2 mm. maximum dimension; carbonate, anhedral, 6%; and sericite, less than 1%. Bedding is defined by planar arrangement of quartz and carbonate grains. The jagged contact is abruptly marked by the presence of two distinctively different lithologies.

Below the argillite is a 1 cm. wide bed of carbonate containing obliterated conical structures with the exception of several fairly-well defined shapes. The carbonate contains amorphous masses of argillite, which possibly are incipient stylolites. Structures do not occur below this zone. The contact between the argillite and 1 cm. wide carbonate is a transition zone, 0.75 mm. - 1.0 mm. wide, contain- both graphite and carbonate.

2858-4

Argillite contains graphite, 87%, as matrix, in which are quartz grains that are angular to aubangular, deformed and elongated, and reach 0.125 mm. maximum dimension. Quartz veins are present, with 8 mm. long X 0.07 mm. wide as a maximum size observed. Other mineral constituents include rock fragments, 5.6%, composed of chert, chlorite, sericite, and graphite, and are rounded, some elongated, with 2.25 mm. as a maximum dimension; sericite, 5%, laths and flakes; carbonate, 2.4%, as irregular grains, 0.1 mm. maximum dimension, and chlorite, 2.7%, as irregular grains and aggregates, 0.1 mm. maximum dimension. Quartz comprises approximately 40%.

Bedding in argillite is defined by subparallel arrangement of long axes of quartz, sericite, and rock fragments.

The approximately 7 mm. thick carbonate bed contains carbonate, pyrite as irregular grains and aggregates, ranging upward to 1.5 mm., and graphite as irregular grains and stringers, 2 mm. maximum length.

2861-4 M

The conical structure consists of carbonate and quartz exhibiting embayed boundaries and recrystallization texture. The layers defining the structures are composed of chlorite in irregular grains and aggregates, and graphite, as irregular grains and seams reaching a maximum size in thin section of 0.025 mm. wide X 2.5 mm. long. Pyrite is present in irregular grains, 4 mm. maximum dimension, being replaced by quartz, and with islands of quartz. Sericite is also noted.

Some conical structures are defined by graphite and chlorite in general outline; in others spikey-appearing layers of graphite are preserved; still in others graphite and chlorite aggregates form masses and consequently detail is difficult to discern. Quartz has recrystallized and obliterated some conical structure.

The argillite consists of a graphite matrix, 66%; quartz grains, angular, anhedral, frequently elongated, 0.125 mm. maximum dimension, 17%; carbonate, irregular grains or rhombs, 9%; and sericite, laths, 0.05 mm. long, and flakes. Bedding is defined by long axes of elongated grains in parallel alignment, and is deformed in some places. A few tiny quartz veins occur, 1.75 mm. long X 0.075 mm. wide, maximum size.

The contact is distinct and planar, consisting of chlorite aggregates at the bases of many structures adhacent to the argillite. The jaggedness results from the bases being at different heights.

2861-4 O

This slide of conical structures consists of quartz, carbonate, graphite, chlorite, and pyrite. Quartz replaces conical structures. Graphite defines conical layers several millimeters in height, and ranging in width from 0.01 mm. to approximately 0.25 mm. Pyrite is present as irregular grains several millimeters in diameter. Carbonate is present as rhombs that have grown and pushed aside the carbonaceous matter.

Layers are often discontinuous along a side or at an apex, where quartz is present; and they commonly have a straight or serrated appearance. Apices are rounded to pointed, and point both uphole and downhole, since many structures share a single side. Graphite layers form conical laminae, but some structures have been annihilated to the point where graphite layers are subparallel.

2861B-4

Annihilated conical structures contain carbonate, graphite, chlorite, pyrite, and quartz which replaces conical structures. Graphite occurs as layers of conical structures which are several millimeters in length, ranging up to 0.25 mm. in width, and ofter are spikey-appearing. Chlorite is present in aggregates along the contact between the structures and argillite, and along some graphite seams. Enough structure is present to show apices pointing away from the argillite.

The laminated argillite is composed of a graphitic matrix, 56%; carbonate, rhombs, approximately 0.04 mm. maximum dimension; quartz, angular, spherical to elongated grains, 0.06 mm. maximum dimension, 2%; sericite, 16%; rock fragments, 0.09 mm. maximum dimension, 1%, composed of carbonate, chert, and muscovite. Bedding is defined by parallel alignment of long axes of grains.

The argillite and chlorite form an abrupt, uneven contact.

2861C-4

Argillite, gray, laminated. It consists of quartz, angular, anhedral grains, 0.23 mm. maximum dimension; chert, 0.12 mm. maximum dimension of grains; together chert and quartz total 6.4%. Carbonate is present as irregular grains and patches, less than 1%; muscovite is present as shreds, 0.2 mm. maximum length, 6%; graphite matrix, 82%; and plagioclase, anhedral to subhedral, with polysynthetic twinning, 0.2 mm. maximum length, less than 1%.

Pyrite is present as irregular grains, 0.35 mm. maximum size, less than 1%. Rock fragments compose 5%, are rounded to angular, and consist of chert, carbonate, chlorite, and sericite, and graphite. Two clastic beds of 0.5 mm. and 1.5 mm. thickness are faulted and offset by approximately 2.75 mm.

2867-4

Argillite, massive. It consists of graphite, matrix, 24%; quartz, 0.125 mm. maximum dimension, angular, anhedral grains, 27%; muscovite, laths and parts of flakes, 0.1 mm. maximum length, 36%; plagioclase, anhedral to subhedral, 0.05 mm. maximum dimension, twinned and altered to sericite, less than 1%; pyrite, aggregates, approximately 10%; carbonate, 4%, irregular grains; rock fragments, rounded, anhedral, 0.1 mm. maximum dimension, containing sericite, chert, and carbonate.

2903-4

This is a massive argillite composed of quartz, graphite, carbonate, and sericite. Quartz is anhedral, angular, and attains 0.05 mm. maximum size; together with chert the total percentage is 20%. Sericite occurs as flakes and laths, 0.06 mm. maximum size, 15%. Carbonate occurs as irregular grains, 0.08 mm. maximum size, and constitutes less than 1%. Graphite occurs as irregular grains and masses comprising the matrix, 64%.

2907-4 X

Conical structures are composed of quartz, carbonate, graphite, and muscovite. Quartz replaces conical structure and occurs as cement on pyrite. Graphite occurs primarily as layers of the conical structures, but is also present as amorphous masses among them. Pyrite occurs as irregular grains, reaching 1.75 mm. maximum dimension, with inclusions of quartz and carbonate, and obliterating conical structures. Chlorite is present along the contact in aggregate form.

Apices point in the uphole direction, and some graphitic layers have a serrated appearance, but most seem to be of a uniform thickness between 0.01 mm. and 0.12 mm. A few seem to grade into stylolites.

The argillite is composed of chert, in patches, 21%. Graphite, 62%, constitutes matrix, in amorphous masses and as layers. Muscovite, occurs as laths and flakes, 0.1 mm. maximum dimension, 17%. Bedding is defined by parallel graphite layers, and lenses of quartz, muscovite, and graphite.

The contact between conical structures and argillite is abrupt, where 0.01 mm. thick layers of graphite form the bases of structures, but elsewhere the transition occurs as a ¼ - ½ mm. thick interval of carbonate, graphite, and quartz.

2907A-4

This slide of conical structures contains carbonate, quartz, pyrite, graphite, and sericite, with quartz replacing the conical structures, pyrite, and graphite. Graphite is present as irregular grains and amorphous masses, ranging upward in size from 0.005mm., and as seams and layers of conical structures, and in stylolites. Muscovite occurs as laths, 0.05 mm. maximum length, and pyrite occurs as irregular grains that contain inclusions of quartz and carbonate, with a maximum dimension of 1.25 mm.

Apices and conical forms are suggested by the convergence of serrated-appearing layers, where discontinuity in layers exists, and point in both uphole and downhole directions. Form is obscured in some structures, because of the diffuse and indefinite nature of the layers.

2907B-4

This slide of conical structure consists of carbonate, quartz, graphite, and pyrite. The crystalline portion is composed of carbonate, and quartz which replaces conical structure land pyrite. Graphite occurs as irregular grains, ranging upward from 0.005 mm., to layers of conical structures. Pyrite is present as irregular grains, 1.25 mm. maximum dimension, with inclusions of quartz and carbonate.

Conical structures are defined by graphite layers, and greater amounts of quartz and carbonate than are present in the mixture of graphite, quartz, and carbonate filling in among the structures. Apices of most of the separate structures point in a downhole direction, although the zigzag pattern of graphite, in the middle of the slide makes this determination difficult. The pattern may reflect stacking of structure, in very close proximity, and apices here may point downhole.

2908-4

This slide represents soft sediment deformation in a zone of argillite; and contains chert, carbonate, sericite, graphite, and pyrite. Graphite occurs as deformed layers and some disseminated clots and grains. Pyrite is present as irregular grains and cubes, 0.75 mm. maximum dimension; it obliterates other structures, but is also cross-cut, fractured, and filled with quartz inclusion. Carbonate occurs as veins and is being replaced by quartz. Argillite exhibits deformed bedding, shredded boundaries, and severed quartz veins.

2911-4

Argillite and graywacke. Argillite is composed of graphite, muscovite, quartz, and carbonate. Graphite occurs as irregular grains, 1.5 mm. maximum dimension, 44%; quartz, 19%, occurs as angular to subrounded grains, as vein filling, and as chert. Sericite occurs as laths and flakes, 36%, 0.01 mm. maximum dimension, and carbonate occurs as rhombs, 0.25 mm. maximum dimension. Carbonate and graphite occur in both lithologies, but carbonate is more abundant in the graywacke, comprising less than 1% in the argillite.

Graywacke is composed of quartz, graphite, carbonate, sericite, plagioclase, and argillite. Quartz is detrital, 0.25 mm. maximum dimension, but also a replacement of carbonate, and comprises 49%. Sericite is present as laths and flakes, 0.08 mm. maximum dimension, comprising 8%; and argillite clasts are present with a maximum dimension of 0.1 mm. Plagioclase occurs as subhedral to anhedral grains with polysynthetic twinning and slight alteration to sericite, 3%, reaching 0.11 mm. maximum size. Carbonate is present as rhombs and anhedral grains, 20%, 0.5 mm. maximum dimension.

478-7

Argillite, laminated, gray. This sample is composed of graphite, 69%, forming a matrix of clots and stringers; quartz, 0.05 mm. maximum dimension, anhedral grains, angular to subangular, 6.4%; sericite, 7.4%, 0.1 mm. maximum length; rock fragments, 17%, rounded and composed of chert and muscovite, 0.075 mm. maximum dimension; and carbonate, anhedral grains, 0.04 mm. maximum dimension, 0.4%. Graphite-rich layers alternate with muscovite-rich layers.

483-7

The first zone is argillite containing lenses of chert embedded in graphitic matrix. Carbonate occurs as irregular grains and patches. Sericite is present as flakes and laths, 0.05 mm. maximum length. The lenses define bedding by parallel arrangement of their long axes.

The second zone of conical structures is composed of carbonate, graphite, and chert that obliterates conical structure. Graphite is in the form of irregular grains ranging upward from 0.005 mm., and layers that vary in width from 0.01 mm. to 0.25 mm. that commonly grade into stylolites. Pyrite is present as cubes and irregular grains, 0.3 mm. maximum dimension.

The conical shape is indistinctly defined by graphite layers, and the direction in which the apices apparently pointe is downhole. Much of the graphitic structure has been obliterated by the recrystallization of quartz, but the "coaxial v" shapes and familiar zigzag patterns are present.

The upper contact is well-defined. Bases of conical structures are in contact with the clastic lenses of the argillite.

The third zone contains carbonate and graphite, now as stylolites and disseminated grains. and conical structures partially obliterated by quartz. The contact between the second and third zones can be considered where conical structure is absent.

The fourth zone contains chlorite, graphite, and carbonate. Chlorite is present in flakes, and carbonate and graphite are present as irregular grains. The well-defined contact occurs as a ½ mm. wide interval marked by the absence of chlorite.

APPENDIX B

MICROPROBE DATA

MICROPROBE DATA

Ca	Fe	Mg	time (sec.)
DOLOMITE	STD.		
00001581	00000007	00001569	00009.79
00002537	00000009	00002046	00009.82
00002608	00000005	00002070	00009.81
00002696	00000007	00002073	00009.92
00002679	00000011	00001991	00009.97
00002613	00000008	00002140	00009.97
SIDERITE STD.			
00000058	00000925	00000145	00009.86
00000055	00000880	00000142	00009.86
00000060	00000899	00000111	00009.79
00000048	00000989	00000105	00009.86
00000066	00000917	00000106	00010.01
CALCITE STD.			
00005321	00000012	00000022	00009.94
00005024	00000007	00000019	00010.12
00004974	00000008	00000021	00010.12
00005111	00000007	00000012	00010.10
00004936	00000008	00000017	00010.04

2861B-4

Ca	Fe	Mg	
00001997	00000248	00001127	00009.98
00002305	00000310	00001080	00009.96
00002189	00000338	00000883	00009.92
00002273	00000131	00001446	00009.88
00002290	00000173	00001080	00009.98
00002421	00000199	00001492	00009.96
00001626	00000070	00001108	00009.81
00001756	00000076	00001237	00009.87
00002508	00000238	00001237	00009.76
00001540	00000147	00000748	00010.26

Ca	Mn	Mg	time (sec.)
00002721	00000007	00001161	00010.21
00002720	00000011	00001174	00010.18
00002442	00000012	00001161	00010.19
00002446	00000026	00001111	00010.17
00002320	00000020	00001147	00010.20
00002414	00000022	00001143	00010.17

Ca	Zn	Mg	
00002552	00000022	00001166	00010.05
00002690	00000021	00001166	00010.11
00002723	00000021	00001060	00010.15
00002606	00000019	00001113	00010.12

483-7

Ca	Fe	Mg	
00001916	00000027	00001383	00010.23
00001942	00000017	00001487	00010.25
00002128	00000012	00001457	00010.23
00001260	00000030	00001196	00010.00
00002397	00000021	00001319	00010.09
00002345	00000020	00001343	00010.19
00002201	00000083	00001399	00010.17
00002231	00000090	00001327	00010.08
00002128	00000067	00001248	00010.00

2039-1

Ca	Fe	Mg	
00001765	00000090	00001209	00009.95
00002064	00000081	00001181	00009.89
00001454	00000068	00001176	00009.90
00002047	00000123	00001954	00009.80
00002147	00000092	00001454	00009.76
00002301	00000112	00001433	00009.91

Ca	Mn	Mg	
00000793	00000012	00000734	00010.08
00002379	00000023	00001447	00010.01
00002381	00000019	00001340	00009.96
00002285	00000022	00001307	00009.92

Ca	Zn	Mg	time (sec.)
00002138	00000025	00001528	00010.02
00002135	00000024	00001505	00010.00
00002121	00000016	00001318	00009.97

Ca	Fe	Mg	
00001884	00000192	00001086	00009.94
00002311	00000236	00001161	00009.93
00002145	00000237	00001323	00009.98
00002221	00000224	00001508	00009.99

2907A-4

Ca	Fe	Mg	
00001527	00000106	00000885	00010.19
00002108	00000144	00001138	00010.19
00001714	00000141	00000854	00010.21
00001762	00000200	00000741	00010.18
00001425	00000067	00000921	00010.13

2769-4

Ca	Fe	Mg	
00001577	00000180	00001260	00009.85
00002507	00000169	00001209	00009.85
00003612	00000021	00000037	00010.04
00003235	00000020	00000051	00009.93
00002597	00000006	00000048	00009.90
00001821	00000120	00001363	00009.89
00001841	00000079	00003170	00009.95

2774-4B

Ca	Fe	Mg	
00003026	00000099	00001571	00009.84
00003022	00000084	00001436	00009.87
00003076	00000091	00001620	00009.87
00003133	00000090	00001620	00009.92
00003151	00000098	00001612	00010.02
00002884	00000173	00001343	00009.92
00002953	00000176	00001397	00009.89
00002950	00000135	00001407	00009.85

Ca	Mn	Mg	time (sec.)
00002939	00000024	00001270	00010.00
00002958	00000036	00001308	00009.99

Ca	Zn	Mg	
00003137	00000025	00001421	00009.85
00003046	00000022	00001383	00009.86
00002260	00000026	00001285	00009.91

2856-4

Ca	Fe	Mg	
00002542	00000208	00000818	00010.22
00002519	00000203	00000866	00010.06
00002519	00000176	00000857	00010.04

2761C-4

Ca	Fe	Mg	
00002461	00000065	00001407	00009.99
00002801	00000079	00001625	00010.01
00002752	00000064	00001605	00009.99
00002767	00000090	00001642	00010.02
00002690	00000073	00001666	00010.00
00002573	00000071	00001554	00009.92

Ca	Mn	Mg	
00002804	00000004	00001670	00010.01
00002815	00000010	00001589	00010.02
00002315	00000019	00001374	00010.06
00002771	00000021	00001562	00010.07

Ca	Zn	Mg	
00002768	00000026	00001727	00010.16
00002895	00000025	00001630	00010.05
00002475	00000024	00001538	00010.02