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Late Famennian *Wetheredella* in Oncoids from Montana and Utah, U.S.A.

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ABSTRACT

The cyanobacterium *Wetheredella silurica* Wood is reported from porostromate macroidal oncoids in Late Devonian (Late Famennian) siltstones located in southwestern Montana, northeastern Utah, and west-central Utah. It is the first report of the genus *Wetheredella* in the United States and all of western North America. Associated cyanobacteria include the filamentous *Girvanella*, which is rarely preserved, and *Renalcis*. Oncoidal nuclei include primarily brachiopod, mollusk, crinoid, or trilobite skeletons but cores of dark structureless micrite or irregular silt are also present. Boring activity, probably by barnacles and annelids, is evident but variable, with greatest activity in Montana. The oncoidal microfabric is spongy and fenestrate, irregularly and concentrically laminated, and/or thrombotic and peloidal. Peripheral regions of the oncoids are either columnar, club-shaped, branching, domal, undulatory, or combinations thereof. Club-shaped and columnar outgrowths, suggesting immobility, completely encircle some oncoids, are present on only one side in others, or are absent. An analysis of size, structure, and preservation at more than 30 localities suggests a generally quiet water origin with periodic overturning of oncoids. Early mobility followed by growth and stabilization appears to be the history of many nodules. Rolling movement appears to have been minor except for skeletal nuclei whose small size or hydrodynamic shape favored mobility. Early pre-burial diagenesis produced rigid pyrite-bearing oncoids which retained their original, high-sphericity shapes despite later compaction.

Keywords: oncoids, cyanobacteria, *Wetheredella*

INTRODUCTION

Oncoid-bearing strata (oncolites) occur within Late Famennian sedimentary sequences in the Rocky Mountains of western Montana and northeastern Utah and in the Great Basin Province of west-central Utah and eastern Nevada. The carbonate oncoids and associated sediments formed an extensive oncoid facies that extended a distance of at least 1200+ km from Fox Mountain in eastern Nevada (Sandberg et al., 1989) northward to southwestern Montana (Fig. 1).

The term "oncolite," formerly used to describe carbonate cyanobacterial nodules, is now preferred instead for

the bed containing those nodules in the same sense that oolite refers to rocks containing ooids. Today, "oncoid" (Heim, 1916) is used by stromatolite workers and paleontologists (Monty, 1979, 1981; Peryt, 1981, 1983; Riding, 1991a) to describe carbonate nodules formed by cyanobacteria (= cyanophytes or blue-green algae of earlier workers). Despite this stated preference by European workers, American authors still frequently use "oncolite" for the nodules (e.g. Toomey et al., 1988).

In Montana, the Famennian oncoids occur in the Sapington Member of the Three Forks Formation. In northeastern Utah they occur in the Leatham Formation. Farther

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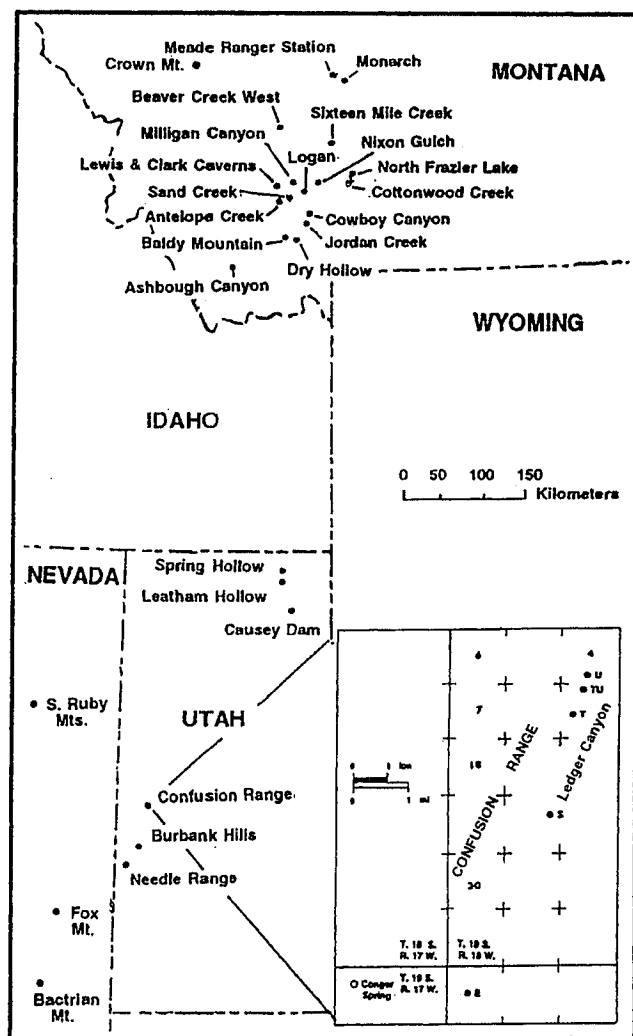


Figure 1. Localities in Montana and Utah from which oncidoids were studied for this report. The Bactrian Mountain locality lacks oncidoids but has rocks of the same age.

south and west, in the Confusion Range, Burbank Hills, Needle Range of western Utah, and at Fox Mountain and the Ruby Range of eastern Nevada, oncidoids are present within the Middle Member ("Leatham Member") of the Pilot Shale. The oncidoid-bearing beds are commonly less than 3 m thick in the three units.

The abundance of both oncidoids and the calcareous sponge *Scaphiomanon* (Gutschick and Perry, 1959) led us to describe these beds as an algal-sponge biostrome (Gutschick and Rodriguez, 1979). This term is inappropriate now that cyanobacteria are no longer regarded as algae, and the unit is now more aptly designated an oncidoid-bearing biostrome rich in shelled invertebrates and sponges. Other Paleozoic algal/cyanobacterial-sponge

associations previously have been noted by Behr and Behr (1976), Toomey and Cys (1977), Toomey and Nitecki (1979), Toomey (1983), Massari and Dieni (1983), and Dreesen et al., (1985).

The Sappington-Leatham-Middle Pilot units have been described in stratigraphic detail by Sandberg and Poole (1977), Gutschick and Rodriguez (1979), Sandberg et al., (1983), and Sandberg et al., (1997). The sediments of the three correlative units are generally similar. They are a fine-grained clastic and carbonate succession that represents eastward sedimentation in response to early pulses of the Antler Orogeny to the west. Generally, the sequence consists of a basal lag sandstone that is overlain by dark, cherty shales (lower black shale), followed by a thin conchostracan-rich dark shale. Above these beds is the distinctive silty, calcareous oncidoid-, shell- and sponge-rich biostromal unit that is the focus of this paper. Higher sediments are largely silty, muddy clastics.

The biostratigraphic zonal assignment of the oncidoid-bearing unit is in dispute. On the basis of *prorsum* Zone ammonoids found in and below the Middle Pilot oncolite unit, Feist and Petersen (1995) have correlated the oncidoid-bearing unit with the latest Devonian Late *praesulcata* conodont Zone. However, Sandberg et al., (1997, p. 141) assign the "algal-sponge-brachiopod biostromal limestone" to the Early *praesulcata* zone.

LOCALITIES

Of the over 30 localities studied for this report (Fig. 1), oncidoids from 12 localities (Fig. 2) were selected for external measurement: three from the Sappington Member (Monarch, Antelope Creek, Dry Hollow), three from the Leatham Formation (Spring Hollow, Leatham Hollow, and Causey Dam), and six from the Middle Pilot (Sections E, S, T, TU, and U, Confusion Range, and section BH' in the Burbank Hills). These localities were chosen so as to cover most of the north-south geographic distribution of the oncidoid-bearing units. Oriented nodules were also collected and studied. In addition to the 12 selected localities, nodules were also examined from outcrops of the Sappington Member at Beaver Creek West, Ashbough Canyon, Jordan Creek, Sixteen Mile Creek, Meade Ranger Station, Crown Mountain, Milligan Canyon, Nixon Gulch, Logan, Baldy Mountain, Cottonwood Creek, Cowboy Canyon, Sand Creek, Lewis and Clark Caverns, and North Frazier Lake (Fig. 1). Through search sampling, these 30 localities yielded 1,761 oncidoids for study.

METHODS

Nodules from each of the 12 selected localities were cleaned in a sonic cleaner in a search for borings on the

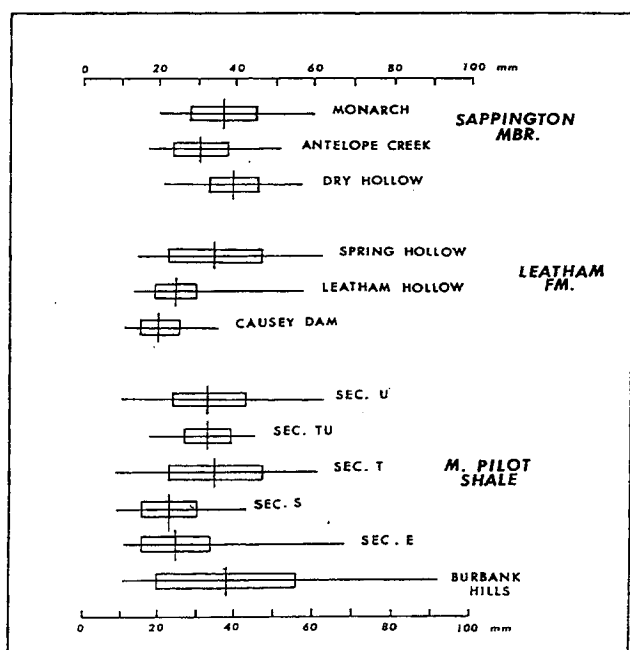


Figure 2. Dice-Leraas diagram showing oncoïd sizes at 12 localities. Long horizontal line depicts observed range; short vertical line is the arithmetic mean; rectangle shows the standard deviation.

outer surface. None were found, possibly owing to the difficulty in removing all of the silt adhering to the nodules. All 1,761 oncoïds collected were measured with calipers. The size range (phi units), mean diameter, standard deviation, Zingg shape, and maximum projection sphericity (Sneed and Folk, 1958) were calculated. A Dice-Leraas diagram (Fig. 2) and shape histograms (not illustrated) were constructed to portray the results graphically. Insoluble residue analysis was also performed on a minimum of ten oncoïds from each of the selected localities. Residues were examined for invertebrates and microfossils. In addition, over 100 thin sections and numerous peels from these and other localities were examined.

Measurement Data

Zingg shape histograms and maximum projection sphericity data reveal that equant shapes are the most common at all localities except at Causey Dam. This locality is unusual in that the deposits surrounding the small, relatively flat *Rhipidomella* cores are unusually thin, the oncoïd shape suggesting the shell forming the core. Maximum projection sphericity histograms show high values with modes in the 0.7–0.8 or 0.8–0.9 class and shapes predominantly in the compact category, and to a lesser extent com-

pact elongate, compact bladed, and compact platy categories. The Zingg and projection sphericity data together suggest that the oncoïds have largely retained their original subspherical shapes during diagenesis.

The size data (Fig. 2) reveal that the Causey Dam locality (Leatham Formation) contains the smallest oncoïds with a mean diameter of 20 mm. The largest oncoïds were collected at locality BH' in the Burbank Hills (Middle Pilot) where the mean diameter is 38 mm and oncoïds with a diameter as large as 9.2 cm have been recorded. Modal size values on size histograms (not shown) generally fall within 16 mm and 45.5 mm but these may be biased toward the larger size classes owing to sampling error. In our view, oncoïd size primarily reflects: (1) the size of the nucleus or core, (2) its residence time under conditions favorable for continued nodule growth (Hottinger, 1983), and (3) the sedimentation rate.

Insoluble Residue Analysis

Insoluble residues (dilute hydrochloric acid) of the calcareous oncoïds contain a diverse and abundant skeletonized macro- and microbiota, quartz silt, and clay (Table 1). The silicified shelly residues contain brachiopods, bryozoans, bivalves, gastropods, cephalopods, incomplete trilobites, and echinoderms (crinoid calices and articulated segments of the column). These siliceous fossils compose some 10 to 15% of the residues. The microbiota consists of silicified cyanobacteria, agglutinated foraminifera, and juvenile shells. The residues suggest that smaller amounts of silt and clay washed into the basin axis to be incorporated into the oncoïds. Conversely, higher silt and clay residue percentages are found along the flanks of the bank where there was a muddy influx and carbonate precipitation was absent.

SYSTEMATIC PALEONTOLOGY

Genus *Wetheredella* Wood, 1948

Wetheredella Wood, 1948, p. 20–21, pls. 3B, 5B

Discussion—The cosmopolitan genus *Wetheredella* Wood (1948) is reported here for the first time from Late Famennian oncoïds of Montana and Utah, its only known occurrence in the United States and in all of western North America. Characteristically, its mode of occurrence relative to oncoïd microstructure is as an encruster along former oncoïd surfaces (Fig. 3). The genus is illustrated here for the first time from a low-energy non-reef environment in North America. Other North American occurrences include the Lower Cambrian of Labrador (Kobluk and James, 1979), where rare *Wetheredella silurica* occurs attached to the roofs and walls of cavities in archaeocy-

Table 1. Results of insoluble residue analysis

LOCALITY	ROCK UNIT	N	BEFORE ACIDIZATION (GRAMS)	MEAN RESIDUE WEIGHT (GRAMS)	MEAN RESIDUE PERCENTAGE
MONARCH	SAPPINGTON	11	45.4	4.78	10.52
LOGAN	SAPPINGTON	10	45.6	6.95	15.24
ANTELOPE CREEK	SAPPINGTON	14	55.9	7.43	13.29
COWBOY CANYON	SAPPINGTON	11	38.14	4.98	13.06
JORDAN CREEK	SAPPINGTON	10	55.43	6.26	11.29
DRY HOLLOW	SAPPINGTON	12	104.91	18.67	17.79
ASHBOUGH CANYON	SAPPINGTON	10	29.62	6.01	20.29
MILLIGAN CANYON	SAPPINGTON	10	51.32	6.91	13.46
SPRING HOLLOW	LEATHAM	10	1088.91	175.28	16.1
LEATHAM HOLLOW	LEATHAM	10	26.42	4.88	18.47
LEDGER CANYON (SEC. TU)	M. PILOT	10	82.29	12.99	15.78
BURBANK HILLS (SEC. BH')	M. PILOT	10	76.8	7.04	9.16

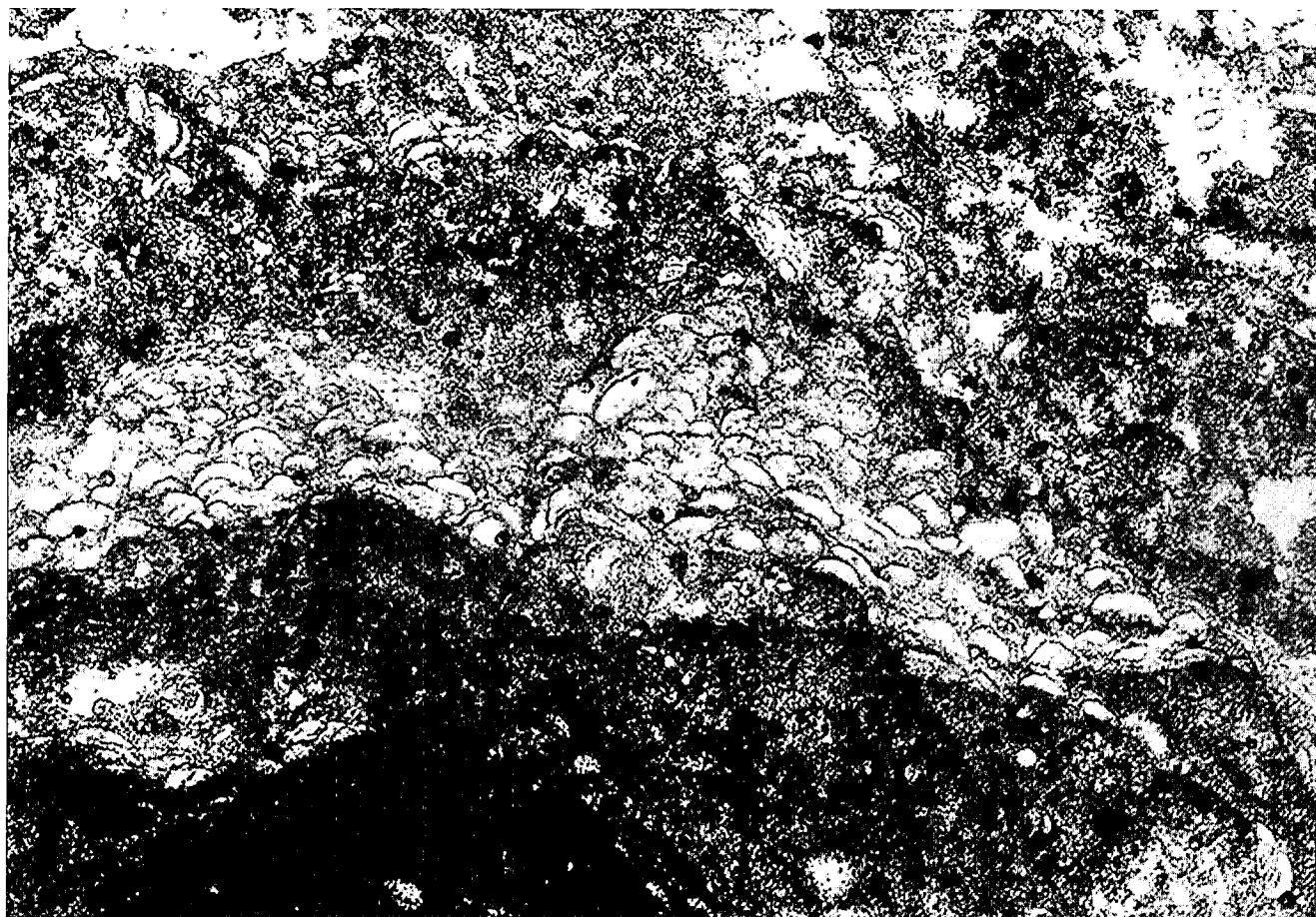


Figure 3. Characteristic appearance of *Wetheredella* in thin section along one long and two short former oncoid external surfaces, X49, Sappington Member, Antelope Creek.

athid patch reefs and the Late Ordovician of Anticosti Island, Quebec (Copper, 1976), where *Wetheredella* was an abundant reef binder, or a frame builder in small isolated mounds. Wood (1948) noted that *Wetheredella silurica* was a nodule builder along with other cyanobacteria, and Wright (1983) reported the genus from Lower Carboniferous oncoids collected from southern Wales.

The stratigraphic range of *Wetheredella* is depicted by Mamet (1991, p. 441) as Silurian to Middle Carboniferous. However, if Kobluk and James (1979) and those authors reporting Ordovician occurrences are correct, the total stratigraphic range is Lower Cambrian to Middle Carboniferous. Kazmierczak and Kempe (1992) have reported Holocene *Wetheredella*-like structures from Satonda Crater Lake, Indonesia. A huge biostratigraphic gap (post-Middle Carboniferous to pre-Recent) of unrecorded *Wetheredella* appears to argue against these being true modern representatives of the genus. Even if the Mesozoic genus *Koskinobullina* Cherchi and Schroeder (1979, 1984) is included in the Wetheredellidae, as Kazmierczak and Kempe suggest, wetheredellids remain unknown from the entire Tertiary System. On the other hand, long-ranging genera are quite common in the cyanobacteria owing to their extremely slow "hypobrydetic" (Schopf, 1999) rate of evolution.

The wall of our Late Famennian *Wetheredella* is as described by Mamet and Roux (1983) and is composed of a thin dark outer layer and a thick inner layer of pseudo-fibrous calcite traversed by subcylindrical pores that are perpendicular to the wall. Both Copper (1976) and Kazmierczak and Kempe (1992) have suggested that the origin of the inner porous layer is of secondary origin and thus not biologic.

The history of biologic interpretation of the microfossil *Wetheredella* has recently been summarized by Riding (1991b), and by Kazmierczak and Kempe (1992) and need not be repeated in detail here. Most past assignments are to calcareous foraminifera (by Wood, 1948), agglutinate calcareous foraminifera (Kobluk and James, 1979), to "probably algal" (Loeblich and Tappan, 1964; Mamet and Roux, 1983), possibly red algae (Copper, 1976), green algae (Istchenko and Radionova, 1981), and filamentous cyanophytes (Copper, 1976). Kazmierczak and Kempe (1992) recently argued that modern *Wetheredella*-like vesicles are actually coccoid cyanobacteria, and Zhuravlev and Wood (1995) have accepted this conclusion.

The co-occurrence and association of *Wetheredella* with *Girvanella* in the oncoids of this study, and less importantly the presence of the probable calcimicrobe *Renalcis*, along with *Wetheredella*'s observed role in helping to build oncoids, strongly suggests the oncoids' microbial (cyanobacterial) origin.

Wetheredella silurica Wood, 1948

(Figs. 3, 4a-d, 10)

Wetheredella silurica Wood, 1948, p. 20, pl. 3, fig. B, pl. 5, fig. B.

Rhabdoporella glomerata Jux, 1966, p. 171-174, pl. 41, figs. 1-6.

Wetheredella silurica Heroux et al., 1977, p. 2901, pl. 12, figs. 7-11.

Wetheredella cuniculi Vachard 1977, in Dřl et al., p. 430, pl. 7, figs. 1, 2.

Wetheredella Tsien 1979, fig. 23.

Wetheredella silurica Istchenko and Radionova, 1981, p. 148, tabl. 1, figs. 1-4, tabl. 3, figs. 8, 9.

Wetheredella silurica Mamet and Roux, 1983, p. 99, pl. 11, figs. 1-8.

Wetheredella silurica Shuysky, 1987, pl. 13, fig. II

Wetheredella silurica Kórtis et al., 1990, pl. 22, figs. 3, 4.

Wetheredella silurica Mamet and Pr  at, 1992, pl. 1, fig. 9.

Wetheredella silurica Mamet, Roux, LaPointe, and Gauthier, 1992, p. 236-237, pl. I, fig. 4, pl. 10, fig. 1.8.

Wetheredella silurica May, 1992, p. 22, pl. 1, fig. 5, pl. 5, figs. 2, 3.

Wetheredella silurica Chuvashov, Shuysky, and Ivanova, 1993, pl. 2, fig. 1

Description—Subcircular to subelliptical and flattened tubes and vesicles, convex upward, flat to concave along the underside; tubes flexuous; diameter variable but between the range of 30 to 145 μ m; arrangement of tubes and vesicles random but often convex in outline; may be relatively thick or thin constructional accumulations; found encrusting along buried former external surfaces or the outermost oncoid surface.

Discussion—*Wetheredella silurica* is the type species and perhaps only known species of the genus found in pre-Carboniferous rocks. It is geographically widespread having been reported from the Baltic region, Belgium, Germany, Poland, the Urals, eastern Canada, and the Frasnian and Famennian of Australia.

The species is reported in small volumes from oncoids from all three rock units of this study. *W. silurica* is known from 11 Sappington localities, from Spring Hollow, Leatham Hollow, and Causey Dam in the Leatham Formation, and from several Middle Pilot localities in the Confusion Range (Table 2). It consists of encrusting tubular and vesicular (coccoid) skeletons which are subcircular to semielliptical in cross section. The tubular nature of some is revealed in sections where the subcircular cross sectional shapes grade into more elongate, probably tubular bodies. The cross sections, which are always convex outward, encrust upon the oncoid's outer surface and are usually enclosed by later deposits.

Table 2. Occurrence of *Wetheredella* and *Renalcis*

LOCALITY	ROCK UNIT	<i>Wetheredella</i>	<i>Renalcis</i>
MONARCH	SAPPINGTON	✓	✓
NIXON GULCH	SAPPINGTON	✓	—
16-MILE CREEK	SAPPINGTON	✓	✓
ANTELOPE CREEK	SAPPINGTON	✓	✓
MILLIGAN CANYON	SAPPINGTON	✓	✓
BALDY MOUNTAIN	SAPPINGTON	✓	✓
JORDAN CREEK	SAPPINGTON	—	✓
LOGAN	SAPPINGTON	✓	✓
MEADE RANGER STA.	SAPPINGTON	✓	✓
COWBOY CANYON	SAPPINGTON	✓	✓
SAND CREEK	SAPPINGTON	✓	—
N. FRAZIER LAKE	SAPPINGTON	✓	—
SPRING HOLLOW	LEATHAM	✓	✓
LEATHAM HOLLOW	LEATHAM	✓	✓
CAUSEY DAM	LEATHAM	✓	—
CONFUSION RANGE SECS. E, S, T, TU, U	M. PILOT	✓	✓ (SEC. T)

Thin sections and peels display the nature of the oncoid-building role of *W. silurica*. Thin section LH9 (Fig. 4a), for example, from Leatham Hollow, reveals a small, well-laminated oncoid with clublike outgrowths on one side and an outer surface layer (2 mm in thickness) consisting of some 20 irregular rows of *Wetheredella*. Thin, irregular strands of the filamentous cyanobacterium *Girvanella* intermingle with the mostly convex *Wetheredella* cross sections. A similar but thinner (0.6 mm thick) outer layer of *W. silurica* has been found in thin section ACA from the Sappington Member at the Antelope Creek locality. A recurrent occurrence is illustrated in Figure 4b where the structures have a domal arrangement over a large (pyritic?) dark area. *W. silurica* also encrusts upon skeletal material. In thin section LH50 from Leatham Hollow (not illustrated), *Wetheredella* grew directly on the surface of a single brachiopod valve. *Wetheredella* is also sometimes found encircling the ends of single valves (Fig. 4c). Similar growth habits have been observed in thin sections from the Sappington Formation at the Ashbough Canyon and Monarch localities. Elsewhere, thin encrustations consisting of only two to three irregular rows of *Wetheredella*, have also been seen (Fig. 4d). In some thin sections these form part of the construction of digitate outgrowths in Leatham and Pilot oncoids.

Terminology and classification of oncoids

Terminology used in the study of oncoids and other stromatolites continues to evolve. Many published papers

introduce at least one new term. Most terms are potentially useful but the result is a required extensive oncoid vocabulary.

Pia (1927) classified his thallophyte Class Schizophyceae into two major groups: the Spongiostromata (without distinct organic microstructure, but often with characteristic growth forms), and the Porostromata (with distinct microscopic tubes). He further divided the Spongiostromata into Stromatolithi (growing attached to the substrate), and Oncolithi (growing loose; mobile on the substrate). It later became apparent that many oncoids contain, or are constructed by, calcified filamentous cyanobacterial sheaths such as *Girvanella* which had been placed in the Porostromata by Pia. Among the many classifications that followed, that of Logan, et al., (1964) was highly influential in the United States. Working with modern agglutinate forms, they assigned oncoids to their Type SS (spheroidal structures) nodules and recognized three modes of this structure: Mode I—inverted, stacked hemispheroids; Mode R—randomly stacked hemispheroids; and Mode C—concentrically stacked spheroids. Aitken (1967) was critical of this scheme, largely because it fails to describe the important properties of size, relief, gross external form, and surface sculpture. Bathurst (1975) suggested that similar growth forms, as defined by their LLH (laterally linked hemispheroids), SH (stacked hemispheroids), and SS structures and their combinations, may arise by the growth of different microbial associations and in a variety of environments.

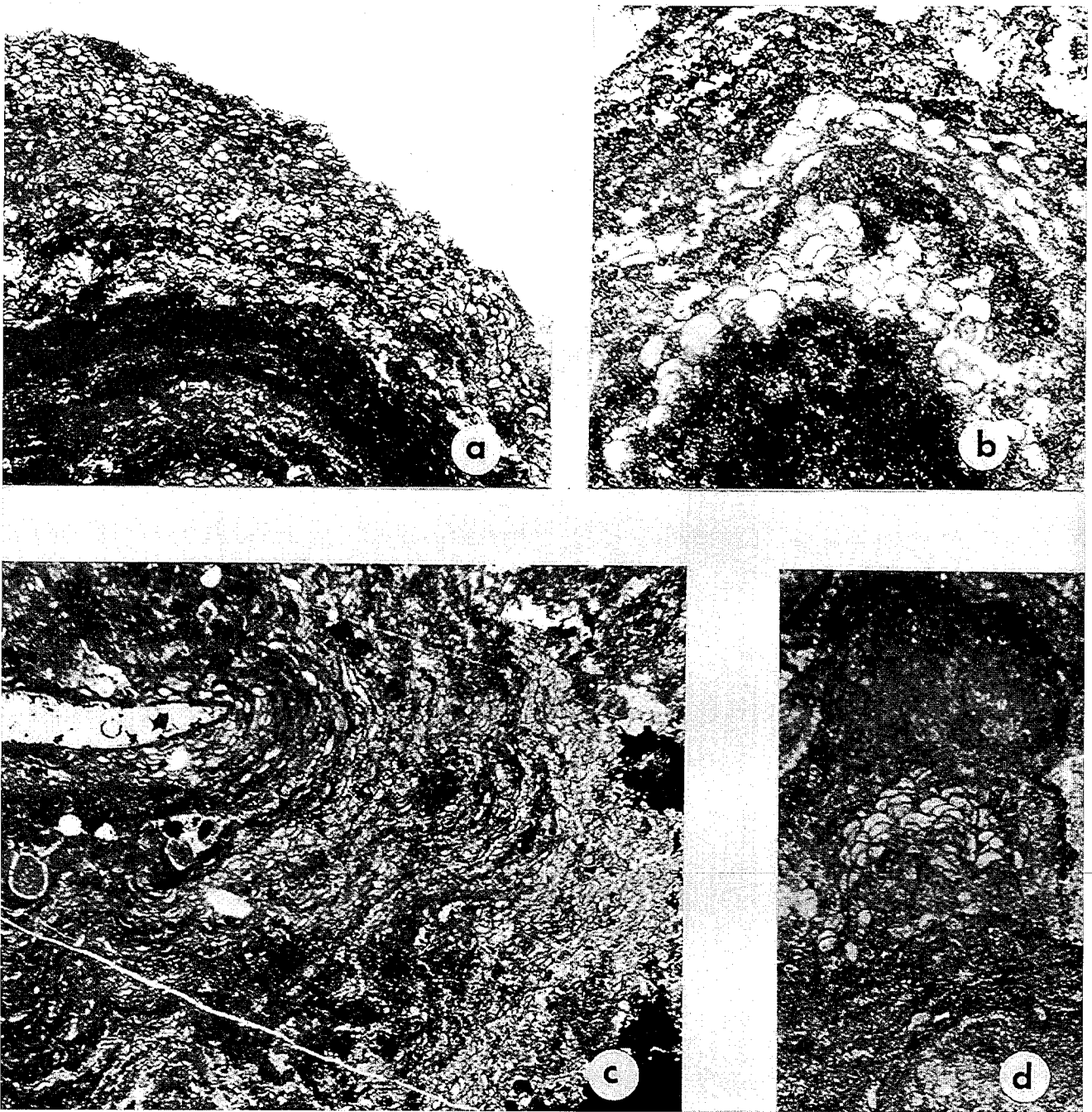


Figure 4. Four modes of occurrence of *Wetheredella*. a) *Wetheredella* encrusting along the exterior margin of an oncoïd, X20.8, Leatham Formation, Leatham Hollow; b) Domal arrangement of *Wetheredella* around an obscure nucleus, X34.2, Middle Pilot Shale, locality S, Ledger Canyon, Confusion Range; c) Thick development of *Wetheredella* wrapping around the end of a brachiopod shell, X18, Middle Pilot Shale, Section E, Confusion Range; d) Thin, slightly curved arrangement of *Wetheredella*, X 17.6, Sappington Member, Meade Ranger Station.

Monty (1981) recognized 3 types of oncoids: (1) spongiostromate oncoids, built by the trapping and binding activity of cyanobacteria; (2) porostromate oncoids, composed of calcified cyanobacterial filaments or threads; and (3) spongioporostromate oncoids, which are a combination of (1) and (2). Catalov (1983) suggested a fourth useful term, "paraporostromate" for those initially porostromate oncoids that have been diagenetically altered to resemble the spongiostromate type, a common occurrence. Riding (1991a) proposed the term "agglutinated stromatolite" for Monty's spongiostromate oncoids, and "skeletal stromatolites" (Riding, 1977) for porostromate stromatolites of any algal affinity. Some now also use the term "calcimicrobialite" for porostromate carbonates. Riding (1977; 1983) also proposed the term "cyanoid" for oncoids of calcified cyanobacterial origin. This term is applicable to the Late Devonian oncoids of this report.

Burne and Moore (1987) introduced five terms to describe microbialite internal structure: (1) stromatolitic (fine, planar, laminated); (2) thrombolitic (clotted texture); (3) cryptic (vague, mottled, or patchy microbial texture; cf. "cryptomicrobial" of Kennard and James, 1986); (4) oncolitic (concentric, laminated); and (5) spherulitic (spherular aggregates). Oncoid microstructures falling into each of categories (1) to (4) have been observed in the Late Devonian nodules of this report. Burne and Moore's characterization of oncolitic structure is not, however, entirely satisfactory as oncoids are known which are nonlaminated or thrombolitic (e.g., see Bowman, 1983; and this report). Also, some may be only partly laminated, and laminae are not always well described by the term "concentric" as they often do not consist of continuous concentric envelopes.

Oncoids of this study—an overview

Our Late Devonian oncoids are macroidal (i.e. > 10 mm, Peryt, 1983), and overwhelmingly of the "spongy" type of Aitken (1967). Aitken asserted that the peripheral segment of a spongy oncoid is similar to a very small digitate stromatolite of Mode SH-V (vertically stacked hemispheroids of Logan et al., 1964). In the Montana and Utah material five types of peripheral segment occur: (1) simple columnar (parallel-sided); (2) branching columnar; (3) club-shaped (widening upward); (4) domal; and (5) irregularly undulatory. In some cases, the peripheral outgrowths are present on only one side; in others they completely encircle the oncoid. Our study indicates that it is possible to have more than one type of outgrowth in a single oncoid.

Small oncoids in the basal beds of the Leatham Formation at Leatham Hollow, and of the Middle Pilot in the Confusion Range, are of Aitken's "simple" type. These appear to represent the initial onset of oncoid-forming conditions and are replaced in higher beds by the larger,

more complex "spongy" type. In the Utah occurrences, some early mobility followed by stabilization with growth, size increase, and development of the characteristic fenestrate "spongy" microfabric appears to be the history for some nodules. Rolling movement was probably minor except for skeletal nuclei whose small size or hydrodynamic shape (e.g. orthoconic nautiloids, crinoid stem segments, and high-spired snails) favored mobility. These oncoids, unlike most of the oncoids in this study, are enclosed by continuous and complete concentric laminae.

Most of the Montana-Utah Famennian oncoids are also assignable to the form genus *Ottonosia* Twenhofel (1919). Toomey et al., (1989) have suggested, and we agree, that the oncoid form genera *Osagia* and *Ottonosia* be dropped because they do not refer to true biologic species and create taxonomic and synonymic problems. They suggest instead the use of "osagid grains" or "algal colonies" for the smaller grains, and "algal biscuits" or "ottonosid grains" for the larger forms.

Sappington oncoids

Oncoid localities in the Sappington member are numerous and widespread. Larger skeletal material, usually complete and identifiable, forms the nucleus of most oncoids. The most common silicified oncoid core is the abundant orthid brachiopod *Rhipidomella*, but silicified spiny productoid and molluscan cores are also present. At some localities, smaller skeletal material is commonly recrystallized and the original outlines are destroyed. Diagenetic recrystallization appears to have affected many more oncoids in the Sappington Member than in the other two units.

Size

Sappington oncoids have been observed in the field to be fewer and of smaller diameter along the margin of the basin. They are generally of intermediate size but commonly have a thick (10 to 38 mm) micritic deposit surrounding a small to intermediate core. The mean diameter at the Monarch locality is 38 mm, although oncoids with a diameter of 60 mm have been measured. Antelope Creek nodules have a mean diameter of 25 mm and those from Dry Hollow have a mean of 40 mm.

Oncoid Microfabric

Oncoids at Antelope Creek and surrounding localities in the central Sappington outcrop area are composed largely of structureless micrite and peloidal micrite. Club-shaped and columnar peripheral outgrowths are rare. Skeletal cross sections, in places recrystallized, are abundant, as is quartz silt which forms some nodule cores and

commonly fills fenestrae and borings. The nodules display a complex internal structure of dark brown undulatory and irregular nonlaminar enclosed former surfaces. Protuberances, in places domal, in the well-defined microtopography in many cases reflect the incorporation of the abundant invertebrate skeletal material along with conodonts, *Wetheredella*, or, less frequently, dense bodies of structureless micrite. Spar- or silt-filled fenestrae directed outward (gas escape?) are generally small and irregular but elongate fenestrae may also parallel the laminae. Spar- or silt-filled circular to oval borings, in some situations penetrating oncoid and shell material alike, are abundant. Molluscan shells have undergone neomorphic inversion to sparry calcite or, in some cases, dissolution followed by void-filling by drusy spar.

Oncoids collected at the Monarch locality in the Little Belt Mountains differ somewhat in microstructure and more closely resemble Leatham oncoids. Some are composed of regular, closely spaced, fine outer laminae forming outward growing columns. The dark laminae maintain undulatory parallelism in the early layers encircling a nucleus but soon depart therefrom. In some thin sections, sheath-like outlines (*Girvanella* and/or *Rothpletzella*?) are barely visible along the laminae. The inner microstructure is peloidal or clotted, resembling an illustration in Semikhatov et al., (1979, fig. 3c). Dense micritic clots display thin, short, straight, clear bodies and tiny circular perforations that might correspond to former calcified sheaths that were later dissolved during diagenesis.

Oncoids from Dry Hollow in the Gravelly Range have either a silt-filled unidentifiable nucleus or a single brachiopod shell. Borings are relatively few and small. The outer areas of the nodules exhibit well-laminated undulatory structure which, in some thin sections, is poorly preserved. Skeletal epiphytes are present but are less abundant than at the Antelope Creek and the Monarch sites. Diagenetic recrystallization has affected many nodules from this locality, obscuring whatever microbial fossil material may be present.

When thin sections from all of the localities are taken into consideration, Sappington oncoids are seen to be composed largely of structureless micrite, peloidal micrite, thrombotic, and, less commonly, crudely laminated micrite. Pyrite is widespread. This combination may correspond to Riding's (1991a, p.37–38) compositional category of Cryptic Microbial Carbonates. These lack distinctive macrofabrics but characteristically possess micritic, clotted, or peloidal microfabrics, in which there may be traces of filaments. Silty, structureless dark micrite is commonly observed in oncoid cores and also in outer areas. Some of the tiny circular openings that speckle this lithology may be cross sections of diagenetically altered *Girvanella* but most of it is quartz silt. Peloids of the peloidal micrites probably

represent broken cyanobacterial sheaths or replaced unicells (Monty, 1967; Bathurst, 1975). Thrombotic, or partially thrombotic oncoids are present. Coccoid cyanobacteria may have played a role in forming thrombotic structure in oncoids (Semikhatov et al., 1979; Kennard and James, 1986). However, Burne and Moore (1987) have pointed out that thrombotic mesoclots may also form from calcified filamentous cyanobacteria. Riding (1991a) has suggested that there is probably a variety of origins for thrombolites and this appears likely.

Skeletal remains are found at all levels within the oncoids, in some cases including the outer surface. Nuclei are often composed of exquisitely preserved silicified spiny productoids. The small brachiopod *Leptalosia* is commonly observed in life orientation with its visceral disk attached to the surface of a former outer surface with its trail upturned. This suggests that *Leptalosia* was living on a hard surface, as its epizoic mode of life on brachiopods and other shelled invertebrates is well known. Encrusting bryozoans also settled on oncoid surfaces and are commonly seen on both present and former outer surfaces.

Borings are internally common in Sappington oncoids, some passing obliquely through encased shells. Other shell borings appear to have been made while the shelled organism was still alive and living on the surface of the nodule. Both acrothoracican barnacle and annelid borings are common. Catalov (1983) suggested the terms "zoogenic" and "zoophytogenic" to describe oncoids rich in invertebrate skeletal material and this term is appropriate for many Sappington algal nodules.

The cyanobacterial fossil *Renalcis*, was also observed in oncoids from 12 Sappington localities. Following Mamet and Roux (1983) and Mamet (1991) we interpret *Renalcis* as a senior synonym of *Chabakovia* Vologdin, *Shuguria* Antropov, and *Izhella* Antropov.

Environment

There are significant geographic differences in the size of Sappington oncoids. Those near the basin margin are smaller and scarcer. This is probably due to their origins at a shallow water depth close to, or just above, effective wave base. Intrabasally, in deeper water, there is little difference in mean size suggesting uniform environmental conditions.

The abundance and diversity of invertebrate life encased in Sappington oncoids testifies to an ecologic setting favorable to a variety of organisms. Warm, clear, shallow subtidal water of normal salinity indicated by the invertebrates similarly indicates ideal conditions for the growth of photosynthetic cyanobacteria and the formation of oncoids. The preservation of delicate long spines in nuclei and elsewhere within the oncoids suggests an absence of

strong water movements. The absence of club-shaped and/or columnar outgrowths in such seemingly favorable conditions is problematical.

Leatham oncoids

Well-preserved Leatham oncoids have been collected from Spring Hollow, Leatham Hollow, and Causey Dam. Oncoids from each of these localities have silicified skeletal material, and are, in most cases, distinctive.

Size

Large oncoids at Spring Hollow often contain a nucleus of the large brachiopod *Schizophoria* (Rodriguez and Gutschick, 1978). These oncoids attain a maximum size of 62.6 mm with a mean diameter of 34.2 mm. Smaller oncoids from this locality typically have a core of *Rhipidomella* or other skeletal nuclei. Oncoids from Leatham Hollow are generally of smaller size than those at Spring Hollow. Causey Dam oncoids are uniformly small, with a mean diameter of 20 mm, the smallest in the Leatham Formation. Cores at Causey Dam are commonly composed of a small, complete but undersized, silicified *Rhipidomella* nucleus enclosed by 5 mm or less of laminated microbial coating.

Oncoid microfabric

Typically, Leatham oncoid cores are encircled by fine, regular laminae (stromatolites of Kalkowsky, 1908; Kennard and James, 1986) of low, undulatory structure passing outward into outward-extending columns or clubs, sometimes partially constructed by *Wetheredella* (Fig. 5). The undulatory structure in some cases can be attributed to the presence of *Wetheredella* structures that are domed outward and present within the clublike outgrowths in some thin sections.

Well-preserved *Girvanella* (Fig. 6) and *Renalcis* are also present. Oncoids with a large core, completely enclosed directly by clublike and columnar outgrowths, are common at Spring Hollow. Clear calcite laminae alternate irregularly with those composed of dark micrite in these outward branches. These dark micrite laminae are interpreted as consisting of diagenetically altered calcified sheaths of *Girvanella* or the "algal dust" or "algal paste" of some authors (Wood, 1941; Johnson, 1957; Toomey et al., 1989). Irregular fenestrae are common and in many cases composed of neomorphic spar. Other openings, some of which are borings, are also filled with spar or silt. Pyrite, some of which is framboidal, is present. Neomorphic recrystallization is evident in some thin sections.

In Leatham Hollow oncoids undulatory structure is well developed. Finger-like outgrowths, in some specimens composed of fine prostrate threadlike (*Girvanella*?)

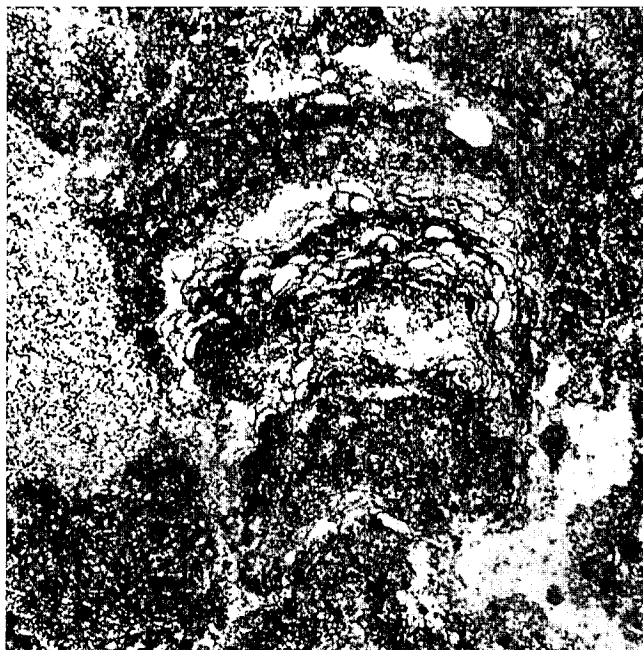


Figure 5. Club-shaped structure showing constructional role of *Wetheredella*, X22, Leatham Formation, Spring Hollow.

laminae, encircle the entire oncoid. Skeletal and silty nuclei (Figs. 7a,b), silt-filled fenestrae, borings, and skeletal epiphytes are common. *Wetheredella* is well-preserved and present in most thin sections. Some sections display a nonskeletal thrombolitic or possibly extensively bioturbated core region, with laminae in the outer region. Pyrite and pyritization of small shells is common at this locality.

The small Causey Dam oncoids recurrently exhibit outgrowths. The nucleus consists of micrite or of a small, complete shell or single valve, coated with less than 5 mm of smooth laminae. Framboidal pyrite is abundant at this locality.

Environment

Both Spring Hollow and Leatham Hollow localities are representative of quiet water sea floors. The rich fauna preserved within their oncoids includes delicate structures similar to those of the Sappington Member and the environment represented was probably similar.

Many Spring Hollow oncoids attain their large size owing to the large brachiopod *Schizophoria* serving as an oncoid nucleus. These heavily weighted oncoids were immobile on the sea floor and club-shaped and/or columnar peripheral outgrowths surround them reflecting phototropic upward growth.

Causey Dam oncoids clearly reflect a different environment than other Leatham localities. Their small size at

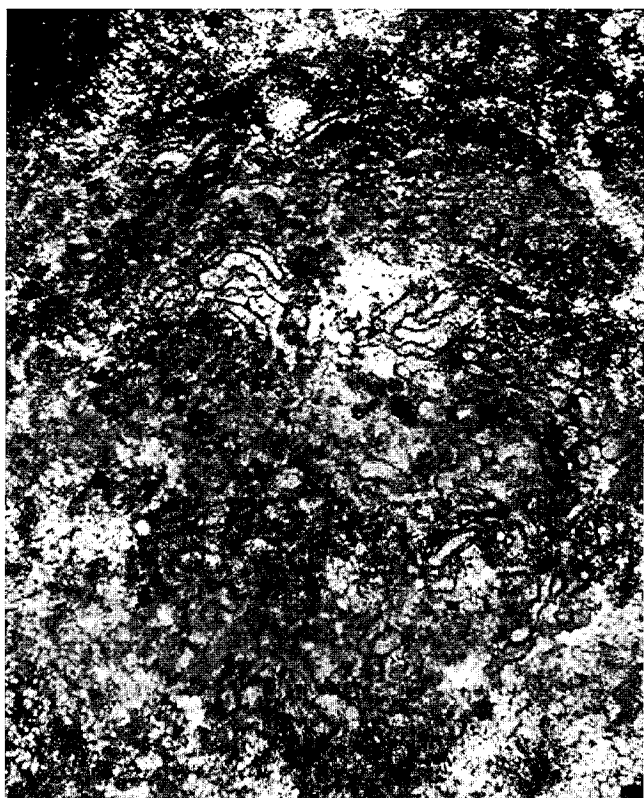


Figure 6. Well preserved *Girvanella* from the Leatham Formation at Spring Hollow, X64.

this locality is interpreted as the result of deposition in a stagnant, organic-rich, oxygen-poor environment and a low rate of carbonate deposition. In addition, where the brachiopod *Rhipidomella* serves as a nucleus, the shell is of smaller size than at other localities and borings are rare to absent reflecting a less favorable environment.

Middle Pilot oncoids

Middle Pilot oncoids occur abundantly in the Confusion Range of west-central Utah along Ledger Canyon and along Deadman's Wash in the Burbank Hills to the south (Gutschick and Rodriguez, 1979). Skeletal cores of mollusks, trilobites, and brachiopods are especially common in the southern part of the Confusion Range but decrease in abundance to the northeast in the strike valley called Ledger Canyon. Nonskeletal thrombolitic cores are dominant at the northeastern end of Ledger Canyon. Unlike the Sappington and Leatham oncoids, skeletal cores are not silicified in the Middle Pilot.

Size

Middle Pilot oncoids increase in size upward, suggesting increasingly favorable conditions for oncoid formation.

The oncoids from the Middle Pilot at the Burbank Hills locality are the largest in this study. Although the mean diameter is only 38 mm, nodules as large as 9.2 cm have been measured. The smallest Middle Pilot nodules, averaging 22.9 mm in diameter, are from Section S which is in Ledger Canyon, in the Confusion Range; their small size is possibly due to selective hydrodynamic sorting or collector error.

Oncoid microfabric

Middle Pilot oncoids in the Burbank Hills display brown to red-brown core areas, with slightly undulatory laminae encircling silt-filled and skeletal cores. Fine, poorly preserved skeletal matter and structureless brown micrite is also abundant. Peloidal microfabrics are commonly observed. A number of compound oncoids, composed of two and in some cases three growth nuclei, suggest *in situ* lateral growth of closely spaced nuclei.

In the Confusion Range of western Utah, Middle Pilot oncoids typically display strong randomly stacked layers toward the southern part (sections A–E of Gutschick and Rodriguez, 1979) of their distribution. Here, they are laminated with skeletal cores and *Wetheredella*. Some oncoids display thick structureless layers of brown micrite separated by dark bands. Towards the northeast (sections T, TU and U of Gutschick and Rodriguez, 1979), the non-laminated to partially laminated oncoid cores pass upward into irregularly branching, columnar outgrowths some of which exhibit nonlaminated micritic microstructure. Although some show only upwardly directed columns, unusual specimens in which the fingerlike and clublike outgrowths completely encircle the oncoid have been found (Figs. 8a–d). These specimens are internally sparsely laminated and sometimes lack skeletal cores. Their accretionary nature precludes the possibility of their being sponges. The northeastern Ledger Canyon oncoids differ from similarly encircled forms in the Leatham Formation at Spring Hollow in that they exhibit fewer laminae or are nonlaminated, and are not as extensively recrystallized.

Environment

Middle Pilot oncoids are generally small and thinly coated with straight laminae at the base of the unit and increase in size upward. This suggests development of conditions that were increasingly favorable for oncoid formation such as a regressive shallowing of depth that gradually increased the level of illumination on the sea floor and thereby favored the presence and photosynthetic activity of cyanobacteria.

The increase in columnar extensions to the northeast in Ledger Canyon suggests a lack of frequent movement of

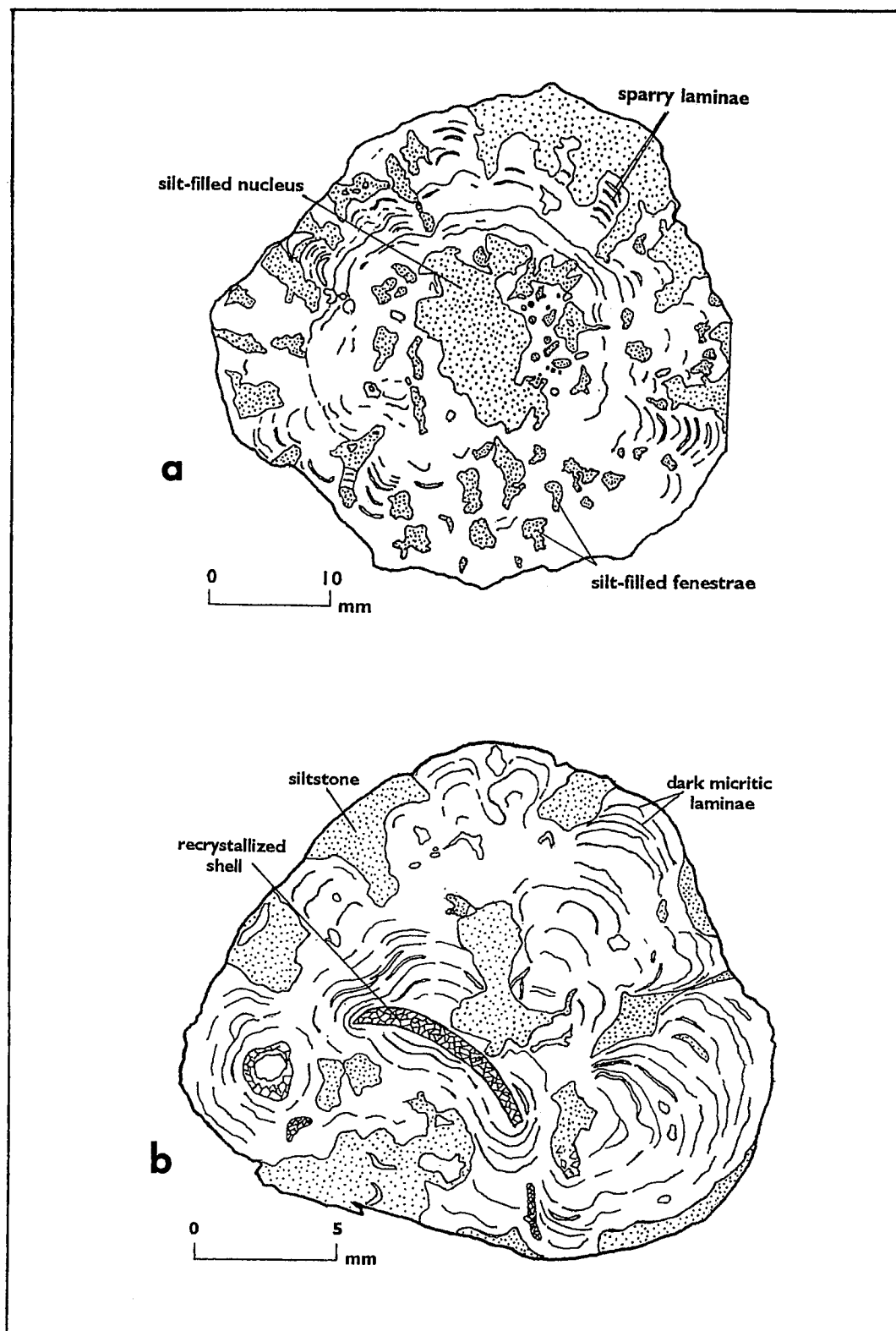


Figure 7. a) Camera lucida drawing of silt-filled nucleus and fenestrae in oncoid from Leatham Hollow, Leatham Formation; b) Camera lucida drawing of oncoid with recrystallized shell core, micritic laminae, fenestrae, and silt-filled intercolumnar areas, Leatham Formation, Leatham Hollow.

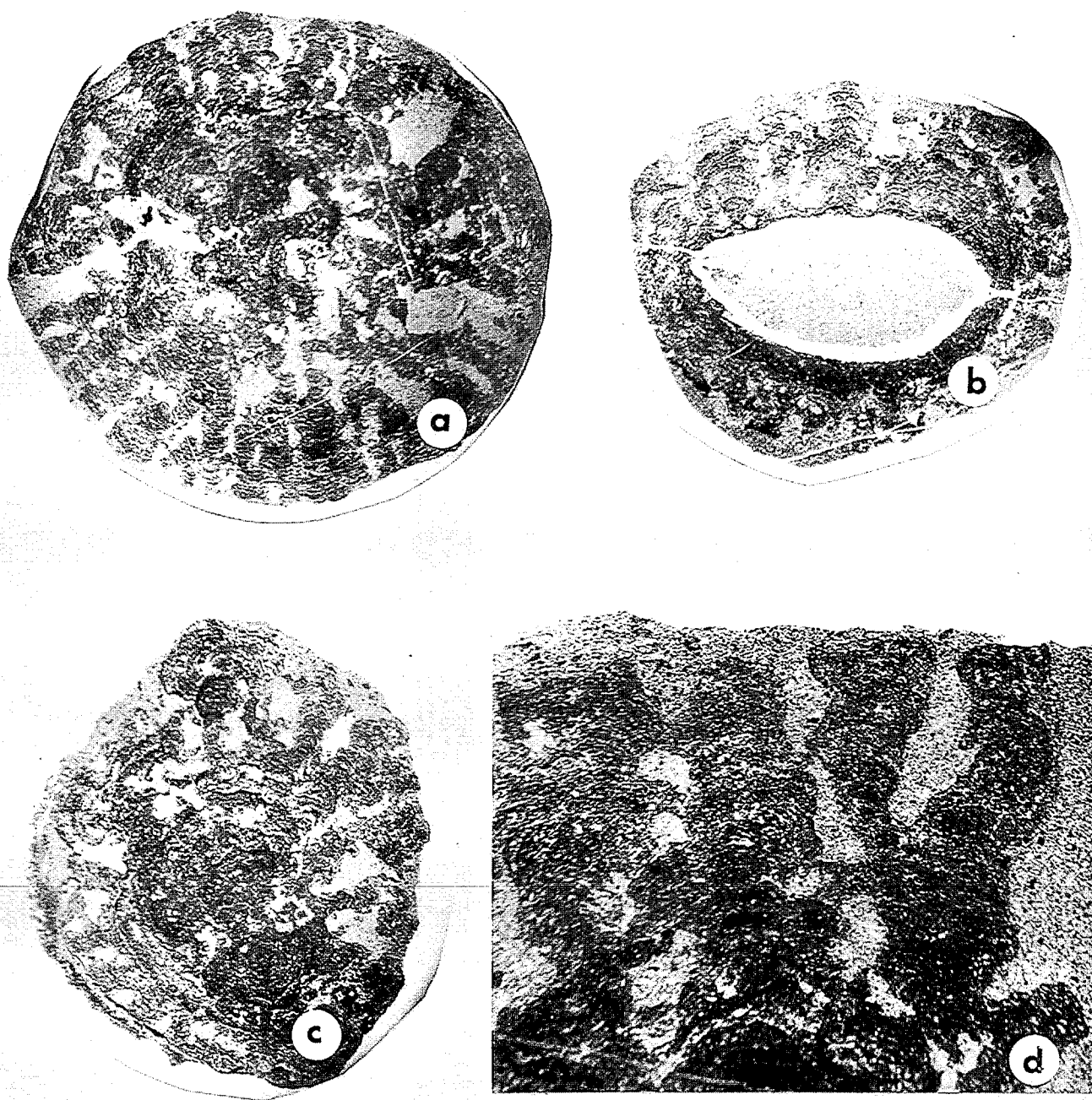


Figure 8. Oncoids surrounded by columnar and/or clublike structures. a) Oncoid encircled by clublike and columnar outgrowths, X2.1, Middle Pilot Shale, locality U, Ledger Canyon, Confusion Range. Most outgrowths are microscopic vertically stacked hemispheroids with concentric laminae. Some outgrowths have microscopic lateral extensions resembling laterally linked hemispheroids; b) Oncoid encircled by weakly developed peripheral outgrowths surrounding a brachiopod nucleus, X2.1, Middle Pilot Shale, Section U, Ledger Canyon; c) Oncoid with micritic core completely surrounded by clublike outgrowths, X2.1, Middle Pilot Shale, Section T, Ledger Canyon. These are laminated as in (a); d) View of club-shaped structures joined by lateral extensions (links or "bridges") formed by lateral growth on silt surface between clubs, X9, Middle Pilot Shale, Section T, Ledger Canyon.

the oncoids and a generally quiet-water environment. Periodic storms or nudging by mobile benthic animals in such an environment are sufficient to account for changes in oncoïd orientation. After these infrequent movements, phototropic upward growth resumed on the newly-oriented upper oncoïd surface; the process was repeated several times until the entire nodule was surrounded by radial digitate outgrowths. By contrast, oncoids from sections A–F at the southwestern end of Ledger Canyon lack these peripheral outward extensions; their absence suggests greater water movement in that direction.

CONCLUSIONS

The cosmopolitan cyanobacterium *Wetheredella* is reported for the first time from western North America. Although Copper (1976) noted *Wetheredella* from an off-reef environment, this is the first North American occurrence of the genus in a quiet-water, non reef-related, basinal environment. *Wetheredella*'s encrustation of oncoïd exterior surfaces during their growth contributed to the construction of these oncoids over a wide geographic area.

Detailed study of the oncoids indicates deposition in a shallow, subtidal, quiet water basin setting with water depths ranging from about five to 30 meters. This would place them within the photic zone yet below the low tide mark. The sedimentation rate must have been relatively low during oncoïd formation so as to prevent burial. Preliminary studies interpreting the oncoids as a product of frequent rolling on the sea floor (Gutschick and Rodriguez, 1979) are accordingly revised. The revision follows examination of many nodules, thin sections, and a number of publications by specialists in calcareous algae in the intervening years.

Five lines of evidence support the conclusion that the oncoids in this study formed in quiet water: (1) the muddy texture of the sediments enclosing the oncoids; (2) the preservation of delicate needle-like spines in silicified productoid and other brachiopods; (3) the lack of evidence of continuous rolling in the oncoïd microfabric; and rolling is no longer considered necessary in order to form concentric or near concentric laminae (Jones and Wilkinson, 1978); (4) upwardly digitate oncoids, such as those at Spring Hollow, Leatham Hollow, and in northeastern Ledger Canyon, are difficult to conceive as the product of high energy environments; and (5) the observed occurrence of compound (composite) oncoids with two or three nuclei that appear to have merged through continued *in situ* growth; such intergrowths are unlikely in frequently agitated waters. This quiet water interpretation for the origin of the studied oncoids does not preclude occasional overturning of the oncoïd during storms nor by benthic

organisms as indicated by one specimen (Fig. 9) that shows upward-directed columnar outgrowths and a *Leptalosia* shell along the underside.

We also now conclude that the Famennian oncoids discussed herein, like most pre-Middle Jurassic oncoids, are predominantly porostromate or paraporostromate. They are not analogous to the modern marine Type-SS stromatolites described by Logan et al., (1964) as has been brought out in more recent work by Monty (1972, 1979), Riding (1977, 1979), Peryt (1981, 1983), and Flügel (1991). Our Famennian oncoids were clearly more solid than the soft spongiostromate oncoids found in present-day marine environments. Their rigid nature is evidenced by the dominant equant and compact shapes (see above), whereas modern soft oncoids would exhibit flattened shapes due to the compaction of the enclosing silty sediments. Their hardness is supported by the presence of borings along former outer surfaces (Fig. 10), and by their encrustation by organisms that customarily attach themselves to hard surfaces.

The frequent occurrence and abundance of pyrite in the nodules also supports a low energy, quiet water environmental interpretation. The sequence of pyrite-forming steps in such an environment is similar to that described by Kobluk and Risk (1977). Although pyrite may be produced by inorganic processes, the framboidal and other sedimentary pyrite reported herein is more likely the result of the presence of organic matter in an anaerobic environment rich in bacteria and microbial cells. The iron component was obtained from dead microbial matter, clay particles, or sea water. Anaerobic bacterial sulfate reduction produced hydrogen sulfide, some of which then reacted with iron to form iron monosulfide. Hydrogen sulfide was subsequently oxidized to produce elemental sulfur, and some of the sulfur then combined with iron monosulfide to form pyrite during very early diagenesis.

Other observations suggest that the nature of the oncoïd microstructure and form may at times be more microbially controlled and coordinated than environmentally controlled as suggested by Monty (1977, p. 23) for stromatolites in general. Significant variation in the microstructure and form of the oncoids, especially in their peripheral areas, was sometimes noted within the same beds of individual exposures and within the same beds of closely spaced localities. Such variations are unlikely to result from environmental changes and do not conflict with our interpretation of club-shaped and columnar peripheral structures as resulting from quiet water phototropic growth. More perplexing and currently inexplicable is the absence of such outgrowths in Sappington oncoids whose nuclei of delicate spinose skeletal fossils otherwise indicate a quiet water environment.

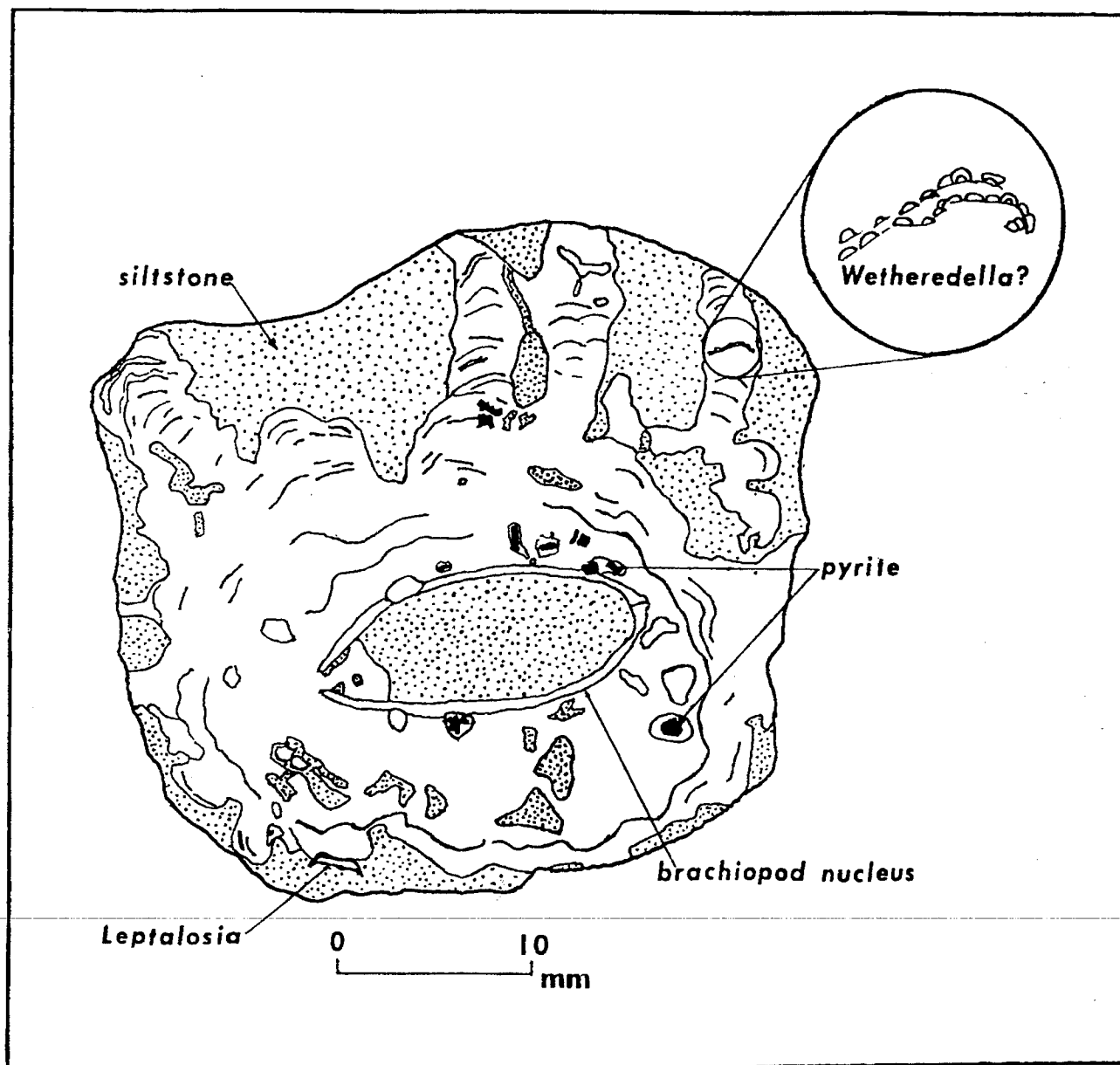


Figure 9. Camera lucida drawing of upward columnar growths on the upper surface of an oncoïd and an encrusting *Leptalosia* brachiopod on the underside. These demonstrate conclusively that the oncoïd has been turned over. Middle Pilot Shale, Section TU, Ledger Canyon.

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Figure 10. Barnacle boring penetrating two distinct former oncoid surfaces lined with encrusting Wetheredella. The black mineral is pyrite, X73.3, Middle Pilot Shale, Section TU, Ledger Canyon, Confusion Range.

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