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26. MIOCENE RADIOLARIANS OF THE SULU SEA, LEG 124[1]

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ABSTRACT

Radiolarians are sporadic in sediments collected in the Sulu Sea during ODP Leg 124. Due to the generally poor preservation and low abundance of radiolarians in Sulu Sea sediments, no biostratigraphic datums are well defined, although three radiolarian zones are identified. Most samples containing radiolarians are pelagic or hemipelagic clays with varying proportions of volcanic ash. Detailed analysis of Sulu Sea radiolarians was limited to Miocene successions. Pliocene and Quaternary occurrences of radiolarians were noted but have not been zoned.

The late middle Miocene of Sites 769 and 771 is represented by an assemblage of radiolarians (*Diartus petterssoni* Zone) that is entirely replaced by massive pyrite. This type of preservation develops only under anoxic conditions. The development of widespread anoxia in Sulu Sea waters in the late middle Miocene was probably the result of hydrologic isolation of basin waters, and may be associated with eustatic sea level fall over the silled basin.

Upper lower Miocene pelagic and hemipelagic sediments that overlie pyroclastics and basalt flows in the Sulu Sea sites contain moderately to very poorly preserved radiolarians of the *Calocycletta costata* Zone. A thin unit of marine claystone was recovered from between the thick pyroclastics and basement rocks at Site 768. Radiolarians present in these claystones are rare and very poorly preserved. This radiolarian assemblage probably represents the *C. costata* Zone, although very poor preservation and low abundance make this interpretation equivocal. The radiolarian zones identified constrain the age of basin formation to late early Miocene or earlier.

INTRODUCTION

The Sulu Sea is a marginal basin in the eastern Pacific, bounded to the southwest by Borneo and to the north and east by the Philippine Archipelago. Two sub-basins are present, separated by the Cagayan Ridge. The basin is silled on all sides, which prevents bottom- or intermediate-water interchange with other water masses. Currently surface waters exchange with the South China Sea to the northwest and the Celebes Sea to the southeast. Exchange with Philippine waters to the northeast is limited (Wyrtki, 1961).

Three sites were drilled in the Sulu Sea during Leg 124 (Fig. 1). Site 768 (08°00.0'N, 121°13.2'E) is located in the center of the southeast basin at a water depth of 4384 m. The sediment column is 1046.6 m thick and ranges in age from early Miocene to Holocene. Other than occurrences in late Pleistocene and Holocene sediments, radiolarians are found only in thin red-brown claystones above and below thick successions of pyroclastic material, coarse lapilli, and tuffs.

Site 769 (08°47.1'N, 121°17.7'E), on the southeast flank of the Cagayan Ridge, is at 3645 m water depth. There, 377 m of sediment were drilled. Radiolarians are abundant in the Holocene sediments but are very rare or absent from Pliocene and Pleistocene sediments. Most middle and late Miocene sediments are barren of radiolarians, but an interval of upper middle Miocene hemipelagic clays contains an assemblage of pyritized radiolarians. Radiolarians are present in upper lower Miocene dark-brown clays that overlie pyroclastic sediments.

Site 771 (08°40.7'N, 120°40.8'E) is in 2856 m of water, on the Cagayan Ridge, to the west of Site 769. There, 304 m of sediment directly overlie a basalt flow and underlying tuffs and lapilli. The sediment column was continuously cored from 144.7 to 304.1 mbsf. Radiolarians were recovered from one core of nannofossil clay of late middle Miocene age and two cores of the middle Miocene nannofossil marl that overlies basalt.

METHODS

In general, standard processing techniques were used. A 10-cm^3 sample was soaked in sodium hexametaphosphate solution and hydrogen peroxide to disaggregate clays prior to sieving. Often the residue had to be dried and procedures repeated before the sample disaggregated sufficiently. In addition to methods described above, numerous samples were disaggregated using a kerosene/water interaction method. This involves three steps: (1) dry the sample completely, (2) soak the dry sample in kerosene until saturated, and (3) replace the kerosene with water by adding a little water at a time. This process was necessary with a few samples that would not respond to the former treatment, and with samples that contained casts of radiolarians that had been replaced by clay minerals and thus would be damaged by the former process. Treatment with hydrochloric acid was necessary only in a few samples from Site 771, because carbonate is rare in all other pre-Quaternary Sulu Sea sediments recovered.

Samples were sieved initially using a 44-μm mesh sieve. Residues were embedded in Balsam or Piccolyte using standard techniques. When the fraction >44 μm contained a large volume of unidentifiable radiolarian fragments, this residue was sieved using a 63-μm mesh screen and mounted as above.

Abundance of radiolarians in the >63-μm fraction as shown on the range charts (Tables 1–3) is according to the chart below. Abundance estimates are qualitative, determined on the visual approximation of the total amount of residue per 10 cm^3 of sediment and of the percentage of radiolarian specimens observed in this residue. Turbidites and ash-rich layers often left volumes of residues greater than that indicated in the relative abundance scheme described below.

A (abundant) = >1 cm^3 of residue, >80% radiolarians.
C (common) = ~0.1–1 cm^3 of residue, 10%–80% radiolarians.
F (few) = ~0.1–1 cm^3 of residue, 1%–10% radiolarians.

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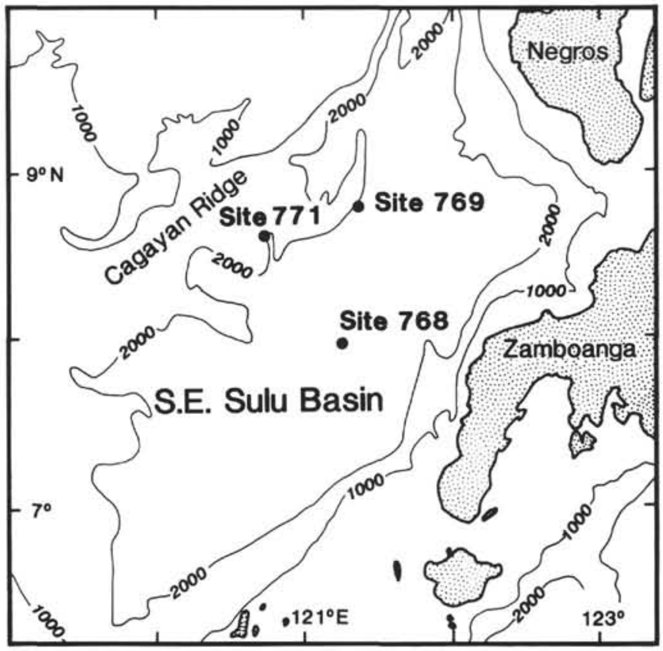

Figure 1. The southeast Sulu Basin, with locations of Sites 768, 769, and 771.

R (rare) = ~0.1–1 cm^3 of residue; more when rich in allochthonous minerals, <1% radiolarians.

T (Trace) = 1–10 radiolarians or radiolarian fragments seen on at least one entire slide.

B (barren) = no radiolarians or radiolarian fragments seen on at least one entire slide.

Abundance counts of individual radiolarian taxa presented on range charts (Tables 1–3) are based on visual estimates in the microscope at 100× magnification (10× objective). Specific abundances are as noted:

A (abundant) = at least one specimen seen in each field of view.

C (common) = at least one specimen seen in five fields of view.

F (few) = at least one specimen seen per transect.

R (rare) = fewer than ten specimens per slide.

T (trace) = single specimen and/or only fragments seen in one or more slides.

Radiolarian preservation ranges from good to very poor. Degraded preservation is a result of dissolution or etching of the siliceous skeleton, recrystallization of opaline silica or replacement by clay minerals, zeolites, etc. Several samples from Sites 769 and 771 have radiolarians preserved by massive pyrite replacement. Preservation as shown on range charts (Tables 1–3) is defined as follows:

G = *Good:* Most specimens are complete with spines mostly preserved, little or no etching or mineral overgrowths are present; cement or clay matrix may fill cavities, but the outer surface is intact. Most specimens can be identified.

M = *Moderate:* A substantial portion of the specimens are broken, and some degree of overgrowth, etching, or replacement by minerals other than quartz or pyrite may be evident. More than 50% of specimens can be identified.

PZ = *Pyritized:* Siliceous skeletons are entirely replaced by massive pyrite. Complete specimens are preserved, including fine detail, allowing identification to the species level in many cases, but most specimens are broken and abundance is low.

P = *Poor:* Specimens are mostly broken and strongly etched or replaced. Fewer than 5% of the specimens can be identified.

VP = *Very poor:* Specimens are only present as inner molds, casts, fragments, or are strongly etched or encrusted. Positive identification is impossible for nearly every specimen. Some tentative identification may be possible.

Radiolarian assemblages were assigned to biozones initially proposed by Riedel and Sanfilippo (1970, 1971, 1978) and later revised by Sanfilippo et al. (1985). Other useful references included Nigrini and Lombardi (1984) and numerous radiolarian studies reported in DSDP Initial Reports volumes (most references can be found in Sanfilippo et al., 1985). Taxonomic treatment of radiolarians in this paper is not exhaustive. Only major biostratigraphic markers and other significant radiolarians identified are included in the range charts and referenced in the species list.

Pyritized radiolarians were analyzed on a JEOL JSP-820 scanning electron microscope (SEM). Chemical analyses were performed by energy-dispersive spectrometry on a Tracor-Northern TN-5500 analyzer attached to the SEM.

RADIOLARIAN-BASED BIOSTRATIGRAPHY OF THE SULU SEA

Site 768

Three holes were drilled at Site 768 in the Sulu Sea. Hole 768A consists of one core, entirely of Quaternary age. Hole 768B was cored to a depth of 364.1 mbsf; Hole 768C was washed down to a depth of 352.2 mbsf and then cored to a depth of 1268.5 mbsf. Basement was reached at a depth of 1046.8 mbsf in Core 124-768C-73R. The sediments range in age from Quaternary to late early Miocene.

Abundant radiolarian remains are found in the upper 60 cm in Holes 768A and 768B. Preservation and frequencies rapidly deteriorate with depth down-core. Degradation of siliceous fossils closely resembles the pattern of dissolution noted in diatoms and radiolarians of the Celebes Sea Leg 124 sites (Scherer, this volume) and Site 769 in the Sulu Sea. Turbidite-rich Miocene through Pleistocene sediments are effectively barren of radiolarian remains due to silica dissolution and dilution by terrigenous debris, with the exception of very rare allochthonous radiolarian fragments found within turbidites. The interval barren of siliceous microfossils spans Hole 768B from Core 124-768B-8H (70.5 mbsf) to the base of this hole at 364.1 mbsf (Core 124-768B-40X) and Hole 124-768C from the top (362.9 mbsf) to Core 124-768C-46R, CC (796.9 mbsf).

An abundant and moderately preserved radiolarian assemblage was recovered from only one core of Site 768 (Core 124-767C-47R). This core is composed of reddish brown pelagic claystone and lies immediately beneath the thick turbidite-rich sedimentary successions. This assemblage contains abundant *Stichocorys wolffii*, common *Calocycletta costata, Calocycletta virginis*, and *Stichocorys delmontensis*. Also present are *Didymocyrtis tubaria, D. violina, D. mammifera, Cyrtocapsella cornuta, Cyrtocapsella tetrapera*, and rare *Dorcadospyris forcipata*. These species define the late early Miocene *Calocycletta costata* Zone. Preservation of radiolarians becomes poor in Core 124-768-48R. A sample from Core 124-768C-48R-3, 104–106 cm contains a radiolarian assemblage that includes abundant *Stichocorys wolffii* and common *Calocycletta virginis*, along with *Didymocyrtis pris-*

matica, *D. tubaria*, *C. cornuta*, and rare *S. delmontensis* and *Dorcadospyris forcipata*. *C. costata* is present at this level, but abundance is very low.

The core catcher of Core 124-768-48R contains a radiolarian assemblage that is highly diluted by volcanigenic debris. The assemblage includes *S. wolffii*, *C. virginis*, *D. prismatica*, *D. tubaria*, *D. violina*, *D. forcipata*, *C. tetrapera*, and *C. cornuta*, but appears to lack *C. costata*. This assemblage falls either in the lower part of the *C. costata* Zone or the upper part of the *S. wolffii* Zone, but low abundance and poor preservation prevents reliable zonal determination. *Stichocorys wolffii* is strongly dominant in Cores 124-768C-47R and 124-768C-48R, reaching more than 60% of the radiolarian fauna. This phenomenon is typical of Pacific sediments of the late early Miocene *C. costata* and *S. wolffii* zones (Romine and Lombari, 1985).

Even if biostratigraphic determinations were unequivocal, absolute and relative dating of these biostratigraphic zones would be difficult due to the considerable variation in published chronostratigraphic correlations for the early Miocene. For example, Berggren et al. (1985) correlated the *C. costata* Zone entirely within nannofossil Zone NN4, whereas Haq et al. (1987) and others correlate this zone with the middle part of Zone NN4 to the lower part of Zone NN5. Most chronostratigraphic correlations place the base of the *C. costata* Zone at about 17.3 Ma.

Radiolarians are absent from the thick pyroclastic successions of Cores 124-768C-49X through 124-768C-68X. Beneath the pyroclastic unit and overlying basalt pillows are some dark reddish and greenish pelagic sediments that span the interval of 1003.6 mbsf (Core 124-768C-68R) to basement at 1046.6 mbsf (Core 124-768C-72R). Radiolarians are present in certain levels of this sequence, but abundance is very low in all samples and preservation is very poor. Most samples from this interval contain radiolarians that are preserved as casts, largely or wholly replaced by celadonite (glauconite of volcanigenic origin) and are compressed nearly flat. Processing the sediment by oxidation techniques using hydrogen peroxide and hexametaphosphate degrades or destroys these fossil remains, but the fossils are retained when the sediment is processed using the kerosene separation method. With most specimens positive identification is impossible, but the distinctive outline of certain forms makes tentative identification possible. Radiolarians identified from sediments of Section 124-768R-69R, CC through Section 124-768C-72R, CC include *C. costata* (Pl. 1, Fig. 8). *C. virginis*, *C. tetrapera*, *C. cornuta*, *D. prismatica*, and forms that appear transitional between *D. prismatica* and *D. tubaria*. *Theocorys spongoconum*(?), a heavily silicified, solution-resistant species, is relatively common in these samples, though it is rare in the better-preserved assemblage above the volcanics. *S. wolffii* has not been found in the sediments beneath pyroclastics. This absence seems surprising, considering the great abundance of *S. wolffii* in sediments overlying this unit, especially if the pyroclastics were deposited as rapidly as sedimentologic criteria suggest (Rangin, Silver, von Breymann, et. al., 1990). The fact that *S. wolffii* appears to be lacking in these brown clays does not provide a strong argument against a *C. costata* or *S. wolffii* Zone age for these sediments. Moore (1969) described *S. wolffii* as solution-susceptible species, so perhaps they are not preserved. Alternatively, the lack of *S. wolffii* in these sediments could be a result of the variable temporal abundance of this species. Westberg and Riedel (1978) note several prominent abundance peaks and troughs of *S. wolffii* during its stratigraphic range. During the abundance lows, *S. wolffii* can be very rare.

The pyroclastic sediments were most likely deposited very rapidly (Rangin, Silver, von Breymann, et al., 1990), so despite the great thickness of sediments in this barren interval (>170 m), the lowermost sediments may still represent the lower part of the *C. costata* Zone, unless an unidentified hiatus is present. Cessation of basalt emplacement at Site 768 was, therefore, during or prior to the late early Miocene. No siliceous fossils are preserved in sediments intercalated between basalt pillows. Radiolarians identified in Site 768 sediments, their relative abundances, and the radiolarian zones recognized are summarized in Table 1.

Site 769

Three holes were drilled at Site 769, which is located on a tilted block of the Cagayan Ridge. Hole 769A was drilled down to 65.4 mbsf. This sequence was repeated in Hole 769B, which then was drilled down to 290.2 mbsf. In Core 124-769B-30X, brown clays overlie andesitic pyroclastics. Hole 769C was washed down to 261.1 mbsf and then drilled to a total depth of 376.9 mbsf. Combined biostratigraphic and magnetostratigraphic results show that time-equivalent sequences were drilled at Site 768 and Site 769. However, a more condensed section is evident at Site 769, due to little input of terrigenous and shelf-derived material by turbidity flows.

The sedimentary successions recovered at Site 769 range in age from Pleistocene to late early Miocene. The Quaternary sediments are rich in well-preserved calcareous microfossils. Radiolarians and diatoms are abundant at the sediment/water interface, but the siliceous fossils show a rapid degradation with depth. With the exception of occasional patches of more silica-rich, olive-green marls, radiolarians are rare and poorly preserved below the surface sediments in Pliocene and Miocene sediments. Samples from about 100 mbsf (Core 124-769B-12H) to 227 mbsf (Section 124-769B-25X-6) are effectively barren of radiolarians.

Samples in the lower part of Core 124-769B-25X, in green clays, contain an assemblage of radiolarians entirely replaced by pyrite. Although most specimens are broken, fine detail on the skeletons is preserved, including delicate lattice structures and spines. Also present, preserved in the same manner, are diatom fragments, sponge spicules, and rare silicoflagellates and ebridians. Unaltered phosphate (fish debris) and etched but otherwise unaltered calcareous planktonic microfossils (foraminifers and nannofossils) are common in these samples, but benthic foraminifers are absent.

Spumellarian radiolarians dominate the assemblage and include large Collosphaerids. Biostratigraphically important radiolarians identified in these samples include few-to-common *Didymocyrtis laticonus*, and forms transitional between *D. laticonus and Diartus petterssoni*, and rare-to-few *D. petterssoni* s.s., *Anthocyrtidium ehrenbergi*, *Lamprocyclas maritalis*, *Pterocanium audax*, and *Cyrtocapsella japonica* (Table 2). This radiolarian assemblage is of the late middle to early late Miocene *Diartus petterssoni* Zone. Deep-dwelling (>200 m) Plectopyramid radiolarians (Kling, 1979; Palmer, 1986), are present in Sample 124-769B-25X-6, 10–12 cm, but appear to be absent from all other samples in this interval. Radiolarians preserved by pyritization are found in most samples in this interval, but some samples are barren. Nannofossils (Zones NN7–NN8; Shyu and Müller, this volume) and foraminifers (Zones N13–N14; Nederbragt, this volume) in Core 124-769B-25X help refine the age of this interval to late middle Miocene.

Radiolarians are absent in the greenish pelagic clays in Core 124-769B-26X down to Core 124-769B-29X. A gradational color change, from dominantly green clay to reddish rown clay, is noted in Core 124-769B-29X. Radiolarians are

Table 1. Occurrence of radiolarians in Hole 768C. Radiolarians are arranged alphabetically and samples are sorted by depth below seafloor. Abundance and preservation codes are defined in the text. Radiolarian zones, as defined by tabulated data, are at far right.

Core, section, interval (cm)	Depth (mbsf)	Preservation	Total Abundance	*Calocycletta costata*	*Calocycletta virginis*	*Cyrtocapsella cornuta*	*Cyrtocapsella tetrapera*	*Didymocyrtis mammifera*	*Didymocyrtis prismatica*	*Didymocyrtis tubaria*	*Didymocyrtis violina*	*Dorcadospyris simplex*	*Stichocorys delmontensis*	*Stichocorys wolffii*	*Theocorys spongoconum*	Radiolarian zone
124-768C-																
44R-2, 67–69	770.8	–	B													
45R-2, 145–147	780.8	–	B													
45R CC, 39–41	787.0	–	B													Barren
45R CC	787.4	–	B													
46R-1, 73–75	788.1	–	B													
46R-1, 146–148	788.9	–	B													
46R CC, 22–24	806.4	M	C	C	F			R		F	F		C	C		
47R CC	806.6	M	A	C	F	F	R	R		F	F	R	C	C		
47R-1, 143–145	808.0	P	C	R	R	R					R		R	F		
48R-2, 141–143	809.5	P	F	R	R	R					R		R	F	F	*C. costata* zone
48R-3, 102–104	810.6	P	A	F	C	R				R	F	R	F	A		
48R-3, 104–106	810.7	P	A	R	C	F			R	F	F	R	R	A	R	
48R CC	815.5	P	C	?	?	F			R		F			C	R	
48R-3, 148–150	829.7	–	B													
50R CC	931.4	–	B													Pyroclastics
60R-4, 50–53	1003.7	–	B													
68R CC	1008.3	–	B													
68R-1, 128–132	1010.0	–	B													
69R-4, 84–90	1013.9	VP	F		?				?						?	
69R CC	1017.6	VP	F		?					?					?	
70R CC	1027.2	–	B													? *C. costata* zone
72R-1, 31–35	1037.2	VP	R												?	
72R-2, 32–36	1038.7	–	B													
72R CC	1046.6	VP	R	?	?					?	?				?	
																Basement

not found in most of this core, but a poorly preserved assemblage was recovered from the core catcher (269.0 mbsf). *Stichocorys wolffii* is the most common radiolarian in the assemblage. Present in very low numbers are *Stichocorys delmontensis, Didymocyrtis violina, Calocycletta virginis,* and *Lithopera baueri*(?). The co-occurrence of *S. wolffii* and *D. violina* define an upper lower Miocene succession. *Calocycletta costata* appears to be present, suggesting that the assemblage is within the *C. costata* Zone; however, the very poor preservation and low abundance makes definitive zonal assignments impossible. Similar assemblages are found in samples from Core 124-769C-2R-4 (275.8 mbsf).

Radiolarians are rare and very poorly preserved below this level in both Holes 769B and 769C. Indistinct remains of radiolarians are found overlying pyroclastics by only a few centimeters in Samples 124-769B-30X, CC (278.7 mbsf) and 124-769C-3R-1, 5–7 cm (~280.5 mbsf). These fossils are too poorly preserved for positive identification, but forms tentatively identified include *S. wolffii, C. virginis, C. costata*(?), and the heavily silicified *Theocorys spongoconum,* all of which are present in the assemblage found in Cores 124-769B-29X and 124-769C-2R. Holes 769B and 769C terminated in pyroclastic sediments that are barren of fossils. The radiolarian assemblage that was found overlying pyroclastics at Site 769 appears to be about the same age as that found overlying a pyroclastic sequence at Site 768. Preservation of radiolarians at Site 769 was generally even worse than the poor preservation found at Site 768. The sediments that overlie pyroclastics contain radiolarians that suggest the *C. costata* Zone, although *S. wolffii* Zone cannot be ruled out due to the tentative nature of identification of *C. costata.* Table 2 shows the preservation and relative abundance of radiolarians identified in Site 769 sediments, with interpreted radiolarian zones.

Site 771

Only one hole was drilled at Site 771, at 2856 m water depth on the Cagayan Ridge. The hole was washed down to 100 mbsf, spot-cored, then washed down to about 145 mbsf. Below that, it was cored continuously, though recovery was generally poor. The sedimentary sequence recovered ranges from early Pliocene in Core 124-771-1R (100 mbsf) to late early Miocene (Zones NN5, N8, *Calocycletta, costata*) overlying the volcanic basement at 239.5 mbsf. The entire sedimentary succession recovered at Site 771 contains rich calcareous microfaunas and floras, demonstrating that deposition was above the carbonate compensation depth (CCD) throughout this interval. As a result, biostratigraphic control based on calcareous fossils is good. In contrast, radiolarians are absent from most of the sedimentary column.

Cores 124-771A-1R through 124-771A-6R are barren of radiolarian remains. Samples from Core 124-771A-7R (202.9 mbsf) contain an assemblage of rare pyritized radiolarians of the *Diartus petterssoni* Zone, late middle Miocene in age. The assemblage has abundant Spumellarians and includes biostratigraphic markers *Didymocyrtis laticonus* and *Stichocorys delmontensis* as well as rare *D. petterssoni* and forms transitional between *D. petterssoni* and *D. laticonus.* This corresponds with a similar pyritized radiolarian assemblage found at Site 769. The assemblages differ in that sponge spicules are more rare at Site 771 and no deep-dwelling radiolarian genera

Table 2. Occurrences of radiolarians in Holes 769B and 769C. Radiolarians are arranged alphabetically and samples are sorted by depth below seafloor. Abundance and preservation codes are defined in the text. Radiolarian zones, as defined by tabulated data, are at far right.

Core, section, interval (cm)	Depth (mbsf)	Preservation	Total Abundance	*Anthocyrtidium ehrenbergi*	*Calocycletta costata*	*Calocycletta virginis*	*Cyrtocapsella cornuta*	*Cyrtocapsella japonica*	*Cyrtocapsella tetrapera*	*Diartus petterssoni*	*Didymocyrtis laticonus*	*Lamprocyclas maritalis*	*Plectopyramids*	*Pterocanium audax*	*Stichocorys delmontensis*	*Stichocorys wolffii*	*Theocorys spongoconum*	*Rhodochrosite grains*	Radiolarian zone
124-769B-																			
23X, CC	211	–	B																
24X, CC	220.8	–	B																Barren
25X-5, 57–59	227.4	–	B																
25X-6, 10–12	228.4	PZ	R	R				R			R	R	R	R	F				
25X-7, 10–12	229.9	PZ	R	R				R		R	R			R	F				
25X-CC, 20–22	230.2	PZ	T																
25X-CC, 10–12	230.3	–	B																*D. petterssoni* zone
25X, CC	230.4	PZ	R	F						R	F	R		R	F				
26R-1, 20–22	230.6	–	B																
26R-3, 20–22	235.1	–	B																
26R, CC	240.1	–	B																
27R, CC	249.7	–	B																
28R, CC	259.4	–	B																
769C-1R-1, 19–22	261.3	–	B															F	
769B-29R-2, 100–101	261.9	–	B																Barren
769C-1R-2, 26–28	262.9	–	B																
124-769B-																			
29R-3, 100–101	263.4	–	B																
29R-4, 60–62	264.5	–	B																
29R-4, 99–101	264.9	–	B																
29R-4, 111–113	265.0	–	B																
29R-5, 10–12	265.5	VP	T																
29R, CC	269.0	P	R			?	?	?								?			
30R-1, 14–16	269.2	–	B																
30R-2, 11–13	270.6	VP	T																
124-769C-																			
1R, CC	270.8	–	B																
2R-1, 31–33	271.1	–	B																?
2R-3, 50–52	274.3	VP	T																
769B-30R-5, 5–9	275.1	VP	T																
769C-2R-4, 47–49	275.8	VP	T																
769B-30R-6, 6–8	276.6	VP	T																
124-769C-																			
2R-5, 120–121	278.0	VP	T																
2R-5, 147–149	278.3	VP	C		?	?	?		?							?	?		
769B-30R, CC	278.7	VP	C		?	?	F								?	?	?		
124-769C-																			? *C. costata* zone
2R, CC	280.5	VP	F																
3R-1, 5–7	280.6	VP	R			?										?			
																			Pyroclastics

have been observed. The latest middle Miocene age of this assemblage is confirmed for this interval by calcareous nannofossils (near the top of Zone NN7; Shyu and Müller, this volume) and foraminifers (Zones N13–N14; Nederbragt, this volume).

Sample 124-771A-8R, CC contains rare and poorly preserved radiolarians of indeterminate age. Samples from Core 124-771A-9R are barren or nearly so, yielding no radiolarian age control. In contrast, radiolarians are present in great abundance in samples from Core 124-771A-10R, but preservation is poor. Samples from 124-771A-10R-3, 73–75 cm (226.3 mbsf) to the core catcher (232.0 mbsf) contain radiolarians of the *Calocycletta costata* Zone (upper lower Miocene to lower middle Miocene). These include *C. costata, Stichocorys wolffii, S. delmontensis, Didymocyrtis violina, Cyrtocapsella cornuta,* and *Calocycletta virginis.* These radiolarians are present in samples from Core 124-771A-11R, with generally somewhat better preservation. Sample 124-771A-11R-1, 149–150 cm, contains Cyrtocapsella tetrapera and abundant *Zygocircus* (Butschli) sp., in addition to those listed above, and Sample 124-771A-11R-2, 35–37 cm contains *Dorcadospyris simplex.* Volcanic sediments underlying this level are barren of radiolarians.

The oldest age obtained by radiolarians at Site 771 is late early to early middle Miocene, *C. costata* Zone. This corresponds well with ages determined from other Sulu Sea sites, although at Sites 768 and 769 it is not certain whether sediments overlying volcanic sediments or basement are of the *C. costata* Zone or the *S. wolffii* Zone, due to poor radiolarian preservation in those sediments. Radiolarians identified in Site 771 sediments, their relative abundances, and interpreted radiolarian zones are shown in Table 3.

Table 3. Occurrence of radiolarians in Hole 771A. Radiolarians are arranged alphabetically and samples are sorted by depth below seafloor. Abundance and preservation codes are defined in the text. Radiolarian zones, as defined by tabulated data, are at far right.

Core, section, interval (cm)	Depth (mbsf)	Preservation	Total Abundance	*Calocycletta costata*	*Calocycletta virginis*	*Cyrtocapsella cornuta*	*Cyrtocapsella tetrapera*	*Diartus petterssoni*	*Didymocyrtis laticonus*	*Didymocyrtis mammifera*	*Didymocyrtis prismatica*	*Didymocyrtis tubaria*	*Didymocyrtis violina*	*Dorcadospyris simplex*	*Pterocanium* sp.	*Stichocorys delmontensis*	*Stichocorys wolffii*	Radiolarian zone
124-771A-																		
1, CC	109.6	–	B															
2, CC	154.6	–	B															
3, CC	164.2	–	B															Barren
6, CC	193.2	–	B															
7-2, 40–42	195.1	–	B															
7-2, 117–120	195.9	PZ	R						R							R		
7-2, 123–125	196.0	PZ	R					R	F							F		*D. petterssoni* zone
8, CC	212.6	–	B															
9-2, 128–130	215.4	–	B															
9-3, 32–34	215.9	–	B															Barren
9-3, 148–150	217.1	–	B															
9-5, 3–5	218.6	VP	R															
10-3, 73–75	226.0	P	A	A	C	F	R			R		R	F			F	A	
10, CC	232.0	VP	A	?	?	?										?	?	
11-1, 96–98	233.0	P	C	F	F	F	?						F			F	C	
11-1, 148–150	233.5	P	C	C	R	F	R							?	F	F	A	*C. costata* zone
11-2, 7–9	233.6	P	A	R	F	F	R				R	R	F			F	A	
11-2, 35–37	233.9	P	A	?	F		F				R	R	F	?		F	A	
14-1, 16–18	261.2	–	B															
																		Basalt flow

DISCUSSION

Because much of the sediment column in the Sulu Sea is barren of radiolarians, correlation based on this microfossil group is only possible for certain stratigraphic intervals. Rough correlation is possible for brief intervals in the late middle and late early/early middle Miocene. Correlation and paleoceanographic significance of these radiolarians in Sulu Sea sediments is discussed below.

Late Middle Miocene Pyritization Events

A nearly identical assemblage of radiolarians of late middle Miocene age, preserved by replacement of biogenic silica with pyrite, is present *in situ* in certain samples from both Sites 769 and 771. The fact that a pyritized radiolarian assemblage of the same age was found at two widely separated sites suggests that pyritization was a widespread phenomenon in the Sulu Sea during brief intervals in the middle Miocene. Preservation of carbonate fossils at these sites suggests that the relative difference in water depth between Sites 769 (3645 m) and 771 (2856 m) today may have been similar in the middle Miocene. Site 771 was accumulating biogenic carbonate near but above the CCD during the interval of pyritization of siliceous microfossils, but Site 769 was at or just below the CCD at that time. Pyritized radiolarians have not been found in samples from the deeper Site 768, but this result is not surprising given the large turbidite influx at this site. Further sampling, guided by nannofossil age control, may yield samples containing pyritized siliceous microfossils.

Preservation of siliceous skeletons by pyritization at oceanic depths is very rare. Pyritized radiolarians and diatoms are found more commonly in nearshore anoxic basins and in Mesozoic black shales (e.g., Lallier-Vergèr, et al., in press). Pyritized allochthonous diatoms have been reported from upper Pliocene sediments of the distal part of the Bengal Fan (Koczmarska and Ehrman, 1990). Rare examples of pelagic deposits containing pyritized siliceous microfossil assemblages include upper middle Miocene sediments of Sites 722 and 731 in the Owen Basin, ODP Leg 117 (Prell, Niitsuma, et al., 1989; Nigrini, in press; Lallier-Vergèr, et al., in press) and upper Miocene–lower Pliocene pelagic sediments of Site 701, ODP Leg 114, in the subantarctic South Atlantic (Ciesielski, Kristoffersen, et al., 1988). Both the late middle Miocene and late late Miocene were times of dramatic sea-level fall (Haq et al., 1987).

Analysis of Neogene pyritized radiolarians in Leg 117 sediments by Lallier-Vergèr et al. (in press) and Leg 116 sediments by Kaczmarska and Ehrman (1990) has demonstrated that the process of pyritization of siliceous skeletons is generally a massive replacement by pyrite, rather than a pyritic coating or encrustation. The presence of pyritized radiolarians in the absence of abundant framboidal or massive crystalline pyrite suggests a high sulfate reduction rate, indicating a syndepositional or very early post-depositional reaction.

Analyses performed on Sulu Sea sediments as part of this study demonstrate that pyritization of radiolarians and diatoms in Sulu Sea sediments is complete, similar to material from Legs 116 and 117. Uncoated specimens of pyritic residues from Sample 124-769B-25X, CC, 12–14 cm, analyzed with energy dispersive X-ray spectroscopy (EDS) showed nearly pure iron sulfide, with minor amounts of silicon, aluminum, and potassium (which are probably from attached clays) on the outsides of skeletons (Fig. 2A) and on the edges of freshly broken specimens (Fig. 2B). The pyrite is both massive and microcrystalline. No cubic crystalline structure could be recognized, even under a SEM magnification greater than 80,000×. Additionally, cubic pyrite overgrowths or infillings have not been seen in SEM investigation of samples

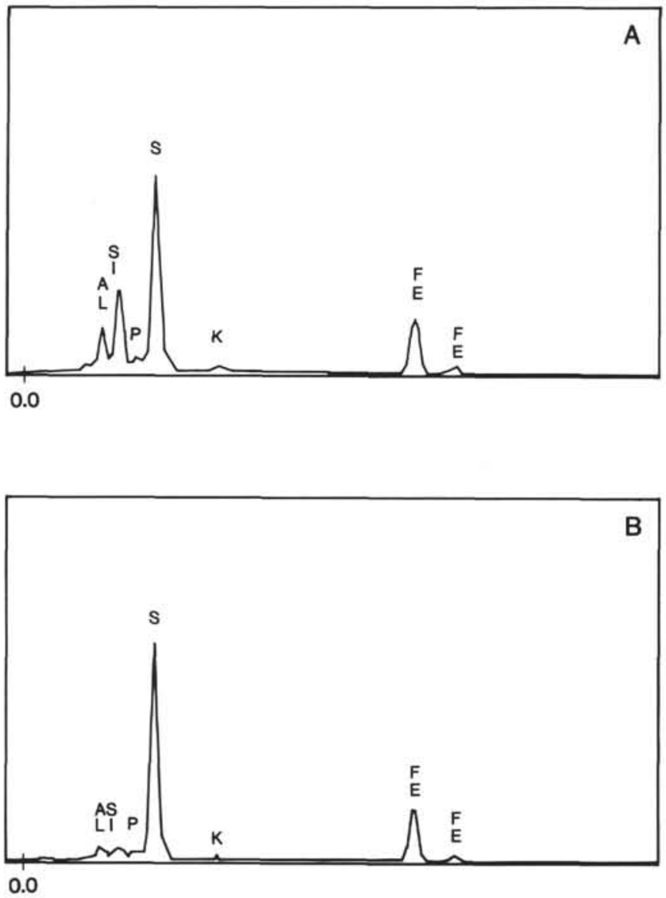

Figure 2. Energy dispersive spectroscopy (EDS) of pyritized radiolarians. **A.** Analysis of *Diartus petterssoni/Didymocyrtis laticonus* transitional form (Plate 1, Fig. 1). Note large sulfur and iron peaks and minor peaks of aluminum, silica, and potassium. The latter three are most likely due to clay infilling. **B.** Analysis of a freshly broken edge of a robust *Collosphaerid*. Note that results are similar to **A**, although clay peaks appear to be lower amplitude.

from either Site 769 or 771. Framboidal pyrite is rare in Site 771 samples and none has been observed in Site 769 samples. This compares favorably with material from Leg 116 (Kaczmarska and Ehrman, 1990). By contrast, the Leg 117 samples from the Owen Basin that contain pyritized radiolarians apparently also contain framboidal pyrite and cubic pyrite overgrowths (Lallier-Vergèr et al., in press).

In addition to radiolarians, all other siliceous microfossil groups, including diatoms, silicoflagellates, sponge spicules, and even rare ebridians are present in these samples, preserved in this manner. Preservation of fine detail, even in diatom tests, suggests that the pyrite replacement was syndepositional (or shortly post-depositional). Despite alteration of siliceous fossils, calcareous and phosphatic fossils are unaltered, other than by normal dissolution processes. The presence of fragments of the large diatom *Ethmodiscus* sp. (probably *E. rex* (Wallich) Hendy), and silicoflagellates, suggest that despite bottom-water or shallow endolithic anoxia, the surface waters were productive. Abundant *E. rex* in sediments has been used as an indicator of high productivity (Pokras, 1987), although *E. rex* has also been considered a dissolution remnant, thus suggesting low diatom productivity (Mikkelsen, 1977; Schrader, 1974).

The narrow intervals in Sites 769 and 771 that contain pyritized siliceous microfossils have little evidence of bioturbation, and benthic foraminifers are absent, further suggesting syndepositional anoxia. The presence of deep-dwelling radiolarians (e.g., plectopyramids) in some samples, but not in others, suggests that there might have been fluctuations in the minimum depth of anoxia in the water column. However, the occurrence of pyritized sponge spicules might suggest that anoxia was only endolithic and not in the water column.

Pyritization events were brief and episodic, as evidenced by the predominance of intervals that lack pyritic fossils and do possess evidence of an active benthic community. This temporal variability may also help explain the occurrence of pyritized sponge spicules in the sediments. It is unlikely that anoxia in the Sulu Sea was a result of high primary productivity and rapid carbon deposition, because of the high accumulation rates of hemipelagic clays during this time. Furthermore, organic carbon does not appear to be significantly higher in pyritic intervals, based on visual estimates of the cores, although detailed geochemical analyses have not been performed. Shipboard carbon analysis of Sample 124-169B-25X-6, 0–3 cm yielded a total organic carbon value of only 0.22%, which is not significantly different from samples elsewhere in the sediment column (Rangin, Silver, von Breymann, et al., 1990; p. 331).

Biostratigraphic resolution of this radiolarian zone is 3.5 to 4.5 Ma, but age assignment of this interval based on co-occurring radiolarians, nannofossils, and foraminifers greatly improves the resolution. Samples from the bottoms of Cores 124-769B-25X and -771A-7R have both been identified as the upper part of nannofossil Zone NN7 and foraminifer Zone N13-N14 (Shyu et al., this volume). According to the biostratigraphic correlation used during shipboard analyses on Leg 124 (Rangin, Silver, von Breymann, et al., 1990, p. 21), which is modified from the Berggren et al. (1985) time scale, Zone NN7 ranges from about 12.2 to 11.1 Ma. Berggren et al. (1985) show ages of 13.1 to 10.9 Ma. By contrast, Haq et al. (1987) suggest younger ages of about 11.6–10.5 Ma for Zone NN7. Based on these three correlations, the total range of ages possible is 13.1 to 10.5 Ma.

Interestingly, the best-developed assemblage of pyritized radiolarians in ODP Leg 117 sediments (Holes 722B and 731A) is also of late middle Miocene age (*D. petterssoni* Zone / Zone NN7 / Zone N13-N14; Prell, Niitsuma, et al., 1989) – identical to the pyritized radiolarian assemblage in the Sulu Sea sites. It is likely that this is more than coincidence. Both the Owen Basin, in the northwest Indian Ocean, and the Sulu Sea are partially silled basins. This configuration makes their hydrographic setting subject to the effects of large-scale sea-level changes. A major drop in eustatic sea level might isolate mid and bottom waters and restrict surface flow. Stratification, bottom-water stagnation, and anoxia could develop under such conditions, with pyritization of siliceous microfossils as an end result.

The timing of this anoxic event in the Sulu Sea suggests that it might be related to the major fall in eustatic sea level in the late middle Miocene, which has been linked with major build up of ice on the Antarctic continent. Haq et al. (1987) date the major eustatic fall at 10.5 Ma, which is also the top of nannofossil Zone NN7, according to their correlation.

Late Early to Early Middle Miocene

The late early to early middle Miocene *C. costata* Zone is recognized in thin claystones that overlie thick pyroclastic sediments at all Sulu Sea sites, though preservation is generally poor. The pyroclastic sediments at Site 771 differ somewhat in chemistry from those at Sites 768 and 769

(Rangin, Silver, von Breymann, et al., 1990) and it is not clear whether or not they are correlative events. At Site 771, *C. costata* Zone is present directly overlying the pyroclastic unit. Because of the presence of carbonate in these sediments it is possible to confirm the late early Miocene age (Zones NN5, N8) equivalent to *C. costata* Zone. By contrast, very poorly preserved radiolarians are the only biostratigraphically useful fossils present in the claystones at Sites 768 and 769. *C. costata* Zone is recognized at both sites, but the biostratigraphic marker *Calocycletta costata* has not been positively identified in the lowermost few meters above pyroclastics, possibly due to low abundances or poor preservation. Tentative identifications of radiolarian remains in these sediments suggest the *C. costata* Zone. Claystones recovered between the thick pyroclastics and basement rocks in Site 768 contain very rare and very poorly preserved radiolarians. The assemblage is too poorly preserved for positive identification of biostratigraphic markers, but tentatively identified specimens suggest the late early Miocene *C. costata* Zone. It must be noted, however, that the *S. wolffii* Zone, or one possibly older, cannot be ruled out, due to incomplete preservation of this radiolarian assemblage. Based on this interpretation, the Sulu Basin formed during or before the late early Miocene.

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SPECIES LIST

Anthocyrtidium ehrenbergi (Stöhr)
Anthocyrtis ehrenbergi Stöhr 1880, p. 100, Pl. 3, Figs. 21a, 21b
Anthocyrtium ehrenbergii (Stöhr) Haeckel, 1887, p. 1277
Anthocyrtidium ehrenbergii ehrenbergii (Stöhr) Riedel, 1957, p. 83, Pl. 2, Figs. 1–3
Anthocyrtidium ehrenbergi (Stöhr) Riedel et al. 1974, p. 712, Pl. 60, Fig. 10, Pl. 61, Fig. 1; Nigrini and Lombari, N147, Pl. 27, Fig. 1
Calocycletta costata Riedel
Calocycletta costata Riedel, 1959, p. 296, Pl. 2, Fig 9; Riedel and Sanfilippo, 1978, p. 66, Pl. 3, Fig. 9
Calocycletta virginis (Haeckel)
Calocyclas virginis Haeckel, 1887, p. 1381, Pl. 74, Fig. 4
Calocycletta virginis (Haeckel) Moore, 1972, p. 147, Pl. 1, Fig. 4
Cyrtocapsella cornuta (Haeckel)
Cyrtocapsa (*Cyrtocapsella*) *cornuta* Haeckel, 1887 p. 1513, Pl. 78, Fig. 9
Cyrtocapsella cornuta (Haeckel) Sanfilippo and Riedel, 1970 p. 454, Pl. 1, Figs. 19, 20

Cyrtocapsella japonica (Nakaseko)
Eusyringium japonicum in Nakaseko, 1963, p. 193, Pl. 4, Figs. 1–3
Cyrtocapsella japonica (Nakaseko) in Sanfilippo and Riedel, 1970, p. 452, Pl. 1, Figs. 13–15
Cyrtocapsella tetrapera (Haeckel)
Cyrtocapsa (*Cyrtocapsella*) *tetrapera* Haeckel, 1887, p. 1512, Pl. 78, Fig. 5
Cyrtocapsella tetrapera (Haeckel) Sanfilippo and Riedel, 1970, p. 453, Pl. 1, Figs. 16–18
Diartus petterssoni (Riedel and Sanfilippo)
Cannartus (?) *petterssoni* (in Riedel and Sanfilippo, 1970, p. 520, Pl. 14, Fig. 3
Diartus petterssoni (Riedel and Sanfilippo) in Sanfilippo and Riedel, 1980, p. 1010
Didymocyrtis laticonus (Riedel)
Cannartus laticonus Riedel, 1959 p. 291, Pl. 1, Fig. 5
Didymocyrtis laticonus (Riedel) Sanfilippo and Riedel, 1980, p. 1010, Text-Fig. 1, e
Didymocyrtis mammifera (Haeckel)
Cannartidium mammiferum Haeckel, 1887, p. 375, Pl. 39, Fig. 16
Cannartus mammiferus (Haeckel) Riedel, 1959, p. 291, Pl. 1, Fig. 4
Didymocyrtis mammifera (Haeckel) Sanfilippo and Riedel, 1980, p. 1010
Didymocyrtis prismatica (Haeckel)
Pipettella prismatica Haeckel, 1887, p. 305, Pl. 39, Fig. 6
Didymocyrtis prismatica (Haeckel) Sanfilippo and Riedel, 1980, p. 1010, text-Fig. 1, c
Didymocyrtis tubaria (Haeckel)
Pipettaria tubaria (Haeckel), 1887 p. 339, Pl. 39, Fig. 15
Didymocyrtis tubaria (Haeckel) Sanfilippo and Riedel, 1980, p. 1010
Didymocyrtis violina (Haeckel)
Cannartus violina (Haeckel), 1887, p. 358, Pl. 39, Fig. 10. Sanfilippo et al., 1973, Pl. 1, Figs. 11, 12
Didymocyrtis violina (Haeckel) Sanfilippo and Riedel, 1980, p. 1010
Dorcadospyris dentata Haeckel
Dorcadospyris dentata Haeckel, 1887, p. 1040, Pl. 85, Fig. 6; Riedel and Sanfilippo, 1978, p. 68, Pl. 5, Fig. 4
Dorcadospyris simplex (Riedel)
Brachiospyris simplex Riedel, 1959 (p. 293, Pl. 1, Fig. 10)
Dorcadospyris simplex (Riedel) Riedel and Sanfilippo, 1970 Pl. 10, Figs. 3, 4
Dorcadospyris forcipata (Haeckel)
Dipospyris forcipata Haeckel, 1887, p. 1037, Pl. 85, Fig. 1
Dipodospyris forcipata (Haeckel) Riedel, 1957, p. 79, Pl. 1, Fig. 3; Riedel and Sanfilippo, 1970, p. 523, Pl. 15, Fig. 7
Lamprocyclas maritalis Haeckel group
Lamprocyclas maritalis Haeckel 1887, p. 1390, Pl. 74, Figs. 13, 14
Lamprocyclas maritalis Haeckel group, Nigrini and Lombari, 1984, N63–N164, Pl. 30, Figs. 1a, 1b)
Pterocanium audax (Riedel)
Lychnodictyum audax Riedel, 1953, p. 810–811, Pl. 85, Fig. 9
Pterocanium audax (Riedel) Lazarus, Scherer and Prothero, 1985, p. 202–204, Figs. 19, 20)
Stichocorys delmontensis (Campbell and Clark)
Eucyrtidium delmontense Campbell and Clark, 1944, p. 56, Pl. 7, Figs. 19, 20
Stichocorys delmontensis (Campbell and Clark) Sanfilippo and Riedel 1970, p. 451, Pl. 1, Fig. 9
Stichocorys peregrina (Riedel)
Eucyrtidium elongatum peregrinum Riedel, 1953, p. 812, Pl. 85, Fig. 2
Stichocorys peregrina (Riedel) Sanfilippo and Riedel, 1970, p. 451, Pl. 1, Fig. 10
Sticocorys wolffii Haeckel
Stichocorys wolffii Haeckel, 1887, p. 1479, Pl. 80, Fig. 10
Theocorys spongoconum Kling
Theocorys spongoconum Kling, 1971, p. 1087, Pl. 5, Fig. 6

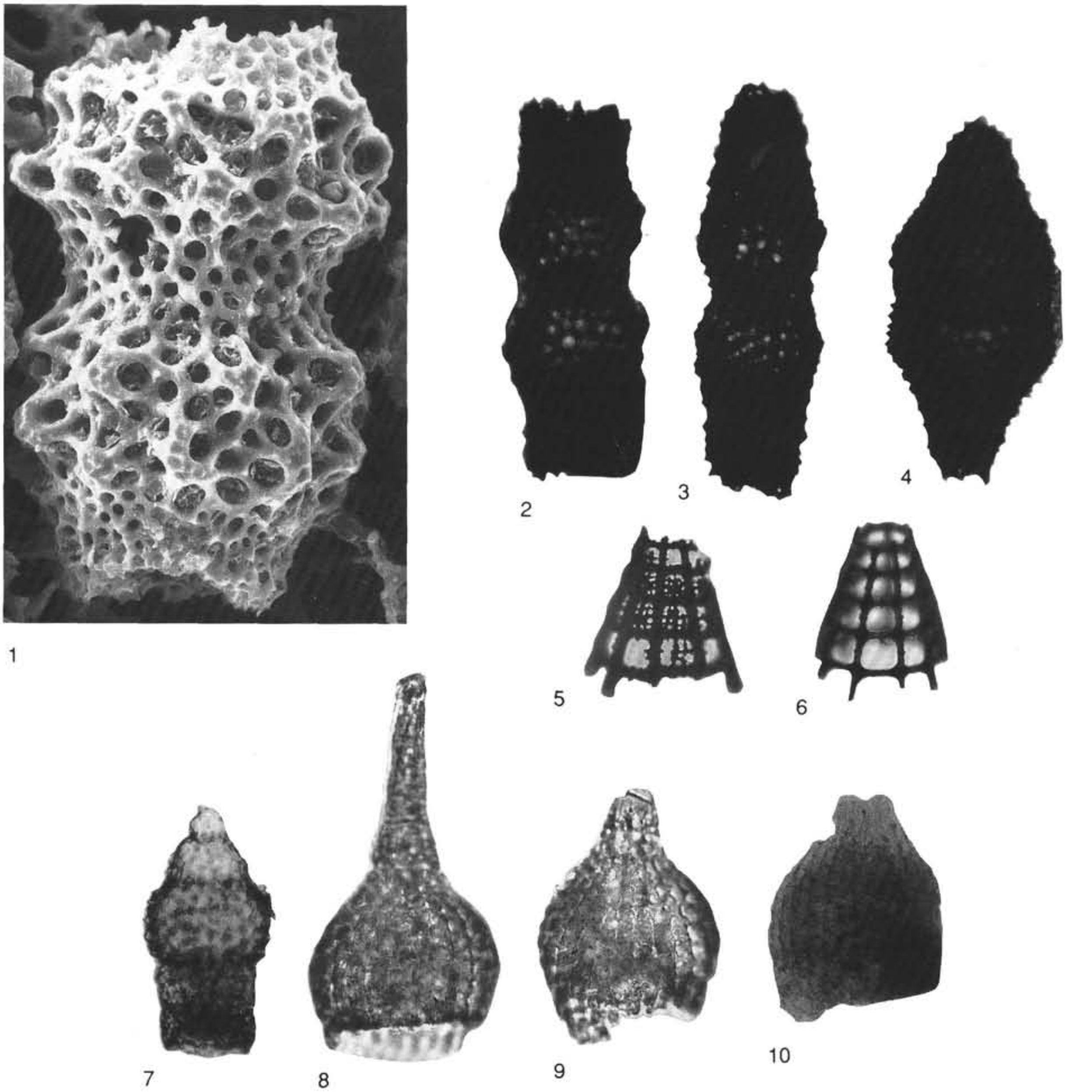

Plate 1. 250× magnification unless otherwise noted. **1.** Scanning electron micrograph of pyritized *Diartus petterssoni/Didymocyrtis laticonus* transitional form. Specimen is not gold coated (see text Fig. 2 for chemical analysis of this specimen). Spongy columns are broken off. Sample 124-769B-25X-CC, 600× magnification. **2.** Pyritized *D. petterssoni,* light microscopy, Sample 124-769B-25X-CC, 10–12 cm. **3.** Pyritized *D. petterssoni/D. laticonus* transitional form, Sample 124-771A-7R-2, 117–120 cm. **4.** Pyritized *Didymocyrtis laticonus,* Sample 124-769B-25X-CC, 10–12 cm. **5, 6.** Pyritized Plectopyramid (deep-dwelling) radiolarian. Genus and species unidentified. Sample 124-769B-25X-CC, 10–12 cm. **7.** *Sticocorys wolffii,* moderate preservation. Sample 124-771A-11R-2, 7–9 cm. **8, 9.** *Calocycletta costata,* moderate preservation. Sample 124-768-47R-CC. **10.** *Calocycletta costata*(?) very poor preservation, celadonite cast. Note longitudinal ribs. Sample 124-768C-72R-CC.