(of about 4 $\mu$m in size) would approach the limit shown in Fig. 1. These *Chlorella* seem to belong to more than one species, no one of which is sufficiently numerous to be included in the top 25 species. The observed lower limit of S/V ratio would be exceeded by a single rare diatom, *Melosira agassizi*, which colonizes the open water from the littoral zone during the annual mixing period when turbulence is greatest, but which never becomes very abundant. The inclusion of rare phytoplankton species would therefore result in essentially the same pattern as that shown in Fig. 1. For the purpose of comparing different plankton environments, however, generalizations should not be made on the basis of data from organisms that are not truly planktonic or that are not really capable of exploiting the resources of the plankton environment in question.

The conservation of S/V ratio raises a number of questions that are not fully solvable from the data at hand. The most obvious of these involve mucilage sheaths, the blue-green algae, and the bacterioplankton.

A large number of species, notably the desmids and filamentous blue-greens, are facultatively capable of secreting large mucilage sheaths around the biomass units. Mucilage sheaths are thought to retard sinking (*4*) and to inhibit digestion by herbivores in some cases (*12*). It is also possible that sheaths beneficially lower the effective S/V ratio, or that their merits in the retardation of sinking and digestion are balanced against a detrimental increase in effective S/V ratio at any particular time of year. Flexibility in secretion of a sheath would obviously have selective value if the optimal S/V ratio changes over the year.

The blue-greens constitute a special subgroup of the phytoplankton in that they are prokaryotic and often have distinctive features, including capacity for buoyancy regulation and nitrogen fixation (*4*) and probably low food value for zooplankton (*13*). Some of these species are thus partially exempt from the problems of sinking, grazing, and nitrogen depletion that are shared by most taxa. The blue-greens of Lake Lanao fall within the GALD and S/V ranges observed for other taxa. However, the Lanao blue-greens do have a higher average S/V ratio than the other Lanao taxa ($P < .01$, Wilcoxon two-sample test). The selective forces that act to increase the volume and S/V ratio of biomass units may not operate so effectively in the blue-greens because of their special characteristics.

The bacterioplankton are not included in the foregoing discussion as they are, for the most part, not autotrophic. If the metabolically active bacteria were added to Fig. 1, the lower limit of GALD would have to be moved down to 1 $\mu$m or less, but the observed range of S/V ratios would probably not be expanded. Although bacteria in the water column have high average S/V ratios, they are spherical or stoutly cylindrical in shape and can thus be equaled or exceeded in S/V ratio by several autotroph species. For example, it is clear from Fig. 1 that a unicellular coccoid form with a diameter of 1 $\mu$m would have a lower S/V ratio than several of the phytoplankton species. The bacterioplankton therefore appear to fit with the scheme of S/V conservation observed in the phytoplankton. Whether this is due to the operation of common selective pressures or is merely fortuitous is unclear.

The exact dispersion of phytoplankton S/V ratios will probably vary from one community to another, but conservation of the S/V ratio is likely to be widely observed in nature, as the balance of selective pressures affecting the ratio is common to the phytoplankton in general. If further studies verify the conservation of S/V ratio, a new set of explanations is available for phytoplankton morphology.

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## Controls on the Preservation of Biogenic Opal in Sediments of the Eastern Tropical Pacific

*Abstract.* *A map of the preservation pattern of siliceous microfossils was constructed from an examination of 125 piston and gravity cores of Quaternary sediments from throughout the eastern tropical Pacific. Preservation is enhanced where high surface water productivity supplies a high input rate of siliceous tests to the sea floor, except in a large area north of 5°N, east of the East Pacific Rise. Here a high input rate of terrigenous silicates may adversely affect preservation of biogenic opal in the sea-floor sediments.*

Maps of preservation patterns of siliceous microfossils in marine sediments can provide new insight into the silica budget of the ocean, silicate mineral diagenesis in marine sediments, and paleoceanographic interpretations of fossil assemblages of radiolarians, diatoms, and silicoflagellates. This study provides a qualitative map of the first-order features in the preservation pattern of siliceous microfossils in Quaternary sediments from the eastern tropical Pacific. The results indicate that biogenic opal is well preserved in sediments underlying surface waters of high productivity except where terrigenous sediments accumulate at a relatively high rate.

Assemblages of siliceous microfossils were obtained from several levels in 125 cores, examined microscopically and estimated to be "well," "moderately," or "poorly" preserved on the basis of their condition in the upper meter of all cores examined (Fig. 1). The map shows that the best level of preservation occurs in a belt trending east-west that extends from between 5°N and 10°N to between 5°S and 10°S. A relatively narrow zone of moderate preservation separates the belt of good preservation from sediment that contains poorly preserved or no siliceous microfossils.

The pattern is a rough reflection of productivity in the overlying surface waters. However, comparison of Reid's map of phosphate-phosphorus concentration at 100-m depth in waters of the eastern tropical Pacific (*1*), which roughly approximates the pattern of surface water productivity there, with the pattern of siliceous microfossil preservation reveals a major discrepancy (Fig. 2). In the region north of 5°N, between the East Pacific Rise on the west and the coasts of Mexico and Central America on the northeast, the surface water productivity is very high, but the preservation of siliceous microfossils in the sediments underlying much of the region is only moderate. The same result is obtained when the preservation pattern of siliceous microfossils is compared to the dissolved silicate and phosphate data presented in the *Eastropac Atlases* (*2*). Well-preserved radiolarians and diatoms are found only in the deepest part of the Guatemala Basin within this area of anomalously poor preservation. This finding is consistent with an earlier observation of better preservation of siliceous microfossils at deeper depositional sites in eastern tropical Pacific sediments (*3*). Such large-scale discrepancies between the patterns of surface water productivity and siliceous microfossil preservation in the underlying sediments have been reported for the Atlantic Ocean as well (*4*).

The reasons for the discrepancy in the eastern tropical Pacific are not clear. It may be that the production rate of siliceous skeletons is lower near Mexico and Central America than farther offshore on the equator, or that the sedimentary environment near Mexico and Central America is more corrosive. The first of these explanations does not seem plausible. The abundance of biogenic opal suspended in surface waters of the North Pacific has been found to correlate directly with dissolved phosphate and silicate concentrations (*5*). In addition, there is, to my knowledge, no evidence to suggest that the production of siliceous microfossils is relatively low in waters adjacent to continents. I know of no report in the literature that diatoms are less abundant in waters of high productivity near land than farther offshore. On the contrary, diatoms apparently are successful primary producers in coastal waters, because there are some occurrences of diatomaceous oozes near continents (*6*). Too little is known about the ecology of Radiolaria. They do not abound in highly productive waters in some temperate areas, and they generally do better in tropical eutrophic waters (*7*). In the waters overlying the Guatemala Basin their productivity must be substantial because, as mentioned pre-

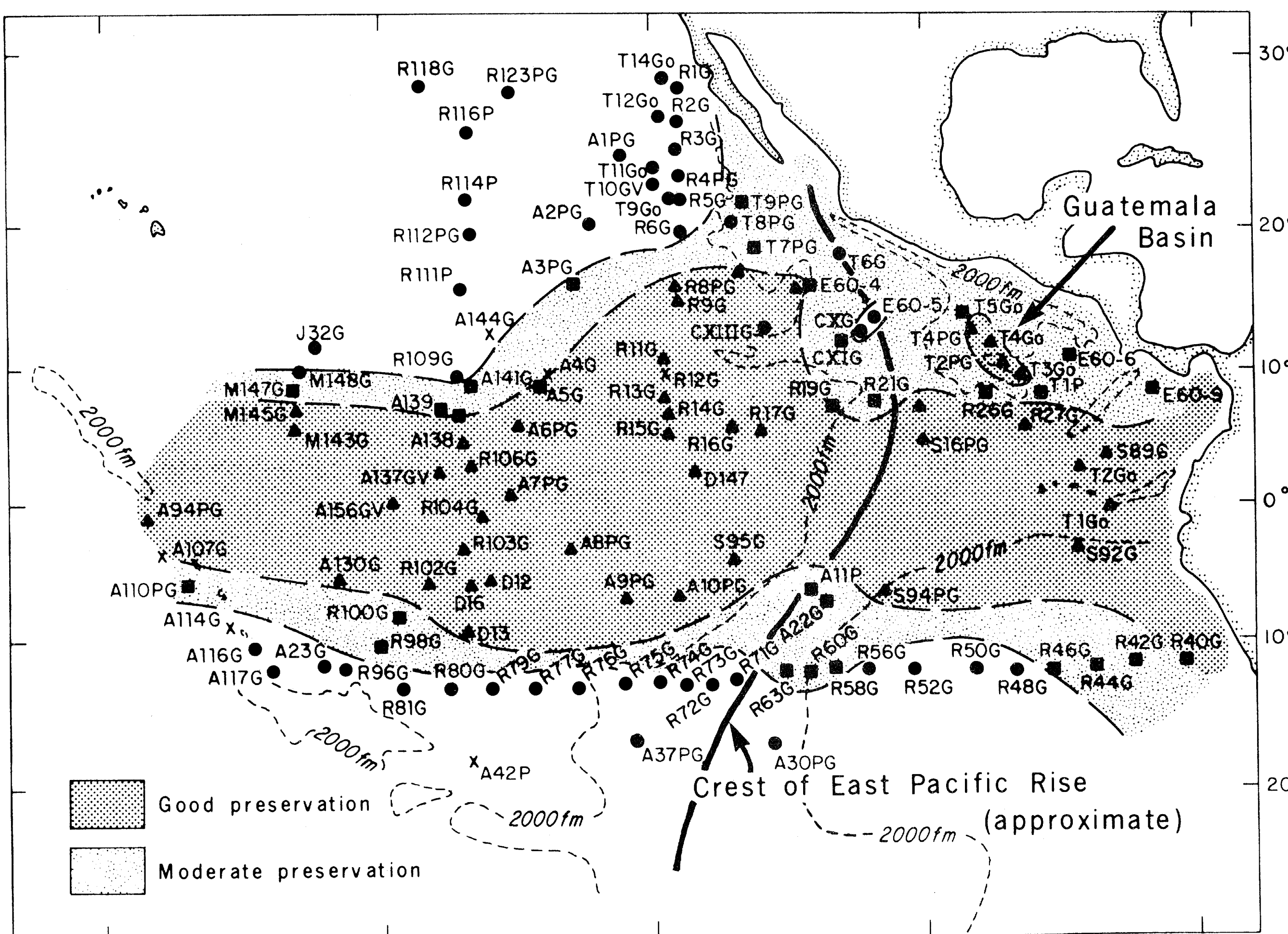


Fig. 1. Map of the preservation of siliceous microfossils within the upper meter of the sediments. Areas that are not shaded or stippled have either poorly preserved or no siliceous microfossils in the sediments. Core numbers are prefixed by a letter designating the Scripps Institution of Oceanography expedition on which the cores were taken: *A*, Amphitrite; *C*, Chubasco; *D*, Downwind; *E*, University of Southern California and U.S. Geological Survey Expedition 60; *J*, Japanyon; *M*, Monsoon; *R*, Risepac; *S*, Scan; and *T*, Tripod. Symbols denote core locations and the level of preservation: ▲, good preservation; ■, moderate preservation; ●, poor preservation or no biogenic opal; and x, outcrops of sediment of Tertiary age; *fm*, fathom (1 fathom = 1.83 m).

viously, they are well preserved in some sediments within the basin.

The anomalously poor preservation of siliceous microfossils in this region may be related to unfavorable chemical conditions in hemipelagic sediments. The interstitial waters of hemipelagic sediments near Central and South America presumably have lower *Eh* values (oxidation-reduction potentials) than those of pelagic sediments farther offshore (*8*), and it has been postulated that preservation of siliceous microfossils can be adversely affected by reducing conditions in sediments (*9*). However, well-preserved assemblages along the equator were found in this study to be well within the region where sediments of lower *Eh* values have been mapped (*8*). In addition, the level of preservation of siliceous microfossils obtained from sediments of low *Eh* in Santa Barbara Basin has been found to be similar to that of microfossils obtained from nearby sediments of higher *Eh* (*10*).

The input rate of certain detrital sediments may be important to the preservation of biogenic opal. Unstable silicate minerals that have low silicon/aluminum ratios may readily react with the silica released from microfossils dissolving in deep-sea sediments to form more siliceous silicate minerals [for example, sepiolite (*11*), talc (*12*), or smectite (*13*)]. Some evidence in support of these reactions is derived from thermodynamic calculations [although the thermodynamic data necessary for such calculations are incomplete at the present time (*14*)] and from laboratory experiments (*15*). In the region off Mexico and Central America, where the preservation of siliceous microfossils is anomalously poor, the input rate to the sea floor of unstable detrital material that is readily reactive may be relatively high as compared to the sedimentation rate of biogenic opal (*16*). If so, the potential sink for dissolved silica in these sediments is large; this large sink tends to lower the interstitial silica concentration, and therefore there is a tendency for the siliceous microfossils to dissolve.

If a high supply rate of silica-depleted detritus from the continents results in a large sink for dissolved silica in the sediments and consequently poor preservation of siliceous microfossils, certain patterns in preservation should be predictable in the sedimentary record. For instance, in a gross sense, siliceous microfossils in Atlantic Ocean sediments should be more corroded than those in Pacific Ocean sediments because the Atlantic receives more terrigenous material per unit area of sea floor. Siliceous microfossils are generally less abundant in Atlantic sediments (*17*) and more corroded (*18*).

During glacial periods when sea level was much lower, sediment loads in rivers were transported to the edge of the continental shelf and distributed directly to the deep-sea floor instead of being trapped on the shelf as they are today. Off the West Coast of the United States, this direct input of terrigenous material probably resulted in a marked decrease in the ratio of the sedimentation rate of siliceous microfossils to the sedimentation rate of detrital silicate minerals. According to the present hypothesis, the preservation of biogenic opal would be poorer in sediments deposited during ice

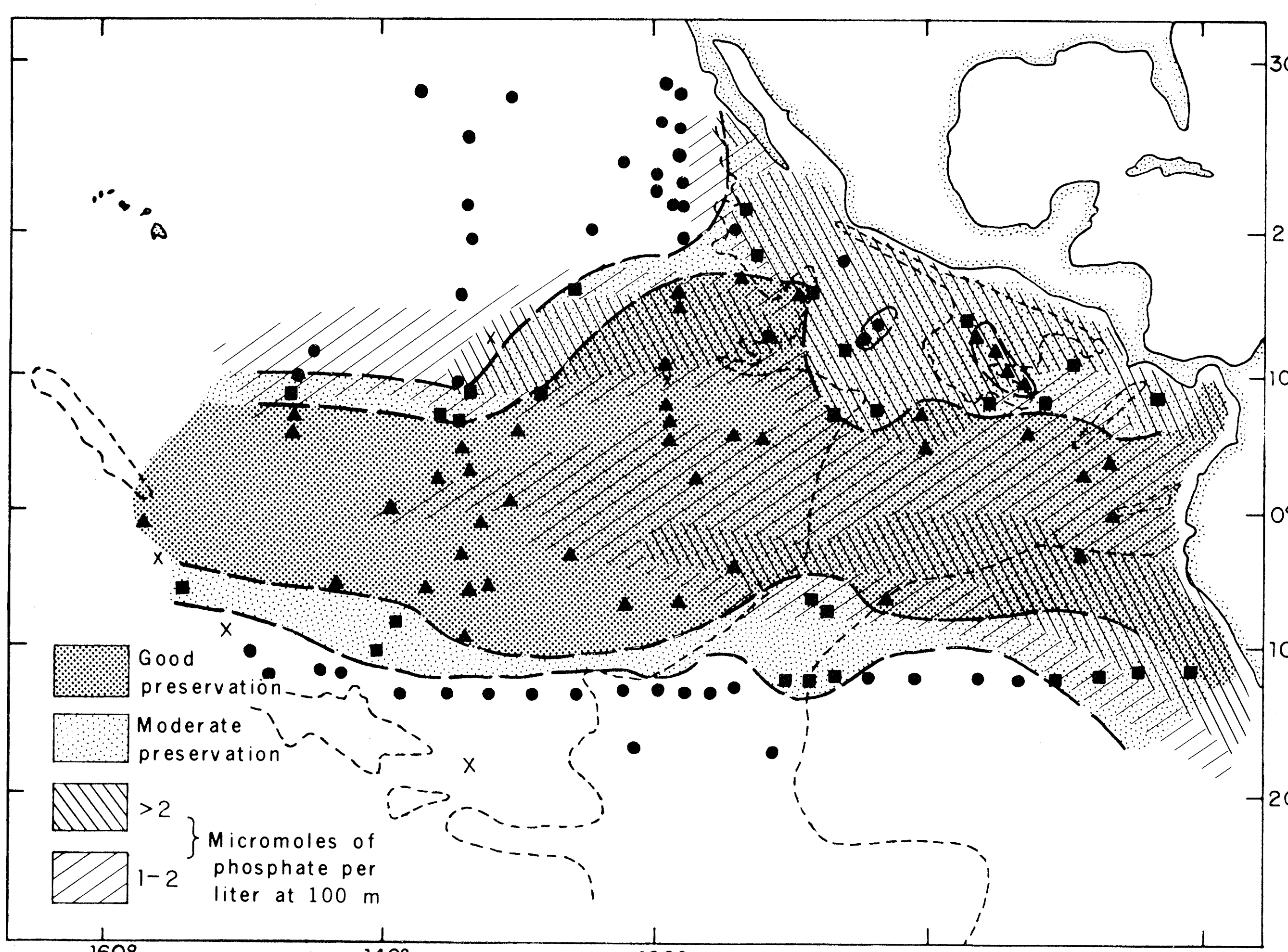


Fig. 2. The distribution of dissolved phosphate-phosphorus at a depth of 100 m in the water column [from Reid (*1*)] superimposed upon the preservation pattern of Fig. 1.

ages than in Holocene sediments. Siliceous microfossils are less abundant and more corroded in glacial sediments than in interglacial sediments off California, Oregon, and Washington (*19*), and in the northeastern Atlantic (*20*). Siliceous microfossils may be better preserved in some hemipelagic sediments deposited during ice ages, especially where greater siliceous microfossil productivity due to intensified upwelling during glacial periods outweighed the effects of increased terrigenous sedimentation caused by lowered sea level. Such appears to be the case off Cape Barbas, northwest Africa, where the abundance and preservation of siliceous microfossils are enhanced in sediments of glacial age (*21*).

In conclusion, the preservation of siliceous microfossils in eastern tropical Pacific sediments is most strongly influenced by the relative sedimentation rates of biogenic opal and certain detrital silicate minerals, especially minerals depleted in silica by intense chemical weathering in tropical regions. If the ratio of the sedimentation rate of biogenic opal to the sedimentation rate of detrital silicates is low, a large sink for dissolved interstitial silica is created by silicate reconstitution reactions, perhaps of the type suggested by Sillén and others (*22*). Biogenic opal present in these sediments dissolves to replace the dissolved silica taken up by these reactions and, if the silica sink is sufficiently large, all of the opal ultimately disappears. If, on the other hand, the ratio is high, the silicate conversion reactions that can take place fairly rapidly occur before a significant proportion of the siliceous microfossils is lost to dissolution. The kinetics of subsequent reactions for the uptake of dissolved silica may be significantly slower, allowing interstitial silica concentrations to increase to a level that considerably reduces the dissolution rate of biogenic opal.

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## Gametogenesis in Planktonic Foraminifera

Abstract. *Gametogenesis in* Globigerinella aequilateralis *and* Globigerinoides sacculifer *in culture is preceded by sinking of the organism and loss of its spines. Hundreds of thousands of flagellated gametes, about 5 micrometers in diameter, are produced within the parent shell and released within a period of 13 hours.*

Life cycles of several species of benthic Foraminifera are known (*1*), but no such knowledge exists for those foraminiferal species having a planktonic existence. The delicate nature of the latter group frustrated previous attempts to study them in culture. Since June 1975, we have succeeded in maintaining planktonic Foraminifera at the Bermuda Biological Station; and recently gametogenesis was observed for the first time in *Globigerinella aequilateralis* and *Globigerinoides sacculifer*. They are among six spinose species of planktonic Foraminifera, which are routinely hand-collected by scuba diving off Bermuda. This collecting method does not damage the fragile cytoplasm and shells which bear long, extended spines and pseudopodia.

Gamete formation was first observed on 6 September 1975 in an adult specimen of *G. aequilateralis* having a shell length of about 1000 $\mu$m collected on 15 August 1975. The previous day it appeared in normal health, was floating, had long extended spines, and accepted food organisms. At 1630 on 6 September, the specimen was on the bottom of the culture vessel and had lost most of its spines. Although short pseudopodial strands radiated outward from the shell and protoplasmic streaming was evident, our previous experience indicated that it was in poor condition because loss of spines and sinking usually precedes the death of the organism. At 2130 a cloud of protoplasm was observed around the shell (Fig. 1a), containing myriads of individually moving cells, which later were shown by electron microscopy to be gametes. The gametes and large dense clumps of parental protoplasm were distributed near the aperture and appeared to have emerged from it. Individual gametes moved away from these dense clumps; but each remained connected by a fine thread of protoplasm until, after further vigorous movement, they broke loose. The gametes had a granular appearance under the light microscope and had variable shapes and sizes (Fig. 1b). The cell surface seemed rough and the perimeter seemed angular and irregular. The smallest are nearly spherical with a diameter of 2 to 5 $\mu$m.

It is difficult to observe the details of cellular division by light microscopy, but it was clear that individual gametes eventually were released since they became free-swimming. Prior to the free-swimming stage the majority of gametes in the clumps outside the shell rotated rapidly and moved in an oscillating manner. Occasionally, individual gametes seemed to move toward one another and stick together in chains, rods, or irregular clumps. It was not possible to determine whether any gametes fused.

At 0100 on 7 September, the gametes had moved farther from the shell and appeared to be sluggish and homogeneous in size. The number of gametes had also increased, while the large clumps had diminished in size and number. The