Silver, E. A., Rangin, C., von Breymann, M. T., et al., 1991.
Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 124

28. CARBONATE SEDIMENTATION IN THE SULU SEA LINKED TO THE ONSET OF NORTHERN HEMISPHERE GLACIATION, 2.4 MA[1]

Braddock K. Linsley[2,3]

ABSTRACT

Pliocene and Pleistocene sediments from Sulu Sea ODP Sites 768 and 769 contain high-resolution records of pelagic sedimentation in a deep marine silled basin. Carbonate analyses reveal that both sites are free of pelagic carbonate up until 2.4 Ma, at which time carbonate becomes a major component of the pelagic marl sedimentation. The timing of this increase in calcium carbonate accumulation is precisely constrained by the position of the Gauss/Matuyama paleomagnetic reversal 2.47 Ma. The rapid increase in carbonate accumulation at both sites coincides with the onset of Northern Hemisphere glaciation 2.4 Ma, suggesting that conditions associated with expanded Northern Hemisphere ice sheets affected the western tropical Pacific. The results of this preliminary study do not allow determination of whether the increase in calcium carbonate accumulation 2.4 Ma is due to productivity changes, preservation changes, or some combination of the two.

INTRODUCTION

The Sulu Sea in the Indonesian tropics of the western equatorial Pacific is a semi-isolated deep basin completely surrounded by a shelf, most of which is less than 100 m deep (Fig. 1). Drilling during Leg 124 recovered two nearly complete Pliocene through Pleistocene sedimentary records from the Sulu Sea; Site 768 was drilled at 4395 m water depth in the Sulu Sea central basin and Site 769 at 3643 m water depth on the Cagayan Ridge (Rangin, Silver, von Breymann et al., 1990). Both sites are currently above the carbonate compensation depth (CCD) in the basin, which lies at 4800 m (Linsley et al., 1985). Site 768 is located below the present lysocline and Site 769 is just above the lysocline. Carbonate concentration data at the two sites show a large increase in calcium carbonate accumulation 2.4 Ma, suggesting that conditions associated with global ice volume changes 2.4 Ma had a strong influence on carbonate sedimentation in the Sulu Sea. This preliminary study discusses the onset of pelagic $CaCO_3$ deposition in the Sulu Sea 2.4 Ma.

DEEP-WATER HYDROGRAPHY

Presently, surface waters are readily exchanged between the Sulu Sea and surrounding seas over the shelf and through channels in the shelf. However, deep-water exchange is limited by the depth of the deepest sill supplying water to the Sulu Sea from the surrounding basins. The Mindoro Strait at 420 m depth is the deepest channel into the Sulu Sea. Mindoro Strait cuts across the sill that separates the northern Sulu Sea from the South China Sea. China Sea Intermediate Water enters the Sulu Sea only through the Mindoro Strait; thus this channel controls the ventilation rate (Frische and Quadfasel, 1990; Wyrtki, 1961; and Van Reil, 1943). Currently, Deep Water below the thermocline in the basin is uniformly warm (10°C), dysaerobic, and has the same physical properties as the water entering from the China Sea. However, even with the silled configuration, nutrient content, radiocarbon, and radium data suggest rapid Sulu Sea Deep Water renewal times of 50–100 yr (Broecker et al., 1986).

[1] Silver, E. A., Rangin, C., von Breymann, M. T., et al., 1991. *Proc. ODP, Sci. Results*, 124: College Station, TX (Ocean Drilling Program).
[2] Department of Geology, University of New Mexico, Albuquerque, NM 87131.
[3] Present affiliation: Department of Geology and Geophysics, Rice University, Houston, TX 77251.

METHODS AND AGE MODEL

Paleomagnetic and sedimentologic results from Leg 124 indicate that both Site 769 on the Cagayan Ridge, and Site 768 in the Sulu Sea central basin contain high-resolution records of Pliocene and Pleistocene pelagic sedimentation (Rangin, Silver, von Breymann et al., 1990). Carbonate content of the pelagic sediments was obtained by coulometric determination of the CO_2 liberated by 2N HCL treatment of the sample. Replicate analyses yield a standard deviation of ±0.5%. Samples from turbidite zones are not included in the data set. The calcium carbonate records from Sites 768 and 769 were plotted vs. time based on paleomagnetic reversal datums (Fig. 2 and Table 1). Only those samples from pelagic, undisturbed sections of core were used in the time series shown in Figure 2. Ages for individual samples were estimated assuming a constant sedimentation rate between paleomagnetic datums.

ANALYTICAL RESULTS

Fluctuations in carbonate concentration at the two sites are generally very similar, and differ mainly in the total thickness of pelagic and hemipelagic marl. The Pliocene and Pleistocene sedimentary section at Site 769 is thinner due to the lack of significant turbidite deposition. Analysis of turbidite sedimentation from Site 768 reveals that both sites have Plio-Pleistocene pelagic accumulation rates of 90 m/Ma. At 2.4 Ma Sulu Sea Sites 768 and 769 experienced a rapid increase in carbonate accumulation, from 0%–2% to 40%, apparently as a result of a deepening of the CCD in the basin. The position of the Gauss/Matuyama boundary at 2.47 Ma indicates that the increase in carbonate accumulation was synchronous at each site in the Sulu Sea. Site 768, the deeper site, displays a brief return to low carbonate values, just after the rapid increase 2.4 Ma. In the Site 768 record the single datum point (Fig. 2) showing increased carbonate concentration 2.4 Ma is not reworked, and actually corresponds to a carbonate-rich zone in the core.

ONSET OF CARBONATE ACCUMULATION IN THE LATE PLIOCENE

A concurrent and possibly related climatic and oceanographic development 2.4 Ma (Gauss-Matuyama transition) was the initiation of moderate-sized ice sheets at sea level in the Northern Hemisphere (Backman, 1979; Shackleton et al., 1984; Zimmerman et al., 1985). Their findings are based primarily on percent-

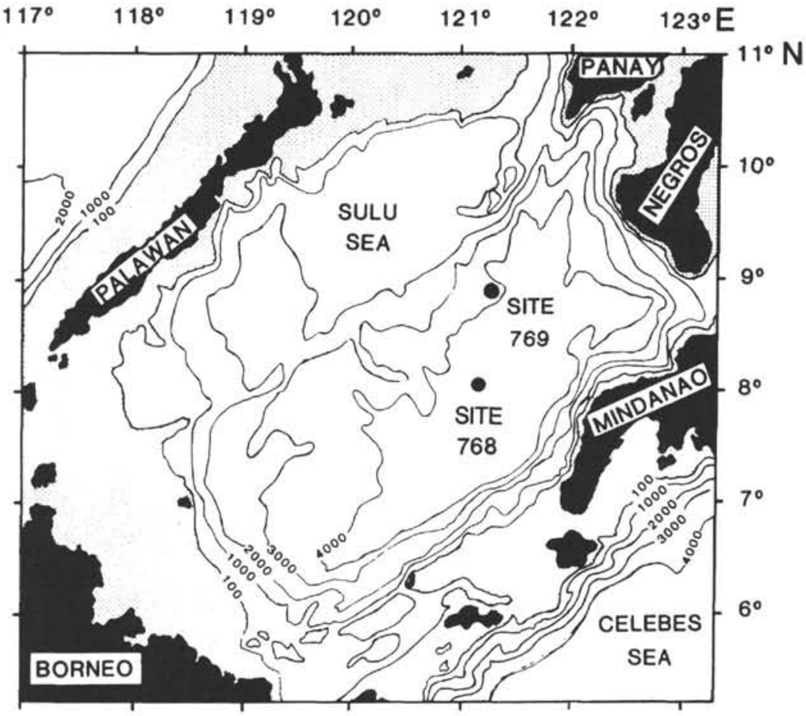

Figure 1. Detailed bathymetric map of the Sulu Sea (depth in meters), showing locations of Site 768 (4395 m water depth) and Site 769 (3643 m water depth).

$CaCO_3$ records from the Deep-Sea Drilling Project (DSDP) Site 552 in the North Atlantic (Fig. 3), where uniformly high carbonate values preserved in the early Pliocene suddenly change to lower concentrations as a result of the influx of ice-rafted continental debris. In addition, ^{18}O values at Site 552 show an abrupt increase at 2.4 Ma partially reflecting the growth of continental ice sheets (Shackleton et al., 1984). However, it was later shown by Curry and Miller (1989), that the onset of ice growth at Site 552A appeared abrupt because of a gap in core recovery from 2.5 to 2.7 Ma. Confirmation that 2.4 m.y. was the age of onset of ice rafting has come from subsequent coring by DSDP and the Ocean Drilling Program (ODP) across the subpolar North Atlantic and in the Labrador and Norwegian Seas (Ruddiman, Kidd, Thomas, et al., 1987; Eldholm, Thiede, Taylor et al., 1987; Srivastava, Arthur, Clement, et al., 1987).

Recent benthic $\delta^{18}O$ results published by Sikes et al. (1991) from Sites 606A and 665A in the Atlantic, and Site 503B in the equatorial Pacific reveal that the 2.4-Ma event was actually a series of three events occurring at 2.39, 2.35, and 2.31 Ma. Furthermore, these events have an approximate periodicity of 40 k.y., suggesting a connection to the earth's orbital obliquity cycle. These benthic $\delta^{18}O$ data show that the glacial events were one-half to two-thirds the size of the latest Quaternary glaciations. This suggests that sea-level change associated with these glacial events were less than the ~120-m change that occurred during glacial stage 2 (Fairbanks, 1989). In addition, the $\delta^{18}O$ data of Sikes et al. (1991) indicate a cooling of northern source bottom water by 2.7° to 4.1°C relative to southern source bottom water during glaciations. In both Sulu Sea Sites 768 and 769, periodic increases in carbonate content were visually observed in cores near 2.4 Ma and may be equivalent to the three events documented by Sikes et al. (1991). In future work we will investigate whether similar $\delta^{18}O$ events occur in the Sulu Sea at ~2.39, 2.35, and 2.31 Ma.

Further evidence for a considerable climatic change ~2.4 Ma comes from a low-latitude proxy record of eolian deposition under the influence of the Asian Monsoon in the western Arabian Sea (Bloemendal and deMenocal, 1989). In this record, variance is concentrated at orbital periodicities throughout the 3.2-Ma record. However, a shift from 23-ka precessional variation to an increase in 41-ka obliquity variation occurs ~2.4 Ma; this shift suggests a causal link between the monsoon circulation and/or dust source area variability and the expansion of Northern Hemisphere ice sheets.

In the Sulu Sea the initiation of carbonate accumulation is not due to turbidite deposition. All samples from turbidite layers were removed from the data set presented here; the apparent drop in the CCD level in the basin must have resulted from other causes. Possible mechanisms include a shallowing of sill depth changing deep-water chemistry, or carbonate productivity changes.

TECTONIC CONTROL OF SILL DEPTH

Tectonic shallowing of sill depths and isolation of the basin ~2.4 Ma could have affected the CCD depth in the Sulu Sea; an isolation of that may have led to a warming of deep waters. The deepest water ventilating the basin would have originated higher in the water column and could have been considerably warmer. The Sulu Sea opened as a result of back-arc spreading in the early Miocene (Rangin, Silver, von Breymann et al., 1990) and is still tectonically active today. The Sulu Arc was volcanically active during the late Pleistocene; consequent uplift of the arc could have limited deep water exchange. However, the precise correspondence with the initiation of sea-level Northern Hemisphere glaciations suggests that climatic conditions associated with expanded global ice volume are a more likely cause for the onset of carbonate deposition than rapid tectonic shallowing of sill depths.

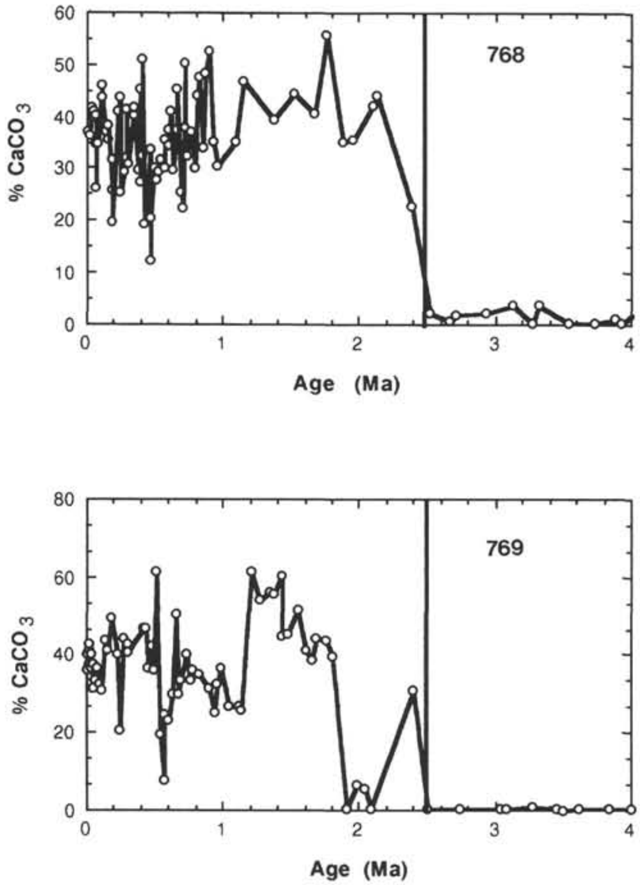

Figure 2. Bulk carbonate content in Pliocene and Pleistocene sections of Sites 768 and 769 plotted against time. Age control is based on location of paleomagnetic datums at each site. Dark line marks approximate time of the inception of Northern Hemisphere glaciation. Note that the single high carbonate value at 2.4 m.y. in Site 768 is from a visually carbonate-rich zone and is not reworked.

The effects of tectonic activity on sedimentation rates could also have affected the carbonate record in the Sulu Sea. Higher sedimentation rates before 2.4 Ma could have diluted the carbonate record. However, a plot of paleomagnetic datums vs. depth reveals that no significant changes in sedimentation rate occurred 2.4 Ma (Fig. 4). Sedimentation rates actually are fairly constant across this interval and do not increase until the late Pleistocene. Foraminifers and nannofossils are absent or scarce before 2.4 Ma, supporting the idea that the CCD was above the depths of these sites before 2.4 Ma.

REGULATION OF CARBONATE PRODUCTION AND ACCUMULATION BY CHANGING SEA LEVEL

The late Pleistocene record of $CaCO_3$ deposition displays cyclic variability at Milankovitch orbital periods (Linsley and von Breymann, this volume). Glacial periods are generally marked by increased $CaCO_3$ and copper accumulation in this 750-ka record, suggesting a carbonate paleoproductivity influence on the carbonate record. Increased productivity during glacial low sea-level stands could be related to the erosion of exposed shelf areas and/or greater nutrient flux from rivers and coastal zones during times of lowered sea level. Other factors include the effects of greater equatorial wind shear during glacial times (Romine, 1982; Rea et al., 1986) on the hydrographic dynamics of the western Pacific and China Sea. A thicker warm water lens in the western Pacific and reduced amounts of high total CO_2 Pacific Intermediate Water could have effected the CO_2 content of Sulu Sea Deep Water. Regardless of the exact cause of the $CaCO_3$ variability in the late Pleistocene, the timing of the $CaCO_3$ cycles demonstrates that the glacial-interglacial climatic-oceanographic change has influenced $CaCO_3$ deposition in this marginal basin in the tropical western Pacific.

The increase in global ice volume at 2.4 Ma could have had an effect on the Sulu Sea carbonate record similar to that of the late Pleistocene glacial/interglacial cycles. Although the present data do not allowed discrimination between the tectonic, paleoproductivity, and carbonate preservation hypotheses, the precise correspondence to the onset of Northern Hemisphere glaciation suggests some linkage to changing global climatic conditions.

Table 1. Paleomagnetic reversal datums and depths in the last 4.5 m.y. of record in Sulu Sea Holes 768B and 769B (from Rangin, Silver, von Breymann et al., 1990).

Chron/subchron	Age (m.y.)	Depth (mbsf) Site 769B	Site 768B
Brunhes			
————	0.73	61.8	76.6
MATUYAMA			
Jaramillo	0.91	79.5	86.1
	0.98	84.5	90.6
Olduvai	1.66	93.6	118.5
	1.88	102.3	122.2
Reunion 2	2.01	104.3	125.6
	2.04	104.7	126.0
Reunion 1	2.12		
	2.14		
————	2.47	114.5	134.4
GAUSS			
Kaena	2.92	117.0	142.9
	2.99		144.4
Mammoth	3.08		144.9
	3.18		146.4
————	3.40		151.0
GILBERT			
Cochiti	3.88		160.9
	3.97	132.6	163.7
Nunivak	4.10	135.2	167.2
	4.24	138.3	170.0

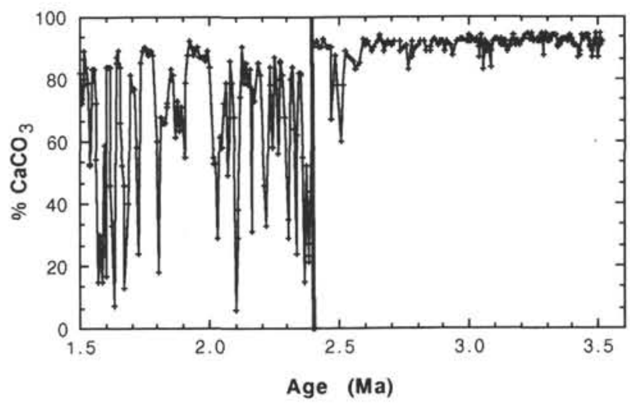

Figure 3. Carbonate percentage for a portion of DSDP Site 552A in the North Atlantic. The decrease in carbonate content shortly before 2.4 Ma marks the beginning of deposition of ice-rafted debris and the onset of Northern Hemisphere glaciation. Data from Zimmerman et al., 1985.

CONCLUSIONS

The synchronous occurrence of carbonate accumulation in the Sulu Sea and the initiation of Northern Hemisphere glaciation 2.4

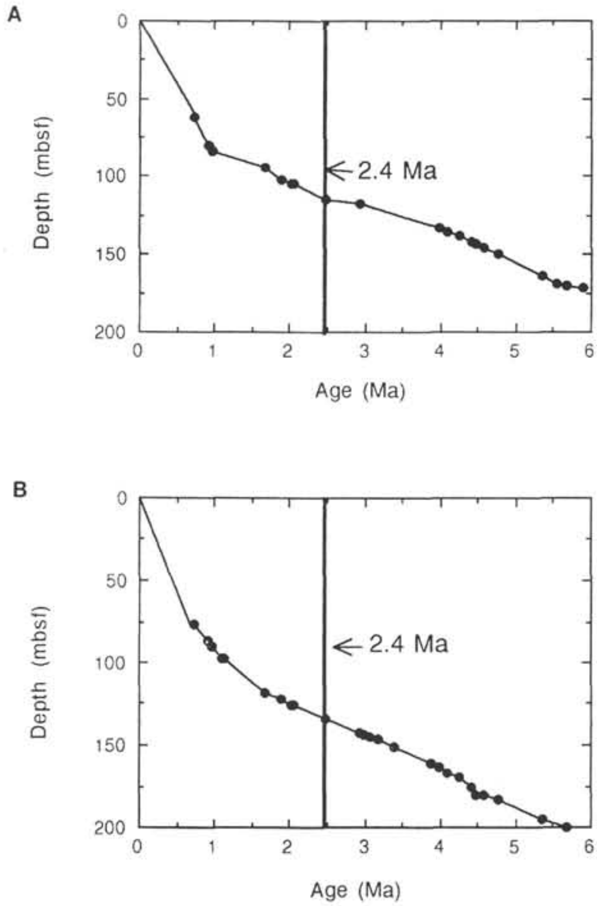

Figure 4. Age of paleomagnetic reversal datums vs. depth in core Holes 769B (**A**) and 768B (**B**). Position of 2.4-Ma increase in carbonate accumulation is marked. Note no significant change in sedimentation rate across the interval spanning 2.4 Ma.

Ma indicates that ice sheet expansion influenced sedimentation in the tectonically active marginal basins of the tropical western Pacific. The precise correspondence suggests that a climatic or glacio-eustatic sea-level change was responsible for the observed carbonate distribution, rather than strictly local tectonic adjustments of sill depth.

REFERENCES

Backman, J., 1979. Pliocene biostratigraphy of DSDP Sites 111 and 116 from the North Atlantic Ocean and the age of the Northern Hemisphere glaciation. *Stock. Contr. Geol,* 32:115–137.

Bloemendal, J., and deMenocal, P., 1989. Evidence for a change in the periodicity of tropical climate cycles at 2.4 Myr from whole-core magnetic susceptibility measurements, *Nature,* 342:897–900.

Broecker, W. S., Patzert, W. C., Toggweiler, J. R., and Stuiver, M., 1986. Hydrography, chemistry, and radioisotopes in the southeast Asian basins., *J. Geophys. Res.,* 91:C12, 14,345–14,354.

Curry, W. B., and Miller, K. G., 1989. Oxygen and carbon isotopic variation in Pliocene benthic foraminifers of the equatorial Atlantic. *Proc. ODP, Sci. Results,* 108: College Station, TX (Ocean Drilling Program), 157–166.

Eldholm, O., Thiede, J., Taylor, E. et al., 1987. *Proc ODP, Init. Repts.,* 104: College Station, TX (Ocean Drilling Program).

Frische, A., and Quadfasel, D., 1990. Hydrography of the Sulu Sea. In Rangin, C. Silver, E., von Breymann, M. T., et al., 1990. Proc. ODP, Init. Repts., 124: College Station, TX (Ocean Drilling Program), 101–104.

Linsley, B. K., Thunell, R. C., Morgan, C., and Williams, D. F., 1985. Oxygen minimum expansion in the Sulu Sea, western equatorial Pacific, during the last glacial low stand of sea level; *Mar. Micropaleontol.,* 9:395–418.

Rangin, C, Silver, E., von Breymann, M. T., 1990. *Proc ODP, Init. Repts.,* 124: College Station, TX (Ocean Drilling Program).

Rea, D. K., Chambers, L. W, Chuey, J. M., Janecek, T. R., Leinen, M., and Pisias, N. G., 1986. A 420,000-year record of cyclicity in oceanic and atmospheric processes from the eastern Equatorial Pacific. *Paleoceanography,* 1:577–586.

Romine, K., 1982. Late Quaternary history of atmospheric and oceanic circulation in the eastern equatorial Pacific. Mar. Micropaleontol., 7:163–187.

Ruddiman, W. F., Kidd, R. B., Thomas, E., et al., 1987. *Init. Repts DSDP,* 94: Washington, D.C. (U.S. Govt. Printing Officé).

Shackleton, N. J., et al., 1984. Oxygen isotope calibration of the onset of ice-rafting and the history of glaciation in the North Atlantic region. *Nature,* 307:620–623.

Sikes, E. L., Keigwin, L. D., and Curry, W. B., 1991. Pliocene paleoceanography: circulation and oceanographic changes associated with the 2.4 Ma glacial event. *Paleoceanography,* 6:245–257.

Srivastava, S. P., Arthur, M., Clement, B. et al., 1987. *Proc ODP, Init. Repts.,* 105: College Station, Tx. (Ocean Drilling Program).

Van Riel, P. M., 1943. The Snellius Expedition 1929–1930, oceanographic results, Part V, *The Bottom Water, Introductory Remarks and Oxygen Content,* 2. Leiden (Brill), 1–76.

Wyrtki, K., 1961. *Scientific results of marine investigations of the South China Sea and the Gulf of Thailand, physical oceanography of the Southeast Asian waters:* La Jolla (Scripps Inst. Oceanography).

Zimmerman, H., et al., 1985. History of Plio-Pleistocene climate in the North Atlantic, Deep Sea Drilling Project Hole 552A. *In* Roberts, D., Schnitker et al., 1985. *Init. Repts. DSDP,* 81: Washington, D.C. (U.S. Government Printing Office), 861–875.

Date of initial receipt: 18 June 1990
Date of acceptance: 25 January 1991
Ms 124B-173