Rangin, C., Silver, E., von Breymann, M. T., et al., 1990
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15. SUMMARY OF SHIPBOARD RESULTS[1]

Shipboard Scientific Party[2]

INTRODUCTION

The numerous western Pacific marginal basins have had a variety of origins and histories, including marginal basins trapped from a larger ocean basin, rifted from active volcanic arcs, rifted from continental margins, or composite events. They often separate collision zones and island arcs, and as such they represent small oases of undisturbed stratigraphic history within an otherwise very complex geological setting. The objectives of Leg 124 were to determine the age, stratigraphy, paleoceanography, and stress within two of these marginal basins, the Celebes and Sulu seas (Fig. 1). Specific objectives within these basins are as follows:

1. Were the Celebes and Sulu seas once part of a larger ocean basin, or did they have different origins?
2. What were the ages of formation of the basins and, if trapped from a larger basin, their times of separation?
3. What does the stratigraphic record tell us of (a) the histories of volcanic activity surrounding the basins, (b) the record of changing paleoceanography and sea level, (c) the record of collisional events surrounding the basins, and (d) the timing of formation of trenches on the basin margins?
4. What are the directions and magnitudes of stresses acting within the basins? Specifically, do the stress patterns clearly discriminate between differing collision and subduction orientations that appear to be acting on both basins? Is there an effect of either or both of the broad collisions between Southeast Asia and the Philippine Sea Plate from the east, or the Australian continent on the south?

To address these questions, Leg 124 scientists drilled five sites, two in the Celebes Sea and three in the Sulu Sea (Figs. 1 and 2), and reached acoustic basement in all of them. The following paragraphs summarize the major results of Leg 124.

BIOSTRATIGRAPHY, LITHOSTRATIGRAPHY, AND SEDIMENTATION RATES

The stratigraphic sequences at the five sites reflect the evolution of the Sulu and Celebes sea basins, including the history of tectonic and volcanic activity in the area and changes in the carbonate-compensation depth (CCD).

The late Miocene to Pleistocene sequences in the two Celebes sites (767 and 770) are dominantly hemipelagic deposits derived from a volcanic terrain, and are composed of smectite-rich clay with silt of crystal, vitric, and lithic volcanic material (Fig. 3). At the deeper basin site (767) the late Miocene to Pleistocene sequence is thicker (about 400 m for NN11 to NN21) than at Site 770, which is located on a plateau (around 300 m for the same period). Thin ash layers redeposited by turbidites or, more rarely, air-fall deposits occur throughout and show a change from lithic ash in the late Miocene and early Pliocene to vitric ash in the Pleistocene. The hemipelagic sediments were deposited below the CCD and are barren of fauna, but calcareous micro- and nannofossils occur in interbedded carbonate turbidites at Site 767 and can be used to date the sequence. Benthic foraminifers, benthic diatoms, and tunicate spines in these turbidites indicate redeposition from shallow water. At Site 770, carbonate turbidites are rare and are diagenetically altered. There is a general increase in the sedimentation rate from 32 m/m.y. in the late Miocene (NN11) to 99 m/m.y. in the late Pleistocene at Site 767.

From the late early Miocene to the late Miocene, the average rate of sedimentation at Site 767 was higher (109 m/m.y. in Zone NN9) with the input of turbidites from a continental source. This sequence of turbidites is 300 m thick and contains quartz sand and silt, plant debris, and reworked Eocene and lower middle Miocene nannofossils. The clay associated with these deposits is mainly illite. The absence of similar turbidites in the cores recovered at Site 770 reflects the location of this site on a plateau above the basin floor where the coarser siliciclastic material was deposited. During the middle Eocene to early Miocene, the difference in elevation between the two sites was about 750 m, but both sites record around 100 m of sediment for that period. Site 770 was close to the CCD, and the middle Eocene to early Oligocene sequence of brown pelagic sediments includes locally abundant calcareous nannofossils (mainly discoasters), whereas the less-resistant foraminifers are rare. Variations in the abundance and preservation of calcareous fauna indicates fluctuations in the Celebes Sea CCD in the Paleogene. In contrast, the sequence at the deeper Site 767 is barren of calcareous fauna, but it contains arenaceous foraminifers, ichthyoliths, and moderate to poorly preserved radiolarians. The middle Eocene to early Miocene sequence at Site 767 is truly pelagic with a slow sedimentation rate (between 2 and 6 m/m.y.), a red-brown color, manganese nodules, and a clay composition typical of western Pacific pelagic sediments. The deposits overlying the basaltic basement contain a radiolarian fauna that indicates a late middle Eocene age at Sites 767 and 770.

The Pleistocene sequences in the two Sulu Sea sites (768 and 769) are 120 and 90 m thick, respectively (Fig. 3). They were deposited above the CCD and are dominated by marls of pelagic clay and calcareous planktonic fossils. As in the Celebes Sea, the clays are smectite rich and volcanogenic in origin, but they are mixed with a rich assemblage of well-preserved calcareous micro- and nannofossils. Siliceous microfossils occur mainly in the top layer (60 cm). Although the sequence is dominantly pelagic, turbidites of reworked pelagic carbonate also occur. As in the Celebes Sea, the average rate of sedimentation increases throughout the Pleistocene: it is about 40 m/m.y. for NN19 and 100 m/m.y. for NN20/21 at both Sulu Sea sites. The shallower setting of Site 769 compared with 768 is also evident in the timing of the transition from deposition below the CCD in the Pliocene to deposition above the CCD in the Pleistocene: pelagic carbonate deposition begins in Zone NN16 at Site 769, a little earlier than at Site 768 (Zone NN17). This deposition timing implies that the CCD gradually dropped in the Sulu Sea during the late Pliocene to early Pleistocene and that there has been no relative movement between the ridge and basin floor during this period.

[1] Rangin, C., Silver, E., von Breymann, M. T., et al., 1990. *Proc. ODP, Init. Repts.*, 124: College Station, TX (Ocean Drilling Program).
[2] Shipboard Scientific Party is as given in the list of participants preceding the contents.

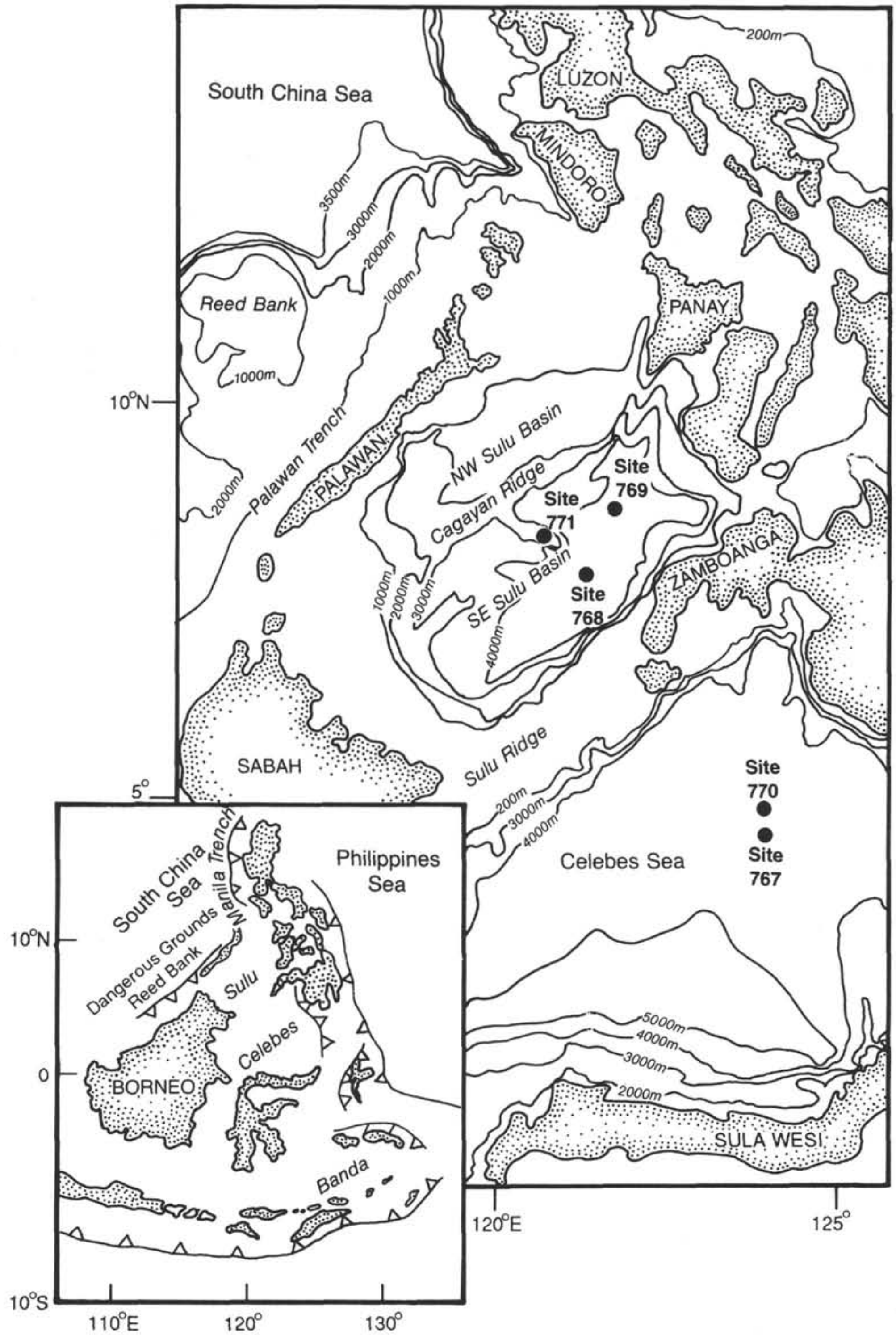

Figure 1. Simplified bathymetric map of the Celebes and Sulu Seas showing the locations of drilled sites on Leg 124. Depth contours given in meters.

Hemipelagic sedimentation of illite-rich, greenish gray clay occurred at all Sulu Sea sites from the middle Miocene to the late Pliocene, accompanied by siliciclastic turbidites at the basin floor site (768). These turbidites are mostly thin and silty with sporadic thicker sandy beds. They are composed mainly of quartz and contain plant material and a sparse shallow-water fauna. Turbidite deposition reached a peak during Zone NN9 (late middle Miocene) and contributed to the considerably thicker middle Miocene to Pliocene sequence in the basin (660 m) compared with Sites 769 and 771 on the ridge (160 m), where turbidites were not deposited. This difference is reflected in the sedimentation rates at the two sites: 293 m/m.y. at Site 768 compared with 10 m/m.y. at Site 769 for middle Miocene Zone NN9. The similarity of the siliciclastic turbidites deposited in

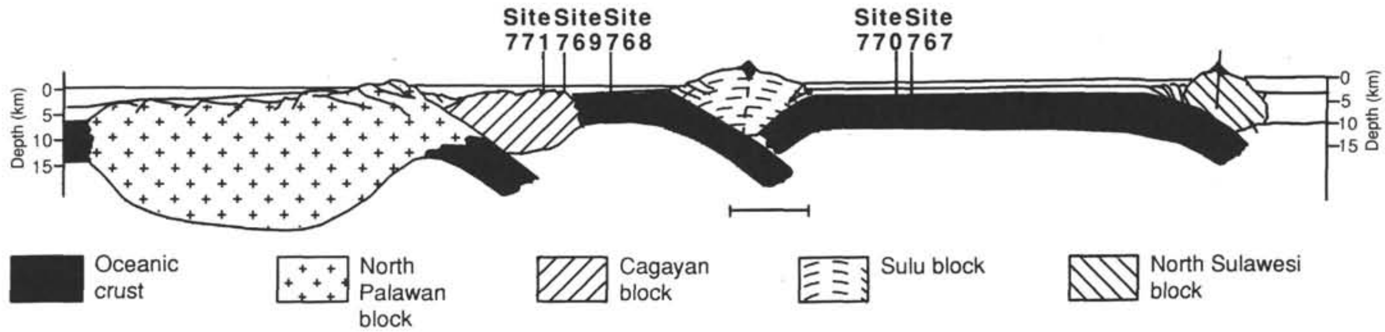

Figure 2. Crustal section of the Celebes-Sulu basins and ridges, showing the locations of drilled sites.

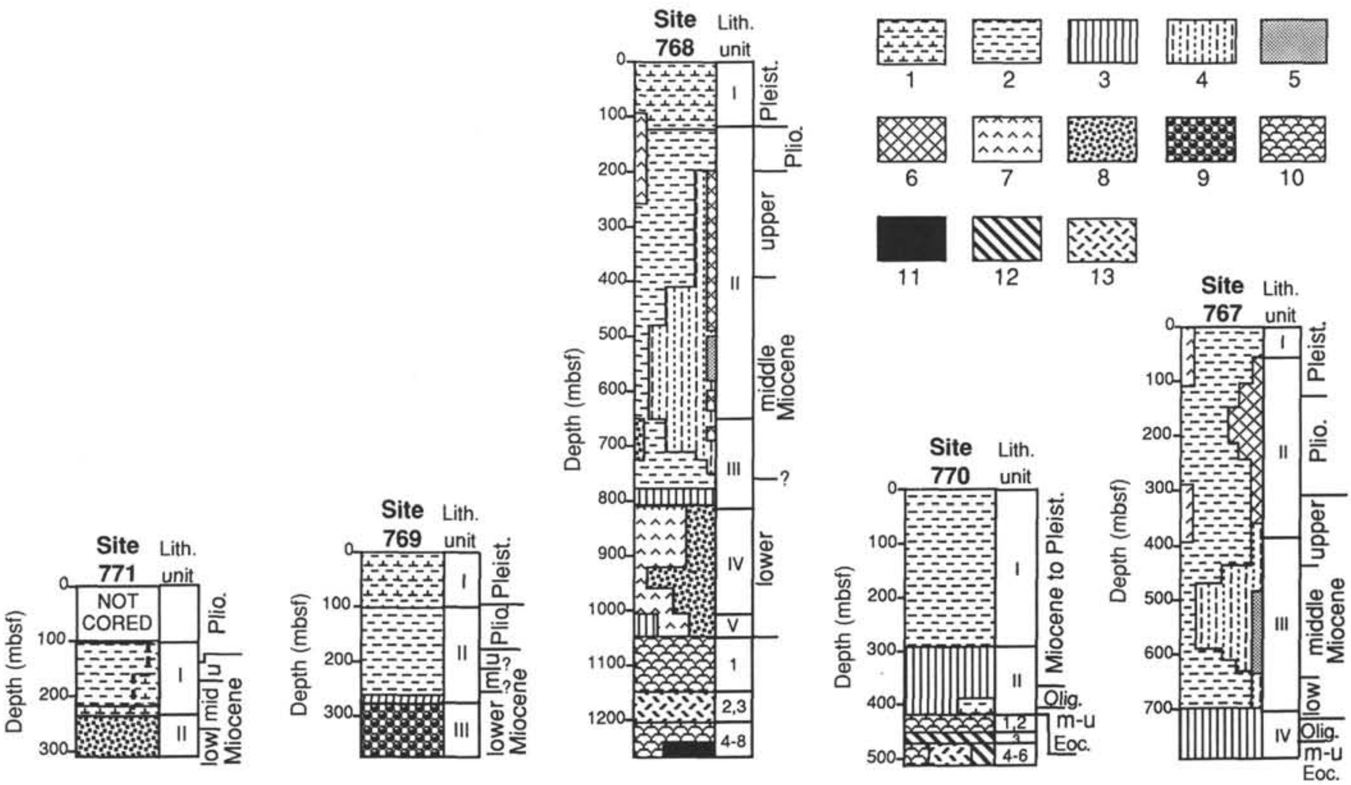

Figure 3. Lithologic columns for Sites 767–771. Symbols used are (1) nannofossil marl or nannofossil-foraminifer marl; (2) hemipelagic sediments including clay/silt (stone); (3) pelagic brown claystone; (4) terrigenous turbidites; (5) quartz siltstone to sandstone; (6) graded carbonate turbidites; (7) fine ash/tuff; (8) pumiceous, rhyolitic to andesitic coarse tuff and lapillistone; (9) andesitic to basaltic coarse tuff and lapillistone; (10) pillow basalt; (11) basalt sheet flow; (12) brecciated massive basalt; (13) diabase sill.

the middle and late Miocene in the Sulu and Celebes seas implies that they have a common source in a continental terrain bordering the two basins. The peak of turbidite deposition was in the late middle Miocene (Zone NN9) in both basins and may be related to the global sea-level fall around this time (NN8 and NN9) or to an increase in tectonic activity in the source area.

Carbonate turbidites also occur in the middle Miocene to Pliocene sequence at Site 768. They contain abundant calcareous fossils, particularly nannofossils, which have been used to date the sequence. Benthic foraminifers occur only in small numbers, and there are no remains of shelf-dwelling organisms, indicating that these carbonate turbidites were reworked from a pelagic source. These carbonate turbidites are rare on the ridge site, but the hemipelagic clays at Site 769 are calcareous with nannofossils locally abundant. Foraminifers are few and poorly preserved. This paucity indicates that the ridge site was close to the CCD during this period, whereas the basin floor was below the CCD.

Volcanic activity in the region in the late middle Miocene to Pleistocene is recorded at both sites by very thin air-fall ash beds. As in the Celebes Sea Basin, crystal and lithic ashes in the Miocene and Pliocene give way to vitric ash in the Pleistocene.

Paleontological data suggest that there is a hiatus between lower middle Miocene Zone NN5 and upper middle Miocene Zone NN8 at Site 768, but the sedimentary sequence of gray hemipelagic clay through this interval shows no indication of a break in the sequence.

Slow sedimentation rates during the late early Miocene to early middle Miocene at all three Sulu Sea sites are indicated by more frequent arenaceous foraminifers and ichthyoliths. However, the red-brown clay deposited in this period is very rich in smectite, indicating that they may not be true open-ocean pelagic clays as seen in the Paleogene in the Celebes Sea. Sedimentation rates of 6 m/m.y. are estimated for this period at Site 769, but at Site 768 the average rate is considerably higher (161 m/m.y.). The high rate at Site 768 is caused by the presence of a thick sequence of volcaniclastic rocks intercalated into the brown clays. The absence of nonvolcanic detritus and fossils indicates a rapid deposition for this material. These deposits are the products of pyroclastic flows; they are glass rich and rhyolitic to dacitic in composition. They contrast sharply with a sequence of volcaniclastic rocks of the same age at Site 769. These latter deposits are coarser, chaotic, and probably deposited in shallow water: they are more mafic in composition (andesitic to basaltic). These two pyroclastic sequences are clearly not derived from the same source.

The lowest brown claystone deposits at Sites 768 and 769 in the Sulu Sea are dated by a poorly preserved radiolarian fauna, and at Site 771 by both nannofossils and radiolarians, as late early to early middle Miocene.

BASEMENT LITHOLOGY

The volcanic rocks recovered from the basement of the Celebes Sea are mostly plagioclase-olivine-phyric basalts and dolerites. The available chemical data suggest that these rocks may be ocean-floor tholeiites. The volcanic rocks recovered from the basement of the Sulu Sea are olivine-phyric basalts and intrusive dolerites and micro-gabbro, some of which are picritic and have unusually high contents of Ni and Cr. The range of compositions shown by the rocks of the Sulu basement can be explained in terms of derivation from the same source and different partial melting and fractional crystallization histories. The high volatile content and trace element characteristics of this suite suggest that they may have an arc-related origin.

PHYSICAL PROPERTIES

A complete program of physical properties measurements was undertaken on Leg 124. The results of these measurements, in particular those of bulk density, porosity, and water content, displayed patterns of variability with depth in the sediment sections drilled that are within the "normal" range for those properties measured elsewhere in deep-ocean-basin environments. Measurements of these properties in the oceanic crustal rocks that were recovered similarly displayed properties typical for these rock types. Site 769, on the flank of the Cagayan Ridge in the Sulu Sea, contained a good example of the relationship between physical properties and the deformation of rock units.

The upper units drilled at Site 769, consisting of pelagic carbonate and clay, displayed typical profiles of increasing bulk density and decreasing porosity and water content with depth. This pattern was interrupted at roughly 360 mbsf by a zone in which the bulk density rapidly began to decrease, and the porosity and water content increased markedly over the levels typical of overlying units. These observations suggested that this lithologic unit, consisting of red pelagic clay, may be an overpressured zone, in which the pore-fluid pressure exceeds that of the lithostatic load. The red clay horizon appeared to be significantly undercompacted relative to the gradients observed above this layer.

Correlation of this apparently overpressured zone with the seismic reflection profile across the site showed that a major structural discontinuity, interpreted to be a décollement surface for faults that disrupt the overlying strata, corresponds closely to the zone of overpressuring inferred on the basis of the physical properties measurements. Thus, the décollement surface identified in the seismic reflection profile is likely to be a zone of low strength within the sediment section caused by the high fluid pressures.

PALEOMAGNETIC RESULTS

Paleomagnetic data at Site 767 exhibit excellent results from the ten APC cores taken at Hole 767B, which included the most recent three reversals, the Brunhes-Matuyama Chron boundary, and the bottom and top of the Jaramillo Subchron. The depths and ages of the reversals display a very linear trend with a sedimentation rate of 67 m/m.y. A very short normal interval (about 12 k.y. in duration) was found at about 1.1 Ma below the Jaramillo Subchron. This reversal was later confirmed at the Sulu Sea. The XCB and RCB cores at Site 767 have scattered but shallow inclinations consistent with the low latitude at this site. More demagnetization of samples from this site is needed before any inclination variation trend can be estimated.

Spot RCB cores in the sediment column at Site 770 also have very shallow inclinations. Some carbonates just above the basement were found to have rather high coercivity secondary magnetization and will probably require thermal demagnetization treatment. The basement basalt has high (about 40°) inclinations, which may be attributable to the tilting of the basement.

Site 768 in the central Sulu Sea produced a long reversal sequence that extends to about 6 Ma (Chron 5). All reversals were well defined by paleomagnetic parameters, except for the last few reversals located below 190 mbsf. Below this depth, magnetic susceptibility and remanent magnetization became very weak, creating scatter in the data. Overall, the 23 APC cores are very well dated and the reversal age-depth relation reveals sedimentation rates of 105, 45, and 21 m/m.y. for the periods 0–0.73, 0.73–1.5, and 1.5–6 Ma, respectively. The short normal interval within the Matuyama Reversal Epoch was positively observed again in this site, and can be correlated with the Cobb Mountain Event.

Magnetic susceptibility and remanent magnetization increased after about 820 mbsf when pyroclastic flows became dominant. Pass-through cryogenic magnetometer measurements were attempted again in an effort to date these pyroclastics. The results of these measurements were not very useful, but based on inclinations only we assigned six reversals at depths between 820 to 1030 mbsf, corresponding to Magnetic Anomalies 5D to 5E, suggesting an age of 18.8 Ma for the basement.

Magnetostratigraphy at Site 769 on the Cagayan Ridge produced a longer reversal sequence extending to about 9 Ma at the boundary between Chrons 10 and 11. The reversals were well defined, but several disturbed beds and a few low recovery cores caused several reversals to be missed including the Cobb Mountain Event.

Inclinations at Site 769 vary from about 8° to −7° between 140 to 210 mbsf. This gradual change between about 4 and 7 Ma cannot be interpreted as a result of slumping. Tectonic tilting during this time period is likely to be the cause.

More than 200 m of basalt were drilled at Site 768. The magnetization was generally stable and mostly of reversed polarity, except for the top 20 m or so, which is of normal polarity. Average inclinations of approximately 40° are hard to explain by a north–south plate movement alone. Because the site is located on a tilted block (block surface has an apparent dip of 7° NW (?)) along one seismic line, a reversed polarity for the basalt and tilting of the basement may be the cause of the high inclination.

Magnetic susceptibility data collected during Leg 124 exhibit high values ($200–1500 \times 10^{-6}$ cgs) before the late Miocene. By early late Miocene (10 m.y.) the susceptibility data decreases to low values ($10–50 \times 10^{-6}$ cgs) at all sites. At Site 767 (Celebes Sea) susceptibility values remain low until approximately 9 Ma, when they slowly increase to an average of 300×10^{-6} cgs by

6 Ma. From 6 Ma to the present susceptibility values remain around 300 $\times 10^{-6}$ cgs, with slight fluctuations in the long-term susceptibility trend. Sharp irregular peaks of up to 1000 $\times 10^{-6}$ cgs are superimposed on this susceptibility curve. At Sites 768 (Sulu Sea) and 769 (Cagayan Ridge), from the late Miocene to lower early Pliocene (10–5 m.y.), susceptibility values do not coincide. Susceptibility values at Site 768 remain low over this period whereas values at Site 769 increase to approximately 120 $\times 10^{-6}$ cgs. From the early Pliocene to the present, the general trends of the susceptibility curves from Sites 768 and 769 closely correspond, with two long-term cycles and several short-term increases evident in each data set, indicating that the same volcanogenic processes were affecting both sites.

SEDIMENT GEOCHEMISTRY RESULTS

Downhole measurements of carbonate content in the sediment cores reveal a complicated history of sediment accumulation in the Celebes and Sulu seas. Carbonate content varies considerably throughout all cores studied and can be related to sediment source input, mode of sedimentation, and changes in the CCD through time.

Higher amounts of terrestrial organic matter are related to turbiditic events in Sites 767 and 768, whereas pelagic sediments only contain smaller concentrations of organic material. Only low amounts of organic material were detected at Sites 769 and 770, and none at Site 771. The maturity of the organic substances is low in sediments from Sites 767, 769, and 770, whereas Site 768 sediments reach the thermogenic hydrocarbon generation zone at around 450 mbsf.

Thermogenic hydrocarbon generation is only observed at Site 768 below 450 mbsf as indicated by significant amounts of propane and butane. With increasing depth and temperature, higher hydrocarbons are cracked and methane and ethane are the only gas components detectable below 820 mbsf. High gas concentrations in organic-lean pyroclastic rocks at Site 768 may be a result of the migration of hydrocarbons by thermal water convection.

With the exception of alkalinity, the depth profiles of pH, salinity, and other major dissolved ion constituents in the sediment cores from these two marginal basins all show a similar pattern, implying that the processes controlling their depth distribution are alike. To interpret our interstitial data better, relevant processes affecting their depth distributions are identified and grouped into the following categories:

1. Decomposition of organic matter: This process is mainly mediated by sulfate-reducing bacteria and is responsible for the observed dissolved sulfate profiles. It also partially controls the production of ammonium and bicarbonate (alkalinity) in the pore water. At Sites 767 and 768, sulfate reduction is completed at 300 and 180 mbsf, respectively, and further decomposition of organic matter proceeds by carbonate reduction and methanogenesis. This metabolic process is evidenced by the methane and ethane distributions at these sites.

2. Diagenetic alteration of volcanic components (i.e., ash layers, pyroclastic deposits, and basement): This reaction largely controls dissolved calcium and magnesium distributions in the middle and lowermost sections of the holes. The silicification during the alteration of detrital silicates of volcanic origin may also be responsible for the low level of silica in the lower sections of the sediment cores. Furthermore, some of the variation in the pH profiles can also be attributed to this process, as volcanic ash layers are frequently found within the sediment column.

3. Carbonate precipitation and dissolution: These processes are partly responsible for the observed calcium, magnesium, and alkalinity variations with depth, especially in the uppermost sections of Sites 768 and 769.

4. Dissolution of biogenic silica: This process is responsible for the high dissolved silica values observed in the upper sections of all the cores studied.

5. Clay diagenesis upon burial: The membrane effect of clay during the transport of fluids and/or a release of chemically bound water from clays upon burial may explain the small decrease in chloride with depth at Site 767. In addition, the ion exchange reaction of ammonium on clay mineral surfaces can account for the gradual decrease in the observed ammonium in all sediment cores studied.

6. The salinity profile reflects a net balance in the sum of major dissolved ion concentrations.

CONCLUSIONS

The Celebes Sea formed in open-ocean conditions in the middle Eocene. The CCD lay between the paleowater depths of Sites 767 and 770. The basin approached close enough to a continental landmass, probably Sundaland, by late early Miocene time, to be receiving significant amounts of land-derived detritus. In the late middle Miocene the deeper Site 767 recorded high rates of turbidite deposition from a continental source. In contrast, the late Miocene to Pleistocene source terrain was volcanic and not continental, suggesting that the development of the north Sulawesi and Cotabato trenches had diverted continental source material from the central part of the basin to its margins. The volcanism could also be related to increased subduction of the Molucca Sea Plate beneath the Sangihe Arc.

The Sulu Sea formed in the late early to early middle Miocene, nearly concurrently with the cessation of volcanism on the Cagayan Ridge. Early outpourings of rhyolitic to andesitic pyroclastic flows marked the early formation of the basin, sandwiched within the deposition of a brown, smectite-rich claystone. Andesitic and basaltic tuffs of similar age underlie the pelagic sections at Sites 769 and 771, but any genetic relationship is yet unclear. Thick, continentally derived turbidites in the late middle Miocene at Site 768 coincide with those seen in the Celebes Sea and may indicate a common source, very likely Borneo, where an active mountain belt was shedding abundant debris at that time. Volcanogenic sedimentation dominates the nonbiogenic components in the Pleistocene, probably indicating the initiation of the Sulu Trench and volcanoes on the Sulu Ridge.

Stress measurements at Sites 770 and 768 in the Celebes and Sulu basins show a northeast orientation of the maximum horizontal stress. This result shows that the dominant factor in the production of stress within these basins is the collision between the basins and associated ridges with the Philippine Mobile Belt. No indication of the impact of the Australian continent is seen, nor do the thrusts on either side of the Sulu Ridge play a role in generating stress within the basins. The Sulu Trench may be inactive or else it possesses very low shear resistance. Leg 124 was remarkably successful in all facets, achieving excellent results in each of the major objectives of the leg.

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