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1. LEG 124 TECTONIC SYNTHESIS[1]

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ABSTRACT

This paper synthesizes the tectonic aspects of the results of Leg 124 drilling. We focus on the petrology, structure, stratigraphy, and paleomagnetism of the cores to evaluate the initial tectonic settings of the basins and their later histories. The type of plate tectonic setting of the middle Eocene Celebes Sea cannot be determined unambiguously, but we do not favor an origin as a fragment of either the Indian Ocean or the west Philippine Sea plates. We cannot exclude an origin as a fragment of the mostly subducted Molucca Sea Plate or a basin rifted from the edge of the east Asian mainland. The Sulu Sea, on the other hand, seems very likely to have formed by back-arc spreading behind the Cagayan Ridge during a short time interval in the early Miocene. Cessation of spreading in the Sulu Sea and volcanic activity on the Cagayan Ridge were coeval, possibly related to collision between the Palawan and Cagayan ridges.

INTRODUCTION

The tectonic objectives of Leg 124 were to determine the age, origin, and history of the Celebes and Sulu Sea basins, to test hypotheses for their formation, and to use the stratigraphic information to constrain the history of major tectonic events in the Philippine and Indonesian archipelagoes. Background information on the regional geology can be found in Rangin and Silver (this volume), including extensive references, and in Rangin, Silver, von Breymann, et al., (1990). This paper summarizes the scientific results of studies bearing on the origin and history of the Sulu and Celebes seas, based largely on the drilling and post-cruise scientific results of Leg 124. Five sites were drilled in the two basins (Fig. 1). Data and results for each basin are discussed separately below.

CELEBES SEA

The Celebes Sea is presently surrounded on three sides by island arcs and is bordered on the fourth by the large island of Borneo. Two sites were drilled in the Celebes Sea (Fig. 1). At Site 767 (Fig. 2) we recovered a continuous section of pelagic sediments and turbidites, 786 m thick, and bottomed in basalt. Site 770 penetrated 420 m of pelagic sediment and recovered 110 m of basaltic basement from a fault block that is 500 m shallower than Site 767.

Basement Petrology

Both Smith and Sajona (this volume) and Serri et al. (this volume) confirmed that the basalts from the Celebes Sea Basin are N-MORB in composition. Serri et al. (this volume) showed by the distributions of major and minor elements, rare-earth elements, and Sr and Nd isotope ratios, that the rocks of the Celebes Sea are mantle-derived, and that they contain no subduction-related components. The isotopes are consistent with an origin in an oceanic setting, not in a back-arc setting. Smith and Sajona (this volume) concurred with this interpretation on the basis of major- and trace-element distributions. They found similarities with the mid-Indian ocean triple junction and suggested a common origin. Although the geochemical evidence is consistent with an Indian Ocean origin, it does not rule out an origin on the Philippine Sea Plate or the Molucca Sea Plate, nor one of rifting of the edge of the China continental margin.

K-Ar ages measured on basalts (Bellon, written comm., 1990) are dated 32–34 Ma on fresh basalts, 24 Ma on altered basalts, and 50 Ma on highly altered basalts. These dates do little to constrain the age of the Celebes Sea, because the isotopic ages have been affected by secondary processes.

Fractures

Studies of borehole televiewer data from the basement of Site 770 revealed a set of fractures clustering around N119E and N143E (Fig. 3) (Kirchoff-Stein et al., this volume). This orientation is consistent with flexure of the crust due to subduction along the northwest-trending Cotabato Trench. Supporting the idea of flexure is a broad gravity high that runs parallel to the trench in the Celebes Sea (Watts et al., 1978). Kirchoff-Stein et al. (this volume) considered alternatives of active vs. ancient processes as causes for the fracture pattern. They could not rule out the possibility that the fractures were relict from an earlier stress field, but they preferred the flexure interpretation because of consistency and relation to the orientation seen in the Sulu Sea as well.

Kirchoff-Stein et al. (this volume) also looked for borehole breakouts as indicators of stress orientation, but concluded that no breakouts are present. Applying the method of Moos and Zoback (1990) to these data, they concluded that the water and burial depths of Site 770 are not sufficient to produce breakouts. A similar analysis gave the same result for Sulu Sea Site 768.

Brown Claystone

Radiolarian-bearing reddish brown claystone makes up the lower parts of the section at Sites 767 and 770 (Fig. 2), with a significant carbonate component at the shallower Site 770. Sedimentation rates are poorly constrained due to difficulty in dating the sediments, but are on the order of 4 m/m.y. At Site 770. A radiolarian-rich layer occurs 1 cm above hyaloclastites that rest on basalt (Rangin, Silver, von Breymann, et al., 1990). These fossils place the base of the sedimentary section in the *P. chalara* zone (Scherer, Celebes Sea radiolarians, this volume) at 42 Ma based on the time scale of Berggren (1985). At the deeper Site 767 similar radiolarian species are present

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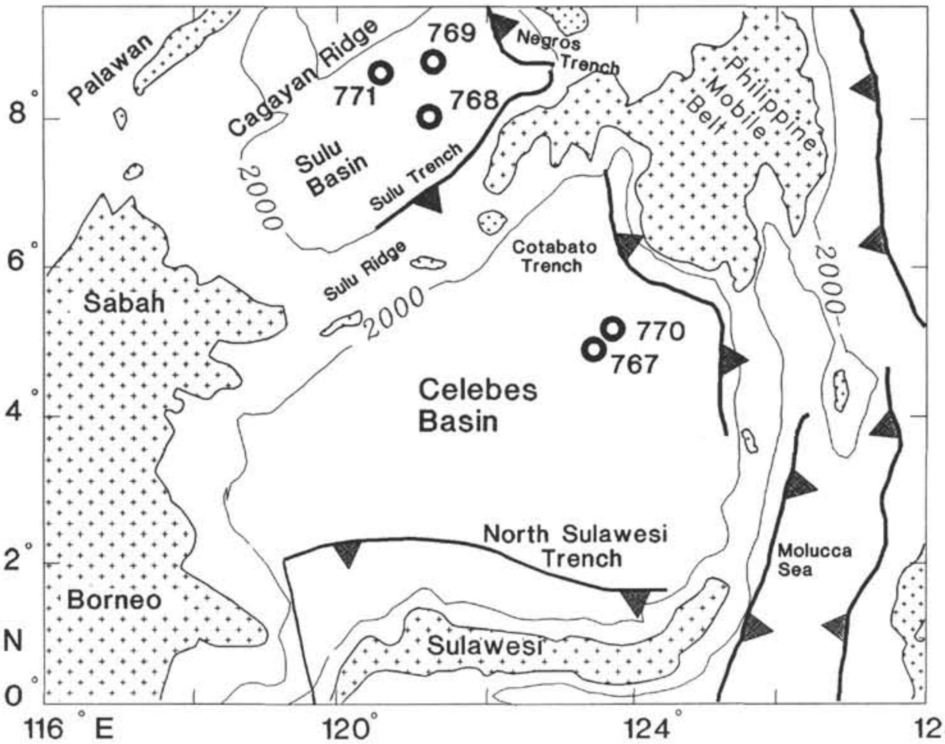

Figure 1. The Celebes and Sulu seas, showing locations of Sites 767, 768, 769, 770, and 771. Also shown are the major thrusts and island arc systems in the region. Depth contours are in meters.

but are more poorly preserved (Scherer, Celebes Sea radiolarians, this volume).

In contrast, Kaminski and Huang (this volume) identified lowermost Eocene deep water agglutinated foraminifers (DWAF) at Site 767, an age that they believe is well-constrained. They argued that the forms recovered are cosmopolitan and unlikely to be a locally restricted fauna. The constraint on radiolarian ages at Site 770, however, looks very tight. We note that the stratigraphy for the foraminifers was determined in the Atlantic and Mediterranean regions (Kaminski and Huang, this volume), and that the tie to the western Pacific is much weaker than for radiolarians. We thus maintain our conclusions (Rangin, Silver, von Breymann, et al., 1990) that the basaltic basement of the Celebes Sea sites originated in the middle Eocene.

Both Bertrand (this volume) and Nicot and Desprairies (this volume) concluded that the source of a significant fraction of the red clay was terrestrial. The organic material of the clay is a residual of mainly continental origin (Bertrand, this volume). Nicot and Desprairies (this volume) concluded that the sediment in the brown claystone was derived from both continental and volcanic sources. The high quartz content of the total sediment is evidence for continental sources, whereas the high smectite indicates a volcanic source rock.

Clay Mineral Data

Shipboard analyses of clay mineralogy indicated that the relative amounts of smectite, illite, chlorite, and kaolinite making up the clay fraction of Site 767 are remarkably uniform within the brown clay section, and they remain uniform for about 40 m into the overlying green claystone (Fig. 4). We concluded (Silver and Rangin, this volume) that this distribution argued against a significant lithologic change at the red/green boundary that is dated (by interpolation) as 18–19 Ma (Rangin and Silver, this volume). The lack of significant change in clay mineralogy at the red/green clay boundary means that this boundary cannot be used as evidence of far-travel of the Celebes Sea.

Carbonates

R. Smith et al. (this volume) studied the evolution of the calcite compensation depth (CCD) in the Celebes Sea and the Indian and Pacific oceans and suggested a relationship with the Pacific, because of a comparable sharp drop in the CCD during the Oligocene. The part of this study critical for tectonic interpretation is that in the middle Eocene through late Oligocene, the Celebes Sea was connected oceanographically with the open ocean and was not a restricted basin.

Turbidites

The Celebes Sea Basin shows a major influx of turbidites in the middle to late Miocene (Fig. 2) (Betzler et al., this volume). At Site 767 the earlier siliciclastic turbidites (Zones NN8–NN9) are dominated by quartz and plant debris. Later turbidite sands contain rock fragments, chert, and volcanic grains, but very little quartz, indicating a mixed source area. Carbonate turbidites also occur in the Miocene-Pliocene section. The earlier turbidites (Zone NN9) are more distal but shelf-derived, whereas the later ones (Zones NN12–NN19) are more proximal and are derived in part from greater water depths (Betzler et al., this volume). Turbidite deposition ceased in the early Pliocene, as basin configuration changed, probably a result of the onset of subduction in the Cotabato Trench and increased activity in the North Sulawesi Trench (Rangin, Silver, von Breymann, et al., 1990).

Paleomagnetism

Shibuya et al. (this volume) used secondary magnetization to determine the present magnetic field direction in the sedimentary cores (cores were not oriented) and then concluded

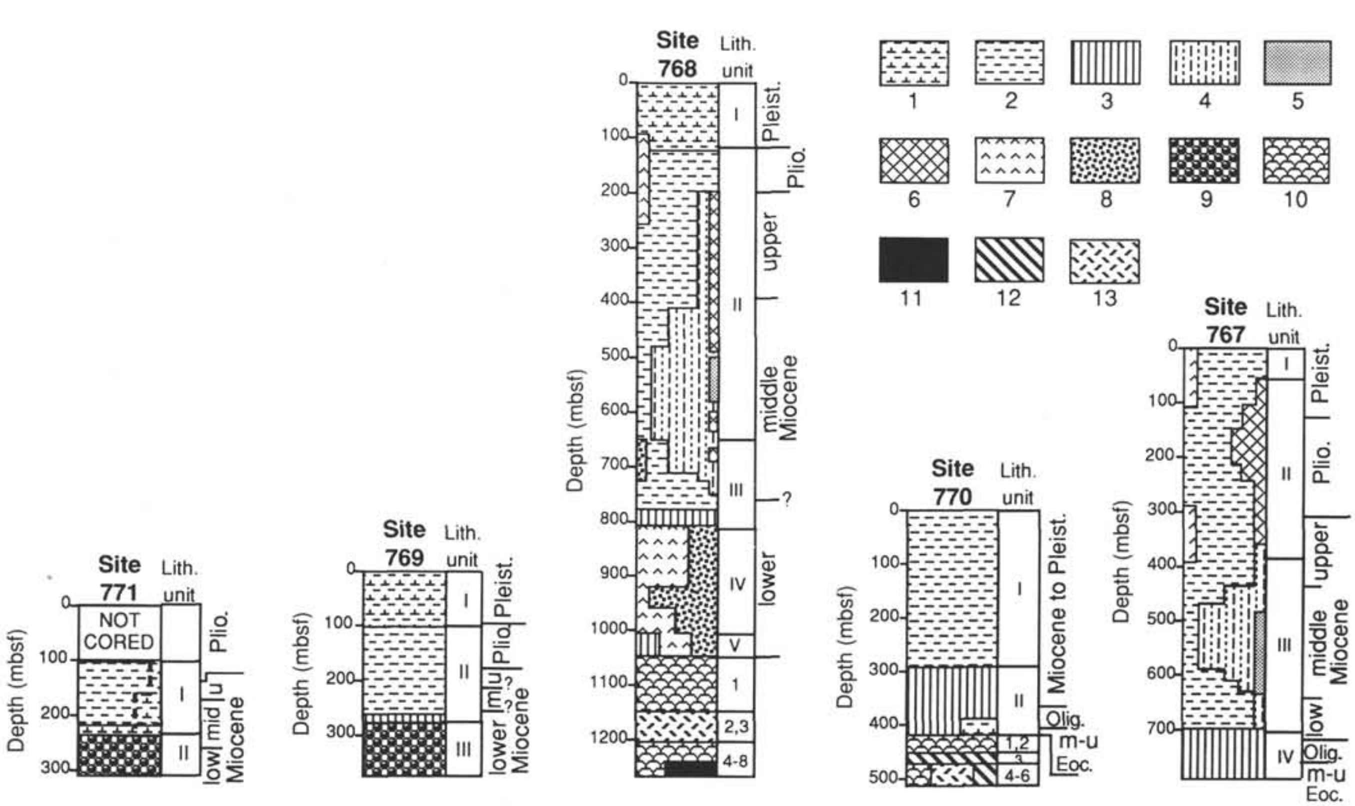

Figure 2. Summary stratigraphic columns for Sites 767–771 across the Celebes and Sulu seas. Symbols for the lithologic columns are (1) nannofossil marl or nannofossil-foraminifer marl; (2) hemipelagic sediments including clay/silt (stone); (3) pelagic brown claystone; (4) terrigenous turbidites; (5) quartz siltstone to sandstone; (6) graded carbonate turbidites; (7) fine ash-tuff; (8) pumiceous, rhyolitic to dacitic 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 (illustration from Ocean Drilling Program).

that the Celebes Sea had rotated up to 60 degrees counterclockwise between the middle Eocene and late Oligocene. No rotation is indicated from this analysis after late Oligocene. That rotation aligns the Weissel (1980) magnetic anomalies in the Celebes Sea with the present magnetic pattern in the west Philippine Basin, leading Shibuya to conclude the two were related. Spreading rates based on Weissel (1980) in the Celebes Sea are less than half that measured in the west Philippine Basin (Louden, 1977; Watts et al., 1977; Mrozowski et al., 1982). On this basis Silver and Rangin (this volume) concluded that the Celebes Sea probably did not form from the Philippine Sea Plate.

Another possibility for the origin of the Celebes Sea is as a fragment of the Indian Ocean (Lee and McCabe, 1986). Examination of the latest magnetic anomaly compilation of the oceans by Cande et al. (1989) indicates that spreading in the Indian Ocean reorganized at or just prior to anomaly 20, when the southeast Indian Ocean ridge jumped to a more southern position. Earlier, the spreading system could have extended east to the possible location of the Celebes Basin, but after the jump the ridge connected with spreading south of Australia, making it unlikely that the Celebes Sea was created from spreading in the Indian Ocean after anomaly 20.

Paleoinclinations at Site 767 show a wide scatter that can be interpreted either as no significant change in latitude, as a sudden change in latitude shortly after formation of the basement, or as a slow continuous decrease in latitude with time. If the data are interpreted as showing a decrease in paleolatitude with time, they would suggest an origin of the Celebes Sea farther north than its present location. An origin farther south would imply decreasing early inclinations passing through zero and increasing later. There is no evidence for the latter implications. Silver and Rangin (this issue) supported the case for rotation of a basement block, giving the anomalously high inclinations relative to the sediments. From the tentative data available at present we favor an origin not far removed from the present latitude of the Celebes Sea, but the data allow movement of up to 19°, more likely from the north than the south.

SULU SEA—CAGAYAN RIDGE

The Sulu Sea is surrounded by island arcs and continental fragments, with the Palawan and Cagayan ridges on the northwest, the Sulu Ridge on the southeast, Philippines on the east, and Borneo (Sabah) on the southwest (Fig. 1). Three sites were drilled in the Sulu Sea. One (Site 768) was drilled in the Sulu Sea Basin and two (Sites 769 and 771) on the flanks of Cagayan Ridge (Fig. 2).

Basement

Site 768 penetrated 220 m into basaltic basement rocks, recovering pillow basalts, massive lavas, and two diabase sills (Rangin, Silver, von Breymann, et al., 1990). All of the basement rocks have been altered, eliminating primary olivine and glass (Spadea et al., this volume). Geochemical analyses indicate that the Sulu Sea basement is transitional between MORB and island arc tholeiite, suggesting contamination of primary basaltic magmas by subduction processes (Spadea et al., this volume; T. Smith et al., this volume). $^{87}Sr/^{86}Sr$ (0.703), and $^{143}Nd/^{144}Nd$ (0.513) for the Sulu Sea lie on the mantle

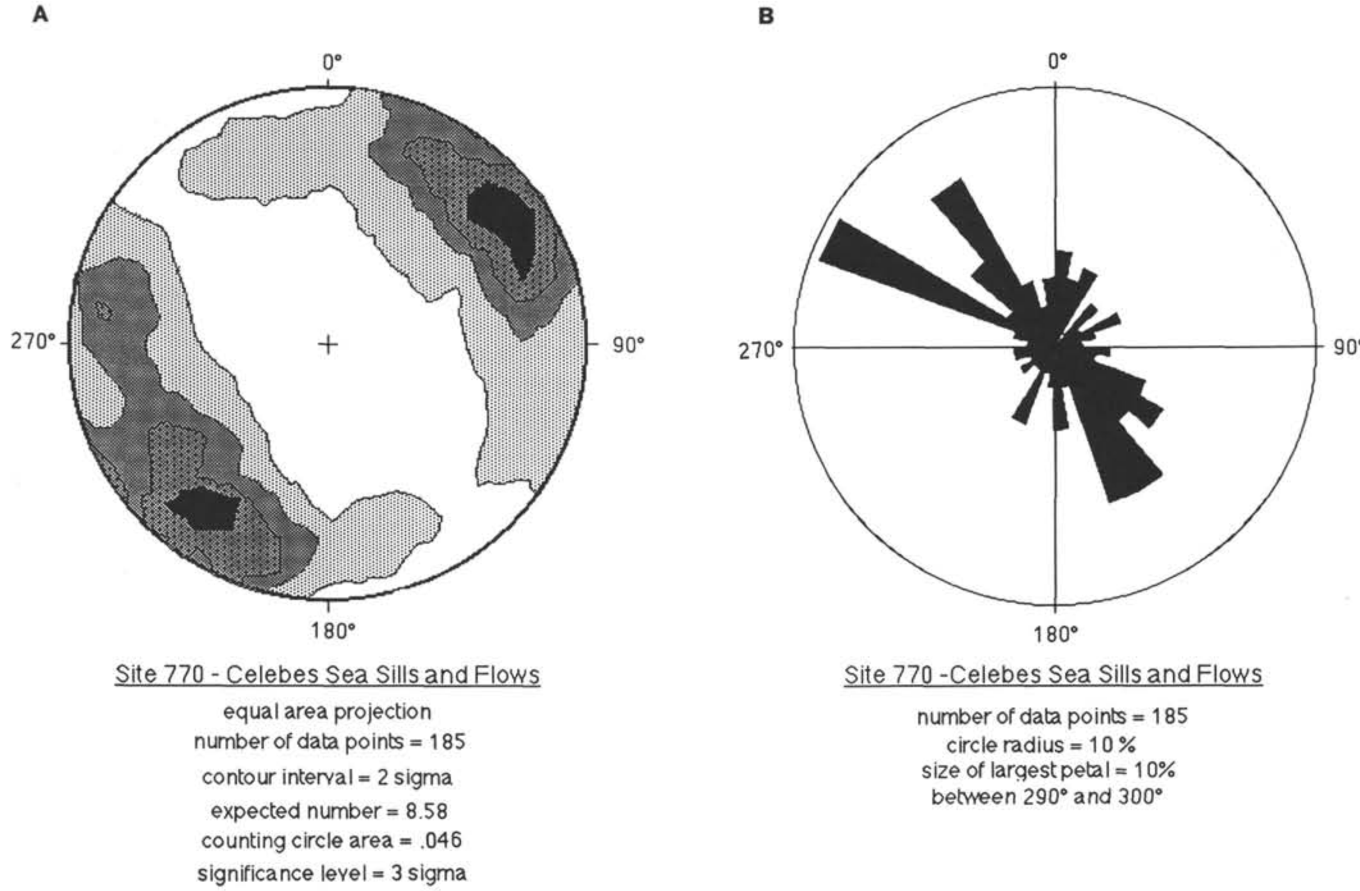

Figure 3. Equal-area and rose diagrams of fracture orientations for the basement section of Site 770, based on borehole televiewer data (from Kirchoff-Stein et al., this volume).

array, indicating primary mantle sources for the rocks (Spadea et al., this volume).

Basaltic and andesitic clasts recovered from the Cagayan Ridge, in contrast, are calc-alkaline at Site 769 and island-arc tholeiite at Site 771 (Kudrass et al., 1990; Spadea et al., this volume; T. Smith et al., this volume). The chemical composition of the rocks imply continental crust contamination, indicated also by petrographic analysis (Kudrass et al., 1989), consistent with eruption of the magmas through continental rocks. Low $^{87}Sr/^{86}Sr$, intermediate $^{143}Nd/^{144}Nd$, and high $^{206}Pb/^{204}Pb$ suggest mantle metasomatism (Spadea et al., this volume).

Radiometric dates on basalts and andesites of the Cagayan Ridge (Sites 769 and 771) and basalts and gabbros from Site 768 in the Sulu Sea Basin were compared with samples from around the Sulu Sea by Bellon and Rangin (this issue). They found that volcanism on the Cagayan Ridge ranges in age from 20–14 Ma, and they inferred two distinct magmatic events on that ridge. The younger event could be coeval with that of the tuffs and pyroclastics recovered at Sites 769 and 771. Volcanic material blanketing the ridge is visible on seismic profiles (Rangin, Silver, von Breymann, et al., 1990).

Brown Clay Layer

Just above basement at basin Site 768 lies a brown clay layer, approximately 40 m thick, rich in poorly preserved radiolarians, and intermixed with gray volcanic tuffs (Rangin, Silver, von Breymann, et al., 1990). About 200 m higher in the section, above a pyroclastic unit, the brown claystone reappears, is about 26 m thick, and contains a rich, well-preserved radiolarian fauna (Scherer, Sulu Sea radiolarians, this volume). The brown claystone also occurs above coarse tuff and lapilli tuff at ridge Site 769 (Fig. 2). Radiolarian faunas indicate that the lowermost strata of Sulu Sea and Cagayan Ridge (Sites 768 and 769) were deposited within or below the *C. costata* zone (Scherer, Celebes Sea radiolarians, this volume). Some forms indicative of the *S. wolfii* zone are also present, but are too few to demonstrate the older age with confidence. The age of the basin and ridge at these sites is most likely early Miocene (Scherer, Celebes radiolarians, this volume).

Pyroclastics

Thick sequences of early Miocene tuff and lapillistone were recovered from Sites 768, 769, and 771. In Site 768 of the Sulu Sea, the tuffs are rhyolitic to dacitic and rich in pumice. Thickness of the pure tuff is 200 m in basin Site 768, underlain by 40 m of mixed brown claystone and gray tuff. At Sites 769 and 771, approximately 100 m of andesitic and basaltic coarse tuff and lapillistone were recovered, ranging from calc-alkaline to arc tholeiite in composition. The base of the tuff in each of the Cagayan Ridge sites was not reached. R. Smith (this volume) examined the alteration of the tuffs with depth in each site. He determined a sequence of alteration of the authigenic minerals at Site 768 of smectite > alkali zeolites > analcime with depth. According to R. Smith (this volume), the attributes allowing alteration of the pyroclastics include the thick, low-permeability sequence of mudstones that cover the

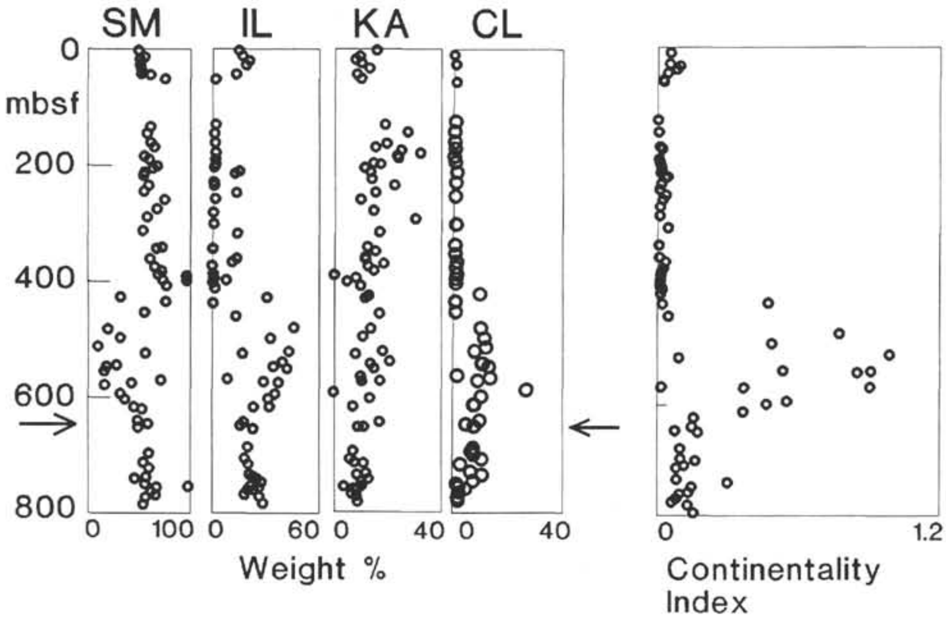

Figure 4. Distribution of clay mineralogy from Site 767 of the Celebes sea, from Rangin, Silver, von Breymann, et al. (1990). SM: Smectite; IL: Illite; KA: Kaolinite; CL: Chlorite; mbsf: meters below sea floor. Continentality index is log[(Sm+Il+Cl)/Sm].

pyroclastics, abundance of volcanic glass, and elevated heat flow.

Fractures

Both the pyroclastics and basement rocks are cut by sets of fractures. The pyroclastics show compaction cracks and extensional normal faults, the latter dipping between 40° and 90° (Rangin, Silver, von Breymann, et al., 1990). In addition, hydrofractures occur in the basalt and diabase, filled with calcite in the upper part of the sequence, and with gypsum and possibly hematite in the lower part. No clear indicator of crack orientation could be discerned from examination of the cores. Kirchoff-Stein et al. (this volume) analyzed borehole televiewer data of the basement rocks from basin Site 768 and determined a preferred direction of high-angle fractures, which trended northwest. They suggested that this orientation could be consistent with flexure of the crust as it is depressed by the Negros Trench.

Turbidites

Siliciclastic turbidites in the Sulu Basin (Site 768) began in the middle Miocene (Zone NN5) with thick-bedded, quartz-rich gravels and sands. During late middle to late Miocene time (Zones NN9–NN10) thin and thick bedded turbidites were derived from two source terranes. One source produced coarser turbidites, with more coated and rounded grains, whereas the other shed thin-bedded turbidites with cleaner quartz grains. The youngest turbidites (Zones NN11–NN18) are thin-bedded, all from quartz-rich sources. Cessation of turbidite sedimentation in the late Pliocene probably corresponded with the onset of subduction in the Negros and Sulu Trenches and a corresponding shift of depocenters into the trenches. Piston cores from the Negros and Sulu Trenches show common siliciclastic turbidites derived from the Philippines (Exon et al., 1981), suggesting that some of the earlier siliciclastic turbidites at Site 768 may have been derived from the same source (Betzler et al., this volume).

Tephrachronology

Systematic tephrachronology (Pubellier et al., this volume) and petrography and geochemistry of altered ash layers (Pouclet et al., this volume) were made to characterize volcanic pulses and to determine their possible origins. Alteration of tephras is marked in both the Sulu Sea and Celebes Sea Basins in a layer dated 3.5–4 Ma (Desprairies et al., this volume). This ash layer may be related to a major tectonic event in the area, such as initiation or renewal of subduction on the Sulu and Cotabato Trenches.

DISCUSSION AND SUMMARY

Our knowledge of the history and evolution of the Celebes and Sulu seas has been greatly improved by the drilling of Leg 124 and post-cruise science. We learned that the Celebes Sea Basin formed in the middle Eocene, initially in an open-ocean setting as seen by its early record of pelagic sedimentation. Paleomagnetic evidence apparently limits any change in latitude of the Celebes Sea to less than about 15°. The spreading rate for the Celebes Sea (Weissel, 1980) was half that of the west Philippine Basin, and its history does not match that of the Indian Ocean. Basement rocks of the Celebes Sea are N-MORB. Compositional trends of turbidites of early Miocene age and younger tie the Sulu and Celebes seas with possible source rocks in Borneo and the Philippines.

These attributes are consistent with splitting of the Celebes Sea crust from an older oceanic basin soon after its formation. They may also be consistent with splitting of the edge of the former China continental margin. Both alternatives have restrictions. If the Celebes Basin split from an open ocean plate, it is unlikely to have been the Philippine Sea or Indian Ocean plates, because of spreading rate, spreading history, and paleolatitude inconsistencies. Such a fragment may have come from the Molucca Sea Plate, which is now nearly subducted, or from a plate north of the Indian Ocean Plate, along a northern spreading center (Daly, 1987). The conjugate part of such a plate probably would have been subducted beneath the Sunda arc.

If the Celebes Basin separated from the former China margin in Eocene time it might have had a history analogous to that of the South China Sea which split off in the Oligocene (Taylor and Hayes, 1983). If so, then the split must have occurred close to the edge of the continental margin, for instance along an outermost borderland basin, in a way that did not restrict open ocean circulation, yet did restrict terrigenous sedimentation from the mainland.

The magnetic inclination data on the sediments of the Celebes Sea is consistent with an origin associated with the China continental margin. Conversely, the evidence for major rotation in the Eocene and Oligocene or rotation of the whole Eocene Oligocene sequence is easier visualized for a fragment separated from a larger plate, than for a plate originating during the opening phase of a rifted margin. The N-MORB composition of basement is consistent with a more mature ocean basin, less so with a rift basin. The sedimentary facies of the Eocene and Oligocene sections demands open ocean circulation, favoring but not requiring the trapped-plate model. Lack of change of clay mineralogy until the influx of turbidites could occur with either alternative, but along with the paleolatitude data, it is consistent with the interpretation that the basin did not move far from its origin.

In summary, an origin for the Celebes Sea as a basin split off from a previously larger Molucca Sea Plate cannot be ruled out. A split from either the west Philippine Basin or the Indian Ocean appears less likely, because the available information concerning those basins shows inconsistent spreading rates, some differences in stratigraphy (west Philippine Sea Basin), differences in spreading history (Indian Ocean), and differences in paleolatitudes (still poorly constrained for the Celebes Sea). Alternatively, an origin by rifting from the outermost part of the East China margin remains a possibility, as long as open ocean circulation was maintained and continental sedimentation was restricted.

The basement of the Sulu Sea apparently formed as a back-arc spreading basin in the early Miocene. Evidence for this interpretation is seen in the transitional geochemistry of the basaltic rocks, the thick volcaniclastic sequence deposited just after the formation of the basin, and the location of the Sulu Sea between the volcanic Cagayan and Sulu Ridges. Several uncertainties were raised by Rangin and Silver (this volume) to this otherwise straight-forward interpretation. They are (1) Although the volcaniclastics are abundant after formation of the basin, they do not interfinger with the basalt flows, as observed in other back-arc basins. (2) The Cagayan Ridge, though capped with volcanic rocks, may have a continental basement, as inferred from possible large basement fault blocks in seismic reflection data and from petrographic and geochemical evidence (Rangin, Silver, von Breymann, et al., 1990). (3) The time of back-arc spreading creating the Sulu Sea coincides closely with that of the last stage of Cagayan Ridge volcanism and with the collision of Reed Bank-Dangerous Grounds with the Palawan-Cagayan Ridge complex (Rangin and Silver, 1990).

In addition to these questions, there remains an additional problem of the polarity of the active island arc at the time the Sulu Sea was formed. Holloway (1982) suggested that the Cagayan Ridge was the active arc. That would explain the collision of Reed Bank-Dangerous Grounds with South Palawan-Cagayan Ridge by collapsing a small ocean basin between them. Rangin (1989) had proposed subduction of the Celebes Sea Basin beneath the south side of the Sulu Ridge, but now disagrees with this interpretation in light of additional seismic evidence along that margin (Rangin, Silver, von Breymann, et al., 1990).

Evidence for some convergence along the north side of Palawan was presented by Hamilton (1979) and Hinz and Schluter (1985). The timing of arc magmatism along the Cagayan Ridge supports the Holloway (1982) hypothesis, although questions remain concerning the degree to which older structures could be discerned along the southern Sulu Ridge. An additional observation is from field geology (Rangin and Muller, unpublished field work, 1990) on Zamboanga peninsula, the northern extent of the Sulu Ridge, which showed that the earliest volcanics are Zone NN5 in age, definitely younger than the age of the Sulu Sea basement or of ages from the Cagayan Ridge (Rangin and Silver, this volume). Despite the uncertainties, the preponderance of evidence at present indicates that the Sulu Sea Basin formed as a back-arc basin behind an active Cagayan arc, ceasing activity concurrently and perhaps as a result of the collision between Reed Bank-Dangerous Grounds and Palawan-Cagayan Ridge.

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