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3. DEVELOPMENT OF THE CELEBES BASIN IN THE CONTEXT OF WESTERN PACIFIC MARGINAL BASIN HISTORY[1]

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ABSTRACT

The Celebes Sea is a marginal basin similar to those found throughout the western Pacific region. These basins represent a number of different origins and histories, including back-arc extension and spreading, entrapment of older crust, formation along collisional plate boundaries, and stretching of the margins of the Australian and Eurasian continents.

The origin of the Celebes Sea is still uncertain. An origin not far from its present location can be inferred from paleomagnetic analysis of the sedimentary sections, which show little evidence of latitudinal change; clay mineral data, which show no change from the red to green claystones; and spreading rate data, which show a factor of two difference between the Celebes Sea Basin and the Philippine Sea Basin. The stratigraphy of the Eocene and Oligocene sediments and comparison of the CCD variation with those of the Pacific Ocean indicate an open ocean origin for the early history of the basin. If the Celebes Sea formed by rifting of the edge of Southeast Asia, it did so in a way that protected the basin from terrigenous input and allowed free interchange with open ocean waters. If, on the other hand, the basin formed originally as part of a larger open ocean basin, such as the Philippine, Indian, or Molucca Sea basins, it has moved less than 15° in latitude from its initial location. The Celebes Sea is presently subducting, as are many of the marginal basins of the western Pacific.

INTRODUCTION

The western Pacific region is characterized by festoons of island arcs and continental fragments that enclose a number of marginal basins (Fig. 1). These features display a variety of structural styles and settings, tectonic activity, sediment thickness, and proximity to active arcs or continental margins. Earlier workers (Karig, 1970, 1971; Packham and Falvey, 1971) viewed the origin of marginal basins solely as a result of back arc spreading. Taylor and Karner (1983) urged caution, however, stressing the non-back-arc nature of the South China (Taylor and Hayes, 1983), Woodlark (Weissel, Taylor, et al., 1982), Coral (Weissel and Watts, 1979) and Tasman Seas (Weissel and Hayes, 1977), and the unknown nature of a number of other basins. We summarize the results of drilling and regional geophysics in the Celebes Sea, compare these results with studies in the South China and west Philippine basins, and tabulate what is known of the timing and rate of development of the other marginal basins in the western Pacific to evaluate the origin of Celebes Sea in a broader context.

ORIGINS OF MARGINAL BASINS

The term "marginal basin" is generally restricted to basins situated marginally to a continent and underlain by oceanic crust (Packham and Falvey, 1971; Taylor and Karner, 1983). Several potential origins have been proposed for marginal basins (Fig. 2), one of which is back-arc spreading (Fig. 2A), as exemplified by the Lau and Mariana basins, initially described by Karig (1971). A second possible origin is extension of the global rift system into a continent (Fig. 2B), as suggested by Weissel and Hayes (1977) for the Tasman Sea and Weissel and Watts (1979) for the Coral Sea.

A third concept, proposed to explain some Southeast Asian basins, is the breakup of the margin of East Asia as a result of India's collision with Asia. Tapponnier et al. (1982) proposed extrusion tectonics in Asia (Fig. 2C), as a model to explain the development of the South China Sea, the Thai and Malay basins, and the Andaman Sea (not shown in Fig. 1).

A fourth concept is entrapment of a fragment of an older ocean basin (Fig. 2D), proposed for the west Philippine (Uyeda and Ben Avraham, 1972), and the Banda, Sulu, and Celebes Seas (Lee and McCabe, 1986). At present, the only marginal basin that can be documented as being a trapped fragment of an older plate is the Bering Sea Basin (Cooper et al., 1976a,b).

A fifth concept, transtensional basin formation by the movement of a major plate past a continental margin, may explain the Andaman Sea (Curray et al., 1982) and the Banda Sea Basins. The latter is composed of an amalgamation of several smaller basins and a displaced continental borderland (Silver et al., 1985).

THE CELEBES SEA BASIN

The Celebes Sea covers an area of 400,000 km^2. It has a mean depth of somewhat over 5 km, a crustal thickness of 6–7 km (Murauchi et al., 1973), and average heat flow of 65 mW/m^2 (Anderson et al., 1978). The basin is bordered on the east by the Sangihe Arc and southern Philippines, on the south by the north arm of Sulawesi, on the west by Borneo, and on the north by the Sulu Archipelago. Subduction zones occur in the northeastern (the Cotabato Trench) and southern (north Sulawesi Trench) parts of the Celebes Basin (Fig. 3).

Magnetic Anomalies A18–A20 have been identified in the basin (Weissel, 1980), and indicate a middle Eocene age. Skewness analysis of the anomalies indicates no significant difference in basin latitude between Eocene and the present (Weissel, 1980). Using the geomagnetic time scale summarized in Berggren et al. (1985), the whole spreading rate indicated by these anomalies is 47 km/m.y.

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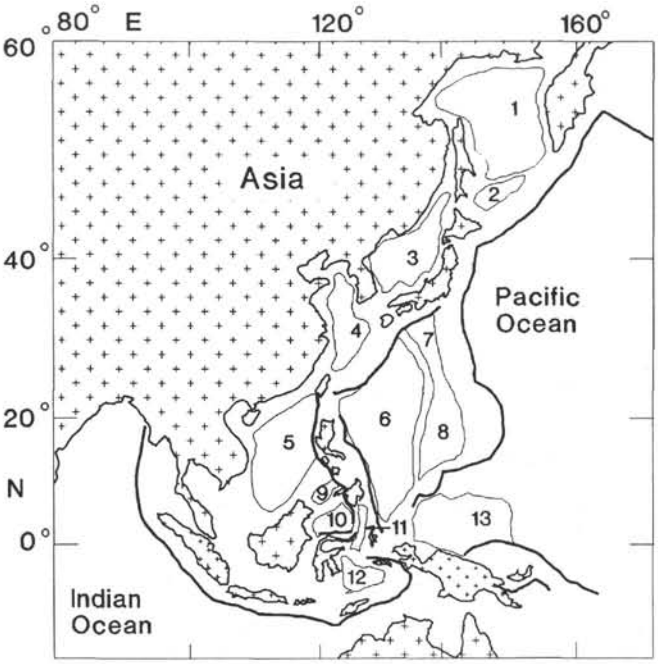

Figure 1. Basins of the northwest Pacific region. (1) Sea of Okhotsk; (2) Kurile Basin; (3) Japan Sea; (4) East China and Yellow seas; (5) South China Sea; (6) west Philippine Basin; (7) Shikoku Basin; (8) Parece Vela Basin; (9) Sulu Sea; (10) Celebes Sea; (11) Molucca Sea; (12) Banda Sea; (13) Caroline Basin.

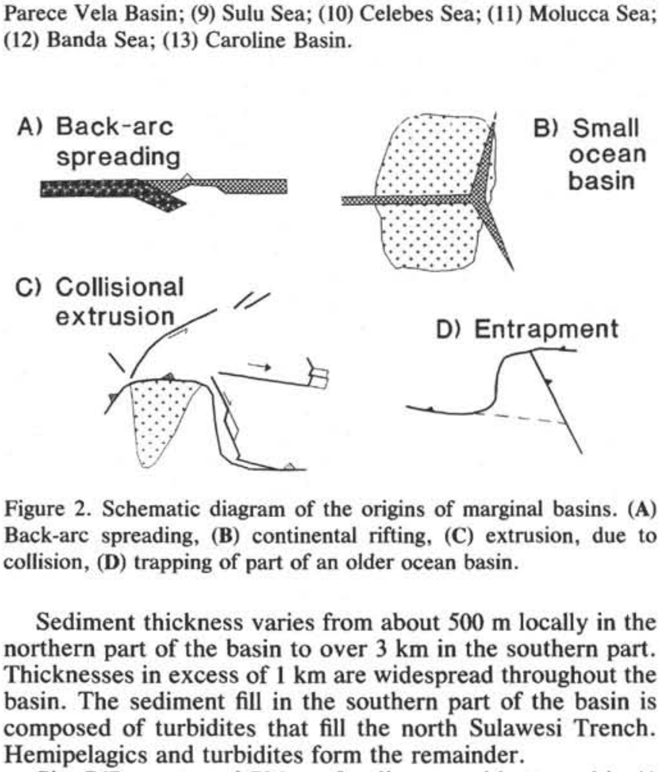

Figure 2. Schematic diagram of the origins of marginal basins. (**A**) Back-arc spreading, (**B**) continental rifting, (**C**) extrusion, due to collision, (**D**) trapping of part of an older ocean basin.

Sediment thickness varies from about 500 m locally in the northern part of the basin to over 3 km in the southern part. Thicknesses in excess of 1 km are widespread throughout the basin. The sediment fill in the southern part of the basin is composed of turbidites that fill the north Sulawesi Trench. Hemipelagics and turbidites form the remainder.

Site 767 penetrated 786 m of sediment and bottomed in 41 cm of pillow basalt (Rangin, Silver, von Breymann, et al., 1990). Site 770, which was offset from Site 767 at a location where the sediment cover was thinner, was spot-cored to 300 mbsf and then cored continuously through 122 m of the lower sedimentary section and 110 m of basaltic basement.

The late Miocene to Pleistocene sequences in the two Celebes Sea sites, 767 and 770, are dominantly hemipelagic deposits derived from a volcanic terrane. They are composed of smectite-rich clay with silt of crystal, vitric, and lithic volcanic material (Fig. 4). Thin layers of ash occur throughout this sequence. The hemipelagic sediments were deposited below the CCD, but calcareous turbidites supplied micro- and nannofossils for dating. Benthic foraminifers, benthic diatoms, and tunicate spines indicate transport from shallow water. Turbidites are rare at Site 770. From late early Miocene to late Miocene the average sedimentation rate was high (109 m/m.y.) with the input of abundant turbidites from continental sources. The sequence is 300 m thick and contains quartz sand and silt, plant debris, and reworked Eocene and lower Miocene nannofossils. The clay in this sequence is dominantly illite (Rangin, Silver, von Breymann, et al., 1990).

The middle Eocene to early Miocene sequence at Site 767 is pelagic, with a sedimentation rate between 2 and 6 m/m.y., a red-brown color, manganese nodules, and a clay composition typical of western Pacific basin sediments (>50% smectite, 25% illite, <10% kaolinite, and <5% chlorite). The deposits overlying basement at both sites contain a radiolarian fauna indicating a late middle Eocene age (42 Ma). Site 770 was apparently close to the CCD during this time, and it contains a large amount of carbonate (mainly discoasters).

Clay mineral distribution at Site 767 can be a useful indicator of the relationship between the red clay unit and the overlying gray-green claystone and siltstone. The lower part of Site 767, from 640 to 786 mbsf, has very uniform clay mineral composition with about 55% smectite, 30% illite, <10% kaolinite, and about 5% chlorite. The continentality index (the log of the sum of smectite plus illite plus chlorite divided by smectite (Rangin, Silver, von Breymann, et al., 1990) is approximately 0.15, with no significant deviation (Fig. 5). The top of the red clay unit lies at 700 mbsf at Site 767, yet the relatively uniform clay mineralogy, just discussed, shows no change until a depth of 640 mbsf. There is a sharp break in the continentality index at 640 mbsf. Thus the change in the cores from red to green clay at 700 mbsf does not represent a change in clay mineralogy. The observations are consistent with the suggestion of Smith et al. (1990), that a slightly greater sedimentation rate in the green clays prevented ferric oxidation. In parallel with this observation, Bertrand et al. (this volume) demonstrated that the organic material at Site 767 is largely of terrestrial derivation, and they noted no change in the character of the organic material across the red/green clay boundary.

Basement was encountered at 786 mbsf at Site 767 and 422 mbsf at Site 770. Tholeiitic pillow basalt was recovered at Site 767, whereas seven flow units were identified at Site 770, where 106 m of basalt were penetrated. The basalt flows are intruded by two dolerite sills near the base of the section. The flows are pillow basalts, breccias, and veined and brecciated basalts. All samples analyzed are tholeiitic, and geochemistry indicates a strong MORB affinity. The volcanic rocks are plagioclase and olivine phyric basalts, with the top flow containing clinopyroxene as well. Vesicles make up 1–15% of the rocks. They are generally 1–3 mm in diameter, spherical, and distributed both randomly and in thin layers. Chemically, the volcanic rocks from Site 770 are tholeiitic basalts, similar to primitive-to-moderately fractionated MORB basalts (Rangin, Silver, von Breymann, et al., 1990).

Magnetic measurements at Sites 767 and 770 do not document any significant change in inclination down the sedimentary sections. Values of calculated paleolatitude determined for Site 767 are scattered over a range of 0° to 15° in the upper 600 mbsf, and range from 0° to 20° below 700 mbsf (Fig. 6). Two values were measured that fall outside of these ranges, one of 42° in the upper section and one of 25° in the lower part. The single value measured on basement material at Site 767

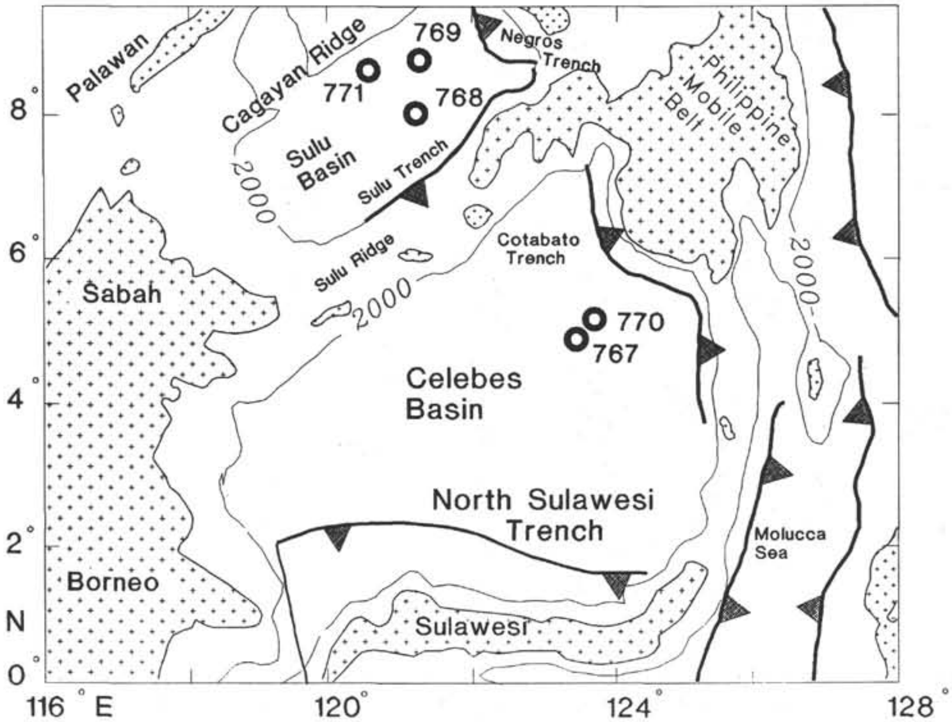

Figure 3. The Celebes and Sulu Seas, showing locations of Sites 767, 768, 769, 770, and 771. Also shown are the major thrusts and island arc systems in the region. Bathymetric contours are in meters.

gave 20°. However, the large age range represented by the red clay section means that it is difficult to rule out the possibility of a 10° or 15° change in latitude caused by data scatter from this section.

The measurements of magnetic inclination in the basement rocks of Site 770 show significantly higher values than those found on the sediments (Fig. 6). Though Site 770 was only spot cored to 350 mbsf, magnetic inclinations cluster very close to 10° from 50 mbsf to 415 mbsf, which corresponds to a paleolatitude of about 6°, equivalent to where Site 770 is today. The basement section gives an average inclination, also very consistent, of about 35°, corresponding to a paleolatitude of 19°. This result could come from a 25° rotation of the basement by block faulting after it was formed, or by a true change in latitude. Although the seismic record (Fig. 7) does not show much dip in the basement reflector, steep dips occur close by. The seismic line was not shot along the dip direction, so a steeper dip is possible.

D. Merrill (written commun. 1990) interpreted the paleomagnetic data as indicating a gradual decrease in paleolatitude with time, from an initial value of 19° in the basement. In addition, Robert McCabe (pers. commun., 1990) suggested that the low inclinations in the sedimentary section could be a result of compacted flattening of the magnetized grains. If the Merrill et al. interpretation is accepted it could imply an origin of the Celebes Sea Basin at a latitude of 19°.

An additional paleomagnetic observation was made by Shibuya et al. (this volume) on the magnetic declinations at Site 767. Using the secondary magnetization to constrain the present field direction, and therefore to orient the samples, Shibuya et al. concluded that the Celebes Sea Basin had rotated counterclockwise between middle Eocene and late Oligocene time. They reoriented the magnetic anomalies mapped by Weissel (1980) and found that the new orientations matched those of the present west Philippine Sea Basin, to

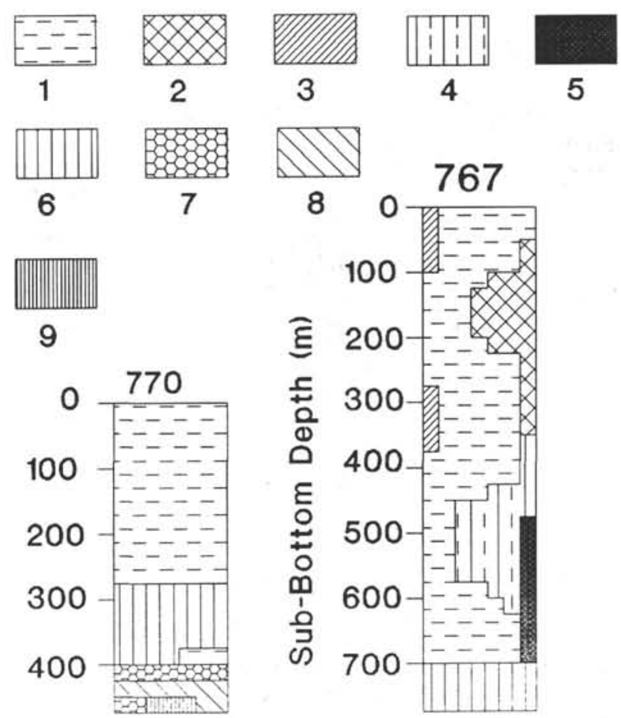

Figure 4. Stratigraphy of the Celebes Sea, Sites 767 and 770. (1) Hemipelagic sediments, including clay/silt(stone); (2) graded carbonate turbidites; (3) fine ash/tuff; (4) terrigenous turbidites; (5) quartz siltstone to sandstone; (6) pelagic brown claystone; (7) pillow basalt; (8) brecciated massive basalt; (9) diabase sill (modified from Rangin, Silver, von Breymann et al., 1990).

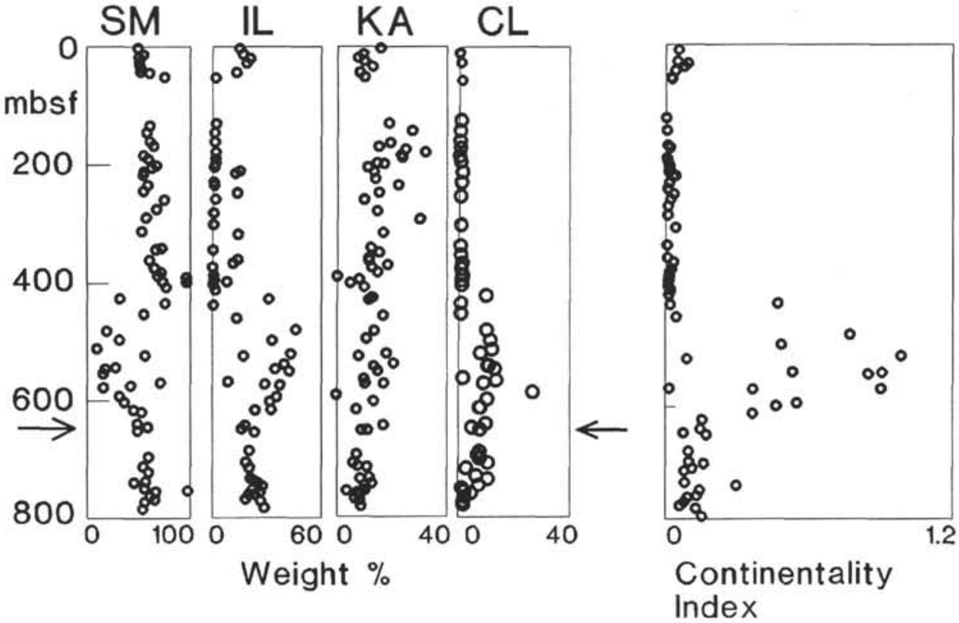

Figure 5. Distribution of clay mineralogy from Site 767 of the marginal basins of the Celebes Sea, from Rangin, Silver, von Breymann, et al. (1990). SM: smectite; IL: illite; KA: kaolinite; CL: chlorite; mbsf: meters below sea floor. Continentality index is log [(SM + IL + CL)/SM].

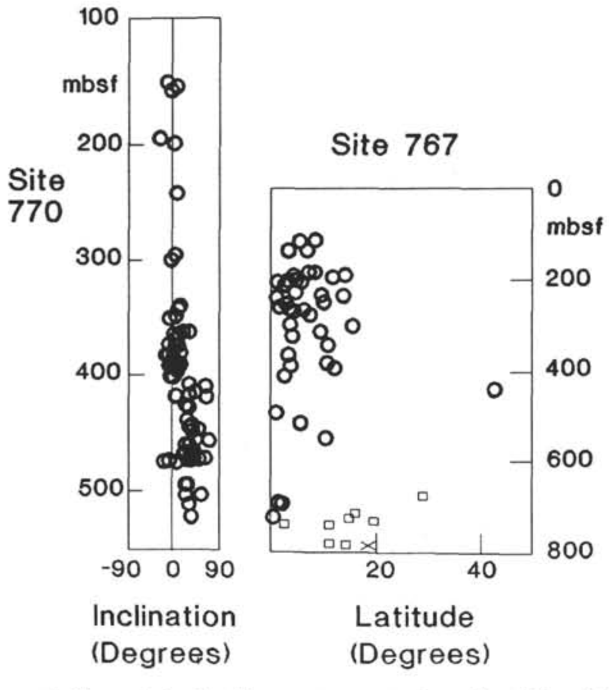

Figure 6. Magnetic inclination measurements from Sites 767 and 770 of the Celebes Sea. For Site 767, circles are measurements from hydraulic piston cores and extended core barrel cores. Squares are measurements from rotary cores, and cross is measurement on basement. For Site 770, all measurements are shown as circles. Basement is at 422 mbsf. (Modified from Rangin, Silver, von Breymann et al., 1990).

which they suggested a correlation. This approach did not consider possible rotation of the west Philippine Sea Basin since middle Eocene, nor did it address the large discrepancy in spreading rates between the two basins.

The Celebes Basin originated in middle Eocene in an environment protected from significant volumes of terrigenous sediment. The preserved organic fraction in the red clays, however, appears to be entirely of terrigenous origin, and the clay mineral composition is indistinguishable from that of the green claystones above. Paleomagnetic inclinations show little if any change in latitude during deposition of the sedimentary section at either Sites 767 or 770, although the latter shows a steeper basement inclination, which could be due either to structural rotation soon after the rocks formed or to a true change in paleolatitude. The basin began to receive abundant terrigenous input in the middle Miocene; the input was decreasing in abundance by late Miocene. Subduction began in late Miocene, as seen by the decrease in turbidite input and increase in volcanic ash component, and the associated trenches and arcs remain active.

THE SOUTH CHINA AND PHILIPPINE SEA BASINS

To evaluate some of the alternative origins for the Celebes Sea Basin, we examine two nearby basins. The South China Sea appears to have originated by rifting of the East Asian continental margin, and the west Philippine Sea Basin represents an older ocean plate from which the Celebes may have been entrapped. Here we review the structure and development of these basins, as well as their stratigraphy, to compare with those aspects of the Celebes Sea Basin.

South China Sea

The South China Sea oceanic crust covers an area of 420,000 km^2, has water depths of 3.7 to 4.4 km, crustal thickness of 6–10 km, and heat flow of 90 mW/m^2. It lies east of the Gulf of Tonkin, south of the China continental margin, and north of the Sunda Shelf (Fig. 1). The northwest and southeast margins of the South China Sea are rifted continen-

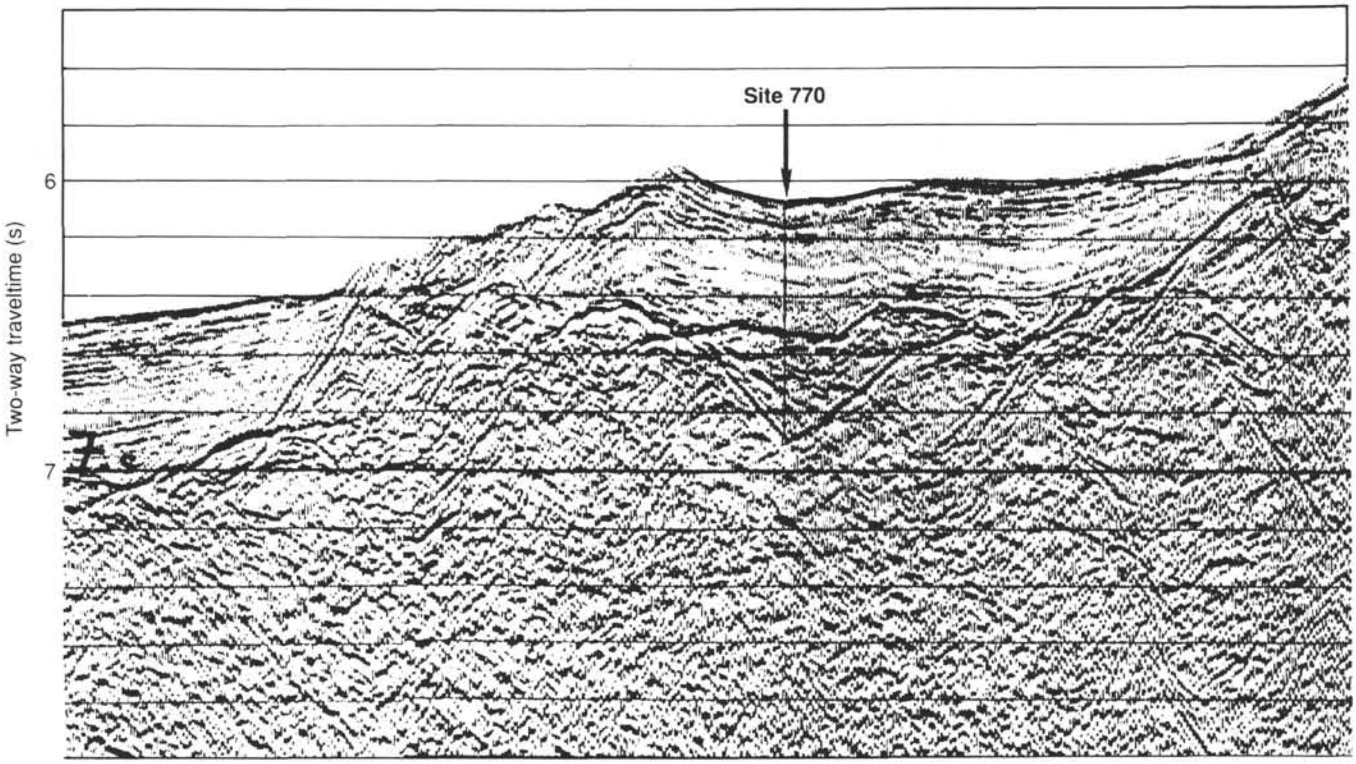

Figure 7. Seismic reflection profile crossing Site 770, migrated time section from Rangin, Silver, von Breymann et al. (1990).

tal margins, whereas the central, triangular region has formed by seafloor spreading (Taylor and Hayes, 1980). The eastern margin of the basin is being subducted beneath the Philippines at the Manila Trench (Lewis and Hayes, 1984).

The formation of the South China Sea Basin occurred in at least two parts. An early rifting phase apparently occurred between the Late Cretaceous and Eocene, as seen by unconformities. Taylor and Hayes (1980) suggested that the initial phase of rifting was Eocene, but this date was disputed by Holloway (1981), who asserted that a Late Cretaceous unconformity is much more widespread. Taylor and Hayes (1983) deferred to Holloway's interpretation, stating that only local unconformities were important in the Eocene. Hinz and Schluter (1985) studied seismic reflection data, dredges and industry wells on Reed Bank. There a marine transgression is recorded by thin, shallow water, late Paleocene limestones covering Triassic sedimentary and igneous rocks. The limestones were deposited during an episode of block faulting. Thus a late Paleocene age of rifting of the east China margin is a likely possibility.

The next stage of formation began in the middle Oligocene (32 Ma) with the initiation of spreading in the central part of the South China Sea. The spreading episode continued until 17 Ma, after which the spreading center jumped from an east-west trend to northeast-southwest, coincident with the Scarborough seamounts in early to middle Miocene time, according to Pautot et al. (1986). The rate of spreading was about 50 km/m.y. in the period 30–20 Ma, based on compilations by Taylor and Hayes (1980; 1983).

The sediment thickness is 500 m in the center of basin and at least 1200 m in the south. Biogenic clays make up the surface sediments (Taylor and Hayes, 1980), and the modern sediments consist largely of coarse silt-sand composed of turbidites, contourites, and debris flows. Very rare occurrences of sediments devoid of terrigenous input are localized on trench or bank slopes (Damuth, 1980). The stratigraphic history shows non-marine to very shallow marine sedimentation from late Mesozoic through mid-Oligocene. By early Miocene the basin was largely formed, and deep-sea deposits had begun to accumulate. The early Miocene carbonate deposition off Palawan was smothered by a middle Miocene clastic influx.

The South China Sea is not a back-arc basin, according to Taylor and Hayes, 1980; 1983). Tapponnier (1982) suggested that it originated as a lateral rift formed by the extension of blocks moved eastward by the India-Asia collision. The movement was taken up as left-lateral slip along the Red River Fault. The age of activity along the fault zone seems to agree with an Oligocene opening of the basin, but not with the late Paleocene initial rifting of the China margin.

West Philippine Basin

The west Philippine Sea Basin covers an area of 1,300,000 km^2. It is bounded on the west by the Philippine and Ryukyu trenches and on the east by the Palau-Kyushu ridge (Fig. 8). In the northern part of the basin an inactive spreading ridge separates the Oki-Daito and Daito topographic ridges from the Benham Rise in the west central part of the basin. The abyssal depths of the northern part of the west Philippine Sea Basin reach 6 km, whereas in the southern part of the basin they are about 5.6 km (Mrozowski et al., 1982). Radiolarian red clays and volcaniclastic sediments, 50–100 m thick, mantle the northern part of the west Philippine Sea Basin, whereas 200 m of sediment cover the southern part of the basin.

Magnetic anomalies 16–20 have been identified in the basin by Louden (1977), Watts et al. (1977), and Mrozowski et al. (1982). These magnetic anomalies are consistent with an age of formation of the basin from 50–37 Ma. The average spreading rate indicated by these magnetic anomalies is 93 km/m.y.

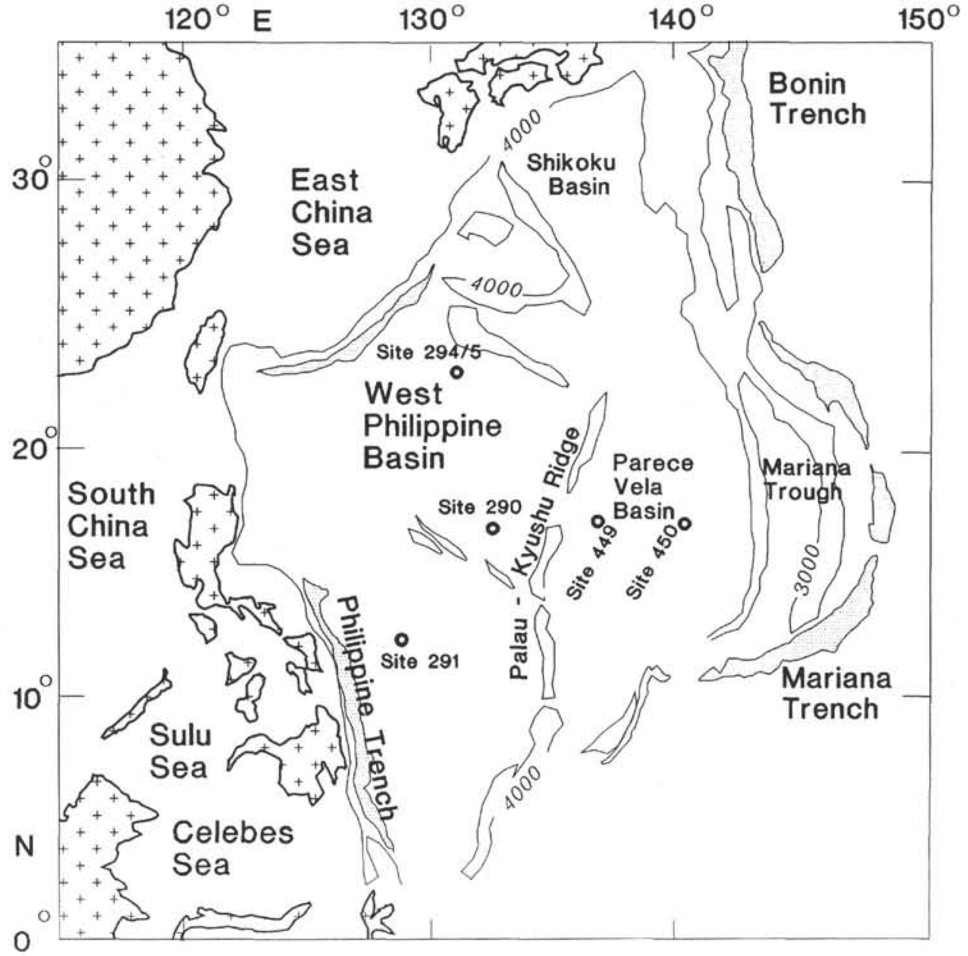

Figure 8. Location of the Philippine Sea region, showing detail of the west Philippine Basin, the Shikoku-Parece Vela Basin, and the Mariana Trough. Also shown are locations of those DSDP Sites in the Philippine Sea that are discussed in text.

Crustal thickness in the west Philippine Basin varies between 5 and 7 km (Hayes et al., 1978; Louden, 1980). Heat flow averages 90 mW/m^2 (Anderson et al., 1978), and gravity values lie between ± 30 mgal (Watts et al., 1978). Paleomagnetic studies by Kinoshita (1980) on sediments drilled in the basin indicate approximately 2000 km of northward displacement of the basin since the middle Eocene. It is unclear whether the west Philippine Basin was formed by back-arc spreading (Seno and Maruyama, 1984; Jolivet et al., 1989) in the Eocene, or by later entrapment of a piece of Pacific Plate (Uyeda and Ben Avraham, 1972; Hilde and Lee, 1984). The northwest trend of the magnetic anomaly pattern is oblique to the Palau-Kyushu Ridge. In addition, Hilde and Lee (1984) called attention to the greater size of the west Philippine Sea Plate than that of most back-arc basins, although the north Fiji Basin is not much smaller. Jolivet et al. (1989) made a good geometrical case for spreading behind a since-rotated Philippine arc, with the Oki Daito and Amani plateaus as remnant arcs. Seno and Maruyama (1984), on the other hand, suggested an origin by spreading behind the Palau-Kyushu ridge.

DSDP Site 291 in the southwestern part of the west Philippine Sea Basin reached basaltic basement below Eocene nannofossil- and radiolarian-rich silty clay and ferruginous zeolite rich clay. The late Eocene to early Oligocene sediments are radiolarian and nannofossil clayey ooze, the Oligocene is clay-rich nannofossil ooze, and the Neogene a dark yellow-brown silty clay. The sedimentation rate for this section was just over 4 km/m.y., very similar to that of the pelagic section of Site 767, discussed above. Site 291 was devoid of volcanic ash, which indicates a formation far removed from active arc volcanism. Site 290, adjacent to the Palau-Kyushu Ridge, is much richer in volcanic components, with a volcanic conglomerate at the base, and clay-, nannofossil-, and radiolarian-rich ash throughout the section above. Sites 294/295 in the northwestern part of the basin contained indicators of ash in the section as well.

Shikoku-Parece Vela Basin

The Shikoku-Parece Vela Basin (Fig. 8) lies between the Kyushu-Palau Ridge and the West Mariana-South Honshu Ridge (Watts and Weissel, 1975; Mrozowski and Hayes, 1979). It occupies an area of 1,300,000 km^2, and lies at an average water depth of 4.5 km. Free-Air gravity varies smoothly from 0 to 25 mgal (Watts et al., 1978), crustal thickness is 8 km (Hayes et al., 1978) and heat flow values are between 105 and 125 mW/m^2 (Anderson et al., 1978). The oldest recognizable magnetic anomaly in the basin is Anomaly 6B (Chamot-Rooke et al., 1987), (late Oligocene age, 30 Ma), and the youngest is Anomaly 5A (12 Ma). The average spreading rate is 40 km/m.y. (Chamot-Rooke et al., 1987).

Chamot- Rook et al. suggested that the basin first underwent late Oligocene E-W rifting that was followed by early Miocene NE-SW oriented spreading.

The magnetic anomalies in the Shikoku and Parece Vela basins generally trend parallel to the ridges (the South Honshu and Palau-Kyushu ridges that bound the Shikoku Basin, and west Mariana and Palau-Kyushu ridges that bound Parece Vela Basin). In addition, the inactive spreading centers within these basins are centrally located, all of which is consistent with a back-arc spreading origin of the basins that split the bounding ridges. This process is occurring presently to the east in the Mariana rift zone, where active back-arc spreading has split the Mariana arc and west Mariana ridges (Karig, 1971; Hussong, Uyeda et al., 1981). Incipient rifting also occurs between the Bonin arc and the south Honshu Ridge (Honza and Tamaki, 1985; Tamaki, 1985).

DSDP Site 449 in the eastern Parece Vela Basin (Fig. 8) reached basaltic basement of late Oligocene age beneath a nannofossil ooze. The early Miocene deposits were dark-yellow brown pelagic clay with ash layers, pumice fragments, and manganese nodules. Radiolarian and nannofossil ooze with ash layers compose the middle Miocene, and dark-brown pelagic clay forms the upper part of the section. Site 450 in the western Parece Vela Basin recovered approximately 250 m of vitric tuffs above basaltic basement, all of middle Miocene age. Dark yellow-brown, ash-rich pelagic clay forms the upper 83 m of the section. The basalt in both sites are chemically N-MORB in composition (Kroenke, Scott et al., 1981), but the abundance of ash at the base of the section near a likely remnant arc (the Palau-Kyushu Ridge) supports an origin by back-arc spreading.

AREAL DEVELOPMENT OF WESTERN PACIFIC MARGINAL BASINS THROUGH TIME

We have examined the temporal history of development of the marginal basins floored by oceanic crust in the western Pacific region (Table 1 and Fig. 9). The sources for the input data are referred to in Table 1. We determined the growth rate of each basin by dividing the basin area by the duration of activity, constrained in most cases by magnetic anomalies. For several of the basins (South China Sea, west Philippine Basin, and Shikoku Basin) we split their activity into two

Table 1. Ages, areas, and growth rates in the western Pacific marginal basin.

Basin name	Age Ma	Area	Growth Rate**	References
1. Japan	18–14	0.35	0.087	1,2,3
2. Okinawa	0–2	0.11	0.055	4,5,3
3. Kurile	18–14?	0.11	0.027	6,7
4. S China	32–23	0.21	0.0255	8,9
5. S China	23–16	0.21	0.03	8,9,10
6. SE Sulu	19–15	0.07	0.0175	11,12
7. Celebes	50–42	0.41	0.051	3,11,13
8. W Philippine	55–47	1.33	0.166	3,14,15,16,17
9. W Philippine	47–39	0.8	0.1	3,14,15,16,17
10. Shikoku	26–20	0.15	0.025	3,18,19,20,21
11. Shikoku	20–15	0.12	0.024	3,18,19,20,21
12. Parece Vela	30–17	0.92	0.071	3,18,19,20,21
13. Mariana	3–0	0.24	0.08	22,23
14. Caroline	36–28	1.3	0.162	3,24,25,26
15. Tasman	82–60	2.2	0.1	27,28
16. Coral	62–56	0.31	0.052	29
17. New Caledonia	65–60?	0.3	0.06	30,31
18. Woodlark	3–0	0.13	0.043	32,33
19. South Fiji	34–26	0.71	0.089	34,30
20. New Hebrides	55–42	0.3	0.023	35,30
21. North Fiji	8–0	1.0	0.125	34,36,37,38
22. Lau-Havre	3–0	0.5	0.163	39,40
23. Manus	3–0	0.12	0.04	41
		$*\times 10^6$ km^2	$**\times 10^6$km^2/m.y.	

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28. Weissel et al., 1977
29. Weissel and Watts, 1979
30. Andrews, Packham et al., 1975
31. Burns, Andrews et al.,1973
32. Weissel, Taylor, et al., 1982
33. Taylor and Exon, 1987
34. Malahoff et al., 1982
35. Weissel, Watts, et al., 1982
36. Auzende, Lafoy, et al., 1988
37. Auzende, Eissen, et al., 1988
38. Chase, 1971
39. Sclater et al., 1972
40. Lawver et al., 1976
41. Taylor, 1979

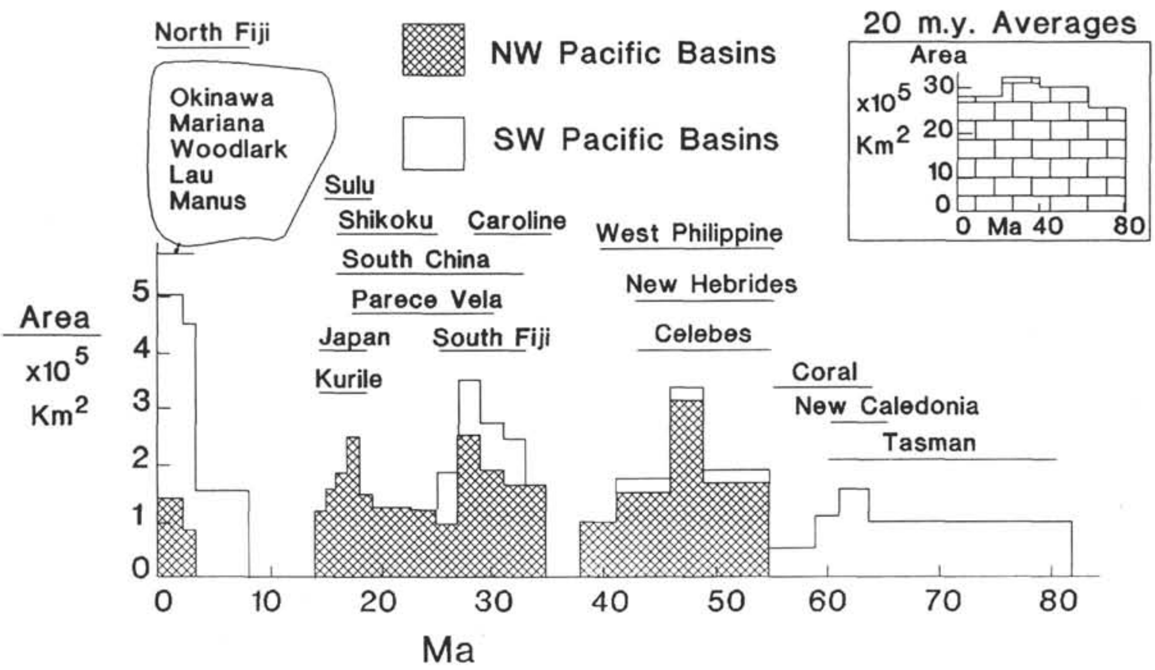

Figure 9. Plot of crustal area vs. age for marginal basins of the western Pacific region. Heavy solid lines show age ranges for individual basins (from Table 1), whereas histograms below show the aggregate ages for all the basins. Inset on the right gives a plot of crustal area vs. age for marginal basins of the western and southwestern Pacific region, using 20-m.y. averages.

periods. This procedure gives the area accreted by each basin per million years. We have also grouped the basins into western Pacific and southwestern Pacific basins for comparison.

The distribution of activity in the southwestern Pacific marginal basins falls into three major groupings: 0–8 Ma, 25–35 Ma, and 55–80 Ma. The youngest grouping is much more widespread than that for the western Pacific, because of the activity in the Bismarck, Lau-Havre, Woodlark, and north Fiji basins. The 25–35 Ma interval is a result of activity in the South Fiji Basin, and the oldest interval is a combination of the Tasman, Coral, New Caledonia, and New Hebrides basins. The peak at 60–65 Ma is due to seafloor spreading in the New Caledonia Basin, but it is not well dated. The continued low activity from 40–55 Ma results from opening of the New Hebrides Basin, whose effect may in fact have been greater, depending on how much of the basin has been destroyed by subduction in the creation of the north Fiji Basin.

The activity in the western Pacific is more concentrated in the periods 15–35 Ma and 40–55 Ma. Very young (0–3 Ma) spreading has occurred also in the Mariana and Okinawa troughs. A striking aspect of the western Pacific marginal basins is the apparent absence of activity between 3 and 14 Ma. This period followed the cessation of spreading in the South China, Sulu, and Japan seas, and is prior to the activity of the modern spreading basins. The southwestern Pacific also has a hiatus in new crustal generation from 9–25 Ma. This appears to be the longest quiet period during the past 80 Ma. Two periods of no reported formation of marginal basins in either the western or southwestern Pacific regions are from 9–14 Ma and 36–38 Ma. Because the older basins are more poorly constrained, we have less confidence in the 36–38 Ma hiatus than of the younger one.

There is a weak suggestion of peak activity in the western Pacific approximately every 15 Ma (Fig. 9). The 60-Ma peak is wholly from the southwestern Pacific, the 45-Ma peak largely from the western Pacific, the 30-Ma peak from both, the 17-Ma peak only from the western Pacific, and the modern peak from both regions. The amplitude of the highest peak in the last 5 Ma relative to the other peaks may be misleading because there is less precision in dating the older basins, a greater focus on actively spreading basins, and a loss of area of older basins by subduction. If we average the area vs. time for all basins into 20-Ma age groupings (Fig. 9), we find that although the formation of marginal basins may be episodic, during the past 80 Ma the averaged aggregate rate of basin formation in the western Pacific has been essentially constant.

Uncertainty in these graphs include measurement error, which should be similar for most of the basins, dating error, which is variable, and destruction of area of some of the basins by subduction on one or more of their margins. Examples are the Japan Sea (Tamaki and Honza, 1984), the New Hebrides Basin (Weissel, Watts, et al., 1982), the Celebes Sea Basin (Weissel, 1980; Silver, McCaffrey, et al., 1983), the South China Sea Basin (Taylor and Hayes, 1983; Lewis and Hayes, 1984), the west Philippine Sea Basin (Lewis and Hayes, 1983), the Sulu Sea Basin (Hinz and Block, 1990), the Caroline Basin (Ryan and Marlow, 1988), the Banda Sea (Hamilton, 1979; Silver, Reed, et al., 1983), and the Woodlark Basin (Taylor and Exon, 1987). Many of these have suffered only small amounts of seafloor loss, such as the Japan Sea, but others, such as New Hebrides and Celebes Basins, may have lost significant area to subduction.

The time of development of both the Celebes (55–42 Ma) and Sulu (19–15 Ma) basins fall on peaks of basin development (Fig. 9). The Sulu Basin formed during the last phases of activity in the South China, Japan, and Shikoku-Parece Vela basins. The Celebes Basin formed concurrently with the west Philippine and New Hebrides basins. The New Hebrides Basin was probably too far removed during the Eocene to have had any effect on the formation of the Celebes Sea, but the west Philippine Basin would have been nearby.

DISCUSSION OF THE ORIGIN OF CELEBES SEA BASIN

Three alternative origins for the Celebes Sea Basin are: a fragment of an older ocean basin, a back-arc basin, or a basin rifted from the Southeast Asian continental margin. If part of a larger basin, possibilities are the northern Indian Ocean, the west Philippine Basin, or the Molucca Sea. No crust of Eocene age has been drilled in the Indian Ocean, so we cannot make direct comparisons with the drilling results. Spreading rates indicated by magnetic anomalies of Eocene age in the Philippine Sea Basin (Louden, 1977; Watts et al., 1977; Mrozowski et al., 1982) are faster (about 93 km/m.y.) by a factor of two than those of the Celebes Basin (45 km/m.y., Weissel, 1980). In addition, both the Indian Ocean and Philippine Sea Plates have moved great distances relative to the magnetic poles, in contrast to the Celebes Sea, which shows little evidence of such motion throughout the sedimentary column.

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.

Sedimentation in the west Philippine Basin is similar in the Eocene and Oligocene to that of the Celebes Sea, although most sites have a higher content of volcanic ash in the red clay section, as well as a significant amount of nannofossils (Ingle, Karig et al., 1975). The basement depth of the west Philippine Basin is greater than that of Celebes (5.6–6 km for west Philippine vs. 5 km for Celebes). While not totally ruling out an origin relating the Celebes Basin to either the Philippine Sea or Indian Ocean, these hypotheses fail several tests.

The Molucca Sea may have originally been part of the Celebes Basin (Fig. 3). The Sangihe arc, which separates the Molucca and Celebes Seas, may have developed on an ancient transform fault within the combined basin (Daly et al., 1987). The advantage of this hypothesis is the proximity of Celebes Basin to the Molucca Sea, and such a connection was suggested by Daly et al. (1987). Unfortunately, the idea is not easily testable, as the Molucca Sea Plate is nearly completely subducted.

An origin for the Celebes Sea Basin by rifting of the Southeast Asian margin (Rangin et al., 1990) is consistent with paleomagnetism (Weissel, 1980; Shibuya et al., 1989; Merrill et al., this volume; Rangin, Silver, von Breymann et al., 1990), as well as with clay mineral data and organic chemistry in some of the cores. These sedimentologic observations support previous arguments (Weissel, 1980) against a far-traveled Celebes Sea. Perhaps as an outer borderland basin it was protected from significant input of continental sediment.

An argument against a continental margin origin of the Celebes Sea is the retrieval of basalt of N-MORB composition from Site 770 (Rangin, Silver, von Breymann et al., 1990), indicating true oceanic magma genesis. We note, however, that basalts of N-MORB composition were also recovered from the west Philippine Basin, Shikoku Basin, and from the center of the Lau Basin, indicating that marginal basins may have crustal compositions very similar to those of major ocean basins (Hawkins, 1976).

We do not favor an origin for the Celebes Sea related to the Indian Ocean or west Philippine Basin because the spreading history and rates in those basins are not consistent with observations in the Celebes Basin. Also, paleomagnetic data on the sediments in the Celebes Sea indicate little apparent change in latitude with time, unlike the data from the Philippine Sea and Indian Ocean. Basement samples from Site 770 in the Celebes Sea give a paleolatitude of 19°, which could indicate either a rotation of the basement block or a real change in latitude.

A change in sediment type from pelagic red clay to hemipelagic green claystone in the Celebes Sea appears not to coincide with differences in clay mineral compositions and ratios, indicating that the color change does not represent a major difference in sedimentary environment. Absence of change in clay mineral provenance and abundance of terrestrial organic matter in the red clays are consistent with a more local origin of the basin, as opposed to a far-traveled origin, but clay mineralogy does not provide quantitative constraints on the amount of movement.

The available evidence suggests that the Celebes Sea Basin has not moved more than about 15° relative to Southeast Asia since its inception. Possible analogous basins are the Coral Sea, which differs by having a high carbonate content in the lower sediments and a higher rate of clay sedimentation than Celebes (Andrews, Packham et al., 1975), or the South China Sea, which has not been drilled. With the presently available evidence we favor an origin for the Celebes Sea as either a basin rifted from the East Asian margin, or one trapped from a once much larger Molucca Sea Plate.

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