5. GEOPHYSICAL SETTING OF THE SULU AND CELEBES SEAS[1]

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INTRODUCTION

The far western Pacific and Southeast Asia region is characterized by the large number of small ocean basins that lie between mainland Asia and the Pacific basin (Mammerickx et al., 1976). These small ocean basins include the Mariana Trough, the Parece Vela and Shikoku basins, and the west Philippine Basin. Together they comprise the Philippine Sea Plate and the South China Sea, the Sulu Sea, the Celebes Sea, and the Banda Sea, which separate Asia from the Philippine Archipelago, Indonesia, and New Guinea (Fig. 1). Numerous hypotheses, based on marine geophysical observations, regional plate kinematic constraints, and regional geological considerations, have been advanced for the tectonic evolution of these small ocean basins. Most proposed models for the origin of these basins fall into one of three general categories:

1. Origin by extension related to subduction and island arc rifting,
2. Origin by extension and rifting of continental margins, or
3. Origin by the entrapment of fragments of major ocean basin lithosphere during plate boundary reorganizations.

Leg 124 of the Ocean Drilling Program set out to determine the age, stratigraphy, state of stress, and paleoceanography of two of these basins, the Sulu Sea and the Celebes Sea, by directly sampling their sediment and underlying igneous crust to address questions related to their origin, tectonic evolution, paleoceanographic history, and the history of the tectono-stratigraphic terranes adjacent to them.

The scientific questions Leg 124 sought to answer were posed largely on the basis of a suite of geophysical observations from the Sulu and Celebes Seas. Thus, this study will discuss the regional geophysical observations to establish the context within which to interpret the Leg 124 drilling results.

CELEBES SEA

Bathymetry

The Celebes Sea lies north of the island of Sulawesi (Celebes), and separates Mindanao, the southernmost major island of the Philippines (to the east) from Borneo (to the west). See Figure 1. The north arm of the island of Sulawesi (Celebes) lies to the south of the Celebes Sea, and the Sulu Archipelago and the Zamboanga Peninsula of Mindanao form the northern edge of the basin. The Celebes Sea is characterized by very steeply sloping margins, with water depths increasing rapidly from very narrow shelves. The deepest portion of the Celebes Sea is the northeastern corner of the

basin adjacent to Mindanao, where water depths exceed 5700 m in the Cotabato Trench (Mammerickx et al., 1976). ODP Sites 767 and 770 were drilled in the eastern part of the basin, seaward of the Cotabato Trench. Another deep, the North Sulawesi Trench, extends parallel to the north arm of Sulawesi (Celebes) and reaches water depths of nearly 5500 m. Active earthquake seismicity associated with both the Cotabato and North Sulawesi trenches documents active subduction along these margins of the Celebes Sea (Hayes and Taylor, 1978; Hamilton, 1979).

Most of the floor of the Celebes Sea lies at water depths between 4500 m and 5500 m, suggesting that this basin is likely underlain by oceanic crust of Paleogene age, based on observed age/depth relationships in major ocean basins (Hayes, 1988).

Crustal Structure and Heat Flow

Six marine seismic refraction experiments have been conducted in the Celebes Sea (Murauchi et al., 1973; Ludwig et al., 1979), and are compiled by Hayes et al. (1978). Three experiments were two-ship reversed refraction profiles that detected acoustic signals to depths greater than 9 km below the seafloor, and three were conducted using expendable free-floating sonobuoys. The velocity/depth plots of these refraction stations are shown in Figure 2.

The results from all six refraction experiments in the Celebes Sea show a remarkable consistency. Near-surface sediments are characterized by refraction velocities of between 1.7 and 2.1 km/s, consistent with shipboard sediment velocity measurements at Site 767C of 1.83 to 2.06 km/s (Rangin, Silver, von Breymann, et al., 1990). Velocities increase to between 3.5 and 5.0 km/s between 2 and 3 km below the seafloor. Crustal velocities between 5.3 and 6.4 km/s appear between 3.5 and 5.0 km sub-seafloor, with a thick layer of 6.4 to 6.9 km/s from between roughly 4.1 to 5.0 km below the seafloor. Two refraction stations detected arrivals from the Moho, with velocities of 7.9 and 8.5 km/s.

The observed distribution of refraction crustal velocities from the Celebes Sea indicate that the crustal structure of the Celebes Sea falls within the range attributed to oceanic crust as measured in major ocean basins. These observations indicate that the Celebes Sea is likely composed of oceanic crust and not foundered continental or island arc crust. This conclusion is supported by data from heat-flow measurements in the Celebes Sea. Twelve shallow heat-flow measurements are reported from the Celebes Sea by Anderson et al. (1978). Nine of these twelve measurements are classified as either good- or excellent-quality measurements. The average heat flow of the nine most reliable heat-flow measurements is 58.2 mW/m², with an average thermal conductivity of 0.7788 W/m·K. These observations are in reasonable agreement with the results from Site 767, where a near-surface thermal conductivity of 0.865 W/m·K was determined from shipboard samples, with a calculated heat-flow value of 62 mW/m² for the depth interval of 0–298 mbsf (Rangin, Silver, von Breymann, et al., 1990). A
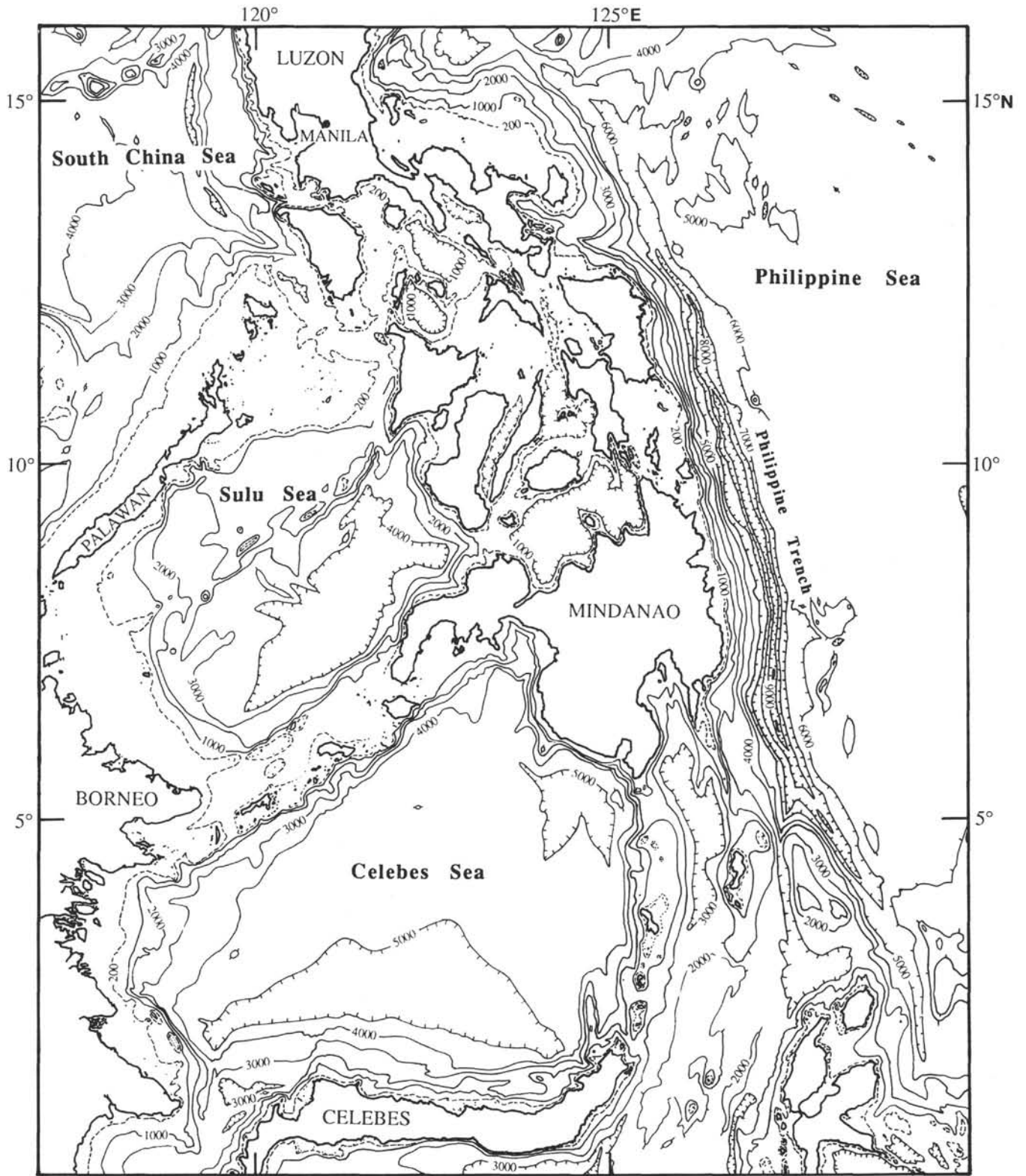
Figure 1. Bathymetry of the Celebes and Sulu Seas, modified from Mammerickx et al., (1976).

Celebes Sea

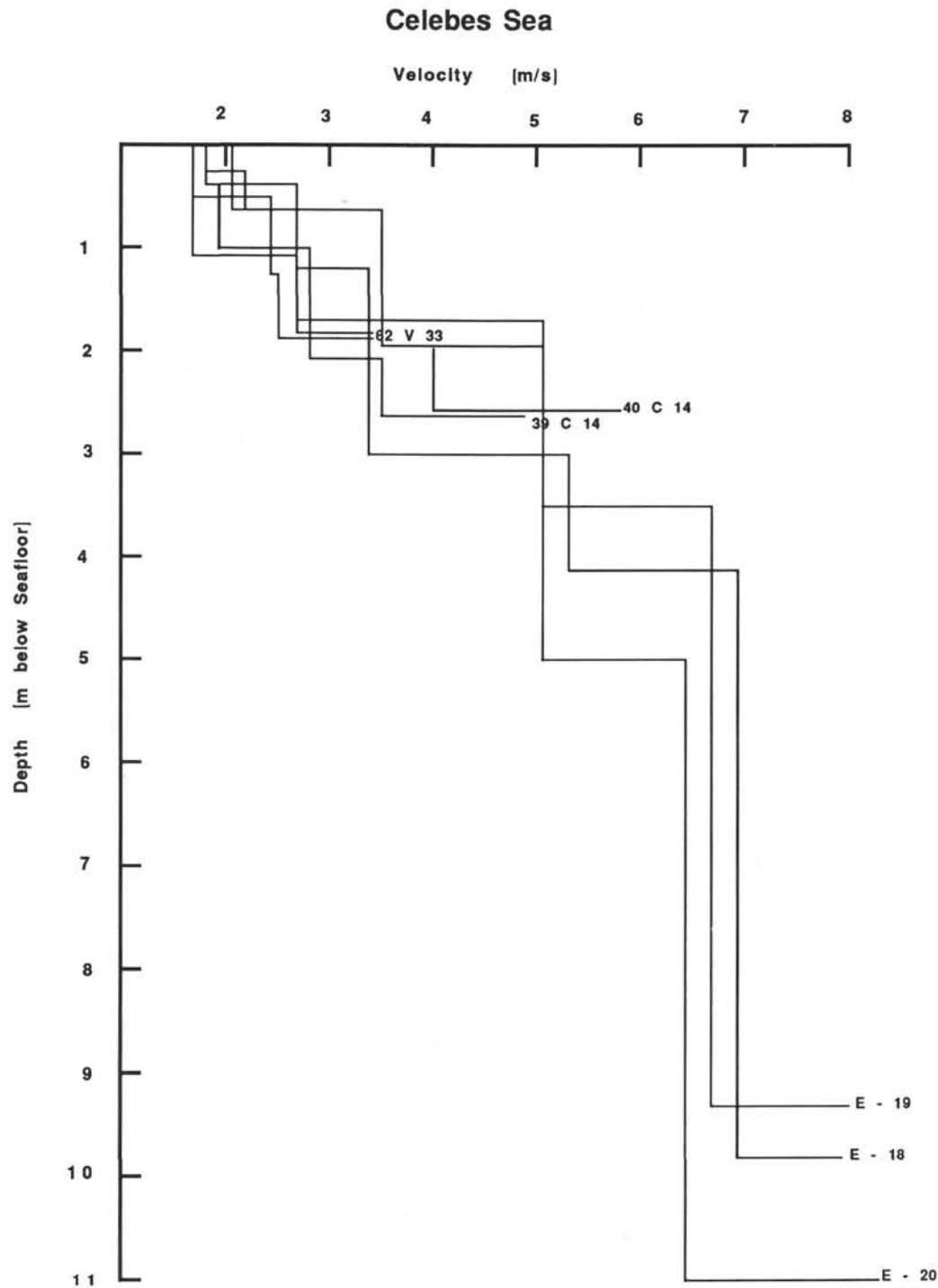Figure 2. P-wave seismic velocity vs. depth plot for six refraction experiments conducted in the Celebes Sea. A remarkable consistency of measured oceanic crustal structure is indicated by the plot.

similar thermal conductivity average value for the near-surface sediments was determined at Site 770 (Rangin, Silver, von Breymann, et al., 1990).

Gravity

The free-air gravity field of the Celebes Sea (Fig. 3) closely follows the bathymetric patterns of the basin, as is typical of many regions of oceanic crustal structure. The main part of the Celebes Sea is characterized by gravity anomalies of +25 mgal to +50 mgal. The Cotabato Trench region in the northeast portion of the basin is associated with negative gravity anomalies of −90 mgal to −100 mgal, reflecting the mass deficit that results from the basement topography of the subducting Celebes Sea lithosphere. Similarly, a linear negative gravity anomaly of up to −90-mgal amplitude corresponds to the North Sulawesi Trench.

The west Philippine Basin, east of the Philippines and the Philippine Trench, which is roughly the same age as the
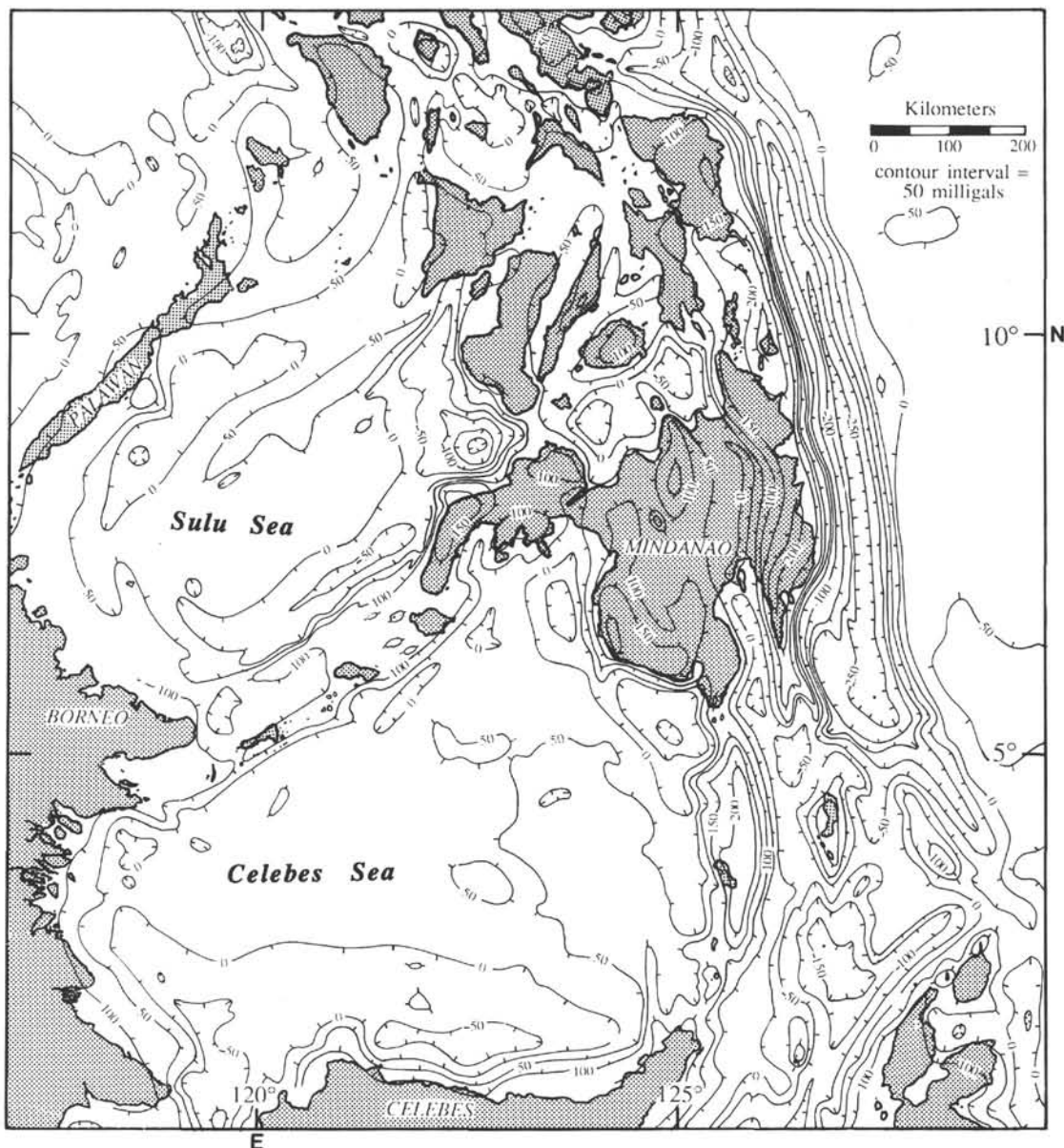
Figure 3. Free-air gravity field of the Celebes and Sulu seas (Watts et al., 1978).

Celebes Sea, shows a gravity field of typically 25 mgal to −25 mgal (Watts et al., 1978), while the Celebes Sea shows base values that are considerably higher. One explanation of this difference is that because of its much smaller size, the Celebes Sea is much more strongly effected by the influence of the flexure of the oceanic crust seaward of the Cotabato and North Sulawesi trenches prior to subduction than is the west Philippine Basin. The west Philippine Basin shows positive gravity anomalies of up to +115 mgal amplitude over the flexural peripheral bulge seaward of the Philippine Trench despite its much lower average gravity field strength. Assuming a value for the flexural rigidity of the Eocene Celebes Sea oceanic crust similar to that of the Eocene west Philippine Basin crust, and hence a similar wavelength of the trench outer bulge, as is suggested by the gravity field of the two regions (Watts et al., 1978), the effects of the peripheral bulges of the Cotabato and north Sulawesi trenches reach almost all of the small Celebes Sea, and serve to elevate the average

observed gravity field strength relative to that of the much larger, but similar aged, west Philippine Basin.

Magnetics

One of the central objectives of scientific drilling in the Celebes and Sulu seas was to sample and date igneous basement to verify the ages of the two ocean basins inferred on the basis of marine magnetic anomaly models (Rangin, Silver, von Breymann, et al., 1990). Two models for the seafloor-spreading history of the two basins have been proposed for the region prior to drilling: The first, a model suggesting that the Celebes Sea is of Eocene age (Anomalies 18 to 20) was proposed by Weissel (1980) (Fig. 4). The second model suggested that Anomalies 30 through 33 were present in the Celebes Sea, suggesting a Late Cretaceous age for that basin (Lee and McCabe, 1986); (Fig. 5), and Anomalies 17 through 19 in the Sulu Sea, suggesting an Eocene age for that basin.
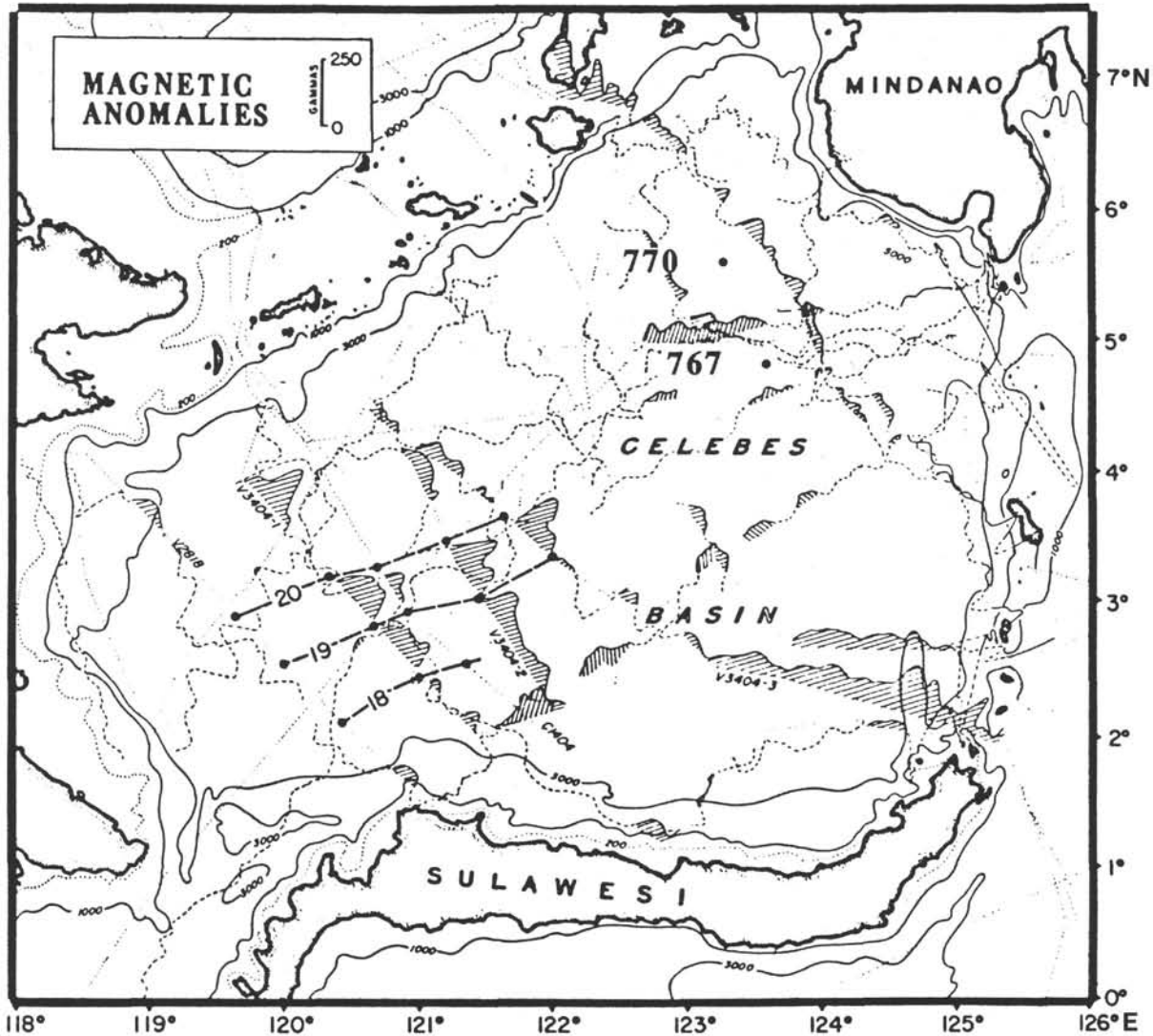
Figure 4. Magnetic anomaly identification in the Celebes Sea by Weissel (1980), showing seafloor-spreading Anomalies 18 through 20 in the western part of the basin.

Because both the Celebes and Sulu Seas are relatively small ocean basins, there is only a small portion of the geomagnetic reversal sequence preserved in the magnetic anomaly patterns of the basins. Short anomaly sequences are notoriously difficult to uniquely correlate with the global reversal sequence, allowing significantly different interpretations of the same magnetic observations. Hence, direct age-dating of the basement in the Celebes and Sulu seas is necessary to distinguish between the two magnetic models proposed for the basins. Fortunately, the predicted age differences between the two models are large enough that drilling is likely to be able to reliably ascertain which (if either) magnetic model was consistent with paleontologic age-dating of the basin.

Drilling results in both the Celebes and Sulu seas are inconsistent with the magnetic model of Lee and McCabe (1986). The Celebes Sea basement is dated at middle Eocene (Site 767) to late middle Eocene (Site 770), consistent with Weissel's (1980) magnetic anomaly identification (Fig. 4). Weissel, however, did not identify the magnetic anomalies in the Sulu Sea. The age-dating of the deep portion of the Sulu Sea at Site 768 indicates an age of late-early to early-middle Miocene (Rangin, Silver, von Breymann, et al., 1990), rather than the Eocene age predicted by the Lee and McCabe (1986) magnetic anomaly identification.

SULU SEA

Bathymetry

The bathymetry of the Sulu Sea (Fig. 1) is more complex than that of the Celebes Sea to the south. Whereas the Celebes Sea is characterized by a broad central region of very low slope and similar topographic slopes around its margins, the bathymetry of the Sulu Sea is much more variable. The Sulu Sea comprises three distinct regions; a deep southern area, the southeast Sulu Basin; the shallow southeast-trending Cagayan Ridge that bisects the basin between Panay to the northeast and Borneo to the southwest; and the northwest Sulu Basin between the Cagayan Ridge and Palawan Island. The southeastern portion of the Sulu Sea, adjacent to the Sulu Ridge, reaches water depths in excess of 4800 m in the inactive (Hamilton, 1979) Sulu Trench. The Negros Trench borders the northeastern flank of the Sulu Basin adjacent to Negros Island; here the water depths reach about 4400 m. ODP Sites 768 and 769 were drilled in the southeast Sulu Basin.
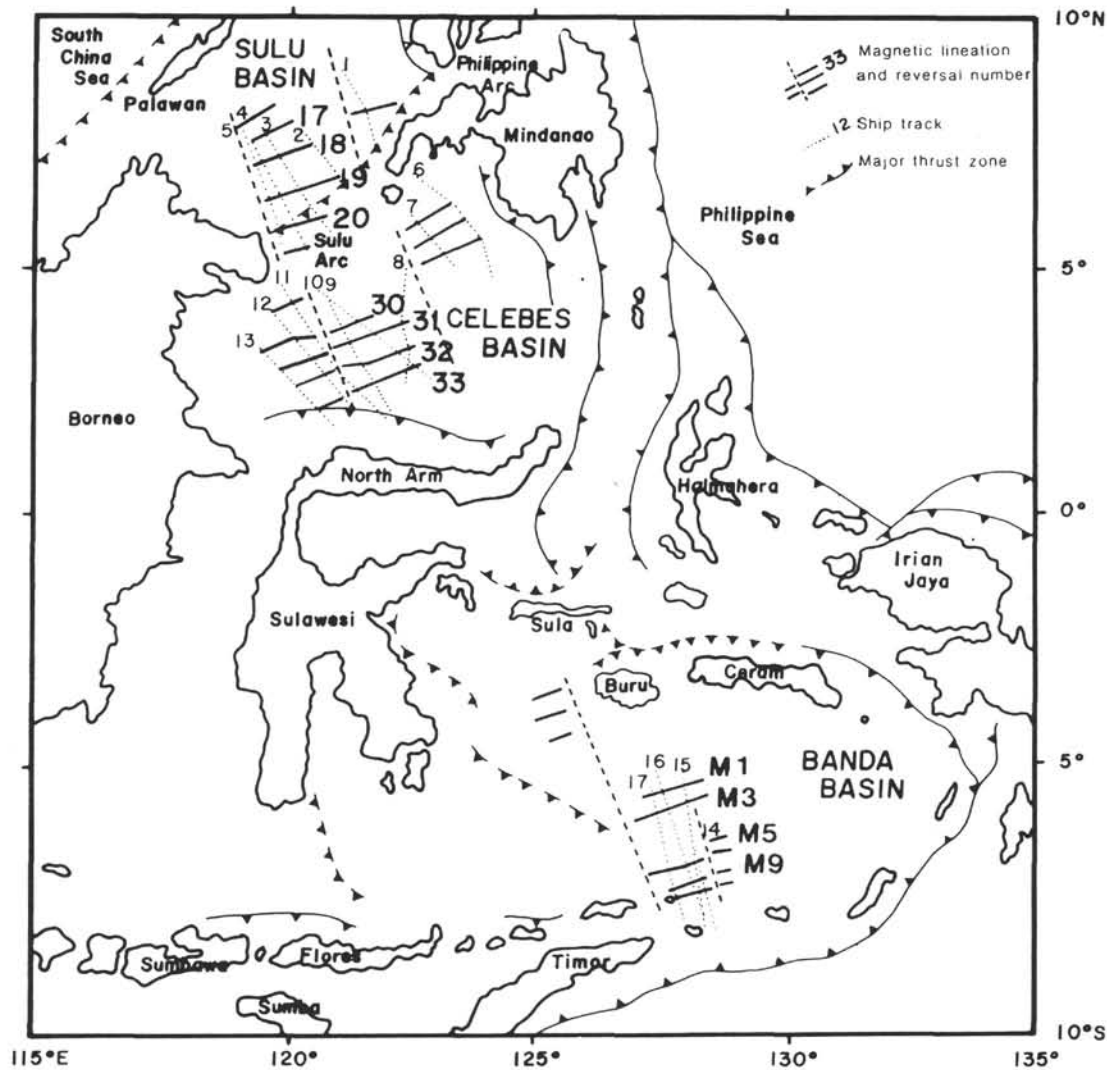
Figure 5. Magnetic anomaly identification in the Celebes, Sulu, and Banda Seas by Lee and McCabe (1986). Compare this magnetic model with that of Weissel (1980; Fig. 4).

Carbonate-topped banks of the Cagayan Ridge reach up to the sea surface in a few locations, while the average depth of the Cagayan Ridge is roughly 750 m. ODP Site 771 was drilled on the southern flank of the Cagayan Ridge. The northwest Sulu Basin exhibits an irregular pattern of water depths (Fig. 1). The northeastern portion of the basin is characterized by relatively shallow water depths, typically between 1000 and 2000 m. To the southwest a large embayment with water depths in excess of 2000 m extends in a northerly direction from the Cagayan Ridge to the southern coast of Palawan. This deep region of the northwest Sulu Basin is adjacent to and along-strike of a possible terrane boundary or suture zone on the island of Palawan that separates Paleozoic strata of continental affinity to the northeast from melange units and ophiolite assemblages of Tertiary age to the southwest (Hamilton, 1979).

The Sulu Sea contains broad shelf regions of water depths less than about 200 m adjacent to Borneo on its southwestern flank and on its northern flank, between northern Palawan and Mindoro Island. This shallow portion of the northwest Sulu Basin is thought to be underlain by continental fragments exposed on both Palawan to the west and Mindoro to the east (Hamilton, 1979; Sarewitz and Karig, 1986).

Crustal Structure and Heat Flow

The crustal structure of the Sulu Sea (Fig. 6) is much more variable than that of the Celebes Sea. Whereas the velocity/depth relationship of the refraction stations in the Celebes Sea showed very little variability (Fig. 2), there is a great deal of scatter in the data from the Sulu Sea.

The refraction results from the deep southeast Sulu Basin (Profile E-16, Fig. 6A) indicate an oceanic crustal structure similar to that seen in the Celebes Sea, with a prominent crustal layer roughly 4.5 km thick with a velocity of about 6.4 km/s, overlain by sediment with velocities between 2.0 and 3.5 km/s. In marked contrast, Profile E-15, from the northwest Sulu Basin, exhibits a much thicker sequence of low-velocity strata, with observed velocities of only 5.6 km/s at depths as great as 10 km below the seafloor (Fig. 6B). This strongly suggests that the northwest Sulu Basin is not underlain by "normal" oceanic crust, but that the crust of the southeast Sulu Basin could be primarily oceanic in nature.

Profile E-17 (Fig. 6A), acquired on the northern flank of the Sulu Ridge, shows a crustal structure intermediate between the oceanic southeast Sulu Basin and the anomalously thick northwest Sulu Basin. This refraction profile, with its thick layer of 6.2 km/s, underlain by a 7.2-km/s layer, is similar to crustal structure results from other island arcs.

The heat flow measured in the Sulu Sea is as variable as the crustal structure. The northwest Sulu Basin is characterized by heat-flow values averaging to 62.38 mW/m^2 (Anderson et al., 1978), while the Cagayan Ridge shows an average heat flow of 73.69 mW/m^2, roughly 18% higher than further north. A total of 47 heat-flow measurements from the deep part of the Sulu Sea, the southeast Sulu Basin (Nagasaka et al., 1970; Sclater et al., 1976; Block and Steinmann, 1988a; 1988b), compiled by Hinz and Block (1990), indicates an even higher heat flow, an average of 115 mW/m^2, more than 80% higher than the northwest Sulu Basin. No heat-flow estimates were made during drilling in the Sulu Sea on Leg 124.

Gravity

The gravity field of the Sulu Sea is characterized by relative gravity minima around the edges of the basin (Watts et al., 1978), and by a prominent gravity high along the crest of the Cagayan Ridge (Fig. 3). The gravity low associated with the Negros Trench reaches a value of −207 mgal south of Negros Island, and gradually increases to the north toward the deformation zone on Panay Island. The inactive Sulu Trench is marked by a linear gravity anomaly of roughly −50 mgal to −85 mgal, a significantly smaller anomaly than that associated with the actively-subducting Negros Trench. Stress measurements conducted during Leg 124 Rangin, Silver, von Breymann, et al., 1990) suggest that plate convergence along the Negros Trench influences the stress orientation within the Sulu Sea lithosphere, consistent with the inference from the observed free-air gravity anomaly pattern.

DISCUSSION AND CONCLUSIONS

The results of scientific ocean drilling during Leg 124 compliment the pre-existing geophysical observations made in the Celebes and Sulu Seas. Inferences regarding the ages and tectonic origins of the ocean basins, largely indeterminant on the basis of geophysical data alone, were effectively resolved and augmented by drilling. The combination of available data provide the observational foundations for well-constrained models of the tectonic evolution of the region to be proposed (Rangin and Silver, this volume).

Additionally, the combination of scientific drilling and geophysical observations provide important explanations for apparently contradictory data, such as age/heat-flow and age/depth relationships (Lee and McCabe, 1986). The direct observation afforded by drilling, combined with the remote but geographically distributed geophysical observations, represent a powerful basis for addressing the tectonic evolution of complex regions of the world oceans such as the Southeast Asian region drilled during ODP Leg 124.

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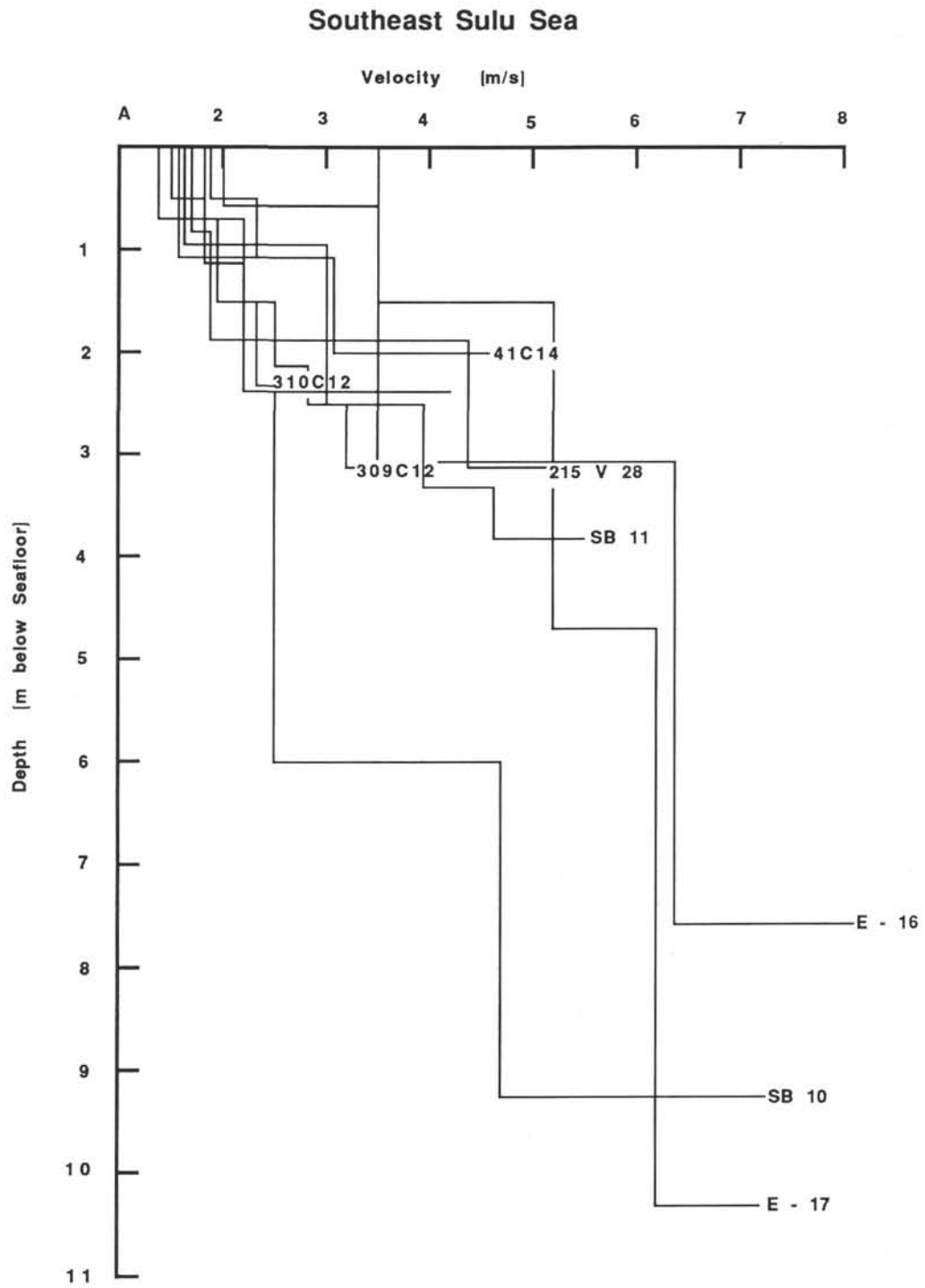
Figure 6. **A.** *P*-wave seismic velocity vs. depth plot for eight refraction experiments conducted in the southeast Sulu Sea. A remarkable consistency of measured oceanic crustal structure is indicated by the plot. **B.** *P*-wave seismic velocity vs. depth plot for 18 refraction experiments conducted in the northeast Sulu Sea. Upper crustal velocity structure is remarkably consistent, but deeper velocities and layer thicknesses are variable.

Northwest Sulu Sea

Velocity   [m/s]

Figure 6 (continued).