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

24. AGE OF THE CRUST OF THE SOUTHEAST SULU SEA BASIN BASED ON MAGNETIC ANOMALIES AND AGE DETERMINED AT SITE 768[1]

H. A. Roeser[2]

ABSTRACT

Magnetic measurements from marine and airborne geophysical surveys show east-northeast-striking lineated anomalies in the southeast Sulu Sea Basin. A seafloor spreading model was developed that indicates an age of 15 Ma for the oceanic crust at Ocean Drilling Program Site 768. Radiolarian ages near the base of the sedimentary sequence at Site 768 give an approximate age of 17 Ma. The age discrepancy might be due to the inaccuracies inherent in both methods and to sediment transportation by turbidites.

According to the magnetics model, it is likely that the Sulu Sea Basin started to open at 30–35 Ma (early Oligocene) with 0.6 cm/yr half-spreading rate. Spreading continued until at least 10 Ma (early upper Miocene). Most of the oceanic crust is already subducted.

INTRODUCTION

This paper presents magnetic anomaly data in the southeast Sulu Sea Basin and a seafloor spreading model interpretation. Possible causes for an apparent age discrepancy of 1.5 m.y. between the model and biostratigraphic ages at Site 768, and inferences, are discussed.

MAGNETIC ANOMALIES

Although the water depth strongly suggests oceanic crust for the southeast Sulu Sea Basin, the magnetic anomalies are very weak and not well lineated, so not easy to interpret in terms of seafloor spreading. The best lineations are observed between 7°N and 9°N, 121°E and 122°E. Figure 1 shows the magnetic anomalies from two data sets.

The western part of Figure 1 is covered by an aeromagnetic survey of the U.S. Naval Oceanographic Office (U.S. Naval Oceanographic Office, 1988). A regular grid of north-south lines with a line spacing of 11 km was flown. Every 55 km there is a tie line in the east-west direction.

The USNOO provides a residual chart of the survey that contains only 50-nT contours. This is not dense enough for the investigation of the existing weak anomalies, and therefore the map is not shown here. For the present study it is important that the map indicates north-south-trending faults at the longitudes 120°00′E and 120°50′E. The one at 120° might be a transform fault, however, other interpretations seem possible.

There are shipborne lines obtained during the *Valdivia* cruise VA-16 in 1977 and the *Sonne* cruises SO-23 in 1982 and SO-49 in 1987. The marine data are reduced with the IGRF for the time of the survey, the coefficients are from IAGA (1988).

Shipborne magnetic data near the magnetic equator suffer from the strong and in part latitude-dependent variations of the magnetic field. They were reduced with a method developed especially for the neighborhood of the magnetic equator (Roeser and Bargeloh, 1988). For the *Valdivia* data records of the Davao geomagnetic observatory were used; for the other cruises, records of a temporary monitoring station near Roxas on the Philippine island Palawan were used. Although difficult to assess with the few available crossovers, we estimate from comparable data in the Dangerous Grounds area of the South China Sea (Roeser and Bargeloh, 1988) that the remaining errors are mostly less than 20 nT.

Figure 1 shows N 80°E-trending magnetic anomalies in the investigated area. They are clearly not parallel to Palawan, the Cagayan Ridge, and the Sulu Archipelago. The mean amplitude of the observed anomalies is only 100 nT. This is surprisingly weak for seafloor spreading anomalies. Low-amplitude seafloor spreading anomalies (200 nT) are associated with large areas of the oceanic crust in the South China Sea (Taylor and Hayes, 1983). Thus the small anomaly amplitude is not a severe argument against a seafloor spreading origin of the anomalies, given that the global variations of seafloor spreading anomaly amplitudes are poorly understood. We know only from unpublished data (*Sonne* cruise SO-49) from the South China Sea that there the anomaly amplitudes are reduced in areas with rough basement.

Only two refraction seismic lines exist in the Sulu Sea (Murauchi et al., 1973). One of them lies in the southeast Sulu Basin. It shows a crustal structure similar to that of oceanic crust, as described by Harrison and Bonatti (1981). Below a thin sediment cover there is a 2-km-thick layer with 3.46 km/s velocity overlying a 4-km-thick layer with 6.41 km/s velocity. Below that layer a mantle velocity was observed, namely 8.28 km/s.

Altogether there is no reason to doubt that the crust of the southeast Sulu Basin is oceanic in character. Then the magnetic anomalies indicate an approximate north-south spreading direction. This is supported by the north-south striking offset of the magnetic anomalies at 120°50′E.

THE CRUSTAL AGE AT SITE 768

A reliable identification of the magnetic anomalies was hopeless without any indication of the age of the crust. ODP Site 768 provided the necessary information by Leg 124 drilling through the sediment cover and 221.8 m into the basement (Shipboard Scientific Party, 1990b).

The sequence above the basement was divided into five strati-graphic units. The lowermost Units IV and V consist largely of pyroclastic rocks. In spite of their thickness of 240 m they may have been emplaced during a geologically short time interval.

[1]Silver, E. A., Rangin, C., von Breymann, M. T., et al., 1991. *Proc. ODP, Sci. Results,* 124: College Station, TX (Ocean Drilling Program).

[2] Bundesanstalt für Geowissenschaften und Rohstoffe, Stilleweg 2, D-3000 Hannover 51, Federal Republic of Germany.

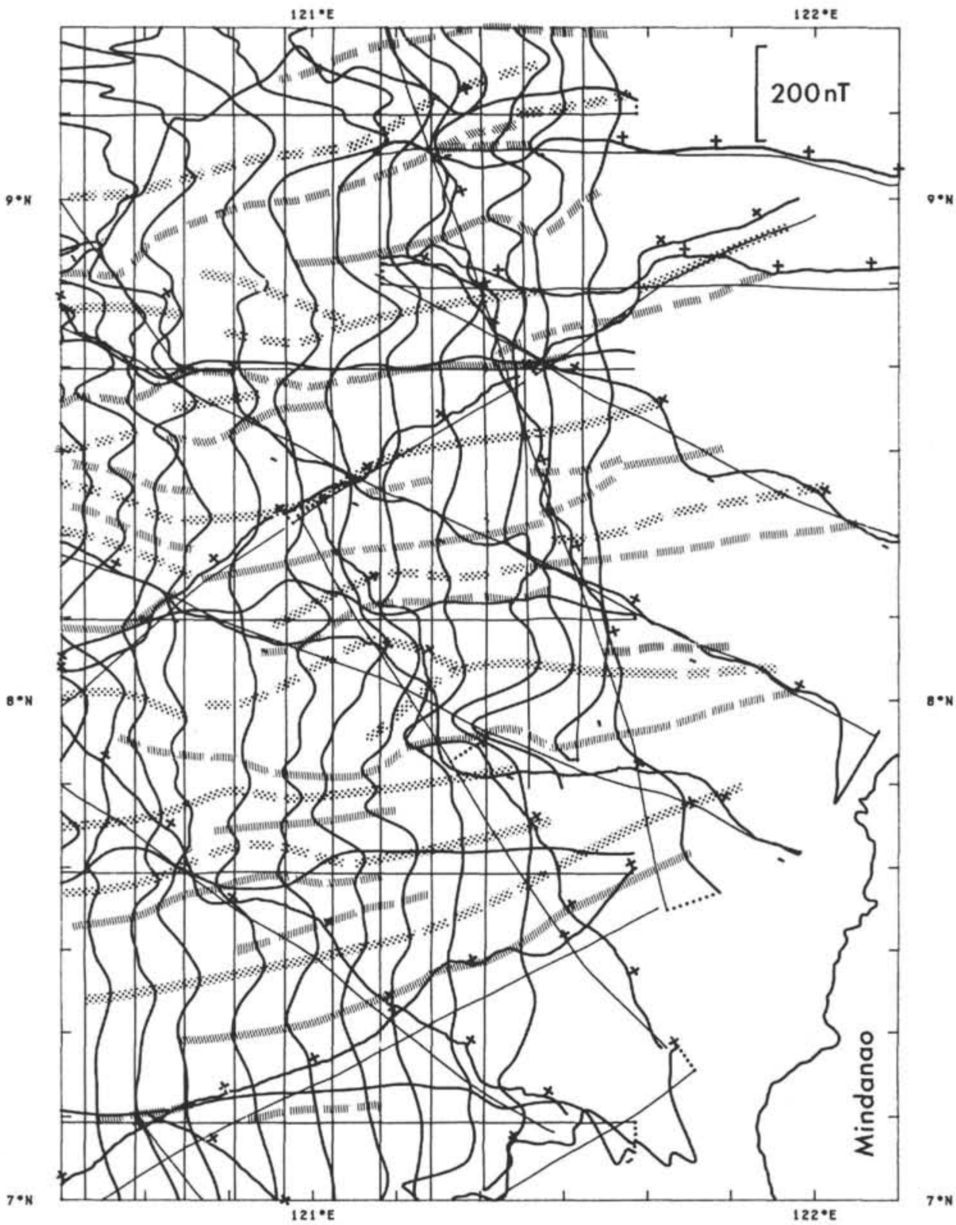

Figure 1. Total intensity magnetic anomalies in the southeast Sulu Sea Basin from an aeromagnetic survey by the U.S. Naval Oceanographic Office and from surveys by the research vessels *Valdivia* and *Sonne*. The magnetic anomalies are plotted perpendicular to the ship tracks.

In Core 124-768C-47R at 800 m below seafloor (mbsf) a radiolarian assemblage is found that is consistent with the *Calocycletta costata* Zone. A sample from Core 124-768C-48R, 104–106 cm near the top of Unit IV (806.6–1003.6 mbsf) is consistent with the base of the *C. costata* Zone. The core-catcher section of 124-768C-48R contains radiolarians that define the boundary between the *Calocycletta costata* and the *Stychocorys wolffii* Zones. Radiolarians from Sections 124-768C-69R-CC through 124-768C-72R-CC at the base of Unit V (1003.6—1046.6 mbsf) are difficult to date, they may belong to the range *S. wolffii* down to the *C. tetrapera* Zone. Other datable fossils are not observed below Core 124-768C-40R-4.

According to the Leg 124 biostratigraphic standard (Shipboard Scientific Party, 1990a) the boundary between *C. costata* and *S. wolffii* lies at 17.3 Ma. This indicates a crustal age of at least 17–18 Ma for the crust at Site 768. The composition of the basement is said to be compatible with a back-arc-spreading origin.

SEAFLOOR SPREADING MODELS

Using this fixed point, a sequence of models for magnetic seafloor spreading anomalies were computed for a wide range of spreading rates. At six sites in the northern Philippines, Fuller et al. (1983) carried out paleomagnetic investigations of Miocene rocks and found that the directions are similar to the present field. Although this does not prove the same for the southeast Sulu Sea Basin, the present inclination (0°) and the present declination (0°) were used. This is in agreement with Taylor and Hayes (1983), who also used the present directions for their South China Sea models.

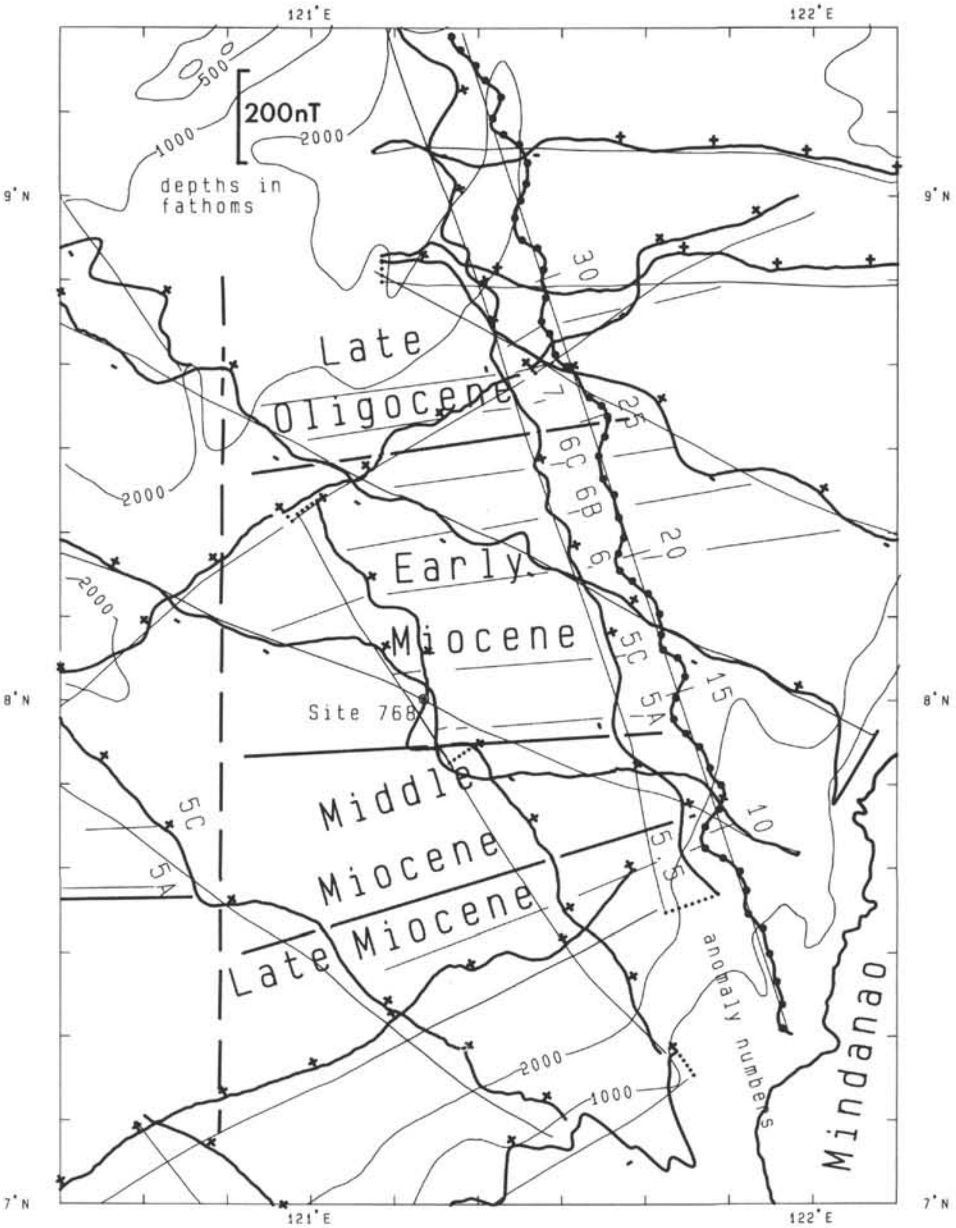

Figure 2. Total intensity magnetic anomalies from surveys by the research vessels *Valdivia* and *Sonne*. The reversal time scale for the model (line with dots) is by Berggren et al. (1985). Magnetization is 1.5 A/m parallel or antiparallel to the present field; thickness of the magnetic layer is 1 km; spreading rate is 0.6 cm/yr.

All models with half-spreading rates greater than 1.5 cm/yr show wavelengths that are too long to match the anomalies. A remarkably good correlation is achieved with the half-spreading rate 0.6 cm/yr (Fig. 2). In contrast to Figure 1 the lines of the USNOO aeromagnetic survey are omitted because their inclusion would complicate the Figure without changing the interpretation.

This model brings Site 768 into the lower part of Anomaly 5B. The time scales by Harland et al. (1982) and by Berggren et al. (1985) give an anomaly age of 15.5 Ma at the site. Thus there is a discrepancy of at least 1.5 m.y. between the magnetic and the radiolarian age.

Certainly the magnetic anomalies are not clear enough to exclude any other age assignments. However, if we make the simplest assumption of a constant spreading rate over the whole range of the lineated anomalies, the assignment is unique. If we allow several changes of the spreading rate, many models become possible.

It is often argued that slow spreading cannot produce high-fidelity seafloor spreading anomalies. However, that is not generally true. In the central part of the Red Sea at 17°N, seafloor spreading is active since about 5 m.y. with a half-spreading rate of 0.75 cm/yr (Roeser, 1975). In spite of a strong asymmetry of the spreading, in a segment of 100 km axis length the pattern is extremely regular and the width of the injection zone is only about 2 km.

Unfortunately, our Red Sea survey was not accompanied by reflection seismic data. The bathymetry of the young crust gives some information on the basement. It does not show a correlation between the size of the topographic relief and the

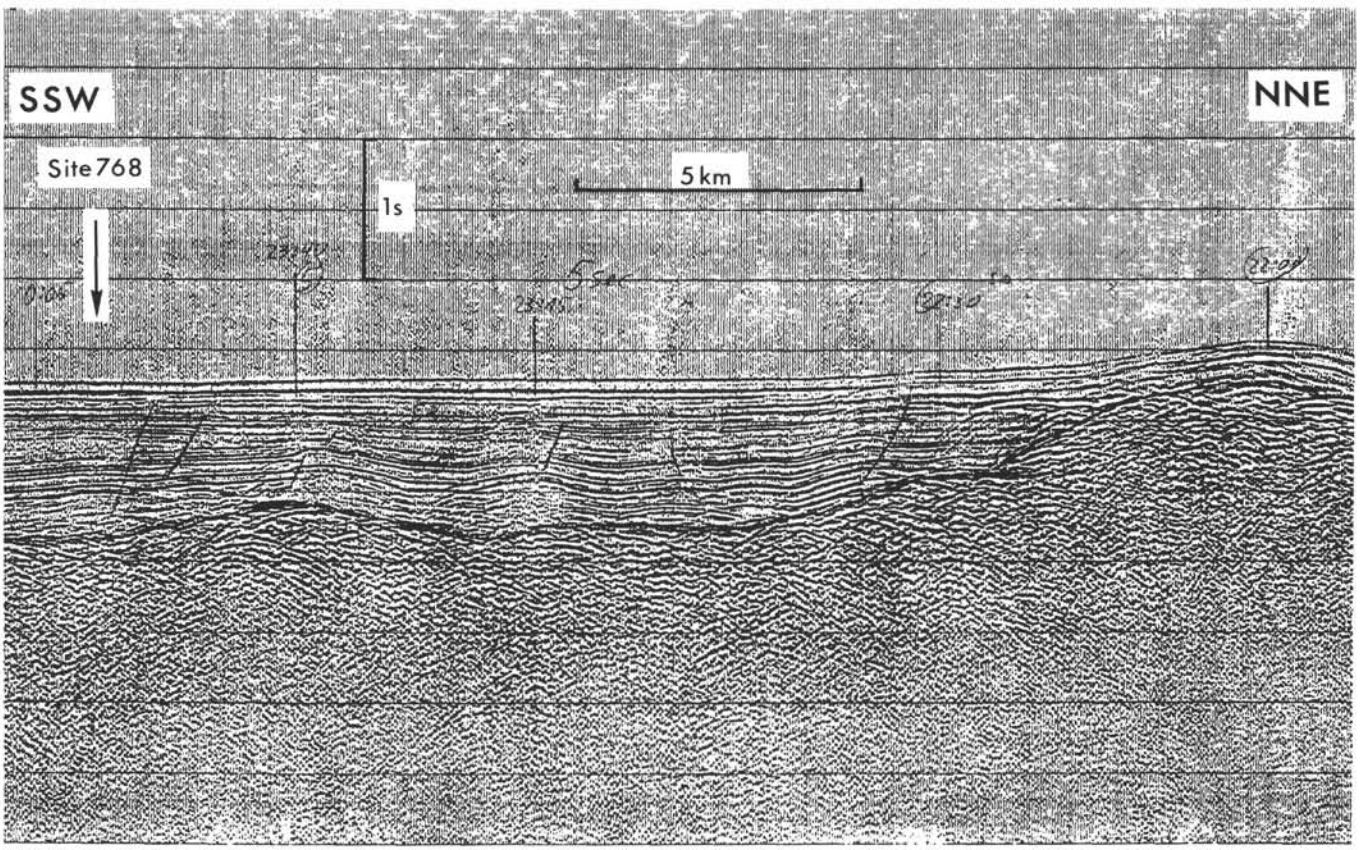

Figure 3. Part of the multichannel seismic line VA-16-33. The increase of 1s in the basement depth over a distance of only 20 km from the north-northwest to the south-southeast may cause frequent turbidites.

regularity of the magnetic anomalies (Bäcker, Lange, and Richter, 1975). However, the bathymetric relief is regular where the magnetic anomalies are regular.

DISCUSSION OF AGE DETERMINATIONS FROM SITE 768

The tables on Cenozoic geochronology by Berggren et al. (1985) assign to the *S. wolffii* Zone the age range 19.2–17.4 Ma and to the *C. costata* Zone the range 17.4–16.7 Ma. These dates are based mainly on a zonation by Riedel and Sanfilippo (1978). Berggren et al. (1985) use several direct correlations between the magnetic stratigraphy and the plankton biostratigraphy. The accuracy of the absolute ages of the magnetic anomalies in the middle and lower Miocene, which is of the order of 0.5 m.y., is thus without great influence. Therefore we must determine whether the 1.5-m.y. discrepancy can be caused by uncertainties in the assumed ages of the radiolarians.

Nigrini and Lombari (1984) discuss age dating problems of the Miocene radiolarians. Theyer et al. (1978) date the appearance of *Stichocorys wolffii* to 19 Ma, whereas data from DSDP Leg 85 (Nigrini, 1985) indicate 17.8 Ma. Similarly, *C. costata* appeared in the Leg 85 region at 16.8 Ma instead of 18.4 Ma.

On Leg 112 (Shipboard Scientific Party, 1988), which drilled the Peru continental margin, a "biostratigraphic standard" was used that for the Cenozoic radiolarians is based on the zonations by Nigrini (1971) and Riedel and Sanfilippo (1978). Here the *S. wolffii* Zone covers only the range 18.1–17.2 Ma and the *C. costata* Zone the range 17.2–15.4 Ma. Although the age of the boundary between the *S. wolffii* and the *C. costata* Zone is nearly the same as for Leg 85, the other ages indicate uncertainties on the order of 1 m.y. Thus the age of the boundary between the *S. wolffii* and the *C. costata* Zone is obviously very stable. The only possibility is that the Sulu Sea may have been a fairly closed ocean basin, similar to its present state, with conditions different from the open ocean. In consequence, some species may have appeared in this basin with a considerable delay. However, it is difficult to explain a discrepancy of 1.5 m.y. in this way.

Another and presumably more likely explanation might be that the oldest sediments at Site 768 are allochthonous. In Core 124-768C-40R-4 (735.1 mbsf) the nannofossil Zone NN8 was encountered (Shipboard Scientific Party, 1990b). Zones NN6 and NN7 are missing, whereas in the sections 124-768C-42R-1 and -42R-3 (749.3–758.5 mbsf) two turbidites with NN5 were observed. This is only 15 m for an age interval of 3 m.y. Possible explanations are a hiatus, a very low sedimentation rate of 5 m per m.y., and a displacement from older crust. The last possibility is indicated by the turbiditic character of the layers bearing Zone NN5.

Figure 3 demonstrates a possible turbidite route. Over a distance of 20 km to the northwest along the seismic line VA-16-33, the basement depth decreases by about 1 s. Although along this line the slope is not continuous, the mean gradient of about 5% is so steep that already small instabilities may cause turbidites that should be able to traverse great horizontal distances and even small rises. Indeed, many thin turbidite layers are observed in Hole 768C. According to the seafloor spreading model proposed here, the distance 20 km corresponds to an age difference of 3 m.y.

Altogether the fossil ages are hardly consistent with my interpretation of the magnetic anomalies if they are autochthonous. However, if the sediments are transported over a distance of at least 10 km, everything would be consistent. Thus I propose that all samples with biogenic ages of more than about 15 Ma might have allochthonous fossils.

The interpretation of reversals in the tuffs of Unit IV as 5D and 5E is based on the radiolarian ages. My interpretation places Site 768 into the reversed interval between 5B and 5C. The indeterminate polarity of most of the basement at Site 768 might be due to the combined effects of inverse thermoremanence and viscous remanence.

DISCUSSION AND CONCLUSIONS

On most of the lines in Figure 2, multichannel reflection seismic data were obtained. They are consistent with an age increase from south-southeast to north-northwest, although the seismic data do not allow assessment of the absolute ages (K. Hinz, pers. comm., 1990).

Mainly based on the magnetic data, I propose that the Sulu Sea started to open in the early Oligocene at about 35 Ma with a low half-spreading rate of 0.6 cm/yr. Spreading continued at the same rate until the beginning of the upper Miocene; the youngest not-yet subducted crust is 10 m.y. old. This interval is very similar to that of the opening of the eastern basin of the South China Sea (Taylor and Hayes, 1983). From all the generated crust only a portion of the northern half is retained, whereas the southern half including the ridge axis is already subducted beneath the Sulu Trench and arc.

Although the determination of the age of the oceanic crust of the southeast Sulu Sea Basin is an important step in the understanding of the present plate configuration in Southeast Asia, we are far from a reconstruction of the whole plate geometry.

The age determination from Site 768 and the model presented here are inconsistent with the concept of trapped oceanic crust by Lee and McCabe (1986). Note that their interpretation requires that Anomaly 20 lies amid the Sulu Archipelago. Nevertheless, it is an important observation that the magnetic anomalies in large parts of the South China Sea, the Sulu Sea, the Celebes Sea, and the Banda Sea are nearly parallel. The simultaneity of the spreading intervals in the South China Sea and the Sulu Sea may contribute to an understanding of this parallelism and hence some of the tectonic processes in Southeast Asia.

ACKNOWLEDGMENTS

I thank the many colleagues who participated in the cruises on which the magnetic data were collected. Special thanks are due K. Hinz, the Chief Scientist of all these cruises. Further, I thank O. E. Avery who provided the magnetic data from the U.S. Naval Oceanographic Office magnetic survey. I am most grateful to H.-0. Bargeloh for his painstaking work in reducing the magnetic variations, which originally were much larger than the crustal anomalies. Many comments by Brian Taylor improved the paper considerably.

REFERENCES

Bäcker, H., Lange, K., and Richter, H., 1975. Morphology of the Red Sea central graben between Subair Islands and Abul Kizaan. *Geol. Jahrb.*, D13:79–123.

Berggren, W. A., Kent, D. V., Flynn, J. J., and Van Couvering, J. A., 1985. Cenozoic geochronology. *Geol. Soc. Am. Bull.*, 96:1407–1418.

Fuller, M., McCabe, R., Williams, I. S., Almasco, J., Encina, R. Y., Zanoria, A. S., and Wolfe, J. A., 1983. Paleomagnetism of Luzon. *In* Hayes, D. E. (Ed.), *The Tectonic and Geologic Evolution of Southeast Asia Seas and Islands*. AGU Geophys. Monogr. Ser., 27:79–94.

Harland, W. B., Cox, A. V., Llewellyn, P. G., Pickton, C.A.G., Smith, D. G., and Walters, R., 1982. *A Geologic Time Scale:* Cambridge (Cambridge Univ. Press).

Harrison, C.G.A., and Bonatti, E., 1981. The oceanic lithosphere. *In* Emiliani, C. (Ed.), *The Sea* (Vol. 7): New York (Wiley), 21–48.

IAGA Div. I Working Group 1, 1988. International geomagnetic reference field revision 1987. *Geophys. J. R. Astron. Soc.*, 93:187–189.

Lee, C. S., and McCabe, R., 1986. The Banda Celebes Sulu Basins: a trapped piece of Cretaceous-Eocene oceanic crust? *Nature*, 322:51–54.

Murauchi, S., Ludwig, W. J., Den, N., Hotta, H., Asanuma, T., Yoshii, T., Kubotera, A., and Hagiwara, K., 1973. Structure of the Sulu Sea and the Celebes Sea. *J. Geophys. Res.*, 78:3437–3447.

Nigrini, C., 1971. Radiolarian zonation in the Quaternary of the equatorial Pacific Ocean. *In* Funnell, B. M., and Riedel, W. R. (Eds.), *The Micropaleontology of Oceans:* Cambridge (Cambridge Univ. Press), 443–461.

Nigrini, C., and Lombari, G., 1984. *A Guide to Miocene Radiolaria.* Spec. Publ. Cushman Found. Foraminiferal Res., No. 22.

Nigrini, C. A., 1985. Radiolarian biostratigraphy in the central Pacific, DSDP Leg 85. *In* Mayer, L., Theyer, F., Thomas, E., et al., *Init. Repts. DSDP*, 85: Washington (U.S. Govt. Printing Office), 511–551.

Riedel, W. R., and Sanfilippo, A., 1978. Stratigraphy and evolution of tropical Cenozoic radiolarians. *Micropaleontology*, 24:61–96.

Roeser, H. A., 1975. A detailed magnetic survey of the southern Red Sea. *Geol. Jahrb.*, D13:131–153.

Roeser, H. A., and Bargeloh, H.-O., 1988. Reduction of geomagnetic measurements at sea in the vicinity of the geomagnetic equator. *Dtsch. Hydrogr. Z.*, 41:237–255.

Shipboard Scientific Party, 1988. Explanatory notes: Leg 112. *In* Suess, E., von Huene, R., et al., *Proc. ODP, Init. Repts.*, 112: College Station, TX (Ocean Drilling Program), 25–44.

———, 1990a. Explanatory notes. *In* Rangin, C., Silver, E. A., et al., *Proc. ODP, Init. Repts.*, 124: College Station, TX (Ocean Drilling Program), 7–33.

———, 1990b. Site 768. *In* Rangin, C., Silver, E. A., et al., *Proc. ODP, Init. Repts.*, 124: College Station, TX (Ocean Drilling Program), 195–297.

Taylor, B., and Hayes, D. E., 1983. Origin and history of the South China Basin. *In* Hayes, D. E. (Ed.), *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands* (Pt. 2). Am. Geophys. Union, Geophys. Monogr. Ser., 27:23–56.

Theyer, F., Mato, C. Y., and Hammond, B. R., 1978. Paleomagnetic and geochronologic calibration of latest Oligocene to Pliocene radiolarian events, equatorial Pacific. *Mar. Micropaleontol.*, 3:377–395.

U.S. Naval Oceanographic Office, 1988. A project magnet aeromagnetic survey of the Sulu Sea. Stennis Space Center (Miss.).

Date of initial receipt: 31 May 1990
Date of acceptance: 17 January 1991
Ms 124B-175