CRUSTAL STRUCTURE OF THE MAKASSAR BASIN AS INTERPRETED FROM GRAVITY ANOMALIES : IMPLICATIONS FOR BASIN ORIGIN AND EVOLUTION

By :
Dr. B. Situmorang

ABSTRACT

The gross crustal structure of the Makassar basin has been interpreted from gravity anomalies in conjunction with borehole informations and seismic reflection data. Considerably attenuated continental crust appears to underlie the basin which reflects a single episode of continental rifting, that has been active in the area during Eocene – Lower Miocene times. The implications of that interpretation for tectonic model are discussed and the overall evolution of the basin from Middle Jurassic onward proposed.

I. INTRODUCTION

The origin and evolution of the Makassar basin (Figure 1) has been explained in a number of ways by various authors. So far, at least four hypotheses have been proposed. The first was given by van Bemmelen (1949) in conjunction with the evolution of South Sulawesi. Based on geological data from Southeast Kalimantan and West and South Sulawesi, van Bemmelen (1949) inferred that the foredeep of a volcanic arc occurred to the west of South Sulawesi with Pulau Laut as a centre of orogenic disturbance. The Makassar undation took place in Middle Miocene, subsequently followed by subsidence and transgression with continuing volcanic activity in the Young Neogene. The Plio-Pleistocene diastrophism resulted in the breakdown of the crust to the west and east of South Sulawesi forming the Makassar basin and the Bone trough.

The second hypothesis was proposed by Hamilton (1979). He argued that the formation of the Makassar basin was due to the opening (spreading) of the Makassar Strait in the Middle or Upper Miocene. His conclusion is entirely based on a stratigraphic correlation between Southeast Kalimantan and South Sulawesi. His concept was later on adopted with some modifications by other workers. For example, Katili (1978) proposed that the opening of the Makassar Strait occurred during the Quaternary, whereas Rose and Hartono (1978) related the formation of the basin to the counterclockwise rotation of Kalimantan during Late Cretaceous-Early Paleogene times.

The third concept was proposed by Burollet and Salle (1979), based on microtectonic studies in East-Southeast Kalimantan and South Sulawesi combined with seismic reflection data from the North Makassar basin. They suggested that the basin was formed in the same manner as grabens or rhombochasms formed in a rigid continental or intermediate crust.

The fourth concept was put forward by the present author (Situmorang, 1982). On the basis of the observed subsidence in well data and on reflection profiles from the Makassar basin, he concluded that the formation of the basin can be explained by the stretching model of McKenzie (1978).

In the first three hypotheses the formation of the Makassar basin is only briefly touched as part of the regional geology of the region. None of those hypotheses address the crustal structure of the basin. The stretching model which make use of sedimentary records directly from the basin itself is capable to present not only a detailed account of subsidence, heat flow, and generation and maturation of hydrocarbons within the basin, but also crustal thickness which can be confirmed by gravity and magnetic observations.

The purpose of the present paper is to discuss the crustal structure of the Makassar basin especially in the light of gravity and magnetic data, and relates that to the origin of the basin in terms of riftihg as recognized from interpretation of seismic reflection profiles (Situmorang, 1987 a). This will then lead to the proposed evolutionary model of the basin within the southeastern margin of the Sundaland.

II. GRAVITY DATA

For the Makassar basin, there is free-air gravity anomaly map, kindly released for the first time by SIPM (Figure 2). It appears that the basin is associated with a negative gravity anomaly. In the South Makassar basin, the gravity anomaly has a minimum value of –100 mgal in the vicinity of seismic reflection lines P.609, P.610 and P.611. In the North Makassar basin, the anomaly reaches a minimum value of –90 mgal near the intersection of seismic reflection profiles P.616 and P.617 just to the South of Mangkalihat Peninsula. The shelf area is characterized by positive gravity anomaly.

Based on these data, a crustal cross section is constructed along the line A' – A' in Figure 2. The position of the line is selected as such that geological information from exploration wells PB-1, TT-1, and TT-2, and seismic reflection data derived from profile P.608 can be used to control the thickness of the sediment column along the cross section. The thickness of the water column is well controlled by the bathymetry.

The density of sea water and mantle is taken as 1.03 g/cm^3 and 3.3 g/cm^3 respectively. The density of the sediments is derived from velocity data on seismic line P.608; using a density-velocity curve of Nafe and Drake (1963), it is obtained as 2.15 g/cm^3. A crustal density of 2.8 g/cm^3 is used as reference density. Hence, the density contrast is –1.77 g/cm^3 for the water column, –0.65 g/cm^3 for the sediments, and 0.50 g/cm^3 for the mantle.

Two-dimensional gravity modeling has been carried out using the method as described by Talwani et al (1959). A value of 15 km is used as an approximation for the depth to the M-discontinuity; this value is the average depth obtained by the stretching model in the South Makassar basin (Situmorang, 1982).

The result of the calculation is summarized in Figure 3. This figure represents the most acceptable crustal cross section among numerous models that have been evaluated, ranging from normal continental crust, intrusive bodies near the basement, to normal oceanic crust with several layering and density variations. It appears that the fit between the observed anomaly and calculated anomaly is good. This fit will significantly change if for instance, several dykes are introduced in the deeper part of the basin, i.e, within 1,000 fathoms bathymetric contours (Figure 4). In this case, the dykes are assumed as made up by basic rocks with density of 2.9 g/cm^3. The greater the volume of basic rocks introduced, the more the calculated anomaly deviates from the observed anomaly, and will eventually become positive if the basin is entirely underlain by basic rocks as in the case of the normal oceanic basin.

Although gravity interpretation is not unique, the result as discussed above tends to suggest that the Makassar basin is probably underlain by an attenuated continental crust with average thickness of 15 km.

III. MAGNETIC DATA

The only magnetic data available from the Makassar basin are the total intensity profiles, also released for the first time by SIPM, which can be seen in Figure 5. However, not much information can be extracted from these data. Minor variations are observed on almost all of the profiles. A long wavelength anomaly exists over the South Makassar basin coincident with seismic reflection line P.609, with peak to trough amplitude about 600 gammas. This is the largest amplitude observed in the Makassar basin.

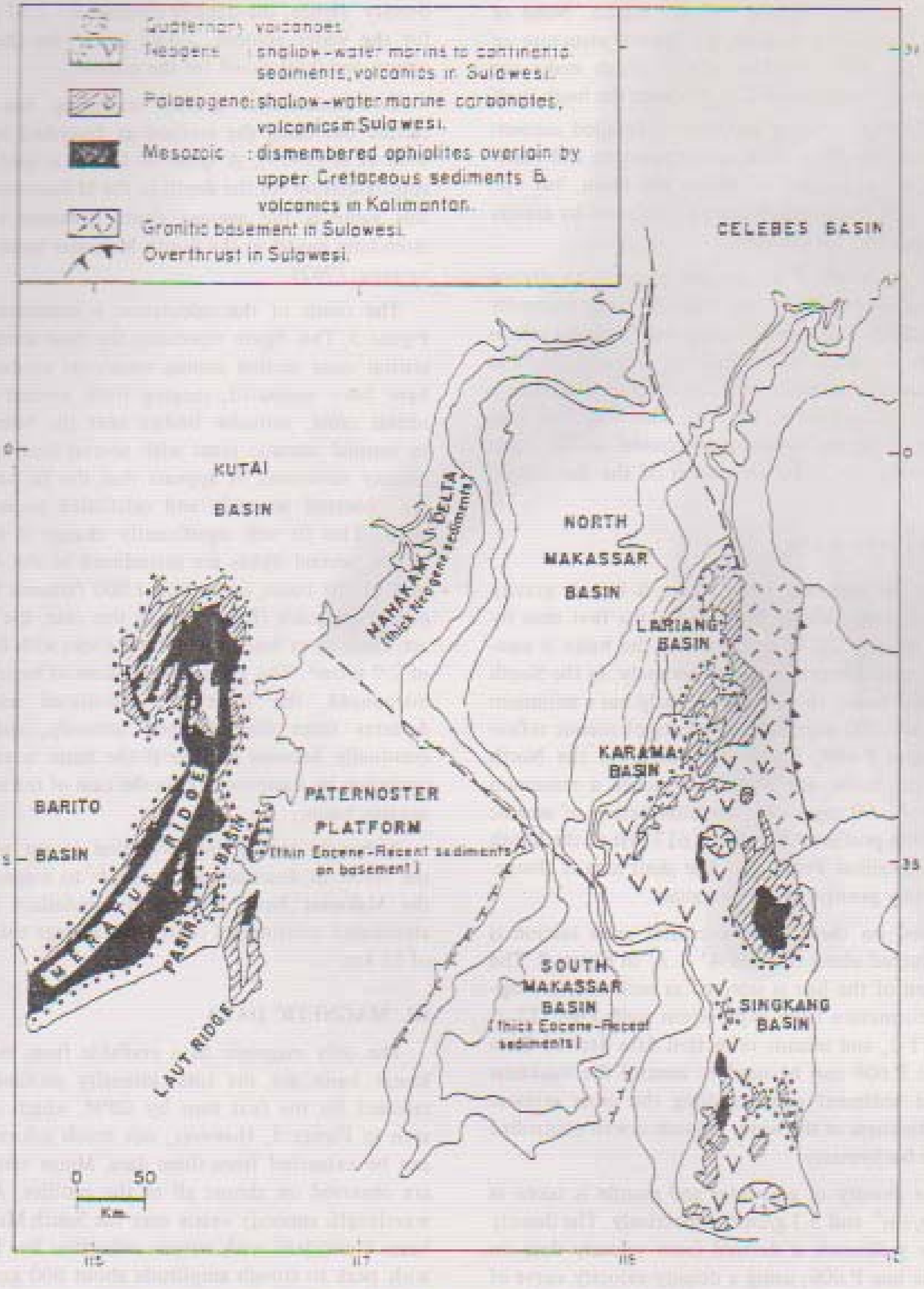

Figure 1. Location map

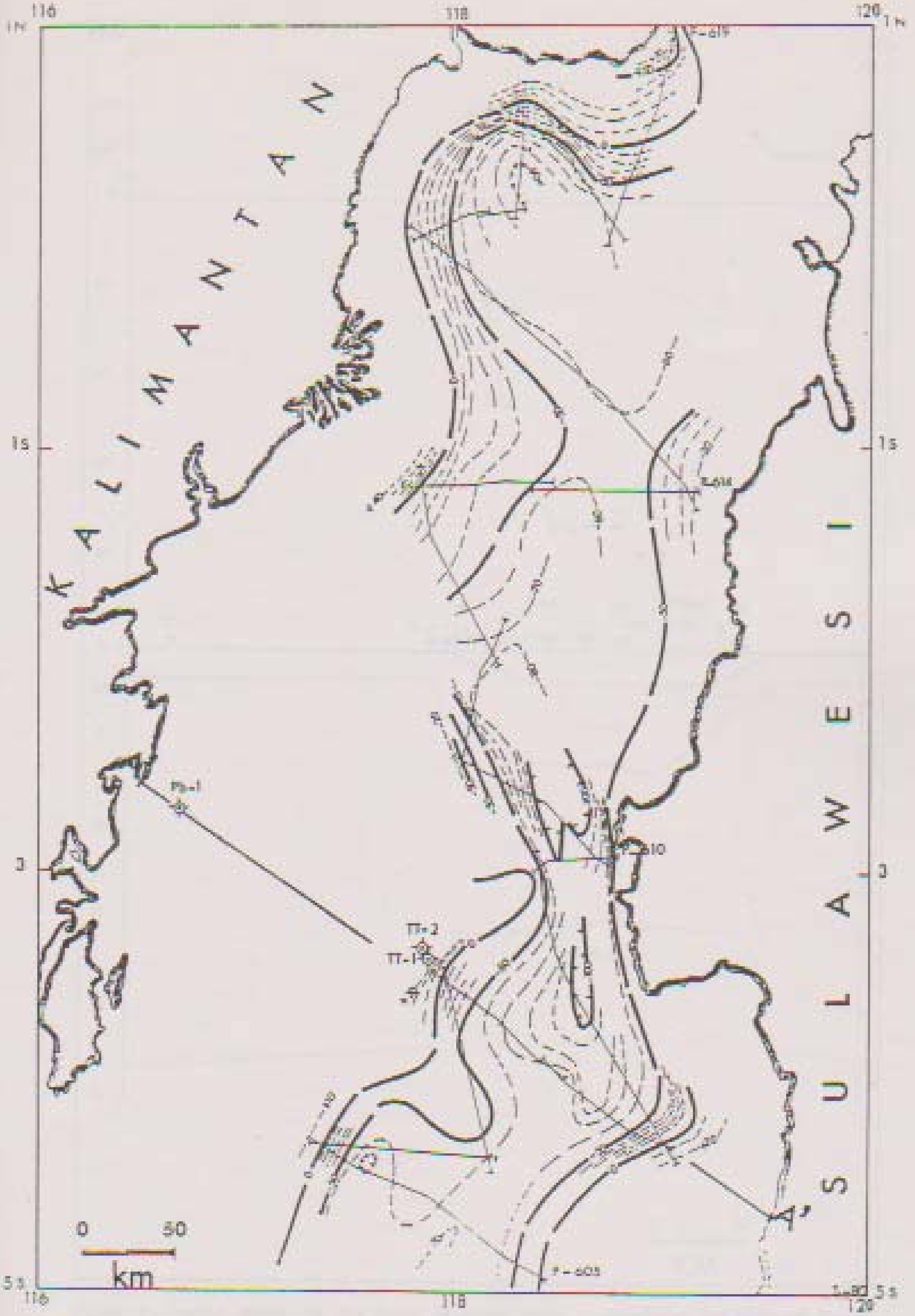

Figure 2. Free-air gravity anomaly map of the Makassar basin. Contour interval : 10mgal. Location of SIPM continuous seismic reflection profiles are shown as e.g.p.605, P.610, P.614, P.619.

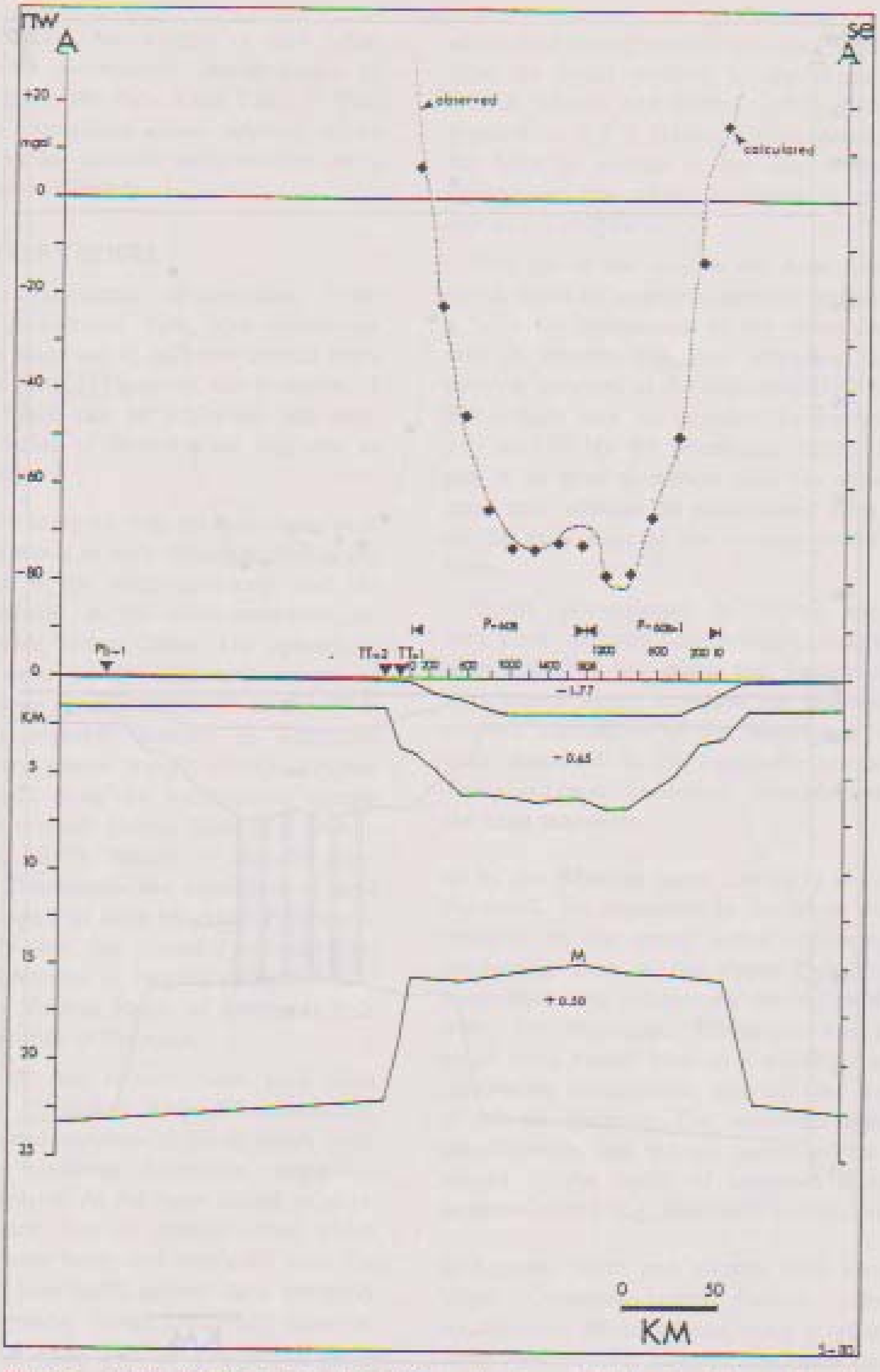

Figure 3. Crustal model for the South Makassar basin, statisfying the observed free-air gravity anomalies along profile A'A' in Figure 2. Numbers at the surface (0 km) are shotpoints on seismic profiles P.608-1, P.608-1, Numbers in the model are density contracst in g/cm3, M. ; Moho-discontinuity.

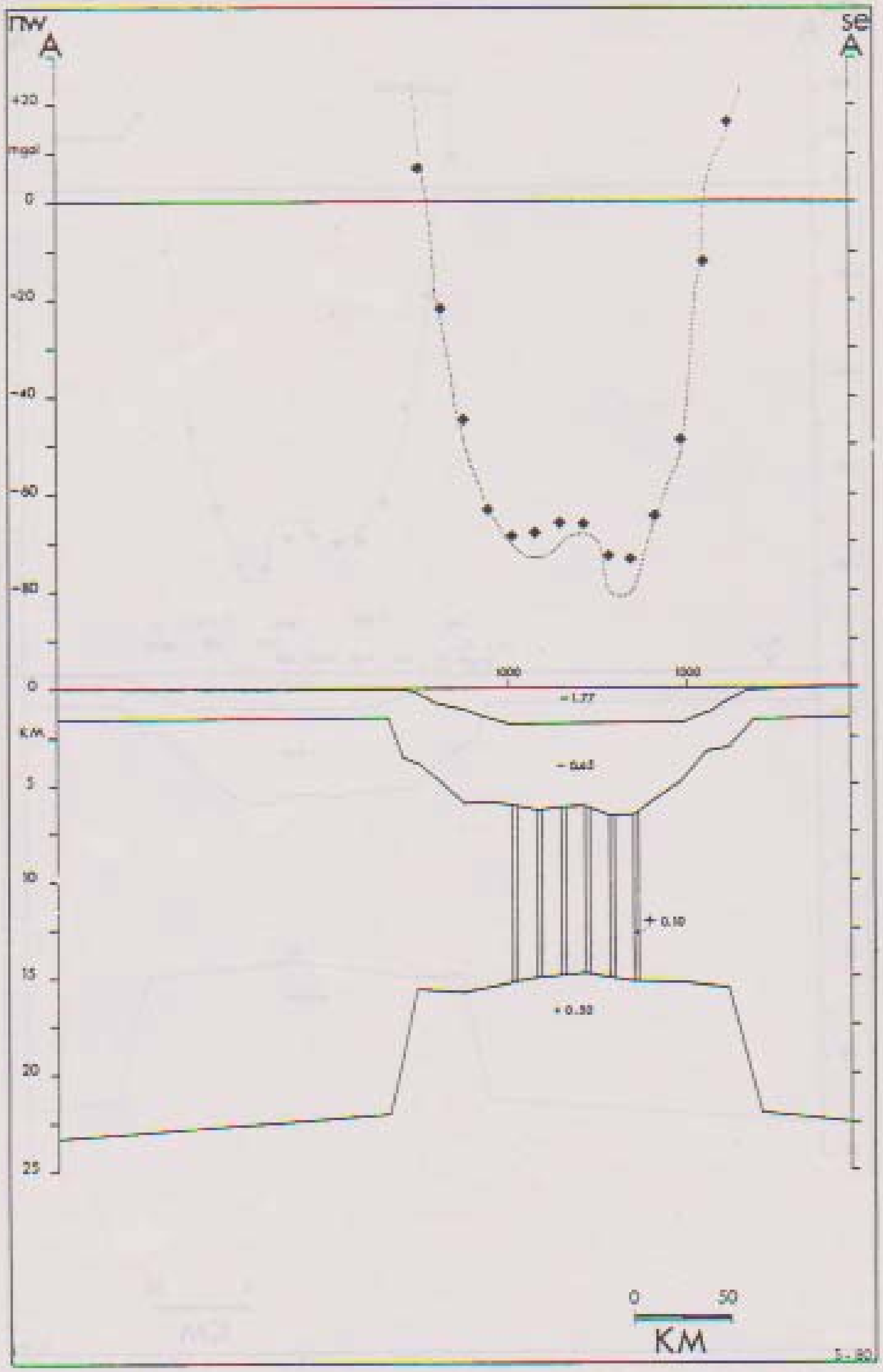

Figure 4. Crustal model as in Figure 3, but with introduction of dyke system within the abyssal plain (limited by 1.000 fashoms water depth), explanation in text.

lateral wrench faults. An example of such deformation has been documented among others by Katili (1970) along the Palu Koro Fault in West Sulawesi. The post-rifting phase appears to be characterized by an uniform sedimentation while the basin subsided uniformly.

V. EVOLUTIONARY MODEL

Based on stratigraphic informations, interpretation of geophysical data, and subsidence history, and by make use of paleocontinental maps of Smith et al. (1981) (Figure 6), the evolution of the Makassar basin can be explained and summarized in a series of hypothetical diagrams as presented in Figure 7.

a) It is generally accepted that the main features of this part of the world in early Mesozoic time is the Asian landmass in the north-northwest, and the Australian continent in the south-southwest, separated by a wide Tethys Ocean. The opening of the Wharton basin in the northwest margin of Australia in Upper Jurassic (Heirtzler et al., 1978; Barber, 1979) probably induced an activation of the previously passive margin of the northern Asiatic continent along its southeastern margin (Sundaland). A residual forearc basin (e.g. Dickinson and Seely, 1979), floored by oceanic crust, was formed at this margin and deposition of basal sequences composed of deep sea Alino Formation, grading laterally into the littoral Paniungan Formation and Orbitolina – bearing sediments now exposed in the Meratus Range of Southeast Kalimantan was deposited in the basin.

b) Destruction of this forearc basin took place in the Middle Cretaceous (Albian-Cenomanian), when the separated continental block which originated from the Northwest Australian margin collided with Sundaland. As the basin closed, an ultrabasic wedge once part of oceanic crust which floored the forearc basin was emplaced onto the margin of the Sundaland, where it is presently found in the Meratus Range and South Sulawesi.

If this is correct, then part of Tethys was being subducted at this time. From the beginning of rifting in the Upper Jurassic to the emplacement of the oceanic wedge in the Middle Cretaceous covers a time span of approximately 50 My, during which time the separated continental block travelled from its initial position at approximately 35°S latitude (Smith and Briden, 1977) to its present position at 2,5°S (Haile, 1975). Assuming there has been no change in the rate of convergence throughout that time, it implies a convergence rate of 7.2 cm/year.

The age of the crust in the Argo Abyssal Plain which dated by magnetic anomaly method provides a value for comparison to the above convergence rate. It appears that slow spreading rate of 2.8 cm/year occurred at the beginning (153 to 149 My BP), which later on increased to 7 cm/year from 149 to 147 My BP (Hamilton, 1978). The latter rate is in good agreement with the above convergence rate, whereas the initial slower value is related to the early stage of the opening of the Wharton basin.

Uplift, accompanied by folding and faulting took place, and also acid intrusion. Faulting at this time probably laid down the framework of the intra massif basin, in which the sedimentary and volcanic successions of the Manunggul Formation were deposited in the Upper Cretaceous (Middle Turonian-Lower Senonian), unconformably upon the basal sequences.

c) As the Wharton basin continued to enlarge in the south, the expansion in the north was accommodated by the newly active northwest dipping subduction zone in the Upper Cretaceous, with a corresponding volcanic arc further to the northwest. The Manunggul Formation was deposited in an intra massif basin in a nearshore marine to continental environment, and the sand is generally of arkosic character. The sediments represent the pre-rift series, and arkosic nature of the sands is related to the uplift of basement rocks during incipient rifting (e.g. Dickinson and Suczek, 1979).

d) Regional uplift and erosion took place during Upper Cretaceous-Lower Eocene, subsequently accompanied by subsidence along a set of normal faults downthrown towards the basin due to the stretching of the lithosphere. The outline of the Makassar basin was developed, flanked on both sides by positive areas. At this time, the subduction zone migrated southeastward and creating Paleo-

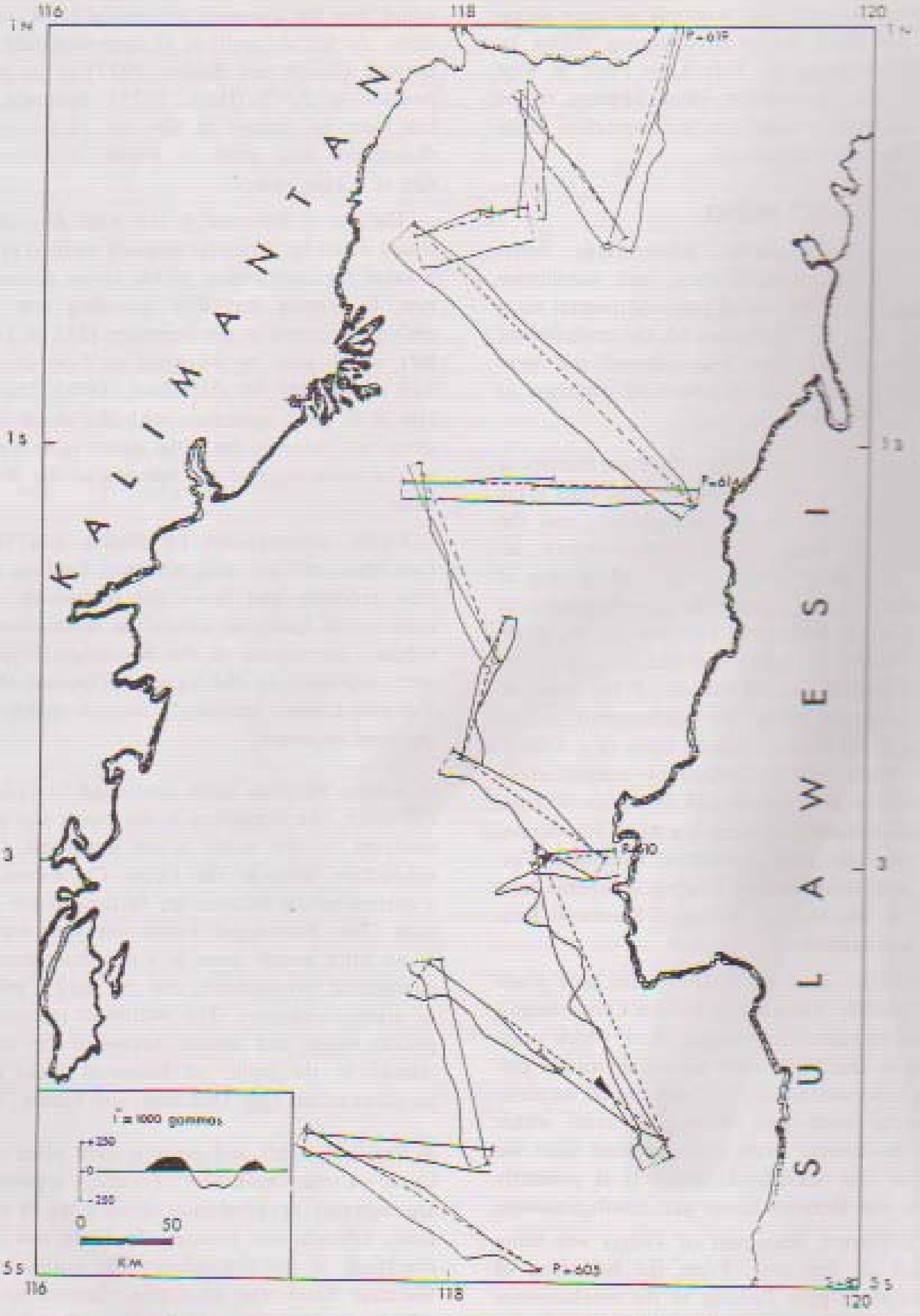

Figure 5a Total intensity magnetic profile along ship's track. Dashed line is zero line for profile plots.

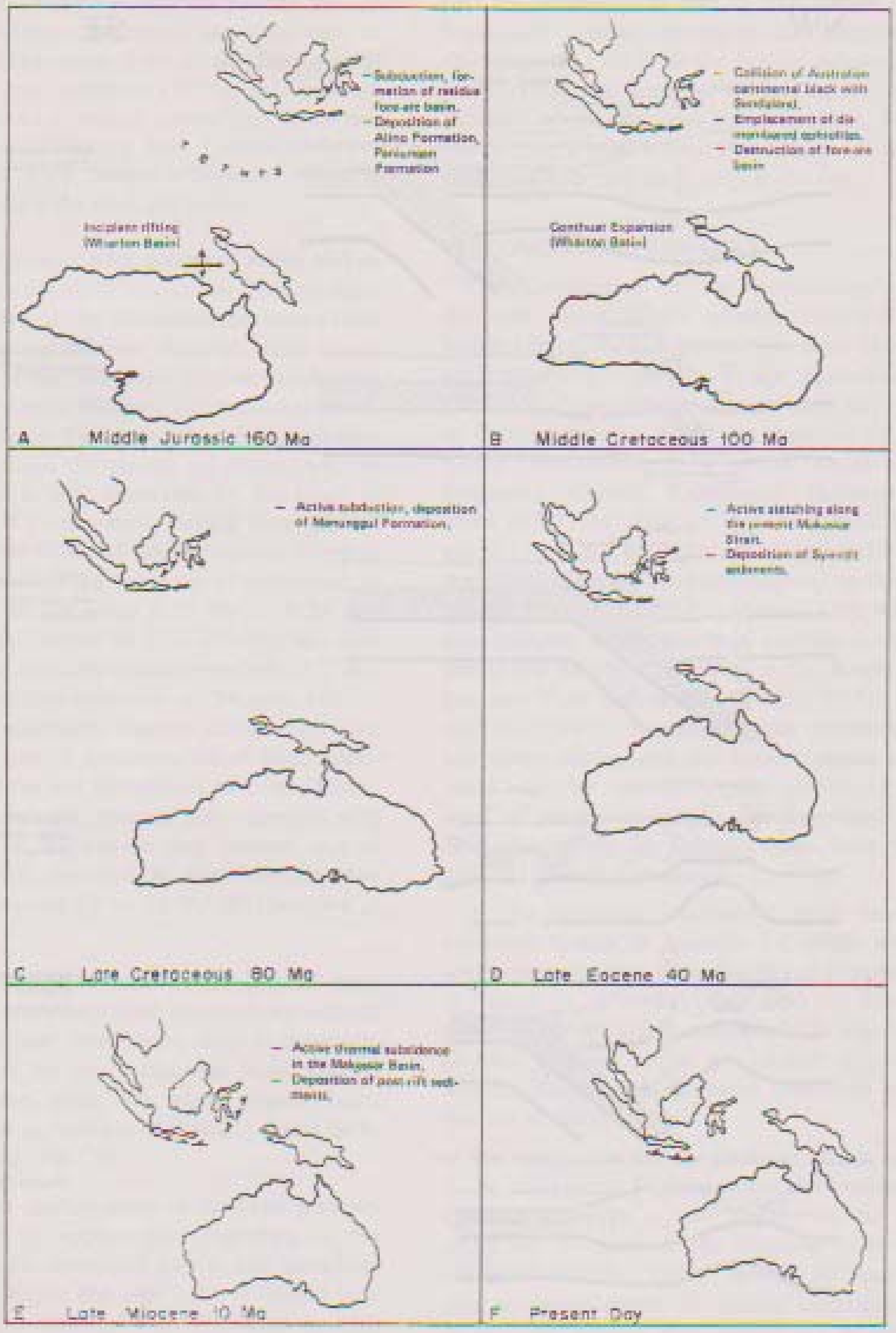

Figure 6. Paleocontinental maps of Australia- Sountheast Asia since Middle Jurassic (after Smith et al., 1981). Present outlines are for reference only.

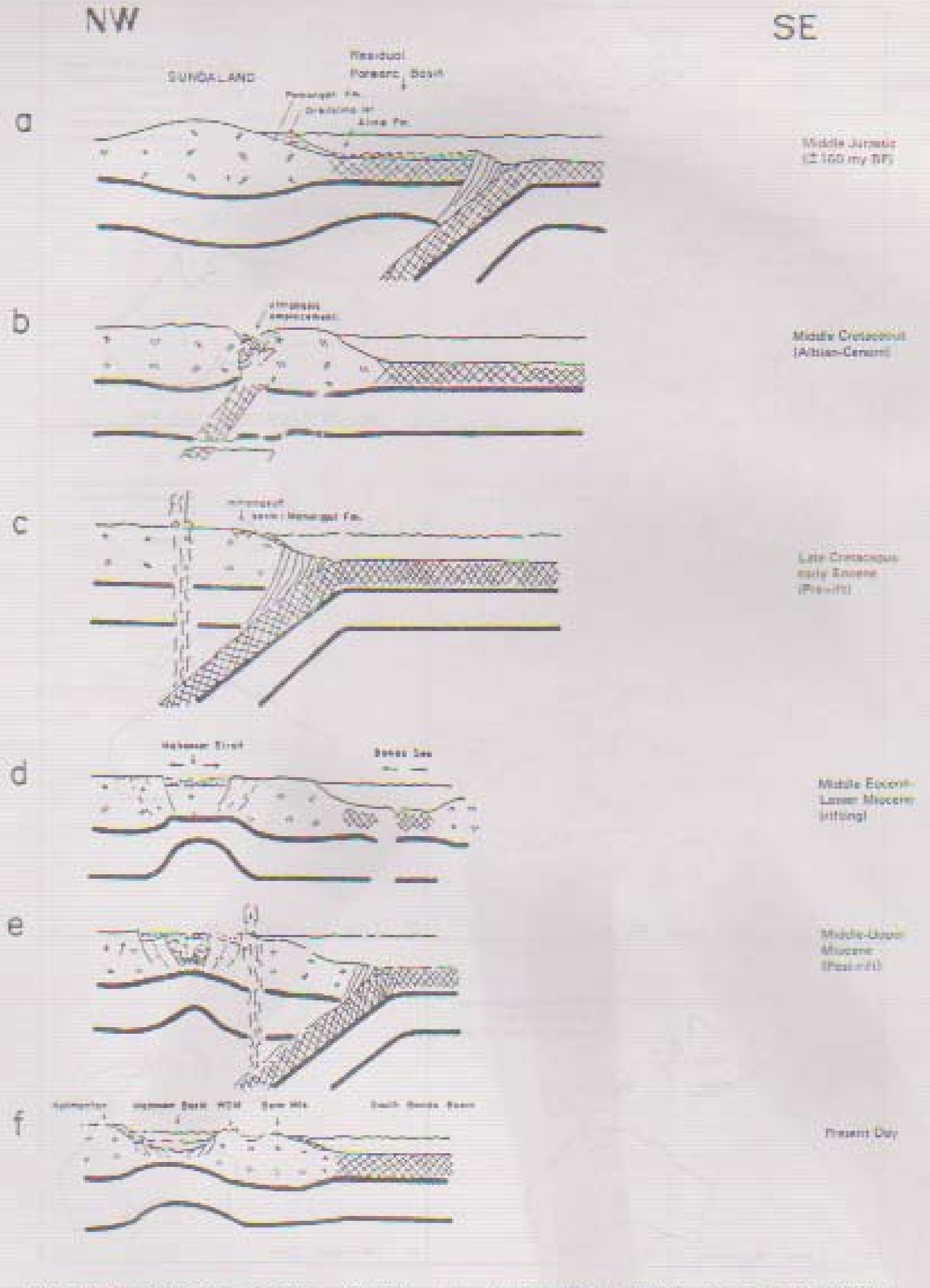

Figure 7. Hypothetical sections, showing the sounthbeastern margin of the Sundaland (not to scale)

cene volcanism along the western part of present Sulawesi. Paleocene sediments are very rare in this region. They occur only in the Biru area as reported by van Leeuwen (1979), and possibly around Tanakeke-1 well. It seems that there was no excessive uplift during Late Cretaceous-Lower Eocene in this region, instead subsidence controlled by normal faults is the main phenomena.

e) Syn-rift sequences were deposited in the Makassar basin unconformably on the pre-Tertiary basement. Stretching of the lithosphere continued from Middle Eocene until Lower Miocene, when it was opposed by active westward dipping subduction at the end of Lower Miocene. Continuous sedimentation prevailed in the basin, whereas calc-alkaline volcanism occurred throughout the present western Sulawesi. This is well illustrated by the result of K/Ar dating of 13 specimens ranging from gabbros to granites from West and South Sulawesi as reported by Sukamto (1975). From the 13 specimens, 10 are dispersed in the range 6.25 My to 9.29 My, 2 specimens fall within 10.6 to 10.9 My, and only one specimen indicates absolute age of 17.7 My. Using the Cenozoic time-scale of Berggren (1972), the first 10 specimens indicate an age of Upper Miocene, the next 2 specimens are of Middle Miocene age, and the last specimen is of Lower Miocene age. This volcanic episode also coincides with the welding of the eastern and western arcs of Sulawesi, which occurred in Lower-Middle Miocene times between 19 to 13 My BP (Sasajima et al., 1980).

From the Middle Miocene to the present, post-rift sediments were deposited continuously without significant tectonic disturbance. Only in the southeastern part of the North Makassar basin, Quaternary movements along left lateral wrench faults resulted in the occurrence of (listric?) thrust faulting (Situmorang, 1987 a).

f) The present configuration of the basin is shown in Figure 7f. It appears that stretching of the crust has not yet developed further into spreading. The pan-like shaped Makassar basin is floored only by a thinner continental crust compared to adjacent areas.

Throughout its evolution, the present western part of Sulawesi was part of the margin of the Sundaland. Similar conclusion also suggested by Otofuji et al., (1981) on the basis of paleomagnetic study. This area later on appears as the eastern shoulder of the Makassar basin (graben). Folding and faulting is more intense here than in the western flank, due to active subduction in the east.

VI. CONCLUDING REMARKS

One implication of the evolutionary model discussed above is the possible existence of a Middle-Upper Jurassic subduction zone along the southeasten-south margin of the Sundaland (Figure 7a). Consequently, a magmatic belt paired to this subduction should be expected to occur further northwestward. A granite specimen from Southwest Central Kalimantan radiometrically dated (K/Ar) by Haile et al. (1977) indicated an age of 153 ± 3.5 My. This value is compatible with the oldest magnetic anomaly detected in the Argo Abyssal Plain as 153 My (Hamilton, 1978). A southward dipping subduction was postulated to exist during the Middle Cretaceous in the South China Sea and West Kalimantan (Katili, 1975 ; Paltrinieri et al., 1976). It is possible that this subduction was active earlier, and the Upper Jurassic granite could also be related to this activity. Further work is needed to clarify this hypothesis, with additional dating of plutonic rocks from Southwest and Central Kalimantan.

If the separated continental block from the northwest margin of Australia did collide with the southeastern margin of the Sundaland as postulated in Figure 7b, it implies that rocks of Australian facies could be found somewhere in this region. Detailed mapping in the pre-Tertiary area of the Meratus Range could probably contribute to verification of the hypothesis.

The formation of the Makassar basin appears to be adequately explained by the stretching mechanism, although a few aspects of the model could not be checked. The thickness of the crust predicted by the model cannot be confirmed, due to unavailability of seismic refraction data. In fact, the amount of extension can be obtained independently from refraction data by comparison to the adjacent unextended region. Further refraction survey in this area will depend on the amount of information which can be derived from the last surveys.

As in the case of crustal thickness, the heat flow values predicted by the stretching model cannot be verified. As far as I know, there has been a very limited heat flôw measurements in the Makassar basin, although it is an important aspect especiallly from the point of view of petroleum exploration. Transformation of organic materials present in the sediments into hydrocarbons and its maturation processes are closely related to the degree of heating experienced by them, in addition to the amount of subsidence. Careful analysis of this aspect can lead to a better delineation of prospective areas for future hydrocarbon exploration in the region. It is recommended that future cruises in this area should also carry out heat flow measurements.

As pointed out by McKenzie (1978), stretching will be accommodated by listric normal faults. These phenomena have been observed in other stretched regions, such as the North Sea basin (Blair, 1975), the Galicia-Portugal and Northern Bay of Biscay (Montadert et al., 1979), and possibly also in the Red Sea basin (Lowell et al., 1975). However, in the Makassar basin the listric nature of the faults cannot be observed on the present available reflection data. This problem could probably be resolved by further interpretation of a more detailed geophysical data.

REFERENCES

Barber, A.J., 1979. Structural interpretations of the island of Timor, Eastern Indonesia, *South East Asia Petrol. Expl. Soc. Proc.*, 4, 9-21.

Bemmelen R.W. van., 1949. *The geology of Indonesia*, V.1A, Govt. Printing Office, The Hague, 732 pp.

Ben-Avraham, Z. and Emery, K.O., 1973. Structural framework of Sunda Shelf, *Amer. Ass. Petrol. Geol. Bull.*, 57, 2323-2366.

Berggren, W.A., 1972. A Cenozoic time scale, some implications for regional geology and paleobiography, *Lethaia*, 5, 195-215.

Blair, D.G., 1975. Structural styles in North Sea Oil and Gas Fields, *In* : A.W. Woodland (ed), *Petroleum and the continental shelf of North-West Europe*, Vol. 1, Geology, Applied Science Publishers Ltd., 327-338.

Burollet, P.F. and Salle, C., 1981. Seismic reflection profiles in Makassar Strait, *In* : A.J. Barber and S. Wiryosujono (eds.), *Geology and Tectonics of Eastern Indonesia*. G.R.D.C. Spec. Publ., 2, 273-276.

Dickinson, W.R. and Seely, D.R., 1979. Structure and stratigraphy of forearc regions, *Amer. Ass. Petrol. Geol. Bull.*, 63, 2-31.

Dickinson, W.R. and Suczek, C.A., 1979. Plate tectonics and sandstone compositions, *Amer. Ass. Petrol. Geol. Bull.*, 63, 2164-2182.

Haile, N.S., 1976. The regional implications of paleomagnetic research in Southeast Asia, *South East Asia Petrol. Expl. Soc. Proc.*, 3, 39-44.

Haile, N.S., McElhinny, M.W. and McDougall, I., 1977. Paleomagnetic data and radiometric ages from the Cretaceous of West Kalimantan (Borneo), and their significance in interpreting regional structure, *J. Geol. Soc. London*, 133, 133-144.

Hamilton, W., 1979. Tectonic of the Indonesian Region, *U.S. Geol. Survey, Prof. Paper*, 1078, 345 pp.

Heirtzler, J.R., Cameron, P., Cook, P.J., Powell, T., Roeser, H.A., Sukardi, S. and Veevers, J.J., 1978. The Argo Abyssal Plain, *Earth Planet. Sci. Lett.*, 41, 21-31.

Katili, J.A., 1970. Large transcurrent faults in Southeast Asia with special reference to Indonesia, *Geol. Rundsch.*, 59, 581-600.

Katili, J.A., 1975. Volcanism and plate tectonics in the Indonesian island arcs, *Tectonophysics*, 26, 165-188.

Katili, J.A., 1978. Past and present geotectonic position of Sulawesi, Indonesia, *Tectonophysics*, 45, 289-322.

Kyushu Oil Development Co., 1968. *Aeromegnetic survey in the offshore Southeast Kalimantan Area, Indonesia*, Unpublished report, Pertamina

File, Jakarta.

Leeuwen, Th. M. van, 1979. The geology of Southwest Sulawesi with special reference to the Biru Area, *In* : A.J. Barber and S. Wiryosujono (eds.), *Geology and Tectonics of Eastern Indonesia*, G.R.D.C. Spec. Publ. 2, 277-304.

Lowell, J.D., Genik, G.J., Nelson, T.H. and Tucker, P.M., 1975. Petroleum and plate tectonics of the southern Red Sea, *In* : A.G. Fischer and S. Judson (eds.), *Petroleum and global tectonics*, Princeton University Press, 129-153.

McKenzie, D., 1978. Some remarks on the development of sedimentary basins, *Earth Planet Sci. Lett.*, 40 25-32.

Montadert, L., de Charpal, O., Roberts, D., Guennoc, P. and Sibuet, J. -C., 1979. Northeast Atlantic passive continental margins; Rifting and subsidence processes, *In* : M. Talwani, W. Hay and W.B.F. Ryan (eds.) *Deep drilling results in the Atlantic Ocean : Continental margins and paleoenvironment*, Am. Geophys. Union, Maurice Ewing Series, 3, 154-186.

Nafe, J.E. and Drake, C. , 1963. Physical properties of marine sediments, *In* : M.N. Hill (ed.), *The Sea*, Interscience Pub., New York, 3, 784-815.

Otofuji, Y., Sasajima, S., Nishimura, S., Dharma, A. and Hehuwat, F., 1981. Paleomagnetic evidence for clockwise rotation of the northern arm of Sulawesi, Indonesia, *Earth Planet. Sci. Lett.*, 54, 272-280.

Paltrinieri, F., Saint-Marc, F. and Situmorang, B. 1976. Stratigraphic and paleogeographic evolution during Cenozoic time in Western Indonesia, *Offshore South East Asia Conf. Proc.*, SEAPEX, Singapore, Paper 10, 29 pp.

Rose, R. and Hartono, P., 1978. Geological evolution of the Tertiary Kutei-Melawi Basin, Kalimantan, Indonesia, *Indones. Petrol. Assoc. Proc., 7th Ann. Conv.*, 225-251.

Sasajima, S., Nishimura, S., Hirooka, K., Otofuji, Y., van Leeuwen, T. and Hehuwat, F., 1980. Paleomagnetic studies combined with fission-track datings on the western arc of Sulawesi, East Indonesia, *Tectonophysics*, 64, 163-172.

Situmorang, B., 1982. The formation of the Makassar basin as determined from subsidence curves, *Indones. Petrol. Assoc. Proc., 11th Ann. Conv.*, 1, 83-107.

Situmorang, B., 1987a. Seismic stratigraphy of the Makassar basin, *Sci. Cont. Lemigas*, 1, 3-38.

Situmorang, B., 1987b. Emplacement of the Meratus ultrabasic massif : A gravity interpretation, *Sci. Cont. Lemigas*, 2, 61-72.

Smith, A.G. and Briden, J.C., 1977. *Mesozoic and Cainozoic palaeocontinental maps*, Cambridge University Press.

Smith, A.G., Hurley, A.M. and Briden, J.C., 1981. *Phanerozoic paleocontinental world maps*. Cambridge University Press.

Sukamto, R., 1975. The structure of Sulawesi in the light of plate tectonics, *Reg. Conf. Geol. Min. Res. S.E. Asia*, Jakarta.

Talwani, M., Worzel, J.L. and Landisman, M., 1959. Rapid gravity computation for two-dimensional bodies with application to the Mendocino submarine fracture zone, *J. Geophys. Res.*, 64, 49-59.