JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 88, NO. B11, PAGES 9419-9435, NOVEMBER 10, 1983

OPHIOLITE EMPLACEMENT BY COLLISION BETWEEN THE SULA PLATFORM AND THE SULAWESI ISLAND ARC, INDONESIA

Eli A. Silver and Robert McCaffrey[1]

Earth Sciences Board and Center for Coastal Marine Studies, University of California

Yoko Joyodiwiryo

Geological Research and Development Center

Scott Stevens

Scripps Institution of Oceanography

Abstract. Much of the tectonic complexity displayed in eastern Indonesia results from a series of Neogene collision events between island arcs, continental fragments, and the Australian continent. Here we examine the emplacement of a large ophiolite belt, resulting from the Miocene collision between the Sulawesi island arc and a continental fragment, the Sula platform. We present the results of several marine geophysical expeditions to the SW Molucca Sea and the NW Banda Sea, plus gravity and geology on the east arms of Sulawesi. The Batui thrust separates the ophiolite from sedimentary rocks deformed along the leading edge of the Sula platform. We mapped this thrust eastward from Sulawesi along the southern margin of the Gorontalo basin. The latter is floored by oceanic crust, and its south edge is uplifted against the thrust. Thus the Sulawesi ophiolite can be traced offshore to its origin as basement of the Gorontalo basin. The ophiolite is composed of harzburgite in the Southeast Arm and passes upward through a complex of gabbros and diabase dikes in the East Arm. Ophiolite melange underlies the harzburgites on the Southeast Arm beneath low-angle thrust contacts where seen. Our local observations show the melange to be composed of thrust packets of both serpentine and red shale matrix varieties. The packets are several hundred meters thick, and the melange, where studied, has a moderate north to northeast dipping foliation. This orientation, if regionally representative of the melange fabric, is consistent with a significant northward component of movement of the lower plate, probably the Sula platform or its margin. Where the ophiolite is in contact with rocks of the central schist belt, it dips under the schist, but where it encounters melange, or Mesozoic or Paleogene sedimentary rocks, the ophiolite is thrust over them. The tectonic overlap sequence, from west to east, is schist over ophiolite over older sediments or melange. The ophiolite appears to have been emplaced by oblique convergence of the Sula platform along the southern edge of the Gorontalo basin. We suggest that the Gorontalo basin represents a forearc basin and the ophiolite is its basement, analogous to a number of other forearc settings. Deformation of the ophiolite may have occurred in part on the seafloor prior to emplacement, but we feel that much of the deformation occurred during emplacement. The Sulawesi ophiolite is only one of a number of ophiolites in the Indonesian region, each of which has a very different origin and tectonic history.

Introduction

Ophiolites are sequences of mafic and ultramafic rock that include a basal ultramafic complex, overlain by a gabbroic complex, a sheeted dike complex, and a mafic volcanic complex [Geotimes, 1972; Coleman, 1977]. They are essentially what we expect to observe in an uplifted piece of oceanic crust [Christensen and Salisbury, 1975], and thus they are of great interest to geologists studying the structure and composition of oceanic crust. While a number of ophiolites have been studied, some in very great detail (e.g., the Oman ophiolite), their origins and mode of emplacement generally remain in doubt because the tectonic settings in which they were emplaced are no longer clear. If any generalization is commonly accepted, it is that many ophiolites appear to have been emplaced shortly after they were formed [Chistensen and Salisbury, 1975; Coleman, 1977].

The Sulawesi ophiolite (Figure 1) is a dismembered but complete sequence, as described above. The difficult access, sparse exposures, and often deep, lateritic weathering have made it less than attractive as an object of detailed study, and perhaps for these reasons no detailed study has yet been made. Its tectonic setting, however, is relatively clear, making it a very useful prospect for study of the mechanism of ophiolite emplacement.

The ophiolite is located within the zone of collision between the Sulawesi island arc and the Sula platform (Figure 1), and it has long been recognized that this collision was primarily responsible for its emplacement [Hamilton, 1979; Kundig, 1956; Silver et al., 1978]. We discuss the regional aspects of this collision in a companion paper. Here we focus on the structure of the ophiolite and its margins in an attempt to present existing constraints on the emplacement mechanism.

Regional Tectonic Setting of the Collision Zone

The Sulawesi arc-Sula platform collision zone (Figure 1) consists of three nearly concentric

[1]Now at Department of Earth and Planetary Sciences, Massachusetts Institute of Technology.

Paper number 3B1160.
0148-0227/83/003B-1160$05.00

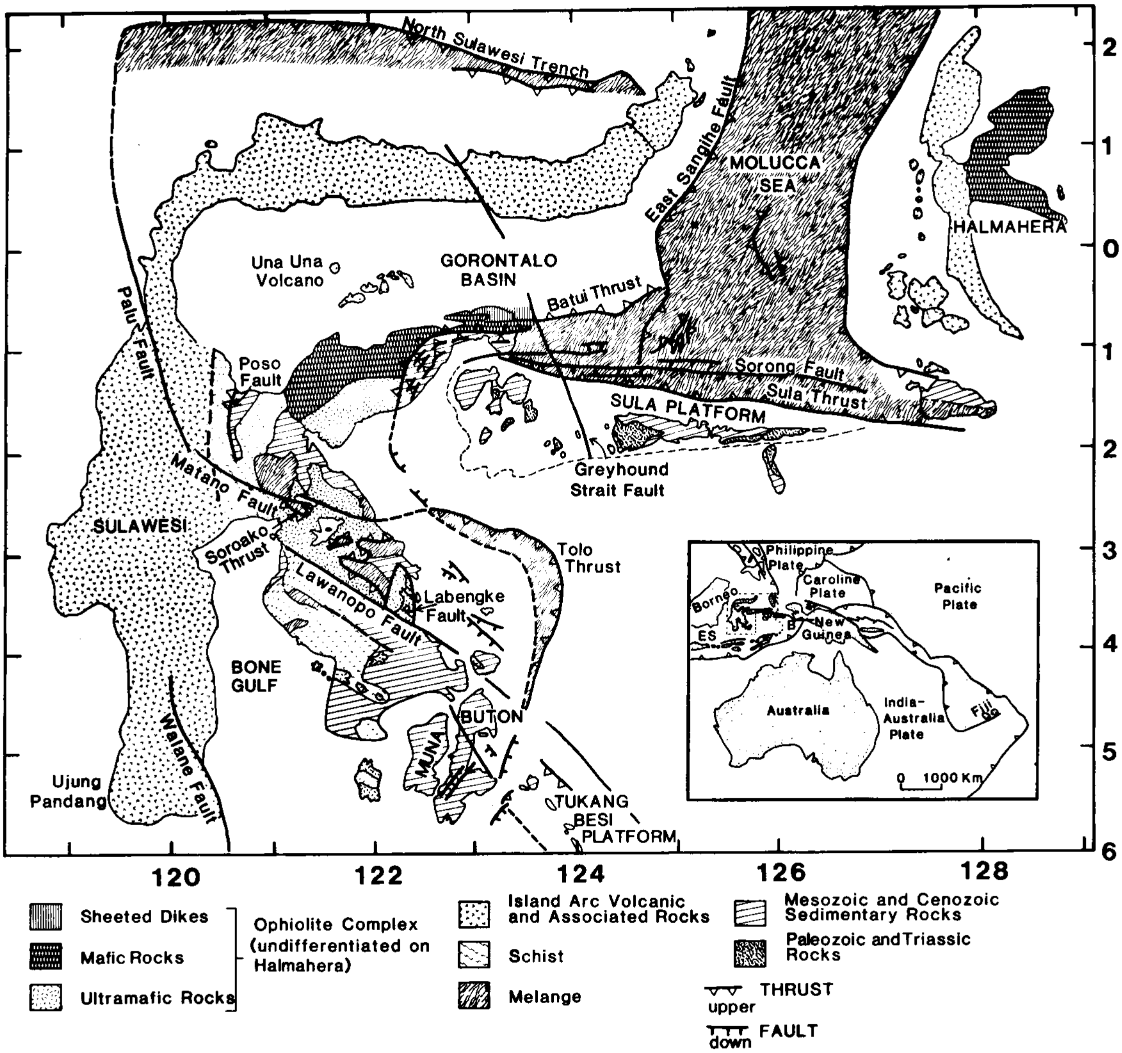

Fig. 1. Generalized tectonic map of Sulawesi and the Molucca Sea region, showing major lithologic sequences and faults. Location map shown as inset (B, Banda arc; ES, Eastern Sunda arc). Bird's Head region of Irian Jaya (New Guinea) is located just north of the symbol "B" on the inset map. Scale along right axis in degrees of latitude, where 1° equals 111 km.

lithologic belts, cored by the central spur to the east. The outer, western belt is a volcanic arc and to its east is a schist belt. The eastern belt on the island of Sulawesi is a tectonized ophiolite and melange belt. The easternmost belt of rocks is the Sula platform. We have mapped zones of thrusting between and within the western belts and most appear to dip away from the Sula platform.

The volcanic arc (Figure 1) consists of a mid-Mesozoic basement complex, a Late Cretaceous to middle Eocene volcanic arc, an upper Eocene to lower Miocene nonvolcanic sequence of carbonate rocks, and a middle Miocene to Quaternary volcanic arc. The most detailed discussions of this belt can be found in the works by Sukamto [1978], Hamilton [1979], and van Leeuwen [1981] and an interpretive reconstruction by Katili [1978]. The Neogene phase of volcanism is widespread in western Sulawesi, beginning in middle Miocene time. Holocene activity is restricted to the NE tip of North Arm and to Una Una volcano. Volcanism waned in the Pliocene and continued sporadically into the Pleistocene (e.g., Mount Lompobatang near Ujung Pandang).

The central schist belt (Figure 1) contains greenschist and blueschist facies metamorphic assemblages, and the latter increase in abundance westward [Brouwer, 1947; van Bemmelen, 1949; Hamilton, 1979]. The western edge of the central belt is where high-pressure assemblages are separated from high-temperature schists, gneisses, and granitic rocks. De Roever [1947] pointed out examples of glaucophane and crossite in radiolarites, the latter inferred to be Cretaceous. No modern study has been made of these radiolarites (except for melange samples discussed below), and while it is tempting to infer a Neogene age for blueschist metamorphism, no radiometric ages are available for any rock in the central schist belt.

The eastern belt of rocks on Sulawesi is dominated by a large, disrupted and tectonized ophiolite. The ophiolite is separated geographically into a northern and southern segment. The

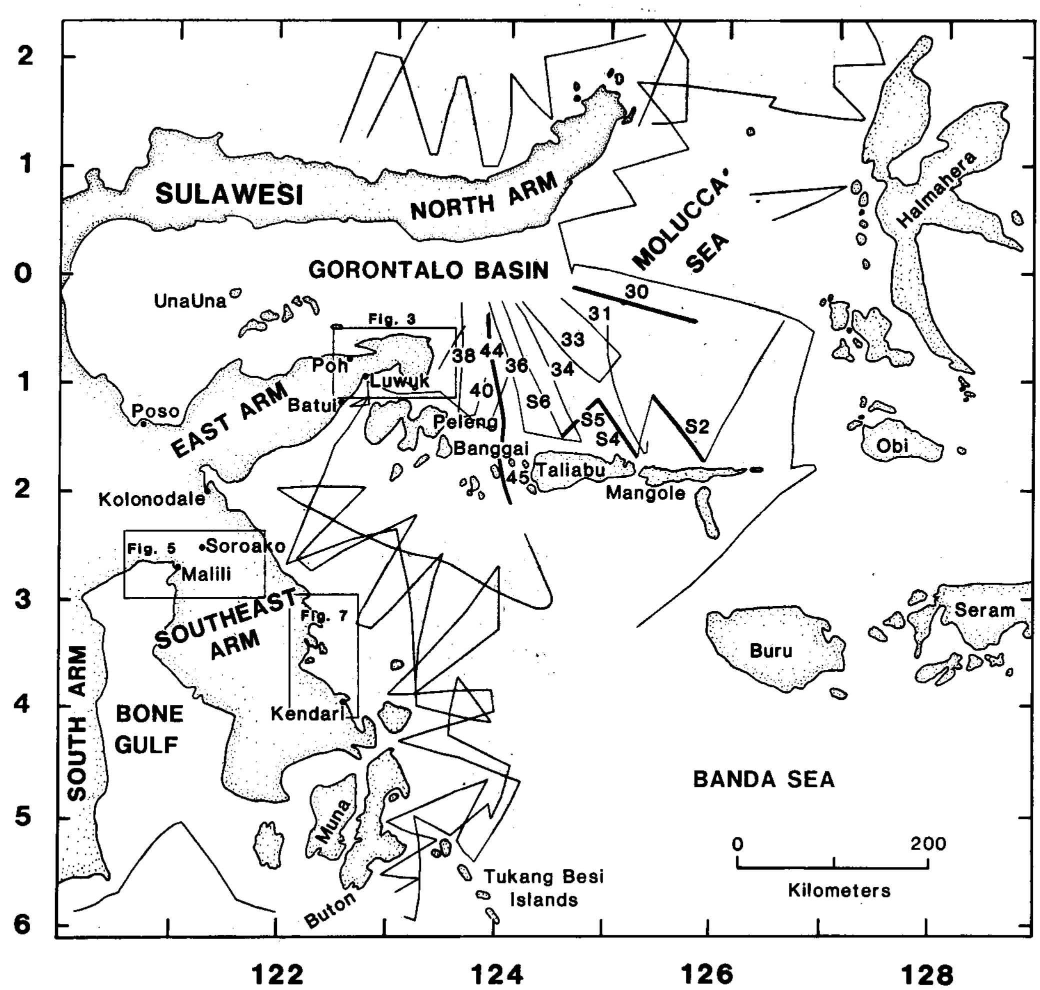

Fig. 2. Track of R/V Thomas Washington on Mariana 9 and Indopac 7 and 10 expeditions. Data along tracks include seismic reflection, gravity, magnetics, and bathymetry. Heavy lines locate profiles shown in this report. Also shown are locations of Figures 3, 5, and 7 and geographical features discussed in the text.

northern segment occurs in the East Arm of Sulawesi and contains a complete, though tectonized ophiolite: ultramafic and mafic plutonic rocks, dikes, basalts, and pelagic sedimetary rocks. The latter are found only in fault contact with the crystalline rocks. The southern segment occurs in the Southeast Arm and comprises dominantly harzburgite and serpentinized harzburgite. Mesozoic and younger sedimentary rocks occur widely on both arms. Extensive melange belts are known on the SE Arm, but have not been described on the East Arm.

The innermost belt of rocks is the Sula platform, which includes Paleozoic and early Mesozoic granitic, volcanic, and metamorphic rocks; Jurassic black shales; Cretaceous clastic sediments and marls; and lower Tertiary sandstone and limestone. A similar geologic setting is found in the Bird's Head region of Irian Jaya, suggesting that the platform was once a part of Irian Jaya that has been displaced westward to its present position in collisional contact with the ophiolite and melange belts of Sulawesi [Hamilton, 1979].

North of the Sula platform is a very thick pile of deformed sediment and melange (called the collision complex) within the arc-arc collision of the Molucca Sea [Hatherton and Dickinson, 1969; Silver and Moore, 1978; Hamilton, 1979; Cardwell et al., 1980; McCaffrey et al., 1980; Moore and Silver, 1983]. The collision complex is in fault contact with the Sula platform in the southern part of the Molucca Sea (the Sula thrust) with the Sangihe arc on the west side of the Molucca Sea (East Sangihe thrust) and with Halmahera on the east (Figure 1).

The Sula thrust extends along the entire length of the north side of the platform and can be traced into the narrow strait between Peleng island and the East Arm of Sulawesi. North of the Sula thrust is an imbricate stack of thrust faults, bounded on the north side by the major fault separating the platform from the ophiolite: the Batui thrust. We have studied this fault on the East Arm of Sulawesi and have mapped it 100 km eastward along the south margin of the Gorontalo basin. In addition, we have identified several lesser faults, both along and across the main structural trends of the collision zone.

Earthquake activity in the vicinity of Sulawesi seems to be concentrated in several discrete zones, although not all can be easily associated with observable surficial features [Silver et al.,

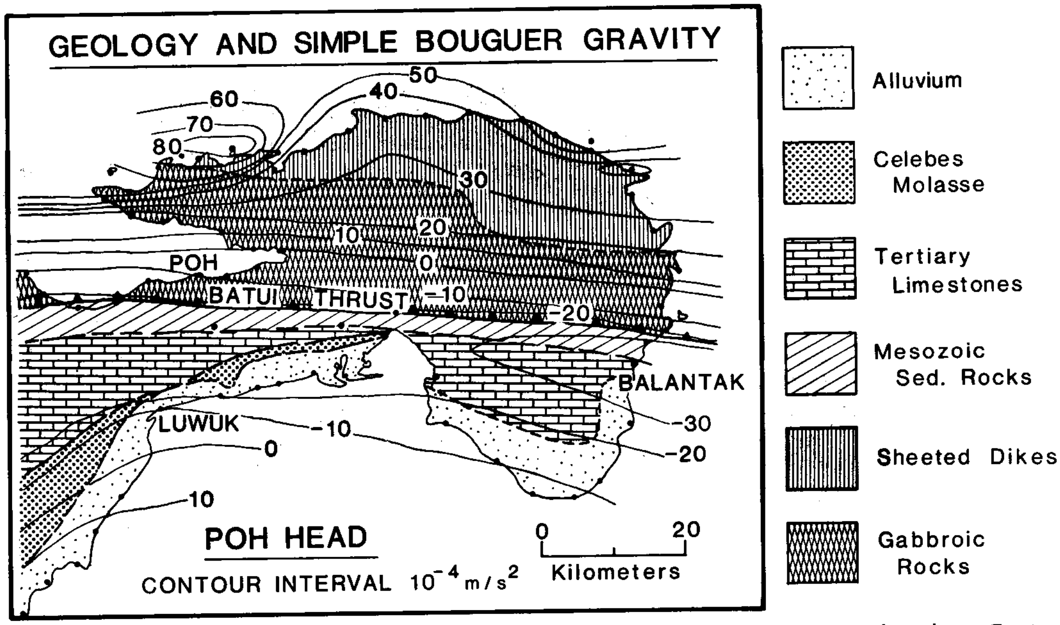

Fig. 3. Generalized geology and simple Bouguer gravity for the Poh district, East Sulawesi (see Figure 2 for location). Shown are the Batui thrust and regional lithologic patterns. Large dots along the coast locate gravity stations.

1983]. The most active region is beneath the east Gorontalo basin, where shallow and intermediate depth foci define a westward plunging, nearly vertical plane of activity. This activity occurs most likely within the southernmost limits of the Molucca Sea plate, which has been subducted westward beneath the Sangihe volcanic arc and the eastern Gorontolo basin. Data from a local earthquake survey by McCaffrey and Sutardjo [1982] show a southward shallowing of hypocenters from beneath the Gorontalo basin toward the Batui thrust. They suggest that these earthquakes may occur within a subducted portion of the Banggai Island block.

Field Program and Data Presentation

Marine geophysical study of the collision zone was carried out during two cruises aboard the R/V Thomas Washington (from Scripps Institution of Oceanography) on Indopac 10 and Mariana 9 expeditions in 1977 and 1979, respectively. Track lines are shown on Figure 2. Supplementary data are from Indopac 7 and 8 and from various cruises through the area by Lamont-Doherty and Woods Hole oceanographic institutions. Most of the data discussed here are from Mariana 9, obtained from seismic reflection, gravity, magnetic, seismic refraction, and bathymetric surveys. A few profiles are multichannel seismic lines which have received preliminary processing. Seismic profiles are presented mostly as line drawing interpretations of original records. Several profiles are shown with free air gravity and magnetic anomaly data. Satellite navigation was used for ship location. All original data are available through the National Geophysical and Solar-Terrestrial Data Center in Boulder, Colorado.

Gravity and geologic studies were made on Sulawesi Island during field seasons in 1977 (6 weeks) and 1978 (5 weeks) and additional geologic studies during short visits in 1976 and 1979 (1 week each). Gravity was measured with a LaCoste Romberg land gravimeter, and the largest errors were due to uncertainty in elevation. Inland elevations were controlled by altimetry using two Baro-Mac precision barometers. Accuracy varied from 1 to 2 m where bench mark control was good (in the Malili-Soroako region, Figure 2) and where coastal stations were taken to as much as 10-15 m on two long inland traverses. Maximum error in gravity varied accordingly: $\pm 5 \times 10^{-5}$ m/s^2 on the long traverses and less than $\pm 1 \times 10^{-5}$m/s^2 along the coast and in the mining districts (The elevation effect on gravity is 0.3 $\times 10^{-5}$ m/sec^2 per meter.)

Geological Observations

The East Arm

A complete though disrupted ophiolite sequence occurs on the East Arm of Sulawesi. The outcrop sequence on Poh Head (Figure 3) and on the East Arm in general is that of a gently north dipping thrust slice. On Poh Head the lowest unit above the thrust is gabbroic, and gabbros plus diabase of wide textural variety occupy the southern part of the ophiolite. Along the north coast just west of Poh (Figure 3) we found gabbro, basalt, diabase, troctolite, amphibolite, serpentine, and some calcite-epidote-quartz schist. On the east coast near Balantak we sampled trondjhemite (plagiogranite). The northern part is a sheeted dike complex. The dikes dip at a high angle and strike north or just east of north in the few places we have measured attitudes. Basalts were found in a very altered state in a few locations but are not widespread along the coastal exposures. On the south coast of East Arm, southwest of Batui, harzburgite is the only representative of the ophiolite. Cherts, limestones, red shales, and a variety of clastic sedimentary rocks occur also, but all are in fault contact with the ultramafic rock.

The gabbroic rocks are commonly hornblende rich. The hornblendes are euhedral or subeuhedral and commonly appear fresh, despite a usually abundant chlorite alteration of other minerals. These hornblendes appear secondary because they are generally not tectonized, as opposed to most of the other minerals. In contrast, the pyroxenes in the diabase and basaltic rocks are commonly replaced by fibrous actinolite. Most samples show greenschist alteration (presence of chlorite, carbonate, actinolite, albite, and serpentine).

This sequence of metamorphic alteration (actinolite replacement of diabase; amphibloite development in gabbros) may indicate its development at least in part on the seafloor, prior to its emplacement. In thin section, however, undulatory extinction, fracturing and bending of grains, and grain boundary slip are common. Faulting and gouge development are common in outcrop and deformation increases toward the Batui thrust. If the hornblende alteration occurred on the seafloor, then the deformation of the ophiolite must have taken place largely prior to emplacement, perhaps along an oceanic transform fault. Alternatively, the mineral deformation may have occurred during emplacement, making the hornblende alteration a post emplacement process.

The rocks south of the Batui thrust can be divided into three stratigraphic groups.

1. The lowermost rocks (cropping out adjacent to the Batui thrust, see Figure 3) are Mesozoic to Paleocene limestones, marls, nodular cherts, and flysch like bedded sandy shales. These rocks are approximately 400 m thick and indicate relatively deep-water deposition. We sampled Belemnites here and limestones near these Belemnite-bearing beds. The limestones have been dated as Cenomanian by D. Jones (written communication, 1980).

2. The second group of rocks is composed of Eocene through lower Miocene sedimentary rocks. These rocks vary from thick (1500 m) reefal limestones in the SE, between Batui and Balantak, to a thinner (less than 500 m) section of clastic sandstone, shale, and conglomerates to the southwest [Hamilton, 1979]. The Mesozoic through lower Miocene rocks are involved in complex thrusting throughout the section [Kundig, 1956].

3) The youngest strata are the Celebes molasse. Kundig suggests that this sequence was deposited as a result of middle to late Miocene uplift of the ophiolite. These molasse deposits are folded and locally faulted, although the intensity of faulting is less than that of the older rocks. Kundig considers the oldest molasse deposits to be upper Miocene reef limestones, but the dominant volume of molasse is Pliocene sandstone and conglomerate.

A late Pliocene phase of folding was followed by Quaternary uplift of up to 900 m on Peleng and 500 m north of Luwuk. Terraces are markedly inclined in the region from Luwuk to Batui (down to the southwest), indicating considerable arching. As indicated above, the rocks SE of the Batui thrust are highly imbricated. The thrust zone is described by Kundig [1956, p. 224] "... as a system of piled up...thrust sheets with differential movements toward the south and southeast. Although the thrust of the individual sheets might not amount to very much, maybe a few kilometers, the sum might be considerable." Kundig [1956]

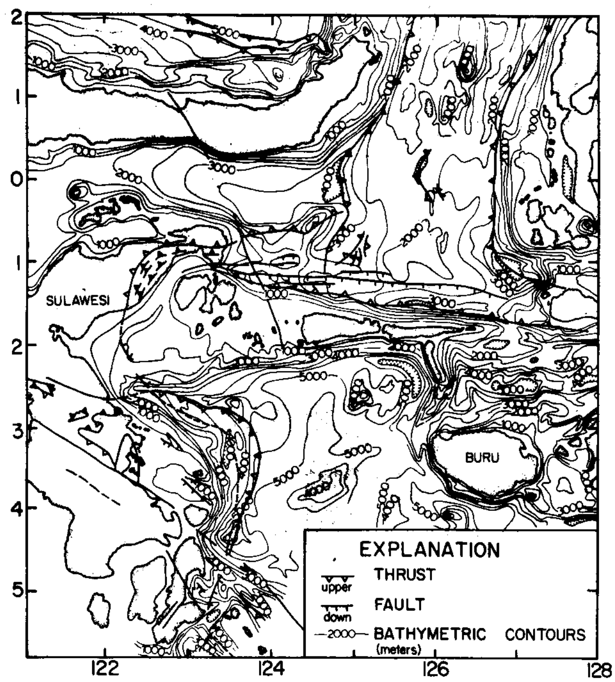

Fig. 4. Bathymetric map of Molucca Sea and North Banda basin, showing locations of major fault zones.

separated the ophiolite into a "frontal imbrication zone (partly hidden below the transgressive molasse) and a backward 'root zone'." The frontal (southern) zone involves imbrication of ophiolite and sedimentary rocks in the vicinity of the Batui thrust. Hamilton's [1979] reinterpretation of a Landsat photo of the Batui area of the East Arm corroborates this view in that the most intense thrusting is confined to the Mesozoic through mid-Tertiary sedimentary section, with lesser thrusting to the south in the younger sediments and to the north on the ophiolite.

The Southeast Arm

Based on bathymetric data (Figure 4), the southern edge of the Sula platform intersects the Southeast Arm of Sulawesi at about 2.5° south, just where the Matano fault enters the Tolo Gulf. We have examined the ophiolite and its contact relations with a large body of melange to the west of this southern edge, in the Malili-Soroako region [Ahmad, 1978] (Figure 5), where International Nickel Company has a large nickel mining operation. The ophiolite is dominantly ultramafic in this region. The ophiolite-melange contact is easily followed because of clear geomorphic and vegetative differences between major rock types. The ophiolite-melange contact is a low-angle thrust, with ultramafic rocks always forming the upper plate. In one road cut a knife-edge contact is exposed, dipping 20° NE.

We studied the melange in some detail in one area of good exposure. At this location the melange contains both red shale matrix and serpentine matrix varieties (see Figure 6). The southern 30 m of the outcrop area have a red shale matrix, the next 15 m are schist and amphibolite, and the northern 40 m have serpentine matrix. The

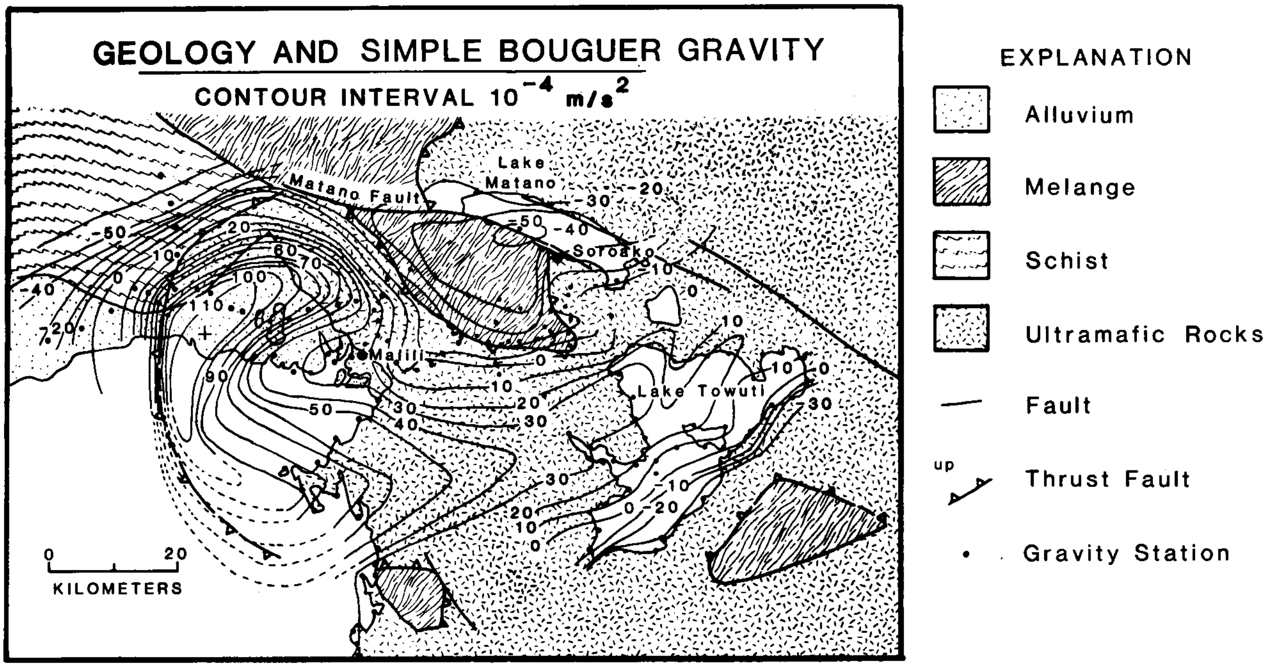

Fig. 5. Geology and simple Bouguer gravity of the Malili-Soroako region, southeast Sulawesi (see Figure 2 for location).

crystalline component of the shale is well over 90% quartz, based on x-ray diffraction analysis. Blocks in this shale matrix are red chert (dated by D. Jones (written communication, 1980) as Cenomanian from radiolaria) and metabasite with rare blocks of serpentine. The metabasite is dominantly quartz-chlorite and is locally foliated to give a schistose texture. Foliation in the matrix is variably oriented, though a dominant N to NE dip prevails. At one locality (15 m on Figure 6) an arcuate zone of foliation is parallel to the edge of a metabasite block.

The schist block contains garnet-quartz-chlorite-muscovite schist, hornblende-chlorite-quartz-muscovite schist, amphibolite, and meta-chert. These blocks are not separated by matrix material. This composition is similar to though not identical with descriptions by Egeler [1947] of rocks found in the central schist belt.

Blocks in the serpentine-matrix melange are

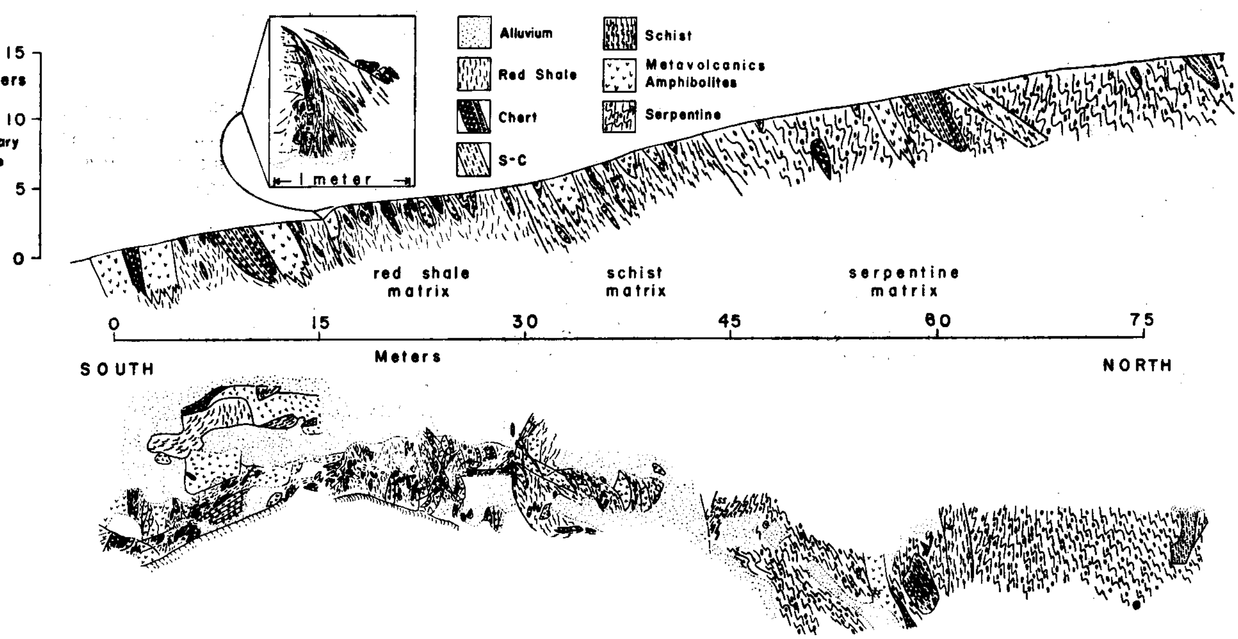

Fig. 6. Detailed strip map and section located in the southeast corner of the melange in central Sulawesi, south of Lake Matano (see Figure 5). S-C stands for silica carbonate rock.

greenstone (serpentinized olivine basalt), serpentine-carbonate, silica carbonate, chert, and metagabbro. The serpentinized olivine basalt contains quartz, antigorite, olivine, magnesite, chlorite, and cryptocrystalline plagioclase in the groundmass. It is strongly foliated and mapped separately as a "schist" block at 62 m.

The contact between the central schist block and the red shale matrix material (30 m on Figure 6) is a prominent zone of shearing which dips 50° N. This attitude is similar to those of foliation of the serpentine and shale matrices. A few hundred meters uphill (north) from this section is more red shale matrix and downhill from the section to the SE is more serpentine. In the latter area, a large chert lens 10-20 m thick and 75-100 m across has been mined. Boreholes through the chert encountered serpentine below.

To summarize, blocks within the red shale matrix tend to be smaller and mixing is greater than within the serpentine matrix. Little fine-scale mixing occurs between matrix types, but interthrusting is common on a scale of hundreds of meters. Not surprisingly, blocks within the serpentine matrix show greater signs of serpentinization. In other locations, rodingites are common in the serpentine, composed of very fine grained chlorite and hydrogarnet.

Large (kilometers long) limestone blocks in the melange are tectonized along their contacts with matrix material. The limestone is also recrystallized and in places brecciated. Although blocks of limestone are sheared off the main masses into the melange matrix, these are found close to the parent blocks and are relatively rare at distances of hundreds of meters or more from the parent blocks.

The schist-amphibolite block in the central part of Figure 6 (hornblende or garnet-chlorite-quartz-muscavite) has undergone burial to greater PT conditions than either the red shale melange to the south or the blocks in the serpentine matrix to the north. The block may have been intruded into this section from below, or it may represent a small fault slice from the central schist belt to the west.

Mixing within the melange appears to occur in two dominant ways. The first is by major thrusting of melange masses on a scale of hundreds of meters. The second is by local shearing or flattening, which results in a diamond-shaped pattern of intersecting joints and foliation planes in the matrix and phacoid-shaped blocks on a scale of meters down to millimeters. Deformation is more intense at the contacts between different matrix types and between matrix and very large blocks than elsewhere in the melange. These observations imply a mixing process analogous, on a scale of tens of meters and more, to that of two immiscible fluids (the "fluids" being red shale and serpentine).

In the Kendari district (Figure 7) along the coast south of the Sula platform, two major faults appear to control the dominant structure. On the west is the linear Lawanopo fault [Hamilton, 1979], which separates ultramafic rocks from schist. We observed a large natural geothermal field along this fault just southeast of Tinobu (Figure 7), and we suspect that the fault is nearly vertical in this region. The Labengke fault (named after a large island which is bounded by

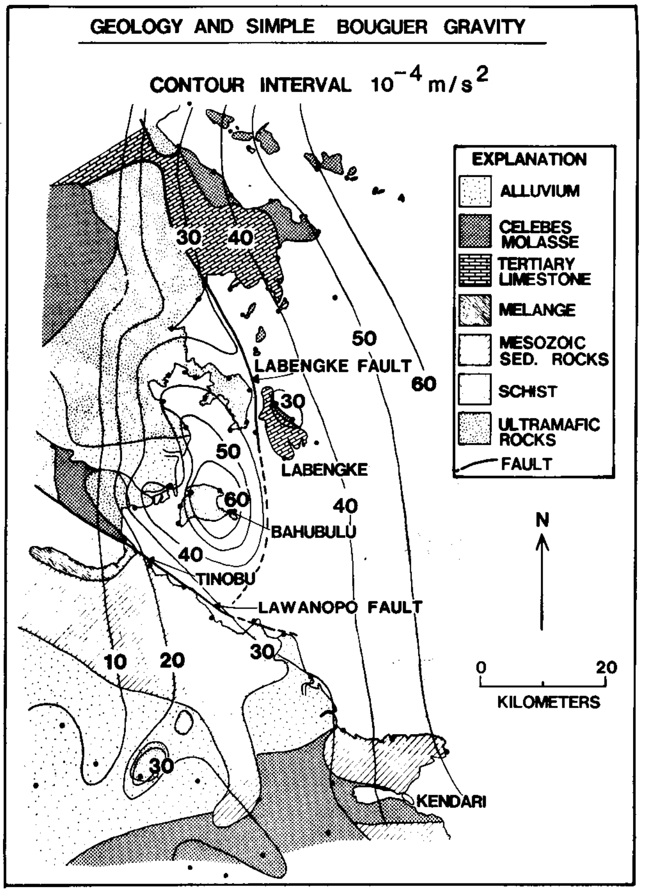

Fig 7. Geology and simple Bouguer gravity of the Kendari district, southeast Sulawesi (see Figure 2 for location). Dots show locations of gravity stations.

this fault) has an irregular map pattern and separates ultramafic rocks on the west from Tertiary limestones. Based on gravity observations, discussed below, we suggest that this fault is a low-angle, west dipping thrust fault.

Gravity Interpretation

A map of the regional gravity field (Figure 8) was constructed using the data along the tracks of Figure 2, onland gravity observations discussed below, and existing published data (Watts and Bodine, 1978). The map is constructed largely from free air anomalies, but locally in central Sulawesi the Bouguer correction is substantial. Contours on land were based largely on coastal observations requiring little Bouguer correction.

The most remarkable anomaly is developed at the southern end of the Molucca Sea, reaching below -250×10^{-5} m/s^2 in water depths of about 2 km. This observation has been explained by the presence of thick (>14 km), low-density, deformed sedimentary rocks and melange underlying the Molucca Sea [Silver and Moore, 1978; Hamilton, 1979; McCaffrey et al., 1980]. The free air low extends toward the East Arm of Sulawesi, and a low of -30×10^{-5} m/s^2 occurs on the southern side of the arm.

A gravity low of -50 to -100×10^{-5} m/s^2 is

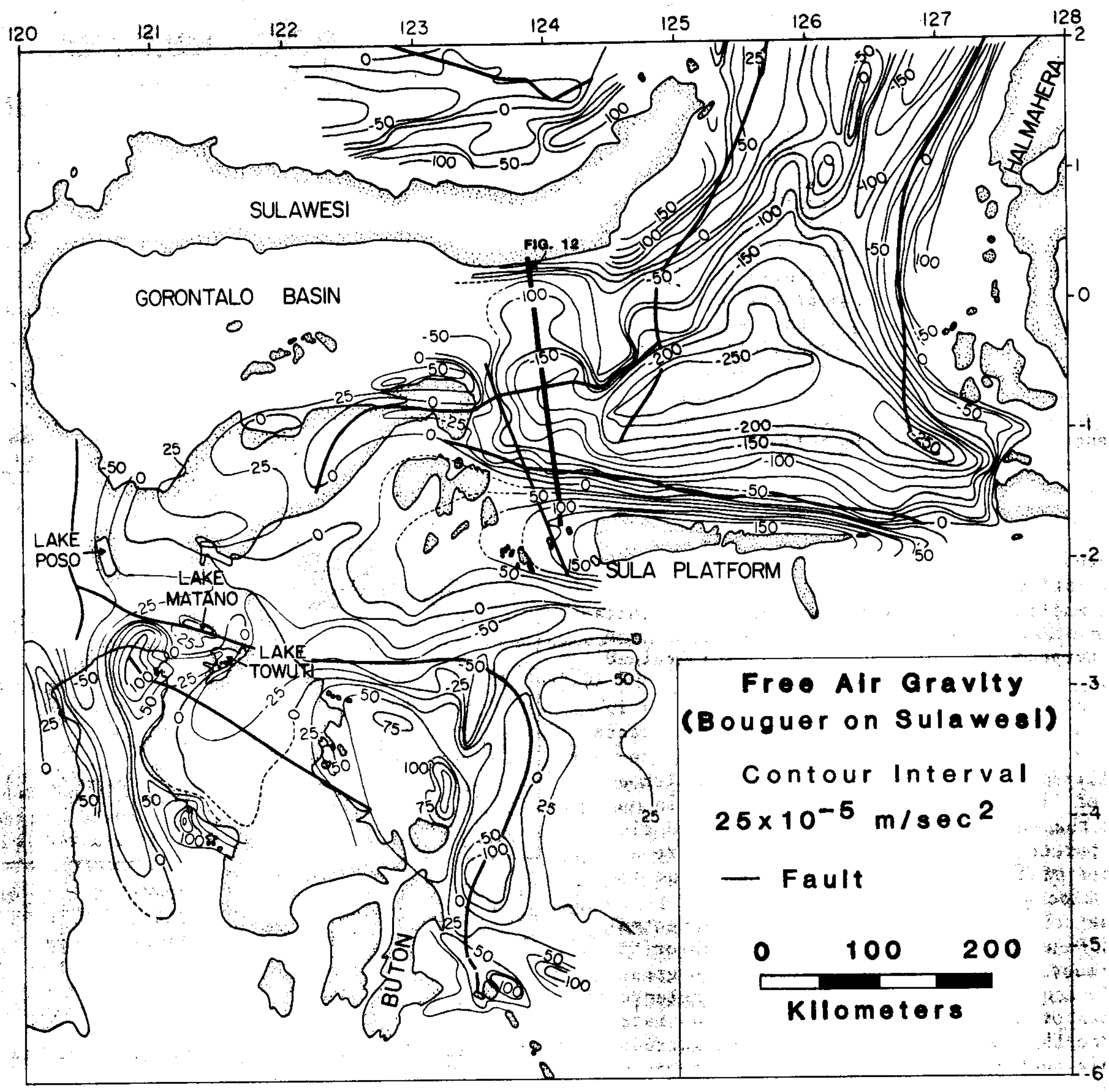

Fig. 8. Gravity map of eastern Sulawesi, the North Banda basin, and the Molucca Sea. Data base discussed in text. Free air anomaly offshore and simple Bouguer anomaly Sulawesi. Maps tie together well because most of the land stations, except for the Lake Matano region, were taken at the coast. Also shown are locations of major faults and Figure 12.

measured over the Gorontalo basin. Its depth is about 3.5 km, and it contains a thick pile of sediment. The basin is actually positive compared with the adjacent Molucca Sea gravity, but it is not in isostatic balance.

Very high gravity values (up to 150 x10^{-5} m/s^2 near the coasts) are found along the Sula platform. Such values seem anomalously high for continental margin rocks, but volcanic rocks, which are common on the platform, may be responsible for the observed anomaly. Bending of the positive contours to the south just east of Taliabu suggests that the gravity over Peleng island may be significantly lower than that over Mangole and Taliabu.

The southern margin of the Sula platform and its intersection with the Southeast Arm of Sulawesi are marked by a nearly E-W trending gravity low of about -50 x10^{-5} m/s^2. This low is controlled by topography, as can be seen by comparison with Figure 4. It also marks the northern end of the Tolo thrust, which is discussed in a separate paper.

Gravity observations on the East Arm were taken largely along the coast within a meter of mean sea level (Figure 3), making elevation and Bouguer corrections minimal for most stations. A gravity low of -25 to -35 x10^{-5} m/s^2 occurs within 10 km south of the Batui thrust. Gravity rises to 40 to 50 x10^{-5} m/s^2 along the north coast of Poh Head, locally reaching values in excess of 80 x10^{-5} m/sec^2. The absence of a sharp gradient associated with the Batui thrust indicates that the thrust is low angle and dense rocks associated with the ophiolite in this region are thin. The gradual increase in gravity northward indicates thickening of the mafic and, perhaps, ultramafic sections in that direction, in support of Kundig's

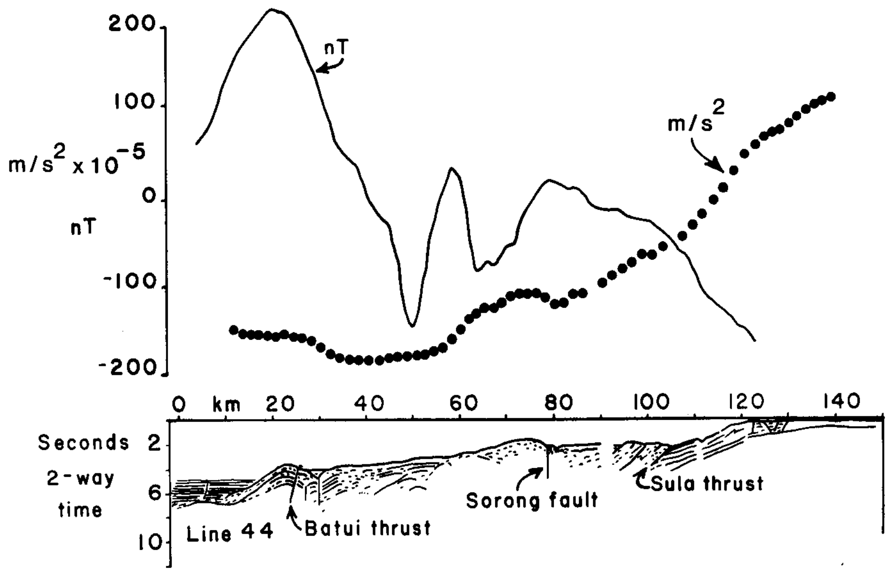

Fig. 9. Line drawing interpretation of multichannel profile 44 (vertical exaggeration (VE) = 3.5x). Free air gravity and magnetic anomaly profiles shown above (see Figure 2 for location).

interpreted northern "root zone" for the ophiolite.

The gravity low just south of the Batui thrust requires a low-density (sediment) wedge, possibly dipping under the ultramafic section of the ophiolite. The high to the north is due to increasing thickness of relatively high-density rocks of the ophiolite. The gradual increase in gravity toward the south coast suggests that the sedimentary section south of the Batui thrust probably thins in that direction. Most simply interpreted, the ophiolite dips gently northward, and the arcuate trace of the Batui thrust cuts across the petrologic "Moho" in the interior north of Batui.

In the Malili-Soroako region of central Sulawesi (Figure 5), gravity is variable over the ultramafic body but measures between 10 and 35 $\times 10^{-5}$ m/s^2 over wide areas, implying relatively shallow depths to its base [Silver et al., 1978]. Near the contact with the melange gravity reaches negative values, locally below -20×10^{-5} m/s^2. This decrease in gravity is gradual toward the thrust contact, implying a thinning of ultramafic rocks approaching the trace of the fault. The mining operations at Soroako are on laterites above unserpentinized harzburgite (3.27 Mg/m^3), yet gravity here is between -20 to -30×10^{-5} m/s^2.

Over the melange, gravity averages -40×10^{-5} m/s^2, and the melange body west of Soroako is outlined roughly by the -20×10^{-5} m/s^2 contour. These low values occur also over the large (10-20 km in long dimension) limestone blocks (density 2.7 Mg/m^3), showing that these blocks have shallow roots and must be considered large blocks in the melange. The gravity and geologic observations imply that the ultramafic rocks form a widespread, thin sheet through which the melange appears locally as windows. Thickening of the ultramafic body is apparent only near the contact with the schist belt.

South of the Sula platform, in the Kendari district (Figure 7), the main gravity anomaly overlies Bahubulu island, reaching a maximum of 60 or 35 $\times 10^{-5}$ m/s^2 after removal of a pronounced regional gradient. The island and associated anomaly lie near the large Lawanopo fault, which separates the ophiolite from the schist belt in this region. The anomaly may indicate a local thickening of the ophiolite adjacent to the fault. On the east side of the ultramafic body, gravity shows no significant effect across the Labengke fault (Figure 7), suggesting that the ultramafic rocks are part of a very thin sheet that thrusts over the Tertiary limestone.

Marine Geology and Geophysics

The Sula platform collision zone consists of several major fault zones which separate the ophiolite, the platform, and the Molucca Sea collision zone. These faults are the Batui thrust, the Sula thrust (Figure 1), the Sorong fault zone, and the East Sangihe thrust. In addition, a major cross fault separates the Banggai Islands from the Sula Islands within the platform. Most of these faults are submarine and are known only through marine geophysical interpretation. The Batui thrust is partly subaerial, on the East Arm of Sulawesi, and we have discussed geologic and gravity information there. The structural relations between these features are indicated in Figures 1 and 4, and the locations of profiles are on Figure 2.

The Batui Thrust

We have traced the Batui thrust eastward about 100 km from the East Arm, using the geophysical control shown in Figure 2. Evidence that the ophiolite underlies the northern block of the fault is seen in profile 44 (Figures 9 and 10) in which subbottom reflectors within the uplifted block north of the Batui thrust can be traced northward beneath subhorizontal turbidites of the Gorontalo basin. Nearly 2 km of basin edge sediment overlies the block, and the sediment surface stratigraphically underlies the turbid-

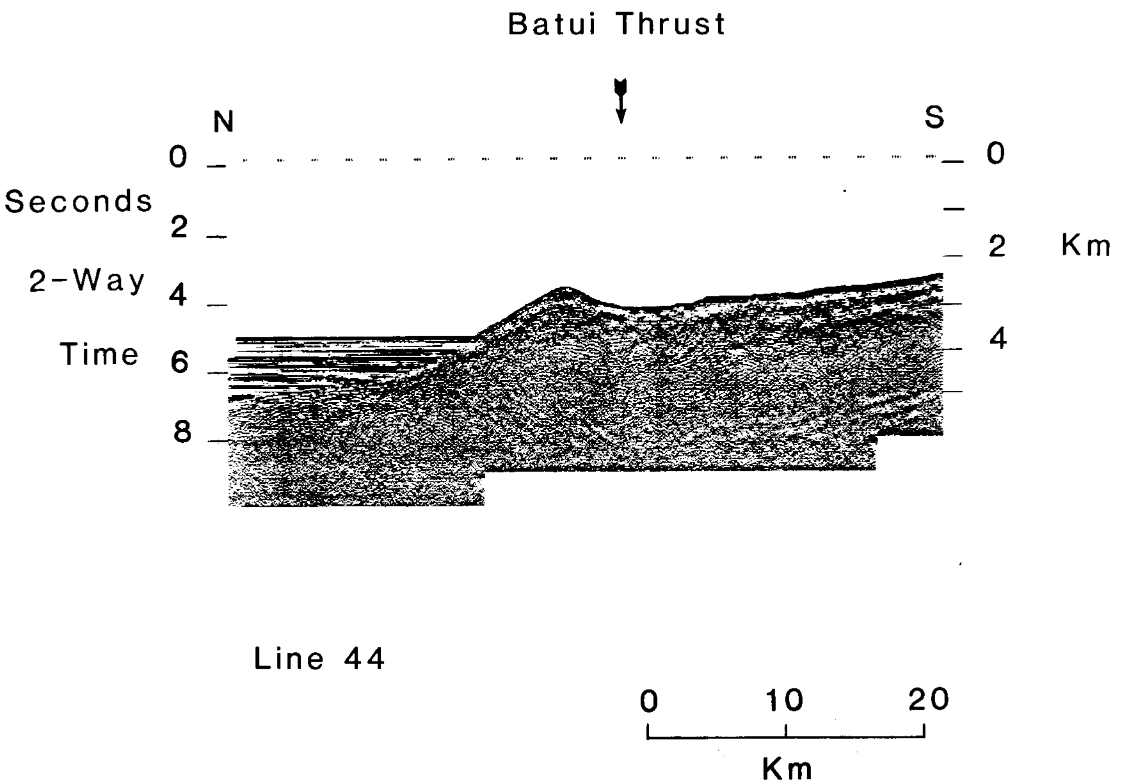

Fig. 10. Photo of original reflection profile 44, showing detail of the Batui thrust.

ites. The basin edge sediments thin as they pass beneath the turbidites, and the basement is continuous with that which underlies the Gorontalo basin.

In addition to seismic reflection evidence for continuity of the sedimentary section overlying the mafic rocks, we can also use magnetic data for evaluating continuity of the basement. The peak in the magnetic anomaly occurs a few kilometers north of the thrust (Figures 9 and 11). Modeling shows that the south edge of a magnetized body must underlie the peak. Although the basement continues part way up the slope, it does not appear to reach the fault. The rocks may lose their magnetic properties in the process of thrusting.

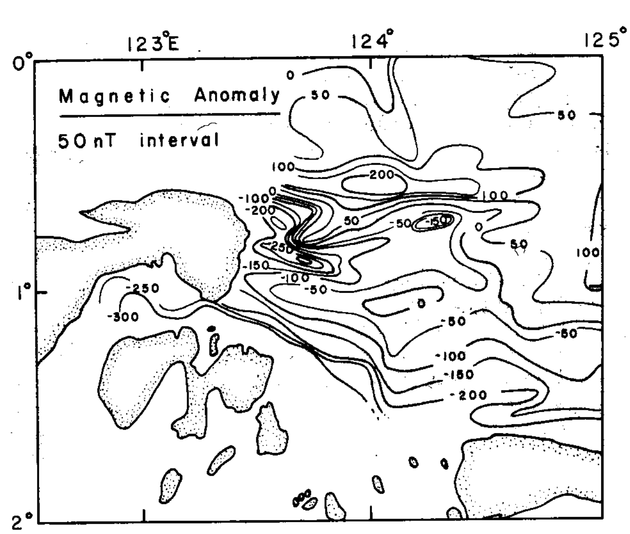

Fig. 11. Magnetic anomaly map of the collision zone east of Poh Head and north of the Sula platform.

The basement of the Gorontalo basin appears to be mafic in character, based on the following observations. First, the depth to basement, after correcting for isostatic loading of the sediment pile, is about 4.5 km. Such basement depths imply thin, dense crust, and this depth is about average for oceanic crust, although the gravity low over the basin must be compensated for by a somewhat thickened crust. Second, a refraction profile run across the southern part of the basin and part-way up the flank of the inferred ophiolite yields a seismic velocity of 6 km/s below the (1-2 km thick) sediment layer [McCaffrey et al., 1981]. This velocity is reasonable for, though not unique to, the upper part of oceanic crust. This velocity structure continues up the seaward flank of the ophiolite, in agreement with structure interpreted from reflection profiles. Third, the basement surface is irregular and complexly faulted, a characteristic of oceanic crust. While these observations represent indirect evidence for oceanic-type crust beneath the Gorontalo basin, our ability to map this uplifted southern edge of the basin laterally westward into the Sulawesi ophiolite provides the most direct tie.

Figure 12 shows a crustal model based on gravity observations, seismic refraction and seismic reflection data (discussed below) for the Gorontalo basin to the Sula platform (Figure 8). The northern half of Figure 12 is based on seismic refraction line 10-9 from McCaffrey et al. [1981] in which basement is observed to dip to the north away from the Batui thrust. This structure also

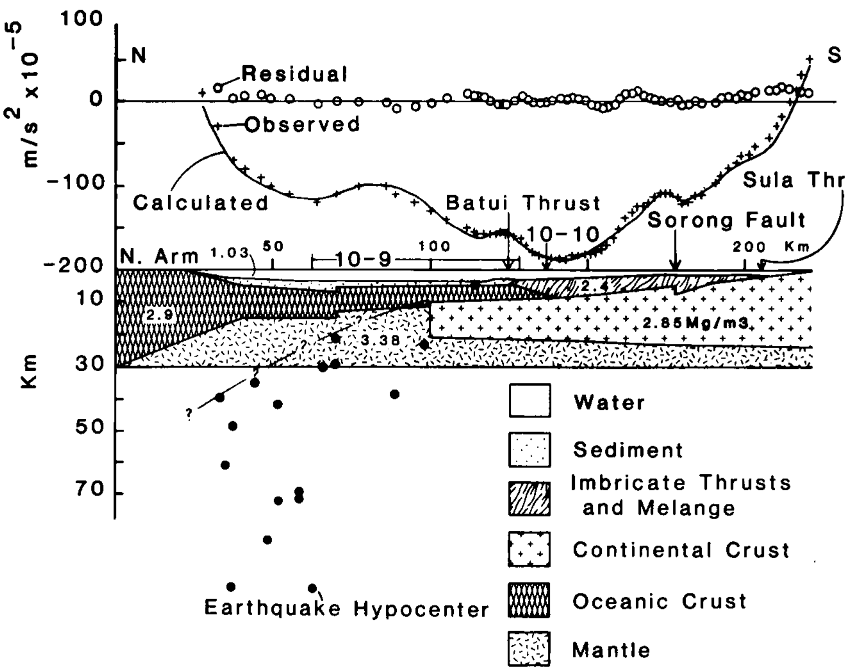

Fig. 12. Alternate crustal models across the Gorontalo basin, Batui thrust, and Sula platform. Model satisfying gravity and refraction data. The 10-9 and 10-10 are locations of refraction profiles. Gorontalo basin crust thrusts over Sula platform, and Sula thrust represents the frontal thrust. Earthquake hypocenters seem to define the upper part of a Benioff zone. Value of 2.9 Mg/m^3 taken a zero density contrast for modeling. See Figure 8 for location.

satisfies gravity observations if the crust is thin (7-10 km), consistent with oceanic thicknesses. A fault with 1.5 km of throw near 70 km is necessary to fit the local high in the gravity field. This fault was observed in refraction profile 10-9 by McCaffrey et al. [1981].

South of the thrust zone, crust must be thicker because gravity values reach -190×10^{-5} m/s^2 and refraction profile 10-10 [McCaffrey et al., 1981] revealed basement at a maximum depth of 6 km below sea level (Figure 12). For reasonable crustal densities, crustal thickness must be about 20 km beneath the region south of the Batui thrust. Gravity is not sensitive to details of the relationship between the Sula platform crust and that beneath the Gorontalo basin. We show it as a shallow angle thrust based on observations on the East Arm. Modeling a thin slab of dense material just above the thrust does not change the fit to the gravity data significantly. A reasonable geologic interpretation of this region would probably involve a series of slices of ophiolitic material at and south of the Batui thrust.

A steep gradient south of the Sorong fault cannot be due to the topographic effect of the ridge flanking the fault, but it is well modeled by a vertical fault in basement with approximately 3 km of vertical separation. The Sorong fault thus appears to be a major basement feature.

The extreme low-gravity values over the area south of the Batui thrust indicate that the crust of the Sula block is depressed. Because the gravity lows extend both south and north of the Batui thrust, the depression cannot be due only to loading by the crust of the Gorontalo basin. A likely source for the force needed to depress the plate is a slab attached to the Sula block. This suggestion is supported by the observation of earthquake hypocenters dipping northward from the Batui thrust to a depth of about 100 km [McCaffrey and Sutardjo, 1982].

From its tectonic setting we suggest that the Gorontalo basin represents a forearc basin, making the Sulawesi ophiolite analogous to the Coast Range ophiolite of California. Perhaps the Gorontalo basin has undergone some flexure as a result of collision. A forearc basin setting provides a good analog for understanding the large negative gravity anomaly of the basin.

The Sula Thrust and Related Faults

The Sula thrust [Silver, 1981] separates north dipping strata deposited on the north flank of the platform from the complexly deformed material to the north. All profiles, from the tip of East Arm to the eastern part of Sula Islands, show the thrust (see lines S4 and S5 for detail of the thrust in Figure 13). The feature we are calling the Sula thrust was mapped by Hamilton [1979] as the "North Sorong Sula fault" [Hamilton, 1979, Fig. 80b], but we feel he incorrectly ended the fault by connecting it with the central longitudinal fault zone of the Molucca Sea. The eastern profiles (S2, S4, and S5, Figure 13) show a wide zone of very deformed material (the collision complex) north of the Sula thrust, whereas the western lines (e.g., Figure 9) show a much narrower deformed zone. These regions are separated by the East Sangihe thrust.

A series of faults can be mapped parallel to and north of the Sula thrust. One fault zone, which we have called the Sorong fault, extends essentially the entire mapped length of the Sula

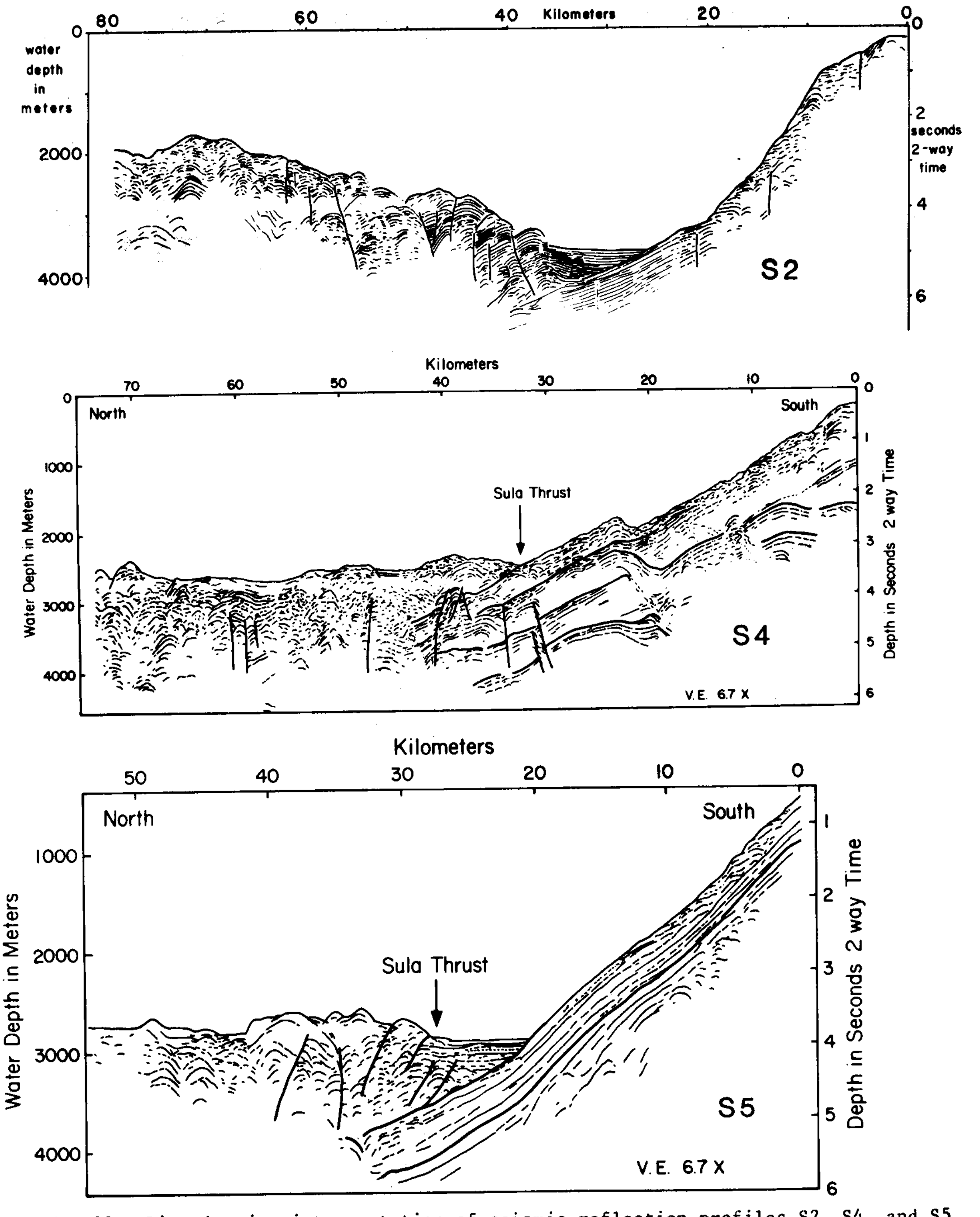

Fig. 13. Line drawing interpretation of seismic reflection profiles S2, S4, and S5 crossing the Sula thrust. (VE = 6.7x.) See Figure 2 for location.

thrust and is characterized by south facing escarpments. The Sorong fault is defined as a left-slip transform along the north coastal region of the Bird's Head, Irian Jaya [see Hamilton, 1979]. We infer that the Sorong fault zone continues west to the region north of the Sula platform, but we have no control on its sense of motion in this region. The zone may represent an earlier thrust front that later propagated southward to its present position, or it may indicate younger activity (either thrust or lateral faulting) within the accretionary wedge.

The tectonic significance of the Sula thrust and related faults is not entirely clear, though their role must be critical. They could indicate continued deep-seated convergence between the Sula platform and the region to the north. Alternatively or in addition, they could result from lateral extrusion of the Molucca Sea collision complex southward over the platform, driven by the arc-arc collision of the Molucca Sea. Based on observations of the East Sangihe thrust, discussed below, we feel that the Sula thrust must represent true crustal convergence, at least in part.

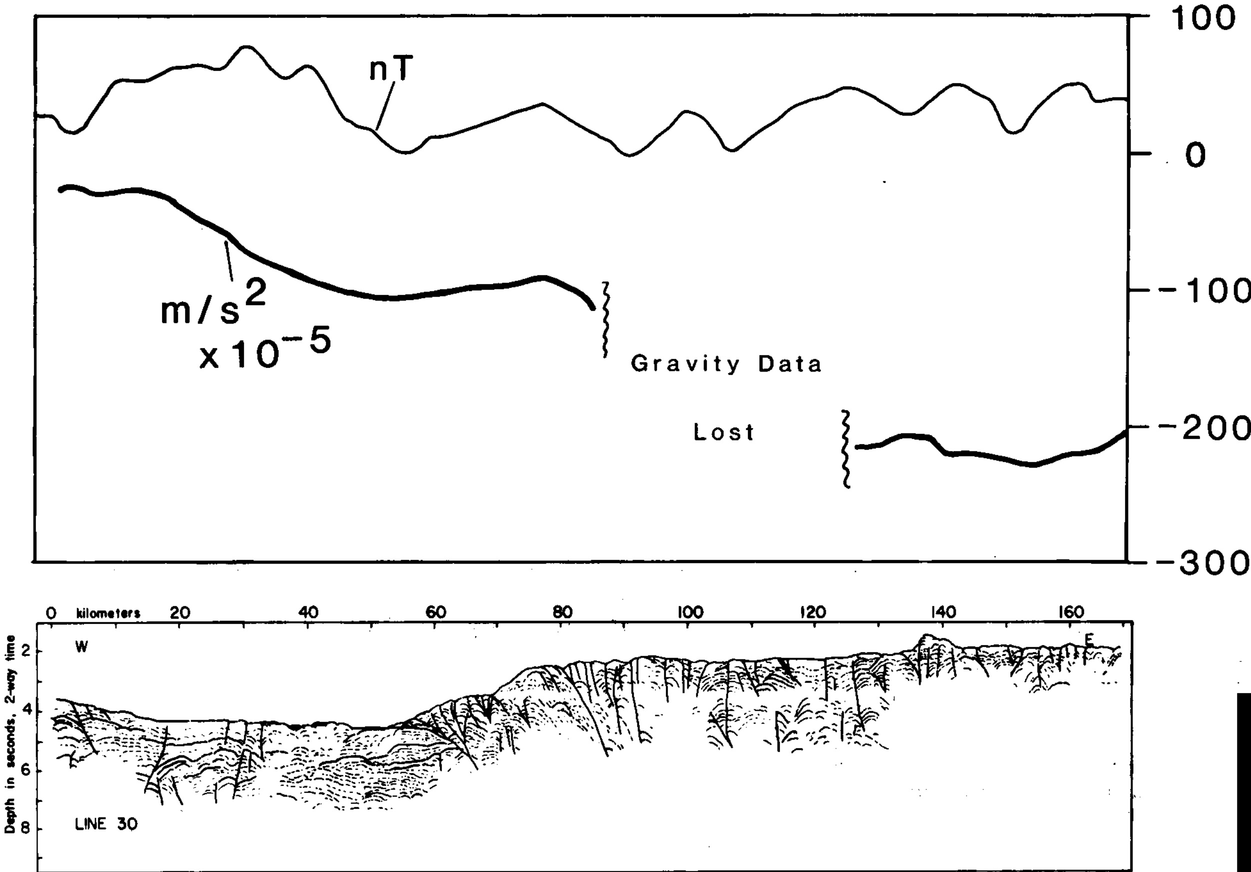

Fig. 14. Line drawing interpretation of seismic reflection profile 30, crossing the East Sangihe thrust along the east edge of the Gorontalo basin. Thrust crops out at 52 kms. (VE = 6.7x.) Upper profiles are free air gravity in m/s^2 and resiaual magnetics in nT. See Figure 2 for location.

The East Sangihe Thrust

The East Sangihe thrust [Hamilton, 1979; Silver and Moore, 1978; Silver, 1981] is a frontal thrust fault along the western margin of the Molucca Sea collision complex. We have mapped the East Sangihe thrust as far north as Sangihe Island (about 4° N). The thrust is well displayed south of the westward bend in the arc but does not bend with the arc. Profile 30 (Figure 14) crosses the fault at 52 km from the Gorontalo basin. The profile shows highly deformed material of the collision complex standing higher and thrusting westward over nearly undeformed sediments in the basin. Although the collision complex stands topographically higher, free air gravity is much lower than over the Gorontalo basin (Figure 8). Using a combination of reflection profiles, the gravity map (Figure 8), the magnetic map (Figure 11), and bathymetry (Figure 4), we can map the edge of the collision complex SW to its intersection with the Sorong fault zone. The collision complex does not continue into the East Arm of Sulawesi, as suggested by van Bemmelen [1949], Veining-Meinesz [1948], and Katili [1975], although an older or different subduction complex lies parallel to the Sula platform to the west of the East Sangihe thrust and is overridden by that thrust.

Bathymetrically (Figure 4), the East Sangihe thrust is marked by a narrow trough along most of its length, allowing us to trace the trough southward to near its intersection with the Sorong fault. Figure 8 shows a sharp gravity gradient from very low values east of the fault to higher values to the west. This gradient dies out south of the Batui thrust. Magnetics are less well defined than bathymetry or gravity, but the magnetic map (Figure 11) shows an area of high-frequency and high-amplitude anomalies west of the fault, which die out rapidly to the east. The geometry implied by this structure is as follows.

The Molucca Sea plate subducts beneath the Gorontalo basin and physically ends at a point about midway along its axis, as defined by seismicity. The collision complex, however, thrusts over the basin along the East Sangihe thrust, as seen in profile 30 and by the gravity data. This fault also covers the Batui thrust because it continues southward while the Batui does not continue eastward. The East Sangihe thrust projects to the Sula thrust but the latter is not affected by it and continues far to the west past this intersection. Because the Sula thrust is continuous on either side of the contact with the East Sangihe thrust, we infer that activity within the Molucca Sea collision zone cannot explain the entire development of the Sula thrust. Thus convergence between the platform and the ophiolite has occurred relatively recently (within the Pleistocene).

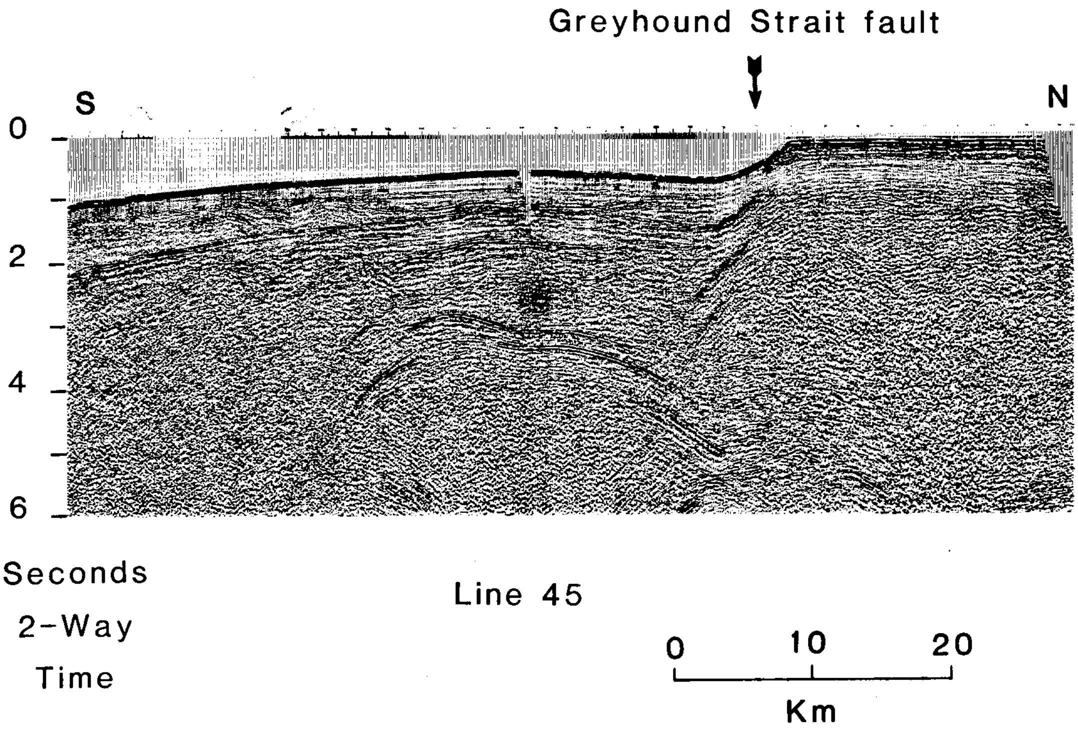

Fig. 15. Photo of multichannel seismic profile 45, crossing the Greyhound Straight fault. (VE = 3x.) See Figure 2 for location.

The Greyhound Strait Fault

The south side of the platform is very steep and can be inferred to have originated by lateral faulting, but profiles crossing the slope do not indicate young or presently active faulting. An enigmatic exception is found on part of line 45, a processed multichannel line (Figure 15). A prominent scarp is developed above a zone of structural discordance, most likely representing a major fault. The problem lies in deciding whether this fault is an E-W structure that marks the trace of the South Sorong fault or whether it is a NW trending fault that cuts obliquely across the platform, subparallel to the profile.

Our crossing was confined to a narrow channel, the Greyhound Strait, which may be structurally controlled. Evidence against this scarp marking the South Sula fault is its location. Any throughgoing South Sula fault would have to make a pronounced reentrant to join this fault crossing, an unlikely geometry for a large transform fault. We feel it is more likely that the fault seen in line 45 trends NW across the platform, through Greyhound Strait, for which we name it here the Greyhound Strait fault.

We have tentative indications that the Greyhound Strait fault continues NW to the east of East Arm. The magnetic map (Figure 11) shows a NW trending gradient on the north end of Greyhound Strait and irregular terminations of high-amplitude anomalies to the NW, off the East Arm. Seismic reflection lines 38 and 40 (not shown), show a north facing escarpment just at the predicted crossing points for this fault. Although we do not have properly placed geophysical profiles to trace this fault farther north, Katili [1975] has indicated a NW trending fault across the North Arm, essentially on strike with the Greyhound Strait fault (this connection suggested by S. Box oral communication, 1981).

Discussion

The collision of the Sula platform with the Sulawesi arc has resulted in emplacement of a major ophiolite and melange belt and development of major thrust and lateral fault zones. These features provide important clues to the kinematics of the collision process. The collision also illustrates several scales of tectonic mixing and a process for amalgamation of "tectonostratigraphic terranes" [Coney et al., 1980], a process that is being found increasingly in the geologic record.

The northwesterly motion of the Sula platform with respect to the crust of the Gorontalo basin was apparently responsible for the emplacement of the ophiolite, at least on the East Arm. This type of motion would have produced oblique slip along the northern margin of the platform. Evidence for oblique slip is based largely on logical reconstructions of the path of the Sula platform, from its origin in Irian Jaya to its present position of collision [Hamilton, 1979]. A major structure to have formed by this movement was the Batui thrust, which developed as the ophiolite was emplaced against the platform. The southern edge of the Gorontalo basin is inferred to have been uplifted by the platform like the lid of a can being sliced by a can opener.

The timing of emplacement of the ophiolite is constrained only in a relative way, as radiometric ages are lacking for the rocks. The ophiolite is often associated with pelagic sedimentary rocks that have radiolaria of Cenomanian age, but these rocks are not found in depositional contact on the ophiolite. Because the ophiolite generally appears to thicken along the contact with rocks of the central schist belt [Silver et al., 1978], emplacement appears to have been beneath the schist. Conversely, the ophiolite thins toward contact with melange or Mesozoic sedimentary rocks and was thus thrust over these rocks. Observed contact relations with the melange on Southeast Arm and along the Batui thrust on the East Arm support this view. Structurally, the ophiolite appears to be thrust beneath rocks toward the volcanic arc and over rocks that lie toward the Sula platform. The age of thrusting on each side need not be the same, and our impression from viewing a number of contact regions is that emplacement beneath the schist preceded emplacement over the rocks of the Sula platform. In the marine seismic profiles we see a clear sense of thrust faults which become younger toward the platform.

The age of uplift of the ophiolite could be constrained in two ways. One is the age of ophiolitic debris found in the "Celebes Molasse" [Kundig, 1956], which are reported to be late Miocene and younger [Hamilton, 1979; Sukamto, 1978]. A minimum relative age of uplift could be found by dating turbidites in the Gorontalo basin which are not turned up against the edge of the ophiolite, whereas older sediment is clearly uplifted. We have no drilling information for the age of these turbidites.

Although disrupted on a variety of scales, the distribution of rock types within the East Arm ophiolite follows a sequence from harzburgite in the SW, through gabbro and diabase in the central part, with basalt and sheeted dikes in the NE. Pelagic sedimentary rocks are in fault contact with the ophiolite, but a clear depositional sequence on basalt has not been described. A petrologic Moho probably crosses the arm roughly east to west in a complex manner. The distribution of rocks on East Arm can be explained by southward thrusting and northward tilting of the ophiolite as the Sula platform attempted to subduct beneath it.

The voluminous serpentine bodies in contact with massive peridotite sheets might indicate early development as an oceanic transform fault. Although serpentinization can occur at every stage of development of an ophiolite, from its origin to emplacement and subaerial weathering [Coleman, 1977], the close proximity of the large serpentine bodies with massive peridotites implies a special kind of development. Saleeby [1978] has made a good case for both formation and emplacement of ophiolites by transform fault processes. Serpentinization and melange formation of exclusively pelagic sources would be understandable in a deep-sea transform fault. In addition, the orientation of dikes on the northern tip of East Arm are roughly north-south or essentially perpendicular to that of the Sula platform and Sorong fault. This relation may be fortuitous, but such orthogonal relations between suspected transform faults and sheeted dike orientations are observed commonly in other ophiolites (E. Moores, oral communication, 1982), a relationship expected from the ubiquitous geometry of ridge-fault intersections in the modern ocean basins.

A transform origin poorly explains the low-angle thrust contacts between melange and ultramafic rocks and the moderately north dipping foliation of the melange. Flatter thrusts and dipping foliation might be expected to result from a component of convergence along the transform fault after it had formed initially. A north to NW direction of subduction (due to the northwesterly direction of collision by the Sula platform) might account for the locally mapped foliation. More extensive mapping of melange structure could provide a tighter constraint on this problem. Mixing with rocks of the schist belt could be due to either transform faulting or subduction processes.

Numerous ideas have been suggested for the process of ophiolite emplacement [Dewey and Bird, 1971; Dewey, 1976; Oxburgh, 1972; Ben-Avraham et al., 1982; Coleman, 1971, 1977; Christensen and Salisbury, 1975; Brookfield, 1977]. Many of these involve some aspect of collisional tectonics, while Brookfield stressed the role of transform faulting, Christensen and Salisbury favored collision of spreading centers with subduction zones, and Oxburgh proposed the obduction of flakes of ocean crust directed opposite to the sense of subduction of the main slab.

The Sulawesi ophiolite does not conform to the "flake tectonic" mechanism of Oxburgh because the sense of emplacement thrusting was the same as that of subduction. We do not have positive ages on the ophiolite so we can't be certain of the time represented between its formation and its emplacement. Its close association with Late Cretaceous cherts and limestones, however, implies that the rocks were at least 50 Ma old when they were emplaced. Models implying orthogonal convergence do not apply here because the direction of convergence was highly oblique, but the setting was that of subduction rather than entirely transform.

Major ophiolites have been emplaced in eastern Halmahera, in the Molucca Sea collision zone [McCaffrey et al., 1980; Moore et al., 1981a, b] and throughout the Philippine Islands [Ranneft et al., 1960; Hamilton, 1979; Hawkins et al., 1981]. These ophiolites represent different origins and different emplacement processes. When this region is finally incorporated into a continent-continent collision, the ophiolites will be molded into a linear belt, shaped by the geometry of the colliding margins, largely destroying the geographic complexity we observe today. Extreme care should be taken, therefore, in interpreting the paleotectonic sgnificancce of ophiolites in ancient, linear mountain belts.

Acknowledgments. We thank John Katili, Joe Widartoyo, H. M. S. Hartono, and Benny Wahju for their continual support in carrying out this work. We are grateful to Warren Hamilton, Robert Coleman, Carl Bowin, Jason Saleeby, and an unidentified AGU reviewer for their careful and thoughtful reviews of drafts of this paper, and to Audrey Wright, Annette Whelan, and Peggy Plumley for drafting figures. We also thank Paul Henkart and Amoco International Oil Company for their roles in processing seismic reflection data; Tony Watts for providing us with regional geophysical data on magnetic tape; and Donna Blackman, Laurie Brown, Perry Crampton, Jeff Deen, and Randy Smith for support in various parts of this project. Finally we thank the officers, crews, and scientific parties of the R/V Thomas Washington on

Mariana 9 and Indopac 10 expeditions, and many very helpful people and officials of Sulawesi for making this work not only possible but also extremely enjoyable.

References

Ahmad, W., Geology along the Matano fault zone, East Sulawesi, Indonesia, in Proceedings Regional Conference on the Geology and Mineral Resources of Southeast Asia, GEOSEA, 143-150, Indonesian Association of Geol., Jakarta, 1978.

Ben-Avraham, Z., A. Nur, and D. Jones, The emplacement of ophiolites by collision, J. Geophys. Res., 87, 3861-3867, 1982.

Brookfield, M. E., The emplacement of giant ophiolite nappes, Tectonophysics, 37, 247-303.

Brouwer, H. A., in Geological Exploration in the Island of Celebes, 346 pp., North Holland, Amsterdam, 1947.

Cardwell, R. K., B. L. Isacks, and D. E. Karig, The spatial distribution of earthquakes, focal mechanism solutions and subducted lithosphere in the Philippine and northeastern Indonesian Islands, in The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, Geophys. Monogr. Ser., vol. 23, edited by D. E. Hayes, p. 1-35, AGU, Washington, D. C., 1980.

Christensen, N. I., and M. H. Salisbury, Structure and constitution of the lower oceanic crust, Rev. Geophys. Space Phys., 13, 57-86, 1975.

Coleman, R. G., Plate tectonic emplacement of upper mantle peridotites along continental edges, J. Geophys. Res., 76, 1212-1222, 1971.

Coleman, R. G., Ophiolites, 229 pp. Springer-Verlag, New York, 1977.

Coney, P. J., D. L. Jones, and J. W. H. Monger, Cordilleran suspect terranes, Nature, 288, 329-333, 1980.

De Roever, W. P., Igneous and metamorphic rocks in eastern central Celebes, in Geological explorations in the island of Celebes, edited by H. A. Brouwer, p. 65-173, North-Holland, Amsterdam, 1947.

Dewey, J. F., Ophiolite obduction, Tectonophysics, 31, 93-120, 1976.

Dewey, J. F., and J. M. Bird, Origin and emplacement of the ophiolite suite: Appalachian ophiolites in New Foundland, J. Geophys. Res., 76, 3179-3206, 1971.

Egeler, C. G., Contribution to the petrology of the metamorphic rocks of western Celebes, in Geological Explorations in the Island of Celebes, edited by H. A. Brouwer, pp. 181-346, North-Holland, Amsterdam, 1947.

Geotimes, Penrose field conference on ophiolites, 17, 24-25, 1972.

Hamilton, W., Tectonics of the Indonesian region, U. S. Geol. Surv. Prof. Pap. 1078, 345 pp., 1979.

Hatherton, T. and Dickinson, W. R., The relationship between andesitic volcanism and seismicity in Indonesia, the Lesser Antilles, and other island arcs, J. Geophys. Res., 74, 5301-5310, 1969.

Hawkins, J. W., C. A. Evans, and S. Bloomer, Ophiolite series rocks from an island arc complex: Zambales range, Luzon, Philippine islands, (abstract) Eos Trans. AGU, 62, 409, 1981.

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

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

Kundig, E., Geology and ophiolite problems of East Celebes, Koninkl. Nederlandsch Geol.-Mijnbouw Genoot., Verh., Geol. Ser. 16, 210-235, 1956.

McCaffrey, R., and R. Sutardjo, Reconnaissance microearthquake survey of Sulawesi, Indonesia, Geophys. Res. Lett., 9, 793-798, 1982.

McCaffrey, R., E. A. Silver, and R. W. Raitt, Crustal structure of the Molucca Sea collision zone, Indonesia, in The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, Geophys. Monogr. Ser., vol. 23, edited by D. E. Hayes, pp. 161-177, AGU, Washington, D. C., 1980.

McCaffrey, R., E. A. Silver, and R. W. Raitt, Seismic refraction studies in the East Arm, Sulawesi - Banggai Islands region of eastern Indonesia, in The Geology and Tectonics of Eastern Indonesia, Spec. Publ. 2 edited by A. J. Barber and S. Wiryosujono, pp. 321-325, Geological Research and Development Center, Bandung, Indonesia, 1981.

Moore, G. F., and E. A. Silver, Collision processes in the northern Molucca Sea, in The Geology and Tectonics of East and Southeast Asian Seas: Part 2, Geophys. Monogr. Ser., vol. 27, edited by D. E. Hayes, pp. 360-372, AGU, Washington, D. C., 1983.

Moore, G. F., C. A. Evans, J. W. Hawkins, and D. Kadarisman, Geology of the Talaud islands, Molucca Sea collision zone, NE Indonesia, J. Struct. Geol., 3, 467-475, 1981a.

Moore, G. F., J. W. Hawkins and R. Villamar, Geology of southern Mindanao, Philippines (abstract), Eos, 62, 1086, 1981b.

Oxburgh, E. R., Flake tectonics and continental collision, Nature, 239, 202-204, 1972.

Ranneft, T. S. M., R. M. Hopkins, Jr., A. J. Froelich, and J. W. Gwinn, Reconnaissance geology and oil possibilities of Mindanao, Am. Assoc. Pet. Geol. Bull., 44, 529-568, 1960.

Saleeby, J., Kings River ophiolite, southwest Sierra Nevada foothills, California, Geol. Soc. Am. Bull., 89, 617-636, 1978.

Silver, E. A., A new tectonic map of eastern Indonesia, in Geology and Tectonics of Eastern Indonesia, Spec. Pub. 2, edited by A. J. Barber and S. Wiryosujono, pp. 343-347, Geological Research and Development Center, Bandung, Indonesia, 1981.

Silver, E. A., and J. C. Moore, The Molucca Sea collision zone, Indonesia, J. Geophys. Res., 83, 1681-1691, 1978.

Silver, E. A., R. McCaffrey, and R. B. Smith, Collision, rotation, and the initiation of subduction in the evolution of Sulawesi, Indonesia, J. Geophys. Res., 88, (this issue).

Silver, E. A., Y. Joyodiwiryo, and R. McCaffrey, Gravity results and emplacement geometry of the Sulawesi ultramafic belt, Indonesia, Geology, 5, 527-531, 1978.

Sukamto, R., The structure of Sulawesi in the light of plate tectonics, in Proceedings of the Regional Conference on the Geology and Mineral Resources of Southeast Asia, GEOSEA, pp. 121-141, Indonesian Assoc. Geol., Jakarta, 1978.

van Bemmelen, R. W., The Geology of Indonesia, vol. 1A, 732 pp., Government Printing Office, The Hague, 1949.

van Leeuwen, T. M., The geology of southwest Sulawesi with special reference to the Biru area, in The Geology and Tectonics of Eastern Indonesia, Spec. Pub. 2, edited by A. J. Barber and S. Wiryosujono, pp. 277-304, Geologic Research and Development Center, Bandung, Indonesia, 1981.

Vening-Meinesz, F. A., Gravity Expeditions at Sea, 1923-1938, vol. 4, 233 p., Delftsche Uitgevers Maatschappij, Delft, The Netherlands, 1948.

Watts, A. B., and J. H. Bodine, Free air gravity field, in A Geophysical Atlas of the East and Southeast Asian Seas, edited by D. E. Hayes, Geol. Soc. Am., MC-25, 1978.

Y. Joyodiwiryo, Geological Research and Development Center, Jalan Diponegoro 57, Bandung, Indonesia.

R. McCaffrey, Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139.

E. A. Silver, Earth Sciences Board and Center for Coastal Marine Studies, University of California, Santa Cruz, CA 95064.

S. Stevens, Scripps Institution of Oceanography, La Jolla, CA 92093.

(Received July 16, 1982;
revised May 10, 1983;
accepted July 1, 1983.)