Gravity results and emplacement geometry of the Sulawesi ultramafic belt, Indonesia

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ABSTRACT

Preliminary results of gravity observations on the Southeast Arm of Sulawesi in eastern Indonesia provide evidence on the structure of the large ultramafic belt and associated melange units. Gravity highs at the schist-ultramafic contact indicate that the ultramafic rocks are very thick there, possibly dipping beneath the schist. The gravity effect of the ultramafic rocks decreases eastward away from the schist, and a gravity low over a large zone of limestone and melange requires a thick body of low density material, probably melange, to nearly surround the limestone blocks. The interpreted structure imposes constraints on models of emplacement of the ultramafic slab and is compatible with slicing off slivers of ocean crust and upper mantle in a subduction zone, but it is not compatible with obduction or with diapiric intrusion. Uplift of ultramafic rocks was aided initially by the presence of abundant low-density melange and, finally, by the collision of Sulawesi with the Banggai-Sula Islands.

INTRODUCTION

The late Cenozoic collision between the Australian continent and the Indonesian island arcs has produced an extremely complex and rapidly evolving geologic setting in eastern Indonesia (Hamilton, 1977); because of this complexity the region now displays a rich variety of active and recently completed collision events (Fig. 1). Of interest here is the emplacement of the large ultramafic and melange belt in eastern Sulawesi.

Sulawesi consists of a western volcanic belt, a central schist belt, and an eastern belt characterized by ultramafic rocks and melange (Sukamto, 1975a; Hamilton, 1978, 1979; Fig. 1). The volcanic arc is largely calc-alkalic and was active from about 17 m.y. ago into the Pleistocene (Sukamto, 1975a), but it is presently inactive except at the northernmost tip where it is a continuation of the Sangihe arc. This active arc forms the west side of an arc-arc collision with the Halmahera arc (Silver and Moore, 1978).

The Molucca Sea collision complex between the two arcs continues southward and is thought to bend westward into the eastern ultramafic and melange belts of Sulawesi, just as the Sangihe arc bends westward to the inactive western volcanic arc of Sulawesi (Hamilton, 1977, 1978; Katili, 1975). The eastern side of the ultramafic and melange belt is bordered not by an arc, but by a continental fragment, the Banggai-Sula Islands, which is believed to have been sliced off Irian Jaya and faulted westward to collide with the Sulawesi volcanic arc (Visser and Hermes, 1962), a distance of 800 to 1,000 km (Hamilton, 1973). It is quite likely that this collision played an important role in the emplacement of the ultramafic and melange belts.

The central schist belt consists of a variety of schist types (de Roever, 1947), attaining metamorphic grade as high as glaucophane-lawsonite facies. No radiometric ages have been reported from the central schist belt, but Kundig (1956) reported that cherts bearing Cretaceous Radiolaria are metamorphosed to blueschist facies.

A generalized version of the geologic map of the eastern arms of Sulawesi is shown in Figure 2. On the Southeast Arm (south of Kolonodale) the ultramafic rock is mostly massive peridotite, largely harzburgite, with little associated gabbro or basalt reported. Local zones of serpentinization occur, and surface samples are sometimes partially serpentinized. In contrast, on the East Arm (north of Kolonodale), a full ophiolite suite is reported (Brouwer, 1947; Kundig, 1956). Ultramafic rocks on the Southeast Arm are in fault contact with Cretaceous and Tertiary limestone and with lesser amounts of terrigenous sedimentary rocks. Melange belts are not shown on the published geologic map, but we observed that the large limestone mass south of Lake Matano is actually cut and surrounded by melange. The melange has a serpentine matrix and produces a low, hummocky topographic surface. Common clasts include Cretaceous(?) chert

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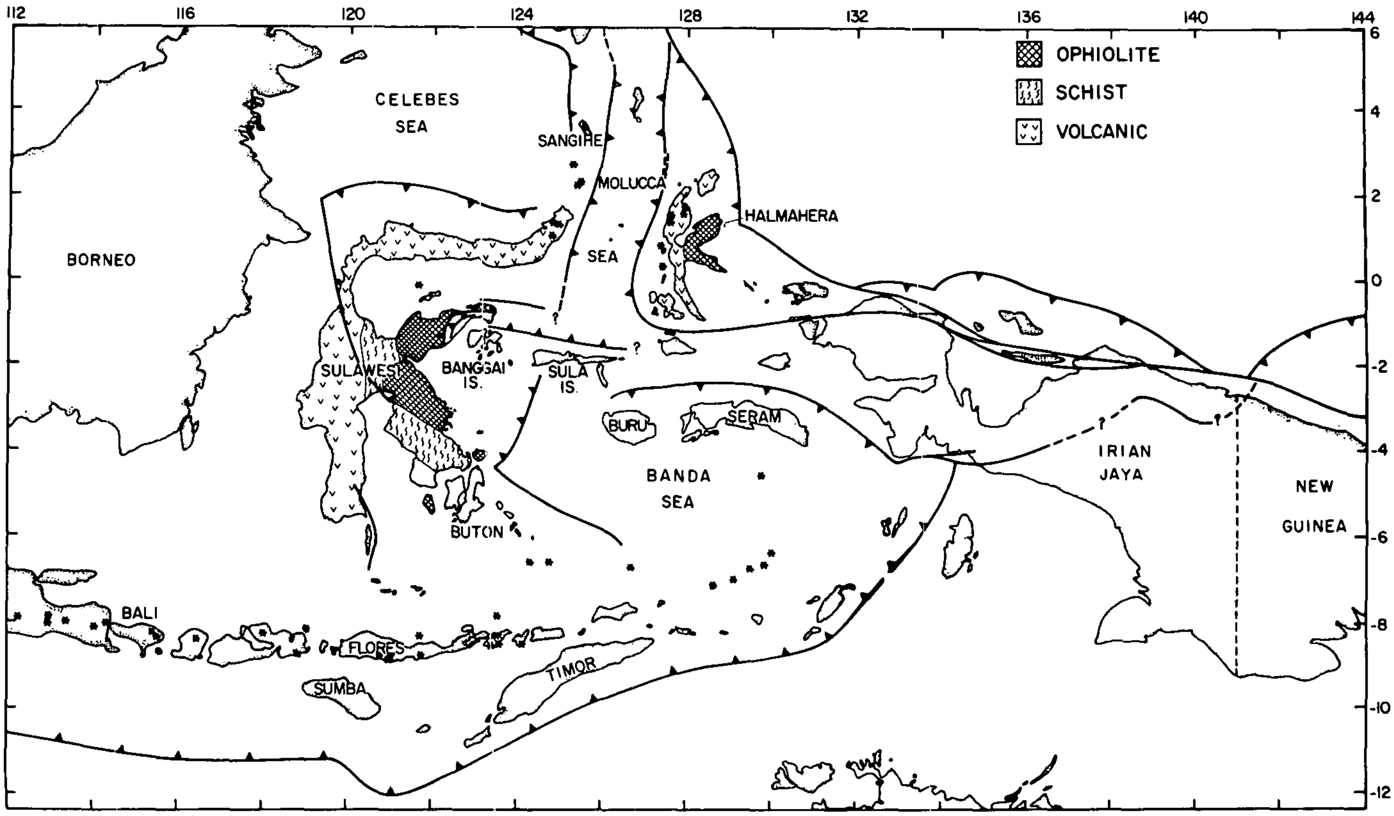


Figure 1. Tectonic map of Indonesia, showing location of volcanic, schist, and ophiolite belts on Sulawesi. Teeth on upper plate of thrust faults as mapped at the ground surface. Asterisks mark reported Holocene volcanoes. Modified from Hamilton (1974) and Silver and Moore (1978).

and limestone; the limestone can be several kilometres in length and is generally fractured, recrystallized, and stylolitized. At one location less than 10 m wide, we observed mafic volcanic rock, chert, magnesite, and a variety of schist types in the melange. Sukamto's (1975b) geologic map was constructed from aerial photos, reports of transects by Dutch geologists, and from a photogeologic map by International Nickel Company geologists. Photos can clearly display the highly resistant ultramafic rocks and the karst limestones but melange belts generally have not been reported, except by Hamilton (1973, 1977, 1979), who infers their presence in east Sulawesi from descriptions of the early Dutch workers. Locally, melanges have been called Tertiary sediment or included with the limestone from photo interpretation. Contact relations between schist and ultramafic rocks have not been observed, but a thrust contact has been mapped between ultramafics and Miocene limestones on the eastern part of the East Arm (Kundig, 1956). The thrusting involves even the youngest molasse deposits (lumped as part of Tertiary sediment in Fig. 2), suggesting that thrusting has continued into the Pliocene or even Pleistocene (Kundig, 1956; van Bemmelen, 1949).

THE GRAVITY MAP

In August 1977 we made two gravity transects across the Southeast Arm (Fig. 3), occupying 262 stations with La Coste–Romberg model G gravity meter 421. Many stations were taken also along the coastline. Meter drift was controlled by base ties once or twice daily. Reading precision was 0.01 mgal, and we corrected all values for tidal effects. Inland elevations were controlled by a recently surveyed oil pipeline that runs southwest from Lake Matano, and by altimetry elsewhere. Values are not terrain corrected but most stations are in areas of low relief, and this correction would be within the error of elevation determination (and always positive). All Bouguer gravity values are considered accurate to ± 3 mgal or better and coastal stations to ± 0.5 mgal. These uncertainties have no effect on the data (25-mgal contour interval) or conclusions presented in this paper. Gravity values were corrected to absolute values relative to station 189-50 of Jezek (1976) at the Hasanuddin Airport in Ujung Pandang, with a gravity value of 978119.11 mgal.

Gravity highs occur at the west side of the ultramafic belt and the east side of the volcanic belt. Lows occur over the melange belt and over a sedimentary prism resting on the schist west of Wotu. A large gravity high (+115 mgal) occurs at Wotu (Fig. 2) over a low fluvial plain and is associated with the schist-ultramafic contact. The north to northeast trend of this anomaly appears to cut across the southern projection of the schist belt and suggests the presence of ultramafic rock rather than schist basement in the northeast part of Bone Gulf just south of Wotu. Gravity decreases eastward from Wotu to below −50 mgal at Lake Matano. The area including this lake, which is surrounded by the −25-mgal contour (Figs. 2, 3), is composed of large limestone blocks and melange. The gravity low west of Wotu reaches −65 mgal over the coastal plain and appears to be the northern extension of the free-air gravity low mapped over the Bone Gulf (C. Bowin and others, in prep.). The low onshore is explained by a thick sedimentary body deposited against the schist and volcanic belts. The gravity high at Palopo is associated with intermediate volcanic rocks.

In the area of Pomalaa a northwest-trending zone of ultra-

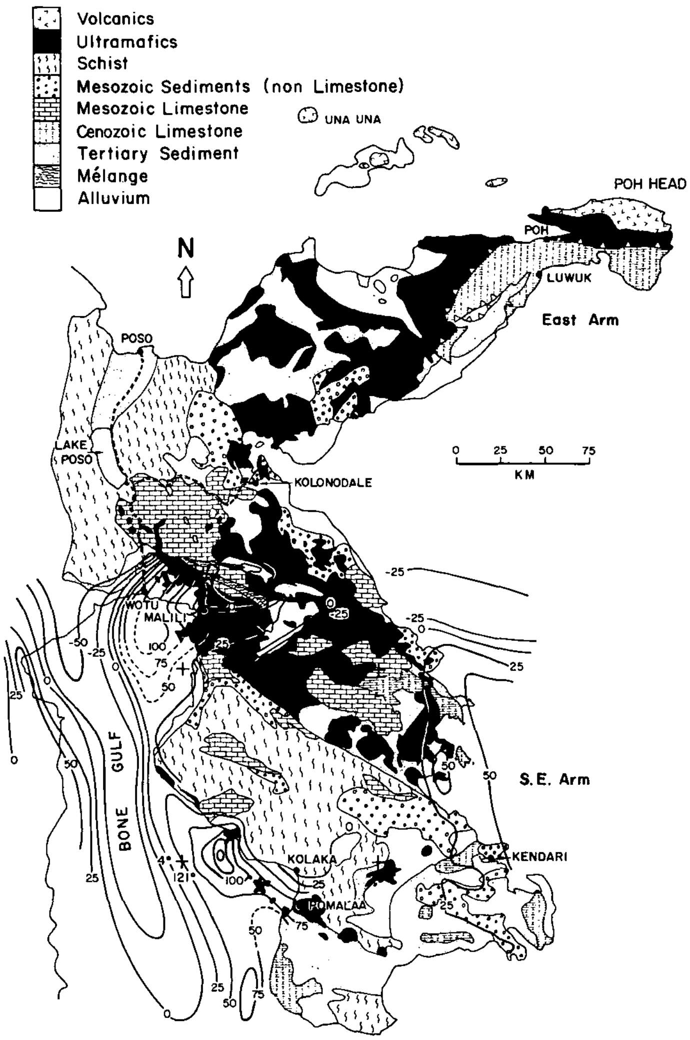


Figure 2. Geologic map of east arms of Sulawesi, simplified from Sukamto (1975b) and modified to include melange belts. Celebes molasse is included with Tertiary sediment. Geology of South Arm is not shown. Gravity contours are superimposed (see description in Fig. 3 caption).

mafic rocks is responsible for a gravity high reaching 85 mgal near Pomalaa and 150 mgal offshore to the northwest. This gravity high appears to trend toward the high at Wotu, but we do not know whether the belt is continuous. The high nearly pinches out at lat 3.5°S, and perhaps the ultramafic rocks are not continuous. Because the Pomalaa gravity high bounds the schist belt on the west side and the Wotu high bounds it on the east, the schist belt appears to be disrupted by the ultramafics. The tectonic significance of this indicated disruption is not clear but is probably related to the development of the Bone Gulf, as well as to the emplacement of the ultramafics.

Between Kolaka and Kendari the Bouguer gravity values are near zero and increase at each coast. The contours trend north at the east coast and appear to cross the schist-ultramafic contact with little effect, except that a gravity high of +60 mgal occurs just north of the contact and trends nearly normal to it. On the coast north of this gravity high is a contact between ultramafic rock and Tertiary limestone. The gravity field increases eastward away from the ultramafic rocks across this contact, despite the observation of unserpentinized and only partially serpentinized peridotite in this area, suggesting that the ultramafic rocks are thin at this eastern contact. The discordance between the trend of the geologic contacts and gravity gradients in this area may be due to differences in density gradients between deep crustal and surface structures; we have not yet attempted to model the structure in this southern transect, but will concentrate on the northern data.

THE GRAVITY MODEL

To estimate relative thicknesses of ultramafic rock we have constructed gravity models (Fig. 4) along A–B, B′–C–D in Figure 3. Rock densities determined on about 100 samples gave the following average results: unserpentinized peridotite, 3.27 g/cc; partially serpentinized peridotite, 2.93; serpentinized peridotite, 2.59; limestone, 2.65; schist, 2.71; granitic rock, 2.61. We observed the peridotite to be only partially serpentinized or unserpentinized over wide areas. In modeling we assume serpentinization to be largely a near-surface phenomenon and the bulk of these rocks to be unserpentinized. Departures from this assumption result in correspondingly greater thicknesses of ultramafic rock from those shown in Figure 4. The model thicknesses of ultramafic rock, therefore, should be considered minimum values. We have taken limestone, schist, and granitic rock to have zero density contrast, 2.7 g/cc, peridotite to be dominantly unserpentinized, with a contrast of 0.55 g/cc, and melange bodies variable, approximately −0.2 to −0.4 g/cc for modeling, but our geologic and gravity control there is poor.

Given this distribution of densities and observed gravity, it is clear that a thick sedimentary body must be responsible for the gravity low west of Wotu, and that the ultramafic body must be thick near the schist contact and must thin eastward. The gravity low at 125 to 155 km on Figure 4 cannot be explained merely by thinned ultramafic rocks or the presence of Lake Matano. Relatively thick, low-density material must be present as well.

The three models in Figure 4 show some of the range of acceptable structure attainable by varying the shape of the ultramafic rocks (Fig. 4A, 4B) and the density of rocks below the ultramafics (Fig. 4C). Note the increased thickness of ultramafic rock and limestone in Figure 4C compared with Figure 4A. The enduring aspects of the models are maximum thickness of ultramafic rock near the schist contact and great thickness of melange associated with the Cretaceous(?) limestone. Gravity is not sensitive to the details of contact relations with our presently poor independent control.

The relative volumes of melange and limestone on the east side of this model may surprise field geologists working there, because the limestone units are so prominent, the melange so seemingly minor in the field. This difference represents relative resistance to erosion. Given the measured densities on all limestone samples, thick low-density material probably underlies and surrounds the limestone blocks. Note also that at location 132 km in Figure 4, where limestone and ultramafic rock appear to be in contact or nearly so, both units must be very thin and underlain by thick melange (or some other low-density material).

EMPLACEMENT OF THE ULTRAMAFIC ROCKS

The ultramafic rocks on the Southeast Arm probably represent the lower part of an ophiolite. A full ophiolite suite was reported by Kundig (1956) and Brouwer (1947) on the East Arm, and we found cobbles of layered peridotite, gabbro, and amphibolite in molasse on the Southeast Arm at the easternmost

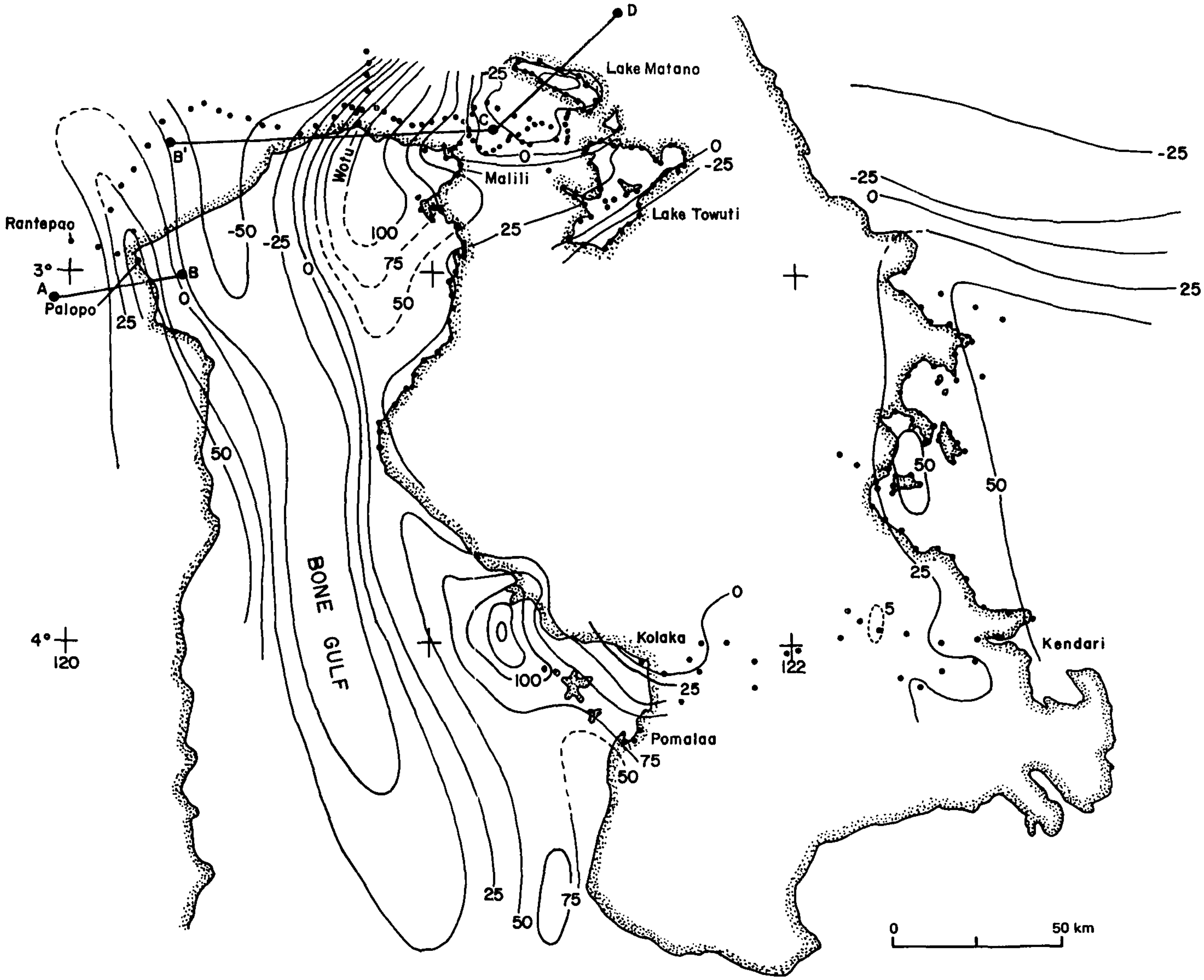
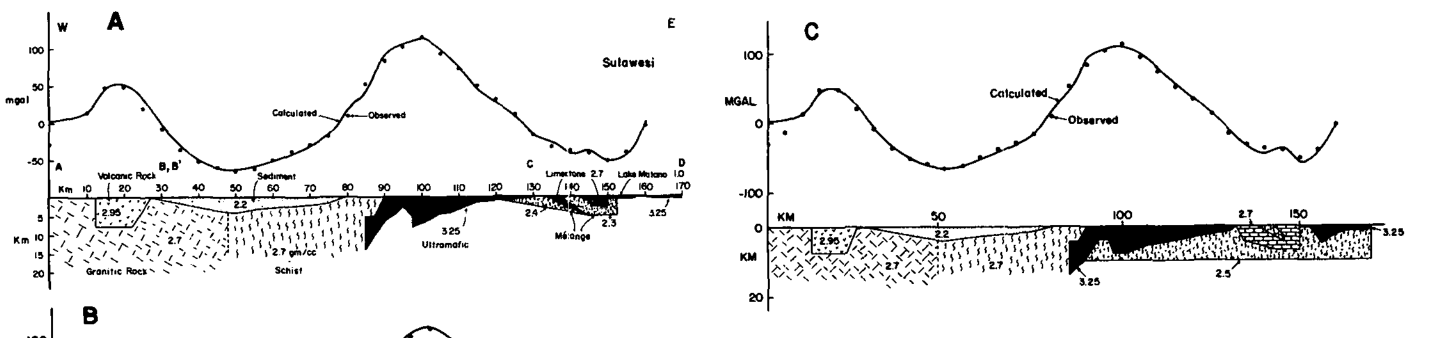


Figure 3. Simple Bouguer gravity map of southeast Sulawesi. Reduction density 2.67 g/cc. Land stations from work reported here. Offshore, data are free-air, modified from gravity map of the Banda Sea by C. O. Bowin and others (in prep.). Contour interval, 25 mgal.



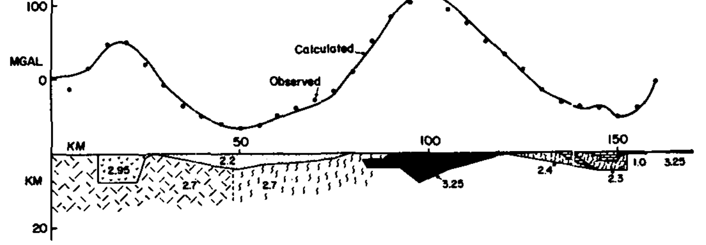


Figure 4. Three upper crustal models that satisfy observed gravity along line A–B, B′–C–D. Location in Figure 3. (A) Assumes material of zero density contrast (2.7 g/cc) below ultramafic rocks. (B) Same density assumptions as in Figure 4A but a different, though equally acceptable, subsurface shape for the ultramafic rocks. (C) Same subsurface shape of ultramafic rocks as in Figure 4A but assumes material of −0.2-g/cc density contrast (2.5 g/cc) below the ultramafic rocks to a depth of 10 km.

outcrop of ultramafic rocks on the coast north of Kendari (Fig. 2).

Several different hypotheses have been suggested for emplacement of ophiolites and other large ultramafic slabs: (1) obduction of oceanic crust along faults dipping opposite to the direction of subduction (Moores, 1970; Coleman, 1971; Oxburgh, 1972; Christensen and Salisbury, 1975); (2) slicing off wedges of ocean crust during subduction along faults subparallel to the sense of subduction (Gansser, 1974; Davies, 1971; Milsom and Richardson, 1976; Milsom, 1973; Dewey and Bird, 1971, Figs. 6a, 6b; Elliott, 1976); (3) diapirism (Maxwell, 1973); (4) cold intrusion along vertical faults (Lockwood, 1972—this model was suggested for development of detrital serpentines rather than ophiolite emplacement); (5) emplacement associated with changing motion along transform faults (Brookfield, 1977).

With regard to emplacement of the Southeast Arm ultramafics, the obduction model specifically predicts ultramafics thinning westward (toward the arc) and thickening seaward, and is most clearly ruled out by the presently available data for Sulawesi (Fig. 4). The gravity model says little about possible association with transform activity and, in fact, large transform movement is postulated for collision of the Banggai-Sula Islands against Sulawesi (Hamilton, 1973). The structure alone does not rule out diapiric or intrusion models, but the absence of high-temperature metamorphic aureoles around the ultramafic rocks on the Southeast Arm, such as are around the Ronda massif in Spain (Loomis, 1972), argues against a hot diapiric origin. On the other hand the westward (arc-ward) thickening of the ultramafics, their eastward thinning, their apparent dip below the schist belt, and their close association with melange all fit the second suggestion, that of fault slices concordant with direction of subduction. Uplift above sea level may have been aided considerably in the early phases of subduction by tectonic inclusion of large melange bodies associated with the ultramafics, and most likely culminated with the collision between the Sulawesi arc and the Banggai-Sula Islands.

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