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Geology of the Talaud Islands, Molucca Sea collision zone, northeast Indonesia

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Abstract—The Talaud Islands lie at the northern margin of the collision zone between the Sangihe and Halmahera island arc systems. Rock units on Talaud are Neogene marine strata, basalt and andesite, tectonic mélange, and ophiolite. The units are exposed in N–S trending belts that are commonly separated by faults. The marine strata consist of tuffaceous siltstone, sandstone, shale and marl. They are strongly deformed by west-verging folds with wavelengths of 20–500 m. Volcanic rocks of island arc affinity are exposed on the east coast of Karakelang Island and appear to be interbedded with the lowermost marine strata. Tectonic mélanges contain blocks of serpentinite, gabbro, basalt, red middle Eocene chert and limestone, and greywacke turbidites. The blocks range in length from a few millimetres to hundreds of metres, and are enclosed in a scaly clay matrix. Several mappable slabs of ophiolite are separated by Tertiary strata or mélange. The dismembered ophiolites consist of serpentized peridotite, gabbro, spilites and cherts. Locally, the mélanges and ophiolites are thrust over the younger sedimentary rocks along east-dipping faults. The dominant eastward dips of mélange foliation, the westward vergence of structures in the Neogene strata, the Eocene ages of the cherts, and the Miocene age of the strata overlying the ophiolite slabs suggest that the ophiolites are pieces of Eocene or older oceanic crust (derived from a mid-ocean ridge or back-arc basin) and upper mantle that were emplaced as thrust slices into the lower slope of a west-facing arc during the Miocene and have been uplifted during arc–arc collision.

INTRODUCTION

COLLISIONS between island arc terranes and continental margins have been called upon to explain the juxtaposition of dissimilar terranes in ancient mountain belts (e.g. Hamilton 1969, Schweikert & Cowan 1975, Jones *et al.*, 1977, Speed 1979, Coney *et al.*, 1980). Although such non-terminal collision events are probably very important in orogenesis, their recognition in the ancient record is difficult, mainly because of the tectonism which is later superimposed on early structures in orogenic belts. The lack of documentation of the structures associated with modern collisions has also hampered our understanding of collision processes. In addition, there has been considerable speculation about the mechanism of ophiolite obduction and emplacement of ophiolites into orogenic belts, and how the mechanisms are linked to collision processes (e.g. Dewey 1976, 1977), but critical field data are often unavailable.

In an attempt to understand the structure of an active collision zone, Moore and Kadarisman visited the Talaud Islands during July and August of 1979. Reconnaissance studies of the islands that were carried out by the Dutch in the 1920's (Roothaan 1925, van Bemmelen 1949) indicated that ophiolite slabs and younger sedimentary strata are exposed on Talaud. Hamilton (e.g. 1977) recognized that the geology and the then-available geophysical data indicated that the islands expose the top of a great wedge of accretionary mélange in a collision zone. Regional geological mapping (1:250,000) was completed in 1976 by the Geological Survey of Indonesia (Sukamto *et al.* 1980), and that mapping was used to guide our more detailed studies of the collision zone structures. This paper reports the results of our field structural and stratigraphic work and preliminary results of our laboratory geochemical and petrographic work. A detailed description of the petrology and geochemistry of the ophiolitic rocks of Talaud will be presented elsewhere (Evans *et al.* in prep.).

REGIONAL TECTONIC SETTING

The Molucca Sea arc–arc collision zone of northeastern Indonesia (Silver & Moore 1978) is the best known example of an active collision zone between facing subduction zones. The Molucca Sea lies in the region of complex interaction between the Pacific, Philippine, Eurasian and Australian plates (Fig. 1). The 'Molucca Sea Plate' is presently being subducted along its eastern margin beneath the Halmahera arc system and along its western margin beneath the Sangihe arc system (Hatherton & Dickinson 1969, Fitch 1970). The Halmahera and Sangihe arcs are thus colliding, and the Molucca Sea represents the collision zone (Silver & Moore 1978, Hamilton 1979). The Philippine Trench marks the eastern boundary of the collision zone. The shallow Benioff zone, small accretionary prism and other evidence led Hamilton (1979) and Cardwell *et al.* (1980) to conclude that the Philippine trench is a young feature. The southern Molucca Sea collision zone is a broad, highly deformed ridge and is composed of very thick, low-density material of low seismic velocity (McCaffrey *et al.* 1980). In the active collision zone, the surface expression of the subduction zones dipping under the Sangihe and Halmahera arcs is obscured by the collision complex which has been

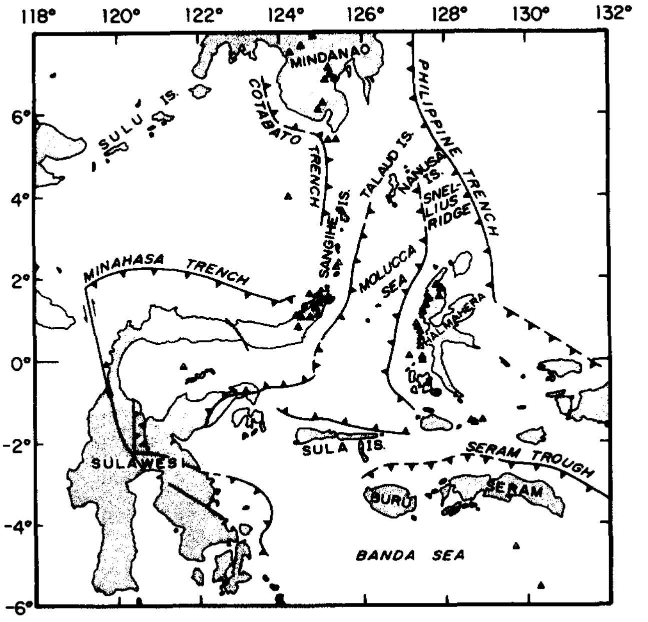

Fig. 1. Regional tectonic map of eastern Indonesia, modified from Hamilton (1979) and Silver (1981). Triangles are Pleistocene and recent volcanoes (from Hamilton 1979).

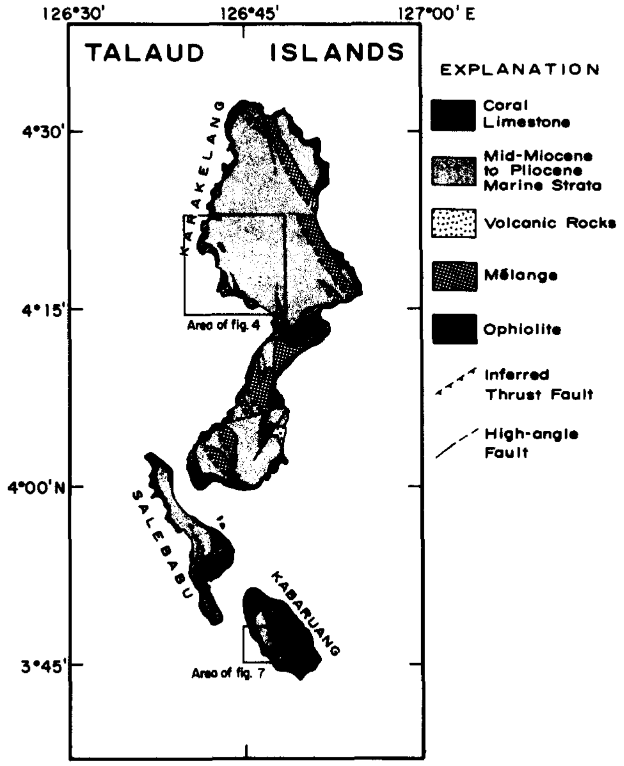

Fig. 2. Geological sketch map of the Talaud Islands, updated from Sukamto & Suwarna (1976).

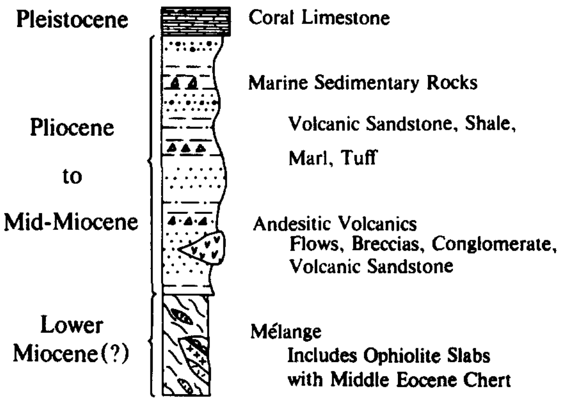

Fig. 3. Stratigraphic column for the Talaud Islands.

thrust onto the arc flanks with the surface thrusts dipping away from the arcs toward the collision complex (Silver & Moore 1978). The Talaud Islands are an emergent part of the block which forms the northern boundary of the collision zone. The collision is complete north of Talaud where convergence has apparently ceased (Hamilton 1979, Cardwell *et al.* 1980).

STRATIGRAPHY AND LITHOLOGY

Five major rock units are exposed on the Talaud Islands (Figs. 2 and 3): Pleistocene coral, mid-Miocene to Pleistocene marine sedimentary rocks, basalt and andesite, tectonic mélange and ophiolite. These rocks units crop out in approximately N–S trending belts which commonly are separated by faults (Fig. 2).

Tectonic mélanges

Tectonic mélanges on Talaud (Sukamto & Suwarna 1976, Sukamto 1981) are mappable bodies that display a characteristic internal fabric dominated by complete stratal disruption and containing tectonic inclusions immersed in a pervasively sheared, fine-grained matrix. The Talaud mélange exposures are broadly similar to the mélanges of the Franciscan Complex of California (e.g. Hsu 1968, Cowan 1974), Kodiak Island (Moore & Wheeler 1978), and Nias Island on the outer-arc ridge of the Sunda Arc in western Indonesia (Moore & Karig 1980). The mélange zones are discontinuous and lens-shaped at the scale of our geological maps (Figs. 2 and 4).

The mélange matrix (Fig. 5a) is generally red and in most localities is composed of a combination of clay and finely-ground sedimentary rock debris. A good foliation is developed only in a few outcrops where the foliation strikes approximately N–S and dips steeply to the east.

The Talaud mélanges contain blocks of sedimentary and igneous rocks, that range in size from a few centimetres to hundreds of metres in length and commonly are angular phacoids. The faces of most inclusions are polished or lineated by slickensides. The majority of inclusions larger than a metre in size are igneous rocks that are interpreted as pieces of a dismembered ophiolite: ultramafic rocks, layered gabbros and pillow basalts (see below). Sedimentary inclusions are subordinate and commonly are smaller than 1 m in length. Red chert, limestone and shale, and greywacke are the most common sedimentary inclusions. The cherts are rhythmically bedded (Fig. 5b) with beds that generally are 2–10 cm thick

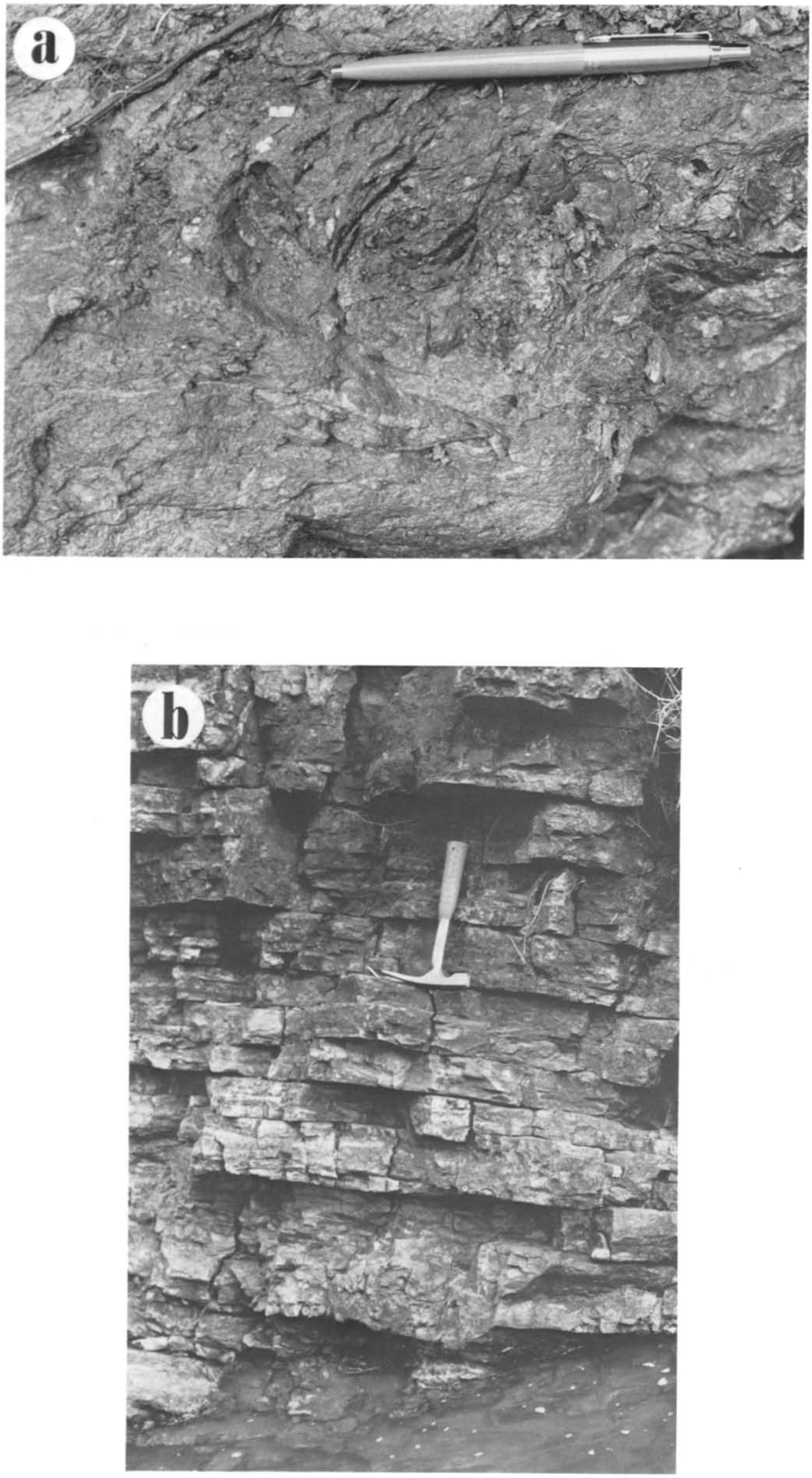

Fig. 5. (a) Mélange matrix, pen is 13 cm long. (b) Bedded chert in mélange, hammer is 27 cm long.

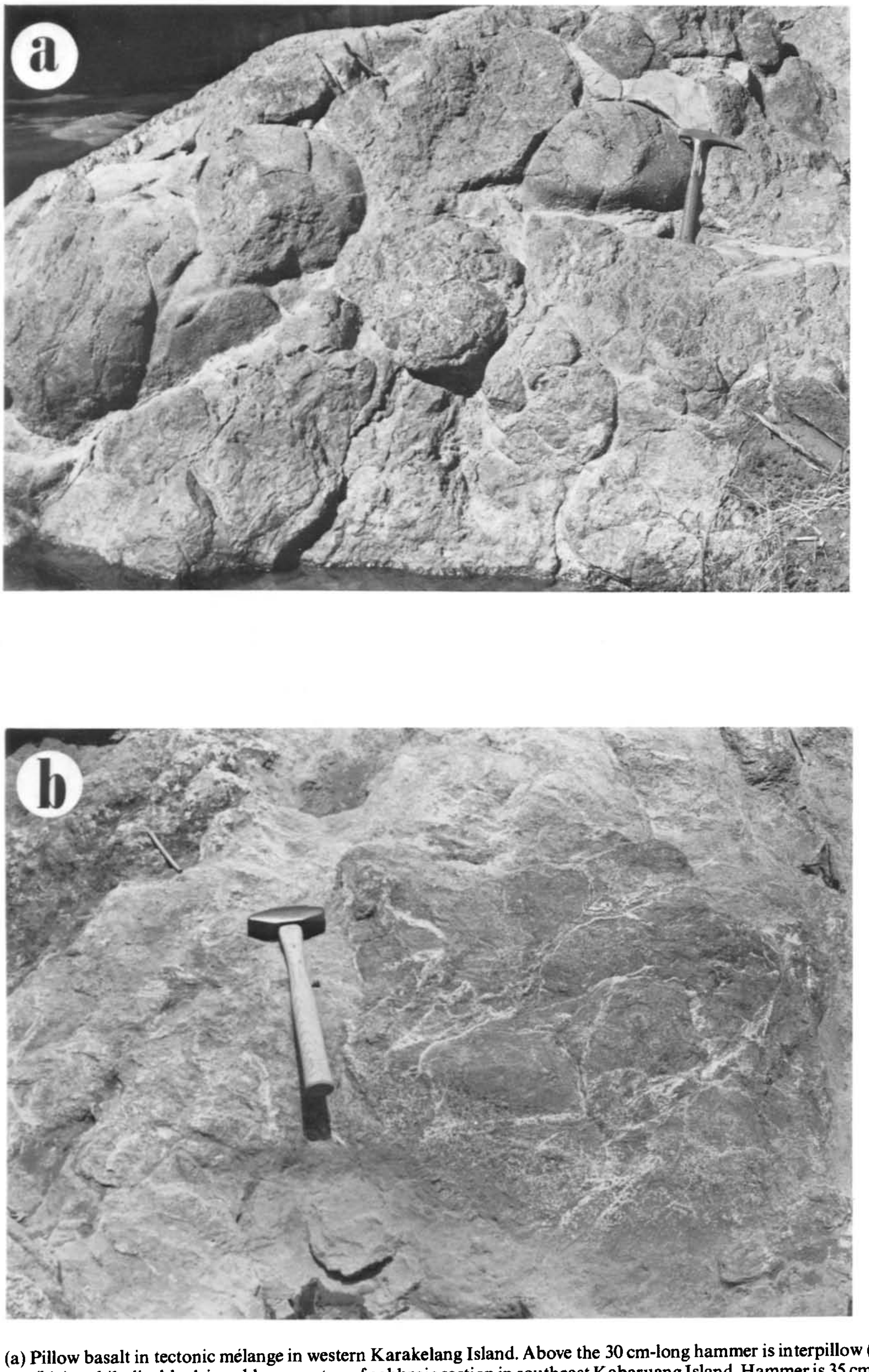

Fig. 6. (a) Pillow basalt in tectonic mélange in western Karakelang Island. Above the 30 cm-long hammer is interpillow (pink) limestone. (b) Amphibolite block in gabbro near top of gabbroic section in southeast Kabaruang Island. Hammer is 35 cm long.

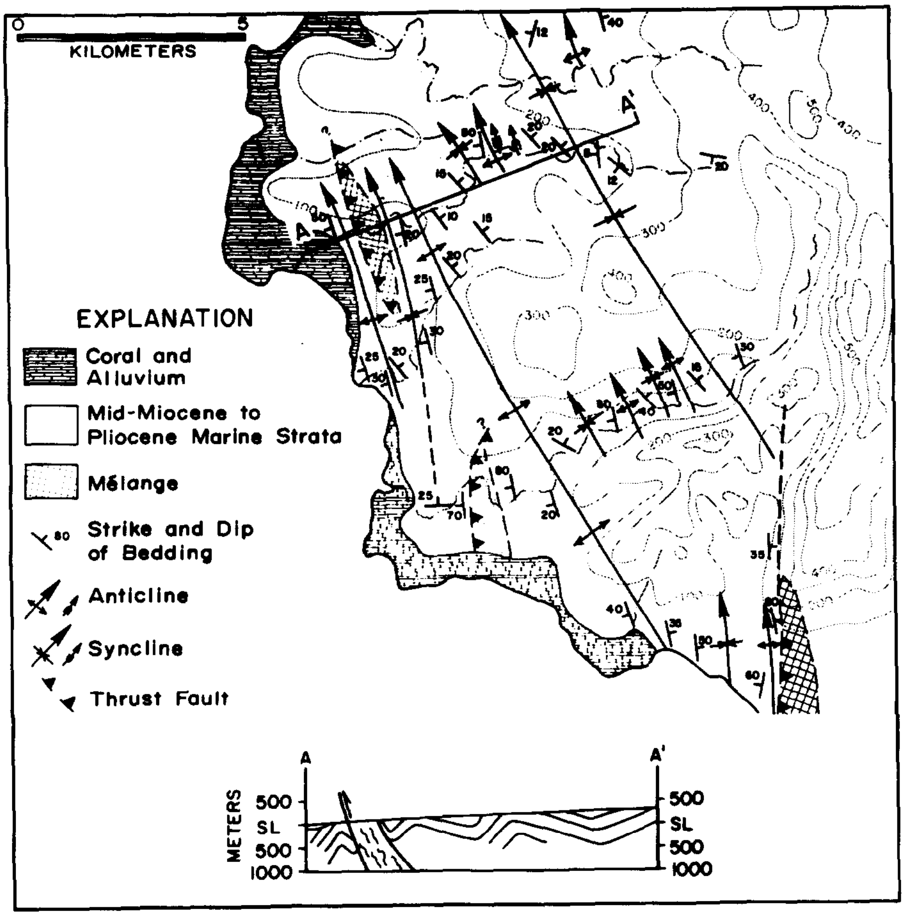

Fig. 4. Geological map of western Karakelang Island (see Fig. 2 for location). Note strip-like outcrop pattern of mélange zones. Thrusts associated with the mélange zones probably continue along strike, but poor exposures did not allow definition of the thrusts in the Neogene strata. Basemap from U. S. Army Map Service 1:50,000 topographic sheet. Contour interval 100 m.

and have some shale partings. Several samples of chert and red limestone yielded poorly-preserved radiolaria of early middle Eocene age (A. Sanfilippo and M. J. Westburg, S.I.O., personal communication 1980). No other lithologies from within the mélanges have yielded recognizable fossils. Bedded chert has not been observed in depositional contact with any other lithology; all contacts are tectonic. Tight chevron folds were observed in two blocks of bedded chert. Clastic sedimentary inclusions are grey shale and thin-bedded grey volcaniclastic sandstones, some of which are graded. Stratal continuity has been totally destroyed by intense shearing, and boudinage of competent beds is common. Sandstone inclusions generally have well-preserved clastic textures, although some thin-sections show diffuse grain boundaries. A few samples have zones of cataclasis, approximately 0.2 mm wide and spaced a few mm apart, that show grain size reduction and concentrations of a dark solution residue.

Ophiolites

In addition to the small fragments of ophiolitic rocks mentioned above, there are three mappable bodies of ophiolite that range in size up to 5 km in width. They are a 'dismembered' ophiolite. Serpentinized peridotite (lherzolite and harzburgite tectonite), gabbro, basalt, and chert are all present, but no complete ophiolite sequence has been observed on Talaud. Pillows are common in stream boulders (Fig. 6a), and the few in-place pillows that were observed indicate that the basalts are right-side up and face to the east. Most of the basalts are altered to spilitic mineral assemblages (Soeria Atmadja & Sukamto 1979), but their variolitic textures are still recognizable (Evans *et al.* in prep.). Chloritic interpillow matrix is common, but pink limestones that contain Eocene radiolaria also occur between pillows. The peridotites are serpentinized to varying degrees (Soeria Atmadja & Sukamto 1979), and there is evidence of deformation at outcrop and thin-section scales. Outcrops are usually strongly fractured and there are many 1–5 cm wide zones of brecciation. Several zones of high-temperature deformation and recrystallization are visible in thin sections of ultramafic rocks (Evans *et al.* in prep.).

The ophiolites are east-dipping slabs with contacts that strike N–S and dip steeply east. In southwestern Kabaruang Island (Fig. 7) a vertical sequence through the gabbro–basalt transition was sampled. The lowest structural unit is gabbro that is layered at both centimetre and

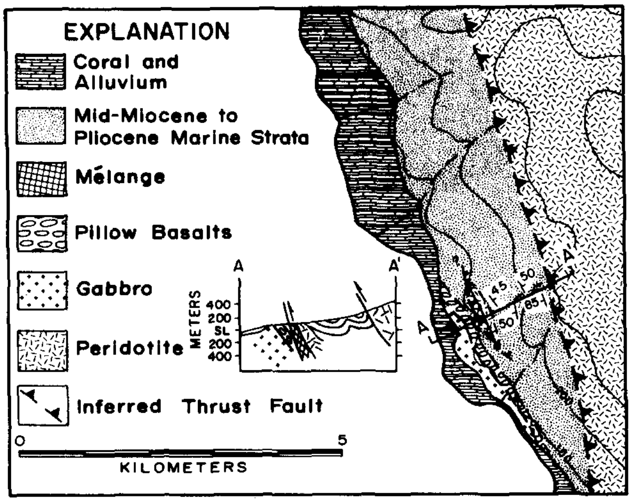

Fig. 7. Geological map of west Kabaruang Island showing field relations of ophiolite slices (see Fig. 2 for location). Basemap from U.S. Army Map Service 1 : 50,000 topographic sheet. Contour interval 100 m.

plagioclase laths and by varying abundances of mafic minerals. Cumulate textures are commonly observed in thin sections of the gabbro. The gabbros show evidence of some shear deformation. Bent twin lamellae and cleavage planes in plagioclase and pyroxenes and minor pyroxene granulation are sometimes present but are not pervasive. Other alteration includes replacement of mafic minerals by chlorite and green amphiboles, sericitization of plagioclase, and cross-cutting veins of chlorite, epidote, prehnite and uralite. Fragments of amphibolite are intimately mixed with the gabbro near the top of the section (Fig. 6b). Overlying the gabbro–amphibolite unit is a 30–50-m thick section of pillow basalt. The basalt is in turn overlain by mid-Miocene shales. In one river, the mid-Miocene shales are overthrust by a steeply-dipping, 75–100-m wide mélange zone which is structurally beneath massive peridotite. This mélange–peridotite unit appears to have a very limited lateral extent, because it was not encountered in rivers 5 km to the north or south. It is overlain depositionally by mid-Miocene strata that are folded into open west-verging folds (Fig. 7). The Neogene strata are in turn overthrust by a slab of massive peridotite along central and western Kabaruang (Figs. 2 and 7).

In central Karakelang there are two smaller fragments of ophiolite (Fig. 2). Both are east-dipping slabs enveloped by thin mélange zones. One slab is massive peridotite and the other is layered gabbro and basalt.

Neogene strata

The mid-Miocene to Pleistocene sedimentary rocks are tuffaceous sandstones, siltstones, and shales with intercalations of limestone, marl and conglomerate. The conglomerates contain pebbles of rounded basalt and andesite, and volcanic debris is dominant throughout the section. Agglomerates or pyroclastic rocks, however, occur only in one isolated locality (see below). Ophiolitic detritus is present only in the upper Pliocene and Pleistocene strata. Miocene and Pliocene marls contain benthic foraminifera which show that the strata were deposited in water depths greater than 2000 m (*Melonis pompilioides* and *Uvigerina senticosa*, H. G. Billman, personal communication). Sedimentary structures and displaced shallow-water foraminifera indicate that most of the sediments were deposited by turbidity currents. The Neogene strata may have been in original depositional contact with the mélanges, although most contacts are now tectonic (see below). Ages of the strata within the outcrop belts generally become younger to the east, away from the mélange zones.

Volcanic rocks

Interbedded with the Neogene sandstones on the east coast of Karakelang Island are exposures of volcanic flows and associated sediments (Fig. 2) which include pyroxene–plagioclase vitrophyre crystal–lithic–vitric breccias and poorly-sorted volcaniclastic sedimentary rocks. The vitrophyres are basaltic andesites that are relatively unaltered and contain euhedral phenocrysts of labradorite (An_{60-65}), hypersthene (En_{65}) and clinopyroxene ($En_{48}Wo_{40}Fs_{12}$) set in a matrix of brown glass (with high SiO_2, K_2O and Na_2O) and microlites of pyroxene, plagioclase and opaque minerals. The age of the flows has not been determined radiometrically, but field relations suggest that they are mid-Miocene.

Pleistocene limestone

The youngest rocks on Talaud are Pleistocene reefal limestones that are exposed mostly along the coasts and as scattered outcrops in stream valleys on Kabaruang Island. The limestones are undeformed except for minor tilting. The dominant lithology is coral and coralline rubble. Some of the coral outcrops of Kabaruang occur at 400–500 m, which attests to the significant amount of recent uplift which has occurred.

STRUCTURE

The Neogene strata are exposed in elongate, north-trending belts, separated by mélange zones. The strata are moderately to strongly deformed, but unlike the melange zones, bedding is well preserved and becomes disrupted only locally adjacent to mélange zones. The eastern margins of the Neogene strata appear to be in fault contact with the mélanges. The strata are vertical or overturned and strongly sheared, and rock units are intercalated at outcrop scale. We interpret these contact relations as indicating that mélange is thrust over Neogene strata (Figs. 2 and 4). The mélange zones are discontinuous along strike (Fig. 4). Mélange exposures probably occur only where erosion has cut deeply into the section. Thrusts at the western margins of the mélange zones probably continue along strike into the Neogene strata, but poor exposures did not allow confident identification of the thrusts.

Away from the mélanges zones, the Neogene strata are deformed into folds that trend parallel to the major structural axis of the islands (NNW, Sukamto 1981). Measurable fold hinges were not found, probably because they have been sheared out. Map-scale folds are defined on the basis of sedimentary facing directions. Major folds have wavelengths of 100–200 m and minor folds have wavelengths of 10–50 m. Fold vergence is to the west. There is no well-defined axial plane foliation associated with the folds.

Contact relations between the ophiolites and adjacent rocks are not clear. Neogene strata in contact with the western margins of the ophiolites are strongly sheared and overturned, implying that the contact is a thrust fault. The strata at the eastern contacts are not strongly sheared and dip nearly parallel to the contact, implying that the contact originally may have been depositional.

DISCUSSION AND INTERPRETATION

The Talaud Islands are characterized by large-scale imbrication, as suggested by the map patterns, mélange foliation and structure of the Neogene strata. The vergence direction of the imbrication, however, is not unequivocal. The eastward younging of the Neogene strata, westward-vergent folds within the Neogene strata and eastward dips of the mélange foliation lead us to infer that vergence is to the west. The ophiolite slabs represent pieces of middle Eocene or older oceanic crust and upper mantle. The mineralogy, textures and geochemistry of the Talaud ophiolite basalts are similar to those of mid-ocean ridge basalts, and the association with fine-grained, non-terrigenous sediments makes this a tenable hypothesis. However, all of the available data for western Pacific back-arc basin basalts indicate that they resemble mid-ocean ridge basalts in all geochemical and mineralogic characteristics (Hawkins 1977), and a back-arc basin origin is considered equally possible. The thin pelagic sediments of the ophiolite suggest that the ophiolites were formed in an open ocean (or wide back-arc basin) environment away from continental or island arc sediment sources. Our geochemical data can rule out an origin as part of an island arc complex. Because of the existence of ophiolite blocks within the mélange, we interpret the mélange zones as sites of intense shearing during the emplacement of the ophiolites. The imbricate structure suggests that the ophiolites were not upthrust into the sediments as is presently occurring south of Talaud at Mayu and Tifore Islands (Silver & Moore 1978). We believe that the imbricate structure on Talaud is similar to that observed on Nias Island, a Neogene subduction complex on the outer-arc ridge of the Sunda Arc where Moore & Karig (1980) have interpreted the imbricate structure as resulting from thrusting on the lower trench slope during subduction. We therefore favour a subduction zone environment for the Talaud rocks. The red matrix of the mélange is interpreted as strongly sheared oceanic pelagic sediment, and the coarse-grained sedimentary rocks with the mélange as deformed trench deposits. We believe that the Neogene strata are slope deposits that accumulated on top of the mélanges in slope basins (Moore & Karig 1976), before and during the collision.

The island arc volcanics on Talaud are still problematical. They may be related to a Miocene volcanic arc to the east of the Talaud Islands that was associated with eastward subduction beneath Talaud. Fine-grained volcanic detritus is common throughout the Neogene section, indicating that volcanic activity was occurring nearby. The structural block east of Talaud (Nanusa Islands and Snellius Ridge) may be the old volcanic arc. Miocene volcanic rocks have been reported from the Nanusa Islands (Sukamto 1981). The Talaud volcanics may have been transported downslope from this arc. Sigurdsson *et al.* (1980) report subaqueous pyroclastic debris flows that have been transported 250 km from their source in a similar setting in the Lesser Antilles arc. We do not believe that the Talaud island arc was related to subduction at the present Philippine Trench, because the Philippine Trench is very young at the latitude of Talaud (Cardwell *et al.* 1980). The arc volcanic rocks could be related to an earlier subduction episode at the Philippine Trench.

Any scenario for the tectonic history of this complex region is necessarily speculative. However, our field work has placed some constraints on the history and thus we offer the following model as one possible working hypothesis for the tectonic development of the Talaud Islands.

The Talaud Islands block was part of a west-facing fore-arc terrane during the Miocene (Fig. 8). We believe that the Talaud arc is structurally part of the East Mindanao arc of Cardwell *et al.* (1980) and is not part of the Halmahera arc to the south. This inference is based on bathymetric, seismic reflection and seismicity data near Talaud. The Molucca Sea Plate was being subducted to the west under the Sangihe arc. The arc volcanics east of Talaud and the probable westward-vergent structures on Talaud indicate that the Molucca Sea Plate was also being subducted to the east under Talaud. Trench sediments and oceanic crust of middle Eocene or older ages were stripped off the plate and accreted to the base of the trench slope, and Miocene slope sediments began to accumulate on top of the accreted mass in deep water. The total disruption of strata in the mélange zones, and the relatively large amount of igneous material with respect to sedimentary material in the mélanges suggest that the Miocene Talaud trench had very little sediment overlying the oceanic crust.

By the Pliocene, the collision to the north (in Mindanao) was complete (Hamilton 1979), and the collision complex was emergent and shedding detritus (Moore, unpublished field data from Mindanao), much of which was probably transported to the south. The Plio-Pleistocene uplift of Miocene strata on Talaud is interpreted as an effect of the accretion of these thick

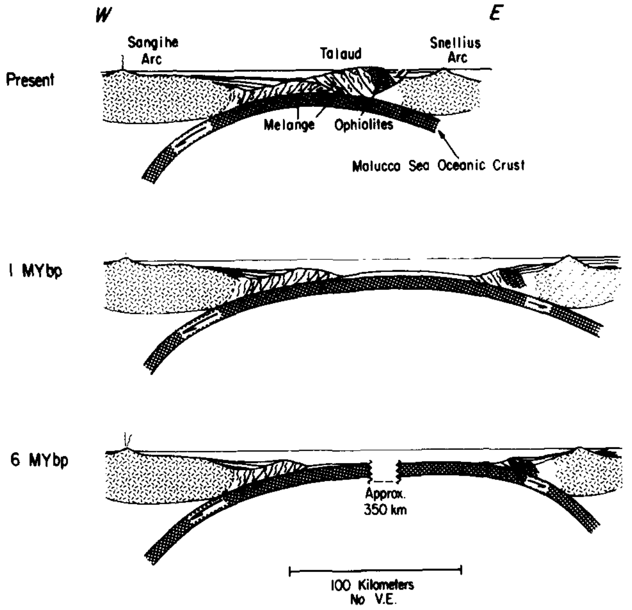

Fig. 8. Speculative scenario for the tectonic evolution of the Talaud Islands. Cross-sections are oriented E–W and are at the latitude of the Talaud Islands. Present structure is based on the model of Silver & Moore (1978) for the active collision zone to the south of Talaud and on geophysical data near Talaud collected by E. Silver and G. Moore.

sediments at Talaud. Ophiolitic detritus began to be eroded and accumulated in the slope basins. The Talaud block reached sea level during the Pleistocene as it overrode the Sangihe fore-arc terrane. Recent seismic reflection data (unpublished data from S.I.O. cruise RAMA, 1980) indicate that the Talaud block is being thrust eastward over the Snellius Ridge (Figs. 1 and 8). In response to the collision, convergence between Talaud and Sangihe has recently slowed and a new trench (Cotabato Trench) is developing northwest of the Sangihe arc (Hamilton 1979, Cardwell *et al.* 1980).

A second possibility is that the ophiolites were accreted in the Oligocene and subduction beneath Talaud ceased at that time. The Neogene strata accumulated on the inactive trench slope. All of the deformation of the Neogene strata and uplift of the Talaud block would have been a result of the recent collision of the Talaud block with the Sangihe arc. In either case, we believe that the collision is post-Pliocene because the Pliocene strata were accumulating in deep water and have only recently been uplifted. In addition, although most of the convergence between Talaud and Sangihe has now ceased, there is still some seismic activity along the Talaud Ridge and there is evidence of recent deformation of sediments in the basin northwest of Talaud (Cardwell *et al.* 1980).

The Talaud ophiolites are about to be obducted onto the Sangihe arc. If convergence between the Talaud and Sangihe blocks continues, the Talaud rocks will be juxtaposed against the Sangihe arc volcanic terrane and the Talaud ophiolites will be emplaced into a suture zone. We conclude that ophiolites can be emplaced into orogenic belts by collision processes. Prior to final arc-arc collision, the shallow structure of the collision is indistinguishable from a normal fore-arc terrane.

The overall regional tectonic development of the Molucca Sea region has been complex (see Murphy 1973, Roeder 1977 and Sukamto 1981 for alternate tectonic scenarios). Final interpretations await further land and marine studies in this complicated area.

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