Journal of the Geological Society, London, Vol. **145,** 1988, pp. 65–84, 17 figs. Printed in Northern Ireland

Basement rocks of the Halmahera region, eastern Indonesia: a Late Cretaceous–early Tertiary arc and fore-arc

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Abstract: Halmahera is a K-shaped island located at the junction of several major arc–trench systems of the western Pacific–eastern Indonesia region. Western Halmahera is an active volcanic arc above a zone of intense seismicity which characterizes the north Molucca Sea. Eastern Halmahera has a basement of dismembered ophiolitic rocks with slices of Mesozoic and Eocene sediments overlain unconformably by Middle Oligocene and younger sedimentary and volcanic rocks. The Mesozoic and Eocene sediments reveal notable stratigraphical and petrological similarities to the Marianas fore-arc and the eastern Halmahera Basement Complex is interpreted as a pre-Oligocene fore-arc lacking an accretionary complex. There is some evidence that the pre-Oligocene volcanic arc behind this fore-arc now forms part of the basement of western Halmahera. The Mesozoic and Tertiary sediments were imbricated together with igneous and metamorphic rocks representing the deeper parts of the fore-arc during the Late Eocene plate reorganization event recognized throughout the western Pacific margins. The eastern Halmahera Basement Complex can be traced into eastern Mindanao, probably further northwards in the eastern Philippines and may be related to similar terranes within and around the present Philippine Sea Plate. In contrast, the southern part of the island of Bacan at the southwestern end of the Halmahera group has a basement of continental metamorphic rocks associated with a deformed ophiolitic complex quite different to the basement of eastern Halmahera. The metamorphic rocks are interpreted to be part of the north Australian continental margin basement which is separated from the Halmahera Basement Complex by a splay of the Sorong Fault system and the deformed ophiolite complex of Bacan is suggested to represent magmatism in the fault zone.

Halmahera is situated in the centre of a mosaic of microplates at the boundary between Australasia, Eurasia and Pacifica in one of the most seismically active regions of the Earth (Figs 1 & 2). Its strange K shape resembles that of Sulawesi on the opposite side of the Molucca Sea and in general terms Halmahera appears to be a smaller scale version of Sulawesi: the western arms of the K form a volcanic arc while the eastern arms include ophiolites and sediments.

Geologically, Halmahera is still poorly known. Van Bemmelen (1970) summarized the stratigraphy of the islands in a single table based on reconnaissance by Verbeek (1908), Wanner (1913), Brouwer (1923*a, b*) and Kuenen (1935). During World War II Bessho (1944) made a study of the geology and later Verstappen (1960, 1964) gave an account of air photographic interpretation with some field investigation. The limited amount of information available is reflected in Hamilton's (1979) review of Indonesian tectonics which showed western Halmahera as a magmatic arc and the eastern part simply as mélange. More recently, the Indonesian Geological Survey mapped the Halmahera islands on a scale of 1:250 000 (Apandi & Sudana 1980; Supriatna 1980; Yasin 1980) and their results and other reconnaissance work were reviewed by Sukamto *et al.* (1981), Soeria Atmadja (1981) and Silitonga *et al.* (1981), indicating that the Halmahera islands include an active volcanic arc in the west, a fragment of probable continental basement on Bacan, and ophiolites and blueschists (Burgath *et al.* 1983) associated with deep-water Mesozoic and Tertiary sediments in the east.

Despite the lack of information on Halmahera, several reconstructions of the geological evolution of the region have been made, principally on the basis of recent seismicity and marine geophysics (Hamilton 1979; Cardwell *et al.* 1980; Moore & Silver 1983). The opposed Sangihe and Halmahera volcanic arcs (Fig. 2), on opposite sides of the Molucca Sea, have been interpreted as the expression of the subduction of the Molucca Sea to both east and west (Hatherton & Dickinson 1969; Hamilton 1979). Geophysical studies (Cardwell *et al.* 1980; McCaffrey *et al.* 1980) suggest that the Molucca Sea plate has been completely eliminated by subduction, forcing it into an inverted U-shaped configuration beneath the colliding fore-arcs (Fig. 3). Collision is thus creating a high central ridge to the Molucca Sea which is being thrust laterally onto the two colliding fore-arcs. This central zone, marked by intense shallow seismicity and a gravity low, is interpreted as the Molucca Sea 'mélange wedge' or 'collision complex' (Silver & Moore 1978; Hamilton 1979; Moore *et al.* 1981) and is exposed on the islands of Talaud, Maju and Tifore.

The length of subducted lithosphere shown on seismic profiles across the region (Cardwell *et al.* 1980; Fig. 3) indicates that eastern Halmahera must have been situated at least 1000 km to the east of north Sulawesi before subduction of the Molucca Sea began. Halmahera is currently moving westwards along the Sorong fault zone with respect to Australasia (Hamilton 1979). Thus an obvious place to search for correlatives of Halmahera is in the collision complexes to the east along the north Australasian margin in New Guinea; the reported

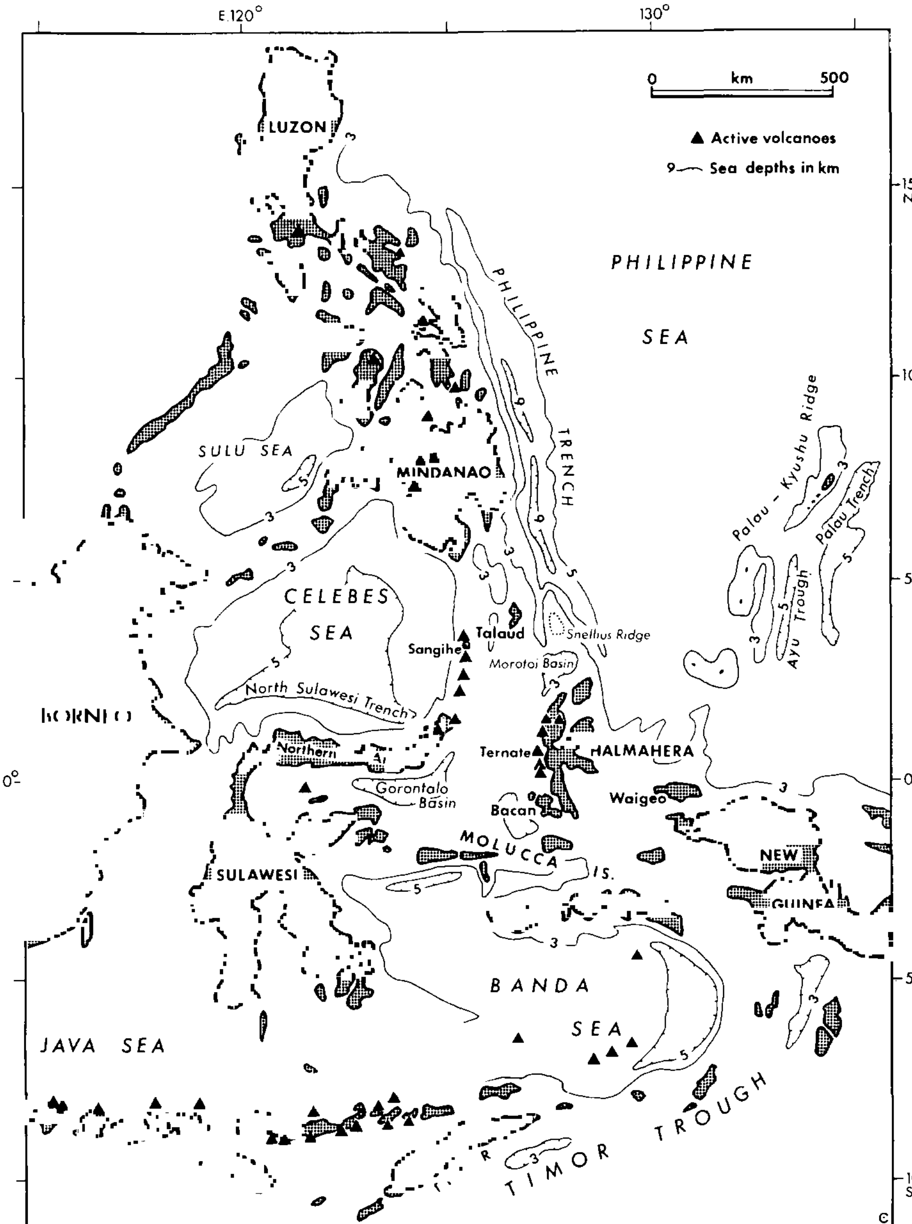

Fig. 1. Location of Halmahera and Bacan.

continental basement rocks on Bacan also suggest a link with the Australian margin. To the north of Halmahera the Philippine Trench is known to be very young (Hamilton 1979; Cardwell *et al.* 1980), with less than 150 km of subducted lithosphere, but it apparently does not extend south of about 2°N. The seismicity of the region, or the local absence of seismicity, have been interpreted to terminate the Philippine trench and thus bound the Philippine Sea plate at its southern end. Interpretations of this part of the plate boundary include thrust or strike-slip faults (compare Hamilton 1979; Cardwell *et al.* 1980; McCaffrey 1982; Moore & Silver 1983). The geological link between the Philippines, the Talaud ridge and Halmahera remains unclear and this is reflected in the variety of reconstructions made by the same group of authors (see discussion in Moore & Silver 1983).

Thus, it was expected that a field investigation of Halmahera would answer some or all of the following questions. What was the relationship between the western and eastern Halmahera regions? A number of possibilities have been proposed by authors cited above or are plausibly interpreted from published maps and literature. These include: initiation of subduction beneath Halmahera after collision between arcs or collision between a continental block and the eastern ophiolitic terrain, flip of subduction with the ophiolites representing a former fore-arc now in a back-arc position, or initiation of subduction within an oceanic plate followed by building of a volcanic arc upon an

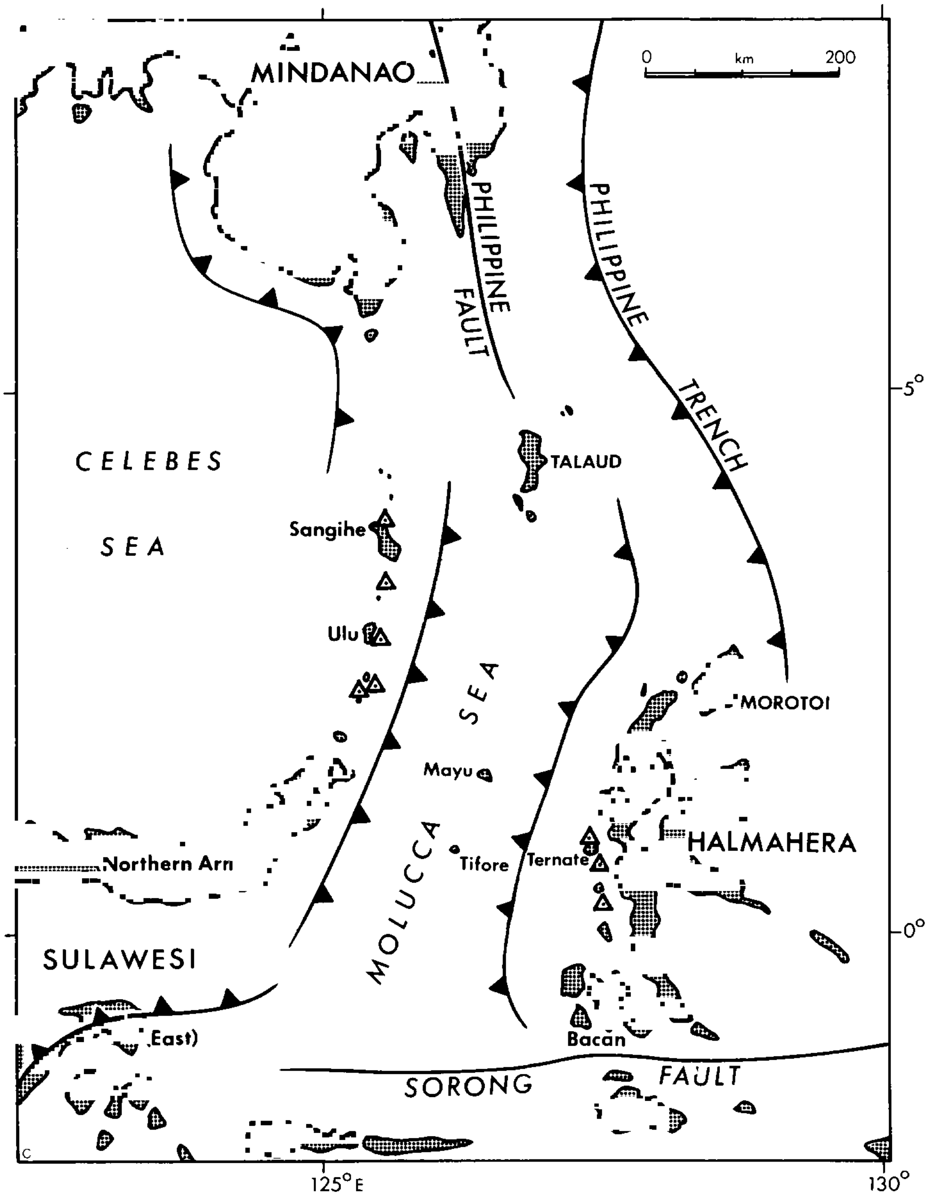

Fig. 2. Principal tectonic features of the Halmahera region after Hamilton (1979) and Silver (1981).

ophiolitic basement. Was the nature of the basement of the islands continental or oceanic and were the small bodies of metamorphic rocks reported associated with the ophiolites of continental origin, subduction zone origin or related to ophiolite obduction? When did arc volcanism begin in the island and could this be related to the development of the Molucca Sea structure: both the asymmetrical inverted U of the Molucca Sea lithosphere and the predictions from marine geophysics of deformation associated with overthrusting of the 'mélange wedge'? Finally, an investigation of Halmahera on land appeared likely to provide important constraints on the geological development of the region and on links between terranes at the Pacific margin. The relatively small size of Halmahera appeared to make it unusually accessible and a suitable target for a small expedition. This paper reports the first part of the results of our field-work and is concerned with the basement rocks of the islands; an account of the Neogene rocks will appear in a second paper (Hall *et al.* in press). A discussion of the evolution of the region is given by Hall (1987).

Despite its small size, field-work in the Halmahera region remains difficult. The islands are covered by dense primary rain-forest and the interiors are practically uninhabited except for a small number of aboriginal people. All equipment and food must be carried in for the whole field season. Access was achieved using small motorized canoes along the coast which carried the geologists, their teams of porters, food and equipment to landing points from which a series of traverses of 5–10 days duration were made. Even with good aerial photographic cover, position finding is handicapped by dense vegetation and weather conditions, and movement is often difficult. All the inland traverses followed river valleys whenever possible which become steeper, deeper and narrower further inland and are subject

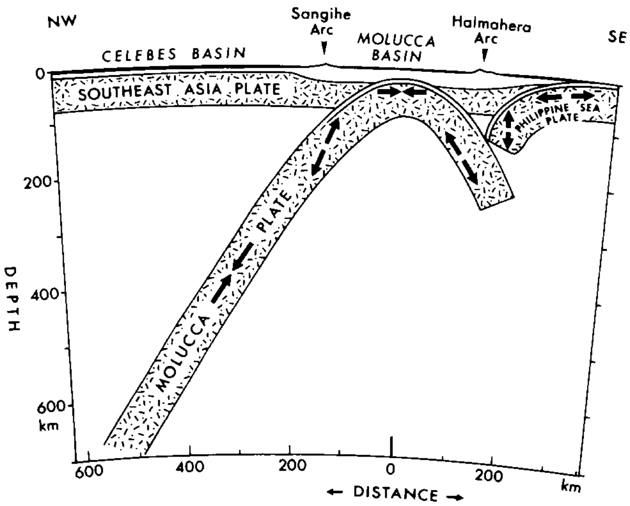

Fig. 3. Present configuration of the Molucca Sea Plate in the region between Halmahera and the Sangihe Arc after Cardwell *et al.* (1980).

to sudden flooding after the briefest storms. Except very locally it is generally impossible to follow geological boundaries across country and maps must be made by a combination of aerial photographic interpretation and correlation between traverses; this uncertainty must be borne in mind when considering any geological map of the islands in this part of Indonesia. Figure 4 shows the traverses made on Bacan and Halmahera which were selected from aerial photographs and published geological maps but were perforce modified by terrain and weather.

Bacan

A summary of the stratigraphy of Bacan is given in Fig. 5. Our principal aim on Bacan was to re-examine the Sibela Mountains (Fig. 6) which form a horst block in the central part of the island and from which high grade continental metamorphic rocks were originally reported by Brouwer (1923*a*). Also reported from the Sibela Mountains were ultrabasic and basic rocks (Yasin 1980; Silitonga *et al.* 1981) although it was not clear whether these formed part of the metamorphic complex, or whether they were linked in some way to the ophiolites found on Halmahera. Our field work showed that the two groups of rocks are separated by a major steep fault zone, the continental metamorphic rocks being exposed in the southern part of the Sibela Mountains and the ultrabasic and basic rocks in the northern part. The southern metamorphic rocks clearly have continental affinities. They include garnet–mica schists, garnet–staurolite–kyanite schists, quartzites, quartzo-feldspathic gneisses, hornblende schists and locally calc-silicates. The rocks have a polyphase metamorphic history. To the north the ultrabasic and basic rocks include harzburgites, serpentinites, gabbros and dolerites. These also have a polyphase metamorphic history but one clearly different from the continental rocks. A complete spectrum of rocks exists within the complex from undeformed gabbros, pegmatitic gabbros and dolerites with mutually intrusive contacts to highly deformed metabasites with ductile folds. Deformed basic rocks pass laterally into less deformed equivalents which are intruded by undeformed gabbros and basalts (Fig. 7), diorites and microdiorites. Because of the nature of the exposure in river sections it is not possible to explore the three-dimensional relationships between these

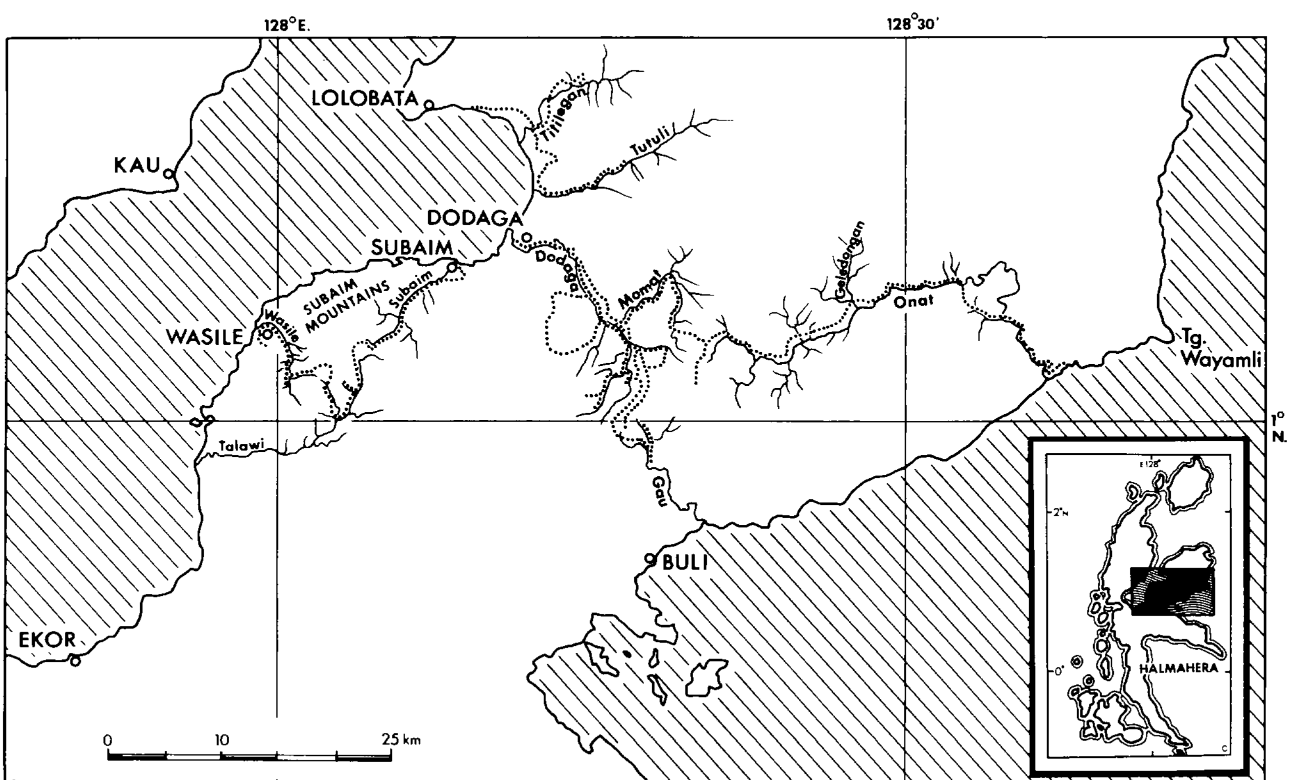

Fig. 4. Location of traverses (dotted) made in the NE arm of Halmahera.

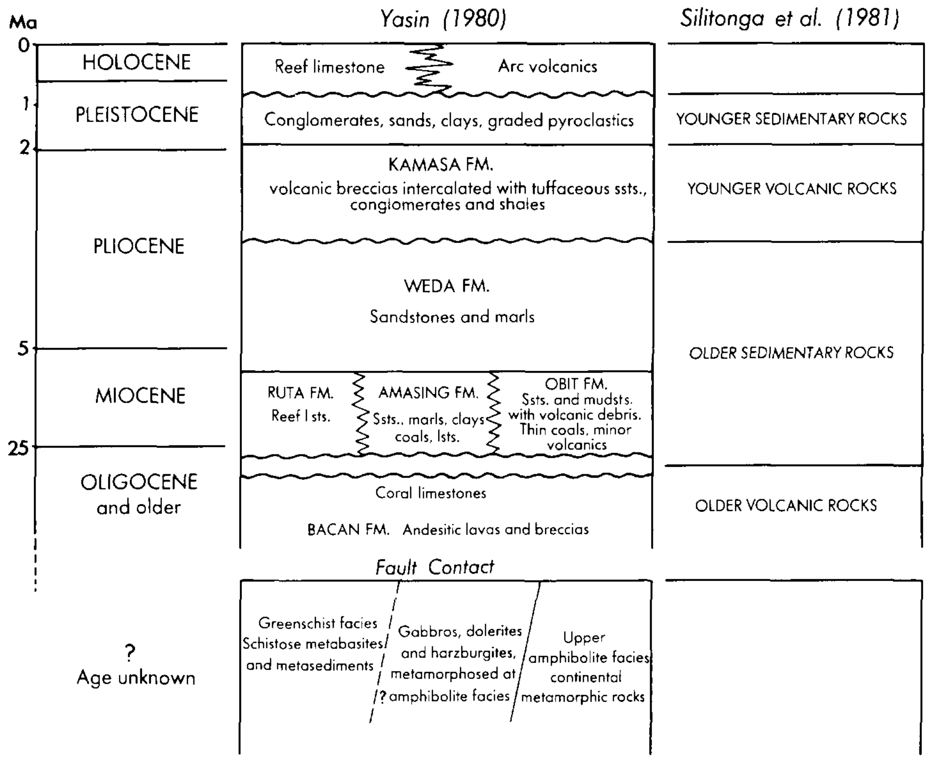

Fig. 5. Summary of the stratigraphy of Bacan. Based on Silitonga *et al.* (1981) and Yasin (1980).

rocks, but in two dimensions it appears that they are cut by repeatedly active shear zones which were equally repeatedly intruded by fresh basic magma resulting in complex magmatic-deformational textures. The association of harzburgites, gabbros and dolerites is typical of the deeper parts of an ophiolite complex, but the Bacan rocks are quite unlike the Halmahera ophiolites, and most other ophiolite complexes elsewhere in the world, in the nature and degree of deformation. The upper levels of an ophiolite complex are not found in the Sibela Mountains but immediately to the north, on the Bacan coast and the islands of Saleh-Kecil, Saleh-Lamo and Kusu, are deformed metamorphosed basic volcanics and sediments (Fig. 6) which could represent parts of the lava sequence and its cover.

Halmahera

The stratigraphy of Halmahera is summarized in Fig. 8 and the distribution of rocks shown in Fig. 9. By making a series of traverses across the NE arm and across the central part of the western arms we were able to build an almost complete stratigraphic column form the late Mesozoic to the Recent. Most of the NE arm consists essentially of dismembered ophiolitic rocks with faulted slices of Mesozoic and Eocene sediments (Fig. 10). This 'Basement Complex' is unconformably overlain by Middle Oligocene and younger sedimentary and volcanic rocks with no major breaks in the sequence until the Pleistocene. Thus the Basement Complex was in existence by late Eocene–Early Oligocene time.

Late Mesozoic and Paleogene sedimentary rocks

Gau Limestone Formation (Late Jurassic?–Middle Eocene?)

This formation is named from a section well-exposed in the Gau River, a few kilometres north of Buli (Fig. 4), over a distance of about 1 km. The thickness of the section exposed is less than 100 m although the base is not seen. The lower part of the type section (Fig. 11) is dominated by thin bedded pelagic micrites and pelagic micro-bedded micrites which locally grade into radiolarian micrites. The occurrence of calcarenites, the presence of redeposited carbonate, and the presence of volcanic debris and other igneous clasts in the section suggests that at least some of the pelagic limestones are distal carbonate turbidites. Non-carbonate material includes fresh plagioclase and pyroxene clasts, a variety of volcanic lithic clasts, grains of opaques and probable volcanic ash shards. All of these are normally highly angular, relatively fresh and of varied size although individual layers are well sorted. The proportion of carbonate to siliciclastic material varies over a few millimetres. The stratigraphically lowest sample contains no siliciclastic debris, but all the remaining samples contain some, often concentrated in thin (<1 mm) bands. Near the top of this part of the sequence there are partings of brown siltstones up to 10 cm thick and red sandstone horizons up to 30 cm thick which are volcanogenic; the red colour is probably a result of recent tropical weathering. The very sudden change from carbonate to siliciclastics and back, and the highly angular and generally fresh character of the

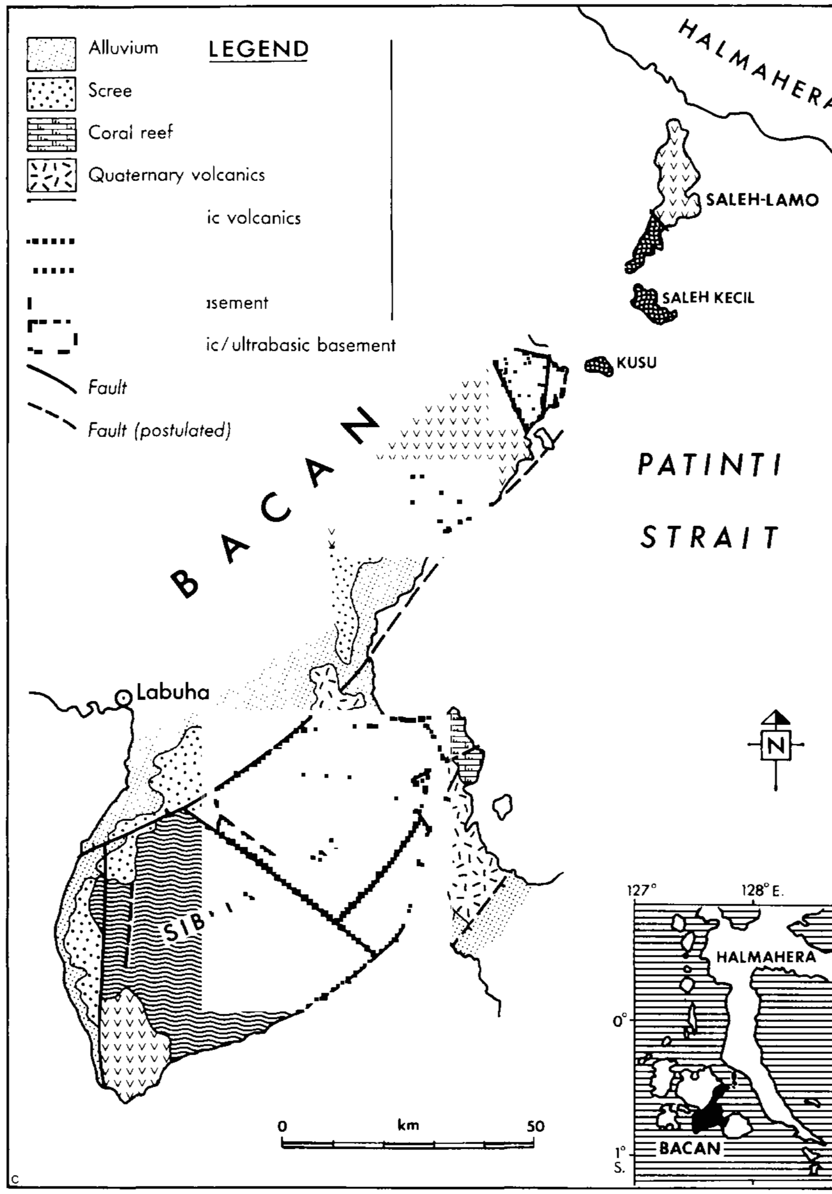

Fig. 6. Geological sketch map of Sibela Mountains and adjacent parts of Bacan. Based on Silitonga *et al.* (1981), Yasin (1980) and our own observations.

volcanic debris, indicate that the siliciclastics represent sudden influxes of debris, presumably as turbidites. Up-section the sequence becomes less dominated by carbonates and there is a gradual transition over a few metres to siliciclastic sediments of the Dodaga Breccia Formation.

In the type section the oldest dated part of the formation is of Coniacian–Campanian age (H127: *Hedbergella, Biglobigerinella, Globotruncana/Marginotruncana, Heterohelix*) and the top of the formation is of late Campanian age (H125: *Rugoglobigerina, Biglobigerinella, Hedbergella, Heterohelix, Planoglobulina, Globotruncanita calcarata*). Numerous exposures of similar limestones are exposed as slices in the Basement Complex, locally with volcanogenic clastic material, and often sheared in with red mudstones, sandstones and breccias dominated by basic igneous clasts, and locally some basalts. The limestones are typically pelagic micrites containing Radiolaria, sponge spicules and pelagic foraminifera, occasional ash layers and a tiny but persistent content of mineral and lithic fragments from an ophiolitic terrane. The pelagic limestone facies is definitely at least as old as Turonian, and a number of isolated slices suggest it may be as old as Barremian (HA100: *Heterohelix, Hedbergella*, probable '*Globuligerina*', ?*Globigerinelloides*), and possibly Late Jurassic (HA41: radiolarians, abundant sponge spicules and rare small Lagenina but no planktonic forms).

The top of the formation appears to be diachronous since exposures of pelagic limestones in the Onat River (Fig. 4) are as young as Maastrichtian (HA63: *Contusotruncana contusa, Plummerita, Globotruncana* spp, *Globotruncanita* gr. *stuarti*). No Palaeocene ages have been recorded from our samples but imbricated within the Basement Complex in the Onat River are rare Middle Eocene pelagic limestones (HA94: *Morozovella* cf. *aragonensis, M.* cf. *spinulosa, Acarinina* cf. *pseudotopilensis, A.* cf. *bullbrooki, Murico-*

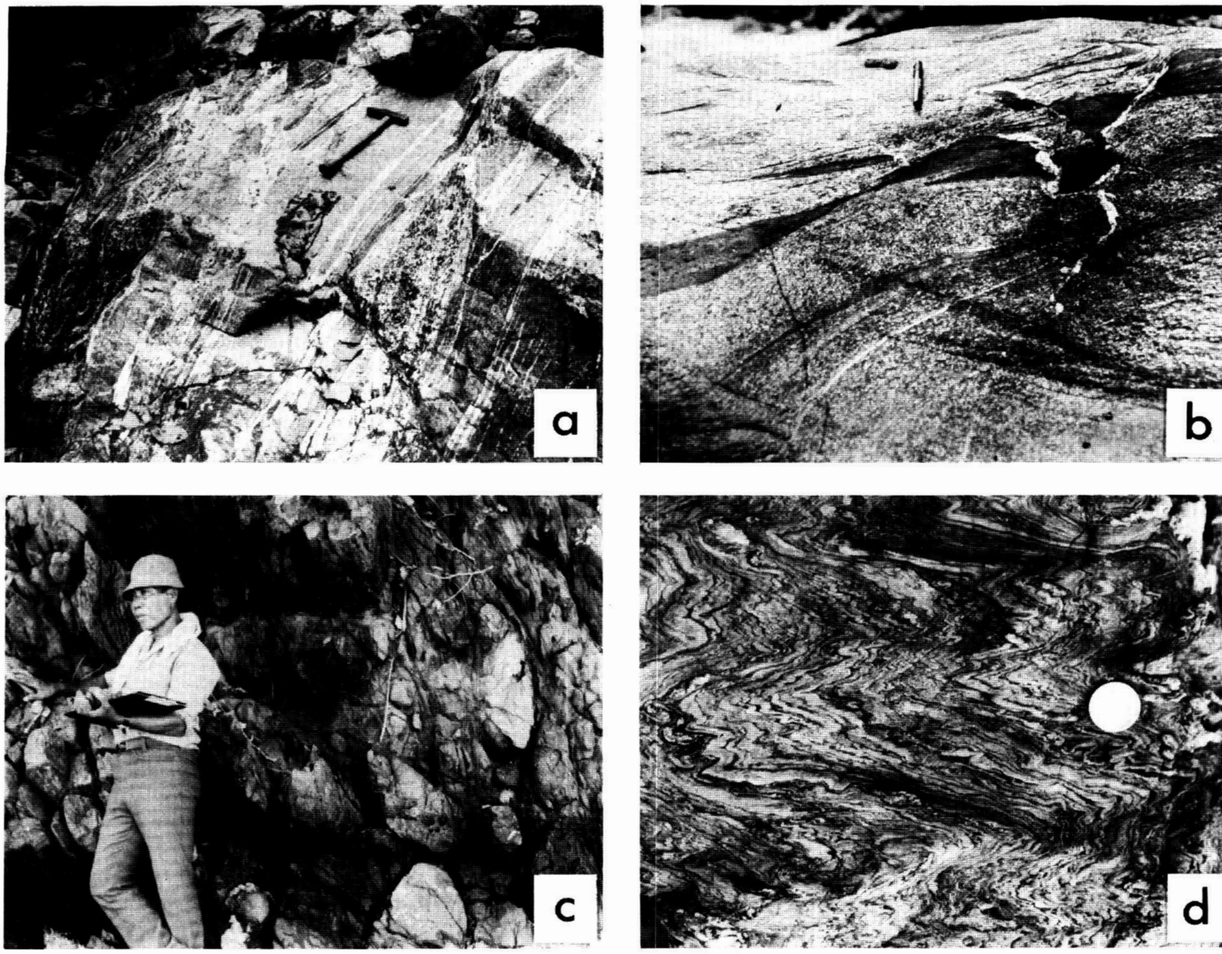

Fig. 7. (**a**), (**b**) Deformed multiple intrusions of basic rocks forming basement of Sibela Mountains of Bacan. Exposures of meta-gabbros in the Ra River in the north Sibela Mountains. (**c**) Deformed pillow lavas on Saleh Kecil. (**d**) Deformed metasediments associated with pillow lavas on Saleh Kecil.

globigerina cf. *senni*, ?*Globigerapsis*) similar to those of the Gau Limestone and similarly associated with red mudstones, siliceous mudstones, red and black cherts and calcareous mudstones with slump structures. All contacts are tectonic and the relationships between the Eocene pelagic limestones, the Cretaceous pelagic limestones and the Dodaga Breccia Formation are uncertain. We tentatively interpret this evidence to indicate that the distal parts of the Gau Formation are continuous into the Middle Eocene and its more proximal parts are transitional into the Dodaga Breccia Formation. The significance of this relationship is discussed below.

Dodaga Breccia Formation (*Campanian–Eocene*?)

The Dodaga Breccia Formation is named from the Dodaga River (Fig. 4) where it is extensively exposed. It probably corresponds approximately to the Dodaga Formation of Supriatna (1980). Exposures in the Dodaga River are extensive although tectonically isolated but the base of the formation is seen in the Gau River where there is a transition over a few metres from limestones of the Gau Formation to thinly-bedded siltstones and fine-grained sandstones of the Dodaga Breccia Formation. Above this the section is dominated by siliciclastic sediments, greyish, with abundant sedimentary structures. Some carbonates remain and a silty pelagic micrite with volcanic debris is late Campanian–Maastrichtian in age. The sandstones are normally graded from very coarse sandstones to fine sandstones, with ripple cross-bedding in some layers, some load structures and stretched and disrupted thin sandy horizons typical of wet sediment deformation. These beds appear to be relatively proximal (compared to the calciturbidites), arc-derived siliciclastics. Above are highly sheared red mudstones, sandstones and breccias (Fig. 12) with igneous and sedimentary clasts up to 20 cm in length. Most of the igneous clasts are basic while identifiable sediment clasts include reworked mudstone, sandstone and breccia and red-white recrystallized limestones. One limestone clast is Campanian or Maastrichtian in age and derived from a shallow marine area (H119: corals, rudists and *Orbitoides*); similar shallow water limestones of Late Cretaceous age are found as clasts in outcrops of the Dodaga Breccia Formation exposed in the Onat River (HA32: *Polygonella incrustata*, *Clypeina*?, *Orbitoides* cf.

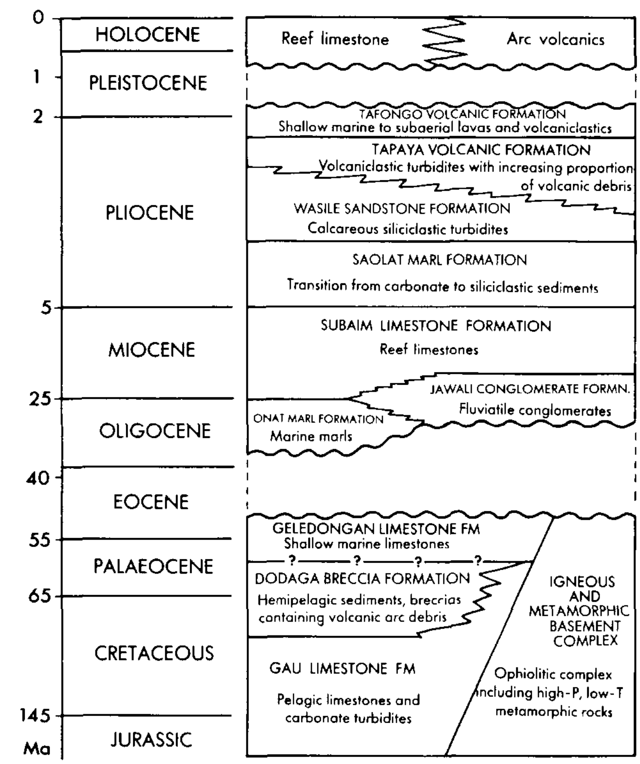

Fig. 8. Summary of the stratigraphy of Halmahera based on our fieldwork.

tissoti, Textulariopsis, ataxophragmiid). Sheared in with these rocks are slices of serpentinite and brecciated dolerite.

The section exposed in the Gau River (Fig. 11) indicates that there is a transition upwards from carbonates into a unit of mudstones and sandstones. These are separated by a shear zone from similar mudstones, sandstones and breccias which characteristically weather to a red colour and now usually found sheared in with basic and ultrabasic rocks of the Basement Complex. Despite its tectonized character this unit is considered to be a formation, originally deposited in a normal sequence, rather than a series of unrelated lithologies sheared together with igneous rocks in the basement. The reasons are: (i) There is an obvious sedimentary transition from the underlying Gau Formation in the Gau River section. (ii) Although the character of the breccias varies from place to place depending on the character and proportion of the clasts, the association of lithologies in the formation (mudstones, sandstones and breccias) is characteristic, and at most localities all of these lithologies can be found in close spatial association. (iii) It is common to find rocks of the Gau Limestone Formation sliced in with the Dodaga Formation. These are the two principal sedimentary formations found in the Basement Complex and their close spatial association suggests an original close stratigraphic association. (iv) The age of the Dodaga Formation is difficult to ascertain with certainty but all the datable material found within it is Cretaceous in age consistent with a close stratigraphic association with the Gau Formation.

Elsewhere, the Dodaga Breccia Formation consists of a series of typically red-weathered (but locally blue-black or brown on unweathered surfaces) mudstones, siltstones, sandstones and breccias. Few sedimentary structures were observed apart from bedding, fine laminations and local grading of sandstones. In part, this is a consequence of the composition of the sediments as the siltstones and sandstones are almost invariably rotted and difficult to sample. Where they are reasonably fresh they are poorly sorted and arkosic. Sandstones and siltstones are subordinate in the formation as regular beds but are more common as the matrix of the breccias which are the principal lithology in the formation. The breccias are typically coarse, very poorly sorted and contain angular clasts. They are locally clast-supported, but typically matrix-supported, and the matrix is usually a red hematitic, poorly sorted sandstone. Clasts range in size up to 50 cm in length, although the average is approximately 10 cm and most of the clasts are less than 20 cm in length. The shape of the clasts varies with the lithology; most of the igneous and carbonate clasts are sub-spherical whereas mudstone clasts are typically elongate, suggesting that some may have been incorporated while semi-lithified. Although most clasts are highly angular to sub-angular, some are moderately to well-rounded, suggesting some reworking.

Igneous rocks comprise more than 90% of the clasts in most localities. No granitic or acid clasts were recognized and in only a few localities were definite volcanic clasts of any type found; these were basaltic or andesitic. The most abundant igneous clasts are gabbros, microgabbros and diorites, and the basic rocks normally constitute about 75% or more of the igneous clasts. Sedimentary clasts are of two types: recrystallized carbonates and reworked clasts of mudstone, sandstone and breccia. All the limestone clasts sampled appear to contain debris of shallow water origin and all are of Cretaceous age. All of these shallow water carbonates contain some siliciclastic debris, some of which is well rounded, including rare glauconite, definite ophiolitic plutonic debris, volcanic clasts and rare metamorphosed volcanic rock clasts. It is not clear from examination of these clasts within the breccias whether the limestones were deposited in shallow water, or are redeposited.

In the central part of the NE arm of Halmahera, in the head waters of the Dodaga River (Fig. 4), the Dodaga Formation is exposed in a fault-bounded block between igneous rocks. In this block (Fig. 13) there is a series of repetitions of breccias and pelagic mudstones. The mudstones are thinly laminated, bluish-green to red-brown, carbonate-free and somewhat silicified. Although exposure is not continuous the same fault block can be recognized in two river sections, running approximately parallel and about 2 km apart, which cut across the strike of the beds (Fig. 13). The rocks within the sequence are not unduly deformed except for a degree of shattering of the splintery siliceous pelagic mudstones. The breccias in this sequence contain abundant elongate clasts of similar mudstones which appear to have been incorporated in the breccias in a semi-lithified state. This evidence suggests that the repetition of pelagic mudstones and breccias is primary.

The age range of the Dodaga Breccia Formation is uncertain since we have been able to date only beds at the base of the formation and clasts within it. We found no material of Palaeocene or younger age within the formation. Supriatna (1980) names a Dorosagu Formation which is said to lie unconformably on Cretaceous rocks, is dated as Palaeocene–Eocene and from its description closely

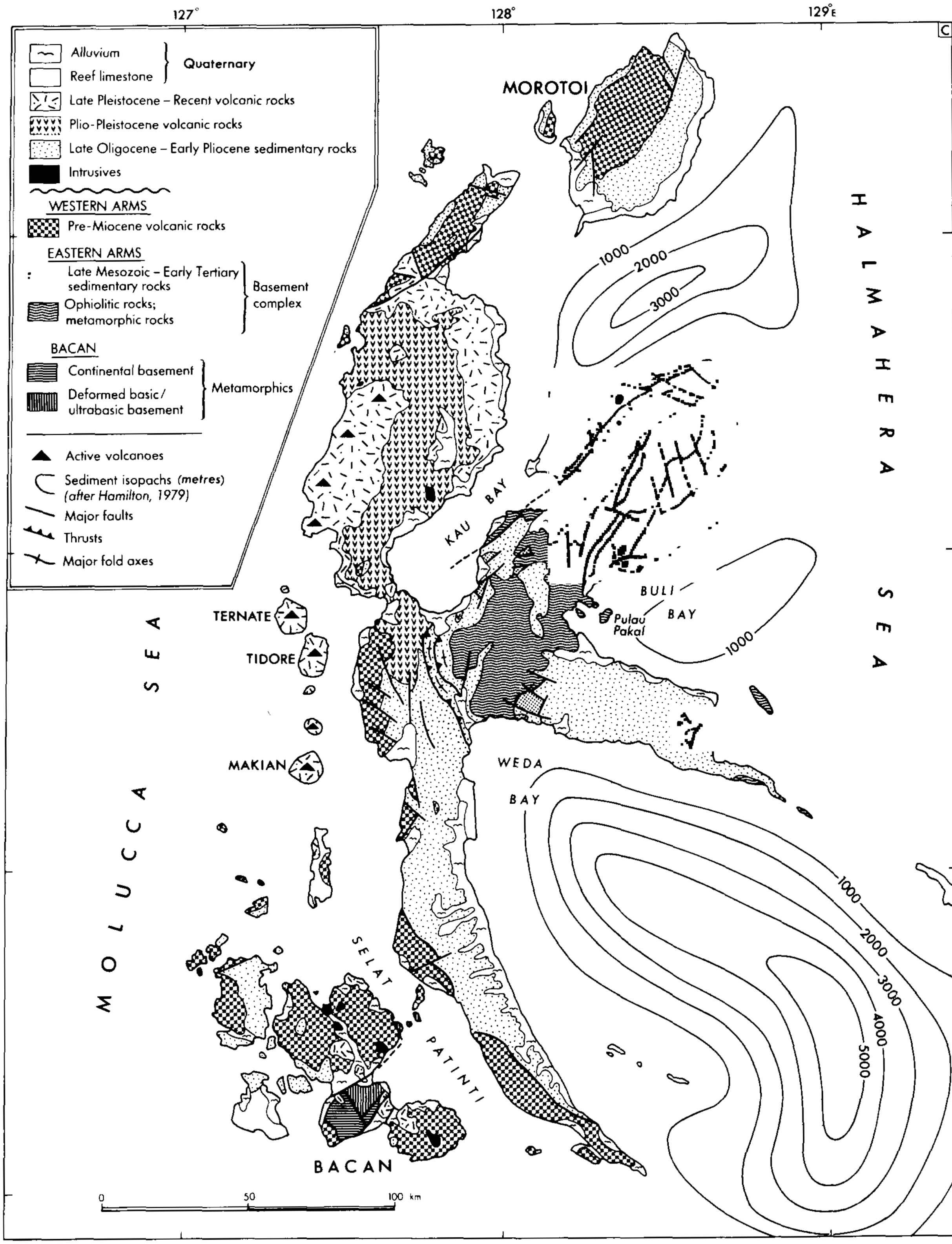

Fig. 9. Sketch geological map of Halmahera based on Apandi & Sudana (1980), Silitonga *et al.* (1981), Supriatna (1980) & Yasin (1980) and modified after our own observations. Note in particular the absence of thrusting in the NE arm and the major NE–SW fault (the Subaim Fault) running parallel to the south side of Kau Bay.

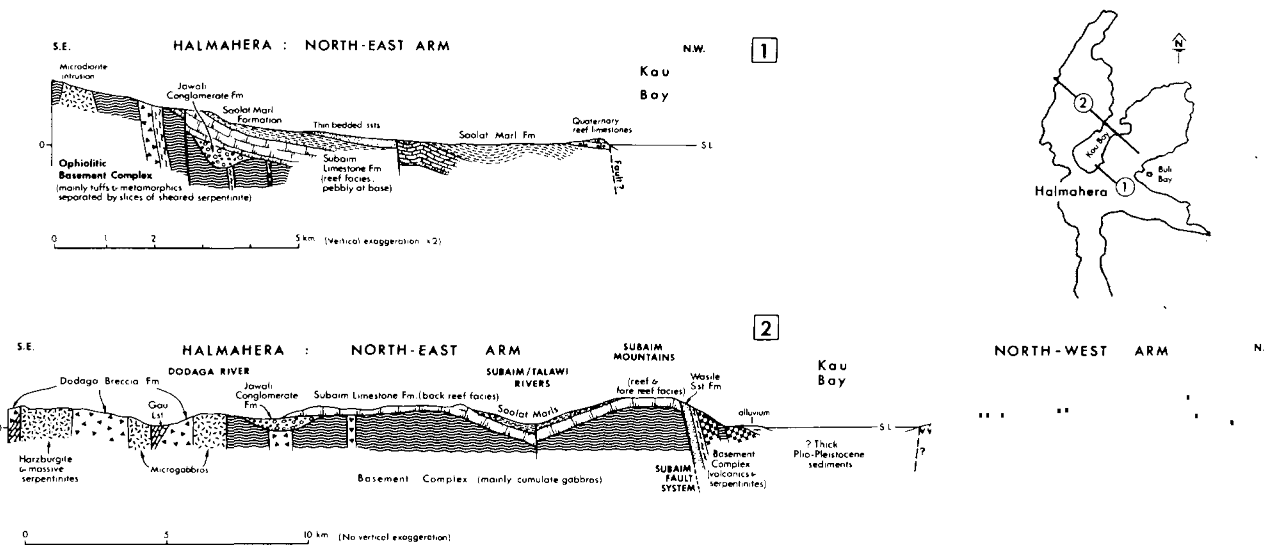

Fig. 10. Sketch cross-sections across the northern arms of Halmahera.

resembles the Dodaga Breccia Formation. This description and reported fauna (Supriatna 1980) suggest that the Dodaga Breccia Formation may extend into the Eocene. However, no details of localities are given and wherever we crossed areas mapped as Dorosagu Formation we found only rocks of Late Cretaceous age. We therefore consider a Tertiary age for part of the Dodaga Breccia Formation to be possible but unproved (Fig. 8).

Geledongan Limestone Formation (Early and Middle Eocene)

In the region close to the junction of the Onat and Geledongan Rivers (Fig. 4) are creamy white and buff coloured, medium-bedded bioclastic, micritic calcarenites, packstones, wackestones (HA97: *Nummulites, Alveolina oblonga, Microalveolina, Neorotalia, Operculina*) and softer marls with large foraminifera *Discocyclina* and *Nummulites* in a section 250 m thick. The relationship between these rocks and other rocks assigned to the Basement Complex is not seen since contacts with all other rocks are tectonic. In view of the difference in facies of the limestones we have assigned these to a separate formation.

Shallow water limestones of Palaeogene age associated with conglomerates and sandstones are reported from SE Halmahera (Apandi & Sudana 1980; Sukamto *et al.* 1981) but these conglomerates are also reported to contain reworked Late Cretaceous pelagic foraminifera, so it is not clear if these rocks are related to the Dodaga Breccia Formation or to the Geledongan Limestone Formation.

Igneous and metamorphic rocks of the Basement Complex

Rocks of the Gau Limestone Formation, Dodaga Breccia Formation and Geledongan Limestone Formation are tectonically intercalated with igneous and metamorphic rocks of uncertain age. All are unconformably overlain by Middle Oligocene and younger rocks (table 2, Hall *et al.* in preparation). The Basement Complex is therefore younger than early Middle Eocene and older than Middle Oligocene, but its maximum age is unknown at present and it may include elements which are at least as old as Late Cretaceous if rocks of this complex are the source of clasts in the Dodaga Breccia Formation. Since small clasts derived from basic and ultrabasic rocks occur in almost all the sedimentary rocks of the Gau Formation it is possible that the Basement Complex includes components as old as Late Jurassic.

Ultrabasic rocks

Contrary to the impression given by the geological map descriptions (Apandi & Sudana 1980; Supriatna 1980; Yasin 1980), the Basement Complex is not dominated by ultrabasic rocks, although the rock types seen vary considerably from area to area. Our estimate on the basis of our traverses is that the Basement Complex includes about 30% ultrabasic rocks. Locally these rocks are highly sheared and serpentinized and may be veined by magnesite. Some large blocks of magnesite, probably representing original veins or zones of alteration in the ultrabasics, occur in sheared serpentinite in the upper parts of the Jawali River (Fig. 4), where they are associated with blocks of rodingitized basic rocks. However, sheared serpentinite is not abundant nor typical of the ultrabasic parts of the Basement Complex. It is most frequently found near to fault zones; the major fault running NE–SW parallel to the coast through the Subaim Mountains (Figs 4 & 10) is marked by a zone of sheared and blocky serpentinite with asbestiform serpentine veins which is about 1 km wide in the Wasile River. Elsewhere in the Basement Complex sheared serpentinite is typical of fault contacts and these shear zones are rarely more than a few tens of metres wide. Where ultrasbasic rocks are found in more extensive outcrops they are typically massive and not highly serpentinized. Both harzburgites and lherzolites are found, typical of the upper mantle part of an ophiolite.

Basic plutonic rocks

Although no section was found that displayed a transition from ultrabasic to basic plutonic rocks, such as might be

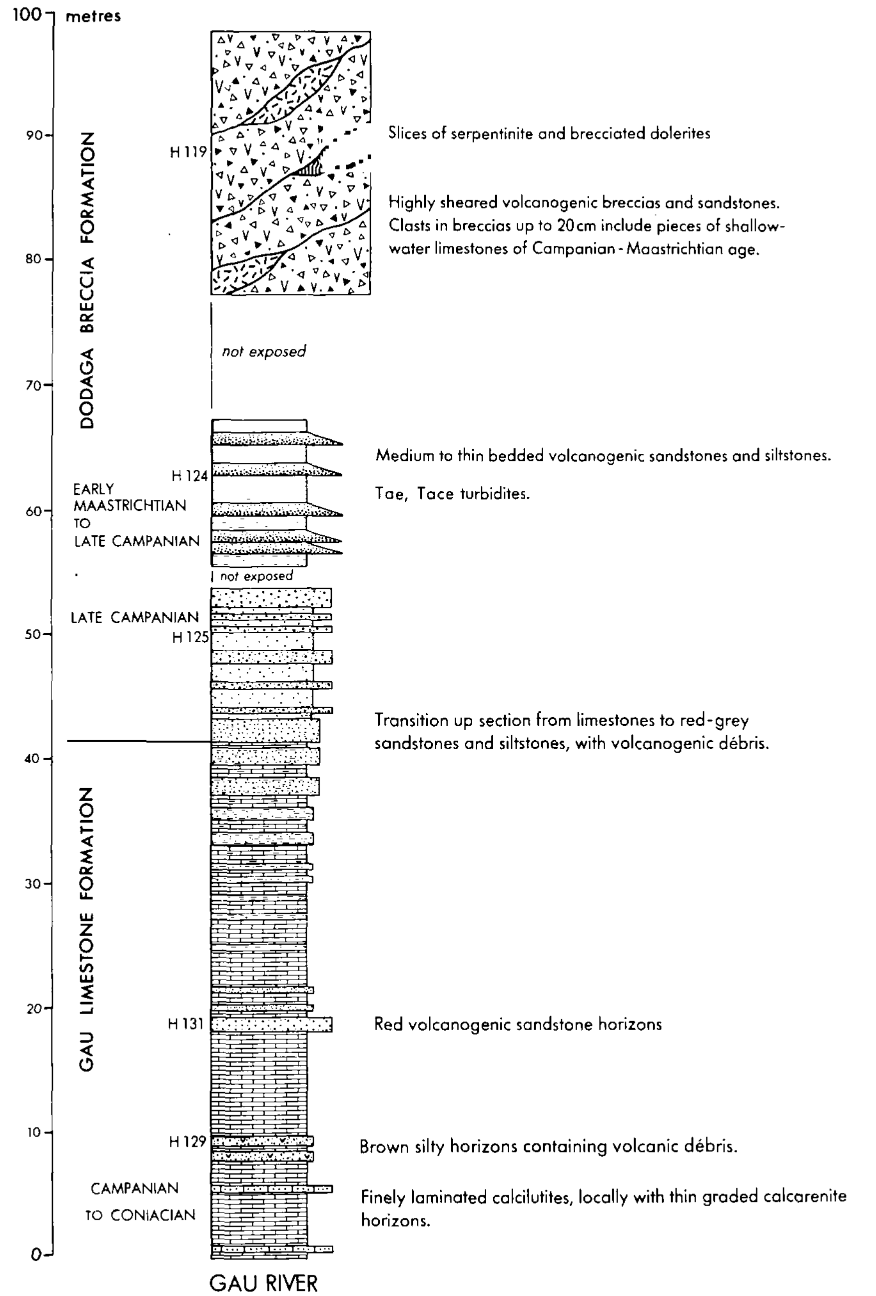

Fig. 11. Log of transition between the Gau Limestone Formation and Dodaga Breccia Formation in type section of the Gau Formation in the Gau River. The boundary between the two formations is taken at the last occurrence of pelagic limestone in the section.

expected in an intact ophiolite complex, a reasonable continuum of material was sampled which is suggestive of an originally coherent sequence. It may be that different parts of the sequence were emplaced at different times and in different places, and there was never a single continuous igneous sequence emplaced. However, the types of rock in the Basement Complex enable a single sequence to be reconstructed, implying that different parts of an ophiolite have been sampled even if they are not parts of a single ophiolite complex emplaced in a single episode.

Dunites and chromite bodies are usually considered to represent the deepest parts of the cumulate sequence expected in the magma chamber established above the upper mantle in ophiolite complexes. Dunites are represented and although we found no chromite bodies, they are reported as boulders in the Dodaga and Tutungan Rivers (Fig. 4) and as schlieren-type occurrences associated with dunites on Pulau Pakal, south of Buli (Burgath *et al.* 1983). Cumulate rocks representing the deeper parts of the magma chamber were found, some with remarkable crescumulate textures (Fig. 14a), indicating crystallization from a supercooled and stagnant magma. There is a complete transition from cumulate peridotites through to cumulate gabbros and norites.

Above the cumulate sequence in an ophiolite complex there is normally considered to be a thick sequence of layered to isotropic gabbros with variable grain size which pass upwards into the lower part of a sheeted complex of dykes. Some ophiolites appear to lack a sheeted dyke complex and there is a transition between microgabbros,

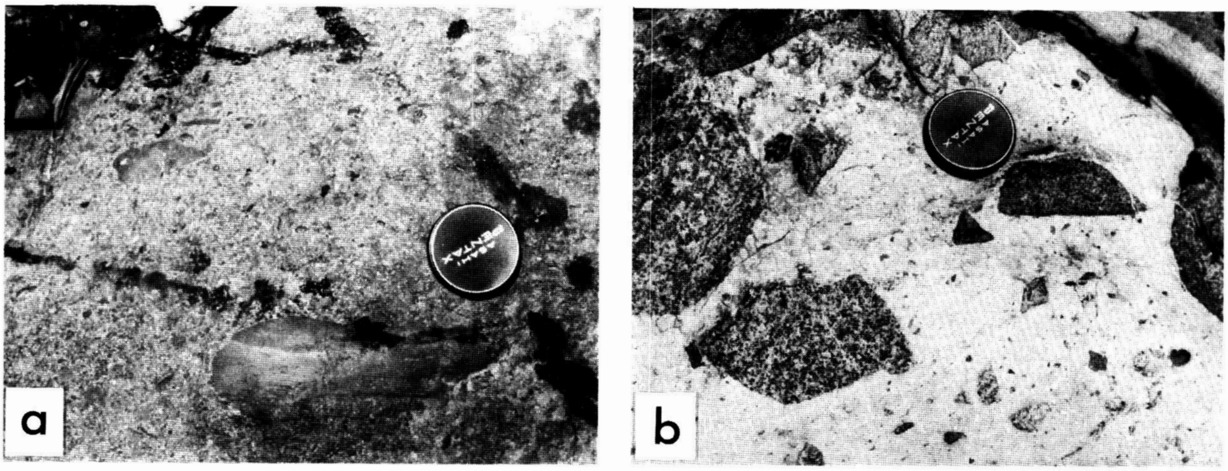

Fig. 12. (**a**) Red mudstone clasts in angular, poorly sorted breccia of Dodaga Breccia Formation. At this locality in the Onat River the formation is dominated by sedimentary clasts. (**b**) Gabbro and diorite clasts in angular sedimentary breccia matrix. Dodaga Breccia Formation in the Onat River.

representing hypabyssal rocks, and lavas representing the volcanic part of the ophiolite. Such a transition may be represented in the Dodaga River (Fig. 13). We were able to find no evidence for a sheeted complex on our traverses (although a dyke complex is shown, without details, by Burgath *et al.* (1983) in the Mountains south of Ekor in central Halmahera). However, microgabbros and fine-grained gabbros, some layered but typically isotropic, do form the major exposed part of the Basement Complex and probably account for at least 50% of the Complex. These rocks are typically sheared in with ultrabasics and rocks of the Dodaga Breccia Formation and together these account for 90% of the Basement Complex in the areas visited. In view of the abundance of the isotropic and fine-grained gabbros, it is somewhat surprising that no sheeted complex was observed. Three explanations are possible: (i) there was no sheeted complex in the original sequence, (ii) the sheeted complex was emplaced but has subsequently been removed, tectonically or by erosion, and the microgabbros represent the upper part of the magma chamber just below the sheeted complex, or (iii) although a sheeted complex was present in the original sequence it was never emplaced.

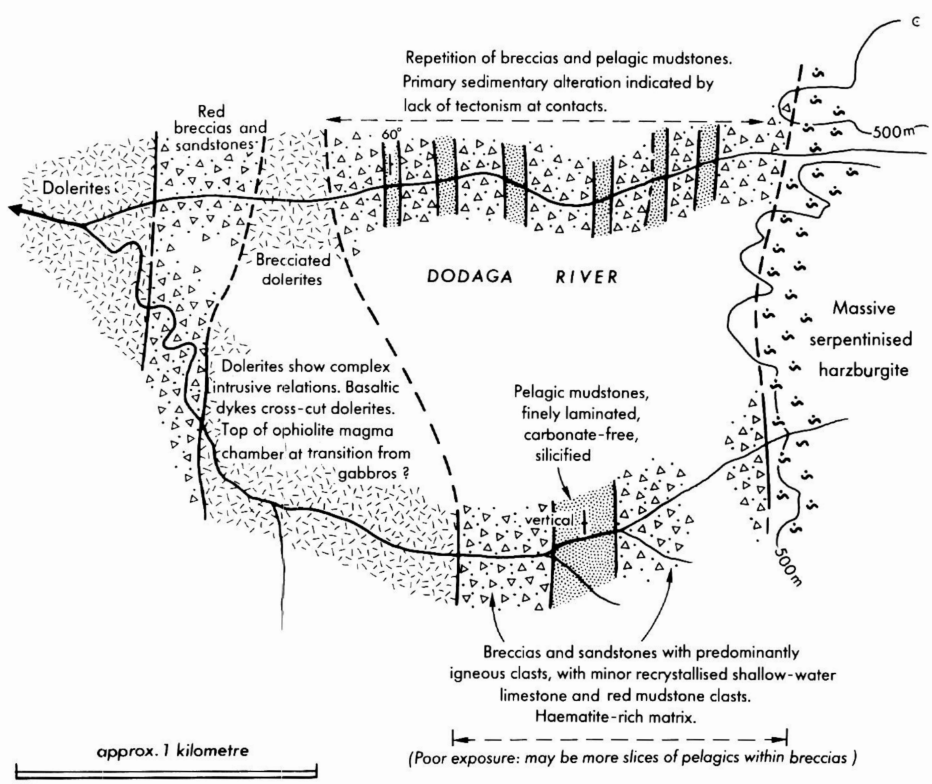

Fig. 13. Sketch map of Dodaga Breccia Formation in headwaters of Dodaga River from field notebook.

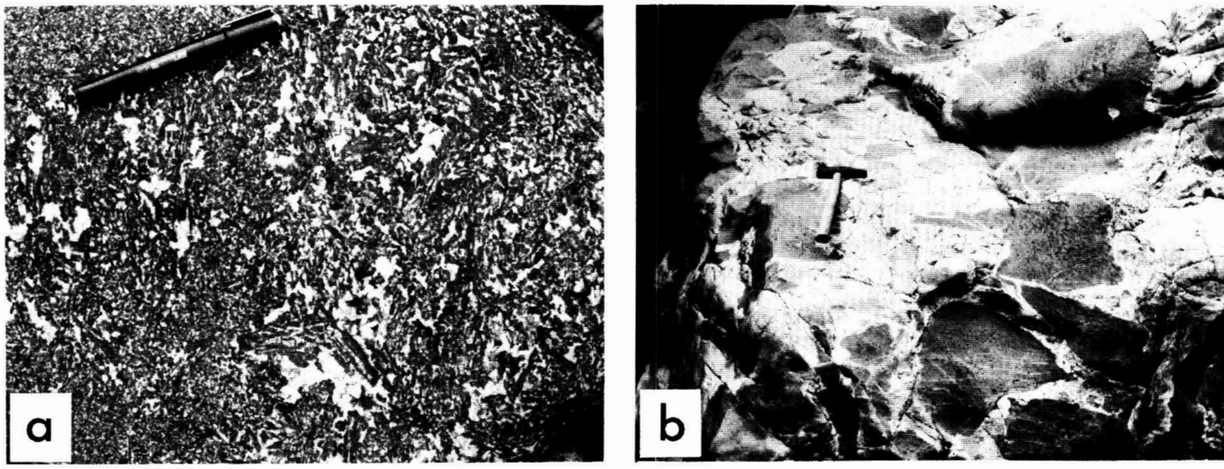

Fig. 14. (**a**) Olivine crescumulate in Dodaga River. (**b**) Gabbro–diorite blocks veined by plagiogranite in Wasile River.

Other plutonic rocks

A number of other plutonic igneous rocks were found in the Basement Complex. Some of these are intrusive into the Basement Complex and are described briefly below; they are probably much younger than the Complex. However, there are a number of non-basic plutonic rocks forming part of the Basement Complex itself which although volumetrically very subordinate to the basic rocks are locally significant. They range in composition from diorites to trondhjemites. Some have somewhat gneissose textures suggesting deformation under sub-solidus conditions, others are intimately intermixed with gabbroic rocks (Fig. 14b) and have unusual magmatic textures. There are obvious xenoliths of dark gabbros and diorites within an acid host, partially absorbed xenoliths, and sheared out fabrics suggesting several episodes, closely related in time, of intrusion and deformation. These rocks would be similar to those found near the top of the magma chamber in many ophiolite complexes.

Volcanic rocks

The final major part of a normal ophiolite is a lava sequence, often with abundant pillows and overlain by pelagic sediments. On Halmahera this part of the sequence is extremely poorly represented; definite volcanic rocks and associated pelagic sediments were exposed in three principal areas, and none of these have provided material suitable for palaeontological dating. Near Wasile, north of the Subaim Mountains, there are pillowed basaltic lavas which are amygdaloidal, with amygdales up to 4 mm with a mean diameter of about 2 mm. The size of the amygdales suggests that these are not typical ocean-floor lavas erupted at substantial depths, but were erupted in somewhat shallower water. The lavas are locally associated with bright red manganiferous and silicified mudstones which are interstitial to the lavas. In the upper reaches of the Saolat and Jawali Rivers, SE of Ekor (Fig. 4) there are small exposures of metamorphosed vesicular and amygdaloidal basic pillow lavas. As at Wasile, the size of the amygdales suggests that these are not typical ocean-floor lavas but were erupted in relatively shallow water. In the same region there are abundant exposures of fine-grained, bluish or greenish, extremely hard and often massive basaltic tuffs. In most places these are well jointed and fractured, but without obvious layering or other primary structures. In a few places these rocks have a definite bedding, grading and other sedimentary structures suggesting wet-sediment deformation. The sedimentary structures indicate that at least some of these rocks are water-laid pyroclastic rocks. In the headwaters of the Onat river (Fig. 4) fresh flattened pillow basalts are imbricated with sheared serpentinites and hard siliceous, purple and pale-green, pelagic micrites. Fresh porphyritic basalt and vesicular basalt found as huge boulders in the Tutuli river were probably derived from slices imbricated with the Gau Limestone and the Dodaga Breccia Formations.

Metamorphism and metamorphic rocks

Preliminary examination of the volcanic rocks present in the Basement Complex indicates that they have been metamorphosed under sub-greenschist facies conditions; probably under conditions between the pumpellyite–prehnite facies and blueschist facies. This is indicated by the widespread presence of pumpellyite in amygdales, groundmass and veins of both volcanic rocks and clasts in volcanogenic sediments, and indications of significant recrystallization and development of new phases (such as epidote, prehnite and chlorite) without destruction of the primary volcanic fabric. Sodic amphiboles (crossite–magnesioriebeckite) occur in a number of samples, although without lawsonite, together with jadeite-poor sodic pyroxenes. A systematic study of the petrology of the metamorphic rocks is currently in progress and it is interesting to note that this type of metamorphism seems to be common in many fore-arc volcanic rocks (Sumatra, M. Wazjer pers. comm.; Kalimantan, N. Sikumbang pers. comm.; East Sulawesi, T. O. Simandjuntak pers. comm.; New Zealand, Bishop 1972).

The plutonic rocks of the Basement Complex are unaffected by regional metamorphism. However, many of these rocks show some signs of metamorphism and recrystallization, for example partial recrystallization of gabbros to amphibolites which locally have acquired a strong foliation. The plutonic rocks also show signs of strain such as bent twin lamellae in plagioclase, deformed cleavage planes and exsolution lamellae in pyroxenes, and local granulation. This limited deformation is likely to be due to tectonic emplacement or later faulting. Most commonly the primary igneous texture is well preserved indicating metamorphism under a changing thermal gradient, but without significant deformation. This type of metamorphism could be due to sub-sea-floor metamorphism associated with spreading-centre magma chambers, or it could have occurred in the deeper parts of the fore-arc region. Some of the rocks with strong planar fabrics may have suffered metamorphism during emplacement of the rocks in the Basement Complex.

Metamorphic rocks of other types are relatively abundant in the Wasile River, and in the Saolat and Jawali Rivers (Fig. 4), as rare blueschists, amphibolites, green-schists and green phyllites, black slates and metamorphosed carbonates and cherts. Some of the schists and phyllites display fold structures indicating a polyphase deformational history (Ramsay type three-fold interference patterns, folded cleavages). These metamorphic rocks form tectonic slivers up to a few hundred metres wide which are subvertical, and which are sliced in with tuffs, serpentinites, rare volcanics and the Dodaga Breccia Formation. Their protoliths are basic or intermediate volcanic rocks, volcaniclastic sedimentary rocks and other sedimentary rocks. They could represent metamorphosed oceanic crust and its pelagic sedimentary cover, although many of the metamorphic rocks are not easily explained in this way (black slates and water-laid tuffs are not typical oceanic rocks, although they could represent arc or back-arc basin rocks). All of these rocks could represent subduction zone metamorphism.

Younger intrusive igneous rocks

A number of igneous rocks occur in the Basement Complex but are not included as members of it because they clearly intrude the Complex. They include aphyric basaltic dykes, porphyritic basaltic/andesitic dykes, and small intrusive bodies (probably plugs) of diorite. The appearance of most of these rocks indicates that they are calc-alkaline minor intrusions related to Neogene and younger igneous activity in the Halmahera arc.

Structure of the Basement Complex

The geological maps of Halmahera (Apandi & Sudana 1980; Supriatna 1980; Yasin 1980) imply that rocks within the Basement Complex are in thrust contact with one another and that the basement rocks form a series of sub-horizontal thrust sheets. We have seen no evidence to support this interpretation. Hamilton (1979) has suggested a mélange character for Halmahera and this interpretation has been adopted for the basement rocks of the Talaud islands by Moore *et al.* (1981) which are exposed in the central Molucca Sea west of Halmahera. Mélange does not seem to be an appropriate term to describe the Basement Complex of Halmahera. Although there is a complex assemblage of different rock types in the basement there is no evidence that these rocks occur as blocks in a matrix. We observed a mélange character in outcrops at two localities only. The first, in the Talawi River, exposed blocks of serpentinite up to 1 m across in a sheared serpentinite matrix; no exotic material occurred within the sheared serpentinite and the zone of sheared serpentinite marks a major vertical fault zone. At the second locality, in the centre of the island in one of the tributaries of the Dodaga River, a 3 m block of coarse gabbro occurs within a blocky serpentinite matrix. In no other locality did we observe that any of the rocks occur as blocks in a pervasively sheared matrix; virtually the only lithology that does often occur in a highly sheared state is serpentinite and although this often marks contacts between different rock types, it is insufficiently abundant to be described as a matrix. The proportion of sedimentary material in the Basement Complex is far too small for this to be considered as a possible matrix. We draw this conclusion after having paid particular attention to areas of Halmahera that seemed likely from aerial photographic interpretation to include regions of 'scaly clay'.

Folding is rare in the Basement Complex. Those folds observed were in metamorphic slices in the Jawali River, in metamorphic rocks of the Wasile River, and as wet-sediment structures in siliciclastic sediments. Our interpretation of the structure of the Basement Complex is that of a series of tectonic slices of different rock types separated by vertical to sub-vertical faults. In some cases the faults are marked by narrow (a few metres at most) zones of sheared serpentinite, but in most cases the faults, where exposed, are marked by intense shearing or shattering of the two juxtaposed rock types. Where there is evidence of the attitude of rocks within individual tectonic slices (for example, from bedding or foliation) the rocks are typically steeply dipping. In some regions it was possible to trace these slices along rivers, across the mountains between rivers, or match up sections in parallel rivers (Fig. 13). These examples indicate that the 'grain' of the basement, marked by the orientation of the tectonic slices and their bounding faults, is broadly N–S, although the strike of the bedding/foliation within a slice may not be N–S. This 'grain' is not evident on Fig. 9 because of the effects of later faulting.

Different regions of the Basement Complex contain different rock types. On the basis of our traverses, and those of earlier workers (Burgath *et al.* 1983), it appears that the central and eastern part of the Basement Complex (Dodaga River system and south towards Kobe) is dominated by plutonic and hypabyssal basic and ultrabasic rocks which are sliced in with limestones of the Gau Formation and the Dodaga Breccia Formation. In the western part of the Basement Complex (Subaim, Wasile, Saolat and Talawi Rivers) volcanic rocks, volcaniclastics and metamorphic rocks form a greater proportion of the Basement Complex and basic igneous hypabyssal and plutonic rocks are subordinate. The Gau Limestone Formation is not found in this area, and the Dodaga Breccia Formation is less extensive. Although the significance of this distribution is not certain it is consistent with the N–S structural 'grain' observed in the Basement Complex.

Interpretation of the Basement Complex

The character of the Gau Limestone Formation suggests that it represents a deep-water deposit originally situated not too far from an uplifted ophiolite terrain, probably similar to present-day eastern Halmahera. The occasional ash layer in the Late Cretaceous limestones suggests proximity to an active arc region, although volcanic ash may be carried far from its source. Similar pelagic and resedimented carbonates with ash layers account for almost

50% of sediment recovered by the Deep Sea Drilling Project (DSDP) from Pacific back-arc basins (Klein 1985), particularly in equatorial regions. Given the abundance of ophiolite terranes in southeast Asia and around the southwest Pacific margin, sediments similar to the Gau Limestone Formation could be expected to be forming today on the rise and slope of an active or inactive margin or back-arc basin in this region.

The similarities in ages, and the close tectonic association of the limestones with the red mudstones, sandstones and breccias suggest that all these rocks were originally part of a single sequence which recorded a transition from a quiet, pelagic carbonate environment to sedimentation close to an active arc. Despite the deformation which obscures the history of the Dodaga Breccia Formation, the coherent stratigraphy of the Gau River section and the gradual transition to siliciclastics, evidently volcanically-derived, suggest a real change in environment. The succession appears to record either the movement of the deeper part of an inactive margin (for example, a passive continental margin or a back-arc basin behind an inactive arc) towards a volcanic arc by subduction of intervening oceanic lithosphere, or the formation of a new intra-oceanic arc supplying volcanic debris to relatively deep waters.

The Dodaga Breccia Formation indicates a relatively deep-marine depositional environment represented by pelagic mudstones, close to a volcanic arc or igneous basement terrain with abundant basic igneous rocks, and also close to a source of shallow-marine carbonate debris. These requirements are most easily satisfied by proposing that the Dodaga Formation represents deposits which accumulated on the oceanward side of a volcanic arc, possibly a sedimentary basin in the fore-arc region, or a deeper submarine fan. The pelagic mudstones represent relatively deep-water, quiet conditions in the fore-arc region, intermittently interrupted by turbidites bringing arkosic silts and sands into the basin and occasional debris-flows carrying a mixture of shallow-water carbonate clasts, reworked igneous clasts, fault breccia and slump material from fault scarps into deep water. Submarine faults are required to provide the large volume of angular igneous debris, and these faults must have sliced through a basement composed mainly of hypabyssal and plutonic rocks, largely basic or dioritic in composition. We prefer a fore-arc region to other arc-related regions because of the characters of the sedimentary rocks described above, their association with rocks recording high pressure–low temperature metamorphism locally up to blueschist facies, as well as the varied character of the volcanic rocks which include tuffs and shallow-water lavas.

Of modern active margins so far drilled by the DSDP the Marianas arc is the most closely comparable to Halmahera because of its equatorial, intra-oceanic position. There is a striking similarity between rocks of the Gau Limestone and Dodaga Breccia Formations and sedimentary rocks drilled in the Marianas fore-arc during DSDP Leg 60 (Hussong *et al.* 1981). Sites 458, 459 and 460 penetrated pelagic carbonates (up to 90% of the section at Site 458) including carbonate turbidites (Site 459). There are levels of vitric tuffs, sands, silts and clays with glass and ash layers throughout each sequence. The proportion of carbonate and volcanogenic material is very variable and changes rapidly within a single sequence and from site to site. Important hiatuses and changes in sedimentation rates were identified at each site within the Oligocene–Recent sequences. Drilling at Site 460 (Fig. 15) showed pre-Eocene basement exposed on fault scarps and proved considerable reworking of older material (including Late Jurassic Calpionellid limestones) into coarse talus deposits. Volcanic rocks reworked into these deposits include basalts, metamorphosed basalts and andesites; rudites also contain clasts of plutonic and hypabyssal basic igneous rocks.

The small proportion of volcanic clasts in the Dodaga Breccia Formation is worthy of note. This is consistent with the apparently small volume of volcanic rocks in the Basement Complex as a whole and suggests that volcanic rocks were not abundant in the fore-arc region, although as noted above the lithologies in the Basement Complex can vary markedly from area to area. The volcanic clasts that are found are often metamorphosed, suggesting erosion of material from deeper parts of the fore-arc, rather than derivation from a contemporaneous arc. Equally notable is the absence of accretionary wedge-type sediments. The small proportion of volcanic rocks may be a reflection of the mechanism of emplacement of igneous rocks in the fore-arc, or may reflect the earlier removal of the volcanic rocks by erosion. One possibility is that most volcanic rocks and pelagic cover were preferentially scraped-off at the toe of the fore-arc region leaving mainly the deeper parts of the lithosphere to be emplaced in the deeper parts of the fore-arc region, closer to the arc. Faulting and erosion of the fore-arc would then shed mainly hypabyssal and plutonic debris into sedimentary basins. In this case the accretionary complex would be located elsewhere, if preserved, probably closer to the trench. A second possibility is that most of the Halmahera igneous rocks were formed closer to an older arc within a region which later became a fore-arc and were mostly not emplaced by accretionary processes. The Marianas fore-arc is notable for its lack of an accretionary wedge and presence of arc-related igneous rocks within the fore-arc region suggesting a history of subduction erosion rather than accretion.

Subsequent tectonism has sliced the Dodaga Breccia Formation and the Gau Formation in with ultrabasic and basic rocks. The simplest possible interpretation of the stratigraphical and palaeontological data suggests that carbonate deposition without major arc influence persisted until the late Campanian when significant amounts of arc-related sedimentary material appear. The lack of Palaeocene rocks could represent a hiatus such as those recorded in the Marianas fore-arc or could be a sampling artifact. Comparison with the Marianas fore-arc suggests that there is no difficulty in maintaining carbonate deposition in some parts of the fore-arc while thick volcanogenic deposits are accumulating nearby. Thus we interpret the Gau Limestone Formation as, in part, laterally equivalent to the Dodaga Breccia Formation, reflecting variation in topography, position and tectonism within the fore-arc (Fig. 15). The arc remained active until the late Eocene–early Oligocene when collision occurred or subduction ceased, terminating arc activity and resulting in uplift and erosion of the old arc terrane. The oldest rocks unconformably above the Basement Complex are of mid-Oligocene age (Fig. 8).

One striking feature is that none of the processes of emplacement in the fore-arc, nor the Late Eocene–Early Oligocene event uplifting the Basement Complex, nor late

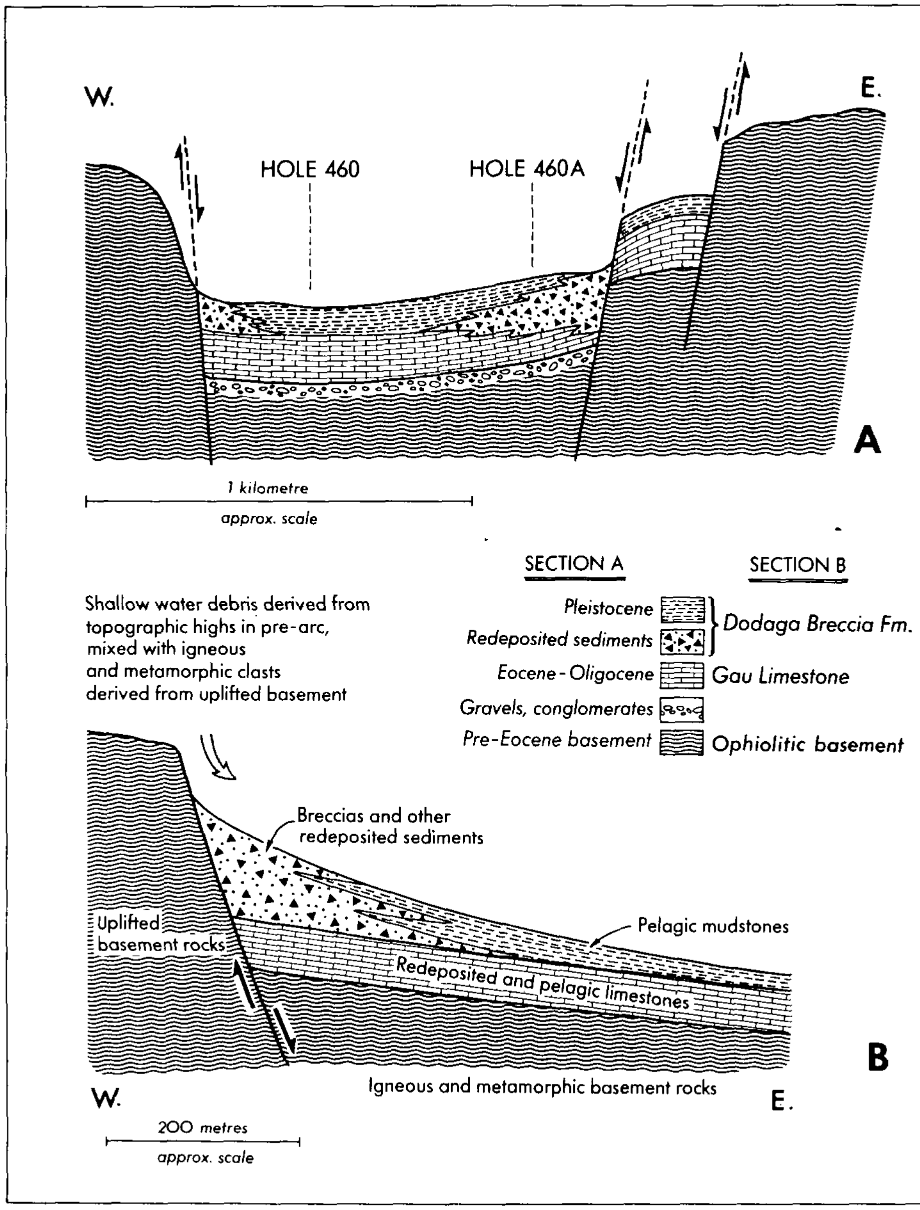

Fig. 15. Sketch section **(A)** of part of Marianas fore-arc based on Leg 60 drilling (Hussong & Uyeda *et al.* 1981) compared to interpretative cross-section **(B)** based on observed stratigraphic relationships between ophiolitic basement, Gau Limestone Formation and Dodaga Breccia Formation in NE arm of Halmahera. The location of DSDP site 460 is shown in Fig. 17.

strike-slip faulting, led to the formation of mélange. In view of the widespread assumption that mélange terranes and subduction zones are associated this may seem surprising. However, this may be partly a real feature of the Basement Complex and partly a confusion. If scaly clay mélanges do exist in fore-arc regions they may be restricted to high structural levels, particularly close to the trench; this appears to be part of the fore-arc not seen on Halmahera. However, it is equally possible that much of what is labelled as mélange on very large scale maps simply reflects a lack of detailed knowledge and almost any tectonically complex terrain could be labelled mélange when investigation is similarly handicapped by lack of exposure, topography and heavy rain-forest as well as the limited history of study. Our observations on Halmahera suggest that mélange is not ubiquitous in fore-arc regions.

The polarity of the Late Cretaceous–early Tertiary arc is unknown, We have two very tenuous indications that it was east-facing from samples taken from the basement on which the younger volcanic arcs were built. A volcanic conglomerate collected on the western coast of central Halmahera contains possible rudist fragments. About 20 km away, on the east side of the western arms, a series of volcaniclastic rocks, tuffs and volcanic conglomerates is interbedded with calcareous mudstones and marls which have yielded small planktonic foraminifera indicating an early Middle Eocene age. This evidence suggests that the Plio–Pleistocene and present volcanic arcs which form the western arms of Halmahera are built on an eroded basement of the late Cretaceous–early Tertiary volcanic arc. This is the first discovery of rocks of such age in the western arms of Halmahera.

Regional correlation

The geology of much of the surrounding region is still as poorly known as that of Halmahera and in most areas only reconnaissance mapping has been carried out. Of immediate interest are comparisons of Halmahera with Mindanao, the southernmost island of the Philippines, which will constrain reconstructions to the north of Halmahera, and with New Guinea since Halmahera has been moving westwards north of the Sorong Fault (Hamilton 1979) since at least the Miocene.

There are two entirely different basement types beneath the Halmahera islands. Bacan is underlain by continental basement indicated by exposures in the Sibela Mountains and by the chemistry of Quaternary volcanic rocks on Bacan which indicate a continental crustal contribution to lavas erupted in southern Bacan (Morris *et al.* 1983). Halmahera, on the other hand, is underlain by rocks which formed part of an arc region until the end of the Eocene and has no continental basement. The continental basement of Bacan must have originated in the Australian continental margin exposed in New Guinea (Hamilton 1979) and we suggest that the continental fragment of Bacan is separated from Halmahera by a splay of the Sorong Fault system which passes through Bacan. This is probably the extension of the Molucca–Sorong Fault which is one of several splays of the Sorong Fault zone identified by seismic reflection work (Letouzey *et al.* 1983) between Halmahera and Seram. Numerous 'microcontinental fragments' in the region close to the Sorong Fault zone have moved at different speeds westwards relative to Australia during its collision with the Pacific (Audley-Charles *et al.* 1972; Hamilton 1979; Dow & Sukamto 1984; Pigram & Panggabean 1984; Silver *et al.* 1985); indeed splintering of the margin along the Sorong Fault system seems to be typical of the history of oblique convergence at the Australian–Pacific plate margin. We suggest that the fault zone is marked by the deformed ophiolite complex in the north Sibela Mountains and offshore Bacan representing magmatism in the fault zone. This suggestion is supported by the position and alignment of volcanoes on Bacan; they are significantly east of the 100 km Benioff zone contour traced by Cardwell *et al.* (1980) unlike all the volcanoes of Halmahera, and they trend at a high angle to the rest of the arc. The chemistry of Quaternary volcanoes suggests that those of Halmahera and north Bacan are typical of an oceanic arc whereas those of south Bacan are underlain by continental crust (Morris *et al.* 1983) indicating a major change in basement type in the position we suggest.

North of the Sorong Fault system we suggest a continuity of basement from Halmahera at least as far north as east Mindanao. Figure 16 compares the Basement Complex of Halmahera to similar age rocks in east Mindanao. Collision between eastern and western Mindanao is considered to have occurred at the end of the Middle Miocene (Moore & Silver 1983). East Mindanao has a basement complex including serpentinites, peridotites, gabbros, diorites, basalts, andesites and the metamorphosed equivalents of these rocks, in addition to metamorphosed sedimentary rocks (Ranneft *et al.* 1960). Volcanic rocks interbedded with Cretaceous limestones are island arc tholeiites (Wright *et al.* 1981). Ranneft *et al.* (1960) report that the basement complex is overlain by Eocene recrystallized limestones with sandstone, conglomerate and shale whereas Moore & Silver (1983) report Eocene and older greywackes, derived from andesitic volcanic rocks, interbedded with volcanics. This apparent inconsistency would be typical of stratigraphic relations in a fore-arc region as the DSDP has shown in the Marianas. In east Mindanao no mélange terrains have been found and the Cretaceous arc tholeiites are overlain by Upper Oligocene limestones without volcanic detritus indicating a cessation of arc activity before the Late Oligocene (Moore & Silver 1983). Lower Miocene rocks are shallow marine or continental rocks as on Halmahera.

The Halmahera arc and fore-arc terrain may be traceable northwards in the eastern Philippines. Hashimoto (1981) extends the eastern ultramafic belt of east Mindanao through the eastern Philippines as far north as Luzon. Karig (1983) interprets eastern Luzon basement rocks as part of an

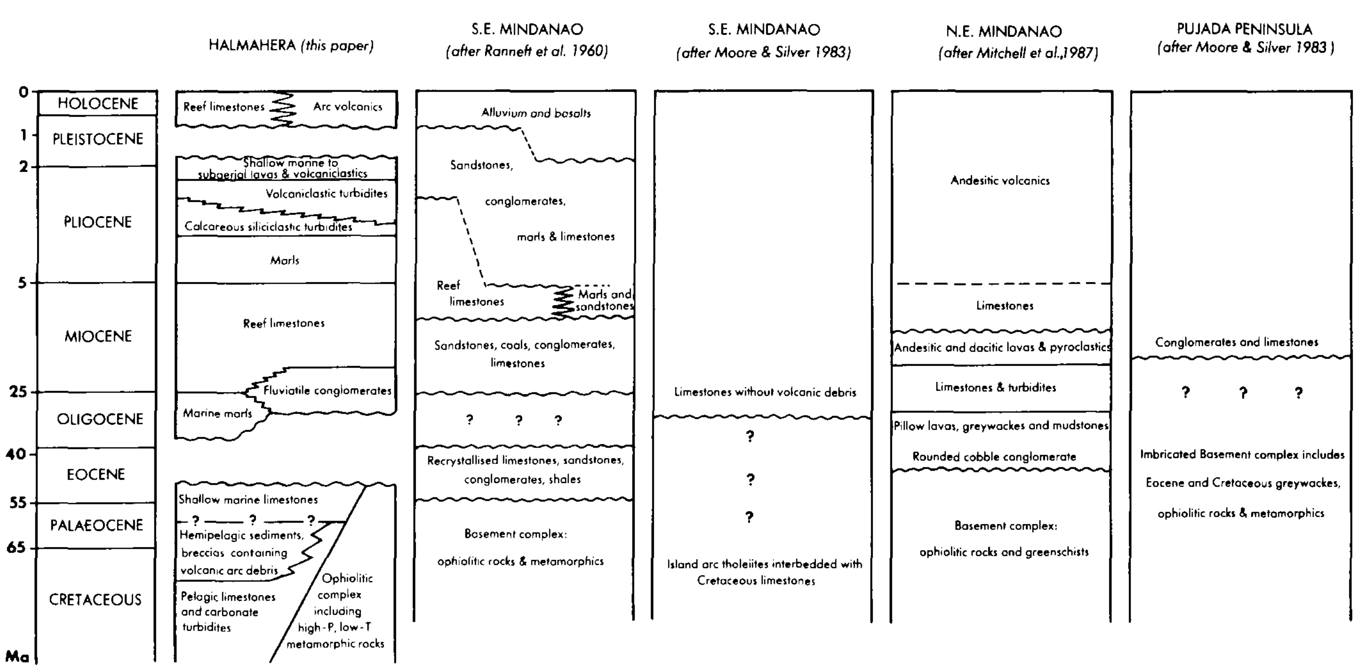

Fig. 16. Comparison of stratigraphy of Halmahera and eastern Mindanao.

east-facing Late Cretaceous–early Tertiary arc system; all present-day arcs east of Luzon were formed more recently. Stephan *et al.* (1986) show this Bicol–Sierra Madre arc as the most easterly arc system of the Pacific margin in the Eocene, suggesting to us that an island arc system extended around the western Pacific whose remains can be traced from the east Philippines through Halmahera into New Guinea. This system apparently became inactive in the Late Eocene–Early Oligocene, perhaps because of collision of part of the arc with the Australian margin in New Guinea (Kroenke 1983), or possibly due to a major change in plate motion. Hayes & Lewis (1984) recognized this end-Eocene event in the western Pacific margins as a period of 'major plate reorganization'. Further work is required in these poorly known regions to establish these connections.

Late Mesozoic–Palaeogene evolution of Halmahera in relation to the Philippine Sea and associated arcs

The Philippine Sea Plate is bounded on all sides by trenches except in the SW where the nature of the plate boundary is ill-defined and hence uncertain. Halmahera is located just south and west of the southern termination of the Philippine Trench, marking the western boundary of the Philippine Sea Plate, where the plate boundary cannot be identified. One factor suggesting a link between the evolution of east Halmahera, east Mindanao and the Philippine Sea Plate is the presence, around the present Philippine Sea Plate margins and within that plate, of remnant arcs with Palaeogene, including Eocene, volcanic arc sequences resembling those of east Halmahera and east Mindanao

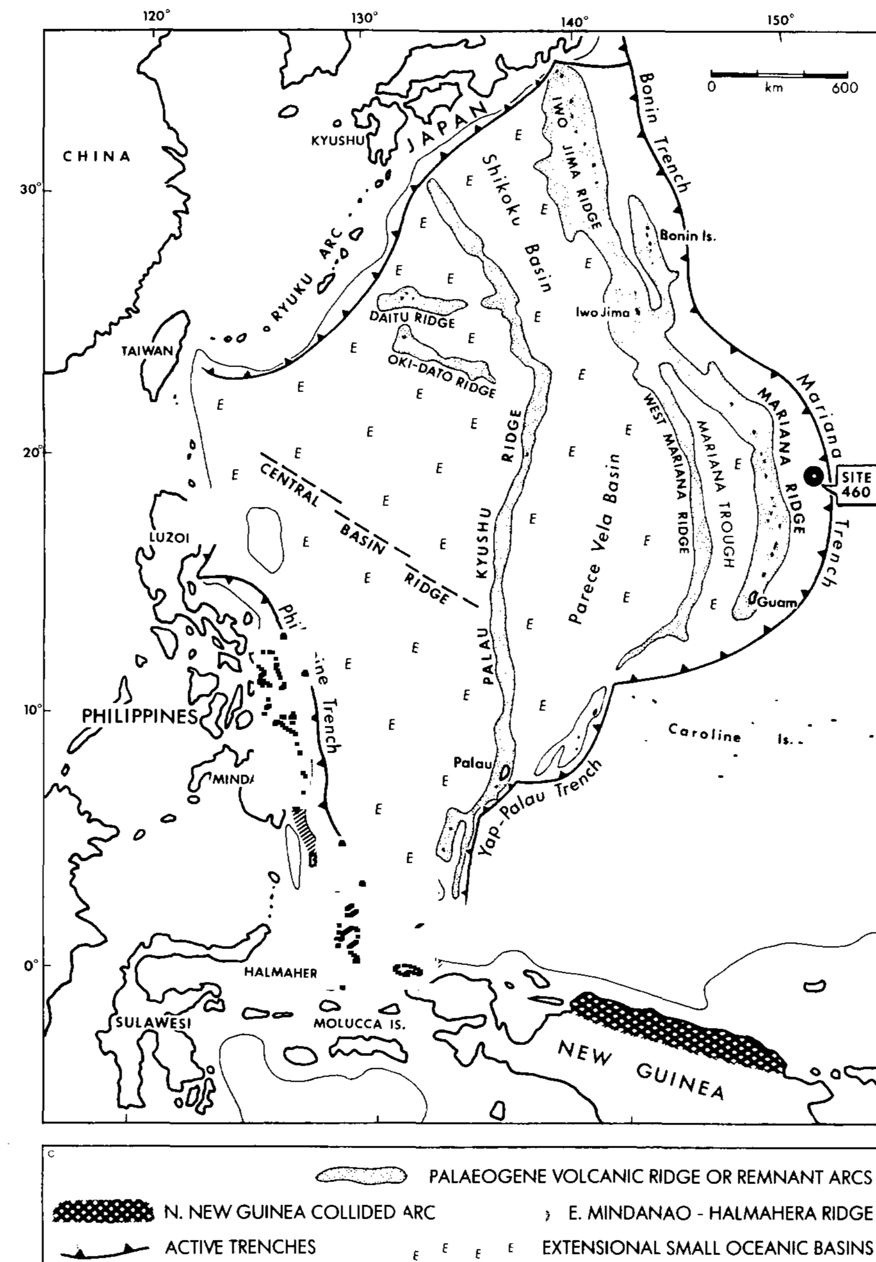

Fig. 17. Distribution of early Tertiary arc-related basement in the western Pacific region.

(Fig. 17). For example, Eocene volcanic rocks have been reported in the Daito and Oki-Daito Ridges (Murauchi *et al.* 1968; Mizunu *et al.* 1975; Shiki *et al.* 1977) and the Mariana arc system (Hussong & Uyeda 1981). The presence of these remnant arcs, with Palaeogene and even late Mesozoic volcanic arc basements, which have been separated by back-arc spreading of 60–40 Ma and locally younger age (Loudon 1967; Watts *et al.* 1977; Shih 1980) suggests that all these remnant arcs were originally much closer together (Seno & Maruyama 1984). At about 40 Ma, probably soon after the opening of the West Philippine Basin ceased (Hilde & Lee 1984), the region including the West Philippine Basin and the Daito Ridge and Basin Province rotated clockwise (Klein & Kobayashi 1981). It is tempting to speculate that all the remnant arcs, together with east Halmahera and east Mindanao, formed a single (but possibly complex) arc–trench system in the Eocene, orientated roughly east–west and located south of the Equator. The clockwise rotation and the development of local back-arc spreading systems dispersed the remnant arcs about the Philippine Sea Plate so that several are found at the plate margins where some (east Mindanao) have already been involved in arc–arc collison and others (east Halmahera, Daito and Oki-Daito Ridges) are in the process of collision with other arcs.

Financial support for our work in Indonesia was provided by the Royal Society, Amoco International, British Petroleum and the University of London Consortium for Geological Research in SE Asia. GRDC Bandung provided aerial photographs and invaluable practical assistance in Indonesia. We thank P. Ballantyne for his work on this project.

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Received 26 January 1987; revised typescript accepted 31 March 1987.