The character and significance of basement rocks of the southern Molucca Sea region

ROBERT HALL,* GARY NICHOLS,† PAUL BALLANTYNE,*, TIM CHARLTON*, and JASON ALI†
*Department of Geological Sciences, University College London, Gower Street, London, WC1E 6BT,
†Department of Geology, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, and
†Department of Oceanography, University of Southampton, University Road, Southampton, SO9 5NH, U.K.

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Abstract—Pre-Neogene basement rocks in the southern Molucca Sea region include ophiolitic rocks, arc volcanic rocks and continental rocks. The ophiolitic complexes are associated with arc and forearc igneous and sedimentary rocks. They are interpreted as the oldest parts of the Philippine Sea Plate with equivalents in the ridges and plateaux of the northern Philippine Sea. In the Molucca Sea region igneous components include rocks with a "supra-subduction zone" character, boninitic volcanic rocks and basic volcanic rocks with a "within-plate" character; "MORB-type" rocks are rare or absent. The ophiolitic rocks are overlain by Upper Cretaceous and Eocene sedimentary and volcanic rocks. Plutonic rocks of island arc origin which intrude the ophiolites yield Late Cretaceous radiometric ages and amphibolites with ophiolitic protoliths yield Eocene ages. The "supra-subduction zone" ophiolites are speculated to have originated during a mid-Cretaceous plate reorganization event. For the Late Cretaceous and Eocene the present-day Mariana arc and forearc provides an attractive model. Volcanic rocks form the basement of Morotai, western Halmahera and much of Bacan. These also have an island arc character and are probably of Late Cretaceous-Paleogene age. Both the arc volcanic rocks and the ophiolitic complexes are overlain by shallow water Eocene limestones and an Oligocene rift sequence including basaltic pillow lavas and volcaniclastic turbidites. The distribution of the Eocene-Oligocene sequences indicate pre-Mid/Late Eocene amalgamation of the ophiolitic and arc terranes. Mid Eocene-Oligocene extension appears to be synchronous with opening of the central West Philippine Basin.

Continental crust probably arrived in this region in the Late Paleogene–Early Neogene, either due to collision of the Australian margin with Pacific arc-ophiolite terranes or by terrane movement along the Sorong Fault Zone.

INTRODUCTION

The Molucca Sea (Fig. 1) is one of several small ocean basins in the western Pacific margin and is situated in the tectonically complex triple junction of the Australian, Eurasian and Philippine Sea plates. The age of the Molucca Sea crust is unknown. To the east and west are the active Sangihe and Halmahera volcanic arcs, to the north is the Philippines archipelago, and to the south are numerous small, non-volcanic islands extending between the larger islands of Sulawesi and New Guinea. The Molucca Sea will soon disappear; the Sangihe and Halmahera arcs are colliding and have over-ridden the Molucca Sea Plate (Hatherton and Dickinson 1969, Hamilton 1979). Collision has created a central ridge which is being thrust outwards onto the two colliding forearcss. The central zone, marked by intense shallow seismicity and a gravity low, is the Molucca Sea “collision complex” (Silver and Moore 1978, Hamilton 1979) and is exposed on the island of Talaud (Moore et al. 1981). The connection northwards between the collision zone and the southern Philippines is uncertain (e.g. Moore and Silver 1983, Hall and Nichols 1990, Pubellier et al. 1991).

East of the Molucca Sea the Philippine Sea Plate is rotating clockwise with respect to Eurasia about an Euler pole near its northern edge (Ranken et al. 1984, Seno et al. 1987, Barrier et al. 1991) and the rate of convergence between Eurasia and the Philippine Sea Plate increases southward. North of 2°50'N the principal expression of this convergence is westward subduction at the Philippine Trench; the trench is very young (Hamilton 1979, Cardwell et al. 1980) with less than 150 km of subducted lithosphere. South of 2°50'N an accretionary prism of deformed sediments becomes a less pronounced feature and dies out, together with bathymetric expression of the trench and seismic activity, at 1°20'N (Nichols et al. 1990). There is no physiographic evidence or seismicity indicating a link between the Philippine Trench and plate boundaries to the southeast, and the southern end of the Philippine Trench is interpreted by Nichols et al. (1990) to be linked to the Molucca Sea Collision Zone via a NE–SW dextral strike-slip zone. The area between eastern Halmahera and Waigeo therefore forms part of the Philippine Sea Plate.

South of the Molucca Sea is a complex fault zone which broadly separates the Australian Plate from the Eurasian and Philippine Sea Plates. In the northern Bird’s Head region of New Guinea (Visser and Hermes 1962) the northern boundary of the Australian Plate is the left-lateral Sorong Fault (Tija 1973, Dow and Sukamto 1984). West of the Bird’s Head, this fault splays out into the Molucca–Sorong Fault, the North Sula–Sorong Fault (Hamilton 1979) and the Buru Fracture (Tjokrosapto and Budhirisna 1982). Lineaments with broadly E–W orientations,interpreted as left-lateral splays, ca be identified on bathymetric maps of the region (Mammerickx et al. 1976), observed on seismic lines (Letouzey et al. 1983) and are seen on GLORIA records crossing the fault zone (Masson 1988). We use the term Sorong Fault Zone for the entire zone of faulting between the Bird’s Head and east Sulawesi.
The movement of Australia northward towards the Pacific has resulted in the development of an orogenic belt which may provide a modern analogue for terrane accretion in older orogenic belts (e.g. Silver and Smith 1983). The basement rocks of the Molucca Sea region are of particular interest since they provide an insight into the processes of terrane movement and amalgamation in this orogenic belt. The nature of the older crust provides the best evidence for the identification and ultimate source of different terranes. Tracing the history of these terranes can identify the sequence of events in the Australia—"Pacific" collision, and the effects of strike-slip faulting at the Eurasia-Pacific—Australia triple junction where there is oblique convergence at the northern Australian margin. In collaboration with the Indonesian scientists from the Geological Research and Development Centre, Bandung we have been investigating the region of the southern Molucca Sea and Sorong Fault Zone (Fig. 2) for the past several years. This paper summarizes some of the results of this
Basement rocks of the southern Molucca Sea region

251

Neogene 25

Paleocene --66

Lower Cretaceous I +---144

Jurassic -- 211

Triassic ~-+-248

Ma

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Fig. 3. Summary of the stratigraphy of the islands of the southern Molucca Sea.

Investigation, in particular the character of the pre-Neogene basement rocks and their significance. The Neogene sequences are discussed elsewhere (Hall et al. 1988b, Nichols and Hall 1991, Nichols et al. 1991).

CHARACTER OF THE OLDEST CRUST

Three distinctly different groups of pre-Neogene basement rock types are known from the islands around the southern Molucca Sea (Figs 3 and 4).

1. Ophiolitic complexes overlain by Upper Cretaceous and Eocene forearc sedimentary rocks are found on east Halmahera, Waigeo, Gebe, Gag and Obi.

2. Arc volcanic and volcaniclastic rocks are known from Morotai, NW Halmahera, SW Halmahera, and north and south Bacan.

3. Continental metamorphic complexes are known from central Bacan and Obi.

OPHIOLITIC ROCKS AND FOREARC SEDIMENTARY COVER

Igneous and metamorphic rocks

Ophiolitic rocks, associated with arc-related sedimentary rocks, form the basement of east Halmahera and Waigeo, and many of the small islands between these two larger islands, such as Gag and Gebe. In all these islands, the ophiolite rocks are situated in the north of the Sorong Fault Zone and now form part of the Philippine Sea Plate. Similar ophiolitic rocks and Cretaceous-(?)Eocene sedimentary rocks form the basement of northern and central Obi, within the Sorong Fault Zone.

The only detailed studies of the ophiolitic rocks are those of Halmahera where the dismembered ophiolite has been described by Hall et al. (1988a, in press) and Ballantyne (1990, 1991). Components of each level of an intact ophiolite (Coleman 1977, Moores 1982), with the possible exception of sheeted dykes, are present. Peridotites include abundant serpentinitized harzburgites and rare lherzolites; the harzburgites record a high degree of mantle partial melting and are similar to those of oceanic forearcs. In contrast, the lherzolites are less depleted than the harzburgites, and compatible with a mantle residue after extraction of a mid-ocean ridge basalt (MORB). Cumulates are common and include dunites, olivine clinopyroxenites, wehrlites, and olivine gabbronorites. They are the product of a moderate to high degree of partial melting and chemical and miner-
alogical evidence (Ballantyne 1991) indicates a genetic link between the harzburgites and the cumulates. Burgath et al. (1983) reported diabase dykes in central Halmahera, associated with pillow lavas, but no sheeted complex has been found elsewhere in east Halmahera (Hall et al. 1988a) although microgabbros are abundant. Hornblende-rich diorites and rare trondhjemites intrude the microgabbros and are not cogenetic with the ophiolitic plutonic rocks. $^{40}\text{Ar}/^{39}\text{Ar}$ dating of diorite hornblends (Ballantyne 1990) indicates two phases of Late Cretaceous arc-related igneous activity (94–80 Ma: Cenomanian–Campanian and 75–72 Ma: Campanian–Maastrichtian). Volcanic rocks in the ophiolite complex include boninitic rocks interpreted as cogenetic with the cumulates, arc tholeiites, and amygdaloidal alkaline basalts (Ballantyne 1991) of similar chemistry to ocean island volcanic rocks and seamounts (Dietrich et al. 1978).

The age of the ophiolitic rocks remains uncertain. The radiometric dating of amphiboles from arc-related igneous rocks intruding the ophiolite (Ballantyne 1990), and the ages of the oldest overlying sedimentary rocks (Hall et al. 1988a, in press), indicate a pre-Late Cretaceous age for the ophiolitic basement rocks.

The basement complex of east Halmahera is polygenetic (Ballantyne 1990, 1991) and is interpreted as representing the basement of a largely non-accretionary forearc similar to the present-day Mariana forearc. The peridotites, cumulates and microgabbros represent different parts of a single ophiolite, now dismembered; the petrology and chemistry of these rocks indicate a "supra-subduction zone" (Pearce et al. 1984) setting for their formation. The association of depleted harzburgites and less-depleted lherzolites suggests a multi-stage melting history resulting from the construction of an island arc upon older oceanic lithosphere. Cumulates of the Halmahera ophiolite closely resemble those dredged from the inner slope of the Mariana Trench (Bloomer and Hawkins 1983). Boninitic volcanic rocks are interpreted as cogenetic with the cumulates, but other volcanic rocks are not cogenetic with the ophiolitic plutonic rocks; most represent magmas formed in an arc environment. There are also volcanic rocks of within-plate character and these alkaline basalts are interpreted as slivers scraped from subducting seamounts and accreted into the forearc basement (cf. Bloomer 1983). Possible MORB compositions are rare. Late Cretaceous arc magmatism in east Halmahera, post-dating ophiolite formation, is indicated by petrology, geochemistry, radiometric ages and the stratigraphic record.

The Halmahera rocks show the effects of subduction zone metamorphism. The volcanic rocks exhibit zeolite, prehnite–pumpellyite and greenschist facies metamorphism, different from that of oceanic crust (Alt et al. 1985). Prehnite–pumpellyite facies assemblages are rare in ophiolites interpreted as displaying ocean-floor metamorphism (Liou 1979) and are generally considered diagnostic of a subduction zone setting (Maruyama and Liou 1988). The association of both blueschists and amphibolites with sheared serpentinite suggests exhumation of forearc basement along fault zones, possibly due to diapiric rise of serpentinite. The Mariana forearc is marked by widespread serpentinite diapirism (Fryer et al. 1985) and the forearc adjacent to such diapirs contains low-grade metamorphic rocks (Johnson et al. 1987).

Forearc sedimentary cover

Cretaceous to Eocene sedimentary and volcanic rocks rest unconformably upon, and are imbricated with, the ophiolitic rocks in eastern Halmahera. All are considered to have been deposited in a forearc setting (Hall et al. 1988a, in press). Similar rocks are known from Waigeo (Charlton et al. 1991) and from Obi (Brouwer 1924; our unpublished results).

The Upper Cretaceous rocks from Halmahera include calcalkaline volcanic and hypabyssal igneous rocks, volcanioclastic breccias, conglomerates, sandstones and siltstones containing calcalkaline debris, red mudstones, and redeposited and pelagic limestones. In the NE arm rocks of this age were assigned to the Gau Limestone and Dodaga Breccia Formations (Hall et al. 1988a), and in the SE arm their equivalents were assigned to the Gowonli Formation (Hall et al. in press). Volcanic rocks in the Gowonli Formation (Ballantyne 1990) are porphyritic calcalkaline basalts and andesites. They are similar to products of the Sangihe (Morrice et al. 1983) and Mariana arcs (Dixon and Batiza 1979) and resemble products of the active volcanoes of the modern Halmahera arc (Morris et al. 1983). Coarse volcanioclastic rocks are dominated by volcanic lithic material with rare clasts of reef limestones. Graded lithic arenites contain abundant debris typical of an arc volcanic origin, such as strongly zoned plagioclase with glass and mineral inclusions, and highly porphyritic lithic clasts. Minor alteration of minerals and lithic clasts indicates a low metamorphic grade (clay minerals, silica polymorphs, zeolites and calcite). Volcanioclastic sandstones and siltstones are turbiditic in origin and are interbedded with both redeposited and pelagic limestones.

Middle Eocene volcanioclastic rocks assigned to the Sagea Formation (Hall et al. in press) closely resemble the Upper Cretaceous rocks. They comprise graded volcanioclastic sandstones, siltstones, red mudstones, and redeposited limestones containing calcalkaline debris. The limestones differ from the Cretaceous limestones in containing abundant coral, algal and mollusc debris, and large foraminifera of shallow water origin. The Eocene rocks are interpreted as deposits of a forearc sedimentary basin in which most clastic material was deposited as turbidites, with subordinate debris flows. New sections discovered during fieldwork in 1990 resemble Franciscan melanges (Cowan 1985) and are interpreted as debris flows and olistostromes deformed in the forearc, perhaps during Eocene sediment accretion.
ARC VOLCANIC ROCKS AND VOLCANICLASTIC ROCKS

Arc volcanic and volcaniclastic rocks form the basement of Morotai, NW Halmahera, SW Halmahera, and north and south Bacan. The age of all of these rocks is currently uncertain. They are covered by Miocene-Recent sedimentary and volcanic rocks and generally lack material suitable for palaeontological dating. Particularly characteristic of the basement volcanic rocks is the abundance of basalts and the rarity/absence of hornblende-bearing andesites; in contrast the Neogene volcanic sequences throughout the region are dominated by andesites, typically containing hornblende, and all rocks are very fresh. Radiometric dating of the basement volcanic rocks is made difficult by alteration and low-grade metamorphism. Early reconnaissance mapping (Apandi and Sudana 1980, Supriatna 1980, Yasin 1980) assigned these rocks to the Bacan Formation, but our more recent work has established that this "formation" includes rocks with a variety of origins and ages (Hall et al. 1988a, our unpublished results). Petrological, chemical and radiometric studies are in progress to establish the age and character of these rocks.

The only detailed study of the basement volcanic rocks is that of Hakim (1989) dealing with the Oha Formation of central and SW Halmahera. The higher and most rugged western parts of central and SW Halmahera consist predominantly of volcanic rocks which are monotonous basalts and andesites, often amygdaloidal and porphyritic. There is generally no indication of their attitude and they are locally brecciated, altered and sheared. There are monomict and occasionally polymict volcanic breccio-conglomerates. The volcanic rocks are basalts and subordinate andesites of calcalkaline character typical of island arc volcanic rocks (Hakim and Hall 1991, Pearce et al. 1984). The REE patterns of more evolved rocks are closely similar to those of Cretaceous volcanic rocks from east Halmahera. The more primitive compositions resemble tholeiites of arc basalt series reported from areas such as the Marianas and New Hebrides (Gill 1981). Zeolite and local sub-greenschist facies alteration indicates deep burial and/or high heat flows. Dating of overlying sedimentary rocks show that volcanic basement rocks are older than Late Miocene; a Late Cretaceous or Eocene age is suspected since petrographically and chemically the volcanic rocks closely resemble the arc volcanic rocks of Cretaceous and Eocene age from east Halmahera. Clasts taken from breccias and conglomerates at the northern end of the SW arm include recrystallised limestones of probable Early Eocene age. Eocene limestones associated with volcaniclastic rocks were collected in central Halmahera (Hall et al. 1988a) and similar limestone clasts have been found in breccio-conglomerates as float further south in the SW arm. Since all the dates are from clasts their significance is uncertain; the clasts may have been reworked at about the period of volcanism, or much later. It is also possible that the volcanic rocks are of Oligocene age although Oligocene volcanic rocks (see below) appear quite different from the Oha Formation volcanic rocks of SW Halmahera: the former are dominated by well preserved amygdaloidal pillow basalts, almost always associated with well bedded volcaniclastic turbidites, and show fewer signs of deep burial and alteration.

Similar rocks form the basement on Morotai and north and south Bacan (Fig. 3). On Morotai volcaniclastic rocks consist largely of monomict basaltic breccias, intruded by basaltic to pyroxene-andesite feldspar porphyries. They are overlain by Miocene clastic sedimentary rocks (Yasin 1980). The Morotai volcaniclastic basement rocks are considerably more altered and indurated than Oligocene basalts and sandstones of NW Halmahera suggesting a greater age. In north Bacan basement rocks include basaltic breccias, volcaniclastic turbiditic sandstones and mudstones, metamorphosed under conditions up to lower greenschist facies. They are overlain in the north Bacan area by Oligocene pillow lavas and turbidite sandstones. The depositional environment of the basement rocks is not clear. Locally, pillow structures are recognizable, and the presence of volcaniclastic turbidites on Bacan indicates submarine accumulation. Elsewhere, coarse angular and poorly-sorted monomict breccias, locally interbedded with coarse sandstones, may indicate a subaerial environment.

EXTENSIONAL BASIN SEQUENCE OF EOCENE-OLIGOCENE AGE

The ophiolitic and arc volcanic basement complexes have previously been speculatively explained as part of a single complex terrane (Hall et al. 1988a, Hall and Nichols 1990). Our recent fieldwork supports this speculation since both these basement rock complexes are overlain throughout the region by a newly-discovered basinal sequence, dominated by pillow lavas, thick volcaniclastic turbidite sandstones, siltstones and mudstones, locally with pelagic limestones. A Late Eocene-Early Oligocene hiatus previously interpreted (Hall et al. 1988a, b) appears now to be largely a result of a combination of circumstances: poor exposure of rocks of this age in the areas investigated earliest, and difficulties in dating the material sampled.

There is a marked unconformity between ophiolitic and arc volcanic basement and younger Eocene sedimentary rocks on Halmahera (Fig. 3). Late Cretaceous and Middle Eocene volcaniclastic rocks are folded and faulted, and locally dip steeply. In contrast, younger rocks are not strongly deformed except in areas of Late Neogene shortening, such as the central Halmahera foldbelt (Hall et al. 1988b, Nichols and Hall 1991). The Middle–Upper Eocene Panitii Formation (Hall et al. in press) of SE Halmahera includes several hundred metres of conglomerates, sandstones, siltstones, mudstones, coals and limestones with most non-carbonate debris derived from ophiolitic rocks. The conglomerates are very distinctive, being composed dominantly of well
rounded serpentinite pebbles with rare clasts of red cherts and gabbros and some oyster shells. These pass up into fine conglomerates and sandstones, again dominated by serpentinite clasts, with coal seams. The sequence of coals and conglomerates passes laterally into fine conglomerates and sandstones, again dominated by serpentinite pebbles with rare clasts of red sandstones. Most limestones contain bioclasts of algae, miliolids, coral, and foraminifera of Middle–Late Eocene age. Identical shallow water limestones from the NE arm were dated as Middle Eocene and assigned to the Geledongan Formation (Hall et al. 1988a). The character of the Paniti Formation suggests deposition in a littoral to shallow marine environment, very close to well vegetated land. Interbedded conglomerates, coals and limestones suggest shifting marginal marine to marine conditions. These rocks are deformed by open folds but show no cleavage and no signs of deep burial.

On Waigeo there is also an important change in the character of sedimentary rocks within the Eocene (Fig. 3). Sandstones of the Lamlam Formation (Supriatna and Apandi 1982) rest unconformably upon the Ophiolite Complex and probably upon older Eocene arc volcanic sandstones (Charlton et al. 1991). The Lamlam Formation may be equivalent to the Middle–Upper Eocene rocks of SE Halmahera; it is also dominated by ultrabasitic clastic debris and contains red chert fragments, as well as limestones with volcanoclastic, ultrabasic and shallow water bioclastic debris. The ultrabasic sandstones of Waigeo are succeeded by olistostromes and turbiditic volcanoclastic sandstones and siltstones of Early Oligocene age although the contact is not seen.

No contact has been found between the Mid–Late Eocene shallow water sedimentary rocks of NE and SE Halmahera and Oligocene rocks. In NE Halmahera the Oligocene is probably represented by amygdaloidal basalts, volcanoclastic sandstones and pelagic limestones; pelagic limestones from disrupted parts of this sequence were assigned to the Onat Marl Formation by Hall et al. (1988b) and are Early Oligocene in age. On Kasiruta, north of Bacan, and on islands off NW Halmahera (Fig. 3) the Oligocene sequence consists of magnificently exposed pillow lavas and sedimentary rocks. A similar sequence is present in parts of NE Halmahera, although exposure and stratigraphic relations are less clear. Basaltic pillow lavas, lava flows and lava breccias contain interpillow sediment and hyaloclastic debris locally containing coralline debris and microfossils. In some areas well-bedded fine-grained sedimentary rocks, are interbedded with the lava flows. The lava sequence is undeformed, except for slight tilting and minor normal faults, and has suffered only very low-grade alteration; amygdales contain zeolites and clay minerals. The pillow lava and sediment sequence is conformably overlain by well-bedded volcanoclastic turbidite sandstones and siltstones which show grading, low structures, dewatering structures and rare cross lamination. In places there are coarse conglomerates in the sequence representing mass flow deposits. The age range of these rocks is not yet certain but the youngest parts identified so far are Mid-Oligocene.

Structural and sedimentary features, including syn-sedimentary normal faults, intraformational unconformities and slumped horizons, displayed in the sea cliffs of Kasiruta and NW Halmahera indicate syn-depositional extension. Because of the problems of rain-forest exposure, evidence for such extension is less certain inland. However, the structural and sedimentary features of all the sequences observed suggest a consistent pattern of syn-depositional extension and rapid deposition. Abundant thick pillow basalts in the Oligocene sequences also suggest an extensional setting. Seismic reflection profiles (Letouzey et al. 1983) across the Weda Bay area of south Halmahera show that in the centre of the bay Miocene limestones rest directly on a sequence of well-stratified older deposits. The distribution and thickness variations in these older rocks suggest deposition during a rifting phase (Nichols and Hall 1991).

We suggest that this previously unidentified pre-Miocene sequence is equivalent to the Eocene–Oligocene sequences seen on land (Fig. 5).

These late Paleogene sequences appear to represent regionally important events. First, it appears that there is a major tectonic event of about Middle–Late Eocene age causing basement uplift and exposure of ophiolites. This tectonic event was succeeded by extension, marked initially by shallow water deposits including clastic sedimentary rocks with an ophiolitic provenance, and succeeded by deeper water volcanoclastic deposits and submarine eruptions of basalts. Second, this extensional interval is recorded throughout areas in which both ophiolitic and arc volcanic rocks form the basement, indicating that these two basement types were amalgamated into a single terrane before the Late Eocene. If, as suggested above, the volcanic rocks of the Oha Formation of SW Halmahera are equivalent in age to Gowonli Formation volcanic rocks of east Halmahera, this amalgamation occurred before the Late Cretaceous.

CONTINENTAL BASEMENT ROCKS

High-grade metamorphic rocks were originally reported from the Sibele Mountains of central Bacan (Fig. 3) by Dutch geologists (Van Bemmelen 1949) and described by Brouwer (1923). The majority of the metamorphic rocks clearly have continental affinities and a complex polyphase metamorphic history. They include garnet–mica schists, garnet–staurolite–kyanite schists, quartzites, quartz-feldspathic gneisses, hornblende schists and locally calc-silicates. Mineral assemblages indicate Barrovian-type metamorphism up to upper amphibolite facies conditions. The age of metamorphism of these rocks is currently unknown. Also reported from the Sibele Mountains are ultrabasic and basic rocks (Yasin 1980, Silitonga et al. 1981). Thick rain forest, difficult terrain and poor exposure mean that the relationship of these rocks with the continental metamor-
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The Sibela metamorphic rocks are everywhere in fault contact with younger rocks and therefore there is no direct evidence for the nature of the contact of continental basement with arc volcanic basement rocks of Halmahera and Bacan. Indirect evidence for the existence of continental basement rocks beneath south Bacan comes from isotope geochemistry. Morris et al. (1983) have shown that the Quaternary volcanic rocks of south Bacan have a different chemistry from those of the rest of the Halmahera Arc. In contrast to the “normal oceanic” character of most of the arc north of central Bacan, isotopic compositions of the south Bacan volcanic rocks are interpreted as indicating a continental crust contribution to the magma. The oldest rocks seen at the surface in south Bacan are arc volcanic rocks (J. Malaihollo, pers. commun. 1990) of probable Cretaceous–Paleogene age which implies that they lie tectonically above continental basement rocks if no lateral contamination of magma is assumed. Juxtaposition due to thrusting may be due to Australia–“Pacific” collision, although all observable contacts of continental basement rocks and other rocks are steep faults.

Similar high-grade metamorphic rocks are present on the small island of Tapas, just NW of Obi. They include highly foliated epidote, chlorite and hornblende schists and coarse, locally pegmatitic amphibolites and hornblendites. These rocks are in fault contact with basic and ultrabasic rocks of the ophiolite complex of Obi. In SW Obi (Fig. 3) the metamorphic rocks are not exposed but there are (?)Triassic–Jurassic micaceous sandstones containing Pentacrinus and an extensive area of black shales, in which we have found belemnites and bivalve fragments indicating an uncertain Mesozoic age; Jurassic ammonites are reported by Wanner (1913) and Brouwer (1924) in float samples from this area. It appears that Obi represents the contact between the Australian continental margin and the ophiolite complex of a “Pacific” terrane. The continental margin basement is interpreted to be the high-grade metamorphic rocks exposed on the west coast of P. Tapas. The contact between the ophiolite complex and the continental basement with its Mesozoic cover may be a thrust or a strike–slip fault.

**SIGNIFICANCE OF THE SOUTHERN MOLUCCA SEA BASEMENT ROCKS**

A common feature of the western Pacific region is the presence of Late Mesozoic and Paleogene volcanic arc rocks built upon older ophiolites, mainly now incorporated in orogenic belts at the Pacific margin (Fig. 6). Such rocks are found in a very large region between New Guinea and the northern Philippines. The similarities of the ophiolitic and arc rocks of Halmahera, New Guinea, the eastern Philippines and the Philippine Sea suggest the existence of an extensive Late Cretaceous and Early Tertiary arc system. This island arc system was built upon older ophiolite basement in an intra-oceanic setting. The ophiolites appear to represent the products of the earliest stages of subduction-related magmatism. As in many other ophiolites a two-stage history is implied by the evidence of peridotite remelting and the supra-subduction zone chemistry of plutonic rocks, most readily explained by development of the ophiolites in a
setting in which the underlying mantle has previously been depleted by extraction of MORB. The very oldest oceanic lithosphere which is implied by this model has not yet been discovered although the rare MORB-like rocks of Halmahera may represent part of it. The precise age of this lithosphere is unknown; Ballantyne (1990, 1991) suggests a Mid-Cretaceous age. A plate reorientation event related to the initiation of rifting of Australia from Antarctica at between 110 and 90 Ma (Cande and Mutter 1982, Audley-Charles et al. 1988) may be responsible for ophiolite emplacement around the Pacific margin (Hall 1990).

Recent interpretations of plate boundaries (McCaffrey 1982, Hall 1987, Nichols et al. 1990) indicate that east Halmahera forms part of the Philippine Sea Plate. We suggest that the ophiolitic and forearc cover forming the basement of east Halmahera, Waigeo and north Obi represent the oldest parts of the Philippine Sea Plate. We also suggest that these rocks have their equivalents in the plateaux and ridges of the northern Philippine Sea Plate. Comparison by Hall et al. (in press) of reports of dredged samples from Oki–Daito and Daito Ridge province and the Amami Plateau show that all can be matched with ages and lithologies of rocks collected from the ophiolite complexes and forearc cover of the southern Molucca Sea. Rocks dredged from the Daito province (Shiki et al. 1977, Mizuno et al. 1978, Tokuyama et al. 1986) and dated (Ozima et al. 1977, McKee and Klock 1980) are very similar in both ages and lithologies to those found in Halmahera. Igneous rocks of similar age to the Halmahera diorites have been dredged from the Amami Plateau in the northernmost Philippine Sea (Klein and Kobayashi 1981, Kobayashi 1983). The Amami Plateau rocks include arc tholeiitic basalts and a hornblende tonalite with an Eocene K–Ar age. Shallow water Middle Eocene limestones have been sampled from the Amami Plateau, Daito Ridge and Oki–Daito Ridge. At DSDP site 445 Middle Eocene conglomerates include clasts of Cretaceous reef limestone and basalt with a Paleocene 40Ar/39Ar age thought to be derived from the Daito Ridge (Shiki et al. 1985). We suggest that supposed continental rocks sampled from the northern Philippine Sea plateaux and ridges are more likely to be intermediate–acid arc magmatic rocks of Late Cretaceous–Eocene age. Tokuyama (1985) similarly concludes that the Amami Plateau was an active island arc with calcalkaline and tholeiitic volcanism in Late Cretaceous time and that plutonic rocks represent the products of an intra-oceanic island arc lacking continental crust. The similarities with Halmahera suggest a symmetrical distribution of Late Cretaceous and Tertiary island arc rocks about the axis of the west Philippine basin within the Philippine Sea Plate.

The distribution and precise character of ophiolitic and arc terranes of the Cretaceous and Eocene "proto"-Philippine Sea is far from clear (see Lewis et al. 1982, Rangin and Pubellier 1990). Ophiolitic and arc volcanic terranes are now juxtaposed in east and west Halmahera but we have no unambiguous evidence to link them in the Cretaceous and early Tertiary. If our speculation of the Cretaceous–Eocene age for the oldest volcanic rocks of west Halmahera is correct, and if these rocks formed a single arc–forearc terrane with east Halmahera, the arc faced east, in the opposite sense to the Cenozoic and present-day arcs. However, similarities in petrology and chemistry of volcanic and plutonic rocks do not require physical continuity and the age of the arc basement rocks is currently poorly constrained. Furthermore, preliminary palaeomagnetic work (our unpublished results) indicates significant post-Eocene rotations.

The most recent results of our fieldwork in the southern Molucca Sea region indicate that the Pacific ophiolitic and arc terranes were definitely amalgamated before the Mid–Late Eocene, as indicated by the distribution and character of Eocene–Oligocene successor basin sequences. Major regional extension began in Mid–Late Eocene time, and shallow marine Upper Eocene sequences probably do not represent local events as previously thought (cf. Hall et al. in press). The regional unconformity at this time corresponds to the Pacific Plate reorganization event of ~45 Ma and in the Philippine Sea Plate the beginning of opening of the central West Philippine Basin (Hilde and Lee 1984). Although more dating is required, our new results suggest that the period of extension recorded by the successor basin sequences of north Bacan, Halmahera and Waigeo corresponds remarkably to the timing of

Fig. 6. Distribution of Mesozoic and Paleogene ophiolitic and arc volcanic rocks within and around the Philippine Sea Plate. The shaded area of the West Philippine Basin is the part of the Central Basin interpreted by Hilde and Lee (1984) to have been produced by spreading between approximately 45 and 35 Ma.
extension in the West Philippine Basin of 45–35 Ma reported by Hilde and Lee (1984). One major question raised by these new discoveries is what was the source and origin of the great thickness of volcanioclastic sediments deposited in these basins?

Australian margin continental basement is exposed in central Bacan and northwest Obi and is interpreted to underlie southern Bacan and much of Obi. The timing of arrival of the continental crust in these regions remains uncertain and two models seem possible. Australian continental crust and Pacific arc-ophiolitic terranes could have been juxtaposed by strike-slip faulting in the Sorong Fault Zone, implying a late Neogene translation of continental crustal fragments. Alternatively, continental and arc-ophiolitic crust could have been first juxtaposed by thrusting related to (?)Oligocene arc–continent collision at the north Australian margin (Pigram 1991) and later translated as complex terranes by strike-slip faulting in the Neogene Sorong Fault system. We cannot clearly distinguish between these two models, but we expect geochemical and palaeomagnetic studies now in progress to allow us to do so. Isotopic work is needed to identify oceanic and continental contributions to Neogene arc volcanic rocks. Palaeomagnetic studies should allow us to recognize which crustal fragments have a Philippine Sea Plate rotation history (Fuller et al. 1991). Currently, it appears most likely that arc–continent collision occurred in the Late Eocene–Early Miocene interval and that Neogene–Recent strike–slip faulting is shuffling complex ophiolite–arc–continent terranes to new positions within the orogenic collage.

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