Plate boundary evolution in the Halmahera region, Indonesia

ROBERT HALL

Department of Geological Sciences, University College London, Gower Street, London WC1E 6BT (Great Britain)

(Received December 1, 1986; revised version accepted March 10, 1987)

Abstract


Halmahera is situated in eastern Indonesia at the southwest corner of the Philippine Sea Plate. Active arc–arc collision is in process in the Molucca Sea to the west of Halmahera. New stratigraphic observations from Halmahera link this island and the east Philippines and record the history of subduction of the Molucca Sea lithosphere. The Halmahera Basement Complex and the basement of east Mindanao were part of an arc and forearc of Late Cretaceous–Early Tertiary age and have formed part of a single plate since the Late Eocene–Early Oligocene. There is no evidence that Halmahera formed part of an Oligo-Miocene arc but arc volcanism, associated with eastwards subduction of the Molucca Sea beneath Halmahera, began in the Pliocene and the Pliocene arc is built on a basement of the early Tertiary arc. Arc volcanism ceased briefly during the Pleistocene and the arc shifted westwards after an episode of deformation. The present active arc is built upon deformed rocks of the Pliocene arc. The combination of new stratigraphic information from the Halmahera islands and models of the present-day tectonic structure of the region deduced from seismic and other geophysical studies is used to constrain the tectonic evolution of the region since the Miocene. Diachronous collision at the western edge of the Philippine Sea Plate which began in Mindanao in the Late Miocene impeded the movement of the Philippine Sea Plate and further motion has been achieved by a combination of strike-slip motion along the Philippine Fault, subduction at the Philippine Trench and subduction of the Molucca Sea lithosphere beneath Halmahera.

Introduction

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 (Fig. 1). Its K-shape resembles that of Sulawesi on the opposite side of the Molucca Sea and in general terms Halmahera is a smaller scale version of Sulawesi: the western arms of the K form a volcanic arc while the eastern arms include ophiolites and sediments. The Halmahera region is remarkable in being the only example of active arc–arc collision and in preserving the processes of subduction in both a stratigraphic record which can be determined by field-based geological studies and a lithospheric record which can be interpreted from seismic and other geophysical studies. The combination of these two approaches can be used to trace the evolution of plate boundaries in the region.

Present tectonic setting

The Molucca Sea separates the opposed Sangihe and Halmahera volcanic arcs (Fig. 1) interpreted as the expression of the subduction of the Molucca Sea Plate to both east and west (Hatherton and Dickinson, 1969; Hamilton, 1979). The Molucca Sea Plate has been almost completely eliminated by subduction (Cardwell et al., 1980; McCaffrey et al., 1980), forcing it into an asymmetrical inverted U-shaped configuration beneath the colliding fore-arcs (Fig. 2). Collision is creating a high
Fig. 1. Principal tectonic features of the Halmahera region after Hamilton (1979) and Silver (1981). Solid triangles are active volcanoes of the Halmahera and Sangihe arcs. Slip rates along the Philippine Trench from Ranken et al. (1984).

central ridge to the Molucca Sea which is being thrust onto the two colliding fore-arc. This central zone, marked by intense shallow seismicity and a gravity low is the Molucca Sea "melange wedge" or "collision complex" (Silver and Moore, 1978; Hamilton, 1979; Moore et al., 1981) which is
exposed on the island of Talaud. This zone continues northwards into Mindanao where collision occurred in the Miocene and the Philippine Fault follows the suture zone (Moore and Silver, 1983). The southern boundary of the region is the Sorong Fault zone along which Halmahera is currently moving west with respect to Australasia (Hamilton, 1979). East of Halmahera plate boundaries are uncertain. Northeast 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 does not extend south of about 2° N. The seismicity of the region, or its local absence, has been interpreted to terminate the Philippine Trench, and thus bound the Philippine Sea Plate at its southern end, in different ways. Hamilton (1979) extended the Philippine Sea Plate boundary from the Philippine Trench southwards as a thrust or strike-slip fault to the northern New Guinea margins and Sorong Fault system; in his model Halmahera and the Philippine Sea are thus separate plates although the northern extension of the Halmahera subduction zone towards Mindanao remains a problem.

Seismicity associated with the Philippine Trench ceases south of about 2.5° N, arguing against Hamilton's interpretation, and Cardwell et al. (1980) proposed a Halmahera–Palau transform fault to connect the Halmahera subduction zone with the Ayu Trough. In contrast, McCaffrey (1982) suggested that the transform fault is located further north and stops at the Philippine Trench. In both of these models Halmahera is part of the Philippine Sea Plate. These differences in interpretation reflect the complex pattern of boundaries at the junction of the Philippine, Australian and Southeast Asian plates and their shifting position resulting from collision in the Molucca Sea region.

The present tectonic setting is an important constraint on models of the short-term geological evolution, but information from studies of land geology is equally vital for reconstructions of the development of the region and to distinguish between interpretations of present-day tectonics, especially where—as in the Halmahera region—the geophysical evidence is ambiguous. The length of subducted lithosphere on seismic profiles across the region (Cardwell et al., 1980; Fig. 2) indicates that Halmahera must have been situated at least 1000 km to the east of north Sulawesi before subduction of the Molucca Sea began. However, the timing of initiation of subduction beneath Halmahera is unknown. The geological link between the Philippines, Talaud, Halmahera and surrounding regions remains unclear and this is reflected in the number of different regional reconstructions proposed (see discussion in Moore and Silver, 1983). Halmahera, situated in the centre of this complex zone, is clearly a source of critical information but its geology is not well known.

Van Bemmelen (1970) summarised the stratigraphy of the islands in a single table based on reconnaissance by Verbeek (1908), Wanner (1913), Brouwer (1923a, 1923b) and Kuenen (1935). Besesho (1944) made a wartime study of the geology and later Verstappen (1960, 1964) made an aerial photographic study of the volcanoes. Hamilton (1979) shows western Halmahera as a magmatic arc and the eastern part simply as melange. Recent mapping reviewed by Sukamoto et al. (1981), Soeria Atmadja (1981) and Silitonga et al. (1981) indicates 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. A new field investigation of Halmahera has provided important new information on the geological evolution of the region (Hall et al., 1987a, 1987b, which is summarised in Fig. 3. The account of the geology of Halmahera below is based on this work and is followed by a discussion of the evolution of the region in the light of the new information.

Geological history of the Halmahera region

Eastern Halmahera has a basement of dismembered ophiolitic rocks with slices of Mesozoic and Eocene sediments overlain unconformably by Middle–Late Oligocene and younger sedimentary and volcanic rocks. The Mesozoic and Eocene rocks 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. The sediments, and igneous and metamorphic rocks representing the deeper parts of the fore-arc, were imbricated together during the Late Eocene. The Halmahera Basement Complex can be traced into eastern Mindanao (Ranneff et al., 1960; Moore and Silver, 1983) and probably further northwards in the eastern Philippines (Kariog, 1983). In contrast, the southern part of the island of Bacan at the south-western end of the Halmahera group has a basement of high-grade continental metamorphic rocks associated with a deformed and metamorphosed 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.

The basement of western Halmahera is largely covered by Neogene–Recent sedimentary and volcanic rocks and remains poorly known. The oldest rocks are volcanic clastics which are typically unfossiliferous and include pyroclastics, lava
breccias and sub-aerial conglomerates, locally hydrothermally altered and deeply weathered and consequently extremely difficult to date. A volcanic conglomerate from the western coast of central Halmahera contains possible rudist fragments and about 20 km further east mudstones and marls interbedded with volcanioclastics contain planktonic forams of early Middle Eocene age. This evidence suggests that the younger volcanic arcs which built the western arms of Halmahera cover the eroded Late Cretaceous–Early Tertiary volcanic arc. The 1:250,000 geological maps (Apandi and Sudana, 1980; Supriatna, 1980; Yasin, 1980) assign these basement rocks to a Bacan Formation, tentatively dated as Late Oligocene–Early Miocene. However, this “formation” includes a number of unrelated units such as Late Cretaceous breccias which are imbricated in the Basement Complex in eastern Halmahera, undeformed late Paleogene volcanic breccias on Bacan (Yasin, 1980; Silitonga et al., 1981), as well as the Eocene rocks noted above. Hamilton (1979) suggested that between the Oligocene and Early Miocene Halmahera was an east-facing island arc and a subduction polarity flip led to the present tectonic configuration. However, in the area of detailed investigation in the northeast arm and central Halmahera, there is no evidence for an Oligo-Miocene volcanic arc. There are no volcanic rocks in the sequence and calc-alkaline volcanic debris is notably absent from the late Paleogene and Neogene carbonates and the siliciclastic debris which they contain indicates derivation from the underlying Halmahera ophiolitic Basement Complex. Oligocene–Early Miocene volcanism is reported from Waigeo (Van der Wegen, 1963) and Bacan (Yasin, 1980; Silitonga et al., 1981). Both of these islands are close to the Sorong Fault system which is a transform fault zone with a history of volcanic activity (Morris et al., 1983; Dow and Sukamto, 1984) and Bacan is situated on a splay of the Sorong Fault which is marked by recent volcanic activity. It is more probable that Oligo-Miocene volcanic activity was related to transform fault motion to the south of Halmahera at the Pacific–Australian plate boundary rather than to a volcanic arc on Halmahera.

At the end of the Eocene the arc and fore-arc terrain forming the Halmahera basement was strongly deformed and uplifted. The Oligocene was a period of uplift and deep erosion of the Basement Complex forming deep valleys containing fluvial ophiolitic conglomerates now being re-excavated by the present-day rivers. Slow subsidence began in eastern Halmahera in mid-late Oligocene, leading to deposition of marls, and reef carbonate deposition began further to the west in the Early Miocene. For the remainder of Miocene times the whole region was the site of shallow marine carbonate deposition. In eastern and central Halmahera there was a change from carbonate to marl deposition in the early Pliocene, followed by a sharp increase in siliciclastic debris deposited as turbidites in a submarine fan setting. Calc-alkaline volcanic debris appeared in the sequence in the mid-Pliocene and the amount of volcanic material increased with time, initially as tuffs and volcaniclastic turbidites and later as lavas. This rapid transition is interpreted as the result of the initiation of subduction of the Molucca Sea lithosphere to the west of Halmahera and the formation of a Pliocene volcanic arc in the western province. Rupture of the lithosphere was preceded by sudden downwarping of the crust beneath eastern Halmahera, immediately behind the arc, resulting in rapid subsidence of the Miocene reef limestones. The sedimentary basin formed was filled by an overall coarsening-upwards sequence with an increasing volcaniclastic component marking shallowing of the basin and increasing arc activity with lavas and sub-aerial volcanic breccias and conglomerates at the highest levels. The Pliocene arc was built on the eroded basement of the early Tertiary arc and the position in which the lithosphere fractured, leading to subduction of the Molucca Sea Plate, was probably determined by the thickened crust beneath the older arc.

A major deformation event affected the arc in the mid-Pleistocene. This caused tilting of major fault-bounded blocks, intense folding with local overthrusting at the junction of the western arc and eastern back-arc regions, uplift and erosion. Arc volcanism ceased briefly and the present active arc was built unconformably on the deformed older rocks after a shift of position of the volcanic
arc westwards by about 30 km in central Halmahera. There is no gap in the seismicity beneath Halmahera (Cardwell et al., 1980) to suggest a cessation of subduction in the Late Pliocene or Pleistocene and this deformation event probably marks a tectonic event at one of the existing or developing plate margins in the region. The nature of this event is considered below.

The evolution of the region

Previous reconstructions of the geological evolution of the region have been based principally on recent seismicity and marine geophysics (Hamilton, 1979; Cardwell et al., 1980; Moore and Silver, 1983). This reconstruction is based on the new data from Halmahera and information from the literature on surrounding regions. A fundamental constraint is the model of a Molucca Sea slab dipping both east and west, first proposed by Hatherton and Dickinson (1969) and refined by Cardwell et al. (1980). The only significant difference between the present-day plate boundaries adopted here and those of Cardwell et al. (1980) is in the omission of their Halmahera–Pulau transform fault which is discussed further below. Information on the pre-Miocene geology of the region is still very limited and it is not yet possible to attempt a reconstruction for the period before the Miocene.

Initial configuration: approximately 10 Ma

An important new result is the demonstration of a link between the Basement Complex of eastern Halmahera and basement rocks of eastern Mindanao. East Mindanao and Halmahera are part of a region of thickened crust representing a Late Cretaceous–Early Tertiary arc terrain which originated within the Pacific region. It was deformed and uplifted during the major plate reorganization event in the Late Eocene–Early Oligocene, possibly by collision with the north edge of New Guinea and represents the continuation of the Papuan arc terrain (Kroenke, 1983) from western New Guinea. This deformation event is recognizable over a widespread region between New Guinea (Kroenke, 1983) and the western Pacific (Hayes and Lewis, 1984) and may be related to a major change in motion direction of the Pacific Plate at 40 Ma (Uyeda and Ben-Avraham, 1972). A second completely new result of the Halmahera field-work is the discovery that the widely-quoted east-facing Oligocene–Early Miocene Halmahera island arc, which is shown on all pre-5 Ma reconstructions and attributed to Hamilton (1979), has no evidence to support it. Volcanic rocks of Oligo-Miocene age are lacking on Halmahera, although they are present on Waigeo and Bacan indicating volcanism along the transform fault system separating the Pacific from Australasia.

These two discoveries mean that the East Mindanao–Halmahera ridge (EMH Ridge) must have been a continuous feature within a single plate, the Philippine Sea Plate, since the Early Oligocene. As the Molucca Sea has been subducted, the EMH Ridge has moved westwards relative to West Mindanao. The western margin of the Molucca Sea, the West Mindanao–Sangihe–north Sulawesi arc, has been an active margin since the Miocene; the age of this arc is discussed below. Collision between West and East Mindanao is thought to have occurred in the Late Miocene (Cardwell et al., 1980; Moore and Silver, 1983) The 10 Ma reconstruction (Fig. 4) shows the position of the EMH ridge and adjacent areas just before collision occurred in Mindanao. It differs principally from earlier reconstructions (Cardwell et al., 1980; Moore and Silver, 1983) in joining Halmahera and East Mindanao and in the absence of subduction under Halmahera; both features are required by the field evidence. The EMH Ridge separated the Philippine Sea from the Molucca Sea, but all of these were moving at this time as part of a single plate with the western margin at ABC. AB represents the Philippine Fault. Before the Late Miocene this was an active margin, with subduction westwards beneath West Mindanao, representing a continuation of the Sangihe Trench. BC represents the trench associated with subduction beneath the Sangihe–North Sulawesi volcanic arc (the Sangihe Trench). DE represents the western margin of East Mindanao. EF represents a former offset of the Molucca Sea margin. FG represents the site of the trench asso-
Assumptions in the reconstructions

(1) The relative direction of motion of the Philippine Sea Plate is assumed to have remained constant for the last 6 Ma (Seno and Maruyama, 1984). The present vectors for the Philippine Sea Plate are given by Ranken et al. (1984). Two features are particularly important (Fig. 1): (a) the high degree of obliquity with which the Philippine Sea Plate approaches the Philippine Trench, and (b) the increase in relative rates of slip moving southwards along the Philippine Trench. Nakamura et al. (1984) suggest that the relative direction of convergence between the Philippine Sea Plate and the Eurasian Plate changed at about 1 Ma; such a change will not alter the form of the reconstructions but does mean that the rate of subduction will have changed and this is discussed further below.

(2) Volcanism on Halmahera began in the Pliocene and a date of 3 Ma for the age of initial volcanism has been taken for ease of calculation. Volcanism is assumed to have begun when the slab reached 100 km. All the volcanoes of the present Halmahera and Sangihe active arcs are situated more than 100 km above the Benioff zone. The present length of the slab beneath Halmahera is the entire length of subducted lithosphere and is approximately 250 km. Assuming a constant subduction rate this means subduction began at 5 Ma (Early Pliocene). These numbers can be adjusted but are consistent with the stratigraphy of Halmahera. The rate of subduction is discussed further below.

(3) Subduction at the Philippine Trench (in the sector between 8° N and 2° N) is considered to have been initiated at the same time as subduction at the Halmahera Trench following collision in Mindanao. The justification for this is that a collisional event is most likely to initiate new subduction zones, the timing of initiation of subduction beneath Halmahera is now reasonably well known and on this time scale the rate of subduction required at the Philippine Trench is reasonable. The precise date of initiation of subduction at the Philippine Trench is unknown; a young age for the southern Philippine Trench is discussed by Cardwell et al. (1980) and is consistent with the lack of associated volcanism.

(4) All the slabs are assumed to be dipping at approximately 45° perpendicular to the trench axis. Cardwell et al. (1980) show that the dip on the Philippine Sea slab in the Talaud region at about 7° N is steeper than for other island arcs, consistent with a young age for the subduction zone in this sector. Further north the dip is less steep and Quaternary volcanoes are situated above the 100 km Benioff zone contour indicating that the northern sector is older and the Philippine Trench is propagating southwards.

(5) West Mindanao is held in a fixed position on all the diagrams as a point of reference.

(6) No subduction is shown under the Sangihe Trench after 6 Ma. It is proposed that the rate of
subduction slowed significantly after the collision of East and West Mindanao, possibly to zero, until quite recently. There is a large gap in the seismicity below West Mindanao between 100 and 600 km consistent with collision terminating subduction in the North Sulawesi-Sangihe-West Mindanao arc. The effect of including subduction at the Sangihe Trench after 6 Ma is to widen the Molucca Sea and move East Mindanao further south.

Model

(1) Consumption of the Molucca Sea began at the Sangihe Trench. The exact timing is not known although the age of volcanic rocks from North Sulawesi indicates 12 Ma or earlier.

(2) Collision occurred between West Mindanao and East Mindanao (Fig. 5) in the Late Miocene (9–10 Ma). For simplicity the margins of West and East Mindanao at the trench (AB, Fig. 4) and the EMH Ridge (DE, Fig. 4) are assumed to have been parallel. This collision may have been diachronous if the EMH ridge was oriented obliquely to the trench and may explain the apparent problems of defining the age and movement amounts on the Philippine Fault. The effect of this collision was to stop subduction beneath West Mindanao (AB, Fig. 4) and to severely hamper continued subduction of the Molucca Sea at the Sangihe Trench (BC, Fig. 4). Therefore, continued movement of the Philippine Sea Plate was accommodated by (a) strike-slip motion on Philippine Fault, (b) subduction of Philippine Sea westwards at the Philippine Trench, (c) subduction of the Molucca Sea eastwards at the Halmahera Trench. Because of the angle between the relative motion direction of the Philippine Sea Plate and the Philippine Trench, subduction of a given length of Molucca Sea lithosphere was equivalent to significantly less subduction at the Philippine Trench (Fig. 6). The equivalent lengths of the subducted slabs depend on (a) the orientations of the Philippine Trench and the Halmahera Trench, (b) the motion vector for the Philippine Sea Plate, and (c) the dip on each slab. Assuming the only variable to be the relative orientation of the trenches, approximately 100 km of subduction at the Halmahera Trench is unexplained (equivalent to about 140 km of horizontal lithosphere before subduction). This can be accounted for by strike-slip motion on the Philippine Fault. Strike-slip motion on the Philippine Fault can also account for any Molucca Sea lithosphere which was subducted in the same period at the Sangihe Trench. There are ways of satisfying the apparent difference of 100 km other than, or in addition to, strike-slip motion on the Philippine Fault. Small changes in the relative convergence direction of the Philippine Sea Plate and the Southeast Asian Plate, or changes in the dip on the subduction zones could reduce the figure. If the convergence rate was greater in the region of Halmahera than further north, the given length of Molucca Sea lithosphere subducted would be equivalent to even less Philippine Sea lithosphere subducted; because of the position of the pole of rotation (Ranken et al., 1984) this may account for up to half of the 100 km. However, if the Philippine slab dipped more steeply than the Halmahera slab, the opposite will be true, although the effect would be smaller. Because of their uncertainty these effects have been omitted in making the reconstructions.
(3) Collision of the EMH ridge with West Mindanao in the Late Miocene was responsible for blocking further significant subduction at the Sangihe Trench. For the period from about 5–6 Ma to the late Pleistocene, there was very little subduction at the Sangihe Trench. The renewal of active volcanism was associated with the final phase of subduction of the Molucca Sea as Molucca Sea lithosphere was forced beneath the colliding plates above. Although active volcanism continued along the Sangihe arc, it is noteworthy that volcanism is dying out along the arc from N to S (Morrice et al., 1983). This is consistent with a gradual change of the plate boundary between Mindanao from subduction to strike-slip (Fig. 6, B). Minor subduction continuing at the Sangihe Trench would be equivalent to some of the strike-slip motion on the Philippine Fault.

(4) Because of the continued motion of the Philippine Sea Plate, which was impeded at its northwestern edge, new subduction zones developed within the Philippine Sea Plate (Fig. 6). In the north this was most easily achieved by the propagation of the existing Philippine Trench southwards (the sector of the trench south of 8°N is considered to be much younger than the northern sector). At the southern edge of the Philippine Sea Plate subduction was initiated in the opposite direction, on the opposite side of the EMH ridge. Here, initiation of a new trench was facilitated by the higher rate of convergence (currently >10 cm/yr according to Ranken et al., 1984) because the Philippine Sea Plate is effectively rotating relative to lithosphere to the west of it.

(5) A progressive development of trenches combined with strike-slip faulting at the Philippine Fault allowed a continuity of motion of the Philippine Sea Plate relative to the Molucca Sea Plate and Eurasian–Southeast Asian Plate. Fitch (1972) suggested that the oblique convergence at the
Philippine Trench can be decoupled into strike-slip motion on the Philippine Fault and normal under-thrusting at the Philippine Trench. In contrast, Seno (1977) suggested that the Philippines behave as a single lithospheric plate with the Philippine Fault as an active intra-plate fault with a low slip rate. The suggestion of Fitch (1972) is accepted here, which is supported by determination of recent seismic slip rates on the Philippine Fault (Acharya, 1980) while recognizing that the Philippine Islands probably represent a zone of complex deformation which is not behaving as a simple plate system (Cardwell et al., 1980; Hamburger et al., 1983; Hayes and Lewis, 1984; C. Rangin, pers. commun., 1986).

The most complex part of the Philippine Sea Plate is that between Halmahera and East Mindanao, approximately the area BEF (Fig. 4). Transform faulting may be required to allow the southern and northern sections of the plate to move relative to one another. An obvious feature of the reconstruction is the way in which the Halmahera Trench migrates westwards relative to the Philippine Trench. This migration could be accounted for by propagation of the Philippine Trench southwards with time; however, it may be necessary to postulate the existence of a transform fault between the two subduction systems. Such a feature has been suggested by McCaffrey (1982). Note that if the initiation of the Philippine Trench is unrelated to that of the Halmahera Trench, a transform of even greater significance must be postulated. The reconstruction of Cardwell et al. (1980) shows such a transform between Palau and Halmahera. If no transform fault is postulated it is necessary to accommodate between 0 and 100 km of lithosphere shortening in the area BEF (Fig. 4). This could be achieved by internal deformation such as folding, strike-slip faulting and thrusting, and this may be the cause of the 1 Ma deformation event on Halmahera which clearly postdates the initiation of subduction.

(6) At about 3 Ma the slab beneath Halmahera reached 100 km and volcanism began (Fig. 7). To the north of Halmahera (beneath the Snellius Ridge), because the trench was oblique to the convergence direction, the slab was less deep at 3 Ma and no volcanism resulted. This offers an explanation of why the Snellius Ridge has the characteristics of a subsided volcanic arc, is continuous with the Halmahera Arc, but volcanism has ceased. Above the Philippine Trench there was no volcanism because (a) oblique subduction meant the slab was not very deep and (b) some of the convergence was being taken up by strike slip-motion on the Philippine Fault.

(7) At about 1 Ma the junction zone between the arc and the back-arc was deformed, arc volcanism ceased briefly and the active arc shifted westwards. There are several possible explanations of this event. Internal deformation of the Philippine Sea Plate is required, as explained above, if there is no transform fault linking the Halmahera subduction zone and the Philippine Trench. Nakamura et al. (1984) suggest a change in motion direction of the Philippine Sea Plate at 1 Ma which may also be responsible. Other possibilities include interaction between the east-dipping Molucca Sea lithosphere with adjacent plates. The Sorong Fault system forms the southern boundary to the Molucca Sea region, and north of the splay passing through Bacan the Quaternary arc (Fig. 1) follows the 100 km Benioff zone contour, whereas
on Bacan the direction of the line of Quaternary volcanoes trend almost at right angles to this contour (Cardwell et al., 1980; Morris et al., 1983). The shift in position of active volcanicity could therefore mark westwards motion of the continental fragment south of this splay dragging the east-dipping slab of the Molucca Sea lithosphere westwards. Such motion would steepen the east-dipping limb of the Molucca Sea Plate (Cardwell et al., 1980) and shift the active arc westwards about a pivot in north Halmahera (Fig. 2). An alternative location is beneath northern Halmahera where the east-dipping Molucca Sea Plate and the west-dipping Philippine Sea Plate are in collision at a depth of 100–150 km. The relative lengths of the subducted slabs suggest that the Philippine Sea Plate collided with the Molucca Sea Plate beneath northern Halmahera at about 1 Ma and the likely effect of such a collision would be to force the east-dipping Molucca Sea Plate westwards, thus shifting the axis of volcanicity in the same direction (Fig. 2).

(8) By 0.5 Ma the whole of the zone between Mindanao and Talaud was a zone of strike-slip movement (Fig. 8). As the Molucca Sea closed the Philippine Fault propagated southward as a strike-slip fault and the Philippine Trench propagated southward as a new subduction zone. This accounts for the very young age of subduction at the Philippine Trench in the Talaud section, as suggested by the steep dip on the Philippine Sea slab. It also explains the lack of significant deformation of Neogene sediments shown on seismic reflection profiles from the Davao Gulf, between the Talaud and Sangihe Ridges.

(9) At present the Molucca sea is effectively completely closed (Fig. 9). This is resulting in arc-directed shallow thrusting in the Molucca Sea (Silver and Moore, 1978). The field-work suggests that blocking of subduction in the Halmahera Trench may also be resulting in motion on strike-slip faults in the northeast arm of Halmahera in an attempt to accommodate continued motion of the Philippine Sea Plate. This suggestion is supported by seismicity in the northeast arm which also indicates strike-slip motion (I. Effendi and S.A.F. Murrell, pers. commun., 1986).
Discussion

Age of volcanism in the North Sulawesi–Sangihe–West Mindanao arc

The model assumes that arc volcanism began before 10 Ma. In north Sulawesi the oldest volcanic rocks reported (Effendi, 1976; Apandi, 1977) are Early to Middle Miocene in age and Dow (1976) records Late Miocene quartz-diorites intruding older Miocene intermediate and volcanic rocks. Further north less is known; Morrice et al. (1983) assume that the Sangihe arc formed part of a single arc which stretched from the west arm of Sulawesi to Mindanao and quote Hamilton (1979) as noting that volcanism was "...especially voluminous from 5 to 14 Ma...". These dates include those from the south arm, west-central Sulawesi and the south end of the north arm, and range between 1.6 and 31 Ma, and although Hamilton does note that volcanism was especially voluminous between 14 and 5 Ma, it is not clear where in this large region this was so. The continuation of this arc into West Mindanao is uncertain; Ranneft et al. (1960) report lavas and volcanic breccias of probable Early Miocene age.

Timing of subduction

The model suggests that subduction beneath Halmahera began at about 5 Ma. This is based on an estimate of the initiation of volcanism beginning at 3 Ma from the stratigraphic evidence, an assumption of a continuous and steady rate of subduction, and an assumption that volcanism began when the subducted slab reached 100 km. This interpretation is supported by stratigraphic evidence from Halmahera, where there was an end to the deposition of reef carbonates and a marked change in the rate of subsidence and a change to siliciclastic sedimentation. Equally, from the little that is known from adjacent regions a 5–6 Ma event seems plausible. In the Ayu Trough, immediately east of Halmahera, there is a marked decrease or cessation of spreading at 5–6 Ma (Weissel and Anderson, 1978). Volcanism in the Sulawesi arc was voluminous between 14–5 Ma (see above). There is thus an implication of less volcanism after 5 Ma: exactly as predicted by the model, which suggests that subduction effectively ceased at the Sangihe Trench from about 5–6 Ma. On Mindanao Ranneft et al. (1960) record changes in sedimentation from the late Miocene, but these may be related to collision rather than subduction further south.

Rate of subduction

Using an average rate of subduction may be misleading. The rate of subduction calculated at the Halmahera subduction zone is 7 cm/yr. Even assuming about 100 km of subduction at the Sangihe Trench for the same time period results in a convergence rate of about 9 cm/yr. The present rate of convergence is about 10–11 cm/yr at the Philippine Trench (Ranken et al., 1984). There is some evidence to suggest a variation in the rate of subduction. Nakamura et al. (1984) have suggested a change in the direction of relative motion between the Eurasian and Philippine Sea Plates at about 1 Ma. If the entire region west of the Philippine Fault and Molucca Sea was part of a single Eurasian Plate, which is uncertain, the rate of subduction would have increased since before 1 Ma the Philippine Sea Plate was moving in a direction almost parallel to the Philippine Trench. The Pleistocene unconformity below the present active arc volcanic rocks on Halmahera may be an expression of such a change in the subduction rate (see above for other explanations). On North Sulawesi the currently active volcanoes are being built on a Miocene substratum, consistent both with discontinuous subduction and the suggestion that subduction virtually ceased at the Sangihe Trench between 5–6 Ma until very recently. Two intervals of higher rates of subduction (say about 5–2 Ma and 1–0 Ma) would be consistent with the present rate of convergence and length of subducted lithosphere. An earlier interval of rapid subduction would explain how a velocity required to break the Molucca Sea Plate and initiate subduction at the Halmahera subduction zone could be achieved (N.J. Price, pers. commun., 1986). It should be possible to refine this aspect of the model by precise dating of volcanic rocks.
The Philippine Fault

The model predicts left-lateral motion on the Philippine Fault with an average rate of 0.5 cm/yr (the range could be 0–1.0 cm/yr). The Philippine Fault is still a region of considerable controversy. Hamilton (1977, 1979), apparently on the basis of aerial photograph examination, states that the Philippine Fault does not reach Mindanao “...as an active strike-slip feature, and is not now a major plate boundary”. In contrast, Karig (1983) states that the northern section is and has been active “...for much of the past 15 m.y., despite arguments to the contrary...” by Rutland (1968) and Hamilton (1979). Interestingly, in Luzon detailed mapping by Rutland indicated three important phases of movement: Late Miocene, Pli-Pleistocene and Recent. Cardwell et al. (1980) also dispute Hamilton’s assertion that the fault does not extend into Mindanao on the basis of geological mapping (Ranneft et al., 1960; Philippine Bureau of Mines, 1963), airphoto investigations by Allen (1962), and the presence of large earthquakes on or near the fault in 1893 and 1911 (Rowlett and Kelleher, 1976). Acharya (1980) records recent seismic slip rates of about 6 cm/yr. Moore and Silver (1983) report field observations from southern Mindanao consistent with left-lateral strike-slip motion on the Philippine Fault. In the north Philippines Karig (1983) estimates the average rate of movement on the fault to have been near 1.5 cm/yr from the mid-Miocene to Recent. Considering the uncertainties, particularly the inadequacies of data from Mindanao, this is not inconsistent with the model.

Talaud and its significance

The Talaud ridge at the centre of the Molucca Sea has previously been interpreted on the basis of marine geophysics as part of a “melange wedge” (Silver and Moore, 1978; McCaffrey et al., 1980) including slices of the Molucca Sea lithosphere. Proposals for the origin of Talaud include part of a west-facing East Mindanao–Talaud arc separate from the Halmahera arc (Cardwell et al., 1980; Moore et al., 1981), an east-facing Talaud–Tifore arc independent of the Sangihe and Halmahera arcs (Sukamto, 1979), and part of the fore-arc of the west-facing Halmahera arc (Moore and Silver, 1983). The reason for these disparate interpretations is the evidence of collision in the southern Molucca Sea with evidence for its absence north of Talaud. On Mindanao Moore and Silver (1983) show that the Agusan–Davao trough separates the East and West Mindanao arcs and contains up to 6 km of Eocene to Recent sediments with a period of intense folding at the end of the Middle Miocene. They trace the Philippine Fault system southwards as far as the Talaud islands where thrusts in the southern Molucca Sea are terminated. North of Talaud there are little-deformed Neogene sediments in the Davao Gulf (Cardwell et al., 1980) not consistent with the very recent convergence in this area and west of Talaud sediments lap onto the Talaud ridge indicating the fault block is not a young feature (Moore and Silver, 1983). On Talaud Moore et al. (1981) describe a post-Middle Miocene sedimentary sequence resting unconformably on ophiolite slabs which are Middle Eocene or older. The Middle Miocene to Pleistocene rocks are tuffaceous sandstones, siltstones and shales with intercalations of limestone, marl and conglomerate in which the sediments are dominated by volcanic debris. They were deposited in deep water (> 2000 m) by turbidity currents. Volcanic rocks occur only in the lower part of the Talaud sequence where they are of probable mid-Miocene age. The Basement Complex of Halmahera is similar to that of Talaud but the Neogene sequence is quite different. Volcanic activity in the Halmahera arc did not begin until the Pliocene and volcanic rocks increase in abundance as the sequence becomes younger. This rules out an origin for Talaud in the Halmahera arc.

These apparently conflicting observations can be reconciled if Talaud formed part of the Miocene Sangihe arc which became inactive in the Late Miocene according to the model. After the Miocene arc became inactive, it shed debris into the Molucca Sea to areas which subsided to depths of several kilometres. This important erosional break is recorded in the north arm of Sulawesi where currently active volcanoes are built upon Miocene volcanics and plutonic rocks. The
northern Molucca Sea therefore included an inactive arc on its western side, and along the Talaud ridge strike-slip faulting on the Philippine Fault system continued southwards into the Halmahera subduction zone. Activity in the Sangihe arc has been renewed only very recently (possibly west of its Miocene position) and Talaud has been uplifted by the closure of the Molucca Sea.

Melange

It is interesting to note that all of the "melange" reported by Moore et al. (1981) is of pre-mid Miocene age; none appears to be related to the present collision. Indeed they note (p. 472) that the Neogene "...strata are moderately to strongly deformed, but unlike the melange zones, bedding is well preserved and becomes disrupted only locally adjacent to melange zones". The similarity in character and structure of the ophiolitic rocks to those forming the Basement Complex on Halmahera suggests that much of the "melange" may have been formed in the Late Eocene deformational event. If the present model is correct in suggesting the gradual change from thrusting to strike-slip motion the juxtaposition of ophiolitic basement and Neogene rocks may in part be a consequence of the strike-slip deformation. It is noticeable that the maps and descriptions of Moore et al. (1981) show steeply-dipping fault-bounded slices of material in the "melange", as on Halmahera. It is likely that the Molucca Sea "melange wedge" is composed largely of sedimentary material dominated by volcanic debris derived by erosion of the Miocene Sangihe arc, the Pliocene Halmahera arc, and material shed from the present active arcs, which is now becoming locally tectonically intercalated with its pre-Miocene ophiolitic basement.

The age of the Molucca Sea lithosphere

The age of the Molucca Sea is unknown. In view of the similar character of the Talaud and Halmahera basements, it is possible that the Molucca Sea formed by rifting of a formerly extensive and continuous terrain in a short interval of spreading in the Oligocene-Early Miocene. This has the interesting feature that it corresponds to the known age of spreading of many marginal basins in the region, including the Caroline Sea, the South China Sea, the Japan Sea, the Parece Vela Basin and the Shikoko Basin (Hayes and Lewis, 1984). It also corresponds to a period without arc volcanicity consistent with models of arc evolution (Kang, 1974; Scott and Kroenke, 1981). Alternatively the Molucca Sea may represent Eocene ocean crust like the Celebes Sea (Weissel, 1983) and the West Philippine Sea.

Terrain accretion

Many orogenic belts include allochthonous terrains although the mechanisms by which these terrains are assembled are still not understood. Karig et al. (1986) have suggested that strike-slip motion has played an important role in the transport and emplacement of terrains in the northern Philippines. The development recorded by Halmahera and the interpretation suggested here is that the EMH ridge has been in the process of transferring from the Philippine Sea Plate to the strike-slip complex of the Philippines at the junction of the Eurasian and Philippine Sea plates. This process has involved a complex sequence of events including strike-slip faulting and subduction in several stages and will be completed by either strike-slip faulting through the northeast arm of Halmahera (Fig. 9) or by continued southward propagation of the Philippine Trench. When this is complete the EMH ridge will be another of the allochthonous terrains of the Philippines. The complexity of events recorded during the last 10 Ma in the Halmahera region confirms the warning of Karig et al. (1986) that certain geological keys should be used more circumspectly and supports their contention that current views of terrain evolution need to be broadened from simple two-dimensional models to more complex models.

Acknowledgements

Financial support for the field-work in Indonesia was provided by the Royal Society, the Central Research Fund of London University, Amoco International, British Petroleum and the
University of London Consortium for Geological Research in Southeast Asia. GRDC Bandung provided aerial photographs and invaluable practical assistance in Indonesia. I thank Mike Audley-Charles for assistance and discussion during and after field-work, Syarif Hidayat and Sahat I. Tobing for their assistance with field-work, and Paul Ballantyne and F.T. Banner for their work on the material collected in the field.

References


