Geodynamic patterns of ophiolites and marginal basins in the Indonesian and New Guinea regions

RON HARRIS
Department of Geology, Brigham Young University, Provo, UT 84602-4606, USA
(e-mail: rharris@byu.edu)

Abstract: Analysis of spatial, temporal, geological and geochemical patterns of ophiolites in the Indonesian and New Guinea region indicates a strong correlation with marginal basin development and closure. The spatial distribution of ophiolites is mostly linked with marginal basin producing zones of oblique convergence and collision. Strain partitioning in these zones creates a series of ephemeral plate boundaries between several independently moving lithospheric blocks. Repeated disruption of the diffuse boundaries between the blocks by changes in plate motion and collision-induced mantle extrusion creates space that is rapidly filled by new ocean basins in the upper plate of subduction zones. Suprasubduction zone (SSZ) spreading of these basins is enhanced by episodic extrusion of asthenosphere escaping collisional suture zones. Various closure events and global plate motion changes are reflected in the temporal distribution of marginal basin and ophiolite ages. Most ophiolite slabs in the Indonesian and New Guinea region represent fragments of oceanic lithosphere with a subduction zone component, as indicated by the common refractory petrochemistry of the mantle sequence and occurrence of boninite. Age and compositional heterogeneity may indicate that some ophiolite bodies are composite terranes. Collisions with buoyant lithosphere transform parts of these ocean basins into ophiolites. The connection between ophiolites and marginal basins is strongest where parts of actively spreading SSZ basins are partially represented as ophiolites in collision zones.

Many of the various tectonic models proposed for the origin and tectonic evolution of ophiolites are supported by plate interactions in the Indonesian and New Guinea region (Dewey & Bird 1970; Silver & Smith 1983; Moores *et al.* 1984; Searle & Stevens 1984; Dilek & Moores 1990; Harris 1992; Dickinson *et al.* 1996). However, the geological associations of these interactions remain poorly resolved, allowing different parts of the region to be used as modern analogues for almost any tectonic scenario. Simple explanations based on plate kinematics alone fail to account for the increasing levels of complexity observed in the Indonesian and New Guinea region. New ideas and supporting evidence for mantle extrusion mechanisms (e.g. Flower *et al.* 2001) also rely heavily on descriptions of plate interactions in this region (Doglioni *et al.* 1999), and raise new questions about how these processes may relate to the spatial and temporal pattern of ophiolites.

This paper provides a synthesis of the temporal and spatial patterns, and tectonic associations of marginal basins and ophiolites throughout the Indonesian and New Guinea region. It explores the relations between various plate boundary processes and ophiolite genesis and emplacement, such as the role of strain partitioning, trench rollback, subduction polarity asymmetry, asthenospheric flow and plate kinematics.

Tectonic evolution of the Indonesian and New Guinea region and its contribution to the ophiolite debate

The Indonesian and New Guinea region is an active collisional amalgamation of the complex Asian and Australian continental margins with crustal heterogeneities of the western Pacific (Hamilton 1979; Hall & Blundell 1996; Hall 2002). Rapid changes in plate boundary location and function in this region are emblematic of incipient phases of continental collision manifest in ophiolite-bearing Cordilleran and Tethyan mountain systems. As in these regions, the Indonesian and New Guinea region has buffered the changing motion and boundaries of some of the Earth's largest plates. Convergence of the Indo-Australian plate from the SW has mostly been absorbed along the Sunda arc–trench system, whereas convergence of the Pacific plate from the east has progressed by sequential movement along an array of short-lived subduction zones and spreading centres. Similar plate boundary asym-

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metry is observed in many other parts of the world (Uyeda & Kanamori 1979; Doglioni *et al.* 1993).

The triple junction between the Indo-Australian, Pacific and Asian plates is a complex repository of island arcs, marginal basins, continental fragments and ophiolites amalgamated by repeated plate boundary reorganizations. Many of the oceanic terranes in the mix were emplaced onto the edge of partially subducted continental margins that began arriving at the triple junction during the mid-Tertiary. The incipient continent–continent collision has progressed to the stage where the Sunda Shelf of Asia and the Sahul Shelf of Australia are now partially connected by a collage of island arcs and continental fragments separated by trapped and partially obducted ocean basin lithosphere (Fig. 1).

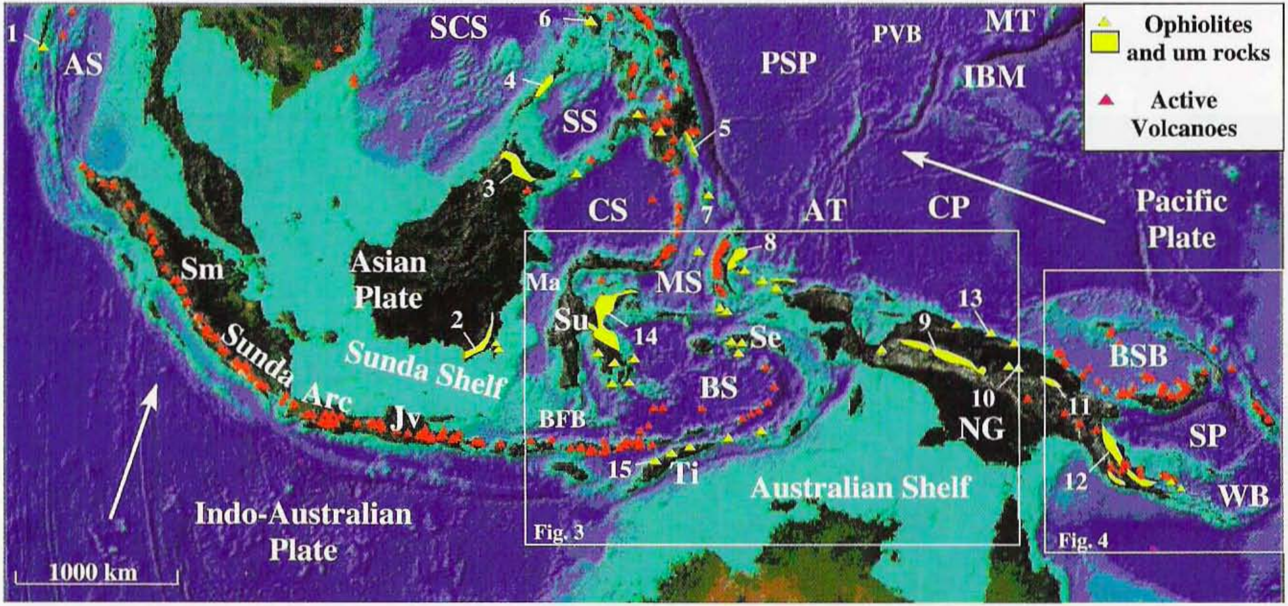
An analogous stage of tectonic development to that in the Indonesian and New Guinea region may have existed in the Jurassic amalgamation of Alaska between North America and Siberia, or the Mediterranean region between Africa and Europe. However, in both of these locations, ophiolites are all that remains of what once was a complex plate boundary system that included ocean basins that have since been closed and partially obducted. The survival of many of these features in the Indonesian and New Guinea region offers a unique perspective into the connection between ophiolites and marginal basins. Although ocean basin closure along this plate boundary zone has already progressed to the stage of producing several classic ophiolites, many of the original tectonic features, such as west-verging subduction zones, that produced these ophiolites remain intact. These features provide a rare glimpse of the complexity associated with convergent triple junctions involving continents.

From the Andaman Sea to New Guinea (Fig. 1), the marginal basins and suprasubduction zone (SSZ) ophiolites in the natural laboratory of the Indonesian and New Guinea region contribute in many ways to the continuing debate about the geodynamic meaning of ophiolites worldwide. Global positioning system (GPS) and earthquake studies throughout the region reveal many fragmentary and transitional plate boundary zones capable of simultaneous opening, closure and obduction of new oceanic lithosphere. The age and chemistry of oceanic crust in these ocean basins and the ophiolites that surround them provide a context for interpreting ophiolites in mountain systems where the original tectonic setting is obscured. Most ophiolites of the Indonesian and New Guinea region also have some component of refractory or SSZ tectonomagmatism, like most other ophiolites. In some cases the SSZ history is superimposed onto or evolves into less refractory lithosphere or is sourced from mantle previously contaminated by subduction.

Geophysical and geological studies of plate boundaries throughout the ING region demonstrate, at a range of temporal and spatial scales, that plate convergence is partitioned by an intricate network of faults that separate independently moving lithospheric blocks (Hamilton 1979; Bowin *et al.* 1980; Cardwell *et al.* 1980; McCaffrey *et al.* 1985; McCaffrey 1988; Curray 1989; Audley-Charles & Harris 1990; Genrich *et al.* 1996; Hall & Blundell 1996; Kroenke 1996; Pubellier & Cobbold 1996; Simons *et al.* 1999; Stevens *et al.* 1999; Kreemer *et al.* 2000). The rapid rates of movement and transitional nature of these microplate boundaries provide a variety of settings for SSZ ocean basin development. Eastward asthenospheric flow may also play an important role in steepening subduction zones and facilitating marginal basin development (e.g. Doglioni 1993). It is the combination of strain partitioning, plate boundary reorganization, asthenospheric flow, and collisional termination of subduction in the Indonesian and New Guinea region that produces and transforms many newly formed SSZ ocean basins into ophiolite-bearing collisional mountain systems. Each stage of this process is represented by the evolving nature of plate boundaries in the Indonesian and New Guinea region, where many ophiolites already abound.

Transitional nature of plate boundary reorganization

The interaction of the three large plates that converge in the Indonesian and New Guinea region produces a wide zone of plate boundary deformation composed of several fault-bounded oceanic and continental fragments (Fig. 2). Most of the fault zones between these discrete lithospheric blocks are ephemeral and accommodate strain for only a few million years or less. The most stable and long-lived plate boundary is the north-directed Sunda subduction system (Fig. 2). However, this boundary has been intensely modified by collision with India in the west and Australia in the east. In both cases indentation of the convergent boundary has increased its obliquity and resulted in partitioning of strain away from the trench into the weak parts of the upper plate. The collision of the Indo-Australian and Asian plates is further modified by the rapid westerly convergence of a series of Pacific microplates linked by multiple subduction zones, spreading centres and large strike-slip faults (Figs



Marginal Basins and Islands

AS - Andaman Sea
AT - Ayu Trough
BFB - Bali and Flores Basins
BS - Banda Sea
BSB - Bismarck Sea Basin
CP - Caroline Plate
CS - Celebes Sea
IBM - Izu-Bonin-Mariana Trench
Jv - Java
Ma - Makassar Strait
MS - Molucca Sea
MT - Mariana Trough
NG - New Guinea
PSP - Philippine Sea Plate
PVB - Parece Vela Basin
SCS - South China Sea
Se - Seram
SP - Solomon Plate
SS - Sulu Sea
Sm - Sumatra
Su - Sulawesi
Ti - Timor
WB - Woodlark Basin

Ophiolites

1 - Andaman Islands
2 - Meratus Mountains
3 - Sabah (Darvel Bay)
4 - Palawan
5 - Pujada
6 - Mindoro (Amnay)
7 - Talaud Islands
8 - Halmahera
9 - Central (New Guinea)
10 - April Ultramafics
11 - Marum
12 - Papuan
13 - Cyclops
14 - East Sulawesi
15 - Timor (Ocussi)

ocation map of ophiolites and marginal basins of the Indonesian and New Guinea region. Arrows indicate plate motion relative to the Asian plate. Locations of more

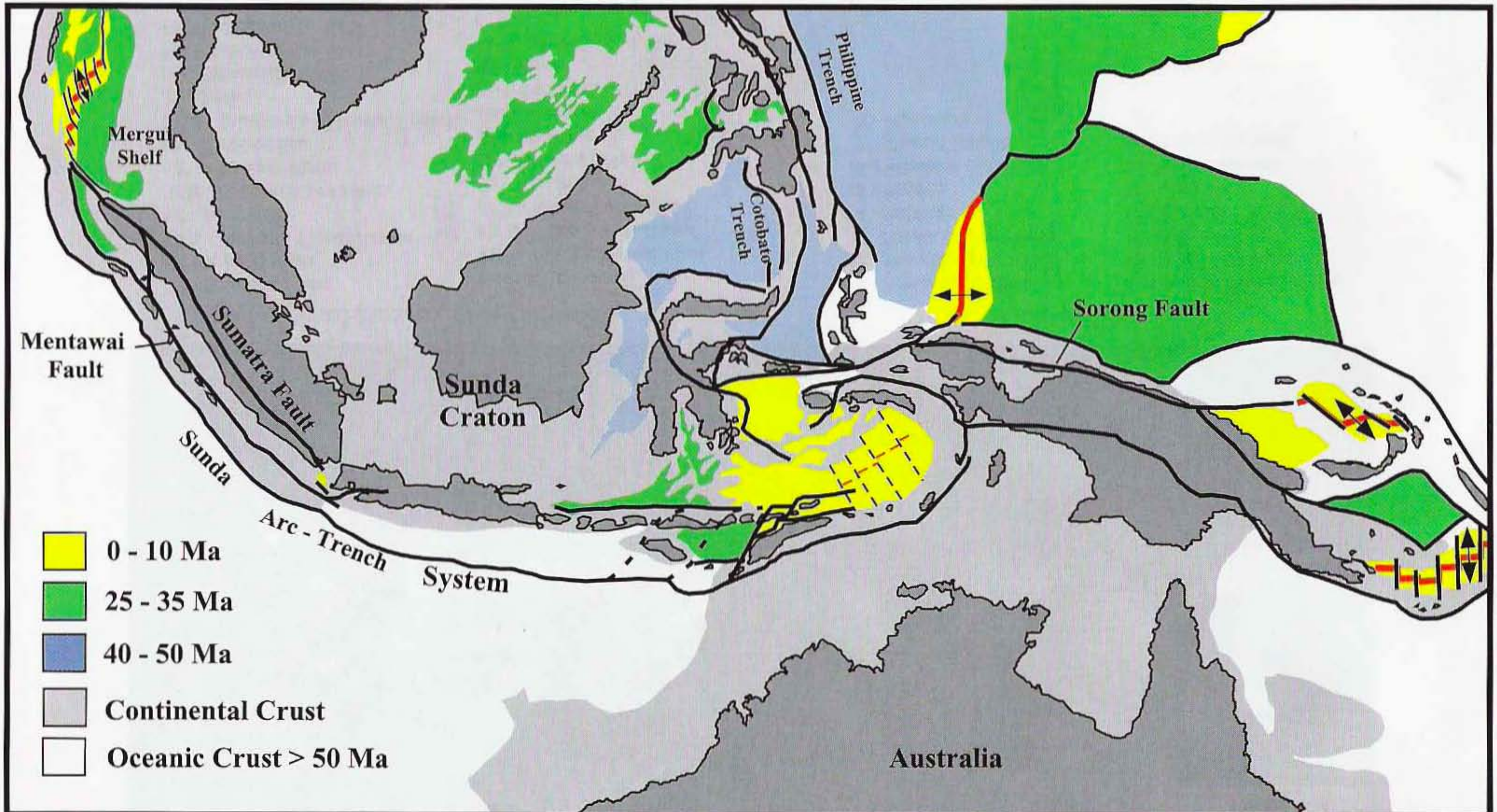


Fig. 2. Plate boundaries, active faults and marginal basin age of the ING region (Modified from Hall, 1996).

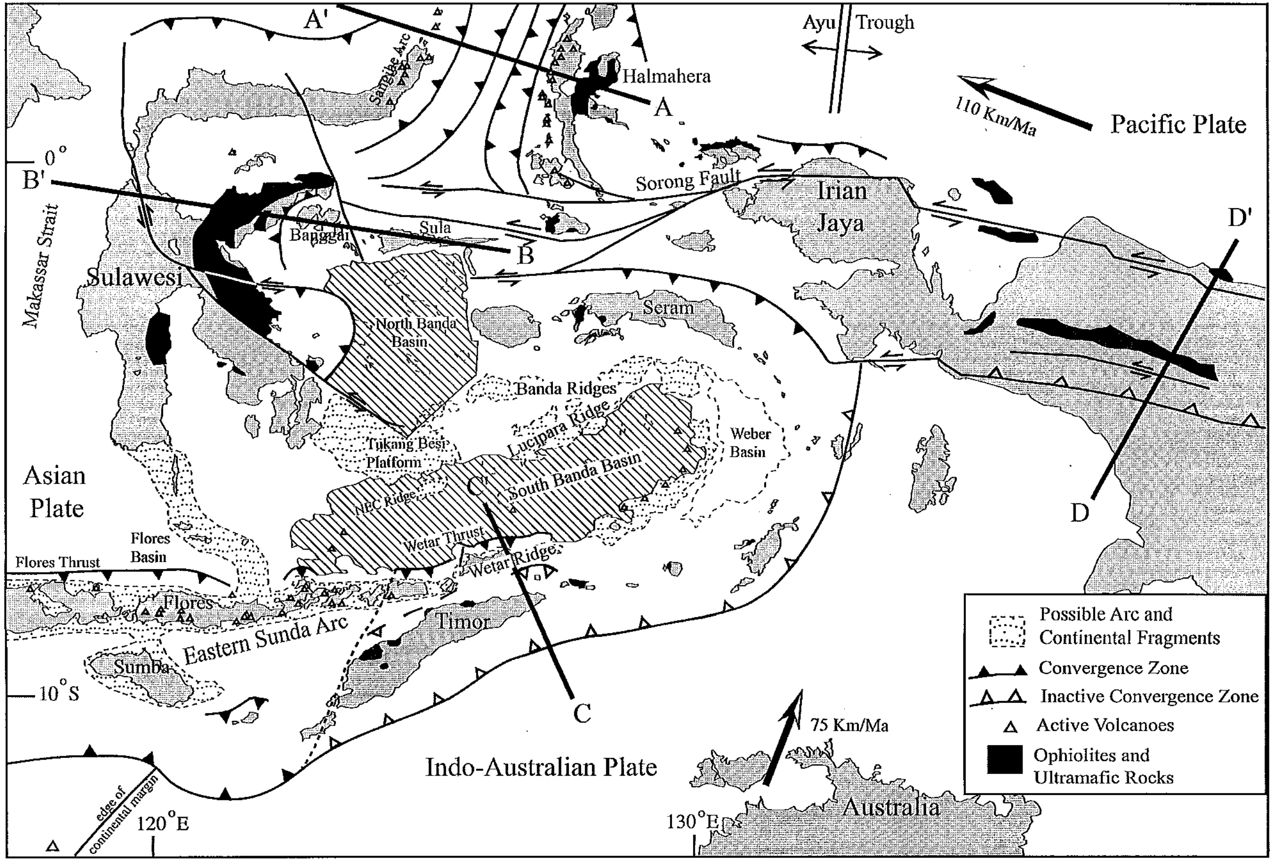


Fig. 3. Tectonic map of the eastern Indonesian region. Banda Sea marginal basins are shown in slanted stripes. Lines of section shown in Figure 4 are heavy black lines. (Modified from Hamilton, 1979)

2 and 3). The convergent triple junction of the three plates has been periodically disrupted by collision with island arcs, oceanic plateaux and continental fragments, and the accompanying extrusion of asthenosphere. It is in these collisional settings that most ophiolites are found.

Seismic tomography

Tomographic images of the mantle to depths of 1400 km produced by Widiyantoro & van der Hilst (1997) and Hafkenscheid *et al.* (2001) show that the entire Indonesian and New Guinea region is underlain by subducted lithosphere. Up to 5400 km of convergence is estimated along the Sunda arc system, resulting in a high P-wave velocity anomaly that stretches from Java to the southern Philippines. The subducting plate begins to lose its seismic and tomographic expression below 600 km depth where it merges with a more diffuse zone of high-velocity mantle that underlies the entire region at depths of 600–1400 km. Well-imaged slabs of lithosphere feed into this high-velocity zone (slab graveyard) from the Pacific side in the New Guinea, northern Banda arc, Molucca and Philippine regions. Tomographic maps of P-wave velocities at 200 and 500 km depth show that all of the actively spreading marginal basins of the Indonesian and New Guinea region are underlain by subducted lithosphere. West-directed slabs are generally steeply inclined, whereas east-directed slabs dip less than 45°. The influence of these slabs on the petrochemistry and stress history of the marginal basins above them is poorly resolved.

NE-directed subduction beneath the Asian continental margin

Subduction along the southern and western margins of the Sunda craton is long-lived and dates back to at least the Early Cretaceous (Hamilton 1979). The most recent expression of subduction along this margin is the Late Neogene Sunda arc, which has formed on top of older subduction complexes accreted to the edge of the Sunda craton (Fig. 2). The Sunda arc–trench system stretches for nearly 6000 km from Myanmar, where it is terminated by continental collision with India, to the Banda Sea, where it is transitional with the Banda arc–continent collision (Figs 1 and 2).

The active accretionary wedge of the Sunda arc consists mostly of Late Paleogene to Recent cover sediments accreted from the subducting Indian Ocean sea floor (Hamilton 1979). Higher rates of accretionary influx exist in the NW because of the influence of the Bengal Fan, and at the eastern end of the Sunda arc where the Australian passive margin collides with the trench. In both locations the crest of the accretionary wedge emerges to form a chain of forearc islands (Fig. 1) that reveal that little, if any, oceanic lithosphere has accreted from the lower, subducting plate. If the lower plate were a common source of ophiolites then there should be an extensive repository of them accreted to the edge of the Sunda craton. However, exposures both on forearc islands and of the older accretionary wedge have only small blocks of oceanic material embedded in mélange, and no ophiolites are documented (Ketner *et al.* 1976; Hamilton 1979).

The 7–8 cm a^{-1} of plate convergence measured between the Indo-Australian plate and the Sunda arc (Tregoning *et al.* 1994; Kreemer *et al.* 2000) is mostly taken up near the trench south of Java, where convergence is orthogonal (Stockmal 1983; McCaffrey 1996). Strain is increasingly partitioned away from the trench at its western and eastern ends, where collisional indentation increases the obliquity of convergence and resistance to subduction (Curray 1989; McCaffrey 1996). West of Java a major component of convergence is distributed to the Mentawai and Sumatra faults (Fig. 1). Obliquity of convergence also increases to the east in the Banda arc region, where plate boundary redistribution is more obscure (Harris 1991; Genrich *et al.* 1996). In both of these pericollisional settings of oblique convergence SSZ oceanic basins have formed within the Sunda arc–trench system. The Banda, Bali and Flores basins formed in the east, and the Andaman Sea basin is currently opening in the west (Fig. 1).

Andaman Sea

The Andaman Sea is an actively spreading interarc basin with a tectonic history associated with ridge subduction (Eguchi *et al.* 1979), pericollisional extension or 'rip-off basin' development (Lee & Lawver 1994), and highly oblique convergence (Curray 1989). Partitioning of strain away from the trench in the region is manifest by the right-lateral Mentawai Fault in the forearc and the Sumatra Fault astride the volcanic arc (Fig. 2). These fault systems segment the NW Sunda arc–trench system into three orogen-parallel sliver plates (Fig. 2) that have a component of northward motion with the subducting Indian plate relative to the Sunda craton (Curray 1989; Malod & Kemal 1996; Prawirodirdjo *et al.* 1997).

Episodic SSZ spreading between these sliver plates in the Andaman Sea region began in the Oligocene with the formation of NNE–SSW-trending grabens of the Mergui and North Sumatra continental back-arc basins (Curray 1989). At 13 Ma NW–SE-directed extension began to form the present oceanic basin within the Mergui Shelf. An overall spreading rate of 4 cm a^{-1} is estimated from the combined motion along six short, east–west-trending ridge segments linked by long (*c.* 100 km) transform faults (Guzman-Speziale & Ni 1993). The total amount of extension is estimated at around 460 km (Curray 1989). This estimate is similar to the amount of right-lateral strike-slip offset measured along the Sagaing Fault to the north (Hla-Maung 1987), which links the Andaman Sea to the eastern Himalayan syntaxis.

Active volcanism in the Andaman Sea is found mostly around the Barren and Narcondam Islands. The sea-bed extent of these volcanoes forms a north–south ridge about 150 km long that is bounded by the west Andaman Fault (Weeks *et al.* 1967). Volcanic rocks include basalt, dacite, andesite, and basaltic-andesite suites with little or no volcanic ash (Dasgupta *et al.* 1990). Although no petrochemical data are available from Andaman Sea oceanic basement, the active volcanic region yields major and trace element abundances that plot in both the island arc tholeiite (IAT) and mid-ocean ridge basalt (MORB) fields of discriminate diagrams (Haldar *et al.* 1992).

Before the onset of sea-floor spreading in the Andaman Sea region, the Sunda arc formed a continuous belt of magmatism that stretched from Sumatra northward into Myanmar (Mitchell 1993). The opening of the Andaman Sea transformed the linear trace of stratovolcanoes of the Sunda arc into a diffuse zone of SSZ spreading centres from the northern tip of Sumatra to the southern coast of Myanmar (Fig. 2). The 'disappearance' of the arc is a common characteristic of many Tethyan-type ophiolites throughout the world (Mitchell 1983). Moores *et al.* (1984) related the segmented and discontinuous nature of Andaman Sea SSZ spreading centres to geological associations of eastern Mediterranean ophiolites. Parallels also exist between the tectonic setting of the Andaman Sea and reconstructions of the belt of Jurassic ophiolites found throughout the Cordillera of North America (e.g. see Dickinson *et al.* 1996). Emphasizing the ephemeral nature of the Andaman Sea SSZ ocean basin, Curray (1989) compared it with the Rocas Verdes ophiolite complex of the southern Andes (Dalziel 1981).

The Late Cretaceous and early Eocene Andaman ophiolite forms the southernmost part of a 2500 km long north–south belt of dismembered ophiolites extending from the Naga Hills near the eastern syntaxis of the Himalaya to the Andaman–Nicobar Islands (Sengupta *et al.* 1990). The ophiolites are interpreted as remnants of narrow, marginal ocean basins that were opened and closed within a short time immediately preceding the collision of India (Acharyya *et al.* 1989). Two groups of volcanic rocks are found throughout this belt. The dominant high-TiO_2 type is interpreted as off-axis seamount basalt because of the mild alkaline affinity and within-plate trace and rare earth element (REE) characteristics (Jafri *et al.* 1990). The other group of volcanic rocks ranges in composition from basaltic andesite to more felsic differentiates that may be cogenetic with plagiogranite found intruding gabbro (Ray *et al.* 1988). These units have characteristics of both island arcs and MORB, and may be associated with a marginal basin similar to the present Andaman Sea (Ray *et al.* 1988; Jafri *et al.* 1990). Emplacement of the ophiolites occurred during the Early Eocene oblique collision of the Myanmar and Indian continents (Acharyya *et al.* 1989).

Banda Sea basins

The Banda Sea is an interarc basin composed of a series of east–west-trending continental and volcanic ridges separated by anomalously deep oceanic basins (Fig. 3). These ocean basins accommodated the eastern expansion of the Sunda arc to form the Banda arc, which is currently in collision with the northern margin of Australia (Fig. 3). The Banda Sea has been interpreted as trapped fragments of old Pacific or Indian Ocean lithosphere (Lapouille *et al.* 1985), as an older continuation of the Celebes and Sulu Basins to the north (Lee & McCabe 1986), and as a young back-arc basin (Hamilton 1979). Dredge samples (Silver *et al.* 1985; Guilou *et al.* 1998; Honthaas *et al.* 1998) and mapping of magnetic anomalies (Hinschberger *et al.* 2001) support the interpretation by Hamilton (1979) and suggest that the ocean basins opened during the Late Miocene to Pliocene, within the stretched eastern edge of the Asian continental margin.

Separating the sub-basins are the Banda and Nieuwerkerk–Emperor of China (NEC)– Lucipara Ridges (Fig. 3). These ridges, along with the Wetar Ridge to the south, consist mostly of Neogene volcanic deposits mounted on much older volcanic and continental metamorphic basement that formed the structurally attenuated edge of the southern Sunda craton and possibly slivers of the Australian continent (Silver *et al.* 1985; Honthaas *et al.* 1998).

Studies of dredge samples and magnetic anomalies in sub-basins of the Banda Sea are interpreted to show that the basins opened sequentially toward the SE behind the incipient Banda volcanic arc (Honthaas *et al.* 1998; Hinschberger *et al.* 2001), predicting that the South Banda Basin is the youngest feature. However, the magnetic surveys cover only a small area, and although the proposed magnetic section used by Hinschberger *et al.* (2001) fits the Late Miocene to Pliocene section well, it does not show how many other parts of the time scale the section may also fit. Another problem is that the area around the Banda ridges (Fig. 3) is hot, bathymetrically high and associated with east–west-trending transform structures (Silver *et al.* 1985), whereas the South Banda Basin is deep, cold and buried by 1–2 km of Pliocene–Quaternary sediment. These data suggest a difference in both age and tectonic evolution between the North and South Banda Basins.

Geochronological studies of the North Banda Basin (Fig. 3) suggest that it opened first at around 9.4–7.3 Ma, and separated the Banda Ridges from the SE part of Sulawesi (Honthaas *et al.* 1998). Dredge samples from horst blocks within the basin and along its margins are basalts and trachyandesites with negative Nb and Ta anomalies in the range of back-arc basin basalt (BABB) (Honthaas *et al.* 1998).

The South Banda Basin opened within the stretched continental borderlands of the southern Sunda Shelf, and is transitional with the Bali and Flores Basins. The NEC–Lucipara Ridges form the northern boundary of the South Banda Basin and the Wetar Ridge forms the southern boundary. Geochronology and magnetic anomaly studies are interpreted to indicate a spreading event at around 6–3 Ma (Honthaas *et al.* 1998; Hinschberger *et al.* 2001). Spreading rates of 3 cm a^{-1} are estimated along what are interpreted as several arc-parallel ridge segments (Hinschberger *et al.* 2001). Although no samples have been dredged from the floor of this basin, geochemical and geochronological analysis of samples dredged from the Wetar and NEC–Lucipara Ridges have strong affinities, suggesting that each of these ridges represents fragments of a single magmatic arc that was split by the opening of the South Banda Basin (Honthaas *et al.* 1998). Calc-alkaline andesites with high ratios of large ion lithophile elements to high field strength elements (LILE/HFSE), negative Nb anomalies, and some cordierite, are a dominant feature of both ridges. OIB-type transitional volcanic rocks are also found, as in the North Fiji back-arc basin (Honthaas *et al.* 1998). The southern portion of the South Banda Basin has been overthrust by the Wetar Ridge along the Wetar Thrust, which now takes up some of the convergence between the Australia and Asia plates (Silver *et al.* 1983; Harris 1991; Genrich *et al.* 1996). Loading associated with the Wetar Thrust may explain the anomalous depth vs. young age of the South Banda Basin.

Fragments of the Wetar Ridge and southern Banda Sea, known as the Banda Terrane (Harris 1992), also occur as nappes thrust over partially subducted Australian continental margin units on Timor (Harris 1991). The nappes probably represent Sunda forearc basement that was detached from the forearc and uplifted during Late Miocene to Pliocene subcretion of Australian continental margin units to the edge of the Asian plate. The Banda Terrane consists mostly of a mix of pelitic and mafic metamorphic rocks overlain by remnants of a Cretaceous–Early Tertiary volcanic arc, and Oligocene–Miocene massive limestone. Radiometric age analysis of the metamorphic rocks yield a Permian Rb/Sr whole-rock age and a consistent 32–35 Ma $^{40}Ar/^{39}Ar$ cooling age from hornblende and biotite (Harris *et al.* 1998). These data indicate that the continental fragments may be parts of the easternmost Sunda craton that were separated from the craton during earlier phases of back-arc extension (Brown & Earle 1983), such as the extensional event that formed the Bali and Flores Basins along the eastern edge of the Sunda Shelf (Prasetyo 1989, 1994).

Ocussi ophiolite of Timor

The northernmost part of the Banda Terrane nappe in Timor consists of a thick succession of basaltic andesite pillow lavas and sheet flows known as the Ocussi Volcanics. These steeply dipping volcanic units have $^{40}Ar/^{39}Ar$ ages (3–5 Ma) and SSZ geochemical characteristics similar to dredge samples from other parts of the southern Banda Sea Basin (Harris 1992). Ultramafic blocks in mélange at the base of the Ocussi nappe are geochemically depleted with an estimated 20–25% partial melting. These blocks are the only ultramafic rocks throughout the Banda arc with any SSZ characteristics (Harris & Long 2000). Based on these relations, the Ocussi Volcanics are interpreted as the emergent tip of part of the SSZ ocean basin that formed within the eastern Sunda arc, like the southern Banda Basin. The southern edge of this intra-arc basin has been emplaced onto the edge of the Australian continental margin by arc–continent collision (Harris & Long 2000). In other words, the same geochemical and age relations found from dredge samples from the South Banda Sea Basin are also found in nappes of the Timor collision zone, where the Australian continent has underthrust, uplifted and exposed the edge of the Asian upper plate.

Several lines of evidence indicate that the most recent phase of extension of the Banda Basins was synchronous with the arrival of the Australian continental margin at the Java Trench and the onset of arc–continent collision. For example, the first part of the Australian continental margin to accrete to the edge of the southern Banda Basin, the Aileu–Maubisse Complex, yields $^{40}Ar/^{39}Ar$ metamorphic cooling ages from hornblende of 5–8 Ma and from biotite of 3–5 Ma (Berry & McDougall 1986). These ages indicate that the distal part of the Australian continental margin had already accreted to the edge of the Asian plate and cooled from 600 °C to 350 °C around the same time as the Banda Basins were opening (3–8 Ma) and forming new oceanic lithosphere. The synorogenic sedimentary record of Timor also dates the initial emergence and erosion of the Banda arc–continent collision at around this time (Audley-Charles 1986; Fortuin & de Smet 1991).

Lherzolite bodies of the Banda arc

Lherzolite bodies and some gabbro are commonly found along the suture of the Australian and Asian plates throughout the Banda arc–continent collision. In Timor these bodies were initially interpreted as parts of young mantle sequence of the Banda Sea Basin (Hamilton 1979; Brown & Earle 1983; Helmers *et al.* 1989; Sopaheluwakan *et al.* 1989; Linthout & Helmers 1994). However, detailed mapping and geochemical analyses indicate continental margin and pre-oceanic rift associations (Berry 1981; Harris 1992; Harris & Long 2000). The most chemically similar rocks to the Timor lherzolite bodies are Red Sea-type peridotites (Bonatti *et al.* 1986) and lherzolite dredged from the Australian (Nicholls *et al.* 1981) and Iberian (Boillot *et al.* 1980) distal passive continental margins. Based on these discoveries and comparisons, the lherzolite bodies of Timor were reinterpreted as fragments of subcontinental mantle exposed by extensional denudation before being incorporated into a collision zone (Harris 1992; Harris & Long 2000). The distal part of the Australian continental margin, where similar lherzolite bodies have been dredged, was the first to enter the subduction zone and be accreted as thrust units. As the arc–continent collision progressed, these thrust sheets were elevated by understacking of continental margin units more proximal to the shelf (Harris *et al.* 2000).

The lherzolite bodies of the external Ligurides, part of the original 'Steinmann trinity' (Steinmann 1906), have been reinterpreted in a similar manner (Rampone & Piccardo 2000). These studies imply that many of the lherzolite-type peridotite bodies found throughout the Tethys and other suture zones may be thrust-stacked fragments of the continental lower plate exhumed by extensional events associated with passive margin development.

Lherzolite bodies of the northern Banda arc island of Seram have similar tectonic associations and geochemistry affinities to those of Timor, but were interpreted by Linthout & Helmers (1994) as the mantle component of a young ophiolite formed by transtension. One of the major problems with interpreting these and other lherzolite bodies as fragments of ophiolites is the notable lack of the crustal component of the ophiolite sequence. The only volcanic units throughout the Banda arc that are geochemically compatible with the lherzolite are Permian–Jurassic age intraplate-type pillow lavas of Australian affinity (Berry & Jenner 1982), which supports a continental margin origin for the lherzolite.

Geodynamics of the Banda arc region and ophiolite emplacement

Initiation of collision in the Banda arc is marked by progressive uplift and emergence of the forearc ridge and eventually the accretion of the eastern Sunda arc to the Australian plate via partitioning of strain away from the trench and incipient subduction polarity reversal (Fig. 4). GPS measurements (Genrich *et al.* 1996) show that at decadal time scales the accreted materials of the collision behave as a number of independently moving blocks with poorly defined boundaries. A similar pattern is also revealed at time scales of 10^3–10^5 years by studies of uplifted coral terraces throughout the region (Merritts *et al.* 1998). These studies help quantify for the first time the processes of plate boundary reorganization that lead to the formation and obduction of ophiolites.

The progressive accretion of the Banda arc–trench system to the edge of Australia is uniquely displayed by the obliquity of arc–continent collision (Fig. 3). The arrival of the Australian rise and slope at the Java trench initiates a phase of rapid accretion and uplift of the forearc upper plate. The thin leading edge of the forearc basement becomes a roof thrust that is folded and detached from its roots by backthrusting and understacking of continental margin units (Harris 1991). In Timor these nappes mostly consist of a heterogeneous mixture of continental and oceanic material (see discussion of Banda Terrane above). However, along orogenic strike to the east the Weber forearc basin, which is at an earlier stage of tectonic emplacement onto the Australian continental margin, is mostly oceanic and represents a future ophiolitic terrane as large as any known.

The arrival of the Australian continental shelf at the trench causes indentation of the deformation front and partitioning of strain to hinterland back thrusts at the rear of the orogenic wedge (Prasetyadi & Harris 1996). This arcward-verging part of the orogenic wedge is progressively thrust over much of the forearc basin until the entire

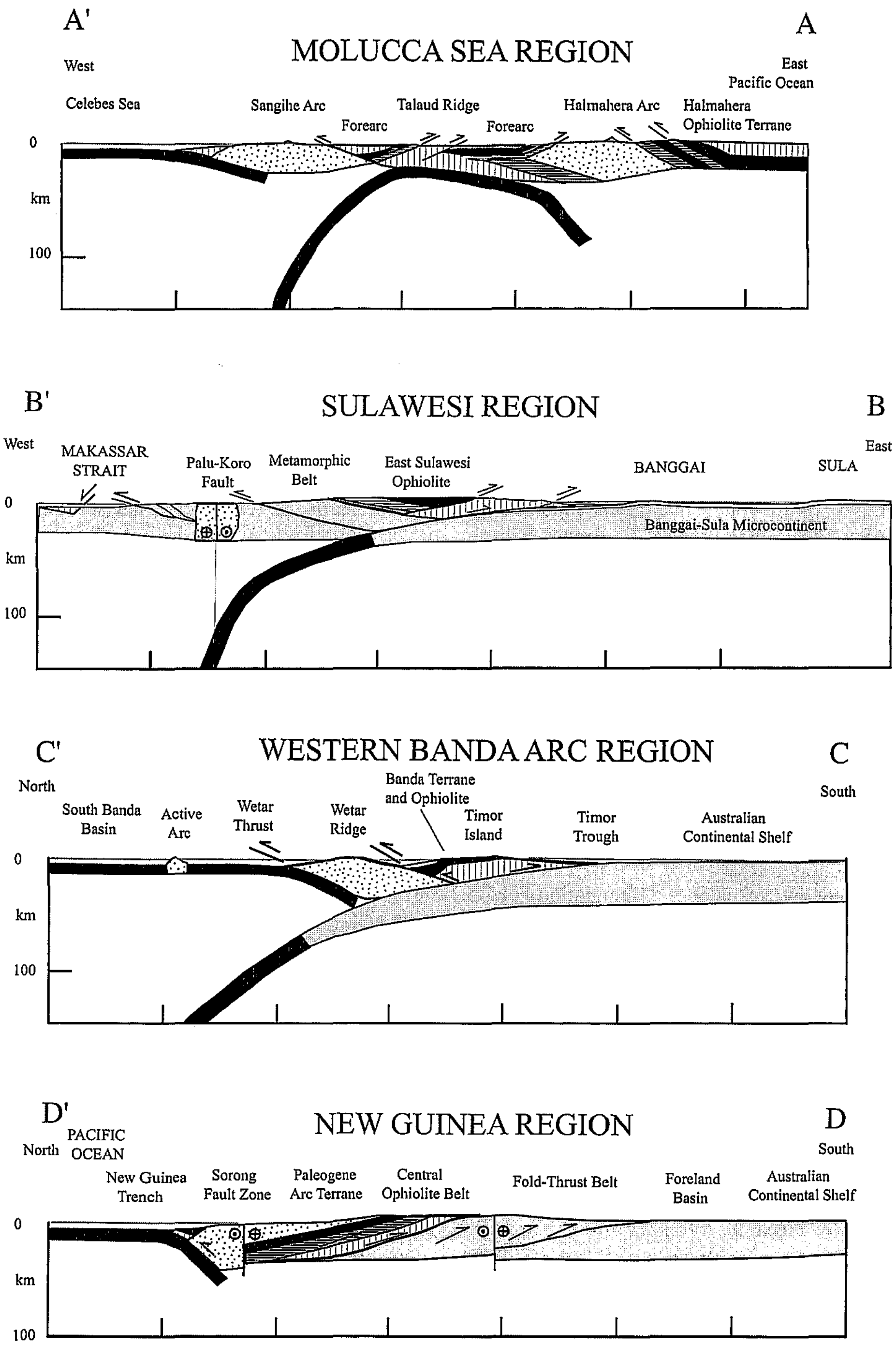


Fig. 4. Crustal cross-sections of different collisional settings for ophiolite emplacement in the eastern Indonesian region. Black – Oceanic crust and ophiolites, horizontal stripes – mantle lithosphere, stipples – island arc terranes, vertical lines – mélange and sedimentary units, grey – continental crust. See Figure 3 for section locations. Horizontal scale = vertical scale.

volcanic arc itself is accreted to the lower plate. GPS measurements (Genrich *et al.* 1996), seismicity (Abbott & Chamaluan 1981; McCaffrey & Nabelek 1984), and coral terrace studies (Merritts *et al.* 1998) indicate that at this stage of collision, much of the plate convergence is taken up along a back-arc thrust system (Wetar Thrust). The Wetar Thrust may develop into a new subduction zone with opposing dip. The eastern Sunda arc is inactive in this region and has accreted to the edge of Australia. A similar scenario of arc–continent collision occurs to the east in New Guinea, where the Australian continent collides with Pacific microplates converging from the east.

Convergence with the Philippine Sea and Pacific plates

Ophiolites throughout the eastern Indonesian and New Guinea region are mostly interpreted as fragments of the southwestern Philippine Sea and Pacific plates that were emplaced onto continental and arc terranes of Asian and Australian affinity. Most of the ophiolites are Mesozoic in age and formed the basement of a Late Cretaceous to Paleogene volcanic arc. Neogene collision of the irregular-shaped Asian and Australian continental margins with these oceanic plates initiated a phase of ophiolite emplacement and plate boundary reorganization that stretches from Taiwan and the Philippines to the Moluccas and New Guinea. The Molucca arc–arc collision and the New Guinea arc–continent collision are two examples discussed here.

New Guinea ophiolites

The New Guinea region represents the northernmost promontory of the Australian continent that initiated a series of arc–continent collisions with the southern boundary of the Pacific plate (Dewey & Bird 1970; Jaques & Robinson 1977; Hamilton 1979). This plate boundary was modified through the course of changes in plate motion into a series of microplates, including the present Caroline, Bismarck and Solomon plates (Figs. 2 and 5). The insertion of the Australian continental margin into this fragmentary plate boundary zone has resulted in the formation and emplacement of some of the largest ophiolites known.

The ophiolite-bearing collisional mountains of New Guinea are an older continuation of the active Banda arc–continent collision to the west (Harris 1991). The collision-related phase of plate boundary reorganization and partial subduction polarity reversal currently initiating in the Banda arc region occurred in the NW New Guinea region during the Latest Miocene (Pigram & Davies 1987). The propagation of collision along the northern margin of Australia provides a unique way to simultaneously observe various stages of ophiolite emplacement and mountain system development along orogenic strike.

Collision in the New Guinea region began in the Early Oligocene, when the northern passive margin of Australia was pulled into a north-dipping subduction zone at the edge of the Pacific–Philippine Sea–Caroline plate (PPSCP). Paleogene intra-oceanic arc terranes mounted on the edge of the PPSCP have since accreted to the margin of Australia via a combination of partial subduction polarity reversal and transvergence (Pigram & Davies 1987). The edge of the PPSCP had experienced a phase of Jurassic SSZ spreading prior to the construction of the Paleogene arc. Arc–continent collision ceased in western New Guinea around 3–5 Ma, but is still active in eastern New Guinea, where collision of the New Britain arc with the Australian continental margin gives rise to the Huon Peninsula (Silver *et al.* 1991). The Huon Peninsula is the onshore extension of the New Britain arc accretionary wedge where continental margin material is stacked beneath and uplifts pieces of the south New Britain plate. This is happening at the same time as a new SSZ ocean basin, the Bismarck Basin, is forming in another part of this plate.

The present tectonic scenario of the New Guinea region is much like the one that existed earlier when the south-facing Paleogene arc terrane, mounted on the edge of the PPSCP, accreted to New Guinea. This arc terrane is bounded to the north and south by ophiolites. To the south, the Central and Papuan ophiolite belts are sandwiched between the arc terrane and fold and thrust continental margin units of Australia. These ophiolites are mostly Jurassic in age and restore to a forearc position of the Paleogene arc terrane. North of the arc terrane is the Cyclops ophiolite belt, which is Tertiary in age and probably represents pieces of a younger interarc basin lithosphere that formed in a similar manner to the present Bismarck Basin and was emplaced around 20 Ma (Monnier *et al.* 1999).

Central (Irian) ophiolite belt

The Central ophiolite belt is exposed for 500 km along the north slope of the Central Range of western New Guinea (Dow *et al.* 1986). It has a minimum age of Late Cretaceous and occupies a suture zone between shortened Australian continental margin units to the south that have stacked-up against accreted arc terranes of the PPSCP to the north (Dow & Sukamto 1984). The ophiolite

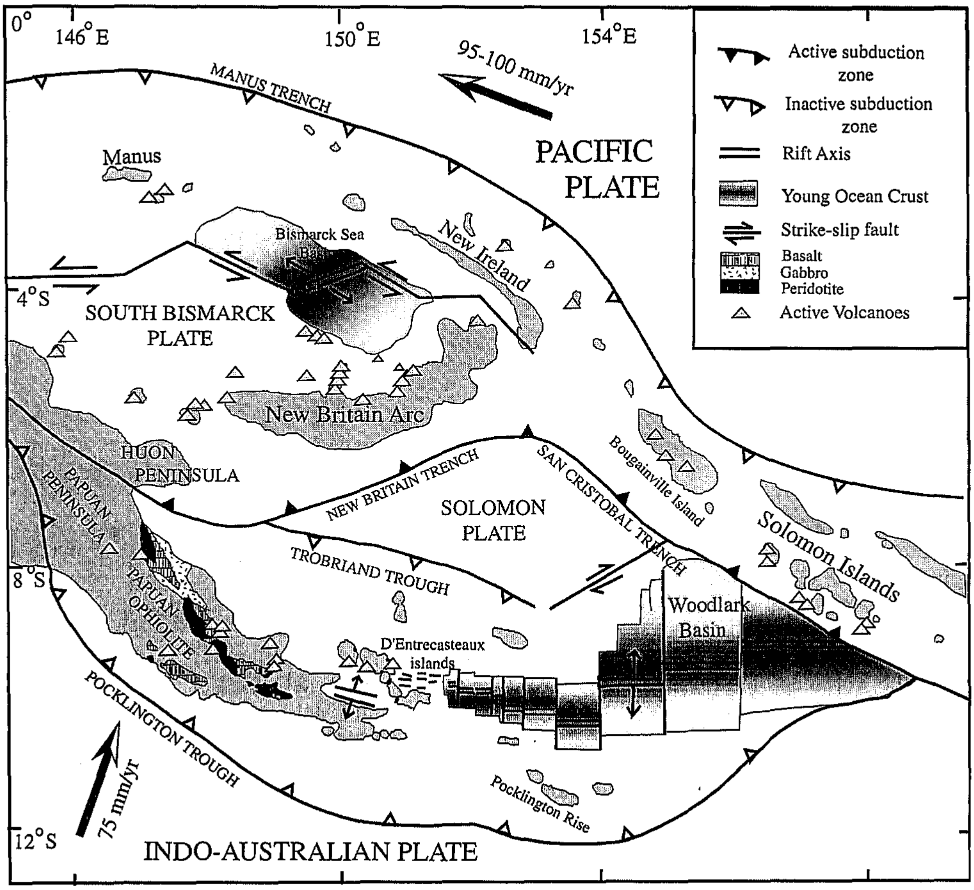


Fig. 5. Tectonic map of ophiolites and young marginal basins east of New Guinea. SSZ oceanic lithosphere of the Bismarck Sea plate is simultaneously opening and accreting to the edge of Australia. The Woodlark Basin has split a Tertiary arc and is currently propagating westward into continental crust. Previous episodes of subduction continue to influence the geochemistry of these new ocean basins. Details of the Papuan ophiolite are taken from Davies and Jacques (1984). The internal structure of the Woodlark Basin is modified from Johnson *et al.* (1987).

is structurally underlain by metabasites (amphibolite and blueschist facies) that yield Late Cretaceous and Eocene metamorphic cooling ages (Warren 1995; Weiland & Cloos 1996). These are structurally underlain by the inverted Ruffaer metamorphic complex, which formed along parts of the Australian continental margin that were stacked beneath the ophiolite as it collided with the distal Australian passive margin around 18 Ma (Warren 1995; Weiland & Cloos 1996).

Reconnaissance studies of the composition and internal structure of the Central ophiolite belt indicate mostly a complete ophiolite sequence from residual mantle peridotite to basalt (Monnier *et al.* 2000). The mantle sequence is mostly harzburgite and dunite with rare lherzolite, all with high-temperature porphyroclastic textures. Chrome spinel numbers (50–60) and REE patterns of the residual peridotite indicate a high degree of partial melting (20–25%). Layered gabbros have adcumulate textures with abundant primary amphibole and labradorite typical of crystallization from aluminous, calc-alkaline magmas. Most volcanic units feature trace and REE abundances intermediate between N-MORB and calc-alkaline series, with Nb and Ta depletion indicative of subduction zone environments (Monnier *et al.* 2000).

Papuan ophiolite belt

Three major ophiolite complexes make up the Papuan ophiolite belt of eastern New Guinea. From west to east these are the April ultramafics, Marum ophiolite, and Papuan ophiolite (Fig. 1). The Papuan ophiolite is the largest and most complete of the group (Davies & Smith 1971). It is exposed as thick thrust sheets rooted in the Solomon Sea oceanic basin and crops out for 400 km along the northern slope of the Owen Stanley Range (Fig. 5). The Marum ophiolite is less complete and consists of two very different thrust sheets (Jacques 1981). The larger upper sheet preserves a sequence of cumulus ultramafic and mafic plutonic units up to 3–4 km thick that are underlain by harzburgite. The thinner lower thrust sheet consists mostly of highly faulted basaltic units that are geochemically unrelated to the structurally overlying sheet. The April ultramafic complex further to the west comprises dismembered thrust sheets that have a maximum thickness of 2–3 km of predominantly highly strained lherzolite with minor layered gabbro (Davies & Jaques 1984). The three complexes each occupy a similar structural position in the New Guinea mountain system but represent different tectonomagmatic settings.

Differences in the tectonomagmatic origin of the three complexes are manifest in contrasting mantle sequence compositions. The Papuan Ophiolite preserves a 4–8 km thick section of residual peridotite (Davies & Jaques 1984) that consists almost entirely of highly refractory harzburgite. The Marum body has a less refractory mantle sequence (Jacques 1981), and the April ultramafics show evidence of only small amounts of partial melting (Davies & Jaques 1984). Differences in composition between the Papuan and Marum ophiolite are minor, and may be attributed to forearc heterogeneity. However, these bodies show little or no affinity to the April complex or the lower thrust sheet of the Marum ophiolite. Similar contrasts are also found in the Banda forearc nappe emplaced over the Australian continental margin in Timor (Harris 1992).

The lherzolitic April complex and the thrust sheet of transitional MORB beneath the Marum ophiolite also have equivalents in the Banda arc–continent collision. Harris & Long (2000) showed that the lowest lherzolite and basaltic (transitional-MORB) thrust sheets in the Timor region are slivers of the distal continental margin of Australia that were accreted to the base of the Banda forearc nappe. Davies & Jaques (1984) interpreted the lower thrust sheet of the Marum ophiolite, and the Emo metabasite beneath the Papuan ophiolite, in a similar way. Tectonic slivers of spilitic basalt are also found at the base of the Central ophiolite belt (Warren 1995). In each of these settings the subduction of the leading edge of the Australian continental margin has stacked forearc basement of a varying refractory nature over non-refractory transitional lithosphere of the lower plate. Examples of this stacking order abound in Tethyan-type ophiolites throughout the world, such as the Haybi volcanics beneath the Oman ophiolite (Lippard *et al.* 1984).

Tectonic emplacement of New Guinea ophiolites

The timing and conditions of ophiolite emplacement in New Guinea are recorded in metamorphic rocks beneath the Central and Papuan ophiolite belts and in the timing of foreland basin development astride the fold belt. Metamorphic rocks of the Emo sheet grade upward from lower greenschist-facies units into amphibolites and granulites toward the base of the Papuan ophiolite thrust sheet (Lus *et al.* 2001). Hornblende $^{40}Ar/^{39}Ar$ ages of the Emo metamorphic rocks yield cooling ages of 60–58 Ma, which are near the same age as boninite of the Papuan ophiolite (Lus *et al.* 2001). Ages of metabasites beneath the Central ophiolite cluster at 68 Ma and 44 Ma (Weiland 1999). These ages are interpreted as a two-stage initiation of northward subduction of the Australian plate beneath the PPSCP plate (Weiland 1999). Jurassic parts of the ophiolite must represent an earlier incipient subduction event.

Ages of metamorphic cooling (Weiland 1999) and incipient foreland basin development (Pigram & Symonds 1991) reveal that the distal New Guinea passive margin began to enter the subduction zone at the southern edge of the PPSCP around 25 Ma. However, the transition from carbonate shelf to siliciclastic synorogenic sedimentation did not reach western New Guinea until around 12 Ma (Quarles van Ufford 1996). Arc–continent collision ceased in western New Guinea at around 3 Ma as a result of continuing plate boundary reorganization involving partial subduction polarity reversal (Hamilton 1979; Cooper & Taylor 1987), delamination (Housh *et al.* 1994), and the development of left-lateral strike-slip fault systems (Sapiie *et al.* 1999).

Cyclops ophiolite

Ophiolites found along the north coast of New Guinea, north of the Paleogene arc terrane, are referred to here as the Cyclops ophiolite belt. These bodies include an assortment of ophiolitic fragments interpreted as remnants of the Central ophiolite to the south (Dow *et al.* 1988). A complete ophiolite sequence is preserved near Jayapura, which includes a 10 km thick ultramafic unit and a 5 km thick crustal unit. The ultramafic unit consists of moderately refractory harzburgite with patches of dunite. High spinel Cr number

(58–63 for harzburgite and 72–90 for dunite) and low bulk and mineral abundances of Al_2O_3 (0.2–0.4%) indicate 25–35% partial melting under hydrous conditions (Monnier *et al.* 1999). Zr and Hf enrichment may also indicate the crystallization of hydrated phases, which is common in SSZ ophiolites.

Crustal rocks include layered and isotropic gabbro, massive and sheeted diabase, massive and pillow lavas, and a sedimentary cover of chert and marl overlain by boninites (Monnier *et al.* 1999). REE patterns of most basaltic rocks show high La/Nb ratios of 2–3 (Monnier *et al.* 1999), which are typical of BABB. The occurrence of Enriched-MORB-like basalt may indicate a trapped fragment of Australian or Pacific oceanic crust in the arc complex.

Variations in composition and age may indicate that the Cyclops ophiolite is a composite of several parts of an arc complex, which may also include slivers of the lower plate. Whole-rock K/Ar analyses yield a bimodal age distribution of 43 Ma for boninites to 29 Ma for BABB (Monnier *et al.* 1999). The metamorphic sole (MacAuthor complex) beneath the Cyclops ophiolite consists of an arc terrane with an inferred metamorphic age of 20 Ma (Pieters *et al.* 1979).

Microplates of the New Guinea region

The combination of changes in plate motion, increased coupling as a result of collision (Kroenke 1996) and a high obliquity of convergence (Sapiie *et al.* 1999) have caused fragmentation of, and renewed spreading within the western edge of the Pacific plate to form the Caroline, Solomon and Bismarck plates. The array of island arcs, and small, young ocean basins in this region has evolved through successive periods of convergence along different subduction zones into a megashear zone between the large Pacific and Australian plates. Left-lateral oblique convergence results in rapid changes in the function and position of plate boundaries. Repeated collisions of these boundaries with buoyant oceanic crust (e.g. Ontong–Java plateau) brought in from the east by the Pacific plate and continental fragments pushing in from the NE margin of Australia have resulted in the emplacement of ophiolites from New Guinea to New Zealand, subduction reactivation and polarity reversals, and terrane accretion (Silver *et al.* 1991; Kroenke 1996). The arc terranes and continental fragments embedded in the easternmost abyssal part of the Indo-Australian plate will make it difficult to subduct without great difficulty.

Differential rigid-body rotation of microplates in the New Guinea megashear simultaneously open and close young ocean basins such as the Ayu Trough (Fig. 2), and Bismarck and Woodlark Basins (Fig. 5). The Bismarck Basin opens behind the New Britain arc as it actively collides with and accretes to the northern margin of New Guinea. The Ayu Trough and Woodlark Basin open along microplate boundaries that are being subducted.

Investigations of the geochemistry of Woodlark Basin volcanic rocks (Binns & Whitford 1987; Johnson *et al.* 1987; Perfit *et al.* 1987) reveal that portions of the basin are underlain by normal, depleted oceanic mantle, yet the majority of the dredge samples, including some from the ridge itself, are arc-like rocks that vary from BABB to boninites. Near where the ridge is being subducted, spatial variations show a pattern of increasing arc-type character toward the San Cristobal Trench (Fig. 5), which may indicate active mixing of N-MORB with arc components. Arc-like rocks were also dredged from seamounts within 30 km of the trench, on both the upper and lower plates. Other geochemical anomalies require recent conditioning of the mantle by previous subduction (Perfit *et al.* 1987). In summary, the Woodlark Basin, like much of the New Guinea region as a whole, demonstrates that igneous geochemical zoning is very difficult to explain by the present configurations of plate boundaries.

Molucca Sea region

The Asian, Australian and Philippine Sea plates converge in the Molucca Sea region, where they are connected by an array of ephemeral subduction zones linked by strike-slip faults and localized rifts (Fig. 3). The major connecting boundary is the left-lateral Sorong Fault system. This fault slices the northern margin of Australia into a series of continental slivers that move west with the Philippine Sea plate until they collide with and are accreted to the Asian margin in the Sulawesi region. One of the most dramatic examples of this process is the collisional underthrusting of the Banggai–Sula Platform beneath the Eastern Sulawesi ophiolite (Figs 3 and 4).

A similar scenario to the Sulawesi collision, but at an earlier stage of development, exists to the north, where amalgamated arc, ophiolite and continental terranes of the Halmahera region are moving westward with the Philippine Sea plate towards the Sangihe arc (Fig. 3). The intervening Molucca Sea slab has at least partly fragmented as the colliding arcs impinged upon it (Fig. 4). Incipient collision of the opposing arcs is manifest by recent rapid emergence of the Talaud Ridge as it is thrust eastward over the Halmahera arc and thrust westward over the Sangihe arc (Silver &

Moore 1978) and accretionary wedge (Moore *et al.* 1981). Seismic refraction profiles indicate that this doubly vergent collision complex that forms the Molucca Ridge is at least 60 km thick (Bader *et al.* 1999). The positive buoyancy of this feature probably influences the development of new subduction zones with reversed motion, such as the Cotobato Trench to the west and the southward-propagating Philippine Trench to the east (Fig. 2).

Closure of the Molucca Sea is creating a suture zone that juxtaposes ophiolites from two sources while tectonically obscuring the associated volcanic arcs. Ophiolites of eastern Halmahera and the nearby islands of Gebe, Waigeo, Obi, and Tapas probably have a Late Jurassic Pacific plate origin like the ophiolites of the eastern Philippines to the north (Hall *et al.* 1991) and New Guinea to the south. On the other hand, ophiolites emplaced onto the Asian margin, from Sulawesi through the Molucca Sea and into the western Philippines, are Eocene and Oligocene in age and have affinities with marginal basins that opened within the Asian continental margin (Silver & Rangin 1989). Most of the ophiolites from both tectonic settings record a polyphase history of incorporation into the forearc of a newly forming subduction zone, remelting of peridotite already depleted by extraction of MORB, collision with continental or arc terranes, and reshuffling by strike-slip faulting.

Halmahera ophiolite

Halmahera forms the eastern part of the Molucca Sea arc–arc collision complex. The western part of the k-shaped island consists of an active intra-oceanic island arc, whereas the eastern arms consist mostly of dismembered oceanic lithosphere (Hamilton 1979). Each unit of a complete ophiolite sequence is present (Hall *et al.* 1988). Although the sequence is structurally disrupted, its geochemistry is arguably cogenetic, with the exception of some units interpreted as seamounts and later magmatic pulses (Ballantyne & Hall 1990). The highly refractory nature of residual harzburgite, cumulate ultramafic and mafic sequences, and many of the volcanic units (including boninites) found throughout Halmahera require that the ophiolite had a shallow, subduction-related tectonomagmatic origin (Ballantyne & Hall 1990). Similar compositions and geological associations to those found in Halmahera are reported from forearc dredge samples of the nearby Mariana–Bonin arc system (Bloomer 1983). These similarities define Halmahera as an uplifted segment of the western edge of the Philippine Sea plate that formed during the Mesozoic in much the same way as the Mariana–Bonin arc system formed along the eastern edge of the Philippine Sea plate during the Tertiary.

Talaud ophiolite

The Talaud Islands are the emergent expression of the Talaud Ridge that rises in the middle of the Molucca Sea arc–arc collision zone (Fig. 4). These islands expose an east-dipping ophiolite sequence (Silver & Moore 1978) interpreted as splintered vestiges of the Molucca Sea slab (Fig. 4) that were pushed beneath the colliding Sangihe and Halmahera arcs (Sukamto 1979; Cardwell *et al.* 1980; McCaffrey *et al.* 1985; Moore *et al.* 1980; Bader *et al.* 1999).

Ultramafic and mafic rocks exposed on islands of the Talaud Ridge represent a disrupted cogenetic ophiolite suite (Moore *et al.* 1980) that is geochemically indistinguishable from MORB or BABB (Evans *et al.* 1983). Whole-rock and mineral analyses of lherzolite and less abundant harzburgite indicate slightly smaller amounts of partial melting than average values for the Oman mantle sequence (Lippard *et al.* 1984). Cumulates and basalt also plot in MORB fields of the discriminate diagrams of Pearce *et al.* (1984) and Beard (1986). Chert and red limestone yield radiolaria of mid-Eocene age, which is considered as the minimum age of the ophiolite. This is also the age of the nearby Celebes Sea marginal basin. Miocene arc-related volcanic rocks and volcaniclastic sedimentary rocks are also found, but are of uncertain origin.

Most interpretations of the origin of the Talaud ophiolite bodies agree that they are slivers of the Molucca slab, which is probably part of the Celebes Sea marginal basin. However, interpretations differ on the size of the slivers and their geometry at depth. Based on data from structural field mapping, Moore *et al.* (1980, 1981) showed the Talaud ophiolite as a rootless, east-dipping thrust sheet embedded in mélange that was accreted to the eastern edge of the Snellius arc. Geophysical studies indicate that the Talaud ophiolite is a west-dipping sliver that connects at depth with the Molucca slab and Sangihe arc, respectively (McCaffrey 1991; Bader *et al.* 1999).

East Sulawesi ophiolite

The East Sulawesi ophiolite is one of the largest and most complete, yet poorly known ophiolite bodies of the Indonesian and New Guinea region. It is exposed over more than 10 000 km^2 throughout the eastern and SE arms of the k-shaped island of Sulawesi (Fig. 3). The eastern arm exposes a complete ophiolitic sequence underlain by a metamorphic sole, mélange, imbricate continental margin material and crystalline basement with a blueschist metamorphic overprint (Parkinson 1998). This sequence mostly faces east (Fig. 4), with sheeted dyke complexes consistently trending NNW–SSE (Silver *et al.* 1983). The structural thickness of the ophiolite varies, but may exceed 15 km in places (Silver *et al.* 1983).

The continental rocks upon which the Sulawesi ophiolite was emplaced were sliced from the northern Australian margin, translated westward and accreted to the eastern edge of the Asian plate (Silver *et al.* 1978; Hamilton 1979). The most recent manifestation of this process is the accretion of the Sula platform (Fig. 3), which has structurally dismembered the ophiolite into a series of eastward–verging imbricate thrust sheets.

The age, internal structure and tectonomagmatic origin of the Sulawesi ophiolite remain poorly constrained by reconnaissance-style studies of limited parts of the body (Kundig 1956; Silver *et al.* 1978, 1983; Simandjuntak 1992; Mubroto *et al.* 1994; Monnier *et al.* 1995; Parkinson 1998). Seventeen K–Ar ages range from 93 ± 2 to 32 ± 2 Ma, with most ages clustering between 60 and 40 Ma.

Sparse geochemical studies of the ophiolite show a broad range of compositions (Monnier *et al.* 1995). For example, only three whole-rock analyses from two locations that are more than 100 km apart are reported for the entire mantle sequence. The two locations vary in Al_2O_3 and CaO abundances by an order of magnitude (0.2–2.0 wt%). Mineral analyses from these samples have Cr numbers for spinel that vary from 18 to 84. These results may indicate that the mantle sequence consists of both fertile and depleted sections or that the ophiolite is a composite of different bodies. A composite origin is also consistent with the size, structural imbrication and broad apparent age range of the ophiolite.

Volcanic rocks mostly from the NE arm of the Sulawesi ophiolite yield MORB-type REE and trace element patterns with the exception of a slight negative Nb anomaly (Monnier *et al.* 1995). Similar compositions are reported from the nearby Celebes Sea marginal basin immediately north of Sulawesi (Serri *et al.* 1991), which is Eocene in age (Weissel 1980).

Several models exist for the origin of the Sulawesi ophiolite. One of the earliest considered it part of the Banda Sea that was thrust onto the edge of the Asian margin by collision with the westward-verging Sula block (Hamilton 1979). Reconnaissance geological mapping and marine geophysical investigations led Silver *et al.* (1983) to propose that the ophiolite is part of the Celebes Sea and Gorontalo Basin to the north. This model was also used by Monnier *et al.* (1995) to explain geochemical similarities between the Sulawesi ophiolite and oceanic terranes to the north. Another model, based on poorly constrained paleomagnetic data, claims that the ophiolite originated as part of the Indian Ocean, 17° south of the equator (Mubroto *et al.* 1994). From studies of the metamorphic sole, Parkinson (1998) concluded that the ophiolite originated in an Andaman Sea-type SSZ ocean basin that opened within the Philippine Sea plate during oblique subduction at the eastern edge of the Sunda arc.

The age of emplacement is loosely constrained by K–Ar analysis of hornblende from the metamorphic sole, which yields cooling ages of 33–26 ± 3 Ma (Parkinson 1998). Garnet peridotite fragments within strike-slip faults beneath the ophiolite yield Sm–Nd mineral ages of 27 Ma for peak metamorphism and 20 Ma cooling ages (Kadarusman 2001). These ages overlap the time when Australia arrived at the subduction zone along the southern edge of the Philippine Sea plate, which initiated the New Guinea collisional orogen and counter-clockwise rotation of the Philippine Sea plate (Hall 1996).

Origin of ophiolites in the Indonesian and New Guinea region

Most ophiolites of the Indonesian and New Guinea region are a composite of new SSZ ocean basins that formed within pre-existing continental or oceanic material. Several examples of composite forearc slabs are provided here. Each has a component of refractory material resulting from high degrees of partial melting during incipient subduction and subsequent trench rollback (e.g. Robinson *et al.* 1983; Pearce *et al.* 1984; Bloomer *et al.* 1995). However, plate kinematic explanations alone do not adequately explain the temporal and spatial clustering (Fig. 6) of ophiolite and marginal basin development in the Indonesian and New Guinea region (e.g. Taylor & Karner 1983; Tamaki & Honza 1991).

A strong correlation does exist in time and space between ophiolite genesis and collision (Edelman 1988) as suggested by the concept of pericollisional extension (Harris 1992; Royden 1993). The pericollisional extension model predicts that increased coupling along collisional promontories can pin a plate boundary at that point whereas adjacent parts of the lower plate are free to roll back and open small ocean basins adjacent to the collisional indenter (Vogt 1973; Miyashiro *et al.* 1982). Perhaps one of the best examples of this process is the deformation of the Izu–Bonin–Mariana trench by the Caroline Ridge (Fig. 1). Other examples in the Indonesian and

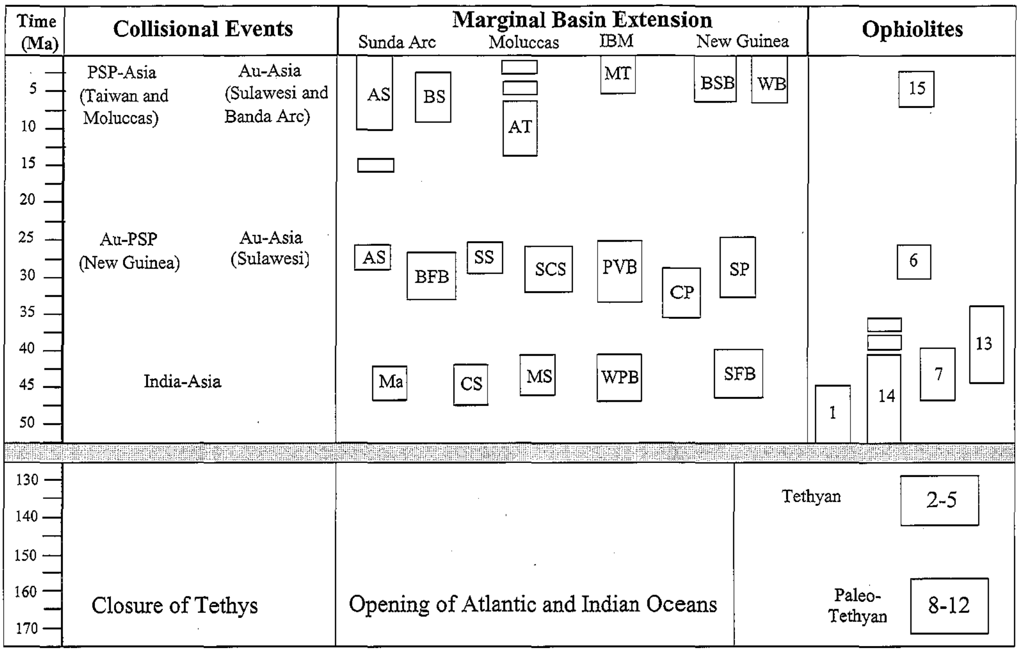


Fig. 6. Spatial and temporal correlation between marginal basin and ophiolite genesis, and collisional events. Many of the New Guinea ophiolites were emplaced during the gap in time (gray)

New Guinea region may be the Banda Sea and associated back-arc basins that formed at the edge of the Sunda Shelf (Fig. 2). There is strong evidence that two other factors associated with collision, increased obliquity of convergence (transvergence) and mantle extrusion (Flower *et al.* 2001), also play a significant role in the marginal basin and ophiolite development in the ING region.

Transtension

Strain partitioning associated with collisional indentation and oblique convergence strongly influences the spatial distribution of ophiolites throughout the Indonesian and New Guinea region (Figs 1 and 2). Clusters of ophiolites occur at highly oblique convergent margins where strain is partitioned away from the trench into the arc and back-arc regions, such as the Andaman and Bismarck Sea regions. These highly oblique configurations can arise from collisional modification of an existing arc–trench system, such as indentation of the Sunda arc by collision of India; or near triple junctions, such as the Sorong Fault system, which buffers changing motions between the Australian, Asian and Pacific plates. Ophiolites are also commonly found along the margins of the actively spreading ocean basins, which may indicate an earlier phase of transtension that was followed by basin inversion.

Mantle dynamics and marginal basin development

The influence of mantle flow on plate interactions may account for the episodic nature of temporal patterns of ophiolites in Indonesian and New Guinea. A global westward delay of lithosphere relative to the underlying mantle in the hotspot reference frame (Minster *et al.* 1974) is attributed to a westerly mantle flow associated with the Earth's rotation (Volpe *et al.* 1990; Doglioni 1993; Smith & Lewis 1999). The influence of this mantle flow on subduction zones may provide an explanation for the consistent asymmetry of orogens associated with steepening and rollback of west-directed slabs (Uyeda & Kanamori 1979; Doglioni *et al.* 1999). Extrusion of asthenosphere during various collisional episodes may also explain the spatial and temporal association of collisional events with rapid marginal basin development in the Indonesian and New Guinea region (Flower *et al.* 2001). According to this model, mantle is driven eastward by collisional constriction, such as the eastward extrusion of terranes toward the western Pacific by the collision of India. Although direct measurements of asthenospheric flow remain elusive, considerable circumstantial evidence supports the notion, such as the asymmetry of subduction zones and associated orogens (Doglioni *et al.* 1999), and DUPAL-like mantle contamination patterns (Flower *et al.* 2001).

The asymmetry of orogens in the Indonesian and New Guinea region is consistent with the global pattern of subduction zone asymmetry (Doglioni 1993). East-directed subduction zones generally have low slab dip angles; wide, doubly vergent thrust belts; and uplifted and highly deformed upper plates as a result of increased buoyancy and coupling induced by movement in the same direction as, and support of, asthenospheric mantle flow. In contrast, west-directed subduction zones generally have very steep dips, deep trenches, small and deep forearcs, and upper plate extension as a result of trench retreat with eastward-flowing asthenosphere. Plate kinematic explanations for this asymmetry, such as differing ages and velocities of subducting plates, do not account for observed differences in subduction zone behaviour in the Indonesian and New Guinea region or elsewhere.

One example is the asymmetry of the doubly subducted Molucca plate. Although there is no significant difference in plate age or velocity, the slab dips steeply to the west and at a lower angle eastward (Fig. 4). The small Sangihe arc–trench system forms above the steep, west-directed limb. The lower-angle, east-directed limb of the plate supports the Halmahera arc, which exposes the oceanic basement upon which the arc is mounted. Not only is the forearc basement exposed, but it is also deformed into a thrust belt that exposes the Halmahera ophiolite (Hamilton 1979). Yet this ophiolite, and the Mesozoic ophiolites to the north in the Philippines and to the south in New Guinea, are probably a product of SSZ spreading above a west-directed subduction zone, such as the present Mariana system (Ballantyne & Hall 1990).

The Banda arc may offer another example of mantle-flow induced subduction zone asymmetry. In this region the slab curves nearly 180°. Where it is west-directed, or influenced most by eastward asthenospheric flow, the slab dip angle is greatest, the forearc (Weber Basin) is more than 7 km deep and back-arc extension has formed the Banda Sea.

East-directed subduction systems in the Indonesian and New Guinea region include most of the Sunda, Halmahera and New Britain arcs. Although most of the features of these subduction systems are similar to those predicted, particularly the low angle of slab dip and high coupling, localized upper plate extension is observed in the Andaman Sea and Bismarck Basin regions (Fig. 1). However, both of these SSZ spreading systems occur where the convergence angle is highly oblique, resulting in transtensional strain partitioning into the arc and back-arc. There also may be an influence in these regions of local mantle extrusion from the Himalayan and New Guinea collisions, respectively. These exceptions illustrate that the complexity of subduction systems cannot be adequately explained by any one simple mechanism.

Three major pulses of mantle extrusion have been proposed by Flower *et al.* (2001) for the SE Asian region, each associated with major collision events. The first is connected with constriction of mantle by the Eocene collision of India, which may have contributed to eastward extension of the West Philippine Sea and Celebes Basins. This phase of extension is coeval with the genesis of ophiolites throughout the Molucca region, such as the East Sulawesi ophiolite. However, this was also a time when plate convergence was highly oblique in the Sulawesi region. The second phase of mantle extrusion is coincident in time with collision between the Australian continental margin and subduction zones along the southern edge of the Pacific and Philippine Sea plates. This phase of extrusion may have influenced the opening of the Japan, South China, Sulu and Makassar Seas, and the Parece Vela Basin of the Izu–Bonin–Mariana arc system. A third phase of extrusion associated with the opening of Okinawa and Mariana troughs, Andaman and Banda Seas, and microplate basins in the New Guinea region may be driven by local collisions in Taiwan, Sulawesi, the Banda arc and western New Guinea. Each of these phases of eastward asthenospheric extrusion is associated with episodic fusion of the Asian and Indo-Australian plates.

Changes in plate kinematics

Strong temporal correlations also exist between events of major plate motion change and the genesis of marginal basins and ophiolites. Most ophiolites of the Indonesian and New Guinea region show evidence of residence in a forearc position at the time of emplacement. However, in many cases these bodies originated as marginal and back-arc basins with no close spatial relation to arcs. An active example of this situation is the current collision of the New Britain forearc, which was formerly part of the West Melanesian back-arc that has been accreted onto the eastern edge of New Guinea to form the Finisterre terrane of the Huon Peninsula (Silver *et al.* 1991).

Frequent changes in motion of one or more of the major plates converging in the Indonesian and New Guinea region are buffered by frequent plate boundary reorganizations that may include phases of ophiolite genesis and emplacement. An example of this is the changes over the past 40 Ma in the complex plate boundary between the Indo-Australian, Pacific and Asian plates in the Sulawesi region (Hall 2002).

Major plate boundary reorganization events in Indonesia correspond to documented changes of global plate motion (Fig. 6). For example, bends in the Hawaiian–Emperor seamount chain document changes in the motion of the Pacific plate through 55° at 43.1 ± 1.4 Ma (Duncan & Clague 1985), 10° at 28–23 Ma (Epp 1984), and 10–20° at 4 Ma (Cox & Engebretson 1985). Motion of the Indo-Australian plate also changed at around 50 Ma from NW to NNE, which is a shift of around 73° relative to the Pacific plate (Weiland 1999). Up to 35° of clockwise rotation of the Philippine Sea plate was also initiated at around 25 Ma (Hall 1996). Each of these plate motion changes coincides with major collisional events throughout SE Asia, which include the collision of India with the western Sunda arc at around 50 Ma, the arrival of the northern Australian continental margin at the southern plate boundary of the Pacific and Philippine Sea plates at around 30 Ma, and the collisions of Taiwan, the Moluccas and the Banda arc at around 5 Ma (Fig. 6).

Temporal clustering of Mesozoic ophiolites of the Indonesian and New Guinea region with those in the Eastern Mediterranean and Cordillera indicate the global influence of plate motion changes on ophiolite genesis and emplacement. The clustering of Mid-Jurassic ophiolite ages throughout the world provides circumstantial evidence that there is a kinematic link between marginal basins on both sides of the Pacific and the Tethys. This global plate motion change event is probably associated with breakup of Pangaea and initiation of rapid sea-floor spreading in the central Atlantic. Many new west-directed subduction zones were initiated in the circum-Pacific as a result of these changes (Dickinson *et al.* 1996; Hall 2002). Another major phase of ophiolite genesis is recorded in the Tethyan and Indonesian and New Guinea regions during the Late Cretaceous (Fig. 6).

Emplacement ages of ophiolites rarely cluster, because of local variations in the timing of collisions of oceanic plate edges with continental and other buoyant lithosphere. The Mesozoic ophiolites of Borneo, New Guinea, Halmahera and the Philippines were all emplaced at different times depending upon when the continental margins and arcs they overrode arrived at the leading edges of the trenches they occupied. The present configuration of marginal basins throughout the Indonesian and New Guinea region separated by sinews of continental material presents a pre-emplacement view of what many ophiolite-bearing mountain systems may have looked like. The Halmahera ophiolite still has not been 'emplaced', but represents exposed forearc basement of an east-directed subduction zone similar to the occurrence of ophiolites in east-directed subduction systems of Cyprus and Macquarie Island.

Resolution of the 'ophiolite conundrum'

Several features of Tethyan ophiolites are considered a 'conundrum' because they have an arc-related petrochemistry, but a lack of 'western Pacific-like island arcs preserved' (Moores *et al.* 2000). Many of the ophiolites and marginal basins of the Indonesian and New Guinea region also lack this close association with island arcs, mostly as a result of the combined effects of strain partitioning away from the trench into the arc and back-arc regions, and rapid plate boundary reorganization. The Andaman Sea and Woodlark Basin provide examples that have been used as a model for the development of Tethyan ophiolites (Moores *et al.* 1984; Dilek & Moores 1990). Other examples of marginal basins with tenuous ties to any specific arc include the South China, Sulu and Celebes Seas. The Molucca Sea region demonstrates how arcs may be obscured during collision.

One model proposed by Moores *et al.* (2000) to resolve the 'ophiolite conundrum' is the 'historical contingency' of mantle sources for ophiolites; in other words, the history of the mantle is not reflected in the current plate configuration above it, such as a spreading ridge above mantle that was chemically altered by a previous subduction event. The Woodlark Basin of the New Guinea region provides an active example of this disparity between the geochemical zoning of the spreading ridge and current plate configurations (Binns & Whitford 1987; Johnson *et al.* 1987; Perfit *et al.* 1987; Dilek & Moores 1990). Magmatism in this actively spreading ocean basin demonstrates that old slabs can continue to contribute volatiles to the asthenospheric wedge long after subduction has ceased, and that the older the slab, the longer the volatile retention time (Abbot & Fisk 1986). Seismic tomography also shows how the entire Indonesian and New Guinea region is underlain by subducted slabs (Hafkenscheid *et al.* 2001), which may have contaminated most of the mantle source regions for oceanic crust production. The combination of strain partitioning above an oblique convergent margin and the possible effects of asthenospheric flow provide a way to open many small ocean basins, like those of the New

Guinea region, that are tapping metasomatized mantle from previous episodes of subduction.

Conclusions

(1) The ophiolites and marginal basins of the Indonesian and New Guinea region provide a glimpse of ophiolite-forming processes at various stages of development.

(2) Marginal basins form mostly in zones of highly oblique convergence where strain is partitioned away from the trench into a wide plate boundary zone consisting of several independently moving blocks.

(3) Periodic disruption of these wide plate boundary zones by global plate motion changes, collision and asthenospheric flow initiates rapid phases of near-simultaneous extension and shortening that can open and obduct new ocean basins in a relatively short time to form ophiolites.

(4) Most ophiolites in the Indonesian and New Guinea region are heterogeneous in age and composition, but have some component of SSZ petrochemistry.

(5) Some ultramafic bodies interpreted as ophiolites are probably thrust sheets of subcontinental mantle that was sheared off the lower plate during collision. Examples may include the ultramafic masses found throughout the Banda arc and in western New Guinea that are thrust up over the Australian shelf.

(6) Temporal patterns of ophiolite genesis in the ING region, and perhaps worldwide, correspond to collision-related global plate motion changes, and possible phases of resulting mantle extrusion.

(7) Eastward asthenospheric flow may explain the consistent asymmetry and behaviour of subduction zones throughout the Indonesian and New Guinea region.

(8) The strong spatial, temporal, geological and geochemical correlations between marginal basins and ophiolites in the Indonesian and New Guinea region resolve many of the problems associated with the 'ophiolite conundrum'.

(9) The Indonesian and New Guinea region demonstrates the diversity and complexity of tectonic scenarios that can result in exposure of oceanic lithosphere.

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