Peri-collisional extension and the formation of Oman-type ophiolites in the Banda arc and Brooks Range

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Abstract: Integration of data from field, geochemistry, and radiometric age investigations of the active Banda arc–Australia collision zone (Banda orogen) and the Jurassic Brooks Range ophiolite provide new constraints for the origin and emplacement of Oman-type ophiolites. These ophiolites are characterized by ultramafic residuals and mafic products that are chemically modified by various degrees of partial melting. The internal structure of the igneous complexes document acute extensional strains. A high temperature metamorphic sole with some continental margin protoliths are locally preserved at the structural base of the massifs. Age relations between the ophiolites, their metamorphic sole, and collisional mountains in which they reside indicate important temporal and spatial associations. Some of these relations are inconsistent with ophiolite genesis in intra-oceanic settings.

Formation of the Savu and Weber basins around the active Banda orogen provide modern analogues of peri-collision extensional processes. These extensional domains are transitional between zones of active supra-subduction zone magmatism (ophiolite genesis) and low-angle overthrusting (ophiolite emplacement). Geochemical data from the volcanic basement of the Savu basin are similar to 'transitional-type' ophiolite volcanic suites. Ar/Ar ages, and stratigraphic and structural data from the basin indicate volcanism and forearc extension coincide in time and space with initial collision between promontories of the NW Australian passive margin and the Java trench, suggesting a link between the two processes. Similar age and stratigraphic relations are also documented in the Brooks Range and other Oman-type ophiolites.

Peri-collisional extension opens small SSZ ocean basins that may be obducted during or shortly after they form by progressive convergence at multi-plate boundaries. These processes provide a self-perpetuating mechanism for ophiolite genesis and emplacement that accounts for both the similar and diverse aspects of many ophiolites.

An unambiguous classification for various mafic and ultramafic complexes in orogenic zones (loosely cited as 'ophiolites') is needed to determine age and tectonic relations between ophiolites and the orogenic belts in which they are found. 'Alpine-type' ultramafics and even 'Tethyan-type' ophiolites include a diverse assortment of mafic and ultramafic rocks. Some of these complexes are severely dismembered and even metamorphosed: others are geochemically anomalous. Notwithstanding this diversity, most ophiolite complexes occupy a similar structural position in continental fold-thrust belts including Tethyan orogenies. At face value the diversity of ophiolites argues against a single mechanism for ophiolite genesis, but structural relations suggest a common mechanism for emplacement.

The distinctive stratigraphic and structural nature of ophiolites (Coleman 1977) limits to some extent possible origins to submarine rift zones. These zones generally involve two major tectonic regimes: (1) continental rifts (e.g. Red Sea), which are transitional with mid-oceanic ridges, and (2) inter-arc basins, which are often transitional with back arc basins (e.g. Lau Basin). Each of these regimes may also include sites with a significant component of oblique spreading or transtension (e.g. Gulf of California and Andaman Sea). At convergent margins these two very different sites of ophiolite genesis are usually juxtaposed and difficult to unravel.

The integration of petrological, geochemical and radiometric data from detailed field studies of many ophiolites reveal some common features that are useful for first order tectonomagmatic discriminations. Compilations of these data by Pearce *et al.* (1984) and Ishiwatari (1985) indicate end-member compositions of MORB-type (Ligurian) and arc-type (Papuan) tectonomagmatic origins. Intermediate compositions are interpreted as transitional-type (Oman).

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The fundamental geochemical differences between the three ophiolite types are: (1) The abundance of incompatible elements (e.g. Al, Ti, Nb, and Zr), which are preferentially concentrated in the liquid fraction during melting and crystallisation (MORB-type is considered 'enriched' and arc-type 'depleted' in these elements). (2) The sequence of crystallization after olivine (Church & Riccio 1977): plagioclase forms after olivine in MORB-type, clinopyroxene in transitional-type, and orthopyroxene in arc-type ophiolites. (3) mineral chemistry: in arc-type ophiolites, spinels have ratios of Cr%/Cr + Al usually greater than 0.60 (Dick & Bullen 1984), plagioclase has An contents often greater than 85%, and olivine Fo contents are usually less than 85% (Beard 1986). Most of these differences are interpreted in terms of different degrees of partial melting of a common lherzolitic source; the more depleted the composition, the greater the degree of partial melting of the mantle source.

The geochemistry of both arc and transitional-type ophiolites usually requires a subduction related origin (Pearce *et al.* 1984). The 'thinness' and internal structure of most of these ophiolites document that acute tensional strains occur at or near the site of ophiolite genesis. The combination of these two characteristics limit the possible sites of ophiolite genesis to inter-arc spreading environments not dissimilar to some forearc basins of the western Pacific region and SE Asia. These constraints have led to the general acceptance of the model for ophiolite genesis by supra-subduction zone (SSZ) spreading (Moores *et al.* 1984; Pearce *et al.* 1984; Hawkins *et al.* 1984; Leitch 1984).

The SSZ model predicts that ophiolites are generated above a subduction zone within pre-existing MORB-type oceanic crust. Presentations of the model usually assume subduction is initiated in an intra-oceanic setting, and spreading in the upper plate can occur during incipient subduction or at a later phase in the evolution of an arc. What initiates the episodic spreading process in intra-oceanic arcs is not understood.

Emplacement of these inter-arc basins onto continental crust is a separate problem. During tectonic emplacement the original tectonomagmatic setting of ophiolites is usually structurally modified beyond recognition. This deformation complicates reconstructions of tectonic regimes responsible for ophiolite genesis. In active orogenic zones the investigative process of ophiolite lineage is simplified by the partial preservation of the tectonic setting where the ophiolite formed.

Focus of paper

This paper focuses on the significance of temporal and spatial relations between transitional-type (Oman) ophiolites and collisional orogens. New data from the Banda orogen of Indonesia, where the NW Australian passive continental margin is actively colliding with the Banda arc, constrain possible mechanisms for ophiolite genesis and structural evolution. These data are integrated with new data from Oman-type ophiolites incorporated into the Brooks Range, Alaska. Both the Brooks Range and Oman ancient continental fold-thrust belts host well preserved and exposed ophiolite massifs. Erosional incisions into the mountains locally expose the low angle structural base of the ophiolites and its thin metamorphic sole. The composition, age and structural evolution of these metamorphic rocks offer clues to the link between ophiolite genesis and emplacement.

The data base used for the research results from four summer field studies in the Brooks Range, three field seasons in Timor, Indonesia and comparative field studies of Cyprus and the Oman Mountains. The origin and emplacement of these ancient transitional-type ophiolites are commonly modeled with reference to active orogenic processes in the Banda orogen (e.g. Moores 1982; Searle & Stevens 1984).

Although the Brooks Range and Oman are temporally and spatially unrelated, their ophiolite thrust sheets are very similar in composition, geochemistry, and structural evolution. Common features of these and other ophiolite complexes structurally overlying shortened passive continental margins suggests a similar origin and structural evolution. These similarities warrant comparative research in order to resolve the relationship between Oman-type ophiolites and collisional mountain systems (Fig. 1). Determining this relationship is a critical part of inferring possible ophiolite lineages and structural evolutions.

Ophiolites of modern arc–continent collisions

Comparative studies between the Brooks Range and Oman mountains with modern incipient collision zones (Banda arc and Taiwan) are revealing in terms of the origin and emplacement of ophiolites. In these active collision zones the Banda and Luzon intra-oceanic island arcs are colliding with passive continental margins. Models for the origin of SSZ ophiolites (e.g. Pearce *et al.* 1984) predict that ophiolite

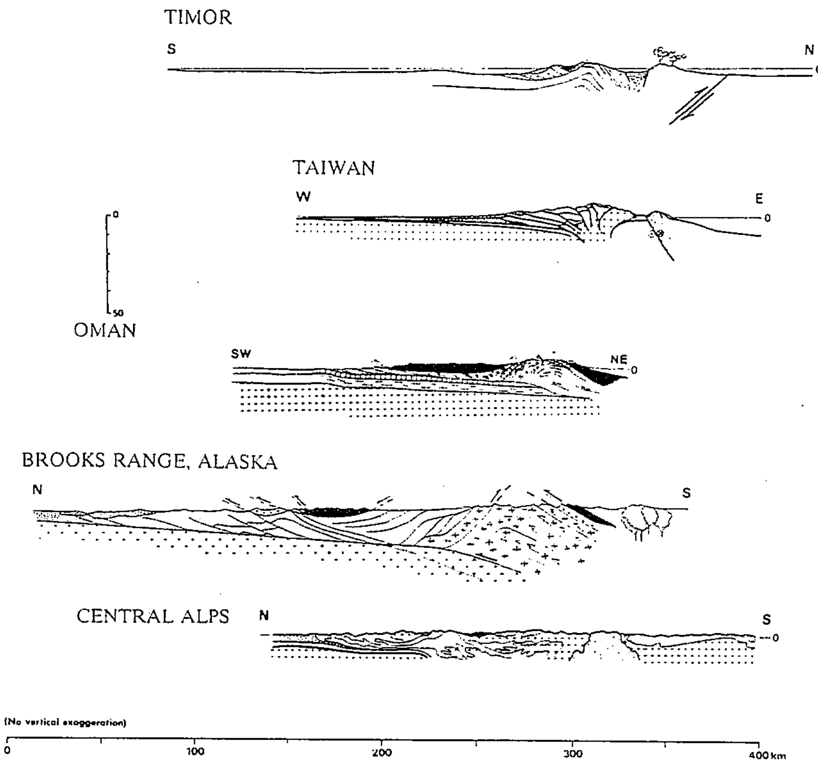


Fig. 1. Comparative generalized cross-sections of Timor, Taiwan, Oman, Brooks Range and Alps. Cross pattern, crystalline basement; random, volcanic arc; solid, ophiolites; dots, orogenic sediment. No vertical exaggeration.

genesis occurs in the forearc of young arc systems like the Banda and Luzon systems. Collision of these arcs with the continental margins is one of the most likely mechanisms used to model the stacking of SSZ (forearc) ophiolites above continental margins (e.g. Moores 1970; Dewey 1976; Gealey 1980; Moores *et al.* 1984; Searle & Stevens 1984; Box 1985; Lippard *et al.* 1986). These models predict that the active arc–continent collisions of Timor and Taiwan should currently be the site of ophiolite genesis and emplacement. This prediction raises important questions about the tectonomagmatic evolution of the Banda orogen and Taiwan, and the structural evolution of the collision process. What evidence is there for SSZ ophiolite genesis and emplacement?

Taiwan

In Taiwan fragments of dismembered ophiolite associated with serpentinite melange occur in the longitudinal valley suture zone. This linear depression represents the present transpressional fault boundary between the Asian and Philippine Sea plates. The Miocene ophiolite remnants, known as the East Taiwan ophiolite, have MORB-type petrologic and geochemical affinities, pelagic sediment cover, and are associated with abundant breccias (Suppe 1981). The mafic and ultramafic fragments are interpreted as parts of the South China Sea oceanic crust accreted to the Luzon forearc during subduction. Unlike Oman-type ophiolites, the Taiwan mafic and ultramafic complexes are chemically similar to MORB, lack internal coherence, occur as dismembered blocks in a serpentinite melange, and reside only in the hinterland of the collision zone.

Arc–continent collisional processes in Taiwan have led to structural burial and local subduction of the arc–forearc domain (Suppe 1984; Pelletier & Stephan 1986). This contrasts with emplacement models for Oman-type ophiolite associations, but may be representative of processes occurring in other ancient collisional orogens. These differences are most likely a function of variations in the pre-collisional history of passive continental margins (Harris & Audley-Charles 1987). For example, the Asian margin was a convergent plate boundary before it rifted to form the South China Sea. The rifting preceded collision in Taiwan by only 20–30 Ma compared to 130–150 Ma in the Brooks Range, 140–150 Ma in Oman, and 150–160 Ma in the Banda orogen. Most continental margins overlain by Oman-type ophiolites were long-lived and attached to relatively old segments of oceanic crust at the time of contraction and ophiolite emplacement. These relationships suggest that pre-collisional thermal and stratigraphic variations control, to some extent, ophiolite genesis and emplacement. These controls are most likely a function of rheological differences responsible for the way collisional strain is partitioned.

Banda orogen

The major islands of Timor and Seram are similar in scale to Taiwan, but represent promontories of the Australian continental margin that collided earliest with the Banda arc (Fig. 2). Magmatic activity has ceased adjacent to these regions of initial collision. Along orogenic strike from Timor and Seram the position of active magmatism progressively changes in time and space (Abbott & Chamalaun 1981). Many active segments of the Banda arc are very young and positioned further from the collisional front (trench) than previous magmatic zones. The previously active segments of the arc now occupy a forearc basin position that is locally a site of amagmatic extension (Bowin *et al.* 1980). These sites of active forearc basin extension in the Banda arc correspond to embayments or recesses in the Australian margin. In these regions the trench bends around indenting continental promontories and may migrate continentward (away from the arc) into the embayments (Fig. 3). Active seismicity in the forearc indicates a regional strain pattern of N-S shortening and E-W extension (McCaffrey 1988). Shape irregularities and oblique convergence of the Australian continental margin add to an inhomogeneous distribution of regional strain. Forearc extension and trench migration around the collisional indentation of Timor widen the arc-trench gap by approximately 100 km adjacent to the Savu and Weber Basins (Fig. 2). These basins represent parts of the forearc affected most by E–W extensional expansion associated with the collision at Timor. First motion studies of earthquakes in these basins indicate active deformation is characterized by extension and strike-slip motion (McCaffery 1988; Eva *et al.* 1988). The composition and age of the rocks in these basins, and the age of various extensional phases forming the basins are critical in terms of the origin of ophiolites.

The Savu and Weber forearc basins are the most likely sites of SSZ ophiolite genesis and emplacement in the Banda orogen. These basins form the upper plate transition between an extensional zone of SSZ magmatism (ophiolite genesis) and a compressional zone of crustal accretion (ophiolite emplacement). Although no well data are available from these basins, geophysical, geochemical and stratigraphic studies indicate that their origin is most likely related to spatial variations in the distribution of collisional strain between the irregular NW Australian continental margin and the Java trench.

Weber Basin

The Weber Basin forms a crescent shaped trough between the Timor and Seram collision zones (Fig. 2). In the widest part of the basin, the Weber Deep, water depths are over 7000 m. A thin sedimentary infill (1500 m average) overlies igneous basement with seismic refraction profiles typical of oceanic crust (Bowin *et al.* 1980). Extinct volcanic ridges locally form bathymetric highs along the flanks of the basin. One of these ridges along the trend of the gravity high is emergent exposing gabbro on an island at the western extremity of the Weber Basin. The gabbro is interpreted by Bowin *et al.* (1980) as a magma accumulate beneath a former volcano now part of an extinct volcanic ridge. The ridge is structurally modified by amagmatic forearc extension and forms part of the eastern flank of the Weber basin.

Subsurface layers in the Weber Deep tilt slightly east (trenchward) suggesting the site of most subsidence has moved trenchward with time. This forearc extension is directed orthogonal to the trench (McCaffery 1988), and

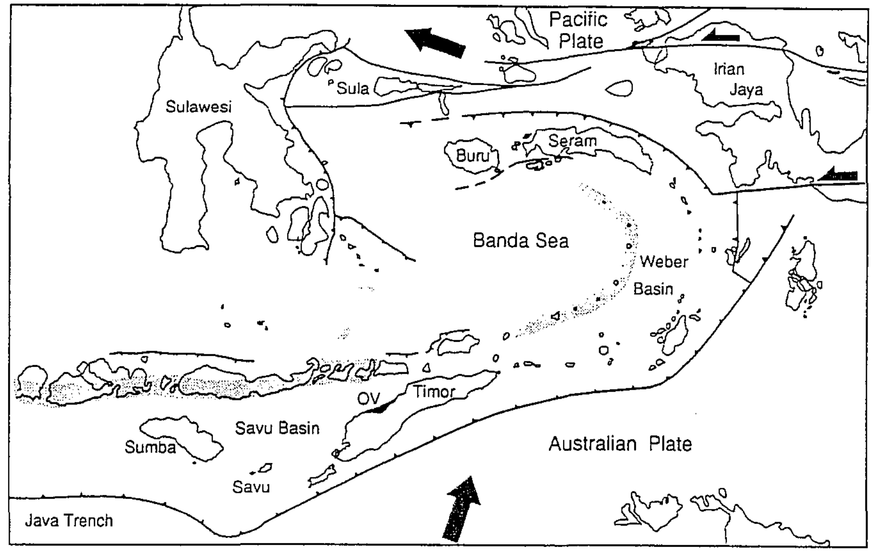


Fig. 2. Reference map of the Banda orogen of eastern Indonesia. Shaded area, zone of active supra-subduction zone magmatism. OV, Ocussi volcanics. Arrows correspond to plate motion directions. Thick lines are major fault zones; teeth are on upper plate of low-angle faults.

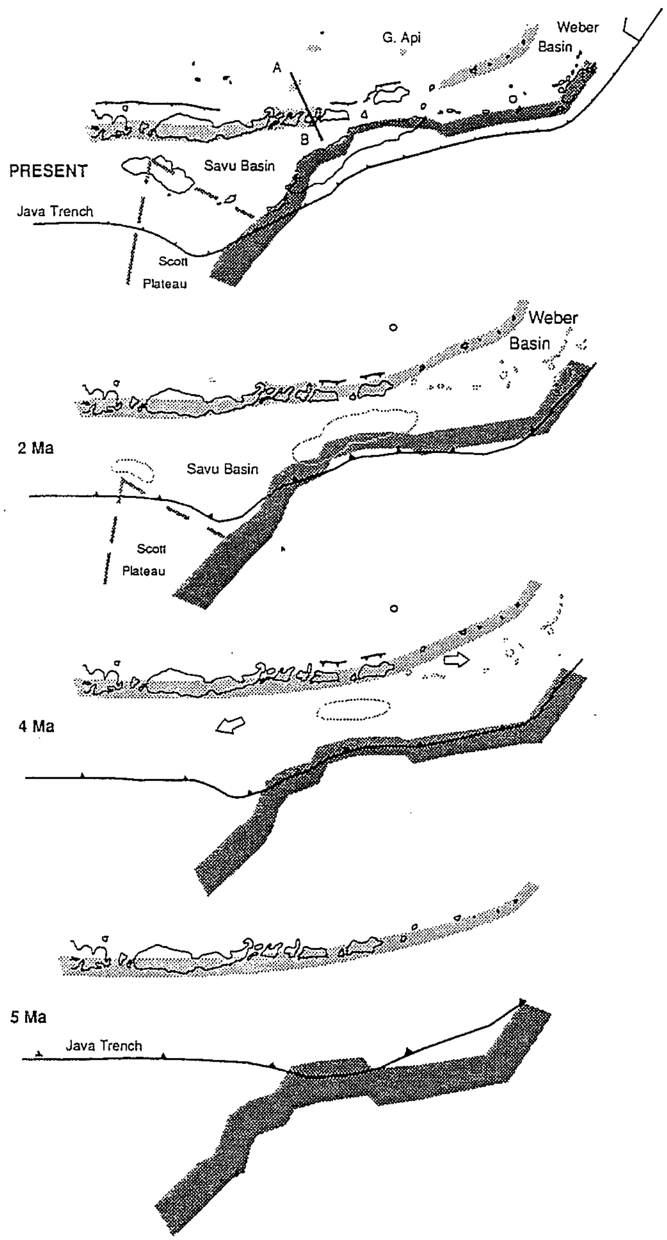
is responsible for a minimum of 2 km of subsidence of the Weber Basin. The crustal thickness (excluding sediment) near the axis of extension is estimated from gravity anomalies and seismic refractions at around 10 km in the south and 7 km in the north of the Weber Deep. Two of the most likely origins proposed for the Weber Basin are: flexural downwarping as an elastic response to increased curvature of the Banda arc (Bowin *et al.* 1980), and sinking of an uncompensated forearc with the subducting plate (McCaffrey 1988). These processes are most likely a function of plate boundary modification and rearrangement as the Australian continental crust enters and destabilizes a former trench–trench–trench triple junction. Some of these mechanisms are discussed in greater detail below.

The progressive curvature of the Banda orogen subjects the Weber Basin region to increasingly oblique convergence with Australia (Figure 3). The present convergence angle is nearly margin parallel, which may accentuate forearc extension processes. Similar syn-orogenic extensional basins are known in the oblique convergence zones of the Philippines, Andaman Sea, and SW California. These processes are related to the generation and emplacement of Oman-type ophiolites by Moores *et al.* (1984).

Savu Basin

The Savu Basin is a bowl-shaped trough that narrows to the west into the Java forearc, and to the east into the Timor collision zone. The basin has a flat floor around 3000 m deep underlain by >2000 m of sedimentary infill in the depocentre. The basement of the basin is exposed locally in NW Timor where fragments are incorporated into the Banda orogenic wedge. These fragments are mostly basaltic-andesite pillow lavas and sheet flows known as the Ocussi volcanics (discussed below).

Seismic-reflection data and stratigraphic correlations suggest extension of the Savu Basin initiated during the Late Miocene (Karig *et al.* 1987). Recent seismic events in the Savu Basin have strike-slip and normal fault focal mechanisms consistent with south and SW directed expansion (Eva *et al.* 1988, McCaffrey 1988). This direction is similar to independent structural constraints from SLR observations of volcanic islands north of the Savu Basin (Varekamp *et al.* 1989). Fault and fracture patterns on these islands indicate E–W com-



pression with west directed translation of the arc away from the collisional indentor. It is important to note that the orientation of the Australian margin presently colliding with the forearc is SSW-NNE (Fig. 3).

Shallow seismicity (<40 km) in the closing eastern part of the basin is characterized by a wide horizontal dispersion over a broad region unlike the well defined Benioff zone typical of most of the Java trench (McCaffrey 1988). This pattern is consistent with strong coupling between the upper and lower plates in the collision zone. South-dipping back-arc thrusts adjacent to this region also manifest the effects of increased coupling. Both the diffuse seismic zone and back-arc thrusts die out to the west. Whether this change is abrupt (McCaffrey 1988) or transitional (Eva *et al.* 1988) is equivocal. In the western Savu Basin earthquake foci between 50–250 km and other seismic observations suggest normal faulting and down stepping in the subducting slab consistent with strong slab pull (Spence 1986; 1987; McCaffrey *et al.* 1985). During the Late Miocene onset of Savu Basin extension the seismic pattern may have been more like that found presently in the western narrows of the basin near Sumba. The Benioff zone here is very steep and continuous with an overlying wedge of shallow extensional seismic events (Eva *et al.* 1988).

Ocussi volcanics

Contractional deformation in the Timor region uplifts and exposes part of the eastern Savu basin crust. The crustal fragment is a thick (1–2 km) pile of interbedded volcanic agglomerates, pillow lavas, tuffs and sheet flows, known as the Ocussi volcanics. Most of the lavas are steeply dipping and appear folded in places. Marls containing late Miocene (early N18) microfauna with some tuffaceous interlayers depositionally overlie the volcanics (Carter *et al.* 1976). The structural unit comprising the Ocussi volcanics, the Ocussi thrust sheet, appears to dips northward into the Banda forearc and is interpreted here as forearc basement (see Timor section in Fig. 1). Similarities in age and composition between dredge samples from the forearc basin (collected by the crew of the RRS Charles Darwin) and the Ocussi volcanics lend support to structural correlations between the two units.

The Ocussi lavas and dredge samples from off the north coast of East Timor are clinopyroxene-phyric basalts and basaltic andesites with a groundmass of varying abundances of plagioclase and glass. Most of the volcanics show very little evidence of alteration. Chemical analyses of these samples indicate they are part of the low-K tholeiite series (Table 1). Silica contents and Mg/Mg + Fe(total) ratios reveal the rocks are fairly evolved. Trace element abundances show affinities with island-arc tholeiites: Cr-TiO_2 abundances are similar to island-arc basalts, and Ti/100-Zr-Y × 3 abundances are transitional between calc-akaline basalt and low-K tholeiite (Fig. 4). $^{87}Sr/^{86}Sr$ ratios of 0.7049 for the Ocussi lavas (Abbot & Chamalaun 1981) are typical of volcanic rocks found above subduction zones. Relative to MORB, the Ocussi volcanics are enriched in large ion lithophile elements and depleted in high field strength elements (Fig. 5) and Nb, which is characteristic of volcanic arc basalts (Pearce 1982). Chondrite-normalized rare earth element trends are flat at values slightly higher than 10 except for sample 52 which is light REE depleted (Fig. 6). Flat REE trends contrast with 'normal' (N-type) MORB, which are generally depleted in LREE as in sample 52.

Varekamp *et al.* (1989) analysed trace element and isotopic trends across a segment of the Banda arc adjacent to the Ocussi volcanics. The four active volcanoes studied form a NNW–SSE trending zone that intersects the Ocussi volcanics at 120 km from the Timor Trough, trends across the arc at a trough distance of

Fig. 3. Progressive collision between the NW Australian continental margin (dark shaded band) and Java trench (solid line). Convergence direction is 020 at 75 km/Ma. Northward motion between Australia and the Banda arc is accommodated by underthrusting, shortening of the lower plate, extrusion by strike-slip motion, and backarc thrusting. 50% shortening is assumed and shown by reduction of continental margin width. Grey outlines of Banda arc islands are inferred positions. Active volcanism in the Banda arc is illustrated by light shaded band. As the collision evolves the volcanic arc is modified by bending, fragmentation, and northward shifts in magmatic positions. Initial collision occurs at 5–6 Ma of what is now the East Timor segment of the Australian margin. East and west of the initial collision zone are continental margin embayments now overlain by upper-plate peri-collisional basins. Arrows in forearc basin are interpretive sites and directions of SSZ spreading and extrusion. Backarc thrusts develop at around 4 Ma due to increased coupling of continental lower plate and forearc. Heavy line A-B corresponds with geochemical transect through the Banda arc by Varekamp *et al.* (1989).

Table 1. *Chemical analyses of the Ocussi volcanics*

Sample	43a	43c	46a	46b	52a	52b	cd30b*
Weight % oxide							
SiO_2	53.45	52.91	51.7	52.59	51.28	51.61	49.57
TiO_2	0.95	0.81	0.83	0.72	0.64	0.64	0.83
Al_2O_3	15.07	15.62	15.67	15.31	15.41	15.39	15.3
FeO	4.7	4.56	3.72	4.27	6.08	5.3	4.65
Fe_2O_3	4.89	4.33	3.67	3.51	2	2.73	3.12
MnO	0.13	0.12	0.12	0.14	0.14	0.12	0.13
MgO	4.48	5.24	5.12	6.34	6.22	5.98	6.11
CaO	8.21	9.29	10.34	10.14	10.62	10.37	10.57
Na_2O	1.81	1.78	1.71	1.85	1.46	1.44	2.09
K_2O	0.88	0.28	0.39	0.27	0.24	0.33	0.34
P_2O_5	0.1	0.1	0.11	0.09	0.06	0.07	0.09
H_2O	4.54	3.73	5.61	3.66	4.85	5.05	6.64
Total	99.21	98.77	98.99	98.89	99.00	99.03	99.44
Li	4	5	4	9	5	7	5
Sc	33	34	33	34	34	34	34
Ti	5695	4856	4956	4316	3837	3837	4956
V	279	276	248	265	241	244	246
Cr	45	72	101	76	120	135	169
Co	46	33	35	37	39	34	48
Ni	35	45	57	65	59	62	56
Cu	45	66	43	160	65	67	40
Zn	73	70	66	50	64	64	60
Rb	19	13	30	35	13	16	12
Sr	130	107	126	99	105	107	167
Y	31	24	23	0	18	21	24
Zr	74	56	64	49	32	32	55
Nb	8	8	7	7	8	6	7
Ba	97	80	70	68	48	52	75
La	6.13	4.8	5.57	5.11	2.13	2.13	7.63
Ce	13.06	10.25	11.83	12.26	4.62	4.79	14.61
Pr	2.37	1.3	1.51	2.34	0.00	0.00	1.99
Nd	8.65	7.12	7.8	7.82	4.16	4.16	10.21
Sm	2.56	2.15	2.29	1.88	1.47	1.43	2.78
Eu	0.96	0.81	0.88	0.79	0.63	0.62	1.03
Gd	4.04	3.37	3.5	2.77	2.55	2.48	3.69
Dy	4.74	3.9	3.92	3.56	3.06	3.03	4.04
Ho	1.03	0.85	0.82	1.84	0.65	0.64	0.28
Er	3.29	2.68	2.65	2.2	2.13	2.06	2.6
Yb	3.15	2.6	2.58	2.14	2.07	2.03	2.45

* Dredge sample from offshore NE Timor

180–230 km, and to a backarc volcano at 300 km from the trough (Fig. 3). Variations in chemistry along the zone show a consistent trend of decreasing abundance of K, Rb, Ba, Sr, and $^{87}Sr/^{86}Sr$ trenchward toward the Ocussi volcanics (see fig. 7. Varekamp *et al.* 1989). This trend corresponds to a northward (forearc–backarc) variation in composition from low-K tholeiite–tholeiite–calc-alkaline–high-K calc-alkaline–alkaline volcanism. The systematic variation in active volcanism with arc–trench distance predicts a composition for the Ocussi volcanics very similar to that observed (Table 1). These data argue for a genetic relation between the Ocussi volcanics and the known subduction related products to the north.

The chemical signiture of the Ocussi volcanics is interpreted here as a product of partial melting of a MORB-like mantle source, which was depleted in high field strength elements by earlier melting episodes. Enrichment in large ion lithophile elements, depletion in Nb, and similarities with predicted trends of active volcanism in the region suggest the partial melting was subduction-related and possibly associated with the formation of new crust by

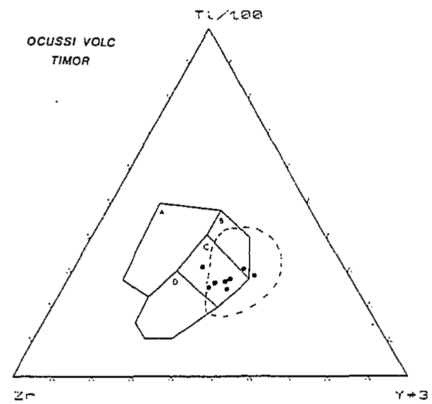


Fig. 4. Trace element discriminate diagram (after Pearce & Cann 1973) of Ocussi volcanics. Field A, within plate basalts; B, low K tholeiites; C, ocean floor basalts. D, calc-alkaline basalts. Island arc series outlined by dashed line.

SSZ spreading. Modern intra-arc basins formed by these processes, such as the Mariana Trough (Natland & Tarney 1982; Hawkins & Melchoir 1985), East Scotia Sea (Saunders & Tarney 1979), and Bransfield Strait (Keller & Fisk, this volume) are characterized by clinopyroxene-phyric basalts with similar trace and rare earth element abundances to the Ocussi volcanics.

The age of Ocussi volcanism is critical in order to understand its relationship to the evolution of the Banda intra-oceanic arc and arc-continent collision. Attempts to determine the radiometric age of the Ocussi volcanics are frustrated by the poor resolution typical of deep sea pillow lava age analyses (Fisher 1971). K-Ar whole-rock analyses of 17 samples by Abbott & Chamalaun (1981) yielded ages that cluster between 2–5 Ma with some ages as young as 0.1 ± 0.4 Ma and three older ages of 58.6 ± 0.5 Ma, 94.6 ± 8.1 Ma, and 109 ± 10 Ma. All of the samples are from pillow basalt except for a dolerite dyke that has an age of 6.1 ± 0.5 Ma. The dyke age is interpreted by Abbott & Chamalaun (1981) as the minimum age of the

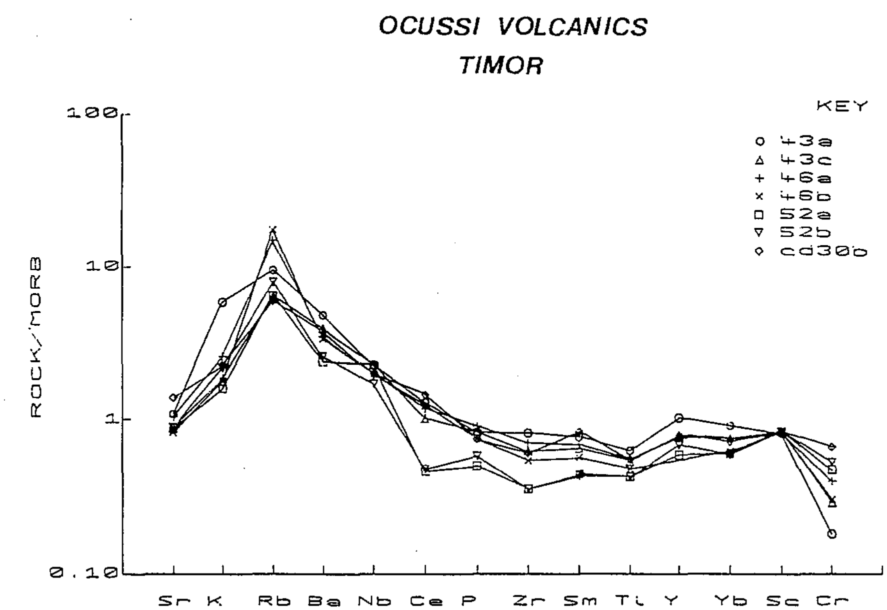


Fig. 5. MORB-normalized trace element abundance of Ocussi volcanics. Light-ion lithophile element enrichment trend. Sample cd30b was dredged off NE coast of Timor.

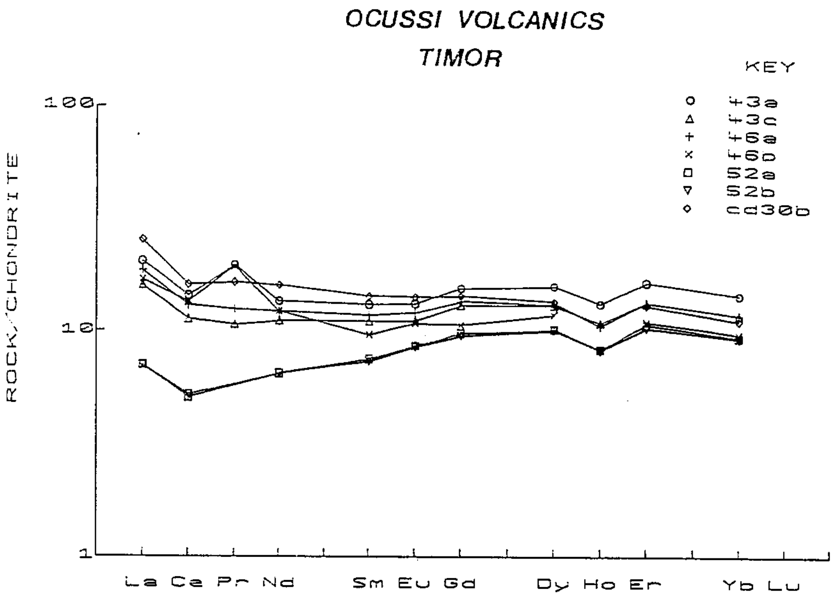


Fig. 6. Chondrite-normalized REE abundance of Ocussi volcanics. Sample cd30b was dredged off NE coast of Timor.

Ocussi volcanics. The bulk of the K-Ar ages are younger than unconformably overlying Late Miocene sediments, suggesting that the K-Ar system experienced open system behaviour since the deposition of the sediments. Microfauna in these sediments provide a minimum age of early N18 (around 6–7 Ma) for most of the lavas (Carter *et al.* 1976). Locally, dolerite intrusions into the overlying sediments have been reported by Leme & Coelho (1962), but no such relationships were found during this investigation.

The wide range of ages from pillow lavas are interpreted to result from migration of various amounts of Ar during cooling of deep sea lavas as discussed by Fisher (1971). Post-eruptive loss of Ar is also common and may be related to devitrification of glass in the volcanic rocks. This interpretation was confirmed by four Ar/Ar age determinations conducted as part of this study. Plagioclase separates from the Ocussi lavas and the Wetar Strait dredge sample were analysed in order to provide age data independent of the contribution of glass. A whole-rock age analysis was also conducted to compare with the K-Ar data of Abbot & Chamalaun (1981).

Age spectra for plagioclase separates are extremely U-shaped with ages at the lowest and highest temperature steps often more than 200 Ma. The age minimums do not yield plateau ages. U-shaped age spectra are usually a function of excess argon (Lanphere & Dalrymple 1976). The whole rock Ar/Ar analysis yielded an age spectrum consistent with exponential Ar loss. The integrated age (same as conventional K-Ar age) is similar to the whole-rock K-Ar age results of Abbott & Chamalaun (1981).

The Ar/Ar age spectra indicate that excess argon and argon loss is responsible for the wide K-Ar age range of the Ocussi lavas, as initially suggested by Abbott & Chamalaun (1981). The most reliable age data for the Ocussi volcanics is the Late Miocene (6–7 Ma) sediment cover and 6 Ma dolerite dyke. Assuming sedimentation was contiguous with volcanism, the maximum age of Ocussi magmatic pulse is Late Miocene (6 Ma). This time marks a transitional phase in the evolution of the Banda arc as it impinged upon the most distal reaches of the Timor promontory of NW Australia (Fig. 3); a transition from subduction to collision. The onset of collision is well documented throughout the Banda orogen by the change from condensed

and starved passive margin conditions to orogenic sedimentation along the NW Australian margin (Audley-Charles 1986). Metamorphic rocks in the hinterland of the collision zone (north coast of Timor) also yield cooling ages as old as 5–7 Ma consistent with the onset of collisional uplift (Berry & McDougall 1986).

Palaeogeographic reconstructions of the western Banda orogen indicate that Ocussi volcanism was positioned more trenchward than the present arc volcanism. However, collision appears to shift the site of arc volcanism northward with time. The Banda arc islands immediately north of central Timor have no record of volcanic activity after 3 Ma (Abbott & Chamalaun 1981). North of these islands 0.7 Ma volcanic rocks are found (Schwartz *et al.* 1986), and further north is the active volcanic island of Gunung Api (Fig. 3). To the west of this region, where the collision is not as advanced, active volcanism occurs both on and off axis, but not as far north.

Temporal and spatial relations between modifications of the Banda arc and collision suggest that the Ocussi volcanics may be related to orogenic impingement of NW Australia with the Java Trench (Fig. 3). The arc–continent collision of the Banda orogen structurally modified the Savu forearc basin by S and SW directed extrusion (extension and strike-slip motion). As the collision progressively moves to the west and continentward, the volcanic pile, and some of the crustal and mantle sequence it overlies, are in the process of emplacement and incorporation into the continental fold-thrust belt of West Timor. If the Ocussi lavas are a representative sample of the greater Savu forearc basin basement, it provides a good modern analogue of a SSZ ophiolite in the initial stages of emplacement. According to this tectonic scenario Oman-type ophiolites may be generated in zones of extension around and within collisional orogens. Kinematic models for these extensional domains are considered below. It is proposed here that ophiolites with similar characteristics and tectonic relations to the Savu and Weber basins may be referred to as 'peri-collisional' ophiolites.

Other mafic and ultramafic masses

Other mafic and ultramafic rocks incorporated into the Banda orogenic wedge are of two types. The most common are lherzolite (Berry 1981; Harris 1989) and Ca-rich tholeiites to alkaline basalt (Berry & Jenner 1982) associated with the Aileu–Maubisse allochthon of Audley-Charles (1968) on Timor island. These rocks are compositionally and chemically similar to dredge samples from distal reaches of the western Australian and other continental margins (Bonatti & Michael 1989).

My recent field investigations of these bodies and others discovered along the central north coast of Timor, indicate that intrusive relations are locally preserved between lherzolitic masses and pelitic rocks of Australian affinity. Near the intrusions the pelitic rocks are metamorphosed to garnet grade. The metamorphic grade decreases to lower greenschist facies within a few kilometres south of the intrusive masses. Both the intrusive bodies and the country rock are overprinted by collisional deformation. Ar/Ar age data from metamorphic amphiboles near some intrusive masses (Berry & McDougall 1986) indicate that the prograde phase of metamorphism is most likely associated with Jurassic rifting of the Australian continental margin and retrograde phases yield collisional ages.

These observations and correlations with chemically similar dredge samples suggest that the mafic and ultramafic masses associated with the Maubisse allochthon have a continental rift origin and lack the unique stratigraphy and internal coherency of most 'ophiolites'. The Ocussi volcanics immediately structurally overlie the Maubisse allochthon mafic and ultramafic rocks. This structural relation indicates that the most distal parts of the Australian continental margin immediately underlie what appears as a modern SSZ ophiolite.

Other major occurrences of mafic and ultramafic rocks found in Timor, Seram, Sumba, and other islands are dismembered fragments of serpentinized harzburgite, gabbro, and arc-related volcanics structurally intercalated with continental metamorphic rocks (Brown & Earle 1983; Sopaheluwakan *et al.* 1989). This complex is part of the Banda Terrane of Audley-Charles & Harris (1990). The terrane represents fragments of early arc–continent collisional episodes, around 30–35 Ma, between northernmost Australia and the Banda arc (Harris 1989). These fragments are not unlike some tectonostratigraphic terranes found in the westernmost Cordillera of North America.

Transitional-type ophiolites of ancient collisions

Most reconstructions of ancient, ophiolite-bearing collision zones suggest that tectonic emplacement of ophiolites results from continent–trench collisional processes (e.g.

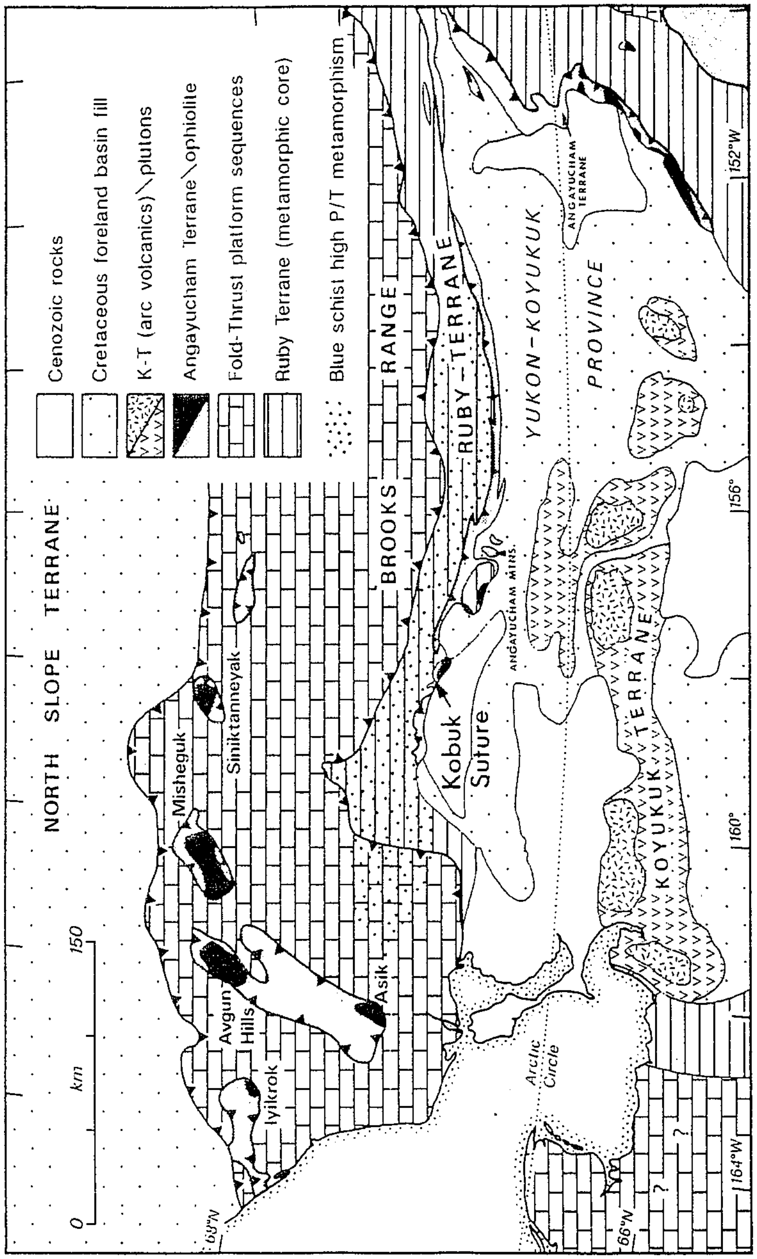


Fig. 7. Reference map of NW Alaska and western Brooks Range. Brooks Range ophiolite klippen shown in black. Root zone for ophiolite is near the Kobuk suture (see cross section along N–S line in Fig. 1). Arcuate nature of collisional boundary is similar in scale and tectonic evolution to active Banda orogen.

Dewey & Bird 1971; Coleman 1977; Moores 1982; Searle & Stevens 1984; Lippard *et al.* 1986). If intra-oceanic arcs, such as the Banda and Luzon arcs, are the most likely setting for the generation of transitional-type ophiolites (e.g. Hawkins *et al.* 1984; Leitch 1984; Pearce *et al.* 1984), then the processes of ophiolite genesis and emplacement should be separated to varying degrees in time and space. However, protolith, thermometric and age data from sub-ophiolite metamorphic soles indicate that most transitional-type ophiolites formed very near the continental margins that they now structurally overlie. These relationships are similar to those discussed above for the peri-collisional Savu and Weber Basins.

In this section, new data from the Brooks Range ophiolite is presented and compared with existing data from Oman-type ophiolites. The discussion aims to address the question of the degree of geologic similarity between perhaps two examples of the same process at various stages of development.

Brooks Range ophiolite

The Brooks Range ophiolite belt comprises the western 200–300 km of the Brooks Range fold-thrust mountain system of Arctic Alaska (Fig. 7). The stratigraphic record of the western Brooks Range represents a long interval (about 150 Ma) of passive continental margin development. Low energy, condensed sedimentation and some distal volcanism (Mississippian to Triassic), was interrupted by Middle Jurassic orogenesis. The orogenic phase initiated by the generation and emplacement of ophiolite nappes.

Unlike most of the North American Cordillera, the western Brooks Range preserves the Oman-type style of Mesozoic orogenesis that influenced most of western North America during the Jurassic Sevier orogeny (Moores 1970; Burchfiel & Davis, 1975; Saleeby 1982; Ingersoll & Schweickert, 1986). Subsequent orogenic pulses overprint these relationships throughout most of the Cordillera. The effects of these later orogens on the western Brooks Range are minor. From the structural relations preserved in the Brooks Range it is clear that emplacement of extensive ophiolite sequences initiated passive margin contraction.

The Brooks Range ophiolite (BRO) consists of internally coherent allochthonous mafic and ultramafic rocks indicative of Oman-type ophiolite associations. It occupies the uppermost structural position of an allochthonous stack of continental margin sequences in the western Brooks Range. The BRO forms five different klippen-like massifs of consanguineous composition, internal organization, structure and age (Fig. 7). The klippen are preserved in synformal depressions of the fold-thrust zone over a present length of 350 km, width of 50 km, and thickness of 2–3 km. Glacial erosion and the sparse vegetation provide comprehensive three dimensional exposure of many critical parts of the BRO.

The structural base of the BRO is well exposed in several locations. Subophiolite metamorphic rocks are preserved along its sole at some locations. The metamorphic sole is transitional in places with a mafic volcanic sequence of interlayered cherts, tuffs, and minor clastic sediment correlative with the Angayucham terrane (Jones *et al.* 1981; Ellersieck *et al.* 1982). Angayucham basalts and diabase have E- and N-type MORB chemical affinities (Moore 1987; Wirth *et al.* 1987; Barker *et al.* 1988; Pallister *et al.* 1989). The structurally complex nature of the terrane, which is locally transitional to melange, make unambiguous age determinations of the terrane difficult. Devonian–Triassic fossils are found intercalated with lavas (Nelson & Nelson 1982; Mayfield *et al.* 1983; Murchey & Harris, 1985); Pallister *et al.* 1989). A thrust assemblage of Devonian to Jurassic sedimentary successions structurally underlie the Angayucham terrane and BRO nappes (Martin 1970; Tailleur 1970). The assemblage is usually arranged with more distal units above more proximal ones and documents over 400 km of shortening (Mull 1982; Mayfield *et al.* 1983). The structural stack provides an impressive display of the geological relations between ophiolites and contractional mountain systems (Fig. 1).

The BRO klippen consist of the following igneous sequence in ascending order (Harris, 1991): (1) depleted tectonized peridotites, (2) dunite and wehrlite cumulates, (3) clinopyroxene dominant layered gabbro, (4) massive gabbro and high level intrusives, (5) out of sequence wehrlite intrusives, (6) rare sheeted dykes, (7) island arc-type basalts and (8) sediments. The various units are usually transitional except for local intrusive and fault relations. The igneous sequence is geochemically similar to transitional-type ophiolites such as Cyprus and Oman (Harris 1988).

Sub-ophiolite metamorphism

Oman-type ophiolites are usually underlain by a thin, discontinuous complex of polyphase metamorphic rocks that increase in grade upward toward the base of ophiolite nappes. These complexes (referred to hereafter as metamorphic soles) usually consist, in descending order, of sheared and serpentinized peridotite and metagabbro, tholeiitic and/or alkalic amphibolite and greenschist, metachert, and marble (Williams & Smyth 1973; Searle & Malpas 1980; Spray 1984). The metamorphic sole is usually structurally underlain by distal facies continental margin deposits. High temperature mineral assemblages typical of sub-ophiolite metamorphic soles require immediate emplacement of the ophiolites after they form (usually <10 Ma). It is suggested here that these relationships establish a link between the processes of ophiolite generation and the kinematics of emplacement. The protolith, structures and radiometric age of metamorphic soles constrain to some extent the tectonic setting, structural evolution, and minimum age of initial ophiolite emplacement. If this age is nearly the same as ophiolite cooling ages, then tectonic constraints provided by data from metamorphic soles may also apply to ophiolite genesis.

The metamorphic sole at the base of the Oman and Brooks Range ophiolites are made up of a complex of amphibolite facies schists, which usually overlie greenschist facies metasediments and metabasites (Searle & Malpas 1980; Ghent & Stout 1981; Harris 1989). Both complexes have many geochemical and petrological affinities to underthrust sedimentary and igneous sequences. Underlying both ophiolites and most other Tethyan-type complexes are an allochthonous assemblage of dominantly within-plate and MORB type lavas (E- and N-type MORB) and shallow-water carbonates. Shale, pelagic sediments, and in some cases greywacke are also found. The assemblage is often chaotic with blocks in a clay matrix and is commonly described as a melange.

These melange deposits are known in Oman as the Hawasina melange (Graham 1980) with the Oman exotics (shallow water carbonates) and Haybi volcanics (Searle *et al.* 1980). Robertson *et al.* (1988) demonstrated that some of the Oman 'exotics' can be correlated with pre-rift sequences of the Arabian continental margin that were detached and isolated during breakup of Gondwana.

Similar stratigraphic and structural relations exist in the Brooks Range where the Okpikruak melange (Crane 1987) consists mostly of blocks and thrust panels of E- and N-type MORB lavas and shallow-water carbonates of the Angayucham terrane, and broken formations of slope and rise facies sediments. Like some of the Oman 'exotics', the many carbonate blocks incorporated into the emplacement assemblage are correlative with pre-rift deposits of the Brookian passive continental margin. The allochthonous lavas and sediments are generally interpreted as accreted seamounts (Pallister 1985; Pallister *et al.* 1989; Barker *et al.* 1988). However, the position of the seamounts relative to the ancient continental margin is unknown. Stratigraphic data indicate that in places the lavas are in depositional contact with carbonates of the continental margin (Dumoulin & Harris 1987). These stratigraphic data indicate some of the seamounts may represent detached blocks of the distal continental margin. A continental margin origin for the lava sequence is not incompatible with the geochemistry of allochthonous lava sequences below the Brooks Range ophiolite.

Thick igneous sequences, similar in chemistry, petrology, thickness, associated sediment, and age relations to allochthonous mafic crust below many Oman-type ophiolites, are common along continental margins (Mutter *et al.* 1988). Some well documented examples are the continent–ocean transition zones of the Norwegian–Rockall, and conjugate East Greenland banks; outer Scott, Wallaby and Naturaliste plateaus of Western Australia; and the SE Weddell Sea of Antarctica. These 'volcanic margins' (Mutter *et al.* 1988) are characterized by a thick wedge (up to 10 km) of seaward dippling tholeiitic lava flows with dominantly E- and N-type MORB chemistry (Eldholm *et al.* 1986). The lavas erupted in continent–ocean transition zones during and after continental break-up as those referred to earlier in Timor (Aileu-Maubisso) uplifted by erosion. These volcanic rocks are very different in age relation and chemistry to Oman-type ophiolites.

The metamorphic sole of the Brooks Range ophiolite preserves in places a transitional relationship between continental margin volcanic and sedimentary sequences and greenschist facies metavolcanics and metasediments. Trace and rare earth element abundances in amphibolite schists of the metamorphic sole are the same as those in the volcanic rocks (Harris 1987*a*). Interlayered with the amphibolites are garnet–mica schists with pelitic protoliths. Staurolite is reported by Boak *et al.* (1987) in a schist with rounded plagioclase and lithic porphyroclasts. The porphyroclasts appear as relict detrial grains. The composition of relict grains indicates that the schist has a feldpathic, lithic graywacke protolith.

Garnet–biotite geothermometry and thermometric data from other minerals in the metamorphic soles of the Oman and Brooks Range ophiolites document minimum temperatures of 550–650°C were obtained during prograde dynamothermal metamorphism. Two-mica granitoids and other types of felsic igneous segregations occur locally along the base of the Brooks Range and other Tethyan-type ophiolites. These segregations most likely represent low temperature anatectic melts in the metamorphic sole.

The temperatures necessary to generate these melts and amphibolite grade conditions are near the maximum static temperature of contact metamorphism given by $(0.5)T$ (Jaeger 1961; Spray 1984). This estimate represents the maximum temperature attainable by linear flow from a hot upper slab of peridotite (1000°C) to a cool lower one (0–200°C). T is the temperature difference between the slabs. According to this relation the Brooks Range, Oman, and other Tethyan-type ophiolites did not cool significantly before coming into contact with underlying rocks incorporated into the metamophic sole. Stratigraphic ties and transitional contacts between material incorporated into metamorphic soles and the continental margins of the Brooks Range and other ophiolites implies that these ophiolites were formed very near the continental margins they now structurally overlie.

Age relations

The relationship of ages between ophiolites and their metamorphic soles is difficult to resolve without radiometric dating techniques that provide a measure of radiogenic daughter retentivity over time. One of the most useful of these methods is the $^{40}Ar/^{39}Ar$ (Ar/Ar) dating method.

Geochronological studies of the Brooks Range ophiolite, using conventional $^{40}K/^{40}Ar$ (K/Ar) dating methods, yielded hornblende crystallization ages ranging from 147 ± 15 to 202 ± 6 Ma (Harris 1987*b*). However, Ar/Ar analyses (using some of the same samples) yielded hornblende plateau ages that cluster between 163–179 ± 5 Ma. Similar results are obtained from K/Ar and Ar/Ar age analysis of hornblende from the same samples of amphibolite schist in the metamorphic sole. The K/Ar analysis yielded ages of 153–157 ± 5 Ma (Boak *et al.* 1987; Harris 1989), compared to Ar/Ar plateau ages of 164–169 ± 3 Ma (Harris 1989).

The significant aspect of this age dating experiment is revealed by Ar/Ar age spectra that show both extraneous Ar and diffusive loss of Ar contribute to the wide range of K/Ar ages. Loss of ^{40}Ar from hornblende in the metamorphic sole is also detected from Ar/Ar age analyses. Due to partial Ar loss, the metamorphic hornblendes yield K/Ar ages a minimum of 10 Ma younger than their Ar/Ar plateau age. Interpretations based on the K/Ar age data alone would significantly exaggerate the time gap between ophiolite genesis and emplacement.

Ar/Ar age data from the Brooks Range, Oman and other Tethyan-type ophiolites, including some cordilleran-type ophiolites such as the Josephine massif (Alexander & Harper, this volume), indicate that subophiolite metamorphic cooling is nearly synchronous with ophiolite genesis. In the case of the Brooks Range ophiolite, the metamorphic sole includes continental margin sequences, which constrain the site of the ophiolite genesis to very near the Brookian continental margin. It is suggested here that other Oman-type ophiolites may also have formed very near the continental margins that they now structurally overlie. This inference is supported by the Ar/Ar age relationship between the formation and emplacement of most Oman-type ophiolites and the age of continental margin collision (see Lippard *et al.* 1986).

The cooling history of the BRO metamorphic sole illustrates the close genetic links between Oman-type ophiolites and collisional deformation (Fig. 8). Ar/Ar age data from metamorphic minerals with differing Ar retentivities provide independent time-temperature control points. These controls are combined with age data from various metamorphic rocks in the core of the Brookian orogen. In this way temperature–time paths are constructed for the ophiolite that show its temporal and gross spatial relationship to metamorphic cooling and uplift of the Brooks Range. These paths intersect with temperature ranges for the thermal maturation of deformed sediments that structurally underlie the BRO around the time of maximum fold–thrust deformation (Fig. 8).

Age spectra from Ar/Ar analyses are available for hornblende, biotite and K-feldspar from the metamorphic sole of the BRO (Wirth *et al.* 1986; Harris 1989). Relating the age spectra to effective closure temperatures of these minerals defines temperature–time coordinates of an empirical cooling curve for sub-ophiolite metamorphism (Fig. 8). Argon closure temperatures are a function of mineral composition and structure, grain size and shape, and cooling rate. An intermediate cooling rate (10°C/Ma) is assumed for the BRO because of the difference in age

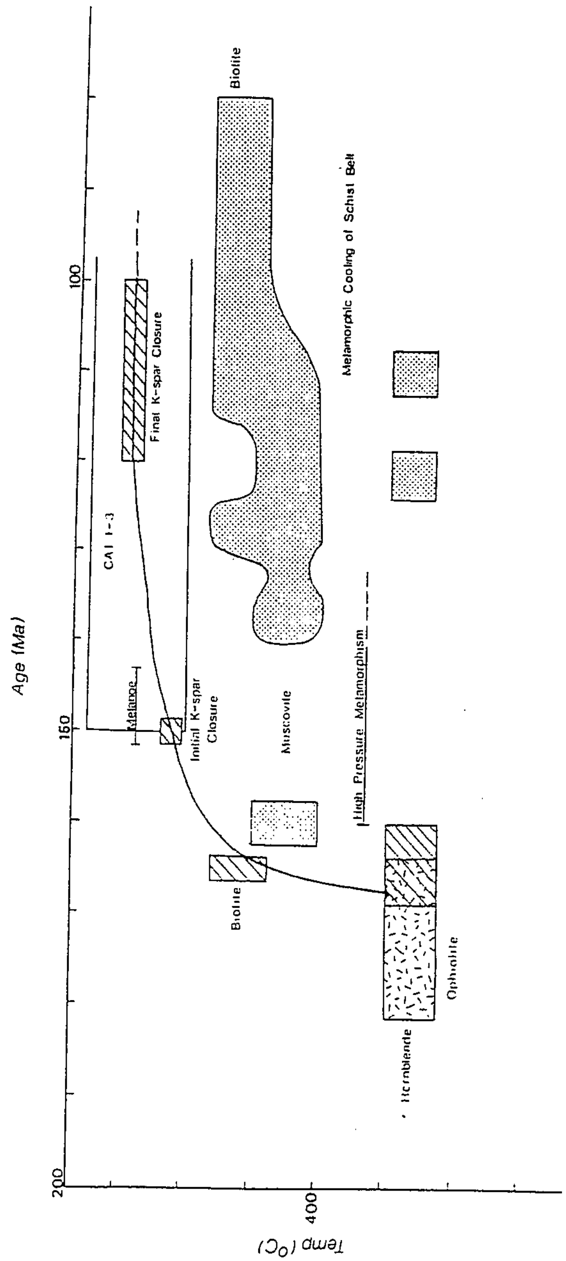


Fig. 8. Cooling curve of sub-ophiolite metamorphics (diagonal stripe) relative to age and blocking temperature of the Brooks Range ophiolite (random), high pressure metamorphism in orogenic core (dots), and Conodont Alteration Index (CAI) of structurally underlying sequences.

between sub-ophiolite metamorphism, basement uplift, and deposition of detritus from structurally underlying lithotectonic units (e.g. high pressure metamorphic rocks; Till *et al.* 1988). At these cooling rates, argon closure for hornblende occurs at 530°C ± 40°C (Harrison & McDougall 1980). This temperature range overlaps with temperature estimates of peak metamorphism for the BRO metamorphic sole (Boak *et al.* 1987; Harris 1988*a*, *b* 1989) suggesting that hornblende Ar/Ar ages most likely document the time of peak metamorphism. Argon closure temperatures are much lower for biotite (280°C ± 40°C) and K-feldspar (150°C ± 30°C) (Harrison & McDougall 1982).

Wirth *et al.* (1986) obtained Ar/Ar age data for hornblende (164–169 Ma) and biotite (165 Ma) from schists, and K-feldspar (146 Ma) from partial melts, of the BRO metamorphic sole. The K-feldspar yields a complex release spectrum compatible with continuous Ar loss until 110 Ma. Time-temperature plots of the data show an exponential decline in temperature from peak metamorphism (Fig. 8). The concavity of the cooling curve indicates that thermal contrasts were sufficient between the BRO and underthrusted rocks for conductive cooling. Ar/Ar analyses of hornblende from other parts of the metamorphic sole (Harris 1989) are consistent with these results. Ar/Ar age data from secondary amphiboles in the metamorphic sole (Wirth *et al.* 1986) and from faults within the BRO (Harris 1989) do not fit the simple exponential cooling pattern of prograde metamorphic hornblende. Although these younger ages are within error limits of prograde hornblende, they may indicate that locally palaeotemperatures were near hornblende closure after most sub-ophiolite metamorphic rocks had cooled to 200–300°C. The non-uniform temperatures may result from shear localization associated with one or more episodes of emplacement-related faulting or from the lower Ar closure temperature of the actinolitic hornblende dated.

The flattened time-temperature path for final cooling from K-feldspar of the BRO ophiolite metamorphic sole intersects with palaeotemperatures obtained from conodont alteration indexes (Harris *et al.* 1987) in sediments underlying the BRO (Fig. 8). At this time the BRO formed part of the Brookian fold-thrust system. The timing of BRO genesis and emplacement relative to other major events of the Brookian orogeny is instructive (Fig. 9) and similar to those from other ophiolite-bearing mountain systems (e.g. Lippard *et al.* 1986; Jamieson & Beaumont 1988). The formation and emplacement of the BRO is the first event to interrupt the protracted passive history of the Ellesmerian continental margin. The emplacement related uplift and cooling of the BRO is followed by the first stratigraphic evidence of orogenic (Brookian) sedimentation. Melange deposits associated with these sediments host exotic blocks derived in part from arc-type lavas. Before the end of the Jurassic, shelf facies and platform sediments were incorporated into the ophiolite-bearing orogenic wedge. The deformation involved southward continental underthrusting as evidence by an extensive Late Jurassic to Early Cretaceous high pressure

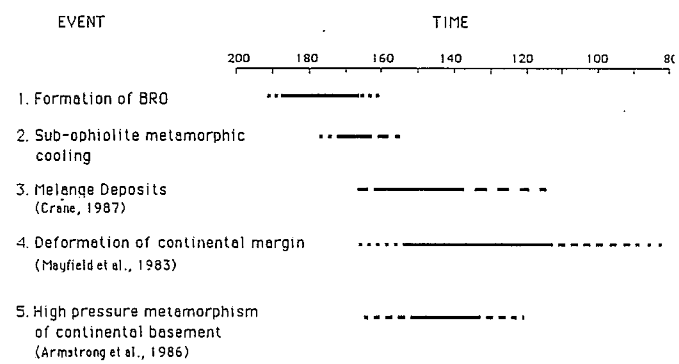


Fig. 9. Timing of Brooks Range ophiolite genesis and emplacement relative to other major events associated with the Brookian orogeny.

metamorphic complex exposed in the core of the Brooks Range (Armstrong *et al.* 1986). These geologic relations mimic those found in Oman and other Tethyan ophiolites (Lippard *et al.* 1986).

Age and thermal history constraints for sub-ophiolite metamorphism and collisional deformation provide critical spatial and temporal links between the processes of ophiolite genesis, emplacement and continental margin contraction. Amphibolite grade metamorphic rocks and partial melts at the base of the BRO require a dynamothermal metamorphic condition at the maximum temperature range of ophiolites. These amphibolites are compositionally and chemically indistinguishable from underlying low to very low grade lavas and sediments of the Angayucham terrane. This terrane is correlative in part with the continent–ocean transition of the Ellesmerian continental margin that the BRO now structurally overlies. Similar correlations exist throughout Tethys including the Aileu-Maubisse Formation that structurally underlie the Ocussi volcanics.

Stratigraphic and structural data indicate that the transition from passive margin to orogenic sedimentation in these collision zones (initiation of collision) occurred around the time of ophiolite genesis and emplacement. This implies that the formation of Oman-type ophiolites are linked in time and space to the arrival of the trench (deformation front) at the continental margin. These constraints suggest that the processes of ophiolite genesis and emplacement are not only kinematically linked but that the mechanisms of formation will normally lead to emplacement.

Kinematic models

Peri-collision temporal and spatial relations, and the discontinuous occurrence of ophiolites in many fold-thrust mountain systems, are difficult to reconcile with models postulating that the formation and emplacement of ophiolites are intra-oceanic processes. MORB-type oceanic crust is rarely represented as ophiolites (Coleman 1984) probably because subduction rarely initiates within this high-strength crustal environment. A possible exception to this rule is at active spreading ridges where high thermal gradients may significantly reduce the strength of oceanic lithosphere. Boudier & Coleman (1981) and more recently Boudier & Nicolas (1988) suggest that intra-oceanic spreading systems are a favourable site for the generation and emplacement of ophiolites. This model predicts that changes in plate motion may cause compression of an actively spreading ridge, leading to overthrusting of one hot ridge segment over the other. The product of such an event may be consistent with the internal structure and hot emplacement of Oman-type ophiolites, but is inconsistent with the compositional differences between ophiolites and their metamorphic soles.

The high temperature metamorphic sole of Oman-type ophiolites document the composition of some of the first rocks the hot ophiolite came into contact with, either by underthrusting (Williams & Smythe 1973), or intrusion (McTaggert 1971; Hall 1984). Initiation of subduction at an active mid-oceanic spreading ridge would imply that the first rocks the upper plate of hot oceanic lithosphere came into contact with would be the upper crustal section of oceanic lithosphere on the other side of the ridge. According to this scenario, the protoliths of the subophiolite metamorphic material should be similar in age and chemistry to the ophiolite itself. This relationship has yet to be documented from subophiolite metamorphic rocks. Little, if any, genetic relationship exists in age and chemistry between, Oman-type ophiolites and the much older E- and N-type MORB rocks that comprise most sub-ophiolite metamorphic soles and structurally underlying allochthons (e.g. Haybi, Angayucham and Maubisse lavas).

Apart from intra-oceanic thrusting models, collision of intra-oceanic arcs with continental margins are most commonly used to account for Oman-type ophiolite emplacement. Although the formation and evolution of intra-oceanic arcs may involve SSZ spreading (Hawkins *et al.* 1984; Leitch 1984; Pearce *et al.* 1984), special circumstances are required to account for Oman-type ophiolite associations if the processes responsible for generating SSZ ophiolites are not kinematically linked to the processes of emplacement (collision). Ideally, the whole history of these ophiolites, from their genesis as a small ocean basin to their incorporation into a fold–thrust mountain system should be explicable in terms of one or a combination of self-perpetuating mechanisms.

Multi-plate interactions

To reconcile the SSZ spreading model for the origin of ophiolites with Oman-type ophiolite associations, mechanisms are needed to drive SSZ spreading around or within zones of collision involving passive continental margins. The Banda orogen of eastern Indonesia provides a natural laboratory for investigating these mechanisms. Active convergence between the Pacific, Australian, and SE Asian plates drives the Banda orogen (Fig. 2). The relative motions of these plates are well constrained throughout the Tertiary by ocean-floor palaeomagnetic data. During most of this time the SE Asian plate has remained relatively fixed in the global reference frame, experiencing only minor rotation (Irving 1977; Morgan 1983). Relative to the SE Asian plate, the Australian plate moves NNE at 77 km/Ma, and the Pacific plate moves WNW at 100–130 km/Ma (Minster & Jordan 1978).

Collision initiated during the mid-Tertiary between arc terranes of the SE Asian/Pacific plate systems and the passive margin of northern most Australia. An arcuate zone of convergence and sinistral shear developed as the irregular passive margin became progressively more involved in the collision. In the collision zone, superposition of WNW and NNE plate motion fragments northern Australia into several continental microplates that move WNW with the Pacific plate (Hamilton 1979; Silver *et al.* 1985). The Irian Jaya, Buru and Sula microplates (Fig. 2) are some of the most conspicuous examples (McCaffrey 1988; De Smet 1989). Palaeomagnetic data suggest that the combined motion of these plates have rotated the northern Banda orogen more than 74° counter-clockwise (Haile 1979).

Interactions between major and micro plates at the Pacific–Australia–SE Asia plate triple junction produce instabilities along plate boundaries that change in time and space. Simplified demonstrations of these instabilities are possible by multi-plate Euler pole analysis (Cox & Hart 1986). For example, the Weber basin is presently situated in a sinistral shear couple between the SE Asia, Australia and Irian Jaya plates (McCaffrey 1988). Extension in the basin may accommodate E–W stretching of the Banda Sea region as it is pinched between the converging Australia and Pacific plates (McCaffrey 1989). This plate configuration is inherently unstable due to eventual closure of the Banda Sea. Parts of the southern Weber basin are already incorporated into the hinterland of the Banda orogen fold–thrust zone (Bowin *et al.* 1980), while other parts of the basin are actively spreading near the axis of SSZ magmatism. The dynamics of these unstable plate boundaries provide an important mechanism of crustal scale noncoaxial strain, common to most collisional orogens where Oman-type ophiolites are found. This deformation mechanism is observable at all scales of rock deformation including the development of pressure fringes and shadows around rigid grains.

Trench retreat

Another fundamental mechanism for driving SSZ spreading is trench retreat. This mechanism is used to explain the kinematics of extension behind several subduction zones (Elsasser 1971; Moberly 1972; Molnar & Atwater 1978; Chase 1978; Dewey 1980; Malinverno & Ryan 1986). The trench retreat model assumes that the structural evolution of a subduction system is controlled by the character and geometry of the down-going plate. In the Banda orogen the character of the lower plate changes profoundly with time and along present orogenic strike (Harris 1991). It is proposed here that transitional-type ophiolites may represent SSZ extensional domains that form around and within collision zones involving irregularly shaped continental margins. The extension may produce small ocean basins that form behind trenches advancing into embayments of an irregular continental margin. These extensional domains are peri- and intra-collisional.

If a subducting continental margin is long-lived, as is usually the case with Oman-type ophiolites, the attached oceanic slab that is subducted usually forms a very steep Benioff zone as in the Banda arc (uncoupled subduction system). The negative bouyancy of this slab has the potential of pulling the continental margin a significant depth below the orogenic arc before it resists further underthrusting. This process may account for the emplacement of large nappes of forearc basement in central Timor and parts of Seram where initial collision occurred between the Banda arc and continental promontories. It can also explain the development of deep foreland basins that require an additional load to that of the orogenic wedge in order to account for the degree of crustal downwarping observed in some active (Timor trough) and ancient (Brooks Range) orogens. The lack of nappes, and the relatively shallow foreland basin in Taiwan where the continental margin is young, is explicable in terms of this mechanism.

It is suggested here that after initial underthrusting of continental promontories, the forearc upper, and continental lower plates become increasingly coupled and kinematically linked in that segment of the collision zone. This coupling is well documented in both the Banda arc and Taiwan by the indentation of the deformation front, late collisional development of strike-slip faults, and the initiation of subduction polarity reversal (Silver *et al.* 1983; Suppe 1984; Breen *et al.* 1989; Harris 1991). If the underthrust continental margin is irregular or its collision with the trench oblique, the lower plate should continue to subduct (roll back) in uncollided regions, while advancement of the upper plate is restricted by increased coupling at the initial points of collision. As the trench retreats toward the descending lower plate and the arc–trench gap widens, the fixed upper plate is required to extend to keep pace with trench retreat.

The arc–trench gap of the Java trench provides an important reference for the precollisional arc–trench distance of the Banda arc. On both sides of the Timor collisional indentation the trench has migrated 100–150 km further away from the volcanic arc than the stable Java subduction system to the west (Figs 2 & 3). The Savu and Weber Basins have opened behind where the trench migrates. Oblique convergence adds a simple shear component that can enhance trench retreat in some regions. The retreat of the trench may also be enhanced by viscous drag beneath continents (Richardson *et al.* 1976). Edelman (1988) suggested that the simple presence of a continent on the subducting plate would contribute to ophiolite generation.

According to the trench retreat model, sites of ophiolite formation most likely coincide with regions where the Banda orogenic front stretches along increasingly oblique margins and to fill embayments in the Australian margin (orogenic 'pressure shadows'). The configuration of the continental margin lower plate then, may exert a first order control on the formation of ophiolites.

Ancient collisional orogens

Many Oman-type ophiolites mimic the characteristics of modern, peri-collisional basins in the Banda orogen. For example, (1) the arcuate nature of the Brooks Range and Oman ophiolites may represent embayments or strike-slip offsets in the ancient Ellesmerian (Box 1985) and Arabian platforms (Robertson *et al.* 1989); (2) the Cyprean arc and its associated ophiolites formed in a major ocean-floored embayment between the Apulian continental block to the west and the Arabian Peninsula on the east at the time of the collision of these blocks with Eurasia (Moores *et al.* 1984; Van der Linden 1985); (3) the formation of the Tyrrhenian Sea and the Calabrian arc is attributed to trench retreat into a continental re-entrant (Malinverno & Ryan 1986); (4) arcuate ophiolite bearing mountain belts occur throughout the irregular and oblique collision zone between the African and Eurasian plates (Alps, Appennines, Calabria, Carpathians, Hellenides and Aegean arc), and the Palaeozoic collisions of Laurentia, Africa and Avalonia (Caledonides and Appalachians).

Implications

The Weber and Savu basins of the Banda arc provide modern examples of peri-collisional SSZ basin development by both simple and pure shear mechanisms. The basins are pinned at their edges by coupled arc–continent collisions that lack Oman-type ophiolites. The tectonic evolution of the Andaman Sea pull-apart basin (Peltzer & Tapponnier 1988) is not dissimilar to that of the Weber Basin, although the Andaman Sea has a clearly defined spreading zone. Both regions represent margin-parallel collisions between continents of the Indo-Australian plate and Asia. Continental indentation causes rotation of the Sunda Trench parallel to the convergence direction and upper plate extrusion, which contribute to basin development in these regions. Peri-collisional extension in the basins form arcuate, concave deeps that open above subduction zones adjusting to collision-induced instabilities. These instabilities may be enhanced by complex passive margin structure and oblique convergence.

It may be argued that the sediment infill of these basins is atypical of many ophiolites overlain dominantly by pelagic sediments. However, the sediment cover of the Savu basin is very similar to Cyprus, where pelagic sediments are dominantly overlain by thick marls and clastic sedimentary deposits. The Weber Basin on the other hand is relatively starved of sediment and is associated with sparse arc volcanism, like the Oman and Brooks Range ophiolites.

Possible geochemical effects of peri-collisional basin development are also important to consider. The SSZ setting of these basins predicts that very thin and extended ocean crust may form above a dehydrating lower plate. The addition of water from the lower plate to the site of magma generation imparts an arc imprint on the new lithosphere (Pearce 1980). It is also possible that attenuated continental crust of the lower plate or accreted material in the forearc may interact with SSZ magmas giving rise to the diverse magma compositions found in many ophiolites. Some of these magmas may lead to volcanics similar in composition to calc-alkaline island arcs, but form in quite different settings (Coleman 1984).

Conclusion

Comparisons between the Brooks Range and Oman ophiolites and modern arc–continent collisions (Timor and Taiwan) indicate that the generation and emplacement of many Oman-type ophiolites are kinematically linked and intimately associated with collisional contraction of long-lived continental margins. Any model which unifies the various mechanisms and characteristics of Oman-type ophiolite genesis and emplacement must account for the following: (1) incipient arc-type geochemical and petrological features; (2) ocean crust extensional structure; (3) thinness when compared to ocean crust and arcs; (4) composition and age of metamorphic soles; (5) immediate emplacement; (6) lateral discontinuities.

Peri-collisional extension in parts of the Banda orogen provide a modern analogue of processes that lead to the opening of temporary SSZ basins that may be obducted during or shortly after they form. Samples of the east Savu basin basement (Ocussi volcanics) document the chemical imprints of SSZ volcanism immediately adjacent to initial collisional indentation of Timor. The age and tectonic relations associated with the origin and emplacement of the Ocussi nappe, and its incorporation into the fold-thrust belt of West Timor, mimics Oman-type ophiolite associations.

The kinematic development of peri-collisional basins in the Banda orogen and Oman-type ophiolite associations may involve: trench retreat into continental embayments, which may require considerable peri-collisional forearc extension; and/or opening of rhombocasmic basins in peri- or intra-collisional settings by transtension. The peri-collisional kinematic model for the origin and emplacement of ophiolites not only accounts for the commonalities of Oman-type ophiolites, but also allows for considerable structural and compositional diversity. The discontinuous nature of ophiolite development in modern arc-continent collisions (Banda orogen and Taiwan) is also explicable in terms of this model, as is the immediate emplacement and arc imprint of the Brooks Range and other Oman-type ophiolites.

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