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The Timor ophiolite, Indonesia: Model or myth?

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ABSTRACT

Geologic and geochemical associations of ophiolite-like rocks in Timor provide conflicting evidence for claims that the collision between the Banda arc and the Australian continent is a modern analogue for the formation and emplacement of Oman-type ophiolites or that an ophiolite emplacement event took place in Timor. The only parts of an ophiolite sequence that are present in Timor are small bodies of spinel lherzolite and various types of volcanic rocks. The lherzolite bodies are mostly found as blocks within a mélange (Bobonaro mélange) derived primarily from the underthrust Australian continental margin. Mineral and whole-rock geochemical properties of the lherzolite bodies are similar to mostly undepleted and unprocessed peridotites found in abyssal and passive-margin settings.

In East Timor, lherzolite bodies are closely associated with the Aileu complex, which is considered part of the Permian–Triassic basement of the Australian passive continental margin. Mesozoic prograde metamorphism of the Aileu complex increases regionally toward the lherzolite bodies via a Barrovian zonation. Both the Aileu complex and the lherzolite bodies were similarly affected by late Neogene collisional (retrograde) metamorphism.

The Atapupu and Nefomasi lherzolite bodies in West Timor are petrologically and geochemically indistinguishable from those of East Timor. The same is true with other lherzolite blocks found within the Bobonaro mélange. The structural position of these lherzolite bodies indicates an affinity to thrust sheets accreted from the distal edge of the Australian continental margin (lower plate) rather than from forearc basement of the upper plate.

Lherzolite bodies and volcanic units in the Ocussi region are different and may represent parts of a young, SSZ (supra-subduction zone) ophiolite that was emplaced within a few million years of its birth.

INTRODUCTION

The Banda arc–Australian continent collision zone of eastern Indonesia features the closure of a Tethys-like seaway composed of marginal basins and arc terranes caught between the converging continents of Australia and Asia (Fig. 1). The region displays a tectonic scenario commonly attributed to the generation and emplacement of Oman-type ophiolites (i.e., Moores, 1982; Searle and Stevens, 1984). From ca. 35 Ma to the present, the passive continental margin of northern Australia has shouldered into and under a series of marginal basins, and the result has been the emplacement of several mafic and ultramafic bodies. The largest body, which is in eastern Sulawesi, is the size of the Oman ophiolite. Other mafic and ultramafic bodies are found throughout the outer islands of the Banda arc, which formed during the Neogene. However, little is known about the origin and tectonic affinity of these rocks.

Most models for the tectonic evolution of the outer Banda arc interpret the mafic and ultramafic rocks incorporated into the forearc as fragments of young oceanic lithosphere derived from the Banda arc upper plate (Hamilton, 1979; Earle, 1980, 1981; Brown and Earle, 1983; Sopaheluwakan et al., 1989; Linthout and Helmers, 1994). Associated metamorphic rocks are interpreted as a metamorphic sole that formed during tectonic emplacement while the "ophiolite" was hot. Volcanic rocks in West Timor of arc affinity and late Neogene age are consistent with this interpretation (Harris, 1991). However, Berry (1981), Berry and Grady (1981), and Berry and McDougall (1986) showed that the Hili Manu lherzolite of East Timor is compositionally akin to peridotite found in oceanic and continental-margin settings. They also showed that the lherzolite is associated with 70 Ma or older prograde metamorphism of Permian–Triassic Australian affinity sequences. These relationships imply more of an association with the lower, continental plate rather than the Neogene Banda arc.

Distinguishing between an upper- or lower-plate origin for the ultramafic bodies of Timor is critical for tectonic reconstruction of the Banda arc–Australian continent collision, which is commonly used as a modern analogue for the emplacement of SSZ (supra-subduction zone) ophiolites. In this paper, we present data from studies of the mineral and whole-rock chemistry and geologic associations of several ultramafic bodies found along the suture zone of the modern arc-continent collision on the island of Timor. The purpose of the study is to test whether the ultramafic bodies are parts of the relatively

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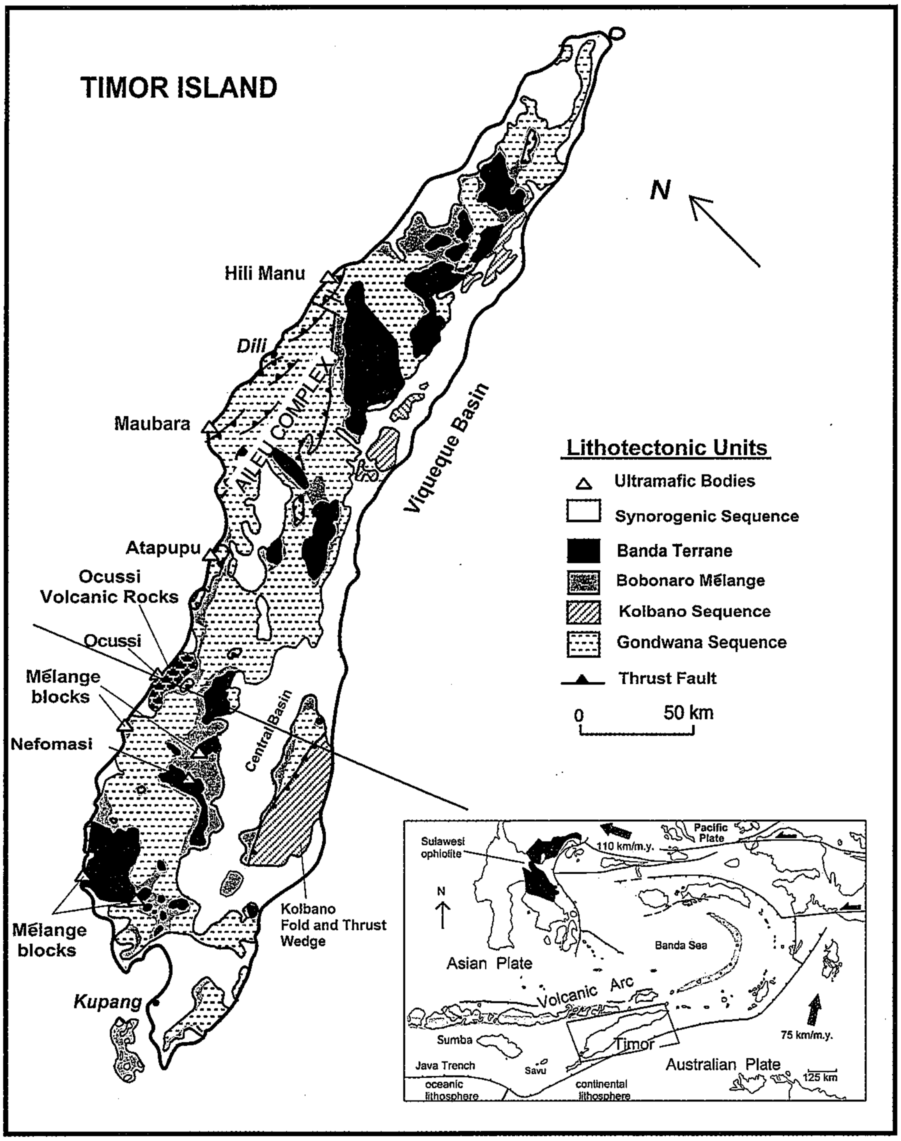

Figure 1. Map of the lithotectonic units of the island of Timor. Nappes of Banda terrane (black) are erosional remnants of the uppermost structural unit of Timor, considered by many as associated with an ophiolite. Ultramafic bodies found throughout the island and sampled as part of this study are labeled and shown (open triangles). The Banda terrane is structurally underlain by the Sonnebaite disruption zone (Bobonaro mélange, gray), a mélange zone that separates units of Asian and Australian affinity. Most of the ultramafic bodies are found in the mélange or hosted by the uppermost nappe of the Gondwana sequence of Australian affinity. Northwest-southeast line of cross section in Figure 2 is shown. Inset: Reference map shows plate motion vectors and the island of Timor in reference to the Banda arc–Australian continent collision (gray is active zone of volcanism). The Banda Sea is trapped by the northward-moving Australian plate and the westward-moving Pacific plate that impinge upon the Sunda Shelf of the Asian plate. The Sulawesi ophiolite may represent a fragment of oceanic crust from the Banda Sea that was emplaced over the Sunda Shelf during the Oligocene (Parkinson, 1998).

young Banda arc upper plate or of Mesozoic suboceanic or subcontinental mantle that was sheared from and shoved back over the lower-plate continental margin during arc-continent collision.

REGIONAL GEOLOGIC SETTING

The island of Timor, Indonesia, occurs above a Miocene to Holocene subduction zone into which the northwest Australian continental margin has entered obliquely (Fig. 1). The resulting arc-continent collision began in central Timor during the late Miocene and has propagated westward at a rate of ~110 km/m.y. (Harris, 1991) to its current position south of the island of Sumba.

Timor is part of the nonvolcanic, outer Banda arc, a contractional wedge formed mostly by mechanical accretion of underthrust Australian continental-margin cover sequences (Gondwana and Kolbano Sequences, Figs. 1 and 2). Most ophiolite-like rock units are found in the hinterland of the wedge, which consists of klippen of distal parts of the underthrust Australian continental margin and the Banda terrane of Asian affinity. The Banda terrane is made up of volcanic and sedimentary sequences associated with the Sunda and Banda volcanic arcs that overlie a polyphase metamorphic complex (Audley-Charles and Harris, 1990). The metamorphic rocks yield K-Ar and ^{40}Ar/^{39}Ar cooling ages of 32–35 Ma (Sopaheluwaken et al., 1989; Dropkin et al., 1993). The Bobonaro mélange is commonly

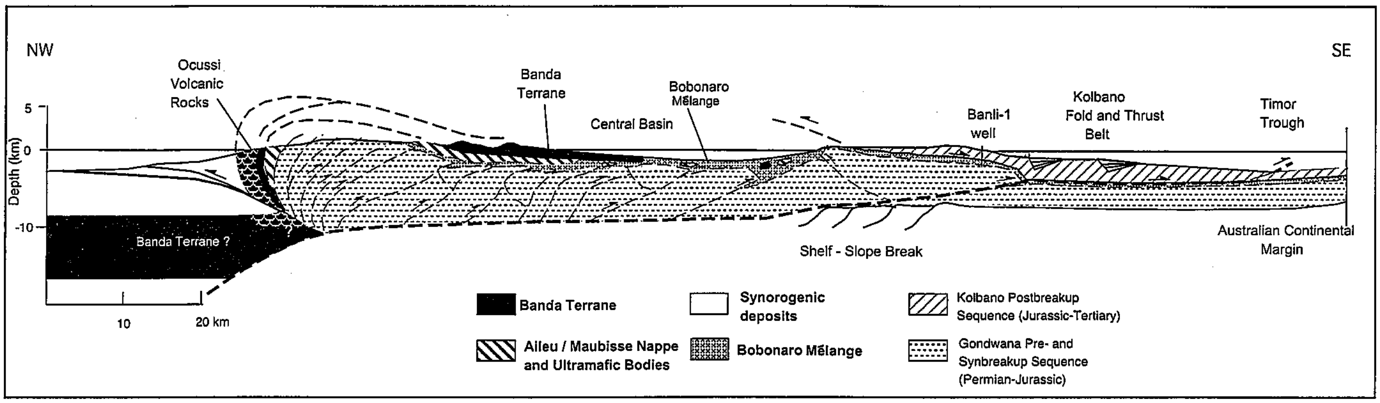

Figure 2. Northwest-southeast structural section across West Timor (modified from Harris et al., 1998). The underthrust and tectonically stacked Australian continental margin is structurally overlain by the Aileu-Maubisse nappe, Bobonaro mélange, and Banda terrane. The collisional suture between units of the Australian and Asian plates is at the base of the Banda terrane. The roots of the Banda terrane are inferred as the footwall to the retrowedge thrust system. The Ocussi volcanic rocks are the only part of the Banda terrane that shows any SSZ ophiolitic affinity. The underthrusting of continental-margin material beneath the roots of the Ocussi body may represent a model for the emplacement of SSZ ophiolites.

found at the structural base of Banda terrane klippen and is composed mostly of material derived from structurally underlying Australian continental-margin sequences (Harris et al., 1998). The mélange marks the collisional suture between the Australian lower plate and the Asian upper plate. Most of the ultramafic rocks in Timor are found as blocks or thrust sheets within this mélange or at the same structural level as the Aileu-Maubisse thrust nappe. This nappe is composed of mostly Permian and Triassic carbonate rocks, alkalic pillow basalt, and psammite that accumulated in an intracratonic rift basin. Seafloor spreading began in the basin during the Late Jurassic, which left the Aileu and Maubisse units at the edge of the northwest Australian passive continental margin. In this position, these units were some of the first ones to accrete to the Banda arc during Neogene arc-continent collision (Audley-Charles and Harris, 1990).

Many different interpretations exist concerning the structural evolution of the collisional event that formed Timor (Hamilton, 1979; Carter et al., 1976; Chamalaun and Grady, 1978, Harris, 1991). However, all conclude that Timor occupies a suture zone between the Asian and Australian plates and that Australian continental crust extends to the northern edge of the island where most of the lherzolite bodies are found. Spinel lherzolite has also been dredged from a large seamount or ridge at the edge of the western Australian passive continental margin near the transition from thinned continental crust to initial (earliest) oceanic crust (Nicholls et al. 1981). Lherzolite bodies uplifted by extensional denudation and serpentinite diapirism are not uncommon in passive-margin settings (i.e., Eldholm and Talwani, 1981; Boillot et al., 1987; Bonatti and Michael, 1989).

GEOLOGIC ASSOCIATIONS AND INTERPRETATIONS

De Roever (1940) and De Waard (1954) were the first to refer to an ophiolite or "Alpine-type" peridotite in Timor. Their interpretations were based on the discovery in central West Timor of peridotite, serpentinite, and pillow basalt that were spatially associated with a multiphase metamorphic sequence. Hamilton (1979), with no additional data, reinterpreted these units as parts of a young ophiolite sequence derived from the Banda forearc, as was predicted from studies of ancient arc-continent collision zones (i.e., Dewey and Bird, 1971). Field studies by Earle (1980, 1981), Brown and Earle (1983), and Sopaheluwakan et al. (1989) represented the mafic and ultramafic rocks of West Timor as a reversely ordered ophiolite that structurally overlies an inversely zoned metamorphic sole of Oligocene age.

Hili Manu lherzolite

Berry (1981) analyzed the Hili Manu lherzolite body of East Timor as part of his study of the Aileu complex schist belt, a mostly pelitic and mafic volcanic metamorphic belt along the north coast of Timor. He found that the petrology and geochemistry of the Hili

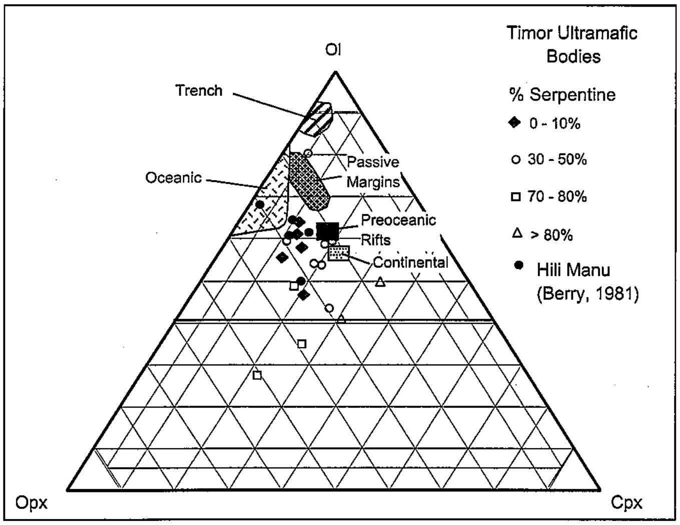

Figure 3. Modal abundance of olivine, orthopyroxene, and clinopyroxene for the ultramafic bodies of Timor compared to ultramafic rocks from known tectonic settings. Rock classification according to Streckeisen (1976). Symbols for the Timor samples correspond to degree of serpentinization, according to the amounts of (Ol + serpentinized Ol) and (Opx + Cpx + serpentinized Px). Samples with <75% serpentinization had roughly equal abundance of orthopyroxene and clinopyroxene or were slightly to moderately enriched in orthopyroxene. Also plotted are modal abundances from the Hili Manu lherzolite of Berry (1981). Fields are taken from Bonatti and Michael (1989). Timor samples cluster with relatively undepleted tectonic settings.

TABLE 1. WHOLE-ROCK GEOCHEMISTRY OF TIMOR ULTRAMAFIC BODIES

	Atapupu*	Atapupu*	Hili Manu*	Hili Manu*	W. Atapupu*	Mélange*	Mélange*	Mélange*	Mélange*	Nefomasi†	Nefomasi†	Nefomasi†	Nefomasi†	Ocussi†
Latitude	−8.97°S	−8.97°S	−8.49°S	−8.49°S	−9.09°S	−9.62°S	−9.62°S	−9.62°S	−9.46°S	−9.52	−9.52	−9.49	−9.49	−9.21
Longitude	124.9°E	124.9°E	125.93°E	125.96°E	124.8°E	123.68°E	123.68°E	123.68°E	123.91°E	124.25	124.23	124.26	124.26	124.36
SiO_2	38.21	38.24	38.2	42.99	38.69	40.47	40.91	41	38.77	39.91	38.96	39.12	39.03	38.7
TiO_2	0.04	0.01	0.02	0.06	0.04	0.04	0.08	0.07	0.03	0.11	0.03	0.05	0.06	0.01
Al_2O_3	1.62	0.77	1.47	2.4	1.74	2.03	2.67	2.65	1.77	3.46	1.02	1.51	2.1	0.94
Fe_2O_3	7.47	8.01	7.89	8.47	7.26	7.78	8.23	8.11	7.86	7.76	8.49	8.08	8.05	7.94
MnO	0.09	0.07	0.01	0.13	0.08	0.12	0.12	0.12	0.12	0.1	0.11	0.1	0.1	0.1
MgO	35.1	37.05	36.88	39.43	36.52	35.81	36.37	36.15	36.77	36.38	36.64	36.54	36.67	36.67
CaO	0.27	0.13	0.45	2.69	0.21	1.96	1.94	2.48	1.55	2.95	0.69	2.09	0.92	0.92
Na_2O	0.02	0	0.01	0.11	0.27	0.07	0.13	0.13	0.05	0.12	0.02	0.03	0.02	0.02
K_2O	0.01	0.03	0	0.01	0.03	0.01	0.03	0.01	0.04	0.03	0.02	0.02	0.02	0.02
P_2O_5	0.013	0.01	0.012	0.007	0.016	0.008	0.007	0.008	0.005	0.011	0.009	0.01	0.008	0.008
LOI	14.54	13.22	13	3.35	14.76	10.18	9.56	7.72	12.51	N/A	N/A	N/A	N/A	N/A
Total	97.38	97.54	97.94	99.65	99.62	98.75	100.05	98.45	99.48	90.83	85.99	87.55	85.33	85.33
Calc'd FeO	6.72	7.21	7.1	7.62	6.53	7	7.41	7.3	7.07	6.98	7.64	7.27	7.24	7.14
Calc'd Fe_2O_3	0.75	0.8	0.79	0.85	0.73	0.78	0.82	0.81	0.79	0.78	0.85	0.81	0.81	0.8
Mg#	89.86	89.72	89.82	89.78	90.47	89.67	89.29	89.37	89.82	89.84	89.06	89.51	89.55	89.71
Sc	10	8.4	10.6	14.5	10	13	13.5	12.4	11.9	11.8	11.2	11.8	12.2	11.2
V	51	38	50	68	43	65	61	58	56	77	36	59	59	33
Cr	2239	2445	2650	2768	2380	2540	2855	2364	2584	2687	2393	2420	2500	2530
Ni	2159	2266	2238	1909	2119	1940	1946	2014	1861	1832	2117	1908	1968	2117
Cu	13	5	13	17	17	19	26	21	22	18	15	19	17	16
Zn	37	31	34	38	37	39	36	38	36	37	37	37	35	33
Y	1.5	0.4	0.9	2.3	1.1	2.3	1.4	2.2	1.2	1.4	1.4	1.5	1.4	1.3
Sr	3.1	4.8	5	2.9	3.8	3.6	4.7	3.9	20.6	5.8	5.8	5.8	5.8	5.7

Note: Oxide contents are in weight percent; trace elements are in parts per million. FeO is partitioned into FeO and Fe_2O_3 based on methods of Ragland (1989).

* ICP analyses

† XRF analyses

Manu body is characteristic of lherzolite found at mid-ocean ridge diapirs and along continental margins.

Studies of the metamorphic rocks of the Aileu complex associated with the Hili Manu lherzolite by Berry and Grady (1981) and Berry and McDougall (1986) revealed a Barrovian prograde metamorphic zonation that decreases in metamorphic grade westward away from the Hili Manu lherzolite body for over 40 km. The prograde assemblage decreases from upper-amphibolite facies within 10 km from the lherzolite to upper-greenschist facies as much as 40 km away. The prograde mineral assemblage is overprinted by a lower-temperature retrogressive assemblage that decreases from middle- to lower-amphibolite facies to lower-greenschist facies toward the south. $^{40}Ar/^{39}Ar$ analysis of the metamorphic rocks has yielded a minimum cooling age of 70 Ma for the prograde assemblage and 5–8 Ma for the retrogressive assemblage. Berry and McDougall (1986) suggested that the prograde phase of metamorphism may be associated with Mesozoic rifting and development of the Australian passive continental margin, whereas the retrograde phase is a product of Neogene arc-continent collision. An apatite fission-track study by Harris et al. (2000) yields similar results. These age relationships and the scale and metamorphic history of the Aileu complex are not characteristic of subophiolite metamorphic aureoles.

Further studies of the Aileu complex by Prasetyadi and Harris (1996) demonstrate that highly serpentinized parts of the Hili Manu lherzolite and some smaller serpentinite and hornblende diorite bodies near Maubara (Fig. 1) have locally intruded into the Aileu schist. These contact relationships indicate a close association between serpentine diapirism and igneous intrusions with the Aileu complex that is also supported by the decrease in prograde metamorphism away from the peridotite bodies over several kilometers. The pattern of retrograde metamorphism, which is most likely related to arc-continent collision, is much more diffuse and shows no correlation with the ultramafic bodies. Transitional stratigraphic relationships between the Aileu complex and Permian and Triassic pillow lavas, shale, and crinoidal limestone of the Maubisse Formation (Barber and Audley-Charles, 1976; Prasetyadi and Harris, 1996) strengthen correlations of the lherzolite with the Australian continental margin.

Atapupu lherzolite

Small lherzolite bodies are found along the north coast of West Timor near Atapupu (Fig. 1) that are similar in composition to the Hili Manu lherzolite. Maps of the region by Simons (1940) and Helmers et al. (1989) show tectonically interlayered lenses of amphibolite, metapelite, hornblende diorite, and serpentinite that is intruded locally by granite and aplite dikes. Fresh lherzolite bodies are found between massive and brecciated serpentinite with mylonitic laminations and lenses of amphibolite. Many of the lherzolite bodies occur as blocks in the Bobonaro mélange along with fragments of the Maubisse Formation.

Thermobarometric studies of the Atapupu lherzolite by Helmers et al. (1989) indicate decompressional ascent from early equilibration of pyroxene porphyroclasts at 1030–1060 °C above 8 kbar. Neoblasts that formed along the rims of the porphyroclasts during mylonitization equilibrated at 940 and 850 °C at 6–8 kbar. Serpentinization became dominant below 550 °C. Pressure-temperature estimates in associated metapelites show initial isobaric prograde recrystallization at 850 to 800 °C at 6–7 kbar, which was followed by decompression and cooling that parallels the trend found in lherzolite bodies. These relatively high equilibration temperature estimates are identical to

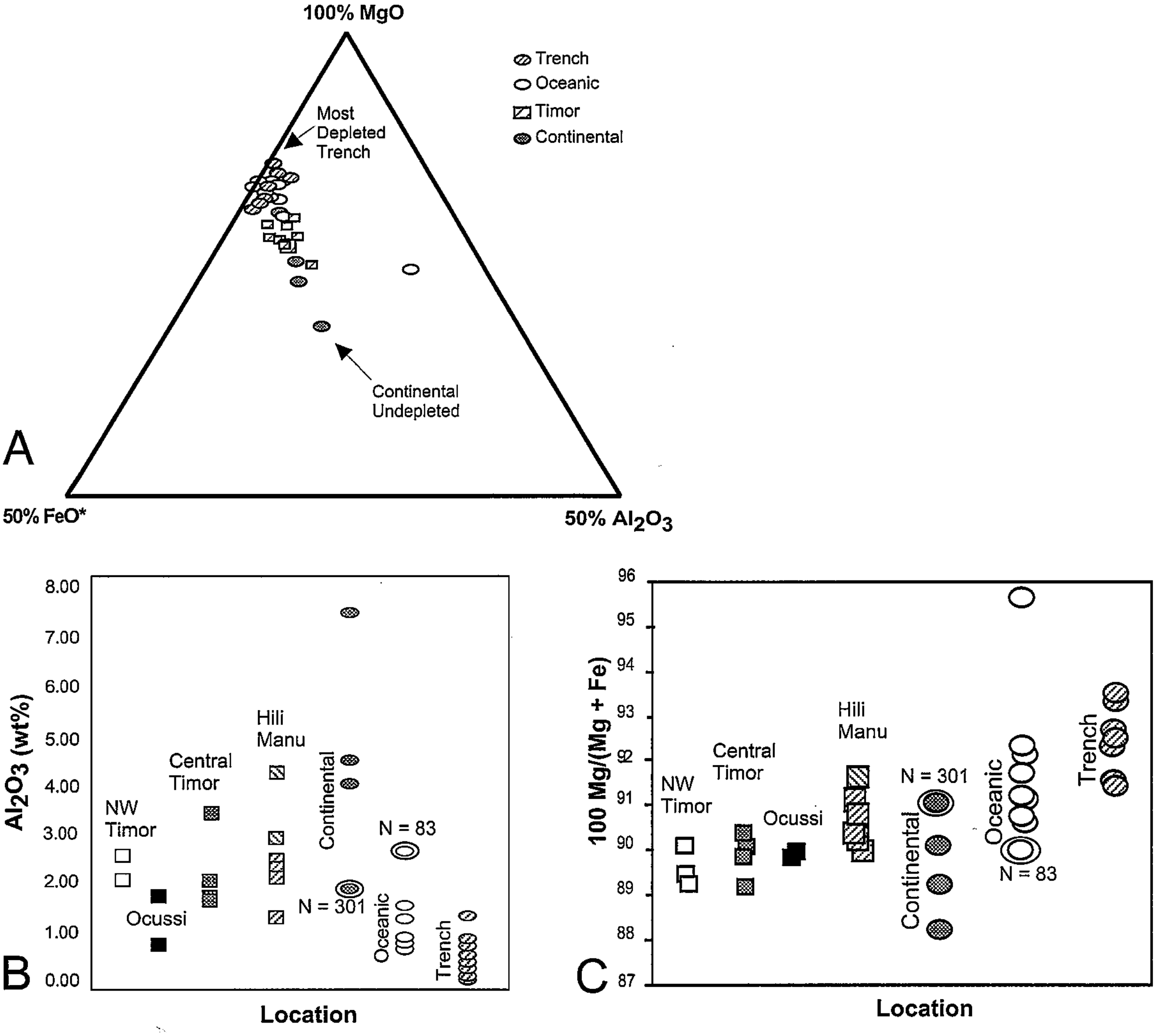

Figure 4. Whole-rock discriminant diagrams comparing Timor samples (<10% serpentine and Hili Manu lherzolite from Berry, 1981) with those from other tectonic settings (see text). A, Mg:Fe:Al ratio shows a depletion trend of decreasing FeO and Al_2O_3. Most Timor samples plot with data from preoceanic-rift upper mantle and continental undepleted and oceanic estimates. B, Al_2O_3 contents (in weight percent) of all Timor samples show some scatter, but mostly overlap with data from continental and oceanic upper mantle. C, Mg# values of Timor samples overlap data from preoceanic-rift upper-mantle samples, continental undepleted samples, and oceanic estimates.

those from lherzolite dredged from the edge of the western Australian continental margin (Nicholls et al., 1981) and require steep geothermal gradients of 40–50 °C/km. Nicholls et al. (1981) associated the steep geotherm with continental rift-valley volcanism prior to seafloor spreading.

Although the composition and pressure-temperature estimates for the Atapupu lherzolite and associated metamorphic assemblage are similar to those found at Hili Manu, Helmers et al. (1989) offered the Hamilton (1979) hypothesis of an obducted arc-type ophiolite and subophiolite metamorphism to explain their observations. They drew attention to the close association of late Neogene volcanic arc rocks with peridotite bodies at Atapupu and in Seram, suggesting that the volcanic arc was the heat source for the high-grade metamorphism during late Neogene arc-continent collision. A similar interpretation is offered for ultramafic bodies found in central Timor near metamorphic rocks of the Banda terrane (Earle, 1980, 1981; Brown and Earle, 1983; Sopaheluwakan et al., 1989).

Ocussi volcanic rocks

Helmers et al. (1989) used the close association between the Atapupu lherzolite and nearby Ocussi volcanic pile to support their claim of a young (hot), upper-plate origin for the lherzolite. The Ocussi volcanic rocks are a 3–4-km-thick sequence of interlayered pillow lavas and sheet flows that are tilted to near vertical along the north coast of West Timor (Figs. 1 and 2). The volcanic units have island-arc–basalt geochemical affinities, such as LILE (large ion lithophile element) enrichment, Nb depletion, and high Cr and low Ti contents (Harris, 1992). $^{40}Ar/^{39}Ar$ plateau ages of basalt are 3–5 Ma, and fauna from interlayered calcilutite are late Neogene age (Harris, 1992). Blocks of lherzolite are found in mélange near the volcanic pile, but no other parts of an ophiolite sequence are found. The geochemistry and age of the Ocussi volcanic rocks indicate that they formed in a SSZ setting probably as part of the upper plate of the Banda arc immediately before tectonic emplacement onto the edge

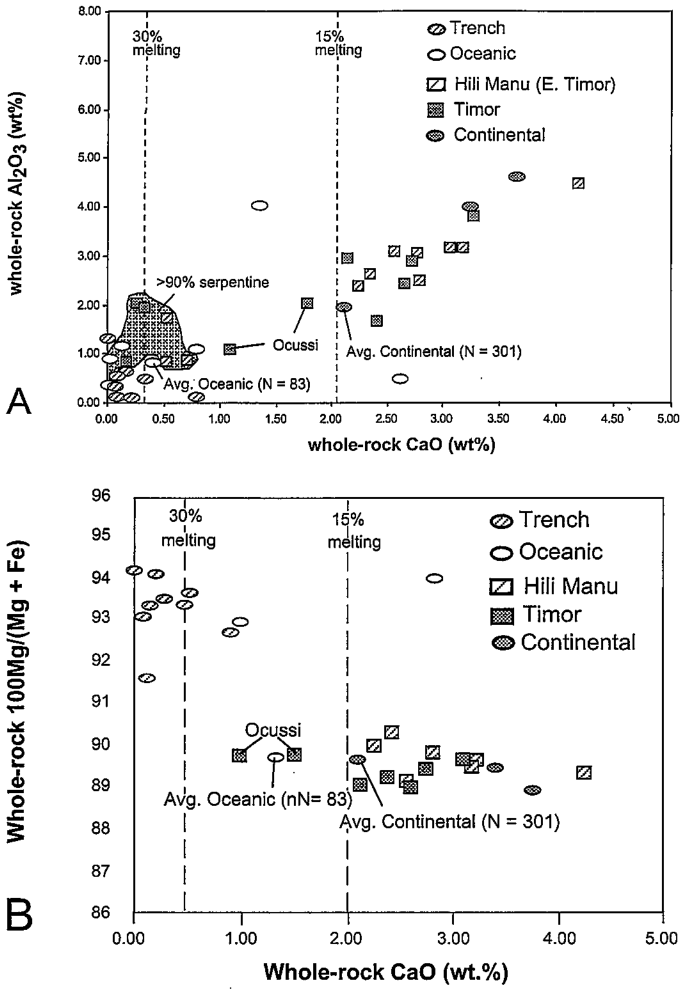

Figure 5. Partial-melting estimates after Mysen and Kushiro (1977) and Ishiwatari (1985). These plots depict approximate locations of 15% and 30% partial melting of previously undepleted upper mantle. A, CaO vs. Al_2O_3. B, CaO vs. Mg#. Except for cases of extreme serpentinization, all Timor samples plot at <30% depletion, and the majority plot at <15%.

of Australia during late Neogene arc-continent collision (Harris, 1992). These characteristics are very similar to those of most Oman-type ophiolites. Yet, little is known about the structural relationships between the Ocussi volcanic rocks and other parts of the Banda arc–Australian continent collision. It is possible that the roots of the Ocussi volcanic unit are structurally underlain by continental-margin rocks, as shown in Figure 2. This interpretation is supported by similar age and geochemical results from samples of basalt dredged from the forearc basin to the north of the Ocussi region (Harris, 1992).

Other ultramafic bodies of Timor

In addition to the Hili Manu and Atapupu lherzolite there are several other ultramafic bodies found throughout Timor. Many occur as blocks in the Bobonaro mélange that is widely exposed throughout recently emergent and less exhumed parts of northwestern Timor (Fig. 1). Below the mélange is a thrust stack composed mostly of accreted Australian continental-margin cover sequences, which are the source for most of the mélange (Fig. 2). Structurally overlying the mélange is the Banda terrane. The close spatial relationships between the Banda terrane and the ultramafic blocks in the Bobonaro mélange have led to correlations between the two.

Earle (1980) and Brown and Earle (1983) associated the metamorphism of the Banda terrane with obduction of a young backarc basin that formed at the edge of the Asian margin. They suggested that the two units were both part of the Banda terrane when it collided with the Australian margin in the Miocene. Sopaheluwakan et al. (1989) presented a similar model, but had the "ophiolite" obducted onto continental fragments hundreds of kilometers outboard of the Australian margin during the Oligocene that later collide with northwest Australia. However, thermochronological studies of Permian-Triassic rocks structurally underlying the ultramafic bodies show no indication of any pre–late Neogene event (Harris et al., 2000).

The Nefomasi lherzolite body of central West Timor is one of the largest on the island. It structurally overlies a mélange and broken formation derived mostly from underlying thrust sheets of Permian-Triassic Australian affinity sedimentary sequences (Fig. 2), as confirmed at two different exposures of the basal thrust (Harris et al., 1998). Contacts found between the Nefomasi body and the Banda terrane are associated with serpentine diapirs intruding Neogene carbonate units. These contacts are similar to those produced by serpentinite diapirs that pierce the Banda terrane throughout Timor (Harris et al., 1998). These observations are consistent with contact relationships first mapped by Rosidi et al. (1979) that show the Nefomasi body structurally underlying the Mutis metamorphic complex and other units of the Banda terrane. However, this interpretation was reversed in the geologic map of the Nefomasi region presented by Sopaheluwakan et al. (1989). Harris et al. (1998) confirmed that the Nefomasi body does not overlie the Banda terrane.

Summary

The close association of ultramafic bodies, volcanic rocks, and metamorphic sequences in Timor has been used to support claims for obduction of hot ophiolite slabs in the Banda arc–Australian continent collision (Hamilton, 1979; Earle, 1980, 1981; Brown and Earle, 1983; Sopaheluwakan et al., 1989; Linthout and Helmers, 1994). However, the lack of an ophiolite sequence, the close affinity of ophiolite-like rocks with the Aileu and Maubisse units, and age and structural relationships of the volcanic and metamorphic rocks are difficult to reconcile with claims that there is an ophiolite in Timor, that the various metamorphic complexes are associated with hot emplacement of an ophiolite, or that ophiolite-like rocks were derived from the forearc upper plate (with the exception of the Ocussi volcanic rocks). We present a new interpretation here that the ophiolite-like units of Timor—particularly the lherzolite bodies and associated pillow lavas and metamorphic rocks of Aileu and Maubisse units—are derived from near the edge of the Australian continental margin.

One way we have tested this hypothesis is by analyzing the mineral and whole-rock chemistry of ultramafic bodies throughout Timor to determine if the mantle material has a within-plate (continental or oceanic) or a SSZ chemical affinity. We assume that these two different settings are distinguishable chemically on the basis of comparisons of results compiled by Bonatti and Michael (1989) and ourselves from ultramafic rocks found in (1) the upper plate of subduction zones throughout the western Pacific (Bowin et al., 1966; Fisher and Engel, 1969; Ishii, 1985; Bloomer and Fisher, 1987; Ishii et al., 1992; Arai, 1994); (2) ocean basins, such as along the Mid-Atlantic Ridge at 43°N (Shibata and Thompson, 1986) and the Owens Fracture Zone (Hamlyn and Bonatti, 1980); (3) passive continental margins of the Red Sea (Bonatti et al., 1986), western Australia

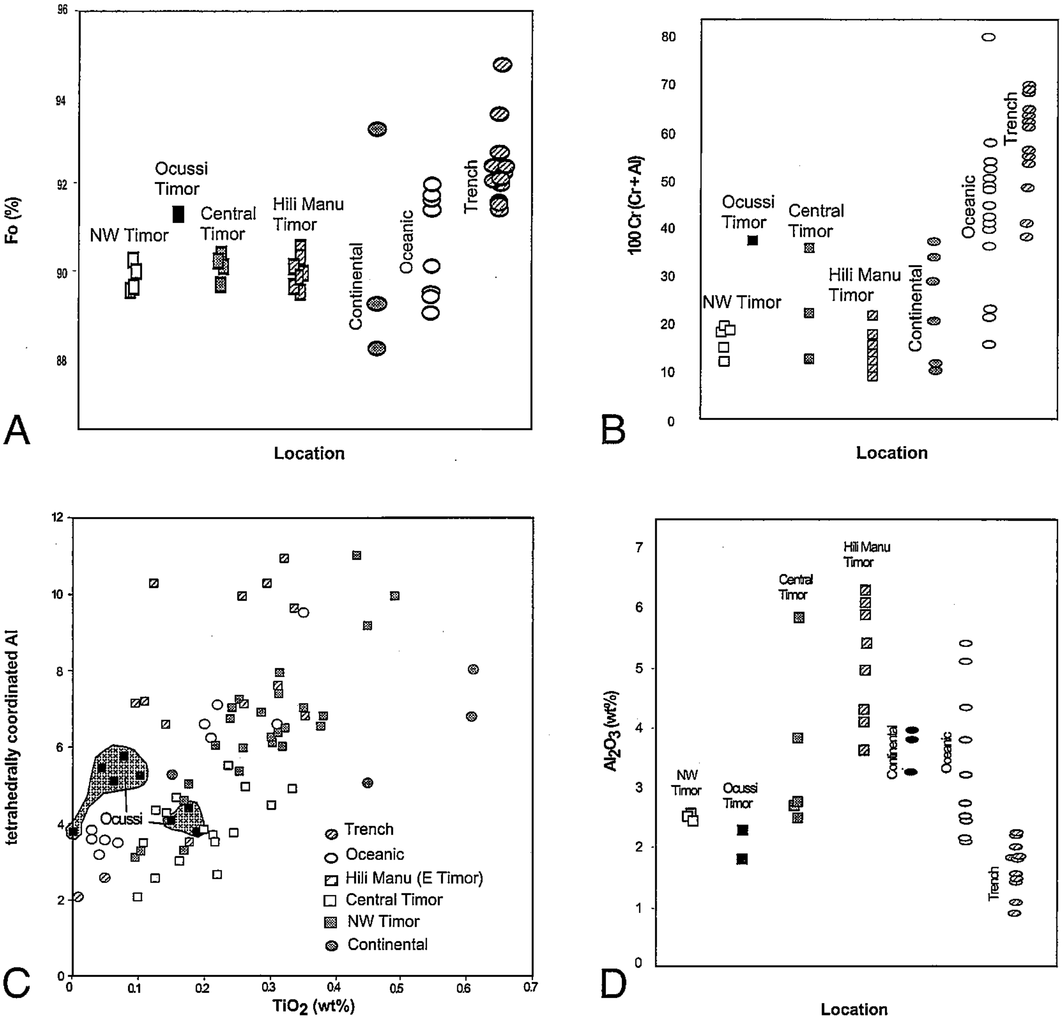

Figure 6. Mineral chemistry of Timor ultramafic bodies compared to those from known tectonic settings, listed from least to most depleted. Analyses obtained with a Cameca electron microprobe at 15 kV acceleration voltage. Points represent the average of five analyses per mineral per thin section. The reported relative abundances of Fe_2O_3 and FeO are a function of the abundance of Al_2O_3, which also occupies the tetrahedral site. Olivine FeO* was not recalculated by the analysis program, as it is assumed that no oxidized Fe was present during olivine crystallization. If only FeO* was reported in data from other sources, we recalculated for Fe_2O_3 and FeO by using the method of Droop (1987). A, Forsterite content (% Fo) of olivine. B, Spinel Cr#. C, Clinopyroxene Al:Ti ratio. D, Al_2O_3 (weight percent) in orthopyroxene.

(Nicholls et al., 1981), and Iberia (Boillot et al., 1980); and (4) nodules from subcontinental settings (Carter, 1970; Frey and Prinz, 1978; Herzberg, 1993). We acknowledge that there are exceptions to these trends, such as depleted harzburgite xenoliths found in volcanic rocks in cratonal settings (i.e., Herzberg, 1993; Bernstein et al., 1998) and relatively undepleted lherzolite found in the Japan arc (Arai, 1994).

PETROGRAPHY

All of the ultramafic rocks we found throughout East and West Timor (Fig. 1) are spinel- or spinel-bearing lherzolite (Fig. 3). The average mineral assemblage of samples from 13 ultramafic bodies consists of relatively large interstitial and subhedral crystals of deformed orthopyroxene with clinopyroxene exsolution lamellae, deformed interstitial clinopyroxene, highly dissected and kink-banded olivine, interstitial spinel, and associated opaque minerals. Some samples contain discrete mylonite zones of grain-size reduction. The majority of the samples are made of 30%–50% serpentine (Fig. 3). Three locations have <10% serpentine.

Comparisons of modal mineral contents of Timor samples with data compiled by Bonatti and Michael (1989) show a depletion trend from undepleted continental settings, preoceanic rifts, passive margins (oceanic to continental transitional type), oceanic fracture zones, and subduction-related active margins. Most Timor samples cluster on the pyroxene-rich side of the trend in the relatively undepleted to partially depleted range, well away from subduction-related active-margin peridotite.

WHOLE-ROCK GEOCHEMISTRY

Whole-rock chemical analyses were performed on samples from 11 different lherzolite bodies throughout East and West Timor (Table 1). Nine samples were analyzed at Texas Tech by using inductively-coupled plasma (ICP) and five others at West Virginia University by using X-ray fluorescence (XRF).

The most discriminating whole-rock geochemical parameters of ultramafic chemical evolution are Al_2O_3 (in weight percent), Mg/(Mg + Fe) = Mg#, and the $MgO:FeO^*:Al_2O_3$ proportions (Ishiwatari,

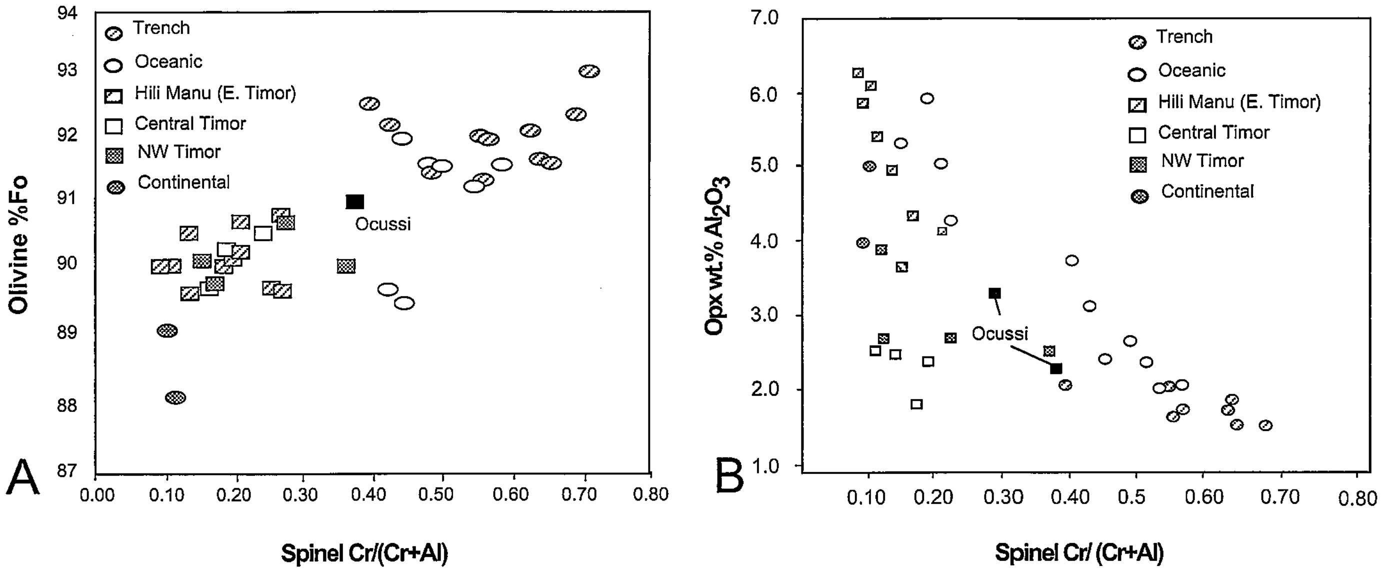

Figure 7. Covariation diagrams showing loss of magmaphile elements Fe and Al from mantle depletion, and complementary enrichment in refractory elements Mg and Cr. Most Timor samples cluster with data from estimated continental undepleted and preoceanic-rift upper-mantle rocks. A, Spinel Cr# vs. Fo content (%) in olivine. B, Spinel Cr# vs. Al_2O_3 (weight percent) in orthopyroxene.

1985; Bonatti and Michael, 1989). Al, Ca, and Fe depletion and Mg enrichment reflect increasing degrees of mantle depletion.

With the exception of lherzolite blocks found near the Ocussi volcanic rocks, most plots show that Timor ultramafic bodies overlap with continental undepleted and preoceanic rift settings (Figs. 4 and 5). There is also some overlap with the mean of oceanic upper mantle. The closest associations are with Red Sea–type peridotite (Zabargad) and peridotite from the Australian and Iberian passive continental margins (Figs. 4 and 5).

MINERAL CHEMISTRY

Samples from eight different ultramafic bodies were analyzed by electron microprobe at Pennsylvania State University. Mineral-chemistry parameters that may indicate the degree of partial melting of a lherzolitic mantle source include forsterite content of olivine (percent Fo) (Fig. 6A), spinel Cr# [Cr/(Cr + Al)] (Fig. 6B), tetrahedrally coordinated Al in clinopyroxene versus weight percent TiO_2 in clinopyroxene (Fig. 6C), and weight percent Al_2O_3 in orthopyroxene (Fig. 6D). Progressive partial melting of relatively undepleted continental upper-mantle lherzolite produces an increase in spinel Cr# and percent Fo and a decrease in orthopyroxene weight percent Al_2O_3 (Fig. 7, A and B). As with the whole-rock chemistries, Al and Fe will show magmaphile tendencies, whereas Mg and Cr are more refractory.

Fo in olivine ranges from 89% to 90.5% (Fig. 6A). Spinel compositions range from 33% to 53% chromite, with low Cr# values from 10 to 37 (Fig. 6B). X-ray diffraction studies also found edenite and magnesiohornblende, and lizardite and clinochrysotile.

In summary, the Timor lherzolite bodies have a mineral chemistry most similar to those from preoceanic rifts and passive continental margins (Figs. 6 and 7). Ultramafic rocks in the Ocussi region are the only samples that consistently show relatively more depletion.

DEGREE OF PARTIAL MELTING

Ishiwatari (1985) estimated the degree of partial fusion based on whole-rock chemistry of residual peridotite by graphing covariations of weight percent CaO with Mg# and weight percent CaO with weight percent Al_2O_3. Relative to an initial pyrolite composition, Bonatti and Michael (1989) estimated degrees of depletion ranging from near zero in Red Sea–type preoceanic-rift settings to ~10%–15% in passive-margin and transitional-crust settings, 10%–25% in oceanic peridotite, and 30% and greater in subduction-zone settings.

Plots of whole-rock weight percent CaO vs. Mg# and weight percent CaO vs. weight percent Al_2O_3 (Fig. 5) show that Timor samples mostly record less than 20% partial melting. Whole-rock Mg# and Mg:Fe:Al indicate similarities with preoceanic-rift, passive-margin, and oceanic peridotite.

Mineral-chemistry comparisons reflect the same trends. Most Fo contents in olivine of Timor lherzolites plot near the overlap between preoceanic-rift and oceanic peridotite (Fig. 6A). The same is found with comparisons of spinel Cr# (Fig. 6B), which fall into the type I abyssal peridotite category of Dick and Bullen (1984). The presence of diopside also reflects limited depletion, as clinopyroxene is typically the first major mineral lost during partial melting.

Samples collected near the Ocussi volcanic rocks display anomalously high values for spinel Cr# and percent Fo in olivine and low values for whole-rock and orthopyroxene weight percent Al_2O_3 (Figs. 6 and 7). However, the geologic association between the ultramafic and mafic rocks in the Ocussi region remains ambiguous.

ORIGIN AND TECTONIC EVOLUTION

Geologic associations with the Aileu and Maubisse units in the Hili Manu region, near Maubara, and throughout West Timor demonstrate a close affinity between ophiolite-like rocks and the Australian lower plate. Geochemical evidence supports this conclusion, but is more equivocal as to whether the lherzolite is from a suboceanic or subcontinental setting. The high temperatures of equilibration associated with Atapupu lherzolite require a geotherm most likely associated with rifting. Pressure estimates on the other hand indicate depths of at least 22–30 km, which is more consistent with the depth of continental rather than oceanic rifts. The lack of plagioclase development is also inconsistent with an oceanic rift zone origin for the spinel lherzolite bodies.

We speculate that the spinel lherzolite bodies originated from near an oceanic to continental lithospheric transition and were initially exhumed by extension during Mesozoic passive-margin development. Later these bodies were thrust with the Aileu-Maubisse nappe over parts of the continental margin more proximal to the shelf during late Neogene arc-continent collision. This hypothesis is consistent with the structural position and lack of an ophiolite sequence associated with the lherzolite bodies, age differences between prograde and retrograde metamorphism of the Aileu complex, and the composition of the lherzolite bodies.

CONCLUSION

Although many features of the Banda arc–Australian continent collision present an attractive modern analogue for the emplacement of Oman-type ophiolites, there remains a paucity of evidence of any such event. Large klippen of forearc crust, represented by the Banda terrane, do structurally overlie much of the orogenic wedge in a manner similar to Oman-type ophiolites, yet the Banda terrane is not an ophiolite. A similar tectonic scenario is found in the Hellenic subduction system on the island of Crete. Although there are many Oman-type ophiolites found along the orogenic strike of the Hellenic accretionary wedge, the "uppermost tectonic unit" or "Asteroussia nappe" of Crete (Bonneau, 1984) is more akin to the Banda terrane of Timor, and no ophiolite is found there.

The Ocussi region is different and may represent the emergent tip of a Banda arc–related SSZ ophiolite. It is also possible that other such bodies have been emplaced over the edge of the Australian continental margin in submerged parts of the orogen that have undergone less uplift. A modern analogue of an Oman-type forearc ophiolite, from an active arc-continent collision, remains to be found.

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