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On-going orogeny in the outer-arc of the Timor–Tanimbar region, eastern Indonesia ☆

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Abstract

The Timor–Tanimbar islands of eastern Indonesia form a non-volcanic arc in front of a 7 km deep fore-arc basin that separates it from a volcanic inner arc. The Timor–Tanimbar Islands expose one of the youngest high *P*/*T* metamorphic belts in the world, providing us with an excellent opportunity to study the inception of orogenic processes, undisturbed by later tectonic events.

Structural and petrological studies of the high *P*/*T* metamorphic belt show that both deformation and metamorphic grade increase towards the centre of the 1 km thick crystalline belt. Kinematic indicators exhibit top-to-the-north sense of shear along the subhorizontal upper boundaries and top-to-the-south sense in the bottom boundaries of the high *P*/*T* metamorphic belt. Overall configuration suggests that the high *P*/*T* metamorphic rocks extruded as a thin sheet into a space between overlying ophiolites and underlying continental shelf sediments. Petrological study further illustrates that the central crystalline unit underwent a Barrovian-type overprint of the original high *P*/*T* metamorphic assemblages during wedge extrusion, and the metamorphic grade ranged from pumpellyite-actinolite to upper amphibolite facies.

Quaternary uplift, marked by elevation of recent reefs, was estimated to be about 1260 m in Timor in the west and decreases toward Tanimbar in the east. In contrast, radiometric ages for the high *P*/*T* metamorphic rocks suggest that the exhumation of the high *P*/*T* metamorphic belt started in western Timor in Late Miocene time and migrated toward the east. Thus, the tectonic evolution of this region is diachronous and youngs to the east. We conclude that the deep-seated high *P*/*T* metamorphic belt extrudes into shallow crustal levels as a first step, followed by doming at a later stage. The so-called 'mountain building' process is restricted to the second stage. We attribute this Quaternary rapid uplift to rebound of the subducting Australian continental crust beneath Timor after it achieved positive buoyancy, due to break-off of the oceanic slab fringing the continental crust. In contrast, Tanimbar in the east has not yet been affected by later doming. A wide spectrum of processes, starting from extrusion of the high *P*/*T* metamorphic rocks and ending with the later doming due to slab break-off, can be observed in the Timor–Tanimbar region.

Keywords: High *P*/*T* metamorphic belt; Wedge extrusion; Mountain building; Timor–Tanimbar region

1. Introduction

Orogeny has been subdivided into subduction of an oceanic plate (Cordilleran-type orogeny) and collision of buoyant masses such as arcs or continents (Collision-type orogeny; Dewey and Bird, 1970). Orogeny is a complex concept that refers not only to mountain building but also to the formation of continental crust and major orogenic structures, welding of previously formed orogens, and erosion and sedimentation related to mountain building (Maruyama, 1997).

☆ Mineral abbreviations of Kretz (1983) are used to represent compositions and reactions of minerals.

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Collision-type orogeny results in: (1) regional metamorphic belts resting on an unmetamorphosed unit bounded by a subhorizontal thrust (Maruyama et al., 1996b; Kaneko, 1997), and/or (2) nappes extruding from its allochthon forming a fore-deep or foreland thrust belt in front of the advancing nappe. The high P/T and UHP metamorphic belt occurs as subhorizontal nappes bounded by a paired-fault system, a normal fault at the top and a reverse fault at the bottom (Maruyama et al., 1996b; Ernst et al., 1997; Liou et al., 1997). The metamorphic belt is tectonically modified by later doming during post-orogenic exhumation, accompanied by numerous high-angle normal faults that cut all units (Maruyama et al., 1996b; Kaneko, 1997).

In this paper, we describe the geology of the Timor–Tanimbar Islands of eastern Indonesia. The 5.4 Ma (Berry and McDougall, 1986) high P/T metamorphic rocks are distributed in a belt over 800 km long from Timor to Tanimbar. Together with the high topographic relief of this area, this occurrence provides an excellent opportunity to investigate processes that may be analogous to the final stages of continent–continent collision zones like the Himalaya (Kaneko, 1997) and the Alps (Maruyama et al., 1996b). We describe (1) tectonostratigraphy and structural geology, and (2) topographic characteristics of the islands, and use chronologic and tectonic constraints to propose a new model to explain the two-phase exhumation and uplift of the high-pressure Timor–Tanimbar metamorphic belt.

2. Tectonic setting

The Timor–Tanimbar island chain forms a non-volcanic outer arc parallel to the Timor trench system, in front of the volcanic Java–Sumatra–Seram inner arc. Gravity studies (Milsom and Richardson, 1976; Chamalaun et al., 1976) indicate that Australian continental crust underlies West Timor. The Australian continent is moving northward at a velocity of 7 cm/year (Genrich et al., 1996) and has been subducting beneath the Timor–Tanimbar Islands since 5 Ma (Charlton, 1991), after the oceanic material fringing the continent was consumed by subduction (Fig. 1A). An unusual 7 km deep oceanic basin, the Weber Deep, developed due to extensional fore-arc collapse (Charlton, 1991), lies between the active volcanic and non-volcanic arcs. In contrast, compressional stress in the south resulted in a series of thrust faults in the frontal part of the accretion zone.

In the Timor–Tanimbar Islands, a fault-bounded high P/T belt (Fig. 1A; Maruyama et al., 1996a) that contains Permian fossils (Leme, 1968) occurs in West Timor. A 5.5 Ma Ar–Ar age reported by Berry and McDougall (1986) in East Timor indicates that the Timor–Tanimbar metamorphic belt is one of the youngest high P/T belt in the world. In contrast, the K–Ar radiometric ages for the metamorphic belt show much older ages and change gradually along the arc: 20–30 Ma (K–Ar) in West Timor (Sopaheluwakan, 1990), 17–8 Ma (K–Ar) in East Timor (Berry and McDougall, 1986) and 11–10 Ma (K–Ar) in Leti Island (Kadarusman, unpublished data). These ages suggest that the Timor–Tanimbar metamorphic rocks had already recrystallized before the Australian continent and Eurasia collided.

3. Previous studies

The presence of metamorphic rocks in Leti, Moa, Sermata and Laibobar (Tanimbar Isles) was first reported by Dutch geologists early this century (Verbeek, 1908; Molenggraff, 1914; Brouwer, 1916). The geology of the Timor–Tanimbar Islands has been classified into many stratigraphic and structural units. Audley-Charles (1968) and Rosidi et al. (1979) distinguished allochthonous, para-autochthonous and autochthonous units in Timor. According to Charlton et al. (1991a), the para-autochthon of Timor is equivalent to Australian continental margin material back-thrust towards Australia during arc–continent collision, and was further subdivided into frontal accreted, underplated blocks and the metamorphosed Aileu-Maubisse block. The allochthon comprises a series of exotic nappes which have migrated southwards from their original position in the hanging-wall of the subduction zone, which was a part of the (pre-collisional) Banda fore-arc (Charlton et al., 1991a). All are overlain by Neogene–Quaternary formations, mainly Quaternary coral reefs.

We simplified and subdivided the Timor–Tanimbar region into four units (Fig. 2A), after Audley-Charles (1968) and Rosidi et al. (1979) for Timor, and Sukardi and Sutrisno (1990) for the Tanimbar Islands. These comprise unmetamorphosed continental shelf sediments (UCSS), the Timor–Tanimbar metamorphic unit (TTM), fore-arc ophiolites (FAO) and Quaternary reef limestones. We follow the stratigraphy of the Timor–Tanimbar region used by Charlton et al. (1991a) and Snyder et al. (1996).

4. Tectonostratigraphy and geology of the individual islands

The mapped area consists of Tanimbar Island in the east and Timor Island in the west through the small islands of Dai, Sermata, Moa and Leti (Fig. 1).

4.1. Timor

Four major tectonostratigraphic sequences can be distinguished from north to south in West Timor; (1) the FAO, (2) the Timor metamorphic rocks (TM) and (3), the UCSS of more than 1 km thickness, that formed on the Australian continental shelf. Each is bounded by major faults, and covered by (4) molasse sediments and Quaternary reef limestone (Figs. 1B and 2). We are including both the Aileu and Mutis metamorphic complexes of previous literature in our 'Timor metamorphic rocks'. The protoliths of the Aileu and Mutis metamorphic rocks are platform-type carbonate, metabasic, peraluminus turbidites and minor bedded chert, and is typical of an A-type metamorphic belt (Maruyama et al., 1996b).

The UCSS is exposed in the central part of Timor, and consists of Permian–Paleocene limestone, chert, shale and sandstone (Fig. 2). The UCSS includes (1) the Permo–Triassic Kekneno Group of West Timor which can be correlated with the Atahoc, Cribas, Aitutu Formations of East Timor, and (2) the Jurassic–Tertiary Kolbano block and Sonnebait unit in West Timor.

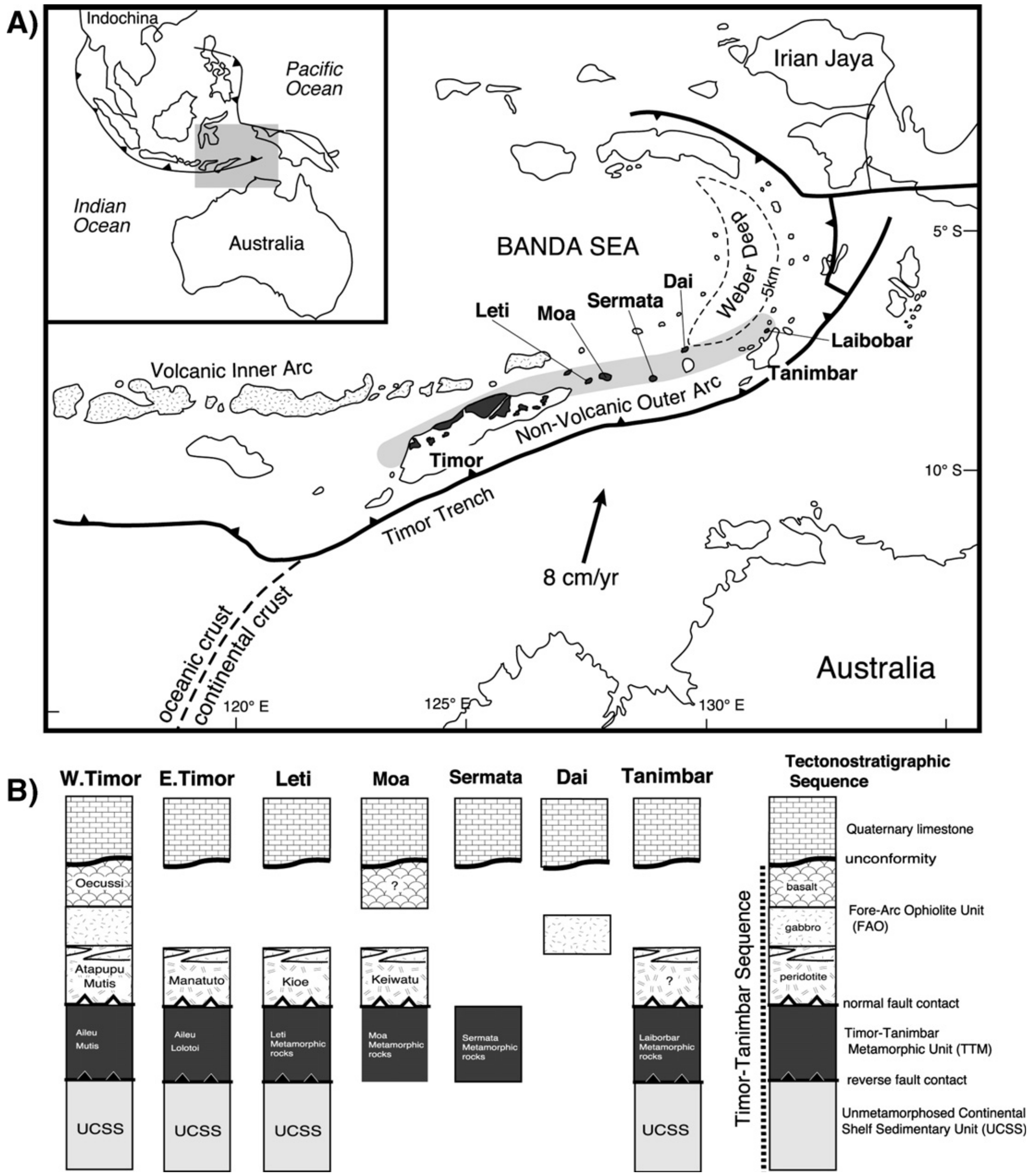

Fig. 1. Index map of eastern Indonesia (A), tectonostratigraphic diagram of the Timor–Tanimbar Islands (B).

The TM rocks occupy a large area in the central and northern part of Timor. They extend 30 km south from the northern coast of Timor (Audley-Charles, 1968). We studied two isolated blocks of TM rocks that are exposed in the Aileu area along the northern coast of East Timor (Aileu complex) and in the Mutis area, central West Timor (Mutis complex; see Fig. 2). The TM consists dominantly of pelitic gneiss and pelitic schist with minor amounts of psammitic schist, calc-silicate schist, greenschist and blueschist. The protoliths of the TM are platform-type carbonate, metabasic, peraluminus turbidites and minor bedded chert, and is typical of an A-type blueschist belt (Maruyama et al., 1996b). Its apparent thickness varies longitudinally, but is about 1 km in West Timor. Leme (1968) reported Permian fossils in the Aileu pelitic rocks. The Aileu Formation has been subjected to polyphase deformation, and regional metamorphic conditions increase towards the northeast (Barber and Audley-Charles, 1976; Berry and Grady, 1981b). The rocks in the core of the Aileu Formation are mylonitic with localized foliation-parallel shear bands. The regional metamorphism reached peak *P*–*T* conditions at 8 Ma and cooled to about 300 °C at 5.5 Ma (Berry and McDougall, 1986). In the core of the Mutis massif, basic and pelitic metamorphic rocks ranging from greenschist to granulite-facies occur (Sopaheluwakan, 1990). The estimated temperature for the higher-grade metabasites is comparable with that for metamorphic rocks from West Timor (Brown and Earle, 1983) and is lower than that of the highest-grade diopside-bearing metabasites, from East Timor (Aileu Formation: Berry and Grady, 1981a,b; Tsujimori, unpublished data). The higher-grade metabasites are retrogressively fractured by prehnite-quartz-albite veins, indicating conditions less than 3 kbar at around 200–300 °C (Frey et al., 1991).

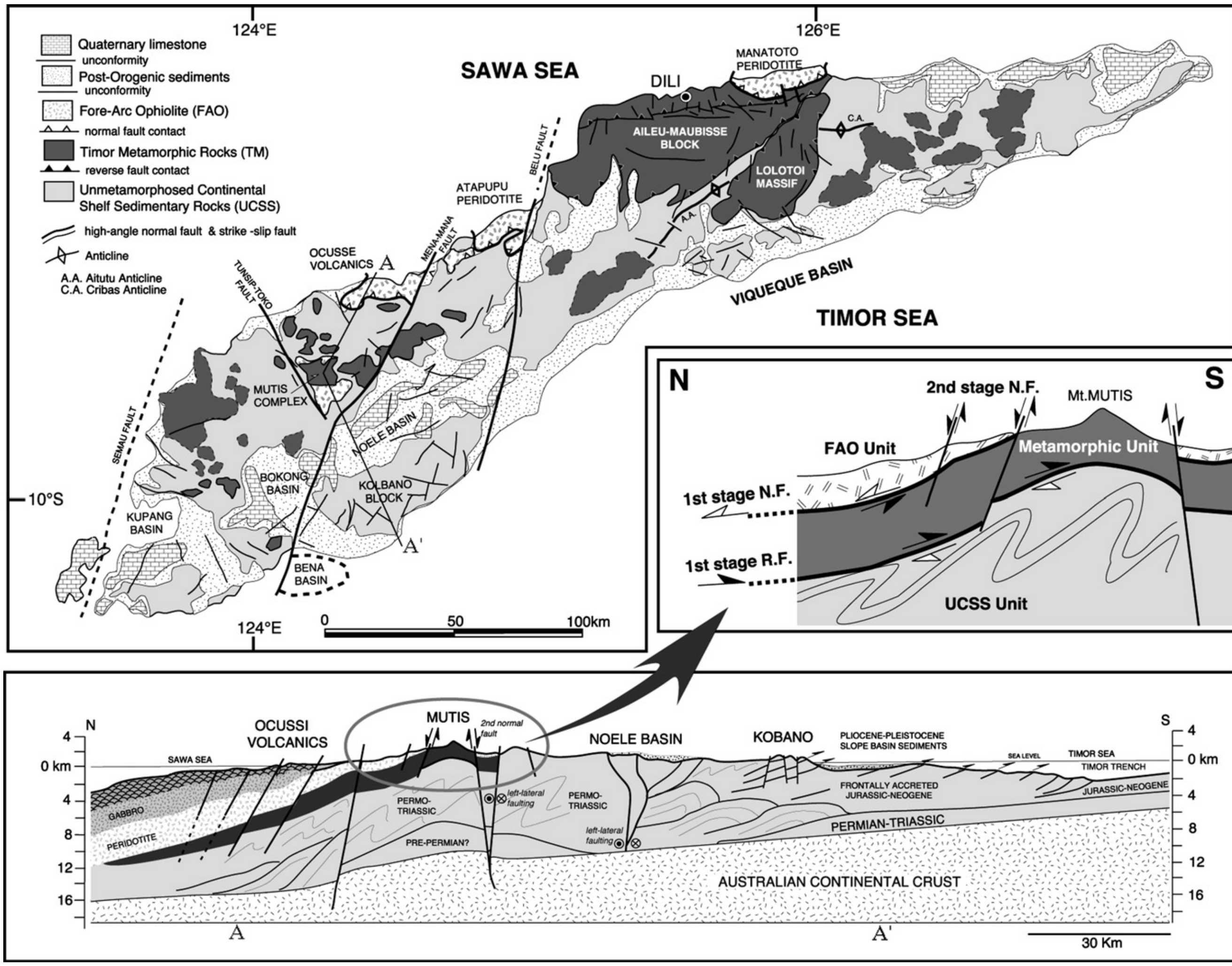

Fig. 2. (A) Simplified geologic map of Timor showing the major tectonostratigraphic divisions. Adapted from Audley-Charles (1968), Rosidi et al. (1981) and Charlton et al. (1991a,b), with additional data from Kenyon (1974), Berry and Grady (1981a), and Sopaheluwakan (1990). A–A′ is the approximate location of the cross-section shown in B. (B) Cross-section through the Mt. Mutis.

The FAO occupies the highest level of the structural pile in Timor. It is exposed in four isolated ultramafic bodies, the Manatuto peridotite in East Timor, the Atapupu peridotite (Helmers et al., 1989), Occusi volcanics (Harris, 1992) and the Mutis ophiolite in West Timor (Sopaheluwakan, 1990) (Fig. 2). These are composed mainly of serpentinite, dunite, gabbro and basalt, and are underlain by the TM. The fore-arc nature of the ophiolite in the Timor–Tanimbar region was first suggested by Maruyama et al. (1996a) based on its tectonic setting.

The Atapupu peridotite is located around 100 km southwest of Dili city (Fig. 2), and is approximately 30 × 10 km in size. The peridotite is mainly composed of tectonite peridotite. The total thickness of the Atapupu peridotite is estimated to be up to 1 km. The Occusi volcanic block is located about 100 km to the west of Atapupu city (Fig. 2), and is approximately 30 × 20 km in size (Fig. 2). The Occusi pillow basalt is of tholeiitic affinity, and was formed between 4 and 6 Ma (Abbott and Chamalaun, 1981; Katili and Hartono, 1983). This is one of the youngest ophiolites in the world. Several hundred meters of thick serpentinite and dunite sequences alternate with minor amounts (tens of meters thick) of gabbroic sequences in the central part. The Mutis peridotite of central West Timor (Fig. 3) occurs in the highest part of West Timor. In the Mutis massif, the ophiolitic sequence consists mainly of peridotites, which occupy the northern and southern parts of the massif. In the lower to central part of the TM, near the contact with the UCSS, the structure is characterized by (1) stretching lineations and (2) flat-lying foliations (S planes) defined by alignment of the basal planes of phyllo-silicate minerals, accompanied by mylonitic shear bands (C planes), that usually indicate a top-to-the-south sense of movement (Fig. 2). In contrast, the sense of shear defined by the relationship of S–C fabrics is top-to-the-north or NNE in the lower part of the FAO (Fig. 2). A series of N-dipping low-angle normal faults on the northern flank of Timor separate the FAO from the underlying TM. Because the textures in the rocks show similar metamorphic conditions, ductile thrusting is hypothesized along the boundary between UCSS and TM, and low-angle normal faulting along the boundary between the TM and FAO.

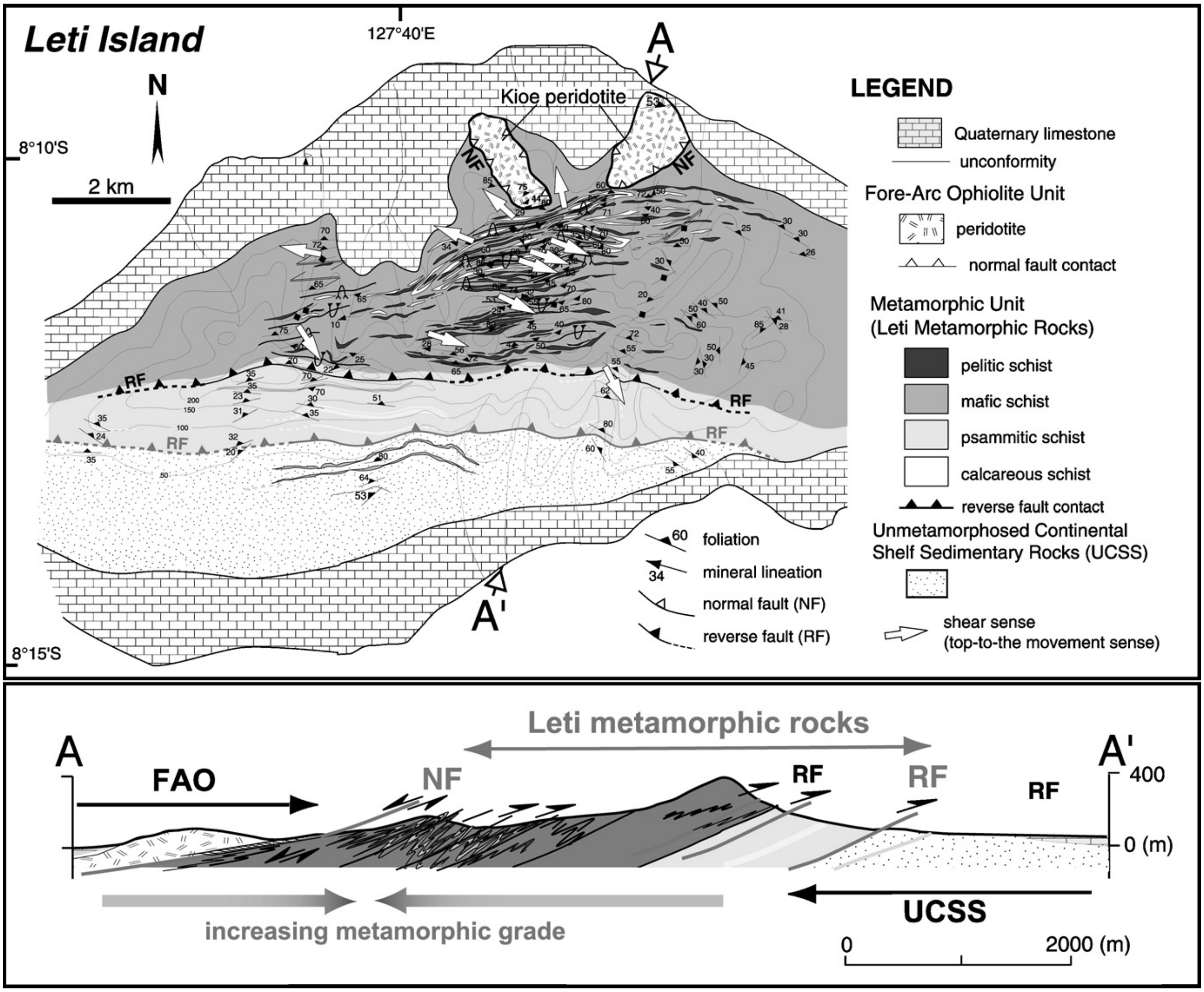

Fig. 3. Geologic map and cross-section of Leti Island.

The post-orogenic Neogene–Quaternary sediments, namely the Viqueque group (molasse sediments), are made up of turbidite-deposited conglomerate, sandstone, siltstone and mudstone of Late Pliocene–Pleistocene age, and have been interpreted as fore arc basin-fill deposits (Charlton et al., 1991a).

Quaternary coralline reef limestones of around 300 m thickness (Rosidi et al., 1979) are developed mainly along the coastal line of Timor, but are also found in the mountains. Exposures of reef limestones reaches 1260 m above sea level in East Timor (Rosidi et al., 1979). Our observations confirm the presence of the limestone outcrops at elevations up to 1400 m in the Kappan to the south of Mutis.

Later tectonic events following the deposition of the reef limestones include open folding, erosion of the Neogene sediments (Kenyon, 1974) and secondary normal faulting (only in section A of Fig. 2) that resulted in tilted blocks (Chappell and Veeh, 1978; Tjokrosapoetro, 1978). On a larger scale, Charlton et al. (1991a) recognized three zones of NNE–SSW left-lateral wrench faults cutting through West Timor (the Semau, Mena-Mena and Belu faults; Fig. 2).

4.2. Leti Island

Four major tectonostratigraphic sequences can be distinguished on the 16 km×8 km island of Leti. From north to south, these comprise: (1) the FAO, (2) unclassified metamorphic rocks (namely the Leti metamorphic rocks), (3) the UCSS and (4) Quaternary limestone (Figs. 2B and 3) which unconformably overlies the first three units that comprise the basement of Leti. Compositional layering, metamorphic foliations and major faults in the basement rocks generally strike E–W and dip moderately to the north.

The UCSS is made up of a sequence of unmetamorphosed and weakly metamorphosed >1 km thick sedimentary rocks. The rocks consist of sandstone, shale, slate, phyllite, calc-silicate rock and limestone. The sequence is juxtaposed against metamorphics across a low-angle reverse fault, as in Timor. Metamorphic conditions in the UCSS increases to the north towards the contact with the Leti metamorphic rocks. The UCSS is gently folded to form a foreland fold-and-thrust belt along an axis parallel to the WNW–ESE arc trend.

The Leti metamorphic rocks consist of pelitic schist, psammitic schist, calc-silicate schist and greenschist. The total of the sequence is about 1 km thick. Metamorphic grade increases towards the centre of the metamorphic pile. Pelitic horizons near the central part of the pile contain Grt + Mus + St + Ky + Sill ± Bt assemblages. The clockwise *P*–*T* path from metapelites displays three stages of metamorphism (Kadarusman et al., this volume). The early stage is high *P*/*T* condition (>300 °C and 6–7 kbar; Kadarusman et al., this volume), followed by peak metamorphism, that reached much higher pressures (9.5–10.5 kbar) and temperatures (570–670 °C), and the third stage records a low-pressure conditions (sillimanite-staurolite stability field). The overprinting mineral relationships in greenschist/blueschist transition schists indicate decompression occurred from 6–7 kbar to <4 kbar with T = 310–430 °C. Textural relationships suggest that Na-amphibole (crossite) recrystallized at the early stage of metamorphism, and that high *P*/*T* assemblages were strongly overprinted by higher temperature assemblages (Kadarusman et al., this volume). We conclude that the metamorphic unit in Leti Island initially suffered regional high *P*/*T* metamorphism and subsequently were converted to assemblages of Barrovian-type metamorphism.

In the central part of the metamorphic pile, sigmoidal polycrystalline aggregates, asymmetric pressure shadows, drag folds and shear bands, clearly indicate top-to-the-south sense of motion. Localized layer-parallel high strain shear bands in mylonites are found in the central part of the metamorphic pile. In contrast, the sense of movement is to the northeast in the upper part of the pile (Fig. 3), as in Timor.

The FAO (Kioe peridotite) occupies the top of the structural pile. The outcrop of the Kioe peridotite is approximately 1 km × 2 km in size and up to 200 m thick, and is in fault contact with the underlying pelitic and psammitic schists of the Leti metamorphic rocks. The peridotite is typically serpentinized. The internal structures of the Kioe peridotite are concordant with those of the Leti metamorphic rocks.

Vertical brittle faults that strike NNE and WNW record the final phase of deformation.

4.3. Moa Island

Only three tectonostratigraphic sequences are exposed in the 30 km × 10 km island of Moa: (1) the Moa metamorphic rocks beneath (2) the FAO, both in turn, covered by (3) Quaternary reef limestone (Figs. 1B and 4).

The basement rocks (the Moa metamorphic rocks and FAO) crop out in two isolated hills: a 250 m high peak in the east and 300 m high peak in the west. Two major basement rock units can

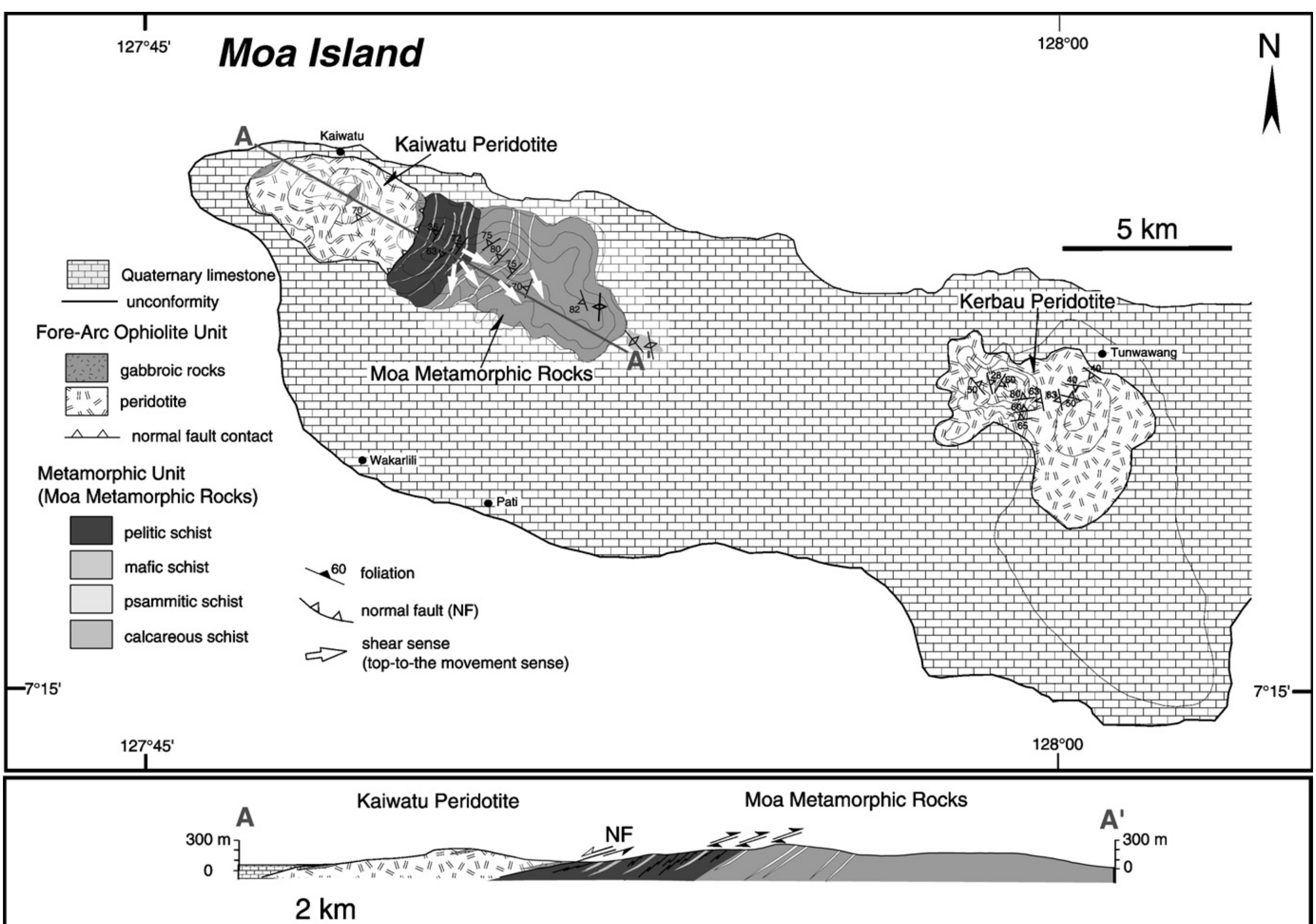

Fig. 4. Geologic map and cross-section of Moa Island.

be distinguished on the western hill (Kaiwatu), (1) peridotite unit in the west and (2) the underlying Moa metamorphic rocks, bounded by a major fault (Fig. 4). The eastern hill, Kerbau Mountain, consists only of peridotite. Both of them are surrounded by horizontal reef limestones that were uplifted up to 20 m above sea level.

The Moa metamorphic rocks are over 1 km thick, and mostly consist of calcareous schist with minor pelitic, psammitic and basic schist, and metachert which occurs as thin intercalations within calcareous schist. Metapelite is dominant near the fault contact with the Keiwatu peridotite. The Moa metamorphic unit is bounded by a series of N-dipping low-angle normal faults in the northwest. The central part of the Moa metamorphic pile is mylonitic with localized foliation-parallel shear bands. Structural fabrics are almost coincident those in the peridotite, i.e. foliation strikes NNE and dips steeply to the west. In the central part of the Moa metamorphic unit, sigmoidal polycrystalline aggregates, asymmetric pressure shadows, drag folds and shear bands clearly show top-to-the-southeast sense of shear, but switch to top-to-the-northwest shear in the upper part (Fig. 4). Like the other islands, the deformation is most intense in the centre of the sequence. Metamorphic grade increases towards the centre (biotite zone) of the metamorphic pile (Kadarusman, unpublished data). Northward from the structural middle of the metamorphic pile, the metamorphic grade decreases down to chlorite zone beyond the normal fault.

The FAO of Keiwatu region is estimated to be up to 500 m thick and is approximately 5 × 3 km in exposed area. These rocks are mostly composed of serpentinized peridotite, minor gabbro and basalt. Relationships between gabbro/basalt and the ultramafic body are unclear. Layer-parallel foliation that strikes NNE~NE and dips 70°W is well-developed and is subparalled to that in the metamorphic pile. The Kerbau peridotite is 8 km × 5 km in exposed, is made up almost entirely of ultramafic rocks (mainly lherzolite) and is covered by Quaternary limestone. Only minor serpentinization was observed. The total thickness of the Kerbau peridotite is estimated at around 300 m. The structure in the western hill is similar to that of the metamorphic pile.

4.4. Sermata Island

Sermata Island is approximately 25 km × 6 km in size, and the highest peak reaches 328 m above sea level (Fig. 5). The central part of Sermata consist mainly of subhorizontal low-grade metamorphic rocks (the Sermata metamorphic rocks), the protoliths of which are continental shelf sediments and basic rocks (Figs. 1B and 5). Horizontal Quaternary reef limestones

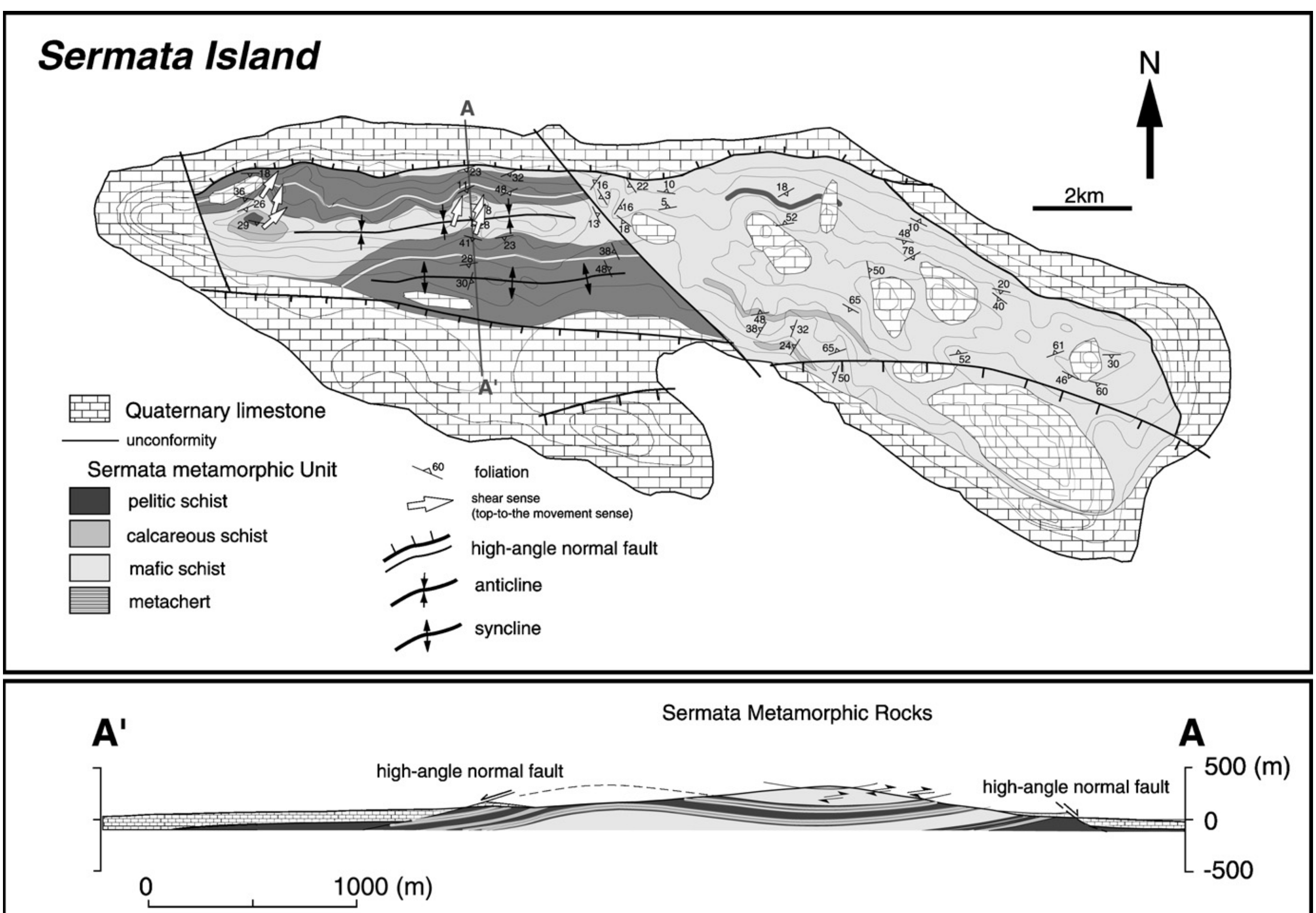

Fig. 5. Geologic map and cross-section of Sermata Island.

encase the Sermata metamorphic rocks. In southeastern Sermata, the Quaternary limestones form six terraces at different elevations, up to 250 m above sea level, near the crests of the hills.

Sermata metamorphic rocks consist of pelitic schist, graphite schist, psammitic schist, calc-silicate schist, greenschist and metachert. Metapelitic/metabasic intercalations with minor amounts of metachert and metalimestone are found in western Sermata. Their total thickness is estimated to be around 500 m. No significant variation in metamorphic grade was observed in Sermata; schists underwent low-grade greenschist/blueschist metamorphism in the chlorite-biotite transition zone, similar to the low-grade rocks of Leti. The co-facial greenschist/blueschist transition rocks contain the following assemblages: (1) Ab + Chl + Ep + Qtz + Act, accessory minerals: Hem + Mag + Spn + Stp + Cal + Ms, and (2) Ab + Chl + Ep + Act + Win + Gln + Qtz, accessories Hem + Mag + Spn + Cal + Phg (Kadarusman, unpublished data). The base of the Sermata metamorphic pile is not exposed. Shear sense indicators such as sigmoidal polycrystalline aggregates, asymmetric pressure shadows, drag folds and shear bands, consistently show a top-to-the-north sense of motion in the upper part of the Sermata metamorphic rocks (Fig. 5).

E–W normal faulting was found in both the north and south of the island. Vertical brittle faults trending NNE–WNW with dip-slip and right-lateral strike-slip displacement represent the final phase of deformation.

4.5. Dai Island

The basement of Dai Island is composed mainly of gabbro with subordinate amounts of pegmatite and clinopyroxenite. The gabbro is approximately 3 km × 1 km in size and unconformably overlain by Quaternary limestone (Fig. 6). The eastern part of Dai Island has been uplifted 650 m during the Quaternary, accompanied by the development of high-angle normal faults.

4.6. Laibobar Islands

Sukardi and Sutrisno (1978, 1981, 1990), Charlton et al. (1991b) and Jasin and Haile (1996) mapped the Tanimbar Islands and other small islands in detail, and reported that they are composed predominantly of Jurassic to Miocene sediments that were deposited on the Australian continental shelf (Sukardi and Sutrisno, 1990; Charlton et al., 1991b; Agustiyanto et al.,

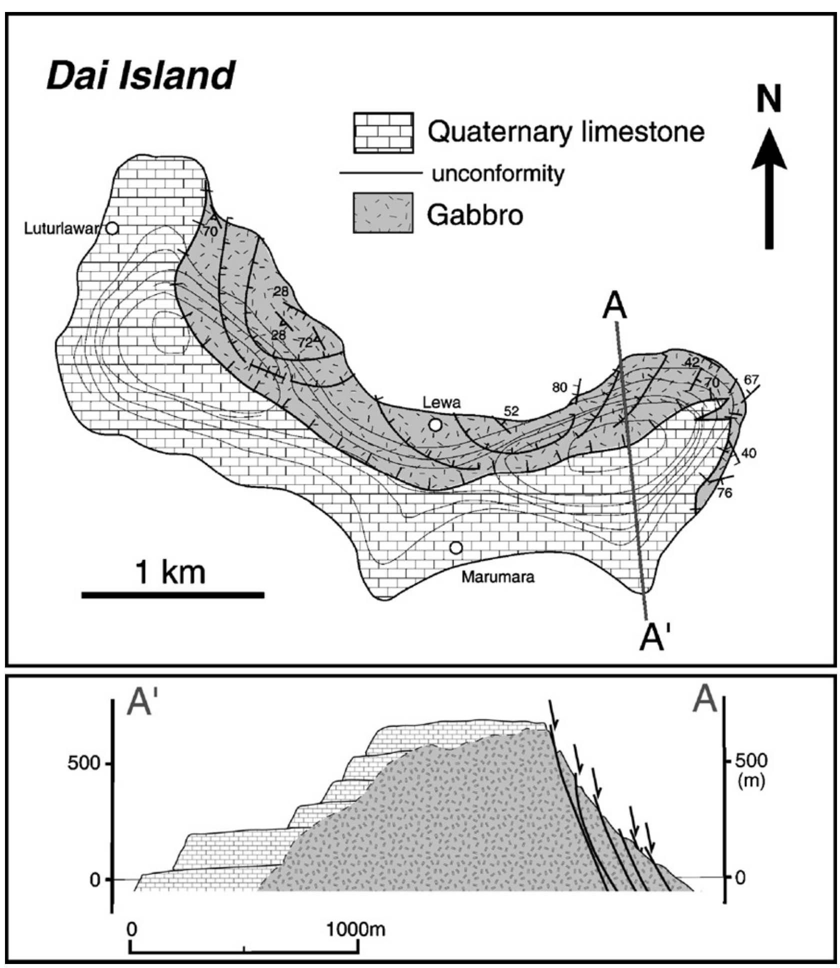

Fig. 6. Geologic map and cross-section of Dai Island.

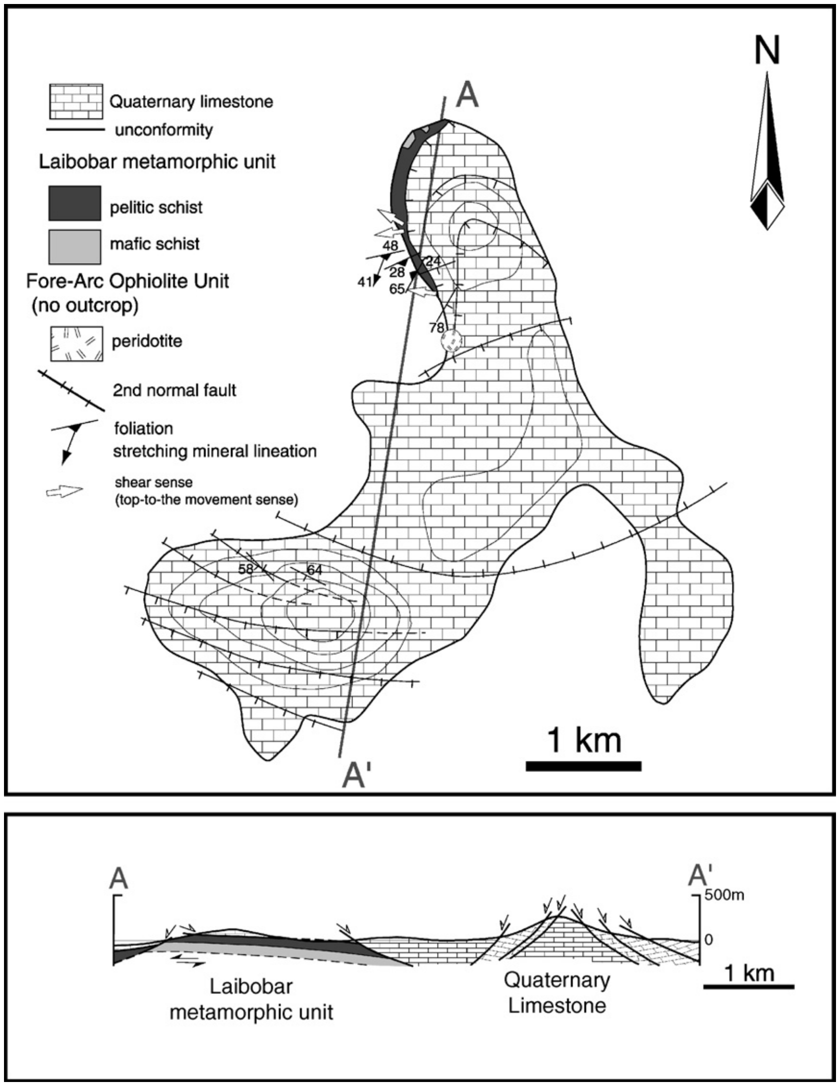

Fig. 7. Geologic map and cross-section of Laibobar Island.

1994a), forming a foreland fold-and-thrust belt. Quaternary limestone overlies the basement rocks.

Metamorphic rocks are found only on Laibobar Island (Fig. 1), about 100 km to the NNE of the Sumlaki City, northwest Tanimbar. They occur as a coherent metamorphic sequence (Fig. 7). The exposure of the Laibobar metamorphic rocks is approximately 400×100 m in size and more than 30 m thick, and consists of metapelite, metabasite and a small amount of marble and metachert. No significant variation in metamorphic grade was observed in Laibobar. All rocks underwent similar metamorphic conditions as in Sermata. The sodic amphibole-bearing metabasite from Laibobar occurs as a massive part within a small hill in the north of the island, whereas the surrounding metabasites are highly foliated with penetrative fabrics. Thus, from the mode of occurrence and texture of sodic amphibole-bearing metabasite, we consider it is a relic of regional high P/T metamorphism and that the higher-grade metabasites are products of Barrovian overprinting. The barroisitic core of magnesiohornblende in the epidote- and hematite-bearing metabasite, indicating ~ 6 kbar as a possible maximum pressure on the basis of the empirical geobarometer of Brown (1977). The metamorphic unit in Laibobar Island initially suffered regional high P/T metamorphism and most rocks were subsequently were converted to assemblages of Barrovian-type metamorphism. Because the base of the Laibobar metamorphic pile is not exposed, we cannot constrain the complete thermobaric structure across the crystalline sequence. Serpentinized peridotites (mainly lherzolite) occur in the southernmost part of the metamorphic pile and as boulders along the faults in the northern part of the island. The metamorphic unit is in a normal fault contact with Quaternary limestones, the fault dips gently to the southeast (Fig. 7).

5. Geomorphology

The youngest structures observed in this study are post-orogenic, high-angle secondary normal faults. Differential uplift by the normal faults and left-lateral strike-slip faults in Timor (including the Semau, Tunsip-Toko, Mena-Mana, Belu faults, etc.) and right-lateral strike-slip faults in Sermata have segmented the three major basement units and Quaternary limestones into several blocks (Charlton et al., 1991a). The distribution of elevated reef limestone in the Timor–Tanimbar region together with rates of vertical movement compiled from published data (Chappell and Veeh, 1978; Rosidi et al., 1979; Audley-Charles, 1986; De Smet et al., 1989, 1990; Vita-Finzi and Hidayat, 1991; Bachri and Situmorang, 1994; Agustiyanto et al., 1994a,b; Fig. 8) indicate rapid uplift. Quaternary reefs in Timor occur locally at elevations up to 1260 m (Rosidi et al., 1981), and the central basin of west Timor has risen about 2 km in the past 0.5 Ma (De Smet et al., 1989). In Timor, two episodes of rapid uplift, 5 mm/year from 2.2 to 2.0 Ma and 7.5 to 10 mm/year during the last 0.2 Ma produced cumulative uplifts of 1500–2500 m (De Smet et al., 1990). Although Timor Island is primarily a fold-belt, late-stage, low-angle normal faulting has been inferred in northern and central Timor (Harris, 1989), and pull-apart structures have been identified in the Wetar Straits to the north. The Quaternary reef elevation gradually changes along strike of the arc from about

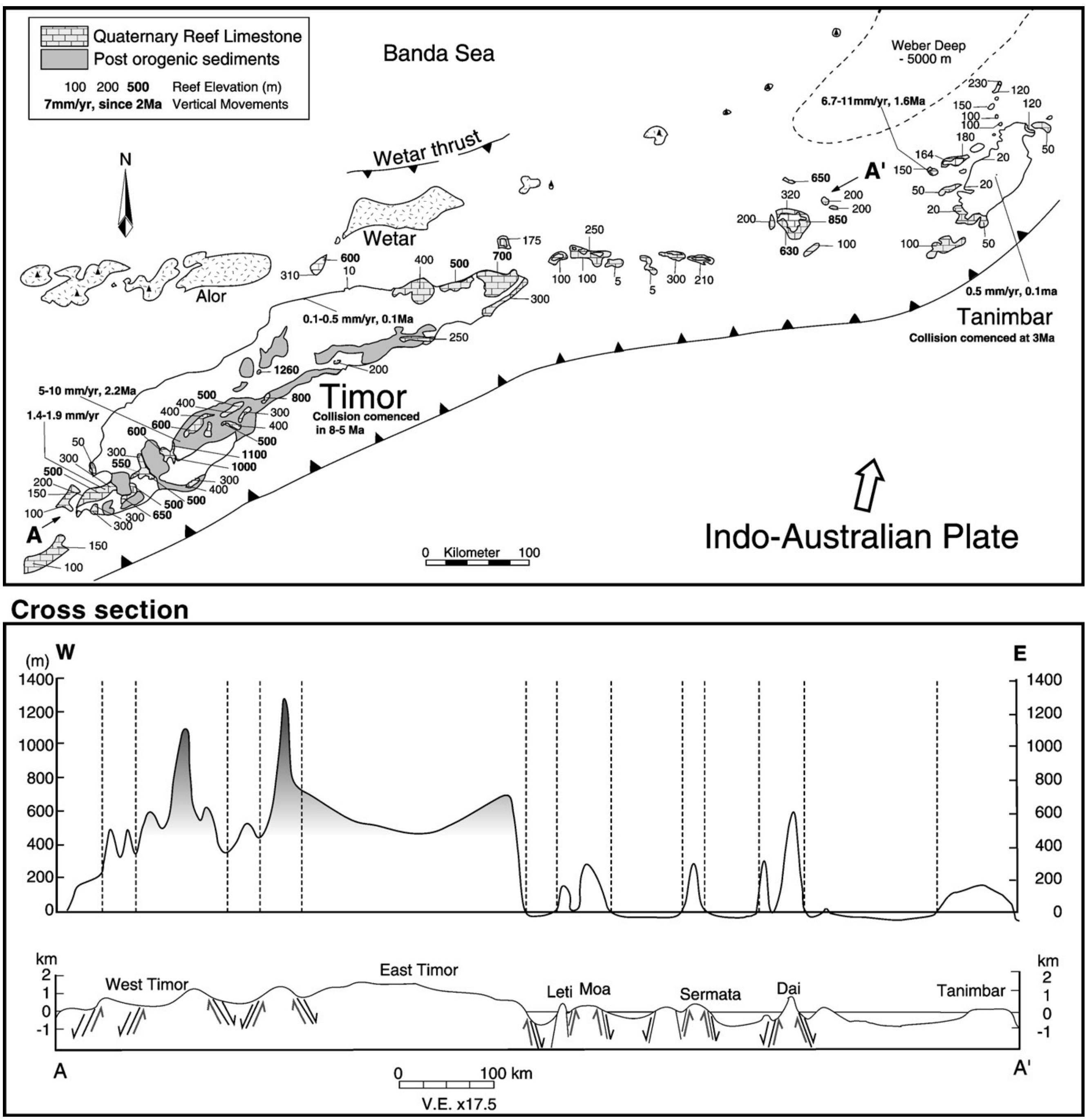

Fig. 8. Reef elevation map and vertical movement data for Timor–Tanimbar region (compiled from Chappell and Veeh, 1978; Rosidi et al., 1979; Audley-Charles, 1986; de Smet et al., 1989; De Smet et al., 1990; Vita-Finzi and Hidayat, 1991; Bachri and Situmorang, 1994; Agustiyanto et al., 1994a,b).

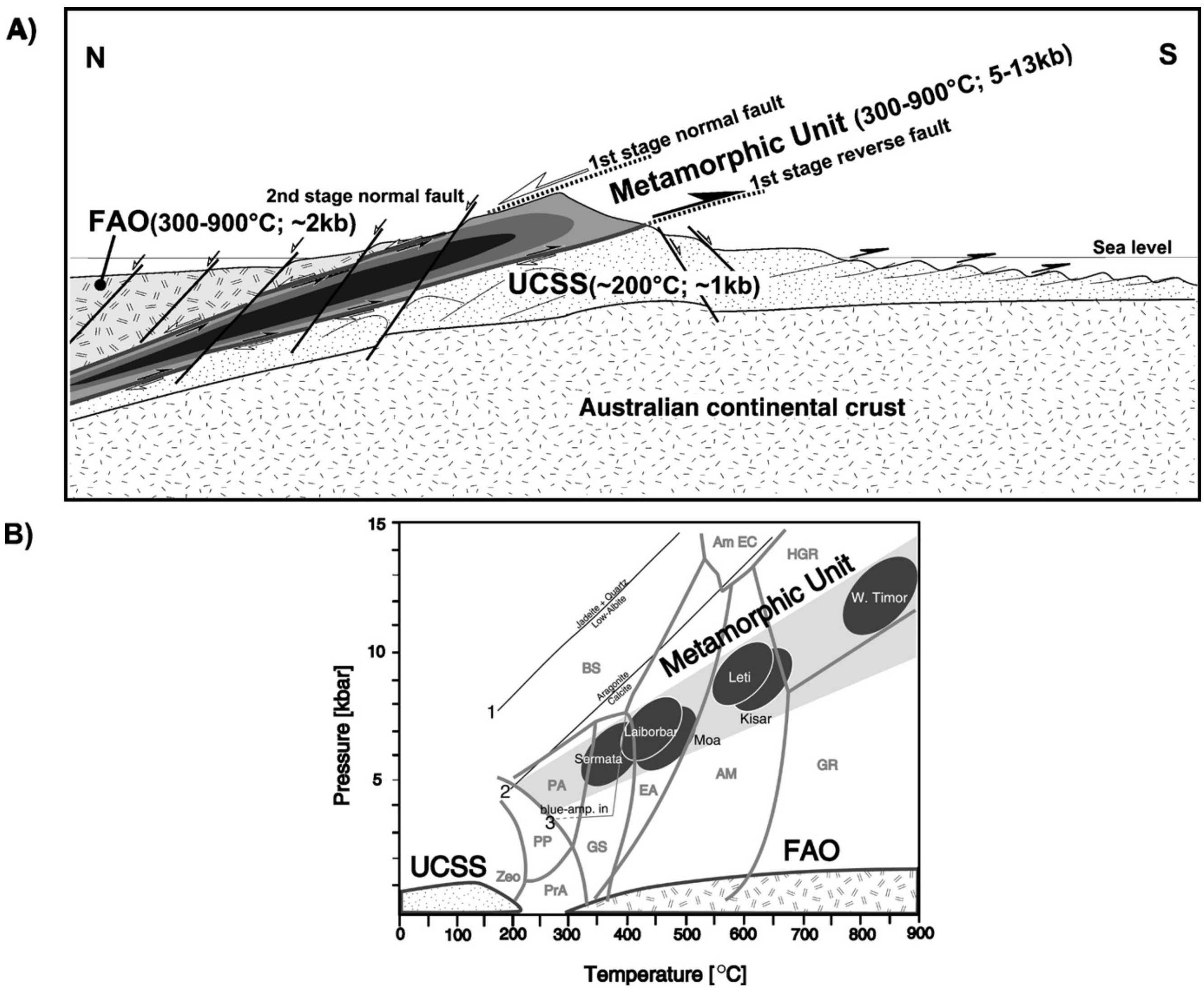

Fig. 9. (A) Simplified cross-section of Timor–Tanimbar orogenic belt. See text for further explanation. (B) Pressure–temperature diagram showing metamorphic conditions of the metamorphic rocks from West Timor (Sopaheluwakan, 1990), Kisar (Tsujimori, unpublished data), Leti (Kadarusman, unpublished data), Moa (Tsujimori, unpublished data), Sermata (Kadarusman unpublished data) and Laibobar (Ota, unpublished data), the unmetamorphosed continental shelf sediments, and the fore-arc ophiolite. A thick grey line indicates the metamorphic field gradient of the Timor–Tanimbar metamorphic unit. Reaction curves: (1) jadeite+quartz=albite (Newton and Smith, 1967), (2) aragonite=calcite (Johannes and Puhan, 1971), (3) stability limit of glaucophane (Maresch, 1977). Boundaries of metamorphic facies are from Maruyama et al. (1996a,b). AM, amphibolite facies; Am EC, amphibole eclogite facies; BS, blueschist facies; EA, epidote-amphibolite facies; GR, granulite facies; GS, greenschist facies; HGR, high-pressure granulite facies; PA, pumpellyite-actinolite facies; PP, prehnite-pumpellyite facies; PrA, prehnite-actinolite facies; Zeo, zeolite facies.

1000 m in Timor, decreasing to a few hundred meters in the east (Fig. 8).

6. Summary of geology along sections across the Timor–Tanimbar region

The characteristics of the Timor–Tanimbar orogeny can be summarized as follows: (1) The regional metamorphic belt rests on an unmetamorphosed unit above a subhorizontal thrust plane (Fig. 9A). The Timor–Tanimber metamorphic belt is up to 2 km thick (in Timor) and the outcrop is 50 km wide (in East Timor) and may extend laterally for more than 1000 km. The metamorphic belt occurs as subhorizontal nappes bounded by normal fault at the top and a reverse fault at the bottom; these two faults are termed paired faults (Fig. 9A). (2) Nappes extrude from north (root zone) to south, towards the foreland, forming a fore-deep or foreland thrust belt in front of the advancing nappe. The metamorphic belt is tectonically modified by a later stage of doming accompanied by numerous high-angle normal faults that cut all units (Fig. 9A). For example, gently folded antiforms of Timor metamorphic unit presumably related to domal uplift have been formed, probably since Pleistocene, and high-angle secondary normal faults are ubiquitous (Figs. 2 and 9A). (3) The thermobaric maximum of the metamorphic belt occurs at structural intermediate levels (Fig. 9A). (4) Large pressure breaks occur across the paired faults. For example, the metamorphic pile of Leti Island was recrystallized at about 5–10 kbar (Kadarsman, unpublished data), where as the overlying FAO (up to 6 km thick in Timor) was formed at about ~2 kbar or less, giving a 3 to 10 kbar gap at near the upper boundary (Fig. 9A,B). Similarly, an approximately 5 kbar gap exists along the lower boundary, as the UCSS is unmetamorphosed (Fig. 9A,B).

7. Discussion

Tectonic models for the exhumation of the TTM can be grouped into five categories (see e.g. Johnson, 1981; Wensink et al., 1987; Richardson and Blundell, 1996): (1) the imbricate model (Fitch, 1972; Fitch and Hamilton, 1974; Hamilton, 1979), (2) the overthrust model (Carter et al., 1976; Barber et al., 1977; Audley-Charles et al., 1979), (3) the rebound model (Grady and Berry, 1977; Chamalaun and Grady, 1978), (4) models invoking collision of micro-continental fragments (Richardson and Blundell, 1996), (5) obduction model (Helmers et al., 1989; Sopaheluwakan, 1990), and combination of (1), (2) and (3) (Charlton, 1989; Charlton et al., 1991a; Harris, 1992).

The first model explains Timor as a chaotic melange, consisting mainly of continental material scraped off from the Australian margin during a continental–island arc collision. Our structural and kinematic data suggest that the metamorphic unit has been extruded along the boundary between mantle wedge and accreted sediments, and the metamorphic rocks cannot be interpreted as blocks in a melange complex as proposed in the imbricate model (Fitch and Hamilton, 1974; Hamilton, 1979). The second model is probably the oldest model, in which Timor was interpreted in terms of Alpine-style thrust sheets. This model involves a Middle Pliocene continental–island arc collision along the Wetar Strait. As a result, some thin thrust sheets from a pre-collision outer arc ridge were pushed over the Australian continental margin. The following plate motion led to uplift of Timor and downwarp of the Timor trench. However, Barber et al. (1977) did not observe basal thrust planes of the major overthrust units in the field. The third model involves the subduction of the Australian continental margin into beneath the subduction zone in the vicinity of the Wetar Strait. Subsequently, the oceanic lithosphere was detached from the continent, resulting in the uplift of Timor by isostatic rebound. This model is similar to ours, except for the driving force of wedge extrusion. The fourth model invokes welding of sediments due to collision of a micro-continent that took place 8 Ma ago. This caused metamorphism of the Aileu Formation along the leading edge of the micro-continental fragment. Richardson and Blundell (1996) proposed that the Timor can be regarded as a micro-continental fragment. However, their model did not refer to the kinematics of the metamorphic rocks, and it cannot explain our kinematic data in the metamorphic unit. The fifth model suggests that, during collision, the heated part underneath the volcanic arc was obducted onto the previously stacked thrust sheets forming the FAO in Timor (top-to-the-south movement). However, our detailed studies revealed that the FAO is bounded to the underlying TTM by normal faults and the shear sense indicates top-to-the north sense of motion.

Our observations show that the imbricated sheets of regionally metamorphosed rocks of the TTMB are confined by a reverse fault at the base and a normal fault along the top surface. A generalized model is required to account for such a subhorizontal thermobaric structure bounded by a pair of faults, because the sandwiched structure is a common feature in other blueschist belts (Maruyama et al., 1996b; Terabayashi et al., 1996), ultrahigh-pressure metamorphic belts (Maruyama et al., 1994; Ernst et al., 1997) and the Himalayan metamorphic belt (Kaneko, 1997). Wedge extrusion is preferable to selectively exhume the higher-grade part in the structural centre, bounded by lower-grade units on both sides. The thin, subhorizontal tectonic slab of the TTMB bounded by paired faults, the internal thermal structure and the vergence of nappe movement all indicate that the TTMB was exhumed from lower crustal depths to shallower levels by subhorizonal tectonic extrusion. The sense of shear also supports the selective tectonic denudation of the structural core of the TTMB. The thermal structure within the TTMB unit implies that the more ductile, higher temperature and hence more buoyant quartzofeldspathic materials moved to the surface faster than the surrounding lower-grade rocks. Tectonic juxtaposition of the rocks formed in the middle to shallow crustal levels suggest cooling of the TTMB unit at this

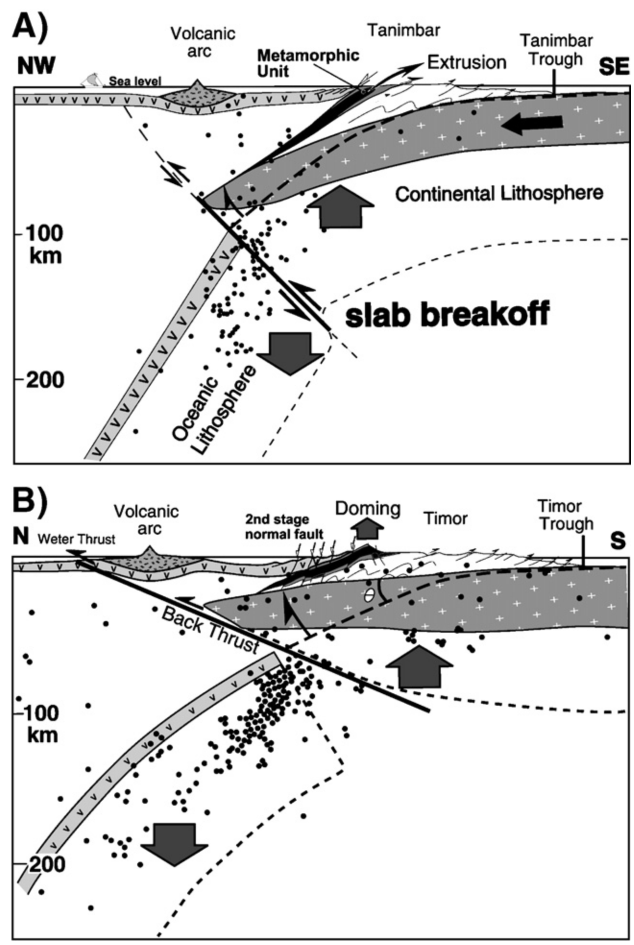

Fig. 10. Different exhumation stages of the Timor–Tanimbar metamorphic belt. (A) The first stage of exhumation by wedge extrusion now is ongoing in the Tanimbar region. Earthquakes plotted from Osada and Abe (1981). (B) The domal uplift currently is in progress in western Timor. Earthquakes plotted from McCaffrey et al. (1985). See text for further explanation.

level; the mechanical change from ductile to brittle behavior would prohibit further transport to the surface. During or after tectonic juxtaposition and low-grade metamorphism, all three units were subjected to domal uplift. Fig. 10 depicts our speculative model for the tectonic evolution of the Timor–Tanimbar orogenic belt.

Since Cretaceous or earlier, the Tethyan oceanic plate (Indo-Australian plate) was subducted beneath the Eurasian plate. After the Tethyan oceanic plate was consumed by northward subduction, the Australian continental crust started to underthrust.

In Late Miocene, the Australian continent and overlying Tethyan sediments were subducted, together with the downgoing oceanic plate to a depth of about 30 km. The subduction zone was choked by buoyant continental material, ruptured, and heated up to be recrystallized and later exhumed. After the loss of the leading portion of the high-density oceanic lithosphere due to “slab break-off”, sialic material began to return to the surface. The driving force of wedge extrusion is buoyancy of sialic material released by the delamination of the oceanic slab. The break-off of the subducted oceanic slab from the Australian continental plate was seismologically well-documented by Osada and Abe (1981). The highly ductile quartzofeldspathic materials are about 15% less denser than the overlying mantle wedge (Cloos, 1993). Due to their positive buoyancy, the quartzofeldspathic materials move upwards against the brittle hanging wall of the mantle wedge. The higher-temperature core is more ductile than the surrounding lower *T* parts of the quartzofeldspathic metamorphic unit, and hence it tends to move faster than low-T parts within the moving wedge. The metamorphic core of the TTMB moved up to the mid-crustal level, then stopped and thermally altered the surrounding units, especially the underlying, less metamorphosed UCSS. Note the absence of mountain building during the rapid transportation of deep-seated sialic materials into mid-crustal levels, likewise in the Tanimbar region. Coeval with the southward extrusion of the subducted wedge, the Pliocene foreland fold-and-thrust belt to the south, and the E–W and N–S extensional Quaternary grabens on the Ombai Wetar Strait to the north were developed.

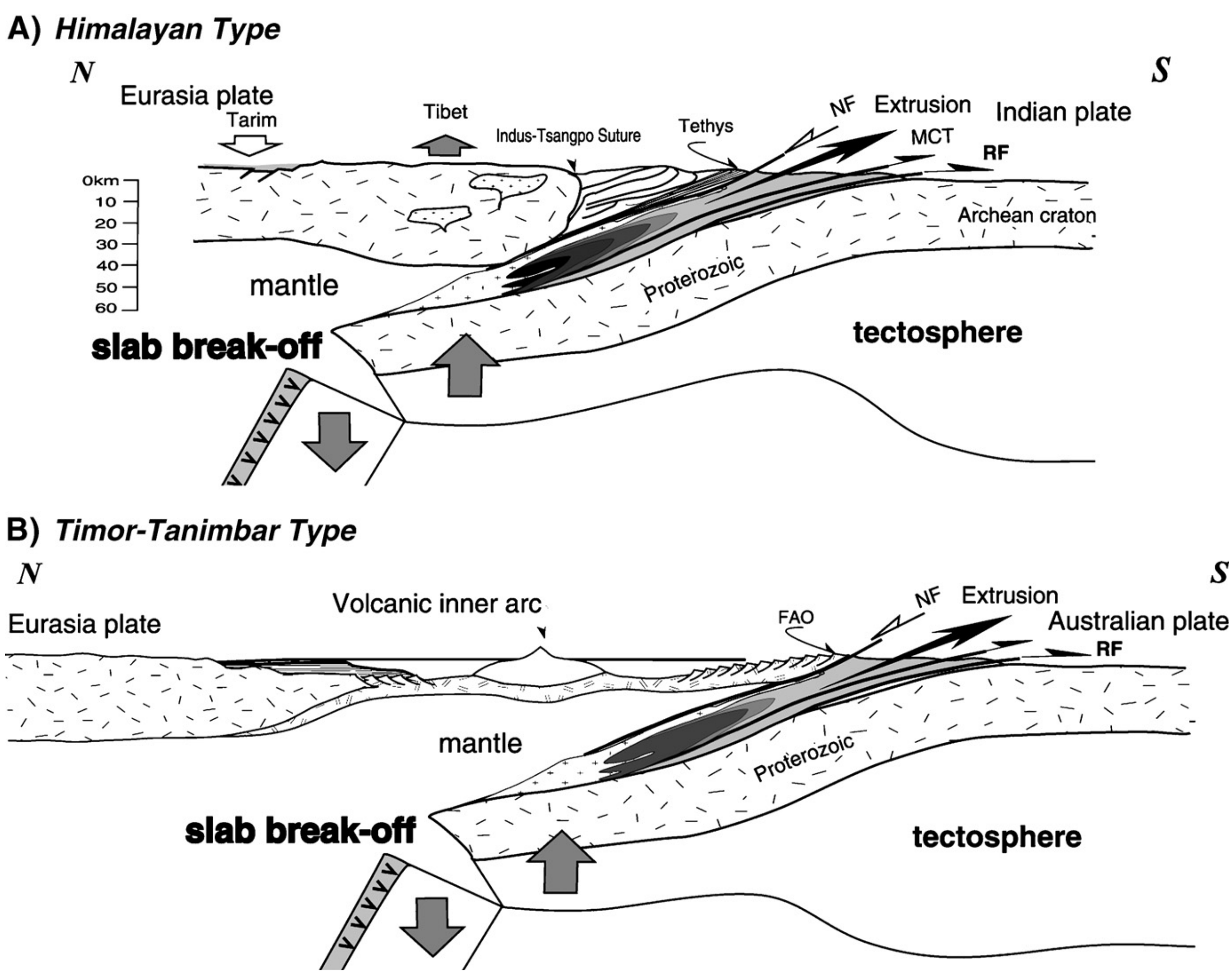

Fig. 11. Schematic diagrams showing the subduction of the Indian continent at 20 Ma (A) and the Australian continent in the Tanimbar area at present (B); subhorizontal extrusion of the metamorphic belt by synchronous paired normal faulting on the top and reverse faulting at the bottom. Tectonic juxtaposition of these metamorphic units at mid-crustal level. Modified after Kaneko (1997).

The three stacked and welded units at mid-crustal levels started to dome at 2 Ma in Timor, developing numerous high-angle faults which segmented the stacked units into several sections. Differential uplift along conjugate normal faults and right-lateral strike-slip faults have segmented the TTMB into several blocks since then. Alternatively, the Aitutu anticlinorium in Timor may be interpreted as a fault-bent fold related to late second-stage normal faulting which produced block uplift/exhumation of the range. A Middle Miocene foreland fold-and-thrust belt developed to the south, as well as the extensional Miocene–Quaternary Mutis fault in the West Timor, coeval with the southward extrusion of the metamorphic wedge. Huge amounts of terrigeneous material began to be supplied to the Banda Sea and fore-deep in which the molasse accumulated. Timor exhibits several geologic phenomena indicative of compressive, continental subduction-related deformation overprinted by late-stage extension associated with rapid uplift. Therefore, final doming after wedge extrusion of the high *P*/*T* unit is currently on-going on Timor. The most spectacular evidence for the wedge extrusion occurs along the northern margin of the island, where a part of the metamorphic unit ranging from subgreenschist, through greenschist, and amphibolite to granulite facies is exposed.

A major difference between Timor and Tanimbar is the extent of the domal uplift. As shown by topographic differences, the domal uplift is nearly completed in Timor, whereas the doming stage is just being initiated in Tanimbar. Enormous quantities of molasse sediments would be expected in the Tanimbar region if the exhumation of the regional metamorphic belt is not accompanied by the paired faults as tectonic transportation, and if it is generated by the restoration process of the isostasy.

We suggest this area is a modern analogue of an A-type high *P*/*T* metamorphic belt because: (1) the protoliths of this metamorphic belt are platform-type carbonate, metabasic, peraluminus turbidites and minor amount of bedded chert, characteristic of typical A-type high *P*/*T* metamorphic belt; (2) the on-going wedge extrusion along consuming plate boundaries were identified for the A-type high *P*/*T* metamorphic belt. This modern analogue of an A-type high *P*/*T* belt has an extremely complicated deformational history. Available radiometric ages of the Himalayan metamorphic rocks indicate that regional metamorphism occurred at 20–25 Ma, about 20–15 m.y. after the initiation of collision (Fig. 11A). However, the radiometric ages reported by previous workers (Berry and Grady, 1981a; Berry and McDougall, 1986; Sopaheluwakan, 1990; Linthout et al., 1991, 1996) suggest that the Timor–Tanimbar regional metamorphic rocks had already recrystallized before the Australian continent and Eurasian continent collided (Fig. 11B). This study lead to a better understanding of the processes of exhumation and mountain building before continental collision.

8. Conclusion

(1) The exhumation of the high *P*/*T* belt started in West Timor and migrated toward the east. (2) The deep-seated high *P*/*T* belt was emplaced into shallow crustal levels due to wedge extrusion. (3) Wedge extrusion did not contribute to the topographical elevation, which can be explained by later doming. Quaternary uplift, marked by elevation of reefs, is estimated to be about 1260 m in Timor in the west and decreases towards the east. In contrast, radiometric ages for the high *P*/*T* metamorphic rocks suggest that exhumation of the highP/T metamorphic belt started in West Timor in Late Miocene time and migrated towards the east. (4) This rapid uplift is attributed to the rebound of subducting Australian continental crust beneath Timor Island, triggered by slab break-off. In contrast, Tanimbar in the east has not yet been affected by later doming stage. A wide spectrum of processes starting from extrusion of the high *P*/*T* rocks and ending up with later doming due to slab break-off can be observed here.

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