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Seismic response to slab rupture and variation in lithospheric structure beneath the Savu Sea, Indonesia

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ABSTRACT

Variations in seismic moment release and stress state across the transition from subduction of oceanic crust to arc–continent collision in the Banda Arc are constrained by focal mechanism solutions from the CMT earthquake catalogue. In particular the slab under the western Savu Sea is unusual in that intermediate depth (70–300 km) events indicate that at this depth range the slab is largely in down-dip compression. This contrasts with the intermediate depth, down-dip tension that typifies the Sunda slab to the west and the far eastern Banda slab to the east. Down-dip compression beneath the Savu Sea reflects subduction of transitional crust of the Scott Plateau, more buoyant than the Indian Ocean crust subducting further west. In this region, enhanced magma flux is indicated by unusually narrow volcano spacing in the overlying arc, and suggests that down-dip compression reflects not only more buoyant transitional crust but also a reduction in slab–wedge coupling induced by enhanced magma flux. East of the Savu Sea, the near complete absence of intermediate depth seismicity is attributed to a slab window that has opened where Australian continental crust has collided with the arc. Differences in seismic moment release around this slab window indicate asymmetric rupture, propagating to the east at a much faster rate than to the west.

1. Introduction

The processes by which subducting slabs rupture and detach from surface plates during arc–continent collision have received a great deal of attention in recent times (Rosenbaum et al., 2008; Regard et al., 2008; De Franco et al., 2008). Breakoff, rupture, severing, detachment and tearing are all terms that describe processes related to the segmentation of slabs inferred in a range of subduction settings around the world. Such processes are often, but not necessarily, associated with the terminal stages of subduction that accompany incipient collision (e.g. central Mexico, Apennines, Italy). Rupture is most commonly evidenced by heterogeneities in slab structure inferred from seismic tomography imaging, but also by inferences drawn from spatial or temporal changes in volcanism (Ferrari, 2004; Rosenbaum et al., 2008), uplift (Rogers et al., 2002) and stress field (Wortel and Spakman, 2000). The considerable diversity in styles and responses to slab rupture has made recognition of diagnostic properties somewhat problematic. This work uses the earthquake record of the Sunda–Banda Arc system in the vicinity of the Savu Sea in order to establish the characteristics of, and controls on, slab rupture in an active arc–continent collision zone.

The Sunda–Banda Arc provides a unique location to investigate the nature of active slab rupture during the early stages of arc–continent collision (Hall and Wilson, 2000; Audley-Charles, 2004; Elburg et al., 2005; Harris, 2006). Key observations pertaining to this region include the association of the rapidly uplifting (0.5–1 m/1000 years; Chappell and Veeh, 1978; Hantoro et al, 1994), inactive segment of the volcanic arc with a prominent gap in intermediate depth (70–300 km) seismicity to the north of Timor. Given that Timor represents the part of the collision zone between the Australian continent and the Banda Arc that is most advanced (Tandon et al. 2000), it is the most likely place for the slab to detach. Some decoupling of surface plate motion from the deeper slab system is indicated by GPS studies that suggest most plate convergence is now being accommodated by backarc thrusting associated with subduction polarity reversal (Fig. 1; Hall and Wilson, 2000; Audley-Charles, 2004). Combined, these observations make a strong case that the slab beneath the segment of the Banda Arc north of Timor in the vicinity of Alor and Wetar has, at least in part, detached from the surface plate. The prominent intermediate depth (70–300 km) aseismic gap, termed the Wetar Seismic Gap (WSG), may represent something akin to a slab window separating a deeper remnant of the subducting slab from the surface plate. Because the WSG is bounded by volcanically-active arc segments overlying seismically active slab systems, this interpretation demands that the slab must be actively rupturing along either side of the WSG. The case for active rupturing is indicated by the occurrence of intense intermediate depth seismicity in the regions bounding the WSG (McCaffrey et al., 1985; Sandiford, 2008). McCaffrey et al. (1985) argued for an active rupture beneath the island of Pantar along the western boundary of the WSG, and Sandiford (2008) showed the eastern boundary of the WSG is marked by a zone of intense down-dip extension

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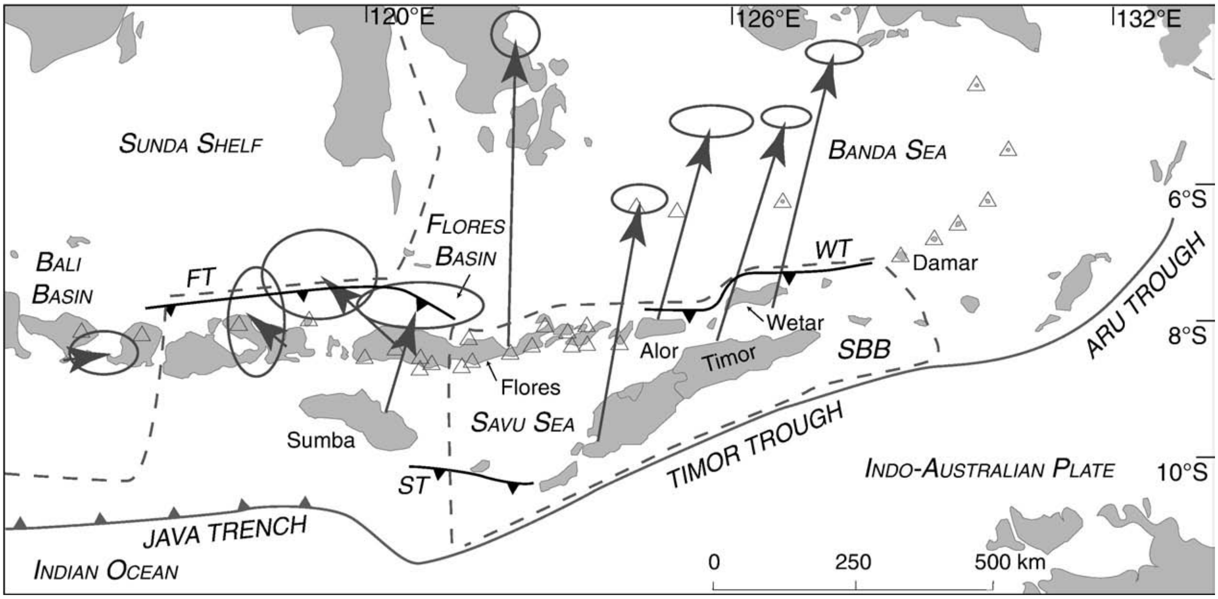


Fig. 1. Tectonic and kinematic map of the Sunda–Banda arc. The Banda Arc comprises an inner volcanic arc and non-volcanic outer arc. Triangles show active volcanoes; the segment of volcanic arc south of the Wetar thrust is no longer active. Dashed lines indicate crustal block boundaries (SBB = South Banda block), and arrows are GPS velocities vectors relative to the Sunda Shelf (Bock et al., 2003). Ellipses indicate 95% confidence limits on the vector.
Structural features, Flores Thrust (FT), Wetar Thrust (WT) and Savu Thrust (ST), are from McCaffrey (1988).

consistent with a horizontally propagating rupture at 100–200 km depth. Sandiford (2008) argued that the anomalously low bathymetry of the eastern Banda arc, compared to the volcanically inactive arc segment overlying the WSG, reflects the extra slab pull transmitted around the slab window through the actively rupturing slab segment. Intriguingly, the arc above the western margin of the WSG is uplifting, and features the closest volcano spacing for the entire arc, presumably reflecting enhanced magma flux. Thus, variations in topography and magma flux seem therefore to be expressed rather differently on either margin of the WSG.

This paper uses earthquake data to provide a new insight into the nature of early-stage slab rupture processes in the Savu Sea region, west of the WSG. It builds on the earlier work of McCaffrey et al. (1985) by using a more complete set of focal mechanisms data, and augments the work of Sandiford (2008) that focussed on the eastern Banda arc. With subduction of Indian Ocean crust in the west, and collision of continental crust in the east, the Savu Sea region provides the opportunity to explore how variation in lithospheric structure influences the nature of seismicity in the subduction zone. Our purpose is to explore the extent to which the subduction of transitional (ocean-continent) crust is reflected in the slab seismicity in the Savu Sea region, and how it might influence the propagation of the slab rupture. The surface expression of subduction processes are also examined, including the relationships with volcanism and the uplift record.

2. Background

The location and characteristics of earthquakes provide one of the most direct insights into the distribution of deformation and, where focal mechanism data are available, the nature of that deformation and associated state of stress in the subduction environment. This is of particular importance at sublithospheric depths where GPS measurements are not applicable. While it is important to recognise that aseismic slip may account for a large percentage of the strain field in subduction or collision zones (Scholz, 2002), the seismic record does provide for robust comparison of deformation style and intensity between adjacent regions. In the Sunda and Banda arcs, the publication of earthquake catalogues combining accurate location data (Engdahl and Villaseñor, 2002; Das, 2004) and focal mechanism solutions (The Global CMT, 2009) now allows the nature of seismicity to be investigated in considerable detail, offering new insights that extend the older studies of McCaffrey (1989).

The pattern of seismicity in the Sunda and Banda arcs has attracted interest since the early 1970s (Fitch and Molnar, 1970; Fitch, 1970; Fitch, 1972). Utilising a dataset of 41 focal mechanism solutions, Cardwell and Isacks (1978) showed that intermediate depth events in the tightly curved, eastern part of the Banda Arc are characterised by shallow plunging P-axes within the plane of the slab. This orientation contrasts to the slab-normal or down-dip orientations typical of most subduction zones, and was attributed to in-plane compression associated with the development of the exceptionally tight curve of the eastern Banda Arc. Cardwell and Isacks (1978) also established regional patterns of seismicity, showing shallow earthquakes to be dominated by thrust and strike-slip mechanisms, intermediate depth events to be mostly consistent with down-dip extension, and the deepest seismicity dominated by normal focal mechanism solutions demonstrating down-dip compression. In the early 1980s, the acquisition of seismic reflection profiles resulted in the research focus shifting to the shallow tectonic features of the arcs. Silver et al. (1983) noted the reduced frequency of shallow earthquakes beneath Timor and attributed an increase in earthquake activity on the western boundary of this zone near Pantar to mark an active slab tear.

In a series of studies, McCaffrey and co-workers investigated the tectonics of the eastern Sunda and Banda arcs using newly acquired seismic event data including focal mechanism solutions (McCaffrey and Nábělek, 1984; McCaffrey et al., 1985; McCaffrey and Nábělek, 1986; McCaffrey, 1988; McCaffrey, 1989; McCaffrey and Abers, 1991). Analysis of shallow earthquake events provided evidence of south-directed backarc thrusting north of Flores that McCaffrey and Nábělek (1984) interpreted as a response to subduction polarity reversal (Fig. 1). Farther east, near Wetar, two large thrust fault events ($M_s = 7.0$ and 7.2) were also attributed to convergence on south-dipping thrusts (McCaffrey and Nábělek, 1986). In the most important study to date relevant to the Savu Sea region, McCaffrey et al. (1985) used the location of 460 events and 45 new focal mechanism determinations

from a microseismic survey to conclude that seismicity at ~100 km depth beneath Pantar suggests that the slab is actively rupturing along near vertical slab-parallel faults.

3. Structural and geodynamic framework of the Savu Sea region

The Savu Sea region is part of the transition zone connecting the Sunda Arc to the west to the Banda Arc to the east (Fig. 1). Along the Sunda Arc, old Indian Ocean crust is being subducted beneath the Sunda Shelf to the north. The Banda Arc is distinguished from the Sunda Arc because it juxtaposes Australian continental lithosphere against the forearc, representing one the best examples of active arc–continent collision on the modern Earth.

The major structural features in the Savu Sea region are the Timor Trough, Java Trench and a series of arc-parallel thrust faults north of the volcanic arc that define the Flores and Wetar thrust zones (Fig. 1). In the vicinity of Timor, arc–continent collision commenced about 3 million years ago (Abbott and Chamalaun, 1981; Hall, 2002; Audley-Charles, 2004), since which time there has been ~200 km of convergence. Some convergence has been accommodated through imbrication of Timor and the outer arc islands along strike from Timor, such as Roti and Savu on the southern margin of the Savu Sea (e.g. Harris et al., 2000; Audley-Charles, 2004). GPS data (see below) imply that south-dipping thrust faults, such as the Wetar and Flores Thrusts to the north of the volcanic arc, now play the major role in accommodating convergence. However, precisely how convergence has been partitioned between forearc imbrication, subduction of continental lithosphere and back arc thrusting across the collision zone is not yet fully understood.

Analysis of GPS data recorded at fixed sites throughout southeast Asia has established relative plate motions in the Banda region (Genrich et al., 1996; Bock et al., 2003). Genrich et al. (1996) defined a number of crustal blocks with minimal internal deformation: Sunda Shelf, eastern Sunda Arc, South Banda and northern Australia, with ~7 cm/year of convergence between the Australian and Sunda Shelf (Fig. 1). Importantly, the GPS data demonstrate the partial accretion of the Banda Arc to the Australian continent, with Timor, Alor and Wetar travelling with ~90% of the relative velocity of Australia (Genrich et al., 1996). The GPS data indicate most of the convergence occurs in the Flores Sea, north of the South Banda block, at a rate of 60 ± 3 mm/year (Bock et al., 2003). The eastern Sunda arc is undergoing rapid deformation across the transition from subduction of oceanic crust along the Java Trench to thrusting north of the arc. The velocities highlight complexity in the Savu Sea region where the motion of western Flores and Sumba is neither coupled to Australia nor the Sunda Arc (Bock et al., 2003).

4. Earthquake datasets

This study uses several earthquake catalogues to characterise the distribution and nature of seismic activity in the Sunda and Banda arcs. The Centennial Catalogue (Engdahl and Villaseñor, 2002) is a global combined catalogue spanning the period 1900–2002, with common, corrected magnitudes and relocated hypocentres. The dataset comprises earthquakes of magnitude greater than 6.5 that were recorded during 1900–1963, and a complete record of all events greater or equal to a magnitude of 5.5 recorded from 1964 to 2002. In the Sunda–Banda region (114–130°E, 12–6°S) this catalogue includes 254 events.

Greater detail of seismic activity in the Sunda–Banda region was presented in studies focussed on intermediate and deep seismicity by Schoffel and Das (Schoffel and Das, 1999; Das, 2004) These authors relocated events from the International Seismological Centre (ISC) and National Earthquake Information Centre (NEIC) catalogues, including all events with body wave magnitude $m_b > 4.5$ in the earlier study, and events of $m_b > 5.0$ in the later work, which focussed specifically on the Banda Arc. The relocated earthquakes have a 90% confidence error ellipsoid of ≤30 km, with the majority of the data located to ≤20 km. Together these data form the 'Das' catalogue, comprising 661 events recorded in the study area during 1964–1997.

While the number of events in the Das catalogue alone makes it a more comprehensive and accurate dataset than those otherwise available, the inclusion of only events deeper than 50 km prevents complete assessment of earthquake location. To address this issue, the Das catalogue is augmented with additional events from the Centennial catalogue. Addition of shallow events from the Centennial dataset, along with events at all depths that occurred from 1997 to 2002 (i.e. since publication of the Das catalogue) has enabled the compilation of a catalogue of well located events for this region containing 804 events. This combined catalogue forms the basis for the analysis of distribution and magnitude of earthquakes presented in this study.

The catalogue of the Harvard Centroid-Moment-Tensor (CMT) Project is a global dataset of moment sensor calculations for earthquakes of magnitude $M > 5$ since 1976 (The Global CMT, 2009). The focal mechanism solutions define the principal axes (P-, T- and B-axes) and nodal planes for individual events, thus allowing for characterisation of the fault mechanisms and insight into the nature of the associated seismic strain field. The coverage of the study area is comprehensive, including 642 events reported as of September 2008 in the region bounded by 114–130°E, 12–6°S. The uncertainties in the calculated orientation of the nodal planes are typically ±20° in strike and ±10° in dip (McCaffrey and Abers, 1991).

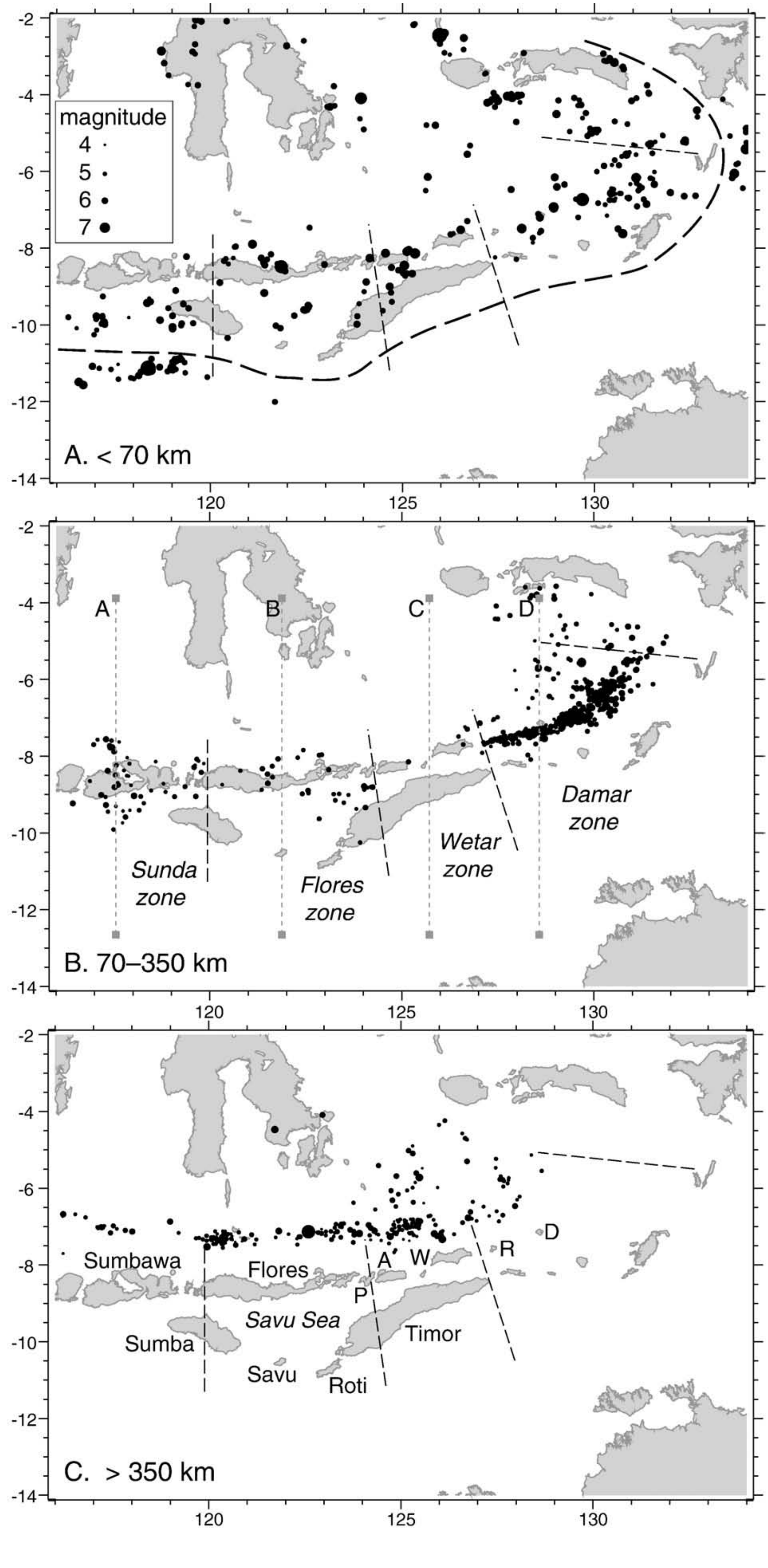
5. Seismic character of the Sunda–Banda subduction system

It has long been recognised that seismicity in southeast Asia is strongly controlled by plate boundary interactions. On a regional scale, there is a high intensity zone of earthquakes along the entire length of the Sunda and Banda arcs, with intermediate to deep seismicity imaging the subducting slabs that underlie the volcanic arcs (e.g. McCaffrey, 1988; Schoffel and Das, 1999, Das, 2004). A striking aspect of the seismic record of this region is the variation in seismic activity at the scale of several hundred kilometres, both horizontally and vertically (e.g. Sandiford, 2008; Fig. 2). For example, intermediate depth seismic moment varies dramatically across the Sunda–Banda arc transition, from moderate beneath Sumbawa and Flores, to negligible beneath Alor and Wetar, to large beneath Damar in the far east. Such variations divide the arc between Bali and Serua (in the eastern Banda Sea) into four zones of different character: Sunda, Flores, Wetar and Damar (Figs. 2 and 3, see also Sandiford, 2008).

The Sunda zone, extending from Bali to western Sumba, features a wide zone of shallow earthquakes. Apart from a mostly aseismic zone at 250–400 km depth, the subducting slab is seismically active to depths of >600 km (Fig. 3A). The majority of shallow earthquakes are located in the outer rise and on the subduction interface beneath the forearc. The frequency and magnitude of outer rise normal fault mechanism earthquakes increases eastwards towards Sumba, and then terminate at ~119.5°E. Western Sumba is seismically active, whereas the eastern half of the island has experienced very little earthquake activity. Intermediate depth earthquakes are dominated by reverse mechanisms (Fig. 4), while deep earthquakes are exclusively normal mechanisms.

Compared to the Sunda zone, the nature of seismic activity in the Flores zone changes in several ways. The cessation of forearc earthquake

Fig. 2. Earthquakes (magnitude≥5) of southeast Asia showing the distribution of seismic activity throughout the Sunda–Banda arc. Increase in symbol size corresponds with larger magnitude earthquakes. A) Shallow earthquakes at 70 km depth. B) Intermediate depth (70–350 km) earthquakes, and the various geographic zones discussed in the text. The locations of Fig. 3 sections A–D are indicated by dashed lines. C) Deep (350 km depth) earthquakes, and locations of islands of the Sunda and Banda arcs discussed in the text. P = Pantar, A = Alor, W = Wetar, R = Romang, D = Damar.


magnitude
4
5
6
7
A. < 70 km
B. 70–350 km
A
B
C
D
Sunda zone
Flores zone
Wetar zone
Damar zone
C. > 350 km
Sumbawa
Flores
Savu Sea
Sumba
Savu
Roti
Timor
P
A
W
R
D
120
125
130
-2
-4
-6
-8
-10
-12
-14

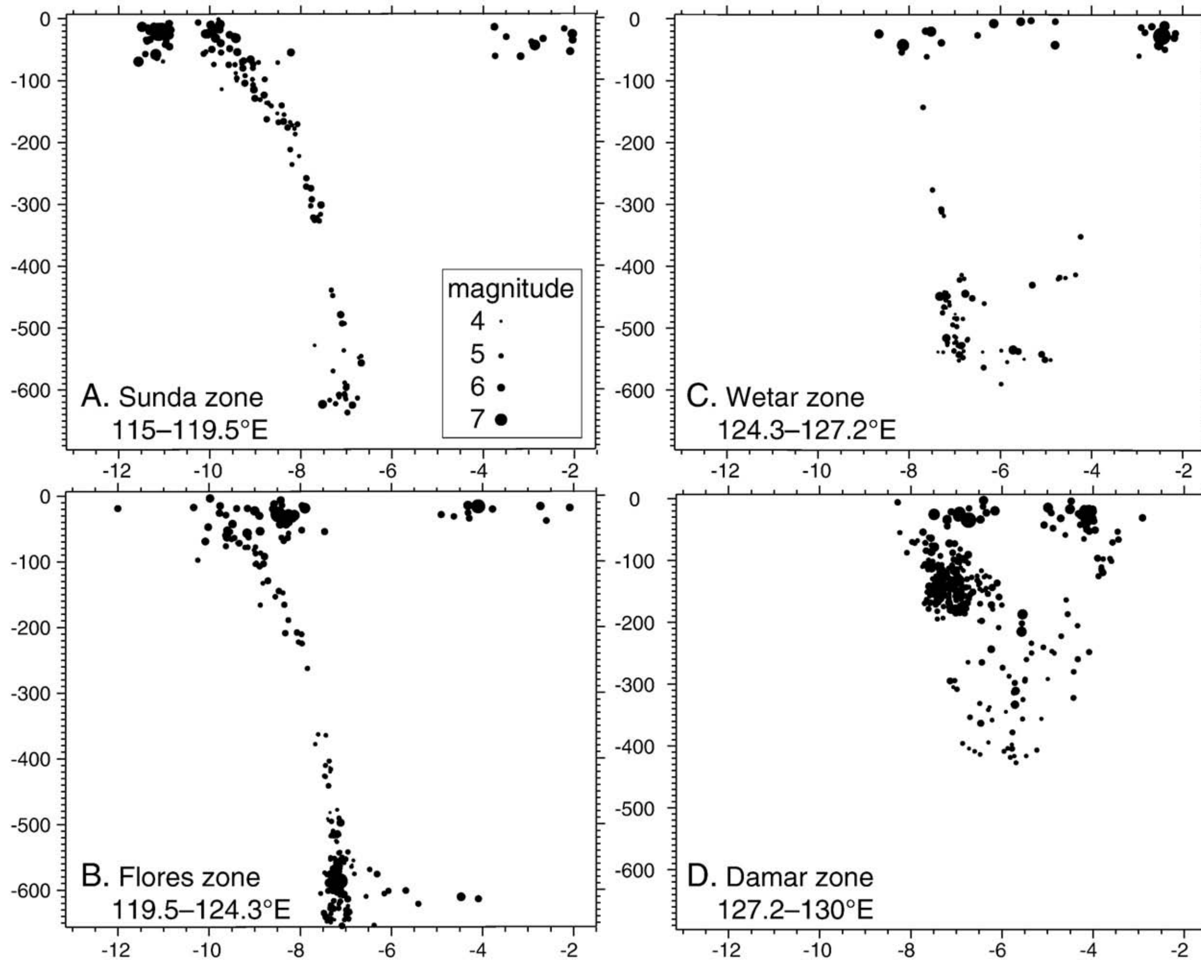


Fig. 3. Projected sections through zones of the Sunda–Banda arc using the combined catalogue. Sections are oriented north–south and show all events within each zone as indicated by the ranges of longitude on each figure. Also refer to Fig. 2 for locations. A) Section through the Sunda zone showing near continuous seismicity down to the base of the slab, and high level of activity along the outer rise. B) Section through the Flores zone, also demonstrating seismicity throughout much of the slab. Note the absence of outer rise activity and the concentration of backarc earthquakes. C) Section through the Wetar zone highlighting the lack of intermediate depth seismic activity. D) In contrast, intermediate depth activity is intense in the Damar zone.

activity along the projected trace of the Java Trench coincides with an increase in the magnitude and frequency of backarc earthquakes along the north coast of Flores (Fig. 3B). Continuous seismicity to depths of around 260 km and then again from 400 to 660 km defines a continuous slab beneath the Flores zone and distinguishes it from the Wetar zone to the east. A moderate number of earthquakes have been recorded in the Savu Sea and western Timor domains. Intermediate depth earthquakes include a mix of normal, reverse and strike-slip mechanisms, while deep events are dominated by normal mechanisms.

In the Wetar zone, the absence of intermediate depth seismicity beneath the extinct volcanic section north of Timor defines the Wetar Seismic Gap (WSG) (Sandiford, 2008), extending from the western edge of Pantar (124.3°E) to Romang (127°E) (Figs. 3C and 4). Shallow earthquakes above the WSG are restricted to the upper ~70 km, and thus can be attributed to lithospheric deformation, while deeper earthquakes only occur at depths greater than 350 km. A distinct cluster of earthquakes lies beneath the narrow strait that separates Timor from Alor. From Wetar to Romang, shallow seismicity is relatively infrequent and mostly restricted to reverse faults in the backarc. The paucity of earthquake events in the Timor Trough is consistent with GPS studies indicating that it accommodates no more than 20% of present plate convergence (Bock et al., 2003). Eastern Timor is notable for its lack of shallow earthquakes.

The eastern boundary of the WSG is defined by intense intermediate depth seismic activity, particularly beneath the volcanic island of Romang, which also marks the boundary between the Damar zone to the east and the Wetar zone to the west. The depth extent of the seismic zone shallows to the east beneath the Wetar and Damar zones, with no deep earthquakes recorded east of Damar (Figs. 2C and 3D).

6. Detailed seismic character of the Flores zone

Variations in the frequency and nature of earthquakes at intermediate (70–300 km) and deep (>300 km) levels reflect heterogeneities in the seismic moment release and stress state within the slab. A significant feature of the Banda Arc subduction system is the apparent asymmetry of seismic moment release on the margins of the WSG (Sandiford, 2008; Fig. 2). This heterogeneity is explored here using CMT focal mechanism solutions west of the WSG, in the Flores zone, to build a more complete model of the distribution of seismic moment and stress state in the region.

6.1. Shallow seismicity

The CMT catalogue includes 74 shallow (<70 km depth) events in the Flores zone (119.5–124.3°E, 7.0–11.5°S, Fig. 5). Within this region, differences in the ratio of the focal mechanisms (normal, reverse and strike-slip) and trends of principal axes (P- and T-axes) orientation of these shallow events define several domains described here and shown

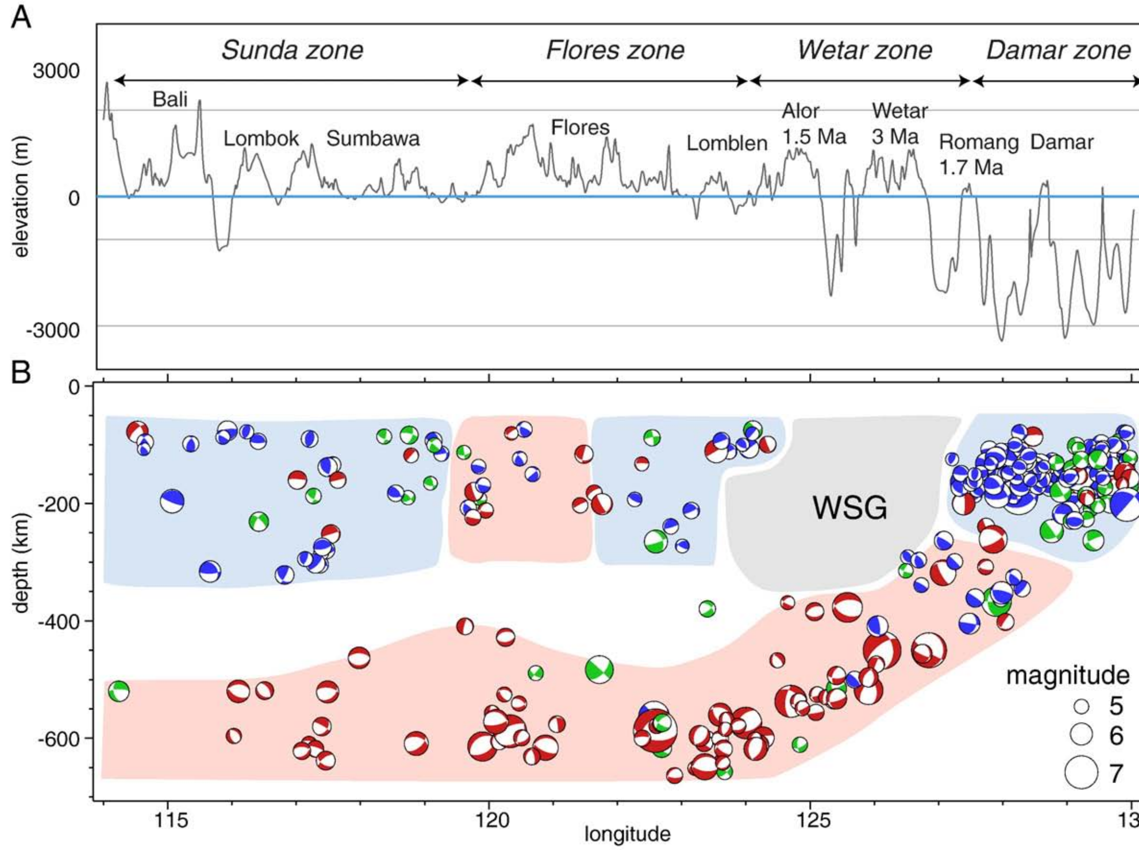


Fig. 4. Longitudinal sections from Java to the eastern Banda Arc. A) Topography and bathymetry show the transition from high topographical expression of the Sunda Arc (in the west), through to subdued topography and deep seaways of the Damar zone (eastern end). Age (Ma) of the youngest dated volcanic rocks from each island is indicated for the inactive segment of the arc (Abbott and Chamalaun, 1981; Elburg et al., 2005). B) Earthquakes from the CMT catalogue at depths > 70 km projected onto a vertical plane ($n = 327$). At > 70 km all earthquakes in this catalogue are confined to the subducting slab (as illustrated in Fig. 3). Interpreted zones of varying stress are shown, of down-dip tension in the slab (blue shading), down-dip compression (pink) and the Wetar seismic gap (WSG, grey). Focal mechanism symbols are lower hemisphere projections (i.e. not rotated to section view) and scaled by magnitude ($M = 4.6$–7.9).

on Fig. 5. The Flores Thrust domain comprises a mix of strike-slip and reverse fault mechanisms with P-axes aligned about an azimuth of 160°, and T-axes forming a girdle orthogonal to the dominant P-axes azimuth. Reverse mechanisms are consistent with slip on shallow SSE dipping planes associated with back-arc thrusting, while strike-slip mechanisms are consistent with either right lateral movement on steep E–W trending planes or left lateral motion on steep N–NE trending fault planes. In the West Timor domain seismicity is predominantly limited to relatively small magnitude reverse and strike-slip events with NNW trending P-axes and an associated girdle of T-axes comparable to the Flores Thrust domain. The Savu Sea domain comprises a mix of normal and strike-slip events with a predominance of N–S trending T-axes that contrast with orientations in the Flores Thrust domain to the north. In central and eastern parts of the Savu Sea the strike-slip mechanisms imply right lateral motion on NE trending planes or left lateral motion on NW trending fault planes. The Sumba domain shows a pattern of seismicity similar to the Timor domain. The Roti domain to the south of the Savu Sea has few recorded earthquakes.

The distribution of earthquakes with different faulting mechanisms implies significant strain partitioning within the lithosphere in the Flores zone (McCaffrey, 1996). The concentration of large reverse earthquakes north of the volcanic arc supports the notion that much of the present day convergence is accommodated through back-arc thrusting. The absence of recorded earthquakes along the southern margin of the basin suggests that the Savu Thrust is no longer active, and that the shortening of the forearc in this region suggested by McCaffrey et al. (1985) is not being accommodated through movement on thrust faults. Importantly, the focal mechanisms imply that much of the Savu Sea is experiencing north–south extension.

6.2. Intermediate and deep level seismicity

Analysis of intermediate and deep level seismicity in the Flores zone is useful in characterising the boundary conditions of the seismic gap, and the distribution of stress is investigated using the CMT catalogue (Fig. 6). The nature of intermediate depth seismicity in the Flores zone defines two domains, the boundary of which coincides with the western margin of the South Banda Block of Bock et al. (2003). In the eastern Flores zone, earthquakes typically have near vertical, northeast trending nodal planes. For these events the differentiation between a normal fault mechanism and a reverse fault mechanism is within the error of the solutions (typical dip precision is ±10°). P-axes and T-axes typically exhibit moderate plunges to the south and north respectively. While the azimuths are quite variable, they are generally consistent with down-dip tensional stresses operating at intermediate depths (Fig. 7). In contrast, seismicity in the west Flores zone features northeast-plunging P-axes, with T-axes orientations forming a southwest-plunging girdle. This alignment of P-axes in the plane of the slab suggests a state of down-dip compression in the slab (Fig. 7). Down-dip compression is evident to depths of 250 km, below which a zone of low seismic activity occurs, with no earthquakes recorded in the combined or CMT catalogues. Below 400 km the seismic record in the Flores zone is similar to that along strike, with common normal mechanism (~85% of events) and fewer strike-slip mechanism earthquakes occurring. The number of earthquakes recorded increases

down-dip, with a zone of intense seismic activity recorded at 550–650 km. Unlike at intermediate depths, focal mechanism solutions in this zone typically have near vertical P-axes, and shallow south plunging T-axes. The combined catalogue shows a significant widening of the seismic zone at depth, suggesting the slab is pooling on the 660 km discontinuity (Fig. 3B).

7. Discussion

The above analysis of intermediate and deep seismic activity in the Flores zone highlights several salient features that warrant further discussion. In particular the down-dip compression at intermediate depths is unusual and bears on the nature and evolution of the Wetar seismic gap (WSG). Here we review mechanisms proposed for such down-dip compression as well as other associated aspects of the geology of the Savu Sea region as a precursor to discussing the nature of the slab processes that govern this region.

7.1. Mechanisms for intermediate depth down-dip compression in slabs

Down-dip compression at intermediate depths is unusual, both in the Sunda–Banda arc system and in subduction zones globally (Vassiliou and Hager, 1988; Chen et al., 2004). A notable example where down-dip compression dominates the intermediate depth seismicity is in the Tonga slab (Nothard et al., 1996). While efforts to reproduce down-dip compression in modelling experiments have proven difficult (Billen and Gurnis, 2003), several mechanisms have been proposed on both empirical and theoretical grounds. Isacks and Molnar (1971) modelled the distribution of stress in slabs and show that down-dip compression only extends to high levels in slabs that are seismically active at all depths. Fujita and Kanamori (1981) noted that a state of down-dip compression at intermediate depths is more likely in both old, quickly subducting slabs and young, slowly subducting slabs. Similarly, Chen et al. (2004) emphasised the importance of thermal control, finding high level down-dip compression occurred in cold (i.e. old) crust. Other studies have found that stress may vary across a slab. For example, by conducting numerical experiments based on a 2D subduction model, Houseman and Gubbins (1997) found that flexing of the slab results in compression on one side of the slab. An alternative to these mechanisms, all of which evoke involvement of 'top down' forces, is transmission of stress from the base of the slab. For the Tonga slab, Gurnis et al. (2000) proposed that lower mantle upwelling beneath the subduction slab has contributed to the down-dip compression throughout the slab. The stress state of a slab may also be influenced by conditions in the overlying mantle wedge. For example, Billen and Gurnis (2003) showed that the presence of a low viscosity mantle wedge above a slab reduces slab–wedge coupling, favouring development of down-dip compression at depths of 100–300 km.

Scale is an important discriminant between some of the factors contributing to the state of down-dip compression described here. Beneath the Savu Sea, the zone of down-dip compression has an along strike extent of 220 km, and is bounded by zones in down-dip tension. Such rapid switching of stress state at depths of 100–200 km seem incompatible with a lower mantle upwelling mechanism, which should produce much longer wavelength continuity in stress regime in the upper part of the slab. Furthermore, unlike the Tonga slab which exhibits continuous seismic activity, the Sunda–Banda slab shows an aseismic zone at 250–400 km depth arguing against transmission of compressive stress from the base of the slab (Fig. 4).

7.2. Uplift and volcanism of the Flores zone

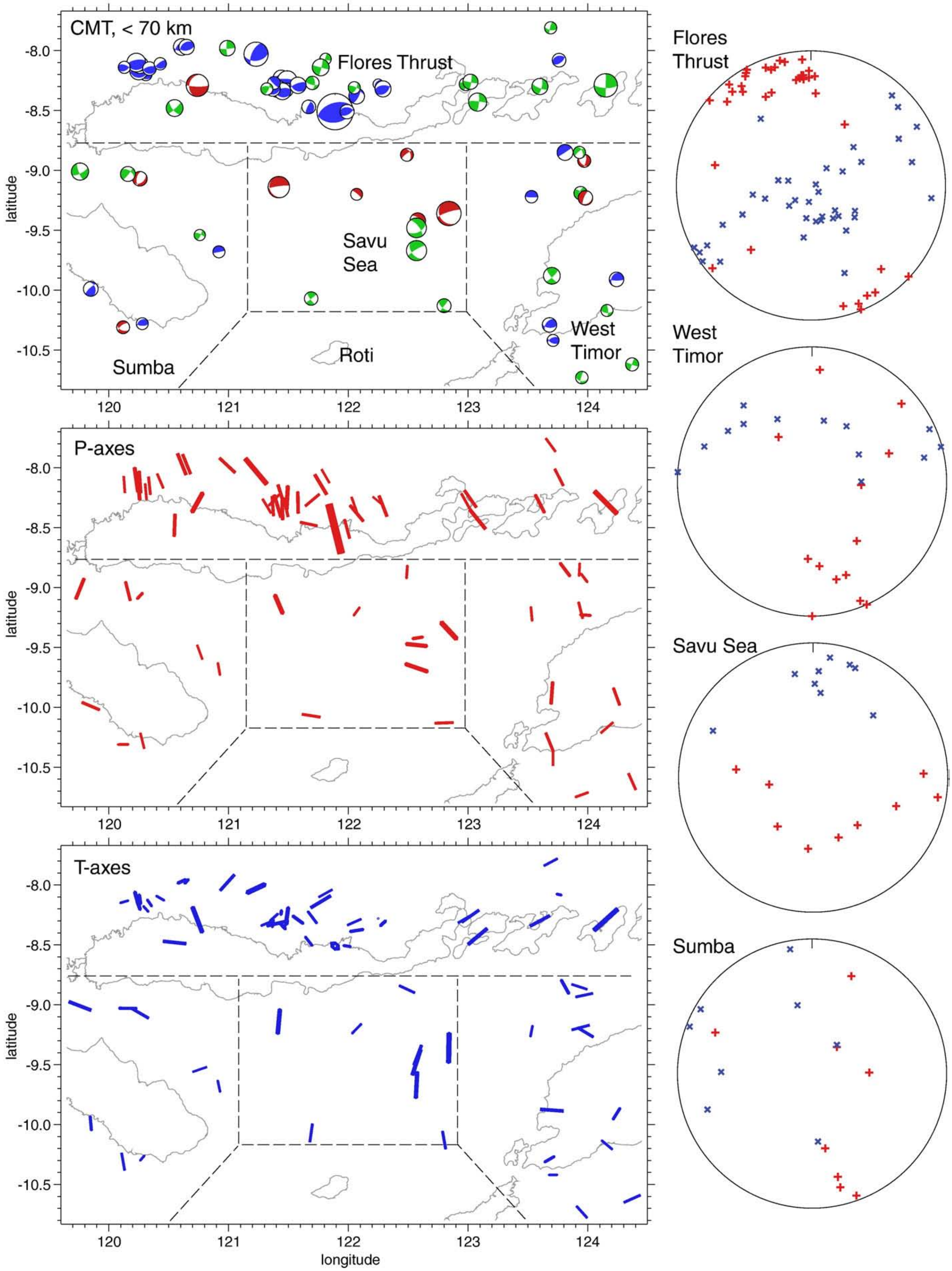
The Flores zone is one of the most elevated parts of the arc to the east of Java, with elevated coral terraces exposed on the active volcanic islands (van Bemmelen, 1949), evidencing late Quaternary uplift. Terraces are recorded up to 550 m ASL, comparable to, but somewhat lower than in the adjacent Wetar zone, where, for example, marine sediments are found at 1200 m ASL on Alor. Like the Wetar zone, where uplift has been linked to the reduction in the stress transmitted from below as a consequence of slab detachment, a decrease in slab pull force provides a plausible mechanism for uplift in the Flores zone. Such uplift would also potentially provide an explanation of the enigmatic, shallow level Savu Sea normal fault mechanisms, through associated increase in gravitational potential energy (e.g. Zhou & Sandiford, 1992). The emergent topography of the Flores zone contrasts with that of the Damar zone at the eastern boundary of the WSG, where the overlying arc is largely submerged and there is no clear evidence for significant uplift (Sandiford, 2008; Fig. 4).

The Flores zone is also anomalous in having the closest volcano spacing along the arc system. Use of the 'nearest neighbour' method of measuring volcanic centre spacing (de Bremond d'Ars et al., 1995), along with volcano locations from the Smithsonian Institute Global Volcanism Program (Siebert and Simkin, 2002), shows volcanic centres from Bali to Sumbawa have an average spacing of 68 km, with a range of 18–118 km (standard deviation of 51 km). Average spacing in the eastern Banda Arc is similar, but less variable, with an average of 72 km (s.d. = 29 km). In the Flores zone, volcanoes are spaced at 6–61 km, with an average of 21 km (s.d. = 15 km). This difference in spacing can be attributed to variation in magma flux (de Bremond d'Ars et al., 1995; Baker et al., 2008) and therefore provide a direct insight into fertility of the underlying mantle wedge. As a key control on mantle wedge fertility is the volatile flux from the slab (Cagnioncle et al., 2007), such differences are likely to reflect variations in slab–wedge interaction. Thus the boundary between the Sunda and Banda arcs, corresponding to the eastern terminus of the Java Trench, marks a key change in mantle wedge fertility, as does the boundary between the volcanically-active Flores zone and the extinct Wetar zone.

In addition to controlling magma flux and volcano spacing, volatile content also impacts on the mechanical properties of the mantle wedge though variations in viscosity. Mantle wedge viscosity has been shown to influence the slab stress state at intermediate depths, by changing the slab–wedge coupling. In particular, Billen and Gurnis (2003) demonstrated a relationship between intermediate depth down-dip compression and an overlying low viscosity region in the mantle wedge. This is because a low viscosity wedge effectively decouples the slab from flow in the mantle wedge, allowing deformation in the slab to be dominated by slab flexure. Dynamic flow models of the Tonga–Kermandec and central Aleutian arcs have shown them to be examples of low viscosity wedges associated with down-dip compression at depths of 100–300 km (Billen and Gurnis, 2003; Manea and Gurnis, 2007). In view of these arguments, we suggest the intermediate depth down-dip compression beneath the western Flores zone is best understood in terms of a fertile mantle wedge with unusually low viscosity.

Variations of mantle wedge properties, and the resulting effect on coupling of the overriding plate, are also important in controlling the extent of slip partition in oblique collision systems. Weak coupling, such as that resulting from the presence of a low viscosity wedge, allows partition of strain to allow strike-slip movement (Del Castello et al., 2005). The high proportion of strike-slip faults in the Flores Thrust zone is consistent with a high degree of strain partitioning and weak coupling, which could result from the presence of an underlying low viscosity mantle wedge.

Fig. 5. Shallow earthquakes of the Flores zone, showing focal mechanism solutions, P-axes and T-axes orientations. The CMT catalogue includes 69 shallow (<70 km depth) events in the region 119.7–124.4°E, 7.7–10.8°S. Dashed lines mark the boundary of the Flores Thrust, Savu Sea, West Timor, Sumba and Roti domains as discussed in the text. Stereonet plots show P-axes (+) and T-axes (x) orientations for each of the domains.


CMT, < 70 km
Flores Thrust
Savu Sea
Sumba
Roti
West Timor
P-axes
T-axes
latitude
longitude
-8.0
-8.5
-9.0
-9.5
-10.0
-10.5
120
121
122
123
124
Flores Thrust
West Timor
Savu Sea
Sumba

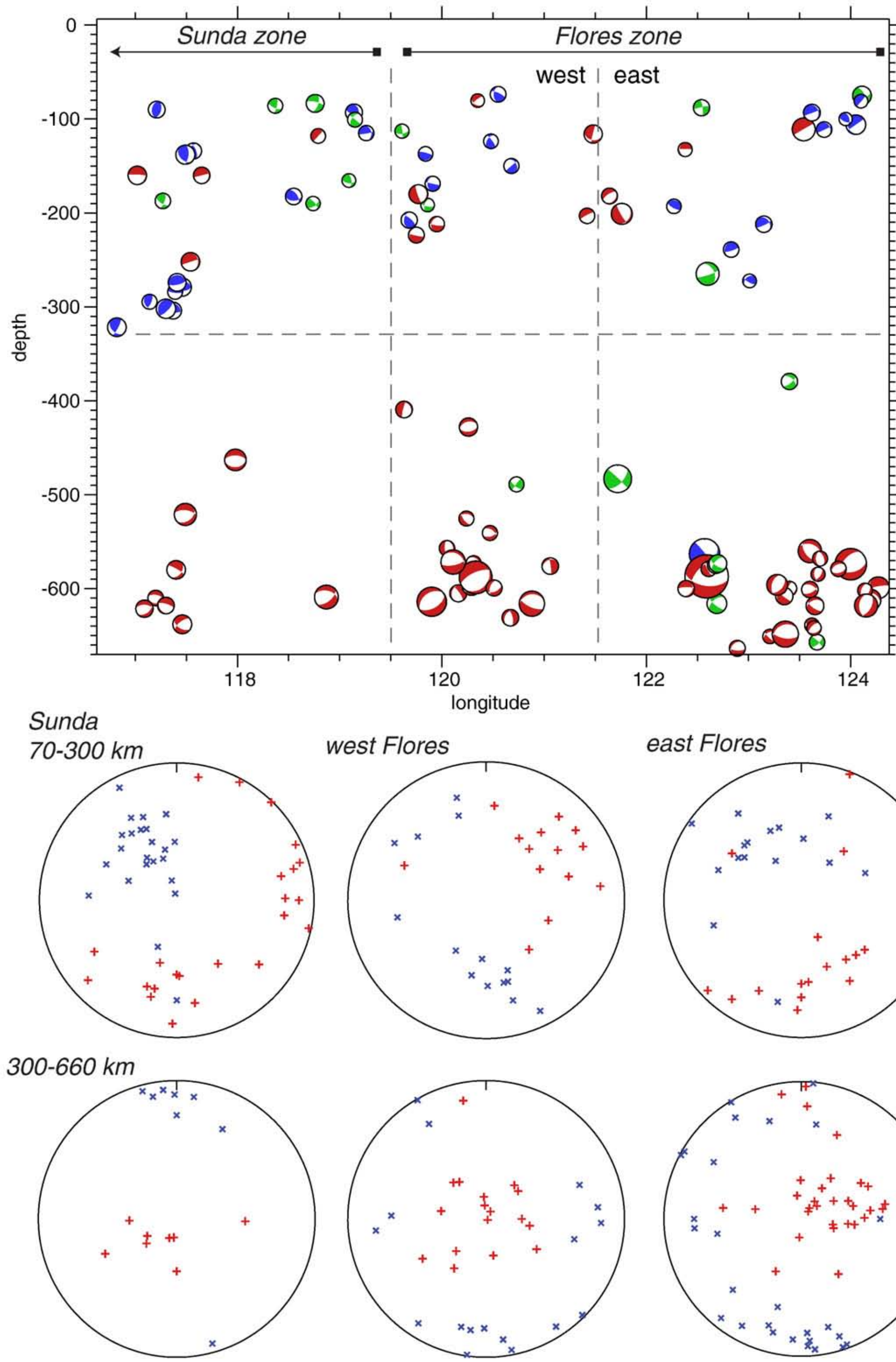


Fig. 6. Long section of the Flores zone showing the variation in orientation of earthquake focal mechanism solutions between the western and eastern sections. The CMT catalogue includes 77 records in the Flores zone (119.5–124.3°E, 6.1–11.5°S), projected here onto a vertical plane. Part of the Sunda zone is also shown for comparison. Refer to Fig. 2 for the location of the Flores and Sunda zones. Stereonet plots show P-axes (+) and T-axes (x) orientations for intermediate depth (70–300 km) and deep (300–660 km) earthquakes. Along strike and down-dip variation is discussed in the text.

7.3. Subduction of transitional crust beneath the Flores zone

The coincidence of unusual seismicity, volcanic flux and uplift in the Flores zone suggests that these are not independent variables, and may have a common origin. The Flores zone is located at the boundary between subduction of oceanic crust in the Java Trench, and collision of the Australian continent to the east. The Indo-Australian Plate immediately south of Savu and eastern Sumba comprises an ocean plateau, the Scott Plateau, which lies at intermediate depths between the abyssal plain and continental shelf (Fig. 8). The Scott Plateau is over 200 km wide at the northern end, and lies at depths of 2.2–3.3 km. It is bound by steep gradients to the abyssal plain (5.5–5.9 km depth) to the west and continental shelf (<0.5 km deep) to the east. Gravity data show that it most likely comprises crust around 24 km thick (Stagg,

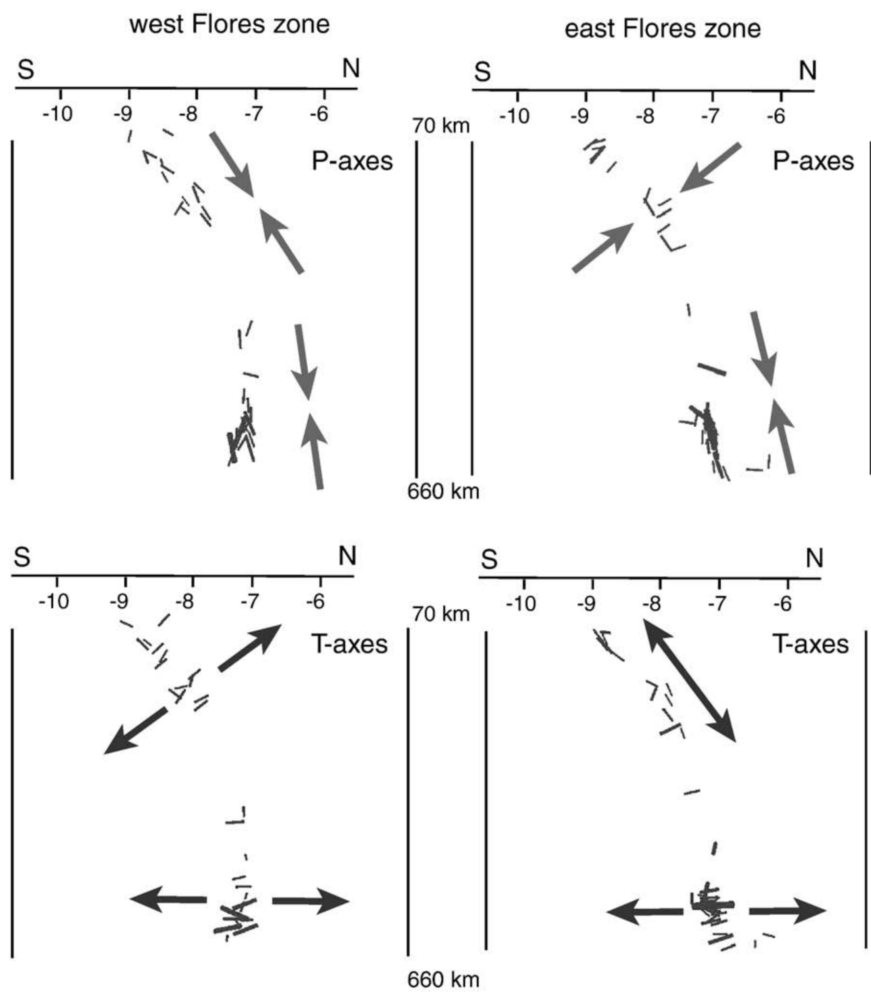


Fig. 7. Projected cross sections through the western and eastern Flores zone, showing P-axes and T-axes orientations from 70 to 660 km depth. Large arrows indicate the overall sense of compression or extension at intermediate and deep levels as interpreted from the CMT data. The west Flores zone is under down-dip compression at all seismically active depths, whereas, at intermediate depths, the east Flores zone in interpreted to be under more typical down-dip tension.

1978) formed of material transitional between continental and oceanic crust, and therefore has an intermediate buoyancy.

Variation in composition of the subducting slab may be reflected in the geochemistry of the overlying magmatic arc. A number of studies of the Sunda and Banda arcs have investigated the collision zone for anomalous geochemical signatures that may reflect collision or subduction of continental material. Using helium isotope ratios, Hilton et al. (1992) demonstrated the presence of a continental crust component in magmas of the Sunda–Banda arc, with the proportion of a modelled crustal end member increasing towards the collision zone. The transition from typical MORB to crustal helium ratios occurs east of Sangeang Api, on the western end of Sumbawa, corresponding with the location of the eastern terminus of the Java Trench and the projected location of the subducted transitional crust (Fig. 8). Variation of Pb isotope ratios also shows anomalous trends in eastern Flores and throughout the collision zone, with elevated $^{206}Pb/^{204}Pb$ interpreted to reflect mixing of Australian lower and upper crust, contrasting with oceanic crust and entrained sediment influences farther west (Elburg et al., 2005). Together these data support subduction of crust in the Savu Sea domain with distinct composition compared to the oceanic crust to the west.

Subduction of crust that is more buoyant than oceanic crust could result in a reduced slab pull force, and thus allow the slab to be in a state of down-dip compression at high levels, as opposed to most subduction zones where the large slab pull force results in down-dip tensional forces dominating. The extent of down-dip compression in the Flores zone suggests that crust of transitional composition has been subducted to a depth of 300 km. The presence of buoyant material in the subduction zone is also consistent with observations of uplift along the volcanic arc in the Flores zone.

7.4. Mechanisms of slab tearing

Aseismic zones in slabs are common at depths of 300–500 km, where stress in the slab transitions from extensional to compressional (Isacks and Molnar, 1969). In the Sunda–Banda arc, this is apparent for much of the length of the subduction zone at 300–450 km depth (Fig. 4). However, this mechanism does not readily explain a lack of earthquakes in the shallower parts of a subduction zone. One possible explanation for a shallow aseismic zone is that the lower part of the slab has detached, and that there is no slab in the aseismic region, which therefore represents a slab window. An implication of this model is that the deep parts of the slab are no longer connected to the surface, thus the response of each part to stress is independent.

The style of deformation in the Flores zone adjacent to the Wetar seismic gap contrasts markedly to the intense zone of extensional deformation recorded beneath Romang at the eastern extent of the WSG (Sandiford, 2008). The eastern propagation of the slab tear is consistent with the general model of Wortel and Spakman (2000) that illustrates the plate boundary response to lateral propagation of a slab tear, particularly with respect to vertical motions (uplift and subsidence). The high intensity of reverse earthquakes at 100–200 km depth beneath

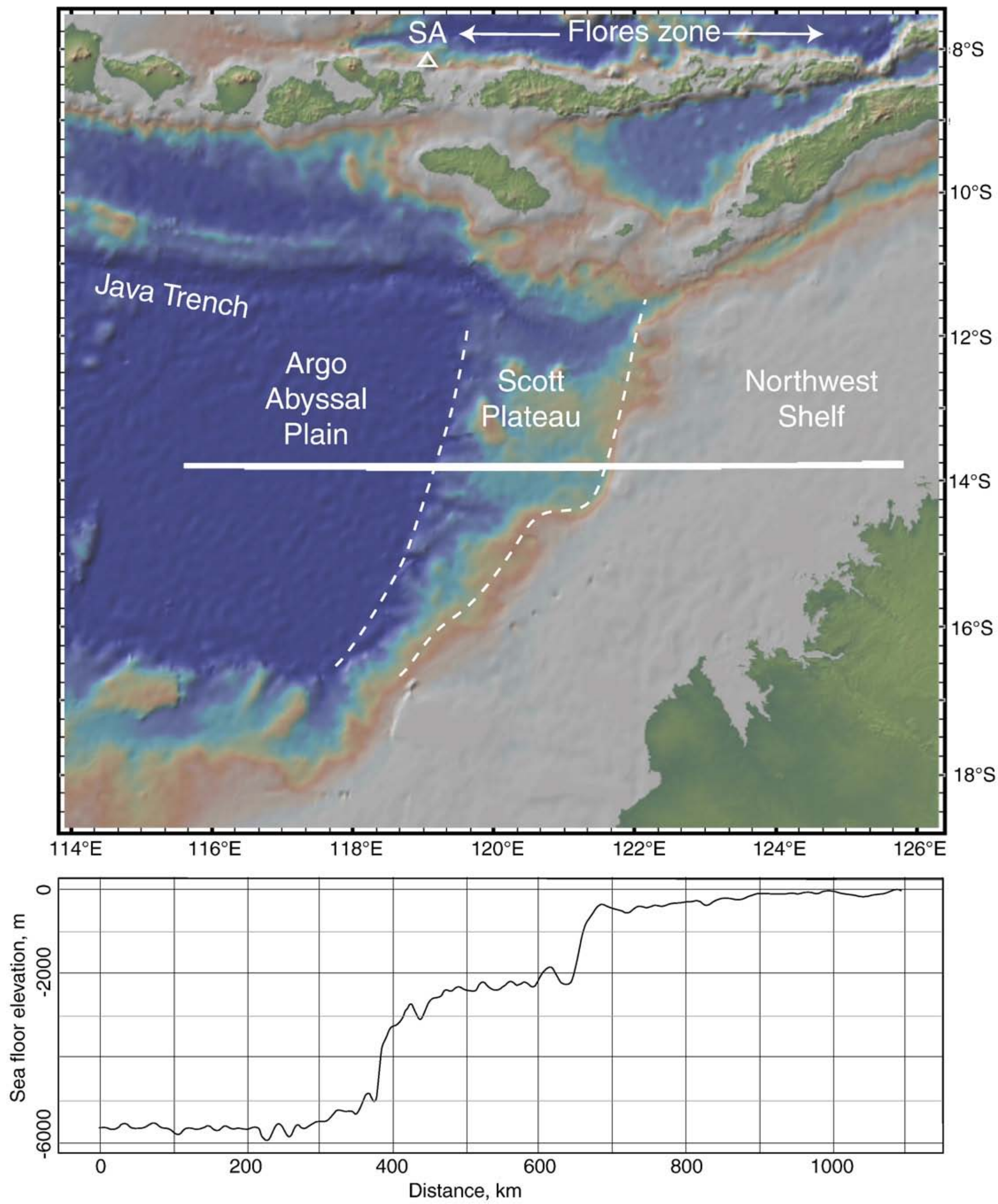


Fig. 8. Bathymetry of the Scott Plateau, showing the location of the Flores zone and Sangeang Api (SA). The line across centre of the image shows the location of the bathymetric cross section. The cross section shows the Scott Plateau to be a well defined bathymetric feature at 2000–2500 m below sea level. Image and cross section created using GeoMapApp 1.7.8. Bathymetry sourced from Smith and Sandwell (1997) and topography from SRTM.

Romang corresponds to the point of tear propagation, and there is topographical evidence to support the subsidence and uplift predicted by the model. The seismic record clearly illustrates that a similar tear process is not occurring beneath the Savu Sea; for example, the observed down-dip compressional stress state is the opposite of the dramatic down-dip tension at the point of tear beneath Romang. Buiter et al. (2002) note that slab detachment must occur at a point of tension in the slab. It appears that additional slab pull originating from the detached section of the slab is not being transferred in the Flores zone. This may also provide some explanation for the extreme seismic moment release in the Damar zone. In addition to the nature of slab deformation, the Damar and Flores zones are different with respect to volcanic record and vertical movements.

A model of slab breakoff along steep faults in the Savu Sea was proposed by McCaffrey et al. (1985) and the much expanded earthquake dataset available for this study is consistent with this model (Fig. 9). Earthquakes above 115 km recorded to the north of Timor (123.4–124.0°E) have steep nodal planes with a strike of 060°, which support the model of a slab break off along steep faults. The asymmetry of seismic moment in the regions bounding the WSG suggest that while there is some evidence supporting the model proposed by McCaffrey et al. (1985) of rupture along high-level, steep normal faults in the west, the slab tear is propagating to the east at a much faster rate.

8. Conclusions

Rupture of the oceanic slab from the continental slab in what is now the inactive section of the Banda Arc has been linked to geochemical signatures (Elburg et al., 2005), the end of volcanism (Abbott and Chamalaun, 1981) and uplift (Charlton, 1991; Hall and Wilson, 2000). The compilation of the Centennial and Das earthquake data showed that this

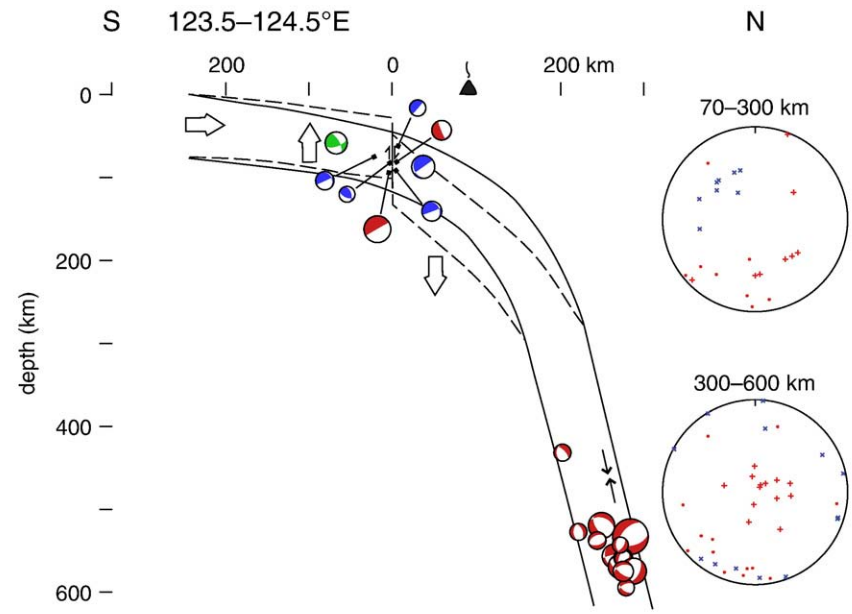


Fig. 9. Model of slab tear beneath the Savu Sea proposed by McCaffrey et al. (1985) with CMT events overlaid. The section is located at 124°E and includes earthquakes within a 1° wide band. Stereonet plots show P-axes (+), T-axes (x) and B-axes (•) orientations for intermediate and deep earthquakes as labelled. Shallow events (<70 km) are omitted for clarity. Note that the FMS are lower hemisphere projections, i.e. they are not rotated to the cross section view. Therefore the focal planes represent possible fault plane orientations in plain view, and most are consistent with detachment along steep fault striking ~060° at around 100 km depth.

rupture to be represented by a 330 km wide aseismic region, the Wetar seismic gap, that extends to a depth of 350 km from the Pantar Strait to near Romang. The presence of a highly asymmetric slab tear has been demonstrated, based on evidence from earthquake catalogues, topography, volcanism and uplift rates. The eastern point of tear propagation is occurring under strong down-dip tension, resulting in an extreme concentration of reverse fault mechanism earthquakes. In contrast, tear propagation at the western boundary appears to be inhibited by the presence of a more buoyant segment of crust in the subduction zone. The buoyant, transitional lithosphere being subducted beneath the Savu Sea is likely to be the northern extension of the Scott Plateau. This has resulted in the unusual stress state in the slab of down-dip compression at intermediate depths (70–300 km), which is correlated with anomalous volcanism and uplift in the arc.

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