Earth and Planetary Science Letters xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Anatomy of the western Java plate interface from depth-migrated seismic images

H. Kopp [a,*], D. Hindle [a], D. Klaeschen [a], O. Oncken [b], C. Reichert [c], D. Scholl [d]

[a] IFM-GEOMAR, Leibniz Institute of Marine Sciences, Wischhofstr. 1-3, 24148 Kiel, Germany
[b] GeoForschungsZentrum Potsdam, Potsdam, Germany
[c] BGR Federal Institute of Geosciences and Natural Resources, Hannover, Germany
[d] U.S. Geological Survey, Menlo Park, CA, USA

ARTICLE INFO

Article history:
Received 25 July 2009
Received in revised form 28 September 2009
Accepted 28 September 2009
Available online xxxx

Editor: R.D. van der Hilst

Keywords:
décollement
splay fault
prestack depth migration
subduction zone
tsunami earthquake
Indonesia

ABSTRACT

Newly pre-stack depth-migrated seismic images resolve the structural details of the western Java forearc and plate interface. The structural segmentation of the forearc into discrete mechanical domains correlates with distinct deformation styles. Approximately 2/3 of the trench sediment fill is detached and incorporated into frontal prism imbricates, while the floor sequence is underthrust beneath the décollement. Western Java, however, differs markedly from margins such as Nankai or Barbados, where a uniform, continuous décollement reflector has been imaged. In our study area, the plate interface reveals a spatially irregular, nonlinear pattern characterized by the morphological relief of subducted seamounts and thicker than average patches of underthrust sediment. The underthrust sediment is associated with a low velocity zone as determined from wide-angle data. Active underplating is not resolved, but likely contributes to the uplift of the large bivergent wedge that constitutes the forearc high. Our profile is located 100 km west of the 2006 Java tsunami earthquake. The heterogeneous décollement zone regulates the friction behavior of the shallow subduction environment where the earthquake occurred. The alternating pattern of enhanced frictional contact zones associated with oceanic basement relief and weak material patches of underthrust sediment influences seismic coupling and possibly contributed to the heterogeneous slip distribution. Our seismic images resolve a steeply dipping splay fault, which originates at the décollement and terminates at the sea floor and which potentially contributes to tsunami generation during co-seismic activity.

1. Introduction

Active convergent margins displaying sediment accretion as the predominant mode of mass transfer have been identified as an end-member type of subduction zones (von Huene and Scholl, 1991; Clift and Vannucchi, 2004). In these systems, sediment may be added to the toe of the margin wedge forming a frontal prism (frontal accretion) or at depth to the base of the upper plate causing uplift (underplating or basal accretion) or both (Moore and Silver, 1987). Basal accretion requires sediment underthrusting beyond the frontal accretionary prism along the décollement zone. Décollements at accretionary margins form detachments between the upper deforming accretionary prism and the underthrusting sequence (Chapple, 1978; Davis et al., 1983) and at some margins continuous, high-amplitude horizons have been imaged for tens of kilometers landward of the deformation front (e.g. Barbados (Westbrook et al., 1988; Shipley et al., 1994), and Nankai (Moore et al., 1990; Bangs et al., 2009)).

Décollement reflection characteristics have been analyzed at the Nankai and Barbados margins to reveal spatial variations of fault properties (e.g. Shipley et al., 1994; Bangs et al., 1996, 1999, 2004; Park et al., 2002a; Tsuji et al., 2005). Underneath the northern Barbados accretionary prism, the décollement zone encompasses a heterogeneously consolidating sedimentary sequence (Moore et al., 1998). Pore fluid pressures in excess of hydrostatic within the underthrust sequence have been predicted by e.g. Saffer (2003) and Tsuji et al. (2008) off Muroto (Nankai) and by e.g. Bekins et al. (1995) for Barbados. Elevated pore pressures beneath the décollement are linked to a decrease in effective stress along the plate boundary (e.g. Skarbek and Saffer, 2009) and are related to the onset of the seismogenic zone (e.g. Moore and Saffer, 2001). Calahorrano et al. (2008) recently quantified physical and mechanical property variations of the underthrusting sedimentary sequence using seismic velocities along the southern Ecuador margin. A common aspect of all these studies is that they reveal a complicated, non-uniform pattern of physical properties along the décollement zone.

Here we present the detailed structure of the accretionary convergent margin off western Java. Frontal accretion has previously been imaged along this central segment of the Sunda margin off southern Sumatra to western Java from refraction/reflection seismics and bathymetric data (Kopp et al., 2001; Schlueter et al., 2002; Kopp et al., 2002, 2008). Mass balance calculations indicate a subduction history dominated by accretion since the Late Eocene (Kopp and Kukowski, 2003). In this study, based on pre-stack depth-migrated

* Corresponding author. Now at: Freiburg University, Freiburg, Germany. Tel.: +49 431 6002334.
E-mail address: hkopp@ifm-geomar.de (H. Kopp).

0012-821X/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2009.09.043

seismic reflection data, we resolve the anatomy of the plate boundary fault. The 190 km long multichannel seismic (MCS) line SO137-03 is located across the western Java forearc (Fig. 1), covering the trench, frontal prism, active and fossil accretionary prisms (forearc high) and forearc basin (Fig. 2). Acquired in 1998 and using a 3500 m long source–receiver offset, these data comprise the highest quality MCS profile available in the area and are complemented by velocity information gained from coincident refraction data (ocean-bottom hydrophone (OBH) line SO138-05, Fig. 1) (Kopp et al., 2001). Wide-angle velocity information was incorporated into the pre-stack depth migration (Fig. 3). We applied an iterative migration procedure, which uses seismic velocities constrained by focusing analyses and common reflection point gathers (Mackay and Abma, 1993). Seismic velocities used during the migration process are interval velocities. The energy of a reflection point in the subsurface is focused using a range of velocities until an optimal image is achieved, which provides the highest energy at zero offset. Using an ideal velocity, the reflection position will be corrected. This in turn will yield better constraints on velocities during the next iteration and ray paths are determined more accurately. Pre-stack depth migration thus images complex, dipping structures even in the presence of a strong lateral velocity gradient far better than conventional time migration procedures (Guo and Fagin, 2002).

2. Margin architecture

2.1. Structural segmentation of the forearc

The central Sunda margin off western Java to southern Sumatra marks the transition from orthogonal convergence in the east to oblique subduction to the northwest (Fig. 1) (e.g. Hamilton, 1979; Lelgemann et al., 2000). The broad-scale margin architecture (Fig. 2), which is predominantly characterized by the evolution of an asymmetrical bivergent wedge (Willet et al., 1993; Hoth et al., 2007), arises from a compressive regime related to the active subduction of the Indo-Australian plate underneath Eurasia since the Eocene (Hall and Smyth, 2008). Initial formation of the wedge occurred against the original arc rock framework, which is of continental origin off Sumatra and its character changes to an oceanic-type basement rock off western Java, as inferred from seismic and gravity data (Kieckhefer et al., 1980; Grevemeyer and Tiwari, 2006). The seaward tapering terminus of this original margin wedge is located under the forearc basin and during the early phases of subduction served as backstop to the juvenile accretionary wedge. This deep-lying boundary previously remained unresolved in conventional processing (Kopp et al., 2001), but is now imaged in the pre-stack depth-migrated section as a highly reflective transition zone (Fig. 4). It coincides with a decisive increase in seismic velocities as revealed by refraction models (Kopp and Kukowski, 2003).

The now quiescent, >80 km wide accretionary wedge (Schlueter et al., 2002), termed the inner wedge' (Fig. 1) fronts the forearc basin and forms the forearc high with vertical dimensions exceeding 15 km between the seafloor and the subducting plate (Kopp and Kukowski, 2003). Accretion rates are sufficiently high for a landward slope to develop at the transition from the inner wedge to the forearc basin (Fig. 4), similar to corresponding structures offshore Sumatra (Moore et al., 1980; Karig et al., 1980a) or offshore Bali/Lombok (Planert et al., in review). Continued wedge growth results in thrusting at the rear (km 125–140), causing progressive deformation of the lower forearc

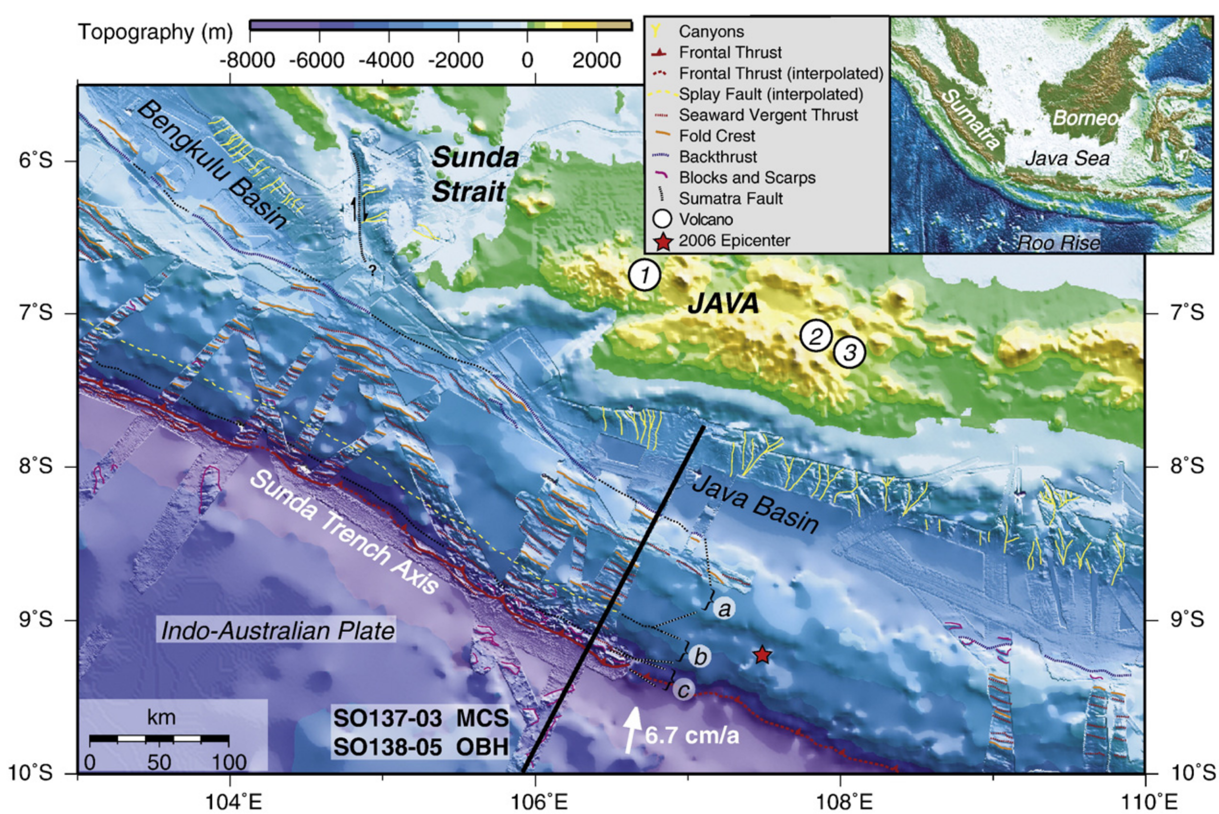

Fig. 1. Shaded bathymetry map of the Sunda trench offshore western Java. Global relief (Amante and Eakins, 2008) is overlain by high-resolution ship track data acquired by RV SONNE (cruises SO137, SO138, SO139, SO176, SO179). Morphotectonic interpretation is based on high-resolution swath data as well as existing seismic data (Schlueter et al., 2002; Kopp and Kukowski, 2003). Thick black line: coincident seismic reflection and refraction profile SO137-03/SO138-05. Forearc segmentation correlates with structural domains: a = Inner Wedge, b = Outer Wedge, c = Frontal Prism. Yellow stippled line tracks surface trace of splay fault system. Star shows epicenter of 2006 Java tsunami earthquake. White circles show western Java volcanoes for which magma geochemical data exist: 1 = Mt. Salak, 2 = Mt. Guntur, 3 = Mt. Gallunggung. Inset shows study area on the Sunda margin.

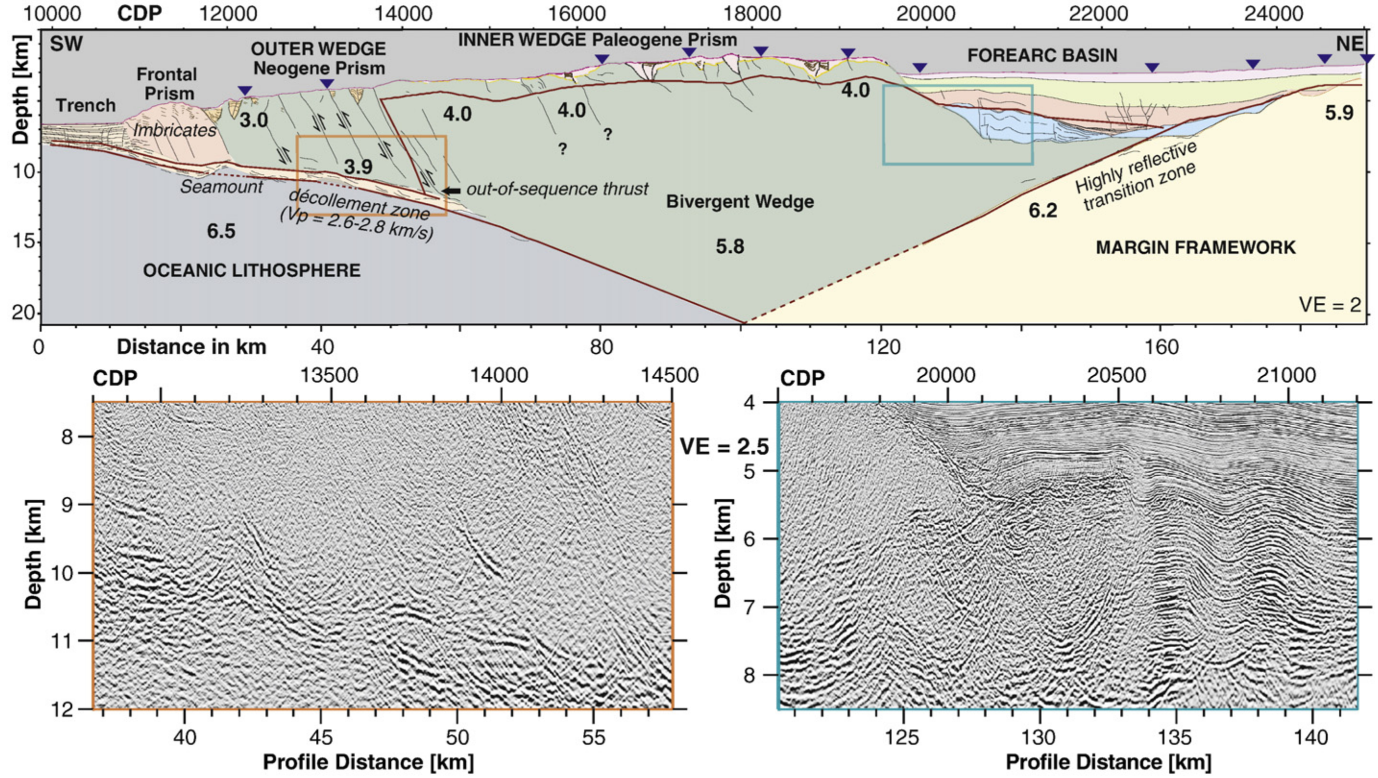

Fig. 2. Structural interpretation (upper panel) and depth-migrated seismic images of the décollement zone (lower left) and seaward limit of the forearc basin (lower right). Colored boxes in the upper panel indicate location of seismic data examples displayed below. The margin macrostructure consists of a >6000 m deep trench adjacent to a frontal prism characterized by imbricate thrusting. The large bivergent wedge is composed of an outer wedge (Neogene accretionary prism) and an inner wedge (Paleogene accretionary prism) (compare Fig. 1).

basin sediment infill as imaged along the seaward margin of the basin in the MCS data (Fig. 2 inset). The upper strata onlap the inner wedge and are only moderately warped.

The internal seismic structure of the inner wedge exhibits limited coherency (Fig. 4), probably due to late stage deformation dismembering former accreted sediment slices, as also seen in the Nankai margin (Moore et al., 1990). Internal deformation of the inner wedge is, at least episodically, persistent, as documented by active out-of-sequence thrusting, which offsets the seafloor (Fig. 2, e.g. around profile km 70–80 and 100). The internal deformation documented by inner wedge thrusting compensates geometry re-arrangements to adjust to boundary conditions and wedge strength (Davis, 1996). Due to limited resolution, the depth extent of these thrust faults remains undetermined.

Fronting the inner, fossil wedge is the outer, Neogene wedge, which is characterized by landward-dipping, thrust-bound sheets each approximately 4–6 km wide (Fig. 3). The imbricate thrusting results in an arcward thickening from 5.5 km at the seaward limit to over 7 km at the transition to the inner wedge (i. e., over a distance of less than 25 km). Tectonic thickening by imbrication is a commonly observed process in accretionary subduction zones where the wedge becomes progressively more consolidated and cemented towards the arc (e.g. von Huene et al., 2009). The outer wedge represents a compressive zone with discrete localization of deformation along the thrust faults. The transition from the outer wedge to the inner wedge is marked by a splay fault system, whose surface trace is recognized in multibeam bathymetry for at least 600 km along strike of the margin (Fig. 1) (Kopp and Kukowski, 2003). A megasplay fault system forming a comparable structural segment boundary and mechanical discontinuity has recently been imaged along the Nankai subduction zone in 2-D and 3-D seismic data (Park et al., 2000, 2002b; Moore et al., 2007; Bangs et al., 2009), along the Ecuador–Colombia margin (Collot et al., 2008) and offshore Bali–Lombok (Lueschen et al., in review).

The internal structure of the inner and outer wedges reflects their evolution history: the lateral growth of the inner wedge is mainly attained by tectonic addition of material from the outer wedge (von Huene et al., 2009). Both wedges are uniformly developed from Sumatra to western Java (compare Fig. 1). They form a characteristic feature along those margin segments dominated by accretionary processes. Off central Java (110°E), however, where underthrusting of an oceanic plateau is occurring, inner and outer wedges cannot be uniquely distinguished and a frontal prism, which is present trenchward of the outer wedge off western Java (Fig. 1), is missing entirely owing to recent and ongoing erosion (Kopp et al., 2006). A structural segmentation similar to our seismic line, however, is also observed along the erosion-dominated Ecuador–Colombia margin, as described by Collot et al. (2008), implying that this general segmentation is not a direct function of material flux (i.e. accretion or erosion).

2.2. Décollement zone and plate boundary structures

Approximately 1.9 km of sediment is found at the deformation front in the sector of the Java trench (Fig. 3) covered by our seismic line. Normal faulting of the lower trench sediment sequence precedes the compressional deformation in the ~13 km wide frontal prism. Normal faulting in the incoming hemipelagic sediments has also been observed in the Nankai subduction zone (Heffernan et al., 2004), where polygonal fault patterns are attributed to differential compaction above irregular oceanic basement.

Seaward growth of the frontal prism occurs by tectonic addition of detached lower plate sediment (Kopp et al., 2001, 2002). Trench sediment uplift is initiated by displacement along a frontal thrust, abruptly truncating the upper portion of the stratified trench sequences at the deformation front and marking the onset of horizontal shortening and contractive deformation of the frontal prism (Fig. 3). Imbricate thrusting is the dominant structural style of the frontal prism, similar to

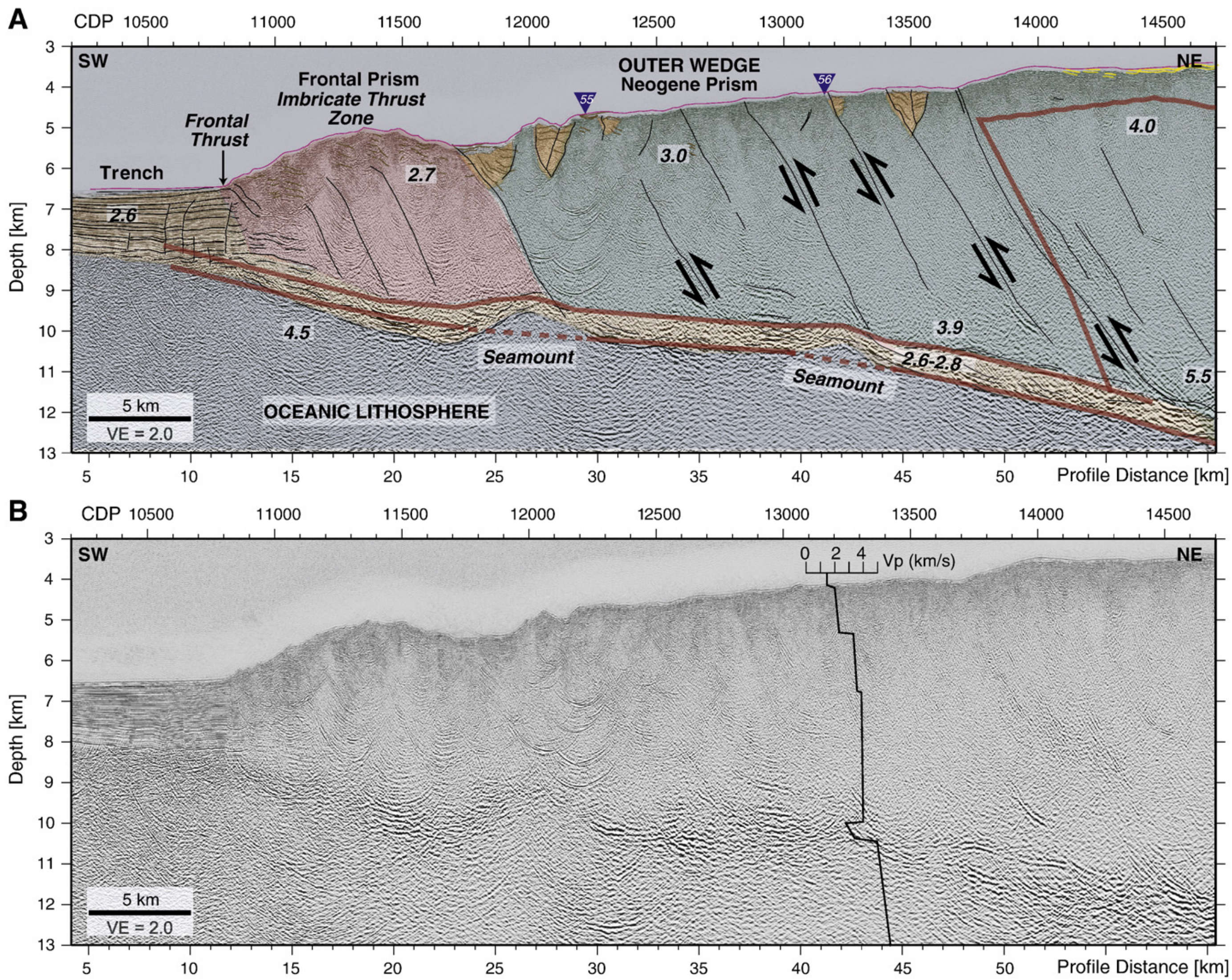

Fig. 3. Pre-stack depth-migrated seismic images of MCS profile SO137-03 (location shown in Fig. 1). A: seismic image of the trench, frontal prism and outer wedge overlain by the interpretive linedrawing of Fig. 2. Thick red lines trace velocity-based boundaries of the corresponding wide-angle model. Numbers are seismic velocities in km/s. Blue triangles denote ocean-bottom hydrophone positions. B: corresponding seismic image. Shortening is accommodated by imbricate thrusting of the frontally accreted sediment in the frontal prism. Approximately 1/3 of the trench material is underthrust beneath the frontal prism in a 500–900 m thick décollement zone, characterized by discontinuous high amplitudes. An upward bulging of the reflective band indicates the location of two subducted oceanic basement highs between 25–29 km and 41–44 km offset, likely small seamounts of approximately 1.4 km and 0.8 km height, respectively. The v–z function of OBH 56 is displayed, showing the seismic velocity inversion in the décollement zone.

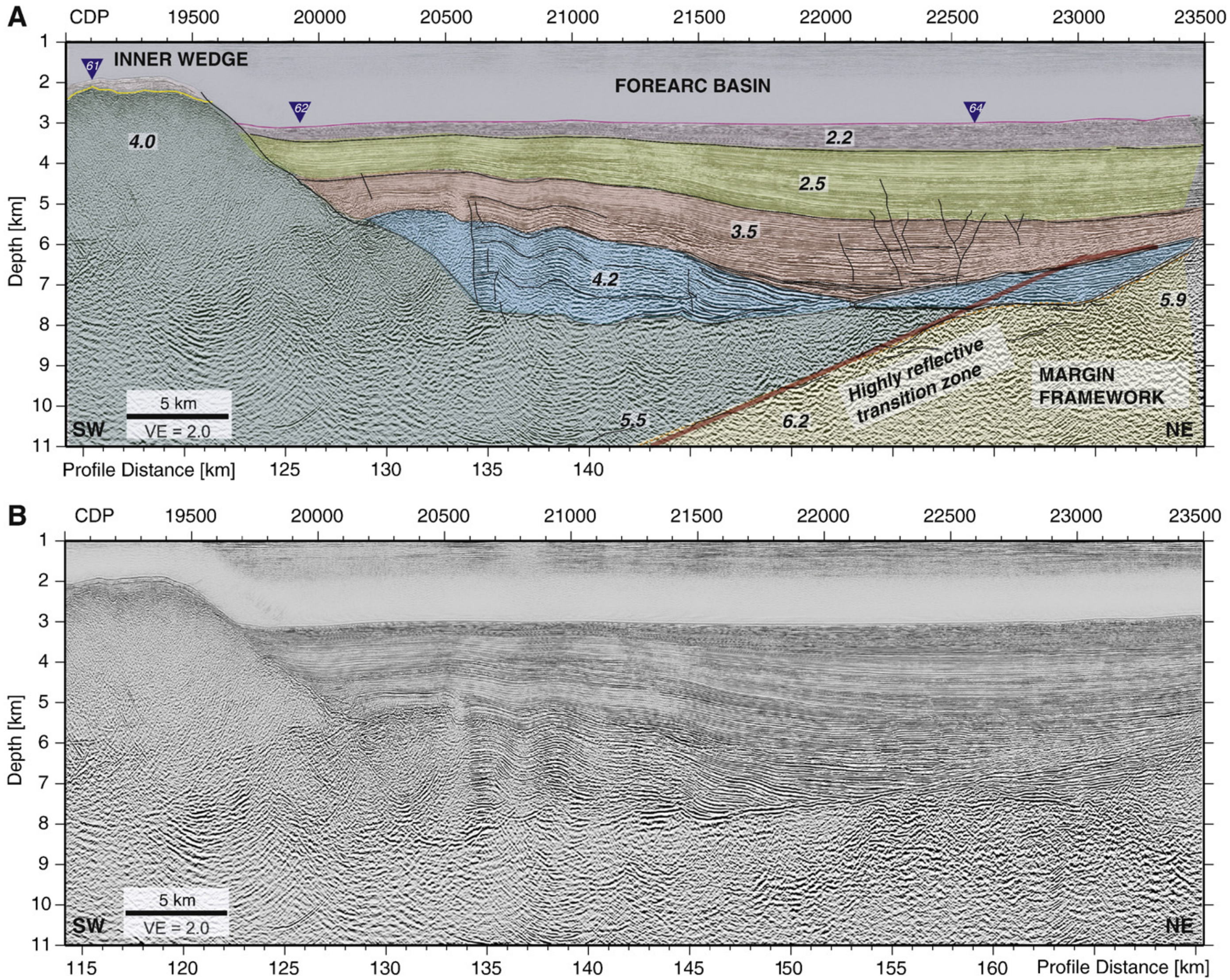

Fig. 4. A: seismic image of the landward portion of the inner wedge and the forearc basin. (Display information as in Fig. 3) B: corresponding seismic image. Thrusting causes deformation of the lower sedimentary units of the seaward portion of the forearc basin (around km 125–140). The highly reflective zone below the basin at ~150 km offset corresponds to a first-order velocity boundary observed in the refraction data. This transition from the inner wedge to the original margin framework plays an important role in the margin kinematics and the formation of a bivergent wedge, but is commonly not observed in reflection data because of limited energy penetration.

the folding and thrusting observed off Nias Island offshore Sumatra (Moore and Curray, 1980; Karig et al., 1980b; Franke et al., 2008). The intense deformation observed here is common for prisms experiencing mass transfer by sediment accretion (e.g. Cascadia (MacKay et al., 1992; Cochrane et al., 1994) or South Chile (Polonia et al., 2007)), though the deformation pattern off Java is more complex than e.g. the classical fold-and-thrust belt with hanging wall anticlines observed in Nankai (Taira et al., 1991; Moore et al., 2001). However, the increase in thickness and length of the imbricate sequences from the frontal prism to the outer wedge as seen off Java has also been observed in the Muroto transect of the Nankai subduction zone (Bangs et al., 2004).

The floor sediment sequence in the proto-thrust zone of the trench is bound on top by a proto-décollement located approximately 700 m above the oceanic basement (Fig. 3). It is in the proto-thrust zone that slip along the décollement is initiated (Tsuji et al., 2005). The stratigraphic level of the décollement is typically governed by changes in physical properties (e.g. Le Pichon et al., 1993; Moore et al., 1998; Bangs et al., 2004) or may be controlled by lithology (MacKay, 1995). Whereas in Nankai (e.g. Moore et al., 1990; Bangs et al., 2006; Moore et al., 2007), Barbados (e. g. Bangs and Westbrook, 1991; Shipley et al., 1994), Ecuador (Calahorrano et al., 2008), and Costa Rica (e.g. Saffer, 2003) a distinct, sharp décollement reflector forms above a minimally deformed subducted section that still retains a stratified structure, a band of semi-continuous, high-amplitude, low-frequency landward-dipping reflections delineates the interplate boundary off Java (Fig. 3) and coincides with the plate interface observed in the corresponding wide-angle data. A moderate strength contrast between overlying, accreting sediment and the underthrusting sequence landward of the deformation front may explain why a sharp décollement reflection similar to Nankai or Barbados is not observed off Java (Tsuji et al., 2008).

The ~500–900 m thick, high-amplitude reflective zone overlying the oceanic basement is resolved to a depth of 15 km underneath the frontal prism and the outer wedge (Fig. 3), but loses its distinct seismic character underneath the inner, fossil accretionary wedge. The interpretation as a décollement zone is supported by the velocity information gained from the wide-angle data, which reveal a low velocity zone associated with the underthrust sediment (Fig. 3). A similar velocity inversion has been identified from pre-stack depth-migrated data e.g. at Nankai (Costa Pisani et al., 2005) and Ecuador (Sage et al., 2006; Calahorrano et al., 2008), where comparable velocity values (2.6 km/s – 2.8 km/s) have been determined. Subducting oceanic basement relief modulates the thickness of the décollement zone, which thins above two subducting seamounts identified between profile km 25–29 and km 41–44, while adjacent lows (at km 19–22, km 37–40 and km 47–53) carry thicker than average sediment. An analogous pattern has also been observed along the Ecuadorian margin (Sage et al., 2006). In addition, differential subduction rates and sediment supply to the trench will result in a variable thickness of the décollement zone, as observed off Java (Fig. 3).

Similar reflective zones have been attributed to subduction erosion involving underthrust sediment and upper plate material fragments disintegrated by hydrofracturing and fluid-induced erosive processes, causing enhanced reflectivity (Sage et al., 2006; Ranero et al., 2008). However, instead of subsidence of the forearc as commonly associated with subduction erosion (von Huene et al., 2004), the Java forearc is experiencing uplift (Schlueter et al., 2002). We thus speculate that basal accretion of trench sediment underthrust beyond the frontal prism and the outer wedge contributes to the vertical growth of the forearc high. Active underplating has previously been observed in pre-stack depth-migrated data e.g. underneath the Nankai accretionary wedge (Park et al., 2002a), where a down stepping of the décollement at ~25 km and at ~45 km landward of the deformation front is resolved in 3-D data (Bangs et al., 2004) and is associated with material transfer to the base of the upper plate, resulting in complete underplating of the entire underthrust sequence. Offshore Alaska, underplating of long, undeformed sheets is observed (Gutscher et al., 1998).

Underthrust sediment that is not underplated but transported to mantle depths of magma generation (~100 km) is often recognized by its imprint on arc magma chemistry (Plank and Langmuir, 1993; Stern, 2002). Underplating is not clearly resolved in our depth section, partially due to multiple interference. Minimal sediment recycling to mantle depth, however, is supported by geochemical data from western Java volcanoes Mt. Guntur and Mt. Gallunggung (Fig. 1), which indicate a low Th/La ratio (Plank, 2005). Other volcanic centers in western Java, however, show more complex differentiation and contamination processes. Mt. Salak is the best-studied volcano today in western Java (Fig. 1) (Handley et al., 2008). Geochemical evidence from Mt. Salak indicates the incorporation of subducted sediment with Nd–Hf isotopic data suggesting a high terrigenous component (Handley et al., 2008). However, the young sediments in the trench and underneath the frontal prism today do not interact with the source of present-day Sunda arc magmas (Gasparon and Varne, 1998) due the potential recycling period of 4 Ma (based on a convergence rate of 6.7 cm/a and a magma-generating depth of 100 km). The geochemical variability and isotopic heterogeneity observed along the Sunda margin (Handley, 2006) reflect the variability of near-trench subduction processes. Reflection seismic data acquired along the Sunda margin (Moore and Curray, 1980; Karig et al., 1980b; Moore et al., 1980, 1982; Schlueter et al., 2002; Franke et al., 2008; Mueller et al., 2008; Singh et al., 2008; Lueschen et al., in review) in combination with refraction data (Kopp and Kukowski, 2003, Kopp et al., 2006; Shulgin et al., 2009; Planert et al., in review) show a remarkable variation in the amount of sediment accreted to the frontal prism or underthrust in the décollement zone. The existence of a large bivergent accretionary wedge implies, however, that only a small fraction of the underthrust sediment is subducted to mantle depth. The marked differences in the deformational framework along strike of the Sunda margin have also been documented for other subduction zones, e.g. at Nankai (Moore et al., 2001) or southern Chile (Polonia et al., 2007) and have been attributed to variations in lithology, physiography of the incoming plate and physical property variations of the prism and décollement zone.

3. Seismogenic processes

Our seismic profile is located approximately 100 km west of the 2006 Java tsunami earthquake epicenter (Fig. 1). Co-seismic strain release of this event involved the shallow portion of the megathrust and triggered a tsunami, which caused more than 630 casualties (Ammon et al., 2006). In the shallow subduction environment, the anatomy of the décollement zone regulates the friction behavior of the megathrust fault, which is influenced by the thickness and physical properties of the underthrust sediment as well as by lower plate basement relief (Bilek, 2007). Based on the model by Bilek and Lay (2002), several authors have speculated that the 2006 Java earthquake involved rupture of regions of unstable friction embedded in areas of conditionally stable material, resulting in the observed slip heterogeneity (Ammon et al., 2006; Bilek and Engdahl, 2007). Subducted high-relief features, including seamounts, ridges or fracture zones, may account for locally enhanced frictional contacts (e.g. Bilek, 2007; Lay and Bilek, 2007) along the Java margin, which otherwise shows low seismic coupling (Newcomb and McCann, 1987; Pacheco et al., 1993). Direct evidence for features causing strong coupling patches for the 2006 event is missing so far due to lack of seismic data. The 1994 Java tsunami earthquake off eastern Java is associated with a subducted seamount, which can be identified in the bathymetric data (Abercrombie et al., 2001). Our seismic line shows two moderate sized seamounts subducted beneath the outer wedge whose passage has left no surface trace. Though our seismic line lies east of the slip region, the tectonic setting of the 2006 rupture area is comparable and we speculate that similar subducted lower plate relief will influence seismogenesis there. The heterogeneous plate interface off western Java is characterized by marked morphological structure,

Please cite this article as: Kopp, H., et al., Anatomy of the western Java plate interface from depth-migrated seismic images, Earth Planet. Sci. Lett. (2009), doi:10.1016/j.epsl.2009.09.043

which potentially serves as an asperity and nucleus to an earthquake. Energy would subsequently be transferred into weaker material patches, as imaged along our profile, thus slowing energy propagation (Bilek and Engdahl, 2007). A retreat of the deformation front seaward of the epicenter location as well as the local morphological structure in the vicinity of the epicenter are indicative of subducted seafloor relief deforming the upper plate (Fig. 1).

The 1992 Nicaragua tsunami earthquake was a comparable event (Ammon et al., 2006; Lay and Bilek, 2007). At least three moderately-sized subducted seamounts (1–2 km high) have been identified from seismic data in the zones of enhanced moment release (McIntosh et al., 2007). The Java and Nicaragua margins, however, show fundamental differences: igneous oceanic crust extents close to the trench off Nicaragua, while an accretionary prism characterizes the upper plate off Java. This may be the cause why subducted seamounts, which are present in both margins, modify upper plate seafloor morphology off Nicaragua, whereas off Java, though comparable in size along our profile, they cannot be unambiguously identified from seafloor deformation.

Another difference regards the splay fault system, which separates the outer and inner wedges off western Java. The splay fault is an out-of-sequence thrust (Kopp and Kukowski, 2003) associated with strain localization and the onset of seismic behavior (Moore et al., 2007). Splay faulting is not observed off Nicaragua (McIntosh et al., 2007), but has been associated with tsunamigenic earthquakes along the Nankai margin (Moore et al., 2007; Bangs et al., 2009). Splay faults are ubiquitous along the northern and central Sunda margin (Kopp and Kukowski, 2003; Sibuet et al., 2007) as well as offshore Bali and Lombok (Lueschen et al., in review). According to the 'dynamic Coulomb model' of Wang and Hu (2006) co-seismic velocity strengthening of the shallow décollement during enhanced compressive deformation of the outer wedge will stimulate upward slip diverged along the splay fault. The splay fault system imaged in our seismic line thus is an attractive candidate for slip to the seafloor, causing tsunamigenesis.

4. Conclusions

The re-processed and newly pre-stack depth-migrated profile across the western Java margin images the structural segmentation of the forearc and provides an account of the kinematic evolution of the subduction complex. The complex plate interface is characterized by local morphologic structure and underthrust sediment patches, which likely influence the frictional properties of the shallow megathrust zone. Compared to other décollement zones in large accretionary systems (e.g. Barbados (Westbrook et al., 1988), Cascadia (Adam et al., 2004) or Nankai (Bangs et al., 2004)), the Java case shows a non-uniform character of irregular thickness (Figs. 2 and 3). Unlike for the well-studied Barbados or Nankai margins, for which a remarkable imaging quality has been documented (e.g. Bangs et al., 1999, 2009), the western Java data are not sufficient to quantify physical property changes along the décollement. The seismic images of the spatially variable, nonlinear pattern of the décollement zone, however, support the inference that differential friction along this margin segment may influence earthquake seismogenesis. The splay fault system, which serves as a mechanical boundary between the inner and outer wedges, potentially transfers slip to the seafloor (Kame et al., 2003). This thrust fault connects to the décollement at a depth of approximately 12 km, rising to the seafloor where it reaches its steepest slope, thus potentially causing significant vertical displacement of the seafloor as often associated with tsunami generation. The 2006 tsunami earthquake occurred 100 km east of our line and underscores the persistent seismic and tsunamigenic hazard of this margin (e.g. Abercrombie et al., 2001; Bilek and Engdahl, 2007; Brune et al., in review).

Acknowledgements

MCS line SO137-03 was acquired during cruise SO137 of RV SONNE by the Federal Institute of Geosciences and Natural Resources, BGR, Hannover, Germany. The SHAPE project is supported by the Deutsche Forschungsgemeinschaft DFG (grant KO2961/1-2). We thank H. Smyth, H. Handley and T. Plank for discussion on arc magma signatures of the Sunda margin and J. Behrmann for discussion on slope basin formation. Reviews by G. Moore helped greatly in improving an earlier version. We thank A. Krabbenhoeft for editing Fig. 1.

References

Abercrombie, R., Antolik, M., Felzer, K., Ekström, G., 2001. The 1994 Java tsunami earthquake: slip over a subducting seamount. J. Geophys. Res. 106, 6595–6607.
Ammon, C., Kanamori, H., Lay, T., Velasco, A., 2006. The 17 July 2006 Java tsunami earthquake. Geophys. Res. Lett. 33. doi:10.1029/2006GL028005.
Adam, J., Klaeschen, D., Kukowski, N., Flueh, E.R., 2004. Upward delamination of Cascadia Basin sediment infill with landward frontal accretion thrusting caused by rapid glacial age material flux. Tectonics 23. doi:10.1029/2002TC001475.
Amante, C., Eakins, B.W., 2008. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. National Geophysical Data Center, NESDIS, NOAA. U.S. Department of Commerce, Boulder, CO.
Bangs, N.L.B., Westbrook, G., 1991. Seismic modeling of the décollement zone at the base of the Barbados Ridge accretionary complex. J. Geophys. Res. 96, 3853–3866.
Bangs, N.L.B., Shipley, T.H., Moore, G.F., 1996. Elevated fluid pressure and fault zone dilation inferred from seismic models of the northern Barbados Ridge decollement. J. Geophys. Res. 101, 627–642.
Bangs, N.L.B., Shipley, T.H., Moore, J.C., Moore, G.F., 1999. Fluid accumulation and channeling along the northern Barbados Ridge decollement thrust. J. Geophys. Res 104, 20.399–20.414.
Bangs, N.L.B., Shipley, T.H., Moore, G.F., Gulick, S.P.S., Nakamura, Y., 2004. Evolution of the Nankai trough decollement from the trench into the seismogenic zone: inferences from three-dimensional seismic reflection imaging. Geology 32, 273–276.
Bangs, N.L.B., Gulick, S.P.S., Shipley, T.H., 2006. Seamount subduction erosion in the Nankai Trough and its potential impact on the seismogenic zone. Geology 34. doi:10.1130/G22451.1.
Bangs, N.L.B., Moore, G.F., Gulick, S.P.S., Pangborn, E.M., Tobin, H.J., Kuramoto, S., Taira, A., 2009. Broad, weak regions of the Nankai Megathrust and implications for shallow coseismic slip. Earth Planet. Sci. Lett. 284, 44–49. doi:10.1016/j.epsl.2009.04.26.
Bekins, B.A., McCaffery, A.M., Dreiss, S.J., 1995. Episodic and constant flow models for the origin of the low-chloride waters in a modern accretionary complex. Water Res. Res. 31, 3205–3215.
Bilek, S., Lay, T., 2002. Tsunami earthquakes possibly widespread manifestations of frictional conditional stability. Geophys. Res. Lett. 29, 14. doi:10/1029/2002GL015215.
Bilek, S., Engdahl, E.R., 2007. Rupture charaterization and aftershock relocations for the 1994 and 2006 tsunami earthquakes in the Java subduction zone. Geophys. Res. Lett. 34. doi:10.1029/2007GL031357.
Bilek, S., 2007. Influence of subducting topography on earthquake rupture. In: Dixon, T.J., Moore, J.C. (Eds.), The Seismogenic Zone of Subduction Thrust Faults. Columbia University Press, New York, pp. 123–146.
Brune, S., Ladage, S., Babeyko, A. Y., Mueller, C., Kopp, H., Sobolev, S. V., in review. Submarine landslides at the eastern Sunda margin: observations and tsunami impact assessment. Natural Hazards.
Calahorrano, A.B., Sallares, V., Collot, J.-Y., Sage, F., Ranero, C., 2008. Nonlinear variations of the physical properties along the southern Ecuador subduction channel: results from depth-migrated seismic data. Earth Planet. Sci. Lett. 267, 453–467. doi:10.1016/j.epsl.2007.11.061.
Chapple, W.M., 1978. Mechanics of thin-skinned fold-and-thrust belts. Geol. Soc. Am. Bull. 89, 1189–1198.
Clift, P.D., Vannucchi, P., 2004. Controls on tectonic accretion versus erosion in subduction zones: implications for the origin and recycling of the continental crust. Rev. Geophys. 42. doi:10.1029/2003RG000127.
Cochrane, G.R., Moore, J.C., MacKay, M.E., Moore, G.F., 1994. Velocity and inferred porosity model of the Oregon accretionary prism from multichannel seismic reflection data: implications on sediment dewatering and overpressure. J. Geophys. Res. 99, 7033–7043.
Collot, J.-Y., Agudelo, W., Ribodetti, A., Marcaillou, B., 2008. Origin of a crustal splay fault and its relation to the seismogenic zone and underplating at the erosional north Ecuador–south Colombia oceanic margin. J. Geophys. Res. 113. doi:10.1029/2008JB005691.
Costa Pisani, P., Reshef, M., Moore, G.F., 2005. Targeted 3-D prestack depth imaging at Legs 190–196 ODP drill sites (Nankai Trough, Japan). Geophys. Res. Lett. 32. doi:10.1029/2005GL024191.
Davis, D.M., Suppe, J., Dahlen, F.A., 1983. Mechanics of fold-and-thrust belts and accretionary wedges. J. Geophys. Res. 88, 1153–1172.
Davis, D.M., 1996. Accretionary mechanics with properties that vary in space and time. In: Bebout, G.E., Scholl, D.W., Kirby, S.H., Platt, J.P. (Eds.), Subduction Top To Bottom. Geophys. Geophys. Monograph, 96. American Geophysical Union, pp. 39–48.
Franke, D., Schnabel, M., Ladage, S., Tappin, D.R., Neben, S., Djajadihardja, Y.S., Mueller, C., Kopp, H., Gaedicke, C., 2008. The great Sumatra–Andaman earthquakes —

imaging the boundary between the ruptures of the great 2004 and 2005 earthquakes. Earth Planet. Sci. Lett. 269. doi:10.1016/j.epsl.2008.01.047.

Gasparon, M., Varne, R., 1998. Crustal assimilation versus subducted sediment input in west Sunda arc volcanics: an evaluation. Mineral. Petrol. 64, 89–117.

Grevemeyer, I., Tiwari, V.M., 2006. Overriding plate controls spatial distribution of megathrust earthquakes in the Sunda–Andaman subduction zone. Earth Planet. Sci. Lett. 251. doi:10.1016/j.epsl.2006.08.021.

Guo, N., Fagin, S., 2002. Becoming effective velocity model builders and depth imagers, part 1— basics of prestack depth migration. Leading Edge 21, 1205–1209.

Gutscher, M.-A., Kukowski, N., Malavielle, J., Lallemand, S., 1998. Episodic imbricate thrusting and underthrusting: analog experiments and mechanical analysis applied to the Alaskan Accretionary Wedge. J. Geophys. Res. 103, 10161–10176.

Hall, R., Smyth, H.R., 2008. Cenozoic arc processes in Indonesia: identification of the key influences on the stratigraphic record in active volcanic arcs. In: Draut, A.E., Clift, P.D., Scholl, D.W. (Eds.), Formation and Application of the Sedimentary Record in Arc Collision Zones: Geological Society of America Special paper, 436, pp. 27–54. doi:10.1130/2008.2436(03).

Hamilton, W., 1979. Tectonics of the Indonesian region. U.S. Geol. Surv. Prof. Paper, p. 1078.

Handley, H.K., 2006. Geochemical and Sr–Nd–Hf–O isotopic constraints on volcanic petrogenesis at the Sunda arc, Indonesia, PhD Thesis, Durham University, UK.

Handley, H.K., Davidson, J.P., Macpherson, C.G., Stimac, J.A., 2008. Untangling differentiation in arc lavas: constraints from unusual minor and trace element variations at Salak Volcano, Indonesia. Chem. Geol. doi:10.1016/j.chemgeo.2008.07.007.

Heffernan, A.S., Moore, J.C., Bangs, N.L., Moore, G.F., Shipley, T.H., 2004. Initial deformation in a subduction thrust system: polygonal normal faulting in the incoming sedimentary sequence of the Nankai subduction zone, Southwestern Japan. Geol. Soc. London Mem. 29. doi:10.1144/GSL.MEM.2004.029.01.14, 143–148.

Hoth, S., Hoffmann-Rothe, A., Kukowski, N., 2007. Frontal accretion: an internal clock for bivergent wedge deformation and surface uplift. J. Geophys. Res. 112. doi:10.1029/2006JB004357.

Kame, N., Rice, J.R., Dmowska, R., 2003. Effects of prestress state and rupture velocity on dynamic fault branching. J. Geophys. Res. 108. doi:10.1029/2002JB002189.

Karig, D.E., Lawrence, M.B., Moore, G.F., Curray, J.R., 1980a. Structural frame work of the fore-arc basin, NW Sumatra. J. Geol. Soc. 137. doi:10.1144/gsjgs.137.1.0077.

Karig, D.E., Moore, G.F., Curray, J.R., Lawrence, M.B., 1980b. Morphology and shallow structure of the trench slope off Nias Island, Sunda Arc. In: Hayes, D.E. (Ed.), The tectonic and geologic evolution of Southeast Asian seas and islands: Geophys. Monogr, 23, pp. 179–208. Washington.

Kieckhefer, R.M., Shor Jr., G.G., Curray, J.R., 1980. Seismic refraction studies of the Sunda trench and forearc basin. J. Geophys. Res. 85 (B2), 863–889.

Kopp, H., Flueh, E.R., Klaeschen, D., Bialas, J., Reichert, C., 2001. Crustal structure of the central Sunda margin at the onset of oblique subduction. Geophys. J. Int. 147, 449–474.

Kopp, H., Klaeschen, D., Flueh, E.R., Bialas, J., Reichert, C., 2002. Crustal structure of the Java margin from seismic wide-angle and multichannel reflection data. J. Geophys. Res. 107. doi:10.1029/2000JB000095.

Kopp, H., Kukowski, N., 2003. Backstop geometry and accretionary mechanics of the Sunda margin. Tectonics 6. doi:10.1029/2002TC001420.

Kopp, H., Flueh, E.R., Petersen, C.J., Weinrebe, W., Wittwer, A., Scientists, Meramex, 2006. The Java margin revisited: evidence for subduction erosion off Java. Earth Planet. Sci. Lett. 242, 130–142.

Kopp, H., Weinrebe, W., Ladage, S., Barckhausen, U., Klaeschen, D., Flueh, E.R., Gaedicke, C., Djajadihardja, Y., Grevemeyer, I., Krabbenhoeft, A., Papenberg, C., Zillmer, M., 2008. Lower slope morphology of the Sumatra trench system. Basin Res. doi:10.1111/j.1365-2117.2008.00381.x.

Lay, T., Bilek, S., 2007. Anomalous earthquake ruptures at shallow depth on subduction zone megathrusts. In: Dixon, T.J., Moore, J.C. (Eds.), The Seismogenic Zone of Subduction Thrust Faults. Columbia University Press, New York, pp. 476–511.

Lelgemann, H., Gutscher, M.-A., Bialas, J., Flueh, E.R., Weinrebe, W., Reichert, C., 2000. Transtensional basins in the western Sunda Strait. Geophys. Res. Lett. 27 (21), 3545–3548.

Le Pichon, X., Henry, P., Lallemand, S., 1993. Accretion and erosion in subduction zones: the role of fluids. Annu. Rev. Earth Planet. Sci. 21, 307–331.

Lueschen, E., Mueller, C., Kopp, H., Engels, M., Lutz, R., Planert, L., Shulgin, A., Djajadihardja, Y., in review. Structure, Evolution and Tectonic Activity of the Eastern Sunda Forearc, Indonesia, from Marine Seismic Investigations. Tectonophys.

MacKay, M., Moore, G.F., Cochrane, G.R., Moore, J.C., Kulm, L.D., 1992. Landward vergence and oblique structural trends in the Oregon margin accretionary prism: implications and effect on fluid flow. Earth Planet. Sci. Lett. 109, 477–491.

MacKay, S., Abma, R., 1993. Depth focusing analysis using wavefront-curvature criterion. Geophysics 58, 1148–1156.

MacKay, M., 1995. Structural variation and landward vergence at the toe of the Oregon accretionary prism. Tectonics 14, 1309–1320.

McIntosh, K.D., Silver, E.A., Ahmed, I., Berhosrt, A., Ranero, C.R., Kelly, R.K., Flueh, E.R., 2007. The Nicaragua convergent margin: seismic reflection imaging of the source of a tsunami earthquake. In: Dixon, T.J., Moore, J.C. (Eds.), The Seismogenic Zone of Subduction Thrust Faults. Columbia University Press, New York, pp. 476–511.

Moore, G.F., Curray, J.R., 1980. Structure of the Sunda trench lower slope off Sumatra from multichannel seismic reflection data. Marine Geophys. Res. 4, 319–340.

Moore, G.F., Curray, J.R., Moore, D.G., Karig, D.E., 1980. Variations in geologic structure along the Sunda fore arc, Northeastern Indian Ocean. In: Hayes, D.E. (Ed.), The tectonic and geologic evolution of Southeast Asian seas and islands: Geophys. Monogr, 23, pp. 145–160. Washington.

Moore, G.F., Curray, J.R., Emmel, F.J., 1982. Sedimentation in the Sunda trench and forearc region. In: Leggett, J.K. (Ed.), Trench Forearc Geology: Geol. Soc. London Spec. Publ., 10.

Moore, G.F., Shipley, T.H., Stoffa, P.L., Karig, D.E., Taira, A., Kuramoto, S., Tokuyama, H., Suyehiro, K., 1990. Structure of the Nankai Trough accretionary zone from multichannel seismic reflection data. J. Geophys. Res. 95, 8753–8765.

Moore, G.F., Taira, A., Klaus, A., Becker, L., Boeckel, B., Cragg, B.A., Dean, A., Fergusson, C.L., Henry, P., Hirano, S., Hisamitsu, T., Hunze, S., Kastner, M., Maltman, A.J., Morgan, J.K., Murakami, Y., Saffer, D.M., Sánchez-Gómez, M., Screaton, E.J., Smith, D.C., Spivack, A.J., Steurer, J., Tobin, H.J., Ujiie, K., Underwood, M.B., Wilson, M., 2001. New insights into deformation and fluid flow processes in the Nankai Trough accretionary prism: results from Ocean Drilling Program Leg 190. Geochem. Geophys. Geosyst. 2. doi:10.1029/2001GC000166.

Moore, G.F., Bangs, N.L., Taira, A., Kuramoto, S., Pangborn, E., Tobin, H.J., 2007. Three-dimensional splay fault geometry and implications for tsunami generation. Science 318. doi:10.1126/science.1147195.

Moore, J.C., Silver, E.A., 1987. Continental margin tectonics: submarine accretionary prisms. Rev. Geophys. 25, 1305–1312.

Moore, J.C., Klaus, A., Bangs, N.L., Bekins, B., Bücker, C.J., Brückmann, W., Erickson, S.N., Hansen, O., Horton, T., Ireland, P., Major, C.O., Moore, G.F., Peacock, S., Saito, S., Screaton, E.J., Shimeld, J.W., Stauffer, P.H., Taymaz, T., Teas, P.A., Tokunaga, T., 1998. Consolidation patterns during initiation and evolution of a plate-boundary decollement zone: Northern Barbados accretionary prism. Geology 26 (9), 811–814.

Moore, J.C., Saffer, D.M., 2001. Updip limit of the seismogenic zone beneath the accretionary prism of southwest Japan: an effect of diagenetic to low-grade metamorphic processes and increasing effective stress. Geology 29, 183–186.

Mueller, C., Kopp, H., Djajadihardja, Y.S., Barckhausen, U., Ehrhardt, A., Engels, M., Flueh, E.R., Gaedicke, C., Keppler, H., Lutz, R., Lueschen, E., Neben, S., Seeber, L., Dzulkarnaen, D.P.S., 2008. From subduction to collision: The Sunda-Banda arc transition. EOS Transact. 89, 49–50.

Newcomb, K.R., McCann, W.R., 1987. Seismic history and seismotectonics of the Sunda arc region. J. Geophys. Res. 92, 421–439.

Pacheco, J.F., Sykes, L.R., Scholz, C.H., 1993. Nature of seismic coupling along simple plate boundaries of the subduction type. J. Geophys. Res. 98, 14.133–14.159.

Park, J.-O., Tsuru, T., Kodaira, S., Nakanishi, A., Miura, S., Kaneda, Y., Kono, Y., 2000. Out-of-sequence thrust faults developed in the coseismic slip zone of the 1946 Nankai earthquake (Mw = 8.2) off Shikoku, southwest Japan. Geophys. Res. Lett. 27 (7), 1033–1036.

Park, J.-O., Tsuru, T., Takahashi, N., Hori, T., Kodaira, S., Nakanishi, A., Miura, S., Kaneda, Y., 2002a. A deep strong reflector in the Nankai accretionary wedge from multichannel seismic data: implications for underplating and interseismic shear stress release. J. Geophys. Res. 107, 3.1–3.19.

Park, J.-O., Tsuru, T., Kodaira, S., Cummins, P.R., Kaneda, Y., 2002b. Splay fault branching along the Nankai subduction zone. Science 297. doi:10.1126/science.1074111.

Planert, L., Kopp, H., Lueschen, E., Mueller, C., Flueh, E. R., Shulgin, A., Djajadihardja, Y., Krabbenhoeft, A., in review. Lower plate structure and upper plate deformational segmentation at the Sunda–Banda arc transition, Indonesia, resolved from the analysis of seismic and gravity data. J. Geophys. Res.

Plank, T., Langmuir, C.H., 1993. Tracing trace elements from sediment input to volcanic output at subduction zones. Nature 362, 739–743.

Plank, T., 2005. Constraints from Th/La sediment recycling at subduction zones and the evolution of the continents. J. Petrol. 46. doi:10.1093/petrology/egi005.

Polonia, A., Torelli, L., Brancolini, G., Loreto, M.-F., 2007. Tectonic accretion versus erosion along the southern Chile trench: oblique subduction and margin segmentation. Tectonics 26. doi:10.1029/2006TC001983.

Ranero, C.R., Grevemeyer, I., Sahling, H., Barckhausen, U., Hensen, C., Wallmann, K., Weinrebe, W., Vannucchi, P., von Huene, R., McIntosh, K., 2008. Hydrogeological system of erosional convergent margins and its influence on tectonics and interplate seismogenesis. Geochem. Geophys. Geosyst. 9. doi:10.1029/2007GC001679.

Saffer, D.M., 2003. Pore pressure development and progressive dewatering in underthrust sediments at the Costa Rican subduction margin: Comparison with Northern Barbados and Nankai. J. Geophys. Res. 108 (B5), 2261. doi:10.1029/2002JB001787.

Sage, F., Collot, J.-Y., Ranero, C.R., 2006. Interplate patchiness and subduction–erosion mechanisms: evidence from depth-migrated seismic images at the central Ecuador convergent margin. Geology 34. doi:10.1130/G22790A.1.

Schlueter, H.-U., Gaedicke, C., Roeser, H.A., Schreckenberger, B., Meyer, H., Reichert, C., Djajadihardja, Y.S., Prexl, A., 2002. Tectonic features of the Sumatra–Java forearc of Indonesia. Tectonics 21. doi:10.1029/2001TC901048.

Shipley, T.H., Moore, G.F., Bangs, N.L., Moore, J.C., Stoffa, P.L., 1994. Seismically inferred dilatancy distribution, northern Barbados Ridge decollement: implications for fluid migration and fault strength. Geology 22, 411–414.

Shulgin, A., Kopp, H., Mueller, C., Lueschen, E., Planert, L., Engels, M., Flueh, E.R., Krabbenhöft, A., Djajadihardja, Y., 2009. Sunda–Banda Arc transition: incipient continent-island arc collision (northwest Australia). Geophys. Res. Lett. 36, L10304. doi:10.1029/2009GL037533.

Sibuet, J.-C., Rangin, C., Le Pichon, X., Singh, S., Cattaneo, A., Graindorge, D., Klingelhoefer, F., Lin, J.-Y., Malod, J., Maury, T., Schneider, J.-L., Sultan, N., Umber, M., Yamaguchi, H., Team, Sumatra Aftershocks, 2007. 26th December 2004 Great Sumatra–Andaman Earthquake: co-seismic and post-seismic motions in northern Sumatra. Earth Planet. Sci. Lett. 263. doi:10.1016/j.epsl2007.09.005.

Singh, S.C., Carton, H., Tapponier, P., Hananto, N.D., Chauhan, A.P.S., Hartoyo, D., Bayly, M., Moeljopranoto, S., Bunting, T., Christie, P., et al., 2008. Seismic evidence for broken oceanic crust in the 2004 Sumatra earthquake epicentral region. Nature Geoscience 1. doi:10.1038/ngeo336.

Skarbek, R.M., Saffer, D.M., 2009. Pore pressure development beneath the décollement at the Nankai subduction zone: implications for plate boundary fault strength and sediment dewatering. J. Geophys. Res. 114. doi:10.1029/2008JB006205.

Stern, R.J., 2002. Subduction zones. Rev. Geophys. 40 (4), 1012. doi:10.1029/2001RG000.

Taira, A., Hill, I., Firth, J.V., Scientific Party, 1991. Proceedings of Ocean Drilling Program, Initial Reports: Ocean Drill. Program, College Station, Tex., 131.

Tsuji, T., Matsuoka, T., Yamada, Y., Nakamura, Y., Ashi, J., Tokuyama, H., Kuramoto, S., Bangs, N.L., 2005. Initiation of plate boundary slip in the Nankai Trough off the Muroto peninsula, southwest Japan. Geophys. Res. Lett. 32. doi:10.1029/2004GL021861.

Tsuji, T., Tokuyama, H., Costa Pisani, P., Moore, G.F., 2008. Effective stress and pore pressure in the Nankai accretionary prism off the Muroto peninsula, southwestern Japan. J. Geophys. Res. 113. doi:10.1029/2007JB005002.

von Huene, R., Scholl, D.W., 1991. Observations at convergent margins concerning sediment subduction, subduction erosion, and growth of continental crust. Rev. Geophys. 29, 279–316.

von Huene, R., Ranero, C.R., Vannucchi, P., 2004. Generic model of subduction erosion. Geology 32. doi:10.1130/G20563.1.

von Huene, R., Ranero, C.R., Scholl, D., 2009. Convergent margin structure in high-quality geophysical images and current kinematic and dynamic models. In: Lallemand, S., Funiciello, F. (Eds.), Subduction Zone Geodynamics. Springer-Verlag, Heidelberg, pp. 137–157.

Wang, K., Hu, Y., 2006. Accretionary prisms in subduction earthquake cycles: the theory of dynamic Coulomb wedge. J. Geophys. Res. 111. doi:10.1029/2005JB004094.

Westbrook, G., Ladd, J.W., Buhl, P., Bangs, N., Tiley, G.J., 1988. Cross section of an accretionary wedge: Barbados Ridge complex. Geology 16, 631–635.

Willet, S., Beaumont, C., Fullsack, P., 1993. Mechanical model for the tectonics of doubly vergent compressional orogens. Geology 21, 371–374.

Please cite this article as: Kopp, H., et al., Anatomy of the western Java plate interface from depth-migrated seismic images, Earth Planet. Sci. Lett. (2009), doi:10.1016/j.epsl.2009.09.043