The Java margin revisited: Evidence for subduction erosion off Java

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Abstract

The eastern Sunda margin off Indonesia (from central Java to Sumba Island) remains a little investigated subduction zone, contrary to its well-studied northwestern segment. Whereas large portions of the Sunda margin are considered a classical accretionary zone, subduction characteristics along the central Java sector indicate erosive processes as the dominant mode of mass transfer. The tectonic framework of the central Java margin, with a convergence rate of 6.7 cm/yr, insignificant sediment input and a pronounced seafloor roughness where the oceanic Roo Rise is subducting underneath Java, facilitates subduction erosion. Evidence for erosion comes from newly acquired geophysical data off central Java: local erosive processes in the wake of seamount subduction are documented by a high-resolution bathymetric survey and result in an irregular trend of the deformation front sculpted by seamount collision scars. Subduction of oceanic basement relief leads to large-scale uplift of the forearc, as recorded on a reflection seismic profile, and to a dismemberment of the previous outer forearc high, giving way to isolated topographic elevations. The broad retreat of the Java Trench and deformation front above the leading edge of the Roo Rise has exposed an area of approximately 25,000 km² of deeper seafloor formerly covered by the previous frontal prism. Frontal erosion coincides with a steepening of the lower slope angle in the central Java sector compared to the neighbouring segments. In global compilations, the key geological parameters of the central Java margin lie in the erosive regime, reflecting the interplay of basement relief subduction, negligible sediment supply and a high convergence rate on the evolution of the margin.

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1. Introduction

Modes of mass transfer at subduction zones vary greatly and include both accretionary and erosive styles. Most margins are non-uniform either in alternating phases of accretion and erosion, or in supporting accretive and erosive regimes simultaneously. While accretionary systems are comparatively easy to identify due to the material accumulation in a compressive setting, the ‘loss’ of material in erosive systems is a more obscure target. The last two decades, however, have brought a tremendous advancement in the understanding of erosive systems (e.g. [1–9]). A limited number of geological and tectonic factors appear to control tectonic erosion over subduction accretion or intermediate non-accretive styles. These include convergence rates exceeding 6 cm/yr, thin (<1 km) sediment cover in the trench, and seafloor roughness, all of which prevail along the central Java margin, implying an erosive regime here. Tectonic erosion may either occur along the front of the margin or along the base of the forearc wedge causing dismemberment of upper plate material.
along the shallow part of the plate interface updip of the seismogenic zone and transfer of material to the down-going oceanic plate [10]. From their global compilation of subduction zones, Clift and Vannucchi [9] recognized that effective erosion is foremost controlled by the collision of bathymetric elevations with the margin. Even though collision of large topographic units is episodic and short-lived along most margins, its influence on the evolution of that margin is profound as it governs the rates of material transfer (e.g. collision of Louisville Ridge with the Kermadec margin [11]). This paper investigates new geophysical data collected offshore central Java, where the oceanic Roo Rise is currently being subducted. Based on a combined analysis with the regional bathymetry, we propose subduction erosion as the dominant tectonic process off central Java. Geological indicators for tectonic erosion at the Java margin include landward retreat of the trench and deformation front, dismemberment of the previous outer forearc high by underthrusting of oceanic basement relief and steepening of the trench slope. In global compilations of accretionary and erosive systems, the central Java margin clearly maps in the erosive regime, contrary to the classical accretionary concept previously applied to this margin segment.

2. Tectonic framework of the Sunda margin

The Sunda margin, including the Sumatra and Java sectors, extends from the Bay of Bengal and the Andaman Sea in the northwest to Sumba Island in the southeast and has been the site of ongoing geophysical and geological surveys since the early years of the last century (e.g. [12,13]). It is regarded as a classical example for an accretionary type margin and was used to promote models of sediment accretion and on the evolution of forearc tectonic structures (e.g. [14–25]). The present subduction system evolved after the Eocene collision of India with Eurasia and has been active since the middle Tertiary, as inferred from dating of the Sundasystem volcanism [26]. The subduction zone is mainly characterized by the variation of two parameters: subduction obliqueness and sediment supply to the trench. The high degree of slip partitioning arising from the oblique plate convergence along the Sumatran sector of the margin gives rise to the lithospheric-scale Sumatra strike-slip fault [27] and additional marine transpressional features [28] to compensate for the lateral component of motion.

Frontal accretion is the dominant mode of mass transfer along the central Sunda margin, where a massive accretionary prism has formed as a result of the high ratio of accreted to subducted sediment [21,22]. Adjacent to the active frontal accretionary prism off southern Sumatra and western Java along the central sector of the margin, the now fossil portion of the accretionary wedge shapes a well-developed outer forearc high of Eocene–Oligocene age [29,30]. The accretionary origin of the outer forearc high is supported by field mapping [25], refraction and gravity data [29,30]. Landward of the outer forearc high, a series of mature forearc basins has developed [31]. Along the central Sunda margin, these basins form between the landward arc-massif backstop and the large accretionary wedge on the seaward side and are of the ‘constructed type’ identified by Dickinson and Seely [32]. Stratigraphic investigations and drilling information on the forearc basins suggest an Oligocene age for the oldest sediments trapped here [33–35,21]. Mass balance calculations conducted along the central sector of the margin from southern Sumatra to western Java have shown that the age of the outer forearc high and the forearc basin sediment fill correlate with an accretionary convergence history that must have remained fairly constant since Eocene times [22], even though a number of geologic and tectonic parameters, such as plate age, sediment load and subduction angle, show a high variability along strike of the margin. Frontal accretion is the dominant mode of mass transfer along the northern and western segments of the margin off Sumatra and western Java [17,21], and only a low percentage of sediment is underplated or subducted, similar to the current situation along the Cascadia margin [36]. Thus, in view of the large fraction of modern margins that have been found to be erosive, the northern and central Sunda subduction zone has been classified as an end-member of convergent margins. However, geophysical and geological investigations along the eastern portion of the Sunda margin, from central Java to Sumba Island, are scarce. This margin sector includes the ocean–continent transition between the Indo-Australian plate and the Australian continent across the North Wilson Fault Zone, which separates the two plates (approximate location shown in Fig. 1) [37].

Along this segment, convergence at a rate of $6.7 \pm 0.7$ cm/yr in a direction N11°E is approximately orthogonal to the trench, as determined by GPS measurements between Christmas Island and West Java [38]. At present, 135 Ma oceanic crust subducts off eastern Java and crustal ages decrease to 96 Ma off western Java and southern Sumatra [17,39]. In correlation with an increasing distance from the Ganges-Brahmaputra Delta, trench sediment thickness decreases along strike of the margin. Sediment input from Suma-
tra and Java is trapped in the forearc basins here and does not reach the trench. In association with the declining sediment supply to the southeast, the size and volume of the accretionary wedge observed off Sumatra and western Java shrinks steadily to the east, where the trench along extensive segments is devoid of any sediment fill.

3. Observations on tectonic style off Java

The western Java margin currently receives approximately 1.3 km of sediment trench input, a large fraction of which is accreted and incorporated into the active frontal accretionary prism (Fig. 1). At present, less than 15% of the trench material is subducted and passes the accretionary prism in a subduction window [22]. Off western Java, a continuous and homogeneously developed frontal accretionary prism and outer forearc high have evolved in conjunction with a mature forearc basin (Fig. 1). More than 4 km of mainly terrigenous sediment with minor volcanic ashes have accumulated in the basin [30]. The horizontal-layered strata lie roughly parallel to the seafloor and are generally undeformed, apart from several anticlinal structures, the largest of which most likely represents the offshore prolongation of the Sumatra strike-slip fault system. The lateral extent of the frontal accretionary prism, the outer forearc high and the forearc basin are abruptly disrupted around 109°E. No distinct frontal prism or prolonged outer forearc high are recognizable along the central Java sector (109°E–115°E) and a continuous forearc basin is not present (Fig. 1). Here, the outer forearc high is characterized by isolated bathymetric highs (labelled 1 through 5 in Fig. 1) contrasting with a continuous ridge, as it exists in the western (105°E–109°E) and eastern Java sectors (115°E–119°E). These isolated highs reach water depths of less than 1000 m, compared to the approximately 2000 m water depth attained by the continuous ridge-like outer forearc high in the neighbouring segment. An active frontal accretionary prism bordering the outer forearc high, as recognized off western Java and Sumatra, is not present off central Java. The subducting oceanic crust of the Argo Abyssal Plain (Fig. 1)
Fig. 2. Four-channel streamer section across the Java margin (location shown in Fig. 1). Uplift caused by the underthrusting of oceanic basement relief affects the outer forearc high, which reaches approximately 1000 m shallower water depth than in adjacent areas. The forearc basin strata onlap the outer forearc high and are tilted landward, indicating syndepositional and postdepositional vertical movement of the seaward portion of the basin and the forearc high. Recent deformation is also indicated by the landward-tilted basement north of the forearc basin.
carries only a thin coverage of Mesozoic and Tertiary pelagic sediments reaching a few hundred meters thickness (Fig. 2) [40]. Whereas the deep-sea trench off western Java displays a flat morphology resulting from >1 km infill, along the central Java segment, the trench forms a V-shaped structure and is generally
devoid of sediment. Along this section of the margin, the trench and deformation front show an irregular shape (Fig. 1). The trench is less deep here, reaching depths of 5600–6000 m, while it is more than 7000 m deep off western Java and seaward of the Lombok Basin [41].

4. Subduction of oceanic basement relief

4.1. Subduction of the oceanic Roo Rise

Subduction processes off central Java are dominated by the collision of the oceanic Roo Rise with the forearc between 109°E and 115°E (Fig. 1). The Roo Rise represents a little investigated oceanic topographic feature, which forms an irregularly shaped broad swell dotted with isolated morphological summits (Fig. 1). It reaches heights of about 2.0–2.5 km above the general level of the surrounding ocean floor. Early reflection profiles indicate thickened oceanic crust underneath the Roo Rise [42] with an average thickness of 11.5 km. The lack of a pronounced free-air gravity response to the relief of the Roo Rise implies that this plateau may be compensated by a low-density root [43], as is common for volcanic features formed at or near spreading centers (e.g. Cocos Ridge [44] or Malpelo Ridge [45]). The Roo Rise continues into the trench and is interacting with the margin, causing large-scale uplift of the entire forearc (Fig. 1). Fig. 2 shows a reflection seismic line (P16) across the Java margin extending from 110°17′E/11°28′S to 110°51′E/8°15′S (location shown in Fig. 1), which was acquired during cruise SO179 of the RV SONNE in 2004 [40]. This profile was recorded using a four-channel streamer and runs roughly parallel to the western flank of the Roo Rise and its projection underneath the forearc [46]. Underthrusting of oceanic basement relief results in uplift and doming of the outer forearc high, which here reaches approximately 1000 m shallower water depths than observed for those adjacent areas not affected by Roo Rise subduction. Uplift also affects the forearc basin sediments (Fig. 2) and causes a narrowing of the basin compared to the western Java or Lombok Basins (Fig. 1). Seismic reflections within the basin are continuous and of variable amplitude and are interpreted as facies of terrigenous origin alternating with volcanic ashes. The forearc basin strata onlap the outer forearc high and are tilted landward, indicating syn- and post-deposition-al vertical movements of the seaward portion of the basin and the forearc high. Uplift has also been documented by Newcomb and McCann [43] on two seismic profiles crossing the margin at 113°E and 114°E (profiles away from the projection of the Roo Rise at 109°E across the West Java forearc basin and at 115.2°E across the Lombok Basin recorded undisturbed strata). Recent deformation is indicated by the elevated and landward-tilted basement north of the forearc basin. Normal faulting of the landward slope of the forearc basin (Fig. 2) may be an indication of extension due to basal erosion; however, the lack of data penetration in this streamer section prevents any further investigation. Large-scale subsidence, which is recognized as an indicator of basal tectonic erosion of forearc crust elsewhere, is not documented for the central Java margin and would be overcast by the vertical tectonics caused by the subduction of the Roo Rise. Where the leading edge of the Roo Rise enters, the deep-sea trench is uplifted and is anomalously shallow, as discussed in the previous section. The collision of the Roo Rise with the margin causes a displacement of the trench and deformation front to the north (Fig. 1). This general retreat of the trench between 109°E and 115°E is superimposed over small-scale anomalies in the curvature of the deformation front. These smaller-scale displacements result from the collision of seamounts with the deformation front.

4.2. Seamount subduction

Numerous seamounts more than 10 km in diameter and at different stages of subduction (e.g. at approximately 108.5°E, 111.1°E, 111.5°E, 113°E and 114.8°E) have been mapped using side-scan sonar [39,41] and high-resolution bathymetry (Fig. 3). The seamount population tremendously increases the roughness of the seafloor entering the trench off central and eastern Java. Bathymetric seafloor investigations further west off southern Sumatra, Sunda Strait and West Java did not detect comparable seamount fields [47]. The indentations of the deformation front caused by the incipient
subduction of seamounts are commonly a few kilometres broad, but reach widths of 50 km where the deformation front has retreated in excess of 10 km [41]. The swath data shown in Fig. 3 reveal a recently subducted seamount ~50 km in diameter at 110°30′E, which causes a northward deflection of the deformation front by ~15 km. Masson et al. [41] noted a correlation between the re-entrant scars along the deformation front and the isolated topographic highs (1–5 in Fig. 1) composing the outer forearc high off central Java (e.g. at 109°E, between 109°45′E and 110°45′E, at 111°40′ and possibly between 112°45′E and 113°45′E). They proposed that the topographic highs represent completely subducted seamounts, as these are predicted to cause continued uplift of the forearc after subduction [48]. A continuous forearc ridge is again present between 115°E and 118°E, comparable to the fossil accretionary wedge off western Java, however, of much smaller dimensions. The morphology of this forearc ridge south of the Lombok Basin is characterized by two trench-parallel elongated highs (Fig. 1), which run along the entire extent of the forearc ridge and are also developed across the easternmost high discussed by Masson et al. [41] between 114°E and 115°E (5 in Fig. 1). This high does not show a seaward scar, but judging from the continuous morphology to the east, we believe that this high is a prolongation of the outer forearc ridge south of the Lombok Basin and does not represent an underthrust seamount causing a re-entrant scar. In the opposite sense, Masson et al. (1991) also note that the indentation of the deformation front at 118°E does not have a correlative high further landward. This site however is the locus of the transition from oceanic subduction to continent–island arc collision [49]. The northward displacement of the trench here may possibly be associated with the North Wilson Fault Zone (Fig. 1) [37], which marks the boundary between the plates here.

4.3. Re-entrant morphology

The collision scars mapped along the deformation front furthermore commonly correlate with sediment accumulations of up to several hundred meters in thickness [17] in the otherwise sediment-devoid trench. These isolated sediment ponds are derived from local erosive processes associated with seamount collision [50,51,6,46]: as any given seamount is completely underthrust under the margin wedge, it is uplifted and shortened, the lower slope experiences oversteepening above the trailing flank of the seamount, inducing gravitational failure and mass-wasting of the margin toe (Fig. 3). In the example shown in Fig. 3, a submarine landslide has disassociated into a debris avalanche, which has slumped into the trench at 110°45′E/10°15′S. The sediment accumulation mapped in Fig. 3 occurs in a local deep within the trench that results from the exposure of deeper levels of the downthrusting plate in the wake of seamount subduction. Masson et al. [41] recorded areas of high backscatter within the collision scars, which are interpreted to be caused by outcropping strata arising from frontal erosion of the margin wedge due to seamount collision. The margin segment mapped during our recent survey (Fig. 3) displays a truncated lower slope, which is indented by the seamount re-entrant. It is sculpted by slumps and normal fault scarps similar to those shown by von Huene et al. [52] in Costa Rica, which developed after the seamount passed the deformation front. Re-entrant scars have been modelled by analogue experiments, which suggest that subducting seamounts of considerable relief will shift the interplate décollement to an elevated level tangential to the crest of the seamount into the trailing wedge of the upper plate [51]. Upper plate and trench material is transferred to the subducted plate behind the underthrusting seamount, which casts a low-stress shadow, allowing passive subduction of debris and sediment [6]. This process accelerates basal erosion in the vicinity of the trench and leads to extensional faulting along the lower and middle slope of the outer forearc high as seen in Fig. 3.

4.4. Lower plate tectonism

The outer rise region of the subducting plate south of the central and eastern Java Trench is fractured by abundant normal faults on the oceanic plate as mapped during the bathymetric survey (Fig. 3). Outer rise normal faulting has been mapped along a variety of subduction zones [39,53,54] and commonly arises from plate-bending induced tectonic stresses. This stress pattern is also reflected in the local seismicity: The outer rise is characterized by intense normal faulting earthquake activity [55]. The distance between the fault zones is only about 2–10 km; the faults display lengths of 5–20 km. However, fault lengths of up to 60 km are also frequently recognized [39,41]. The vertical throw along these faults in the vicinity of the trench reaches 100–500 m [56,57,17,14]. Profile P16 acquired during RV SONNE cruise SO179 records vertical offsets at the seafloor reaching more than 350 m south of the trench. This intense pattern of trench-parallel normal faulting increases oceanic plate seafloor roughness south of the Java Trench in addition to the morphological effects caused by the Roo Rise.
and seamount population. Charging of the upper oceanic crust with water is facilitated by the intense fracturing and normal faulting of the oceanic plate. Subduction of water may enhance basal erosion by hydrofracturing in the deeper parts of the forearc: Over-pressured water may be expelled into fractures along the base of the upper plate and disintegrate basal rock [7,10]. Outer rise normal faulting varies along strike of the margin. Whereas the lower plate south of the central and eastern Java Trench is characterized by abundant faulting, previous surveys along the central sector of the margin from western Java to southern Sumatra did not reveal comparable plate-bending induced tectonism [21,22,29,30,47] and thus these accretionary parts of the margin are not affected by an intense lower plate topography. In addition, the thicker sediment cover on the oceanic plate to the northwest will mask oceanic relief, whereas the oceanic crust south of central Java lacks any significant sedimentary coverage. Deep-penetrating reflection seismic data would be required to unravel whether erosion along the central Java margin results mainly from hydrofracturing (which would require a clastic interplate layer) or from the lack of trench sediment.

Fig. 4. Bathymetric tracks across the Java margin between 107° E and 118° E. The mean frontal slope presented here was calculated over a distance of 50 km from tracks taken every minute longitude and sampled at 0.01°. The tracks displayed run in a N–S direction and are representative for the geographical region indicated to the right of the track. The frontal slope between roughly 109° E and 115° E, where the Roo Rise is currently subducted underneath Java, is increased compared to the neighbouring regions, which is interpreted as an indication for subduction erosion.
Fig. 5. Global compilation of convergent margins modified from Clift and Vannucchi [9]. Erosive and accretive systems map in two different regimes when plotted against geological key parameters. The central Java margin clearly maps in the erosive regime, whereas western Java experiences accretion.
5. Key indicators for subduction erosion off central and eastern Java

5.1. Bathymetric slope and taper analysis

Tectonic erosion has been found to have the potential to steepen trench slopes (e.g. [58,59,9]). Steepening of the lower slope angle is also recognized along the Java margin (Fig. 4). The mean frontal bathymetric slope between 109°E and 115°E is gained from 60 bathymetry tracks trending orthogonal to the trench at an incremental distance of 0.1° longitude and sampled at 0.01°. We follow the approach of Clift and Vannucchi [9] and calculate the average slope angle over a distance of 50 km to eliminate small-scale anomalous trends. Some variation in slope angle occurs along the trench, such as the anomalously large angle of >13° at 110°E, reflecting the domal uplift of the forearc high by seamount subduction as displayed in Fig. 3, that causes slope failure on the leading flank of the seamount as manifested in a submarine landslide here. The mean forearc slope angle of 4.0°, however, reflects the overall trend of the inner trench slope. To the east and west of the central area affected by the Roo Rise subduction between 109°E and 115°E, forearc slopes decrease again (Fig. 4). The accretionary plate margins compiled by Clift and Vannucchi [9] exclusively display forearc slope angles smaller than 3° (Fig. 5). Their analysis of the Java margin is mainly based on data from the western Java segment and thus maps in the accretionary regime. Due to lack of seismic data in the area considered here, the exact dip of the oceanic plate underneath the forearc is unknown. The nearest modern seismic refraction profile crossing the forearc is found off western Java at 107°E [30] (Fig. 6). The oceanic plate is underthrust at an average dip of more than 6.5° underneath the accretionary complex here. Tomographic investigations indicate a general increase in plate dip from Sumatra to Java [60,61] and do not reveal any large-scale anomaly in plate dip due to the increased buoyancy of the Roo Rise, so we consider it reasonable to extrapolate this value to central Java. This then yields a forearc taper of 10.5°, which again is larger than for any of the accretionary margins documented by Clift and Vannucchi [9], but lies well within the range of values gained for erosive plate boundaries (Fig. 5).

5.2. Estimation of eroded volume

The geological framework of a subduction zone, namely the thickness and the properties of the subducting sediments, the convergence rate and the oceanic plate roughness, control whether accretion or subduction erosion will dominate, since these features guide the amount of material necessary for accretion and subsequent growth of a wedge or prism. Off central Java, these three factors clearly favour tectonic erosion over sediment accretion. While the minimal sediment supply (0 < trench fill < 1 km) and convergence rate (6.7 cm/yr) would also be sufficient for intermediate type processes, i.e. non-accretive subduction, the subduction of the severe oceanic basement relief causes active tectonic erosion of the forearc. This is best documented by the broad retreat of the Java Trench and deformation front in the projection of the Roo Rise (stippled white line in Fig. 1). Between 109°E and 115°E, over a distance of more than 600 km, the trench is deflected northward by 40 km on average from its normal curvature trend. Frontal erosion has exposed an area of approximately 25,000 km² of deeper seafloor where the trench has retreated northward. This area (between the white stippled line and the current trend of the deformation front tracked by the white dotted line in Fig. 1) correlates with the expanse of the active frontal accretionary prism as observed off western Java, implying that the entire frontal prism has been eroded by the

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**Fig. 6.** Structural models of the frontal accretionary prism off southern Sumatra (102°E/7°S), Sunda Strait (104°E/8°S) and western Java (107°E/9°S) developed from refraction seismic surveys and pre-stack depth migrated MCS-data (black line-drawing) along coincident profiles (modified from Kopp and Kukowski [22]). The frontal accretionary prism, underlain in grey, extends from the deformation front neighbouring the Sunda Trench to the active backstop composing the outer forearc high. Off central Java, the frontal prism has been eroded and the deformation front shifted northward by 40 km on average.
subduction of oceanic basement relief and the seamount population. From existing refraction and reflection seismic profiles [29,30] off southern Sumatra, off the Sunda Strait and off western Java (Fig. 6), the size of the frontal prism here, which extends about 40 km from the deformation front across strike of the margin, has been mapped. From the pixel information contained in the graphic display of these seismic lines, we calculate an average volume of eroded forearc per trench km of 160 km$^3$. To account for the decreasing sediment availability along the central to eastern Java margin segment, this value is adjusted and reduced by 25%. This yields a total estimated volume of 75,000 km$^3$ of eroded material (with an error of $\pm$ 30%) above the now exposed area of 25,000 km$^2$. Judging from the large-scale topographic features visible in the bathymetry map, seamount and oceanic basement relief subduction has completely eroded the frontal prism and has furthermore largely destroyed the previous outer forearc high as its ridge-like framework gave way to isolated topographic units arising from subducted basement relief.

As the onset of the Roo Rise subduction is unknown, it is impossible to provide rates of margin erosion; however, it may be expected that erosive processes due to ridge subduction are extremely effective as suggested by Clift and Vannucchi [9]. Without better seismic coverage of the region, it remains unclear what volume of the eroded material has been transported beyond the forearc to the landward, as suggested by Masson et al. [41], and to what extent the material has been transported beyond the forearc to the magmatic roots of the arc or back into the upper mantle. Subduction erosion is typically documented along convergent plate boundaries with negligible trench sediment input, such as the central to eastern Java margin. The impact of underthrusting oceanic basement relief, such as ridges and seamounts, will accelerate forearc truncation along these margins. With its large forearc slope and taper, the high convergence rate and low slope and taper, the high convergence rate and low trench sediment fill, the central Java margin clearly maps the erosive regime of global diagram compilations, reflecting the destructive influence of the Roo Rise on the margin.

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