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Lateral variation in slab orientation beneath Toba Caldera, northern Sumatra

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Abstract. The Investigator Fracture Zone (IFZ) subducts beneath Toba Caldera, the Earth's largest Quaternary caldera, in northern Sumatra, suggesting a possible relationship between them. Locations of sub-crustal earthquakes based on arrival times of P and S waves at a seismograph network surrounding Toba reveal the geometry of the subducted slab and the IFZ beneath Toba. A vertical tear of less than 20 km in the slab across the IFZ, as previously suggested, cannot be ruled out but the large-scale geometry of the slab is dominated by a broad bend of slab contours parallel to the concave-seaward indentation of the trench. The slab shape is probably a response to the trench curvature, can explain the change in trend of the volcanic arc near Toba, and may cause shallowing of the forearc basin near Nias Island. The decrease in radius of curvature of the slab contours is not accompanied by an observable decrease in dip angle, possibly resulting in lateral compressive stress in the slab. The high rate of seismicity along the subducted Investigator Fracture Zone, that intersects the slab obliquely to its plunge direction, is uncommon at subducted fracture zones and is likely caused by such lateral stress in the slab.

Introduction

The Sumatra volcanic arc coincides with the Sumatra fault throughout its length in central and southern Sumatra, both forming approximate small circles. In north Sumatra, however, the volcanic chain diverges northward from the trend of the Sumatra fault and appears to step toward the backarc region by a few tens of kilometers (Figure 1). Based on this apparent offset of the volcanic arc trend, *Page et al.* [1979] suggested that an E-side-down vertical tear exists in the subducted slab along the down-dip extension of the Investigator Fracture Zone (IFZ).

The IFZ is particularly interesting because it subducts below the south end of Toba caldera, the Earth's largest Quaternary caldera that formed at 0.075 Ma [*Chesner et al.*, 1991] when 2500-3000 km³ of material was erupted [*Rose and Chesner*, 1987]. Although a causal relationship between Toba and the tear has been suggested [*Page et al.*, 1979], evidence for a tear of significant offset in the slab has not been compelling. We investigate the slab geometry beneath Toba caldera using earthquake hypocenters based on local arrival time data from eight short-period, vertical component, digital, telemetered seismic stations operated by the Meteorological and Geophysical Agency of Indonesia. Hypocenters reveal that the slab beneath Toba changes strike from NNW south of Toba to more NW north of it. We suggest that this bend, which is concentric with a change in trench orientation, is the primary structure in the slab and that the high seismicity in the N-trending IFZ occurs because it cuts obliquely across the bend. The earthquake data may allow a vertical tear at the IFZ but of not more than 20 kilometers.

Earthquake Data

We manually picked arrival times of P and S waves from computer displays of digital seismograms of the telemetered network in northern Sumatra and from paper copies of regional analog seismic stations (Figures 1 and 2a) for October 1990 to April 1993. Estimated uncertainties in the arrival times at digital and analog stations, respectively, are 0.05 s and 0.5 s for P-waves, and 0.5 s and 1.0 s for S-waves. We use a one-dimensional velocity model (Figure 2b), slightly slower than a global average owing to the island arc setting, and a P/S wave speed ratio of 1.77, estimated from relative P and S times. The location program, HYPOINVERSE [*Klein*, 1978], uses the reading errors of the P-waves, S-waves, and specified uncertainties in the velocity model (assumed to be 0.5 s) to estimate formal uncertainties in hypocenters. Earthquake locations used to infer the slab geometry and shown in the figures are those with root-mean-square of arrival time

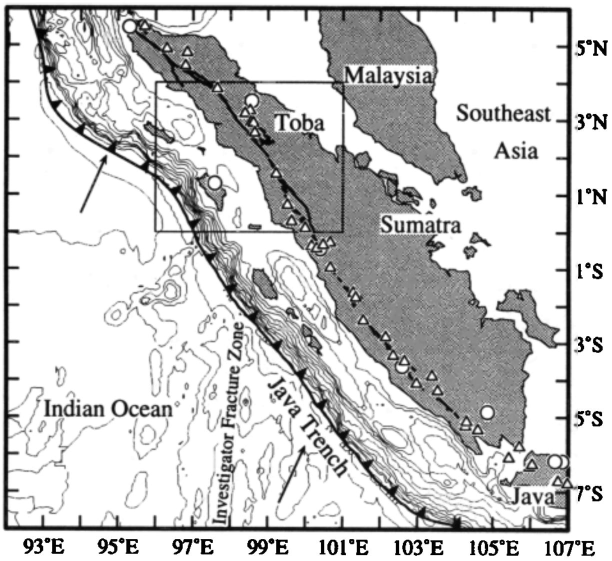

Figure 1. Map of bathymetric contours (500 m interval), volcanoes (triangles), and regional analog seismograph stations (circles). Sumatra fault is solid line parallel to west coast of Sumatra. Box shows area of Figure 2 (lake in Toba caldera is blackened). Arrows show motion of Australia relative to Eurasia [*DeMets et al.*, 1994].

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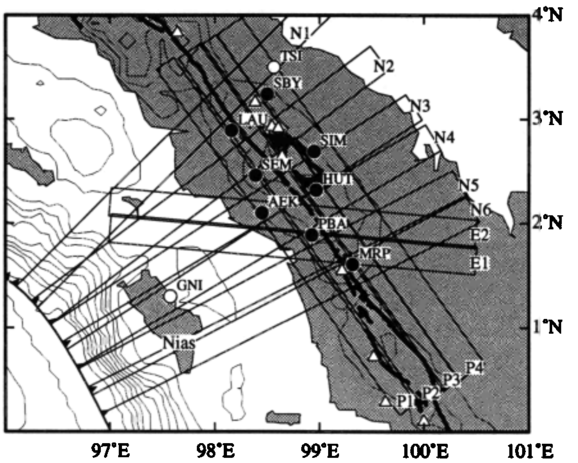

Figure 2a. Boxes show regions of cross sections of Figure 3 (as labeled). Dots show telemetered seismic stations, open circles show analog seismic stations, and triangles show volcanoes. Contours of topography are at 500 m intervals.

residuals less than 1.0 second, standard errors in the horizontal position and depth less than 20 km, total number of P and S first arrivals greater than 6, and at least one S arrival. Slab contours at 25 km intervals for depths of 75 to 200 km were estimated by making cross-sections of the hypocenters perpendicular to the trench, drawing and digitizing smooth envelopes above the earthquakes in cross-section, and contouring the slab surface.

We also plot teleseismically-located earthquakes from the ISC and USGS catalogs (1964-1993) with magnitudes greater than 4.5 that were recorded at 20 or more stations. The teleseismic hypocenter distribution generally agrees with the locally determined hypocenters in the cross-sections (Figure 3), except that teleseismic locations are deeper beneath the forearc in the offshore region. Relocated teleseismic earth-

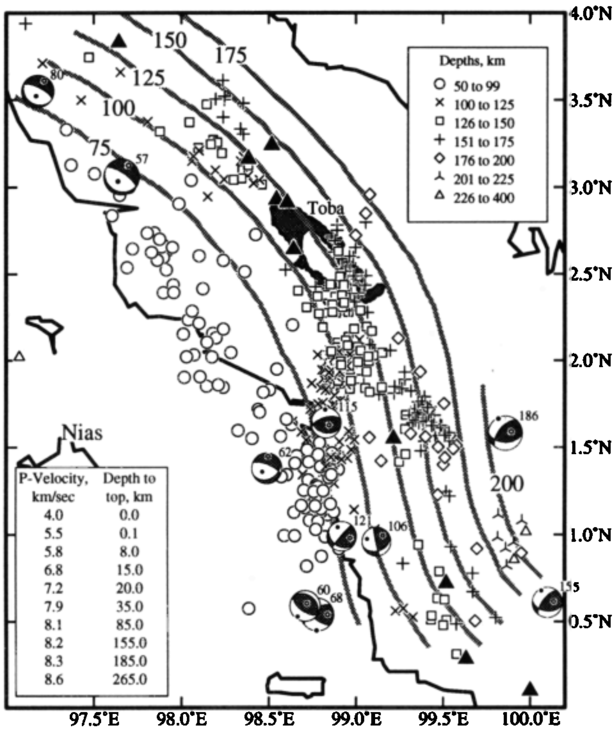

Figure 2b. Earthquake hypocenters (>50 km) located by local network. Harvard CMT fault plane solutions are labeled by depth in km. Shaded lines are slab contours, labeled in km, from local earthquake distribution. Triangles show volcanoes. Inset at top right shows symbols for hypocentral depths and at lower left is assumed P-wave velocity structure.

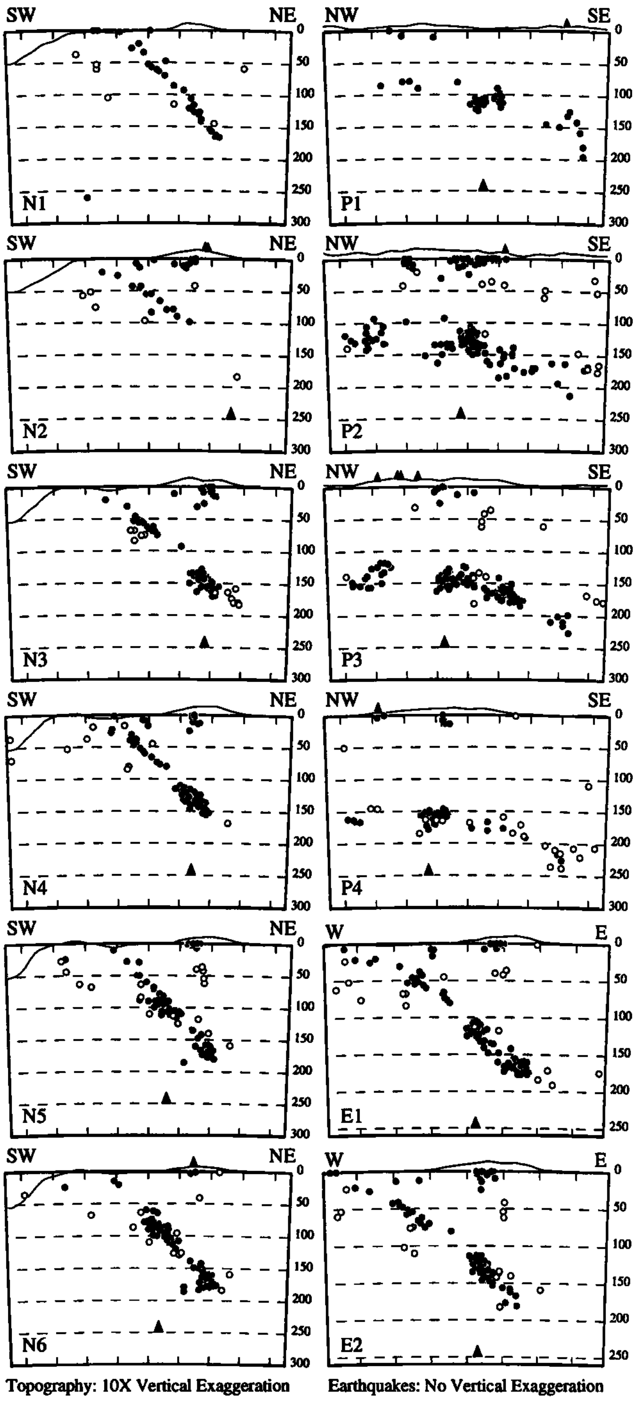

Figure 3. Cross-sections of local earthquakes in vertical planes. Profile locations are shown in Figure 2a. (No vertical exaggeration.) Solid dots are local hypocenters and open circles are teleseismic locations. Triangles at top are volcanoes and thin lines near top of each plot show topography with 10x vertical exaggeration. Triangles at 250 km depth show the horizontal position of the intersection of the IFZ with the profile.

quakes along the arc also display a suggestion of a change in the slab orientation near Toba [*Okal and Kirby*, 1993; *E. A. Okal*, personal communication, 1993].

Shape of the Slab

In cross-sections parallel to the trend of the trench and arc (P1 through P4; Figure 3), hypocenters reveal an apparent dip of the slab to the southeast, the nominal strike direction, which indicates a rotation of the slab strike out of the plane of the cross-section. Slab contours show the same general trend as the trench and volcanic arc, including a change in strike near Toba (Figure 2b). The distance from the trench to the point where the earthquakes reach 150-km depth is roughly the same in trench-normal profiles N1 through N6 (Figure 3) indicating that the contours follow the trench and that the average dip of the slab from the trench to 150 km depth is uniform through the change in strike.

The change in the radius of curvature without a change in the slab dip results in lateral stress in the plane of the slab (*Frank*, 1968). Beneath Toba the decrease in radius of curvature is not accompanied by a shallowing of the dip - hence compressive stress in the plane of the slab and parallel to depth contours may be greater here than in subducted lithosphere outside the bend. We suggest that this stress is exhibited by CMT mechanisms in Figure 2b (labeled 115, 186, and 155) that have P axes parallel to local slab contours. The slab does not change dip in response to the change in the trench strike possibly because slab pull forces overcome the lateral buckling force that would otherwise cause a shallower dip angle.

The bend in the slab contours can explain the change in the trace of the volcanic arc, because the arc everywhere follows the 125-km depth contour of the slab (Figure 2b). Elsewhere in Sumatra, the trace of the volcanic arc corresponds with - and indeed, most likely controls - the position of the Sumatra fault (Figure 1). In contrast, where the slab contours turn near Toba, the fault maintains a straight path and no longer follows the arc trend. The Sumatra fault maintains its trend along a small circle path instead of bending sharply to the north to follow the zone of crustal weakness produced by the arc magmas because a deviation from the small circle path would result in distributed deformation off the fault.

The change in slab geometry beneath Toba may be similar to the change in the strike of the subducted Juan de Fuca plate beneath NW Washington State following a similar change in the trench strike. From slab hypocenters, *Crosson and Owens* [1987] and *Weaver and Baker* [1988] suggest that the dip of the plate beneath Washington is less than beneath Oregon and southern British Columbia, where slab seismicity is sparse. The change in dip correlates with and may control the uplifted forearc at the Olympic Peninsula [*Brandon and Calderwood*, 1990]. In contrast, from the slab geometry beneath Oregon based on receiver function analysis, *Nabelek and Li* [1996] argue for simply a change in strike without a significant change in dip. In Sumatra the slab contours are constrained better than in Pacific Northwest and do not show a change in dip along strike. Nevertheless, the forearc basin southwest of Toba is much shallower than it is to the NW and SE (Figure 1) and free-air gravity over the forearc region is also relatively high (Figure 4) suggesting that the forearc high is isostatically under-compensated, as would result if the slab pushed up on it. We speculate that the elevated forearc may indicate that the shallow part of the slab beneath the forearc offshore is bowed up even though the deeper part beneath the volcanic arc is not.

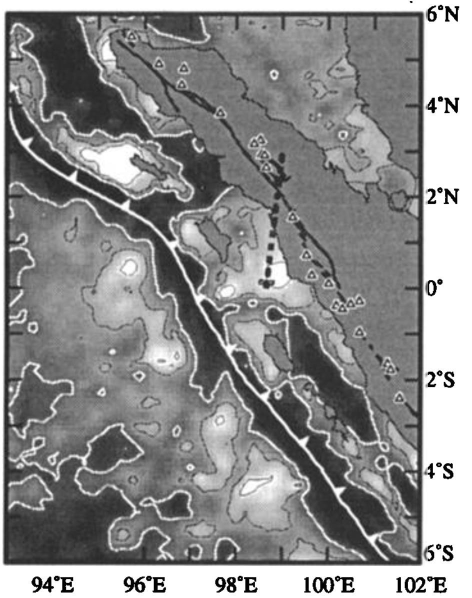

Figure 4. Free-air marine gravity contoured at 25 mGal intervals [*Sandwell and Smith*, 1994]. Lighter shading used for more positive values. White contour is zero. Dashed line shows trace of IFZ seismicity. On Sumatra, darkened region is Toba caldera, solid line is the Sumatra fault, and triangles are volcanoes.

Seismicity and a Tear at the IFZ

In the locally determined hypocenters, a band of earthquakes extends from 100 km depth near 1°N, 98.7°E in the south to greater than 150 km depth north of Toba caldera (Figure 2b). South of and on trend with this seismicity, the Investigator Fracture Zone (IFZ) intersects the Java trench (Figure 1). We infer that the seismicity largely occurs within the subducted IFZ. Hypocenters projected onto vertical planes perpendicular to the IFZ do not clearly reveal a tear (E1 and E2; Figure 3). Any vertical offset across the IFZ, if present, is smaller than a few tens of kilometers. The deepening of the seismicity to the SE across the fracture zone is part of the broad bend in the strike of the slab over a distance of a few hundred km.

More than 80% of P-wave first motions (not shown) from earthquakes in 100 to 200 km depth range along the IFZ are consistent with both a vertical fault plane that strikes parallel to the trend of hypocenters and an east-side-down sense of slip. Two Harvard CMT solutions (near 1°N at 106 and 121 km depths; Figure 2b) and composite focal mechanism solutions from a local earthquake network [*Kieckhefer*, 1980] for intermediate depth earthquakes reveal one near-vertical nodal plane along strike of the IFZ with the east side down.

In contrast to the subducted Amlia fracture zone in the Aleutian arc [*House and Jacob*, 1983] and the subducted D'Entrecasteaux fracture in New Hebrides [*Marthelot et al.*, 1985] where little seismicity occurs, we find high seismicity along the subducted IFZ. Some property of subduction beneath Sumatra that is different from the regions cited above may activate the fracture zone. The obliquity of plate convergence can result in arc-parallel right-lateral shear stress on the top of the slab and increase the vertical shear stress on the IFZ. However, this vertical shear should have an east-side-up sense, opposite to that indicated by seismicity. Also, the IFZ and D'Entrecasteaux trends are much closer to their relative plate convergence vectors (differences of less than 15°) than is the trend of the Amlia fracture zone (difference of 50°). Hence, we feel that the convergence obliquity is not a major factor in activating the subducted IFZ.

The density contrast due to age differences across the IFZ may also cause vertical shear stress on the IFZ. Several kilometers south of the intersection of Java trench and IFZ and west of the IFZ is a 46 Ma age extinct spreading center that has been subducted on the east side [*Royer and Sandwell*, 1989]. The difference in age across the IFZ is less than 10 Ma where magnetic anomalies are observed. The length of the subducted fracture zone from the trench to 180 km depth is about 670 km and we estimate that the age of the plate at 180 km depth is 68 Ma west of the IFZ and 62 Ma east of it. Assuming that oceanic lithosphere increases its average density from 3000 kg/m^3 to 3300 kg/m^3 in 100 Ma at a square-root-of-age rate, the density difference from 62 to 68 Ma is 11 kg/m^3, or 0.3%. This is probably too small to be responsible for the difference in depth between the eastern and western parts of the IFZ.

Our preferred interpretation for the high seismicity of the IFZ is that the IFZ, which trends north, obliquely intersects the southeastern limb of the bend in the slab where it is under lateral compression. Unresolved is whether or not the spatial correspondence of the IFZ with Toba, the site of the world's largest Quaternary eruption, indicates a genetic relation between the two. One possibility is that the IFZ, perhaps being more altered (hydrated) than normal oceanic crust and now more exposed due to post-subduction faulting, serves as a site of focused volatile release into the overlying mantle wedge. Finally, while the offset of the slab at the IFZ may be small, this offset and the topography of the IFZ beneath the forearc may limit the lateral rupture of great earthquakes along the subduction interface [*Newcomb and McCann*, 1987].

Conclusions

Thirty months of local earthquake data reveal the shape of the slab beneath Toba caldera. A change in slab geometry coincides with the apparent offset of the volcanic arc in the vicinity of Toba. However, we are not able to distinguish unequivocally whether there is a tear beneath Toba caldera. We suggest that the slab is broadly bent beneath the Toba section of the arc producing a change in strike that parallels the change in strike of the trench. Anomalously high seismicity along the subducted Investigator Fracture Zone is suggested to result from the intersection of the IFZ with the bend in the slab, where it is under compressive stress.

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