Evaluating slab-plate coupling in the Indo-Australian plate

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ABSTRACT

Distributed seismicity in the central Indian Ocean affords a unique opportunity to evaluate the extent of slab-plate coupling in the Indo-Australian plate. The mix of reverse-fault and strike-slip mechanisms in this region, with northwest-southeast to north-south maximum horizontal stress, S_{Hmax}, implies that the effective slab pull is no more than ~10% of the total negative buoyancy operating on the subducting slab. Numerical models of the intraplate stress field predict a slab-pull component along the Sumatra and Java boundary segments of 2.82 ± 0.82 and 0.89 ± 0.35 × 10^{12} N·m^{-1}, respectively. Mantle tomographic constraints coupled with insights from analogue modeling suggest that the differences relate to variations in the depth extent of the slabs and the degree of slab support provided by the transition zone. These results help resolve apparent contradictions between insights from intraplate stress fields and plate dynamics; i.e., although plate motion is dominated by subduction, slab pull is only poorly expressed in the intraplate stress field because of low slab-plate coupling.

Keywords: subduction, plate tectonics, stress, Indo-Australian plate, slabs.

INTRODUCTION

Subduction plays a key role in plate tectonics, localizing the return flow of old oceanic lithosphere to Earth's convective interior and thereby controlling the velocity field of most of Earth's major plates (Lithgow-Bertelloni and Richards, 1998). The negative buoyancy within old subducting slabs provides the principal source of energy driving plate motion. Compared to other shallow density anomalies, such as those produced by cooling of the ocean lithosphere (~2–3 × 10^{12} N·m^{-1}), the negative buoyancy of subducting slabs (typically a few times 10^{13} N·m^{-1}) is the dominant shallow source of stress (e.g., Turcotte and Schubert, 1982).

Since the classic study of Forsyth and Uyeda (1975), the correlation between plate motion and net driving torques applied to plates has been debated (Coblentz et al., 1994; Lithgow-Bertelloni and Richards, 1998); there is uncertainty about how the forces that drive plate motion and those that maintain plate-scale torque balance act together to produce the various manifestations of the plate dynamics such as the intraplate stress field (e.g., Coblentz et al., 1994; Lithgow-Bertelloni and Guynn, 2004). Of persistent concern has been the degree of coupling between subducting slabs and their trailing plates. For example, Richardson (1992) and Coblentz et al. (1994) argued that the intraplate stress field is largely explicable in terms of a balance between lithospheric potential-energy distribution (including the so-called ridge-push force) and plate-boundary resistance, implying that a relatively low degree of slab-plate coupling in plates is the norm. This is supported by recent analogue modeling studies (Schellart, 2004a, 2004b) scaled to simulate oceanic lithosphere subduction. These models show that as much as ~10% of the negative buoyancy force of the slab is transmitted to the trailing plate, with the majority of the energy release from subduction dissipated by exciting mantle flow (~70%) and bending the plate at the trench (~15%–30%). In contrast, Lithgow-Bertelloni and Guynn (2004) found a relatively weak correlation between lithospheric sources of stress and observed stress indicators, but a better correlation when lithospheric sources are augmented with tractions imparted by a mantle flow consistent with the Cenozoic history of subduction. By comparing predicted and observed plate motions, Conrad et al. (2004) argued that the degree of slab-plate coupling varies from almost completely coupled slab-plate systems to systems with virtually no coupling. Conrad et al.'s (2004) highly coupled systems include the Java-Sumatra slabs on the Indo-Australian plate. In strongly coupled systems, the slab-pull force should be strongly expressed in the trailing plate, whereas in weakly coupled systems, the density defect of the subducting slab is dissipated through exciting flow in the adjacent mantle that drives plate motion through basal tractions.

The extent of slab-plate coupling has proved difficult to establish, in part because the general paucity of intraplate oceanic earthquakes means that the intraplate stress field is poorly resolved in plates with significant length of subducting slab. The Indo-Australian plate provides an exception to this rule. The earthquakes in the central Indian Ocean (e.g., Bull and Scrutton, 1990; Fig. 1) provide unequivocal constraints on the nature of the in situ stress regime in the oceanic realm of the Indo-Australian plate. The deformation of the central Indian Ocean testifies to the unusually high stress levels associated with the progressive fragmentation of the plate (e.g., Gordon, 2000) in response to forces arising mainly along the plate boundaries, including the subduction zones along its northern boundary with Southeast Asia. In this paper numerical methods are used together with inferences on the in situ intraplate stress field in the central Indian Ocean to constrain the magnitude of stress transmitted from the Java and Sumatra slabs. Insights into the inferred variation in the degree of slab-plate coupling between these slabs are provided by independent mantle tomographic and analogue modeling studies.

DEFORMATION AND GEODYNAMIC SETTING OF THE CENTRAL INDIAN OCEAN

The distributed seismicity in the central Indian Ocean (Fig. 1A) is unique, inasmuch as this is the only part of the old ocean lithosphere accumulating strain at an appreciable rate, and suggests that the Indo-Australian plate is in the process of fragmenting into separate Indian, Australian, and Capricorn plates (e.g., Gordon, 2000). The Indian Ocean earthquakes yield both reverse-fault and strike-slip focal mechanisms (Fig. 1B) with a well-defined maximum horizontal stress, S_{Hmax}, trending northwest-southeast to north-south, approximately orthogonal to the plate motion vector and parallel to the oceanic trenches (e.g., Sumatra) and associated subduction complexes that separate the northeastern Indian Ocean from the Indonesian archipelago. The active seismicity can be related to ongoing deformation of the ocean lithosphere most evident in the characteristic long-wavelength gravity anomalies of this region (e.g., Bull and Scrutton, 1990). These gravity anomalies reflect lithospheric-scale buckling with characteristic wavelengths of several hundred kilometers and amplitudes of several kilometers (Bull and Scrutton, 1990; Martinod and Molnar, 1995; Gerbault, 2000; Krishna et al., 2001). Several general insights relevant to our discussion of the nature of the intraplate stress field are provided by the earthquake mechanisms and associated lithospheric deformation of the central Indian Ocean.

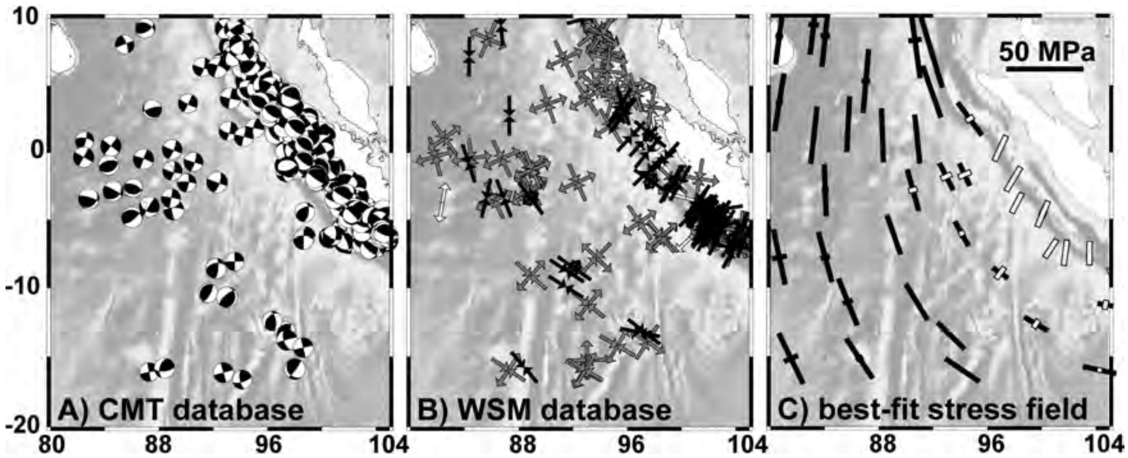

Figure 1. Distribution of (A) seismicity (CMT—Centroid Moment Tensor), (B) inferred intraplate stress (WSM—World Stress Map), and (C) best-fit predicted stress field for central Indian Ocean. Focal mechanisms are from CMT database. Intraplate stress indicators are from World Stress Map database (Reinecker et al., 2003) and include quality A and B earthquake indicators only. Symbols in B: black—reverse-fault stress regime indicators; gray—strike-slip stress regime indicators; and white—normal stress regime indicators.

Stress Magnitudes

The seismicity testifies to unusually high stress magnitudes, constraints on which can be gleaned from analysis of the associated buckling phenomenon (e.g., Martinod and Molnar, 1995). While thin elastic plate theory suggests stress levels on the order of 1 GPa, Martinod and Molnar (1995) showed that with a yield criterion appropriate to lithospheric plasticity, buckling instabilities in the central Indian Ocean may require horizontal compressional stresses (S_{Hmax}) as low as ~44 ± 12 MPa (averaged over a 100-km-thick zone), comparable with those predicted by plate-scale stress models (see following).

Qualitative Expression of Slab Pull

The seismically active region provides a qualitative constraint into coupling between subducted lithosphere and the trailing plate. The expected expression of slab pull is northeast-directed tension. The occurrence of both strike-slip and reverse-fault mechanisms indicates that the stress regime is on the cusp of reverse- and strike-slip regimes with minimum horizontal stress approximately equal to vertical stress ($S_{\mathrm{Hmin}} \approx S_{\mathrm{v}}$). As such, implying that the effective slab pull in this part of the Indo-Australian plate is comparable to other sources of stress acting on the intraplate stress field.

Temporal Evolution of the Stress Field

The central Indian Ocean deformation apparently began in the late Miocene ca. 8–10 Ma, on the basis of stratal onlap sequences imaged with seismic reflection profiling (e.g., Krishna et al., 2001). As such, it is just one of a number of indications of an apparent increase in Indo-Australian plate stress levels in the late Neogene (see also Sandiford, 2003), reflecting the general increase in plate-boundary resistance provided by the developing collisions between the Indo-Australian plate and the Eurasian and Pacific plates (e.g., Molnar et al., 1993; Sandiford et al., 1995, 2004).

Plate-scale modeling studies have shown that the dominant northwest-southeast to north-south S_{Hmax} orientation observed in the central Indian Ocean reflects a balance between the plate-driving forces (subduction, asymmetric distribution of gravitational potential energy associated with aging ocean lithosphere, tractions at the base of the plate) and resistance provided primarily by the Himalayan and Papua–New Guinea orogenic systems (e.g., Cloetingh and Wortel, 1986; Coblentz et al., 1995, 1998; Reynolds et al., 2002; Lithgow-Bertelloni and Guynn, 2004). In the most recent incarnation of this modeling, Reynolds et al. (2002) used a set of boundary forces that best fit the S_{Hmax} orientation data across the whole plate. The Reynolds et al. (2002) solution yields a local maximum in S_{Hmax} in the central Indian Ocean where the predicted stress levels (>30 MPa averaged over a 100-km-thick lithosphere) are comparable to Martinod and Molnar's (1995) estimate for initiation of buckling instability.

NUMERICAL MODELING

To evaluate the sensitivity of the predicted intraplate stress field in the Indo-Australian plate to the magnitude of the boundary forces acting along the Java Trench, we have used the basis-function approach (Reynolds et al., 2002) to compute variation in the goodness of fit between the calculated and observed stresses. This approach works by exploiting the linearity of the purely elastic model used in the analysis. For each force acting on the plate the balancing basal drag is computed and a "basis-response" stress field is computed. These results form a basis function for computing the predicted stress field. The most important feature of this approach is that for any combination of forces acting on the plate the predicted stress field is simply a linear combination of basis function stress fields, providing a way to explore the character of the solution space in the vicinity of a best-fitting model in a forward sense. Our modeling approach is subject to two important qualifications. First, tractions along the base of the plate are treated implicitly. The basal tractions are determined by balancing the plate-scale torque subject to all other imposed plate boundary loads. While the basal tractions are therefore an important component of our best-fit model, one limitation is that we consider only the plate averaged basal traction, and do not allow spatial variations as might apply to complex flow patterns in the mantle. Second, our treatment of the lithosphere as an elastic plate is a simplification, since our information about the stress state in the central Indian Ocean derives from active deformation. The resulting solutions we derive are therefore only as robust as the elastic approximation. Such an approximation is most likely to be valid if the deforming region shows strong stress coupling; a notion supported by the continuity in the S_{Hmax} azimuths deduced from focal mechanism solutions across the zone of deformation in the central Indian Ocean (Fig. 1B).

Starting with the best-fitting model of Reynolds et al. (2002), the magnitude of the boundary forces acting along the Java Trench was varied from -9×10^{12} N·m^{-1} (here a negative force is directed outward from the center of the plate, i.e., a "pull") to $+9 \times 10^{12}$ N·m^{-1} (push on the plate), with a resolution of 0.1×10^{12} N·m^{-1}. Here we have used a misfit measure that is the average difference for two quantities (the stress regime and S_{Hmax} orientation) between the observed and predicted stress field in the central Indian Ocean where the former is determined by 52 intraplate stress indicators from the World Stress Map Database (Reinecker et al., 2003)

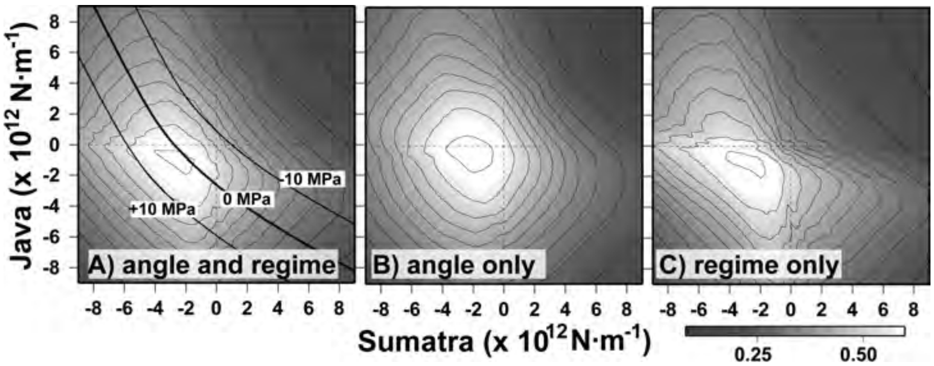

Figure 2. Estimates of goodness-of-fit of computed stress (S) field with observed stress field, for stress indicators in central Indian Ocean where stress state is on cusp between strike-slip and reverse-fault mechanisms (i.e., $S_{Hmin} \approx S_V$). Variables are forces applied along Sumatra and Java segments of Java Trench (positive for push inward on plate, negative for pull outward on plate). A: Goodness-of-fit criterion incorporating both orientation (angle) of S_{Hmax} and stress-state regime data. Best-fit solution constrains effective pull from Sumatra and Java slabs of 2.82 ± 0.82 and 0.89 ± 0.35 × 10^{12} N·m^{-1}, respectively. Contours show average S_{Hmin} values for region of central Indian Ocean encompassing stress indicators shown in Figure 1B (S_{Hmin}—minimum horizontal stress, S_{Hmax}—maximum horizontal stress, S_V—vertical stress). B: Goodness-of-fit criterion for orientation (angle) data only. C: Goodness-of-fit criterion for regime data only. Scale bar shows computed goodness-of-fit measure.

bounded by the geographic coordinates (75°E, 10°N), (112°E, 10°N), (112°E, 25°S), and (75°E, 25°S) and the latter are the stresses computed using a two-dimensional elastic finite-element analysis of the intraplate stress field (see discussion in Reynolds et al., 2002).

Figure 2A shows the goodness-of-fit as a function of the boundary forces acting along the Java Trench, using a measure that combines both orientation and regime data. Figure 2 shows a high degree of coherence between the best-fit using the combined measure and measures of best-fit using only orientation data (Fig. 2B) and regime data (Fig. 2C). Our best-fitting force magnitudes acting along the Sumatra and Java boundary segments are -2.82 ± 0.82 and $-0.89 \pm 0.35 \times 10^{12}$ N·m^{-1}, respectively, with the forces pulling on the plate. Figure 1C shows the predicted stress field for the region south of the Java Trench using (1) our best-fit forces for the Java Trench and (2) the Reynolds et al. (2002) best-fit boundary forces for all other boundary segments. Predicted S_{Hmax} magnitudes averaged over a 100-km-thick lithosphere average ~40 MPa for the region of active Central Indian Ocean deformation. The required balancing basal traction exerts a torque of $\sim 7.9 \times 10^{25}$ N·m about a pole located at 15°S, 169°W, implying that mantle flow acts as a mechanism that at the plate scale resists Indo-Australian plate motion.

VARIATION IN SLAB-PLATE COUPLING

In this section we use insights from independent analogue modeling studies to interpret the variation in the slab-plate coupling inferred for the Java and Sumatra slabs. Using analogue models scaled to simulate oceanic lithosphere, Schellart (2004a, 2004b) derived quantitative constraints on the relative magnitude of the net slab-pull force (F_{NSP}) and the negative buoyancy force of the slab (F_B) during progressive subduction. The results of five experiments are reproduced in Figure 3 showing the development of the F_{NSP}/F_B ratio with progressive subduction. In three experiments (models 8, 9, and 10) the trailing edge of the subducting plate is fixed while in the other two (models 11 and 12) the trailing edge is free, thereby simulating the full range of possibilities likely to be encountered in Earth. Furthermore, some of the physical parameters for the slab differ for the individual experiments, including slab width and slab thickness (for details, see Schellart, 2004a). Irrespective of the different physical parameters and boundary conditions, the experiments show a progressive increase of F_{NSP}/F_B to a maximum of 0.08–0.12 for a slab length equivalent to ~500 km. Most of the energy released from the subduction of the negatively buoyant slab is utilized in stimulating mantle flow (~70%) and bending the slab (~15%–30%). With further subduction, F_{NSP}/F_B decreases due to interaction of the slab tip with the lower model boundary (simulating the upper-lower mantle transition zone).

The results summarized in Figure 3 can be applied directly to the Indonesian subduction system to quantify the net slab-pull force along the Sumatra and Java segments. The total negative buoyancy force per meter trench length of the slab can be calculated by multiplying the density contrast between slab and ambient mantle ($\Delta\rho$), the gravitational acceleration, the slab length (L) and the slab thickness (T). The slab age at Sumatra is Late Cretaceous–Eocene and at Java it is Cretaceous. For such slabs, $\Delta\rho \approx 40$–80 kg/m^3 (Cloos, 1993) and $T \approx 100$ km. The slab length is constrained by the mantle tomography published in Replumaz et al. (2004), whose data show that the Sumatra slab is 600–700 km long (i.e., partly interacting with the transition zone). Using the results in Figure 3, with $L = 600$ km, then F_{ESP}/F_B is about 0.10 (F_{ESP} is effective slab-pull force), and F_{NSP} per meter trench length is ~ 2.4–4.7×10^{12} N·m^{-1}. With $L = 700$ km, $F_{ESP}/F_B \approx 0.05$, and F_{NSP} per meter trench length is ~ 1.4–2.7×10^{12} N·m^{-1}. The same tomographic data show that the Java slab continues significantly further into the transition zone to depths >700 km, where it shallows significantly. Such a scenario suggests that the slab is being supported in large part by the lower mantle. With reference to the results in Figure 3, taking $L = 750$ km for the upper mantle slab length, then we estimate $F_{NSP}/F_B \approx 0.02$, and thus F_{NSP} per meter trench length is ~ 0.6–$1.2 \times$

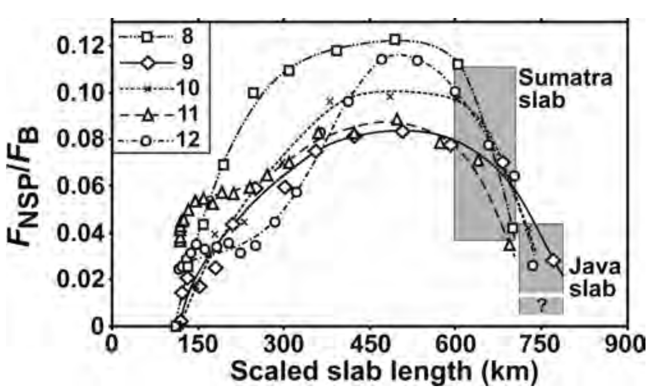

Figure 3. Diagram illustrating magnitude of net slab-pull force to buoyancy force ratio (F_{NSP}/F_B) versus slab length for five of Schellart's (2004a) analogue experiments with different subduction conditions. Curves illustrate that for wide range of model conditions F_{NSP} reaches maximum value equal to 8%–12% of F_B in advanced stage of subduction (equivalent to slab length of ~500 km). With further subduction F_{NSP}/F_B ratio decreases due to interaction of slab tip with lower boundary of model simulating upper-lower mantle transition zone. Boxes show estimated upper mantle slab length of Java and Sumatra slabs as deduced from mantle tomography (Replumaz et al., 2004), consistent with lower degree of slab-plate coupling that we infer for Java slab on basis of our analysis of stress field data (Fig. 2A).

10^{12} N·m^{-1}. The F_{NSP} values calculated here for Sumatra and Java are very similar to the numerical results for Sumatra ($\sim$2.8 $\times$ 10^{12} N·m^{-1}) and Java ($\sim$0.9 $\times$ 10^{12} N·m^{-1}), and suggest that the variation in slab-plate coupling between the Sumatra and Java slabs inferred from analysis of the intraplate stress field relates to the degree of interaction with the transition zone.

DISCUSSION

The occurrence of widespread distributed seismicity in the Central Indian Ocean affords a unique opportunity to evaluate the influence of subducting slabs on the intraplate stress field. The occurrence of reverse-fault mechanisms, along with strike-slip mechanisms, indicates that the tension exerted by the slabs along the northern margin of the Indo-Australian plate is on the same order as other sources of stress related to internal variations of density within the plate and continental collisions. As such the effective slab pull transmitted to the trailing plate is required to be about one order of magnitude lower than the total negative buoyancy of the slab, implying a rather weak slab-plate coupling in the sense of Conrad et al. (2004). Both the numerical analysis of the intraplate stress field described here and the results of independent analogue models (Schellart, 2004a) provide a consistent insight supporting the notion that no more than $\sim$10% of the negative buoyancy force of the slab is transmitted to the trailing part of the plate during subduction of the Indian Ocean lithosphere beneath Indonesia. The analogue models provide the possibility of further insight into the energy balance in the subduction process, with the observed variation in the degree of slab-plate coupling between the Sumatra and Java slabs reflecting the greater interaction of the Java slab with the mantle transition zone, as implied by available tomographic data (e.g., Replumaz et al., 2004). Our analysis provides an additional insight into the magnitude of stresses responsible for the active deformation in the central Indian Ocean (e.g., Martinod and Molnar, 1995; Gerbault, 2000). As the most active zone of diffuse deformation in the oceanic realm, this region has long attracted attention; the long-wavelength ($\sim$200 km) undulations in topography and gravity are now generally regarded as manifestations of lithospheric-scale folding. The magnitudes of stress responsible for this deformation have been controversial (see Gerbault, 2000). Our best-fit model solution shows S_{Hmax} values of $\sim$40 MPa averaged over a 100-km-thick lithosphere for the actively deforming region in the central Indian Ocean (Fig. 1C). Given that the thickness of the stress guide controlling such buckling is $\sim$20%–25% of the buckling wavelength, then our predicted maximum stress magnitudes associated with buckling equate to $\sim$100 MPa.

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