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Tonga slab deformation: The influence of a lower mantle upwelling on a slab in a young subduction zone

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Abstract. There are fundamental geographic variations in the deformation of slabs in the transition zone. The seismic energy release and morphology of the Tonga slab show that it is deforming faster and has accumulated more deformation than any other slab. We show that Tonga overlies the edge of the large-scale Pacific superplume. There is no substantial aseismic penetration into the lower mantle beneath Tonga, consistent with initiation of subduction during the Eocene. Other major subduction systems overlay seismically fast structures. For long-lived subduction systems, the lower mantle tends to pull down on slabs while in Tonga the lower mantle pushes upward, partially accounting for the intense deformation. The perturbation to the state of slab stress due to large-scale mantle flow is 10 to 40 MPa – nearly as large as that expected from slab pull.

Introduction

Seismic energy release, on average, has a pronounced peak within the transition zone (410 to 660 km depth) [*Abe and Kanamori*, 1979]. Transition zone seismicity shows strong geographic variability (Fig. 1A). A few subduction zones, particularly the Tonga-Kermadec, have intense seismicity within the transition zone while most subduction zones have little or none [*Isacks and Molnar*, 1971; *Vassiliou*, 1983]. The number of transition zone earthquakes associated with the Tonga slab is an order of magnitude larger than that within any other subduction zone (Fig. 1B). Especially within the transition zone, the three-dimensional morphology of Tonga–Kermadec is more complex than all other slabs [*Chiu et al.*, 1991; *Giardini and Woodhouse*, 1984]. Since the length scale of the deformed portion of slab is > 100 km and if the slab is descending at < 10 cm/yr, then the total time required to accumulate the deformation must have lasted for > 1 Myr. Consequently, the present day deformation rate (seismic activity) is not an ephemeral, short time-scale process.

The causes of such fundamental geographical variations in transition zone deformation have received little attention. The increase in seismicity with depth and stress orientation from focal mechanisms [*Isacks and Molnar*, 1971], have been interpreted in terms of slabs encountering: An impenetrable chemical boundary [*Richter*, 1979], a jump in effective viscosity [*Vassiliou et al.*, 1984], or a force associated with the spinel to perovskite phase transition [e.g. *Christensen and Yuen*, 1984]. While there are few doubts that a combination of these effects could be important, it is reasonable to suppose that large-scale mantle density structure has an important influence on the state of stress within slabs and that it plays a role in modulating the geographic variability in transition zone seismicity and slab deformation. Now that seismic constraints on mantle structure have improved, it is time to reevaluate the controls on slab deformation.

Large-scale mantle structure There are large-scale variations in seismic velocity and density in the mantle. Recent tomographic inversions show high seismic velocity structures at the core mantle boundary (CMB) attached to present day subduction beneath Central America and Japan [*Grand*, 1997; *van der Hilst et al.*, 1997; *van Heijst et al.*, 1999]. This is particularly obvious in a cross section through central Honshu (Fig. 2A) showing the subducting Pacific oceanic plate as a high velocity upper mantle slab which in turn is connected with fast structures down to the CMB.

Not all Benioff zones are attached to high shear-velocity structures in the lower mantle. Two cross sections through Tonga-Kermadec (Fig. 2A, B) show that high shear velocities do not extend into the lower mantle below the transition zone. Resolution kernels for seismic model S20RTS show that the difference between the transition zone and the top 500 km of the lower mantle, and hence the absence of slab penetration through the 660 km discontinuity, is resolved (Fig. 3). The high seismic velocities just below 660 km discontinuity (Fig. 2) are likely an artifact of the inversion procedure and are probably not indicative of penetration into the lower mantle (Fig. 3). The contrast between Tonga–Kermadec and both Japan (Fig. 2A) and South America (Fig. 2B) is striking. Tonga–Kermadec has a transition zone structure dominated by high shear velocities immediately atop a large-scale, low velocity anomaly in the lower mantle. Within both the Japan and South America subduction zones, high shear velocity structures in the transition zone continue into the deep mantle.

Geologic history of the Tonga system The morphology of the Tonga-Kermadec subduction zone and associated lower mantle (Fig. 2) suggests that subduction has not been operating for extended periods of geological time. Subduction within the Tonga-Kermadec system initiated only during Eocene times [*Gaina*, 1998; *Gaina et al.*,

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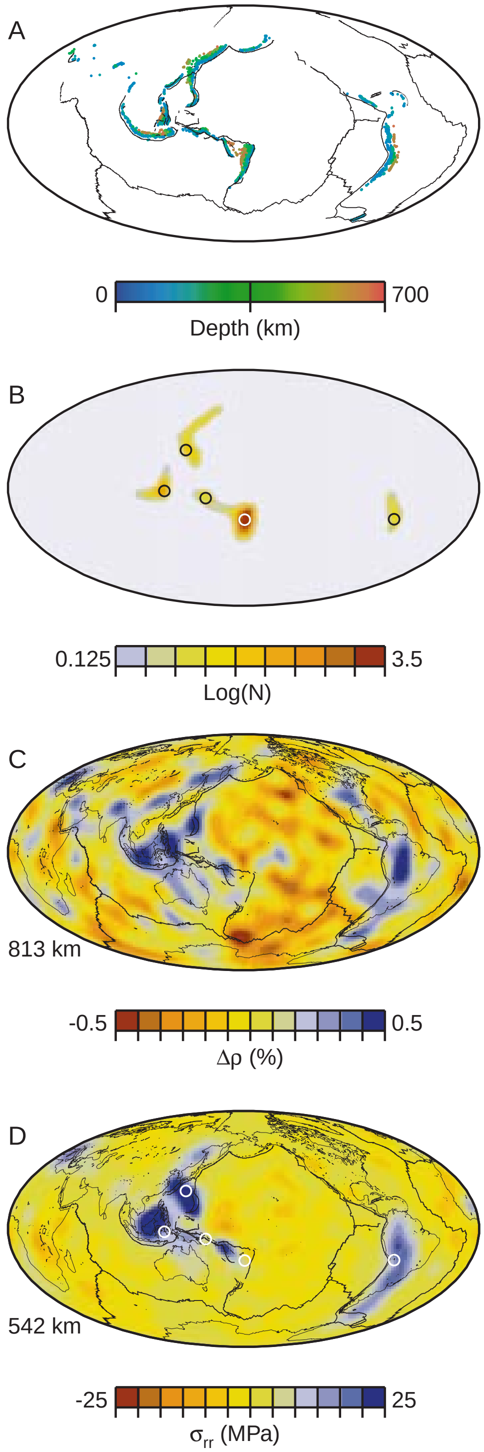

Figure 1. A. Earthquake locations with magnitude >5 and deeper than 100 km, color coded according to depth using the relocated hypocenters of *Engdahl et al.* [1998]. B. Only those events between 400 and 700 km depth color coded according of number of events per $10^{\circ}\times10^{\circ}$region. C. Density at 813 km by scaling S20RTS by $\partial\rho/\partial v_s = 200$ kg m^{-3}/km s^{-1}. D. σ_{rr} (positive values tensional) in the middle of the transition zone derived from a global flow model with density is given in C. Viscosity increases by 50× from surface to lower mantle and is temperature-dependent (see *Gurnis et al.* [1999]).

2000] in contrast to the much longer periods of subduction ($\sim$ 200 Myr) beneath Japan and the Americas [*Engebretson et al.*, 1992].

Although the Pacific margin of Gondwanaland in the vicinity of the restored position of the southwest Pacific was the site of long-term subduction, the margin only remained convergent until Late Jurassic/Early Cretaceous. Recent interpretations of the Cretaceous geology of eastern Australia suggest that there was no Andean-type magmatic arc there [*Bryan et al.*, 1997]. From the Cretaceous to the Eocene, tectonics in the region east of Australia, which includes the opening of the Tasman Sea and Coral Sea, was dominated by rifting [*Gaina*, 1998].

Subduction reinitiated during the Eocene along the Norfolk ridge, including the area around New Caledonia. Prior to $\sim$ 43 Ma, Pacific motion was parallel to the Norfolk ridge while after $\sim$ 43 Ma it was perpendicular [*Gaina*, 1998]. New Caledonia is dominated by an ophiolite that was em-

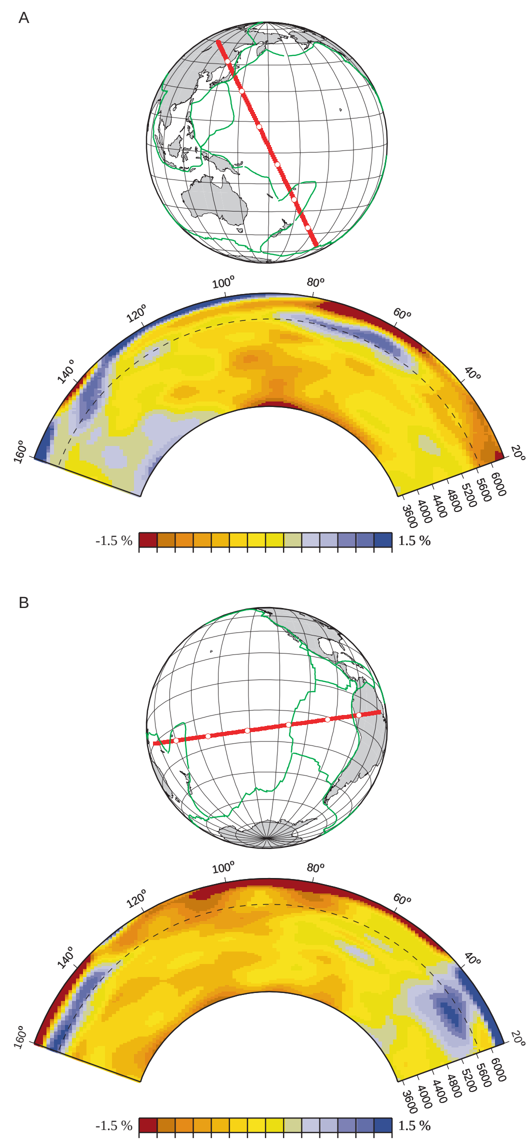

Figure 2. Cross sections through the global shear wave velocity model S20RTS. A. For Tonga-Kermadec to Japan. B. From Tonga to Peru.

placed over Mesozoic basement during the Eocene [*Aitchison et al.*, 1995]. Although the Eocene position of the island arc is uncertain, the thrusting event is thought to mark the resumption of convergence in the southwest Pacific [*Aitchison et al.*, 1995]. A short-lived, northeast verging subduction zone may have occurred from ~ 50 to ~ 45 Ma before an opposite polarity WSW verging proto–Tonga system initiated at ~ 43 Ma [*Eissen et al.*, 1998].

Dynamic Models

We now determine how large-scale mantle density variations could perturb the regional stress field within subduction zones using a tomographic inversion of mantle seismic structure, S20RTS [*van Heijst et al.*, 1999]. The setup of these models is only slightly different from those described in *Gurnis et al.* [1999]. Using a full spherical finite element model [*Zhong et al.*, 1999], we solve for the instantaneous state of stress in a mantle with lateral and radial variations in viscosity. Above a depth of 200 km the density variations are set to zero. Elsewhere, a simple linear scaling is used to obtain density from shear wave perturbations. The free parameters are $\partial\rho/\partial v_s$, the radial variation in viscosity, and the temperature-dependence of viscosity.

Independent of these free parameters, the radial deviatoric stress, σ_{rr}, in the middle of the transition zone is tensional in nearly all major subduction systems around the world except Tonga (Fig. 1D). This quantifies what we have seen in the subduction zone cross sections: Most systems have extensive high seismic velocity (dense) anomalies beneath, except Tonga which has an extensive low shear velocity anomaly beneath it. In map view, there is a correlation between the predicted state of stress within the transition zone (Fig. 1D) and density anomaly within the top of the lower mantle (Fig. 1C). In long-lived subduction systems the lower mantle tends to pull slabs down while in Tonga the lower mantle pushes upward.

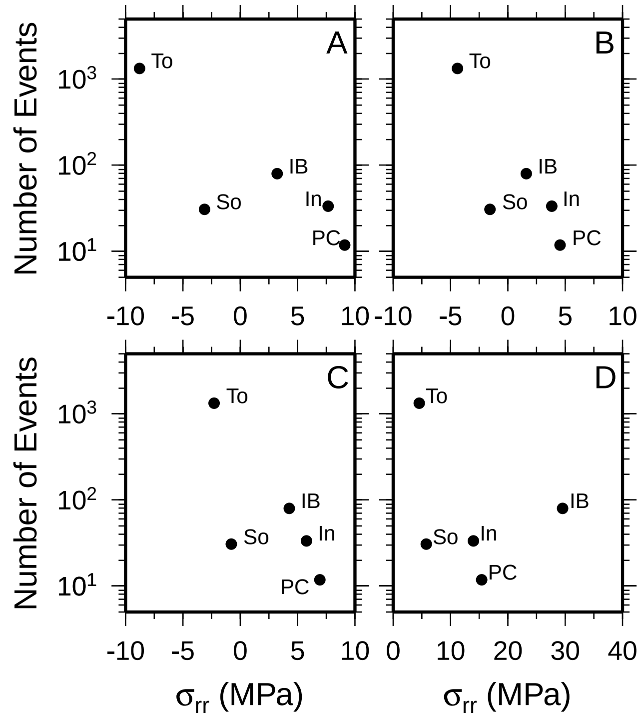

Figure 4. Number of earthquakes with magnitude > 5 against σ_{rr} from four different dynamic models. Individual regions shown in Fig. 1B and labeled as: To (Tonga), So (Solomon), In (Indonesia), IB (Izu-Bonin), and PC (Peru-Chile). A. $\partial\rho/\partial v_s$ = 400 kg m^{-3}/km s^{-1} with a 50× increase in viscosity; B. 200, 50×; C. 200, 10×; D. 200, 50× and with temperature-dependent viscosity (see Fig. 1C,D).

We have selected five regions (circles, Fig. 1B) with transition zone seismicity to show how model parameters influence the state of stress. The geographic variability in the rate of seismicity between these regions was estimated by considering all earthquakes with magnitude > 5 between 400 and 700 km (Fig. 1B). We use $\partial\rho/\partial v_s$ = 400 kg m^{-3}/km s^{-1} and a jump in viscosity of 50 from the surface to the lower mantle (Fig. 4A), parameters typically used to explain the geoid [*Hager et al.*, 1985]. A negative correlation is found between the number of earthquakes and the deviatoric stress, σ_{rr}, with a range of ~ 20 MPa. If $\partial\rho/\partial v_s$ is reduced by a factor of two then the stress range is reduced to ~ 10 MPa (Fig. 4B). A smaller increase in viscosity from the surface to the lower mantle of a factor of 10 has only a minor influence on σ_{rr} (Fig. 4C). When temperature-dependent viscosity is introduced, the entire range in stress between subduction zones is ~ 30 MPa (Fig. 4D).

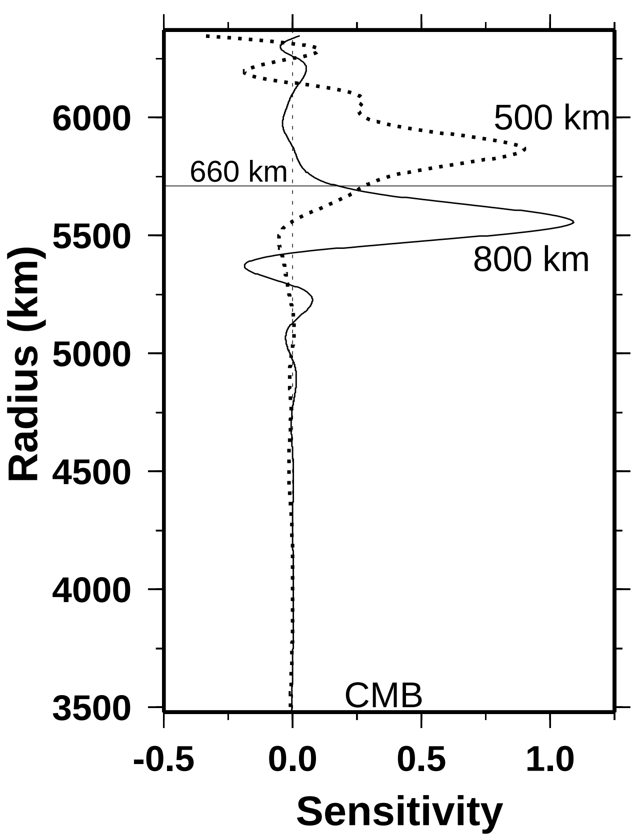

Figure 3. Backus–Gilbert resolution kernels of the S20RTS tomography model (see *Ritsema et al.* [1999]) beneath Tonga (179°E, 22°S) for point anomalies at 500 km (dotted line) and 800 km (solid line) depths.

Discussion

We have shown that the geographic variations in the deformation of slabs in the transition zone may be partly controlled by large-scale mantle flow. Compared to any other slab, we argue that the strong deformation of the Tonga-Kermadec slab in the transition zone is caused by the short period over which subduction has persisted ($\sim$ 40 Myr) and by the upward flow in the lower mantle. The slab in this subduction zone is now descending into the top of a large mantle upwelling. Global variations in stress driven by large-scale structure is 10 to 40 MPa and is of the same magnitude as the resisting stress from chemical layering or jumps in viscosity [*Vassiliou et al.*, 1984]. The correlations shown in Figure 4 between seismicity and model predictions are not perfect. Prefect correlations are not expected since there are good reasons to think that other features (the age of the slab, rate of local convergence, etc.) are also important.

One of the controls on this variability is the recent, regional plate motions. An important control on the morphology of the Tonga-Kermadec slab has been the recent geological history, especially the rapid trench rollback associated with the opening of the Lau Basin [*Bevis et al.*, 1995; *Taylor et al.*, 1996]. We have no reason to think that $\sim$1 to 10 Myr history is unimportant. Indeed, the detailed morphology of the slab can be partly accounted for by rapid trench rollback [*Han and Gurnis*, 2000]. However, we have now shown that subduction into the lower mantle occurring over the longer term history (>10 Myr) is also likely to be an important control on the state of slab stress. Slabs underlain by aseismic slabs in the lower mantle have an additional down-dip tensional force, while slabs descending into hot upwellings will have an additional downdip compressional force.

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