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Evidence for active subduction at the New Guinea Trench

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[1] Recent seismic tomography imaging shows clear evidence for southwestward subduction along the entire length of the New Guinea Trench (NGT) in Indonesia and Papua New Guinea. Viewed in conjunction with the occurrence of large ($M_w > 7$) thrust earthquakes that are known to have occurred on the trench, this confirms conclusions of earlier studies that the NGT is an active, inter-plate boundary. The ~650 km long slab is visible to a depth of about 300 km and subducts with a dip angle that varies from ~30° at 136°E to ~10° at 143°E. The improved clarity of the seismic tomography in this region stems from the use of a more accurate data set of P- and S-wave arrival times and hypocentral locations. *INDEX TERMS:* 7230 Seismology: Seismicity and seismotectonics; 8123 Tectonophysics: Dynamics, seismotectonics; 8150 Tectonophysics: Plate boundary—general (3040); 8180 Tectonophysics: Tomography. **Citation:** Tregoning, P., and A. Gorbatov (2004), Evidence for active subduction at the New Guinea Trench, *Geophys. Res. Lett.*, *31*, L13608, doi:10.1029/2004GL020190.

1. Introduction

[2] The Australian and Pacific Plates converge obliquely in the southwest Pacific, trapping several microplates in the collision in the Indonesian and Papua New Guinea regions. The predicted relative motion of ~111 mm/yr [e.g., *DeMets et al.*, 1994] between the Australian and Pacific Plates implies a convergent component of over 70 mm/yr across the New Guinea continental land mass but the location and possible partitioning of this convergence has not yet been identified quantitatively. It may occur by either subduction on the New Guinea Trench (NGT), as compression and uplift in the Highlands Fold-and-Thrust Belt (FTB) or as a combination of both processes. Conclusions from existing studies are conflicting as to whether active subduction occurs on the NGT and available estimates of the rates of shortening are significantly smaller than the total predicted convergence.

[3] The New Guinea Trench is a deep trench, clearly defined in bathymetry and gravity anomaly data, that extends about 700 km along the northern coastline of New Guinea from the eastern margin of the Ayu Basin near the Mapia Ridge at ~134.5°E [*Milsom et al.*, 1992] to 143°40′E [*Hamilton*, 1979] (Figure 1). Further to the west, the tectonic setting becomes more complicated with interactions between Halmahera, the Molucca Sea Plate and Sulawesi while east of 148°E subduction of the Solomon Sea Plate occurs beneath the South Bismarck Plate on the New Britain Trench [*Hamilton*, 1979].

[4] Previous studies have suggested that convergence may occur on the NGT [e.g., *Hamilton*, 1979; *Cooper and Taylor*, 1987; *Puntodewo et al.*, 1994; *Tregoning et al.*, 2000] along with partitioning of normal convergence and left-lateral slip in the FTB [e.g., *Abers and McCaffrey*, 1988; *Puntodewo et al.*, 1994] (Figure 1). The lowlands of New Guinea south of the FTB are part of the rigid Australian Plate [*Hamilton*, 1979; *Kreemer et al.*, 2000]. The North Bismarck Plate lies to the north of the NGT from 143°E west to the Manus Trench (~140°E) [*Johnson and Molnar*, 1972; *Tregoning*, 2002], while the Caroline Plate abuts New Guinea along the NGT further to the west [*Weissel and Anderson*, 1978; *Hegarty et al.*, 1983; *Altis*, 1999].

[5] Cross-sections of earthquakes dipping gently to the south beneath New Guinea west of 145°E were interpreted by *Denham* [1969] as indicating an overthrust zone of mountain building where the Australian and Pacific Plates collided. *Hamilton* [1979] interpreted an imbricated melange wedge over basement seen in seismic reflection profiles as evidence for shallow, south-dipping subduction. From earthquake locations spanning 1964–1984, *Cooper and Taylor* [1987] described a seismic zone beneath New Guinea that dipped ~40° to the southwest and associated this with a Wadati-Benioff zone caused by subduction on the NGT. They also showed that all focal mechanisms available at the time indicated subduction in a S-SSW direction.

[6] *Gutscher et al.* [2000] found that the global tomographic model of *Bijwaard et al.* [1998] did not provide sufficient spatial resolution to draw inferences about the existence of a slab beneath New Guinea, although the imaging did not proclude the possibility. On the basis of earthquake hypocentre data of *Engdahl et al.* [1998], they classified the subduction to be a flat slab and produced a profile of the subducted slab at 138°E. More recently, *Hall and Spakman* [2002] found no evidence in their seismic tomography model for significant subduction beneath New Guinea in the last 25 My. *Milsom et al.* [1992] concluded from an analysis of sidescan radar imagery that the NGT is a relic feature and that the convergence must be absorbed by deformation within New Guinea. *Pegler et al.* [1995] showed a single cross section of southwest-dipping seismicity in the western part of the Indonesian province of Papua (formerly known as Irian Jaya) (their Figure 4, section J-J′) but did not associate it with a subduction process.

[7] *Stevens et al.* [2002] estimated that only about 10 mm/yr convergence occurs on the NGT to the north of Biak and suggested that basal shear acting on the Bird's Head causes it to subduct in preference to subduction at

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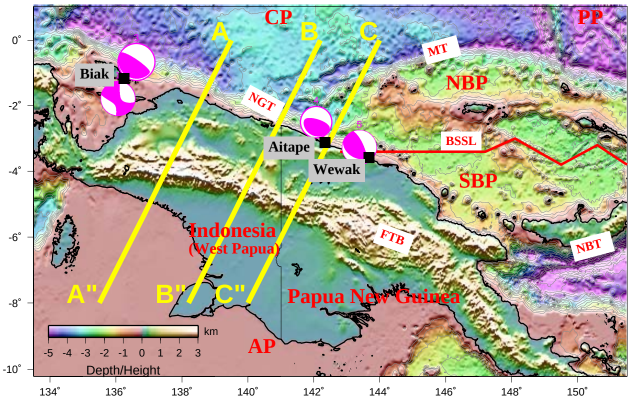

Figure 1. Configuration of tectonic boundaries in Papua New Guinea and eastern Indonesia. Available CMT focal mechanisms ($M_w > 7$) are plotted for events located reliably on the New Guinea Trench (plus the 1979 Yapen strike-slip event). Lines in yellow indicate surface traces of tomographic cross-sections (see Figure 3). AP: Australian Plate; BSSL: Bismarck Sea Seismic Lineation; CP: Caroline Plate; FTB: Highlands Fold-and-Thrust Belt; MT: Manus Trench; NBP: North Bismarck Plate; NBT: New Britain Trench; NGT: New Guinea Trench; SBP: South Bismarck Plate; PP: Pacific Plate. See color version of this figure in the HTML.

the NGT. *Kreemer et al.* [2000] concluded from an inversion of GPS velocities and seismicity that the trench-normal component of strain occurred at "a relatively low rate" (but did not quantify it) and that most of the deformation is taken up in a zone of almost pure strike-slip deformation trending east-west. It is not possible that the remaining convergent component is accommodated in E-W strike-slip motion - the convergence must occur somewhere; therefore, if it is true that the rate of convergence on the trench is low, there must be other zones accommodating convergence.

[8] *Puntodewo et al.* [1994] summed seismic moments spanning 1963–1993 and concluded that <1 mm/yr shortening and <10 mm/yr left-lateral shear had occurred in the Papua Highlands FTB (134.5°E to 140.5°E) but that 22 mm/yr of thrusting was accommodated in the Mamberambo Thrust Belt. They also concluded from GPS measurements between 1991 and 1993 that 40 mm/yr convergence probably occurred at the NGT. *Abers and McCaffrey* [1988] used estimates of crustal thickening in both Papua and western Papua New Guinea (and made assumptions about crust and mantle densities, conservation of crustal volume and erosion rates) to derive a rate of convergence in the FTB of 4–9 mm/yr assuming that all the thickening occurred in the past 10 My, or 1–3 mm/yr if it began 30 Ma when the first collisions with the Australian continent occurred. They noted that these estimates are likely underestimates and also pointed out that the assumptions made are associated with potentially large errors. Nonetheless, this remains the most recently quantified estimate of convergence in the PNG Highlands. The implication is that the remaining ∼40–60 mm/yr of normal convergence must occur further north than the FTB, with the only feasible location being the NGT.

[9] We show below that a southwest-dipping subducted slab can be seen beneath New Guinea in recent seismic tomography modelling, thereby providing clear evidence to support earlier conclusions that the NGT is an active subduction zone. Furthermore, the slab can be seen in previous tomographic images and seismic cross-sections, although the evidence is less compelling.

2. Seismicity

[10] The largest recorded earthquake on the NGT in the last century was the M_w = 8.2 Biak thrust event on 17 February, 1996, occurring on a section of the trench that had had a marked absence of recorded seismicity [*Okal*, 1999]. *Henry and Das* [2002] recalculated the moment tensor of this event and their preferred solution (ϕ = 109°, λ = 9°, ψ = 72°) has a strike close to the strike of the trench (as defined by bathymetry) and with a slip vector azimuth normal to the trench. Harvard CMT focal mechanisms of aftershocks following the 1996 Biak earthquake were interpreted as either principally thrust faulting consistent with the orientation and dip of the main thrust event, right-lateral strike-slip or extensional events [*Taylor et al.*, 1998].

[11] *Henry and Das* [2002] calculated that the combined slip caused by the 1996 Biak earthquake and the 1979 M_w = 7.5 earthquake that occurred on the Yapen Fault amounted to 14 m in an azimuth of 253°, nearly parallel to the azimuth of convergence of the two major plates (248°). Given that the total convergence rate is 111 mm/yr [*DeMets et al.*, 1994], this represents ∼130 years of convergent motion, assuming that all the convergence is accommodated on only these two tectonic structures. Since this is not likely to be the case, the relative motion accommodated during these two events may represent the convergence of considerably more than 130 years.

[12] *Okal* [1999] relocated over 220 historical and recent earthquakes and concluded that seismic activity has occurred more or less continuously along the NGT from 134.5°E to 139.75°E (the eastern limit of his study). Up to three earthquakes with magnitudes of 7.3–7.9 may have occurred on the NGT east of 139°E between 1913 and 2001 [*Henry and Das*, 2002].

[13] The 1998 M_w = 7.0 Aitape earthquake occurred near the NGT and had a thrust-type mechanism. On the basis of aftershocks located from distant and local seismic stations, *Hurukawa et al.* [2003] concluded that the event was an interplate earthquake that occurred on the nodal plane parallel to the plate interface (ϕ = 124°, δ = 19°). Aftershocks were relocated down to a depth of ∼60 km.

[14] The M_w = 7.6 earthquake that occurred on 8 September, 2002 near Wewak was modelled by the Harvard CMT analysis with a focal mechanism consistent with the Australian/North Bismarck Plate convergence (ϕ = 106°, δ = 34°, λ = 43°). Field observations of tsunami runup and coral terrace uplifts were well matched by those predicted from a thrust event on the NGT [*Borrero et al.*, 2003]. Thus, present-day active thrusting occurs on the NGT as far east as 143°E. The focal mechanisms of events located on the NGT with $M_w > 7$ are plotted on Figure 1.

3. Tomographic Model

[15] We used the tomographic model of *Gorbatov and Kennett* [2003] generated from an inversion of updated catalogue of events and phase arrival times of P-wave and

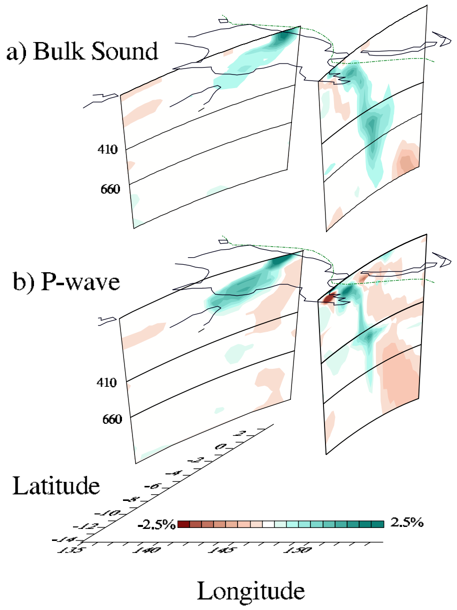

Figure 2. Cross-sections of the bulk-sound tomographic model and P-wave model, showing southwestward subduction at the New Guinea Trench (left) and northward subduction at the New Britain Trench (right). See color version of this figure in the HTML.

S-wave [*Engdahl et al.*, 1998] in terms of bulk-sound and shear wave-speed variations in the mantle. Only events with both P and S arrival times reported were used in the inversion, a criterion that improved the accuracy of the hypocentral locations of the input dataset. While the total number of observations decreased because of this condition, the actual quality of those observations used was much greater, thereby increasing the resolution of the structures visible in the tomography and reducing the noise caused by inaccurate hypocentral locations. Continuous extensive updating of the catalogue presented by *Engdahl et al.* [1998] permitted the selection of ~900000 ray-paths for this regional study, nearly twice the amount of data used by previous global tomographic inversions [e.g., *van der Hilst et al.*, 1997]. Readers are referred to *Gorbatov and Kennett* [2003] for the details of the generation and features of the tomographic model and corresponding resolution tests. Although all generated models (including P-wave tomographic images) show similar features for the region under study, we focus here on the bulk-sound model for presentation which is dependent mostly on density contrasts of the mantle (whereas the shear is also dependent on temperature and/or chemical heterogeneities). This feature of bulk-sound tomography allows us to show clearly images of the subducted slab unobscured by thermal processes caused by volcanic activity. Since the P-wave model combines bulk and shear, it can also be difficult to interpret in some cases.

4. Results and Discussion

[16] Profiles across the New Guinea Trench show a high-velocity zone dipping to the south-west to a depth of ~300 km (Figures 2 and 3). The slab is imaged clearly as far west as 135°E. The dip angle increases smoothly from ~10° at 143°E to ~30° at ~136°E. This high-velocity zone can be associated with subduction of the North Bismarck and Caroline Plates descending into the mantle (we also show in Figure 2 the northward-dipping subduction of the Solomon Sea Plate at the New Britain Trench to demonstrate that our tomographic model also detects features seen previously in other studies). The bulk-sound image has fewer low-velocity zones, possibly induced by hot mantle upwelling or volcanic activity. However, both subducting slabs are still evident in the P-wave tomography.

[17] Cross-section 4B of *Hall and Spakman* [2002] aligns with our section A-A″ (Figure 3). A close inspection of the former does indeed show a high velocity zone trending to the southwest, although the lower resolution of their image tends to obscure the feature. Furthermore, it is possible that a Wadati-Benioff zone associated with the subduction is present in the cross-sections of *Pegler et al.* [1995] (e.g., Figure 4, section H-H′) but that it merges with the southward-dipping arm of the inverted U-shaped zone identified in that study.

[18] The ~650 km length of subducted slab beneath New Guinea suggests that subduction commenced ~9 Ma assuming a constant subduction rate of 70 mm/yr, or even earlier if the convergence across the FTB is more rapid than currently thought. This date coincides with the period when all the terranes comprising the New Guinea orogen had

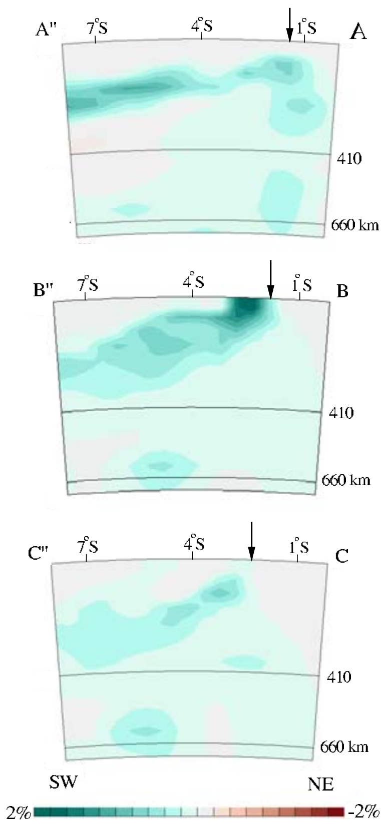

Figure 3. Cross-sections (at true scale) showing high-velocity zone beneath New Guinea. Refer to Figure 1 for the geographical locations of the sections. Arrows indicate the location of the coastline in each cross-section. See color version of this figure in the HTML.

docked with the Australian craton (~10 Ma) [*Pigram and Davies*, 1987], a likely time when subduction at the NGT began. The existence of a slab beneath New Guinea from 143°E extending west to at least 135°E is consistent with a Wadati-Benioff zone identified in previous studies [e.g., *Cooper and Taylor*, 1987] and with the occurrence of interplate, thrust-type events that have been located on the New Guinea Trench (see Section 2).

[19] *Pegler et al.* [1995] showed evidence for an inverted U-shaped doubly-dipping subducted slab beneath eastern New Guinea (east of 145°E). The slab shown in Figure 3 subducting to the southwest must lie above this U-shaped slab. Our tomographic model has a cell size of 50 km in depth which does not provide sufficient resolution to identify separately the U-shaped slab and the slab subducting at the NGT. This would require cell spacing of less than 25 km (the separation distance between the two seismicity patterns). To achieve spatial resolution less than 50 km one would need data from a very dense local seismic network over the zone of study, data that do not currently exist.

[20] **Acknowledgments.** We are grateful for comments from two anonymous reviewers that improved the manuscript. Figures were plotted with the GMT software [*Wessel and Smith*, 1991].

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