When slabs collide: A tectonic assessment of deep earthquakes in the Tonga-Vanuatu region

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ABSTRACT

An unusual group of more than 100 earthquakes is located ~600 km beneath the North Fiji Basin in the southwest Pacific Ocean. These earthquakes are attributed to seismicity within detached segments of the subducted Australian plate. One of these detached slab segments has collided with, and now impinges on, the subducted Pacific plate at a depth of ~500 km. The region in the mantle where the two slab segments meet is also characterized by an unparalleled abundance of large-magnitude (Mw >7.0) earthquakes for this depth. The folded shape of the Pacific slab beneath Fiji, as well as the abundance of earthquakes, is interpreted to result from deformation and deformation-enhanced phase transformations as the two slabs collide and settle on the 660 km discontinuity. Detachment of the slab segments is interpreted to have occurred at ca. 5 Ma, but collision between the eastern segment and the west-dipping Pacific slab is interpreted to have occurred at ca. 4 Ma, coincident with initial opening of the overriding Lau Basin.

INTRODUCTION

More large-magnitude earthquakes occur at depths of between 400 and 600 km below the Tonga subduction zone than anywhere else in the world (Richter, 1979; Tibi et al., 2003; Isacks et al., 1969). Most deep earthquakes can be attributed to deformation (Isacks and Barazangi, 1977; Frohlich, 1989; Gurnis et al., 2000), dehydration reactions (Hacker et al., 2003; Omori et al., 2004), or phase transformations (Kirby et al., 1996; Okal and Kirby, 1995) within the subducting slab. Researchers such as Tibi et al. (2003), Giardini and Woodhouse (1984), and Jiao et al. (2000) have suggested that the large-magnitude earthquakes within the subducting Pacific slab may be caused by deformation and reactivation of structures, possibly exacerbated by the resistance to subduction imposed by the Pacific superplume, as proposed by Gurnis et al. (2000).

A second domain of unusual seismicity is located well outboard of the subducting Pacific slab (Hamburger and Isacks, 1987; McGuire et al., 1997; Okal and Kirby, 1998). More than 150 earthquakes occur within a well-defined, semiplanar horizontal zone at a depth of 550–650 km below the North Fiji Basin (Fig. 1). This unusual zone of seismicity appears to be connected to the Wadati-Benioff zone of the west-dipping Pacific slab (Brudzinski and Chen, 2003) and was interpreted by Okal and Kirby (1998) as a detached segment of the Pacific slab. In contrast, Hamburger and Isacks (1987) interpreted the earthquakes as occurring within a remnant fragment of the now-extinct, south-dipping Vitiaz subduction zone. There is general agreement between researchers that these deep earthquakes are triggered by phase transformations within a now-stagnant section of detached slab, but the origin of that detached segment remains unresolved. Research presented here focuses on explaining a geodynamic link between the abundant large-magnitude earthquakes beneath Tonga and the anomalous seismicity beneath the North Fiji Basin.

METHODS

We have set out to create a three-dimensional (3-D) map of the Earth focused on delineating the structure of subducted slabs. This 3-D map has its foundations based in seismic tomographic data from Widiyantoro et al. (1999) and hypocenter data sets (Engdahl et al., 1998). Such data sets have been successful in imaging subducted plate geometries in regions including Central America (Rogers et al., 2002), Taiwan (Lallemand et al., 2001) and Southest Asia (Replumaz et al., 2004; Richards et al., 2007). Additional earthquake data sets, including the National Earthquake Information Center (NEIC) and the Harvard Global Centroid Moment Tensor (CMT) catalogues, are used for comparison; published tomographic models of the region (van der Hilst, 1995) are also used to aid interpretation.

The surfaces of the subducting slabs (oceanic crust and lithosphere) are initially constructed by computationally draping a triangulated mesh over the outer limit of the seismicity for each subducting plate. The mesh is manipulated incrementally in 3-D to best fit the earthquake data following the methods

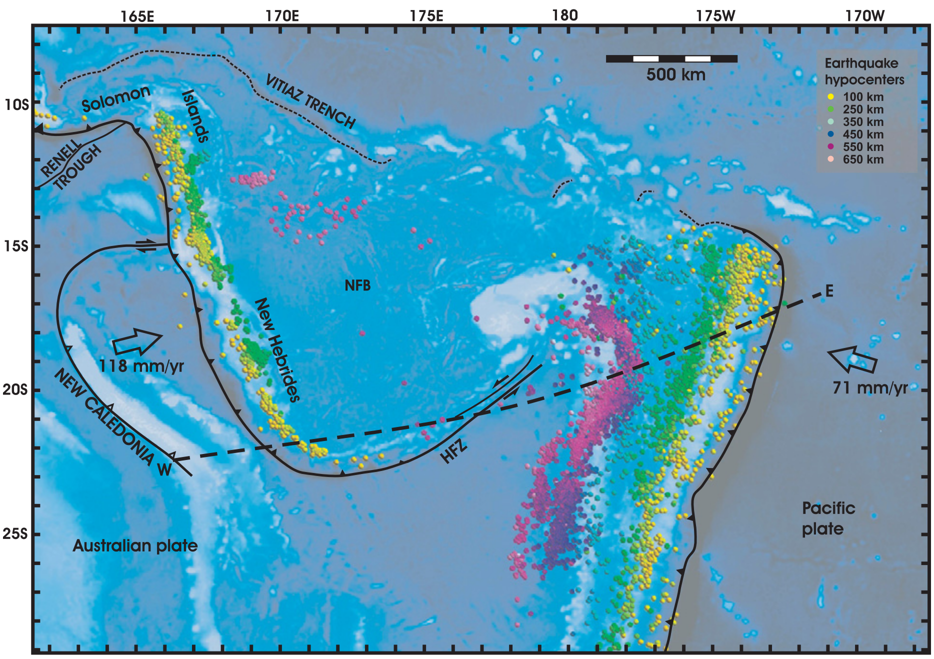

Figure 1. Topography, bathymetry, and major tectonic element map of the study area. The Tonga and Vanuatu subduction systems are shown together with the locations of earthquake epicenters discussed herein. Earthquakes between 0 and 70 km depth have been removed for clarity. Remaining earthquakes are color-coded according to depth. Earthquakes located at 500–650 km depth beneath the North Fiji Basin are also shown. Plate motions for Vanuatu are from the U.S. Geological Survey, and for Tonga from Beavan et al. (2002) (see text for details). Dashed line indicates location of cross section shown in Figure 3. NFB—North Fiji Basin; HFZ—Hunter Fracture Zone.

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described in Richards et al. (2007). The final surface represents a close approximation to the top of the subducting slab. Complexity arises in the region west of Tonga where earthquakes occur below the North Fiji Basin, well outboard of the typical Wadati-Benioff zone of seismicity. Three-dimensional visualization of CMT solutions is undertaken using the software Gocad™ (Geological Object Computer Aided Design). Plate tectonic reconstructions of the Vanuatu (New Hebrides) arc and Tonga arc from 10 Ma were initially based on those presented by Schellart et al. (2002), with modifications made using age dating of the North Fiji Basin seafloor presented by Pelletier et al. (1993) and Auzende et al. (1994).

GEOMETRY OF THE PACIFIC SLAB

The final interpreted geometry of the Pacific slab is shown in Figure 2. Between 50 km and 350 km depth, the geometry of the subducted Pacific slab beneath Tonga is relatively simple and defined by a single, west-dipping zone of seismicity (Fig. 2). With increasing depth (350–500 km), the geometry of the slab becomes more complicated. The density of earthquakes increases dramatically, and the slab is characterized by a well-developed concave bend (Fig. 1). More than 100 earthquakes also occur within the asthenosphere to the west and outboard of the well-defined Pacific plate Wadati-Benioff zone (between 12°S, 167°E and 22°S, 179°W). In order to explain some of these earthquakes, van der Hilst (1995) included them in his interpretation of the upper and lower boundaries of the subducted Pacific slab (Fig. 3). This unusual cluster of earthquakes outboard of the Pacific slab have also been imaged by Brudzinski and Chen (2003), but no explanation of their origin was provided. When examined in 3-D, these earthquakes define an approximately planar sheet that dips away (west) from the Pacific slab (Figs. 2 and 3). Analysis of the limited CMT data from this region shows no consistent pattern in the focal mechanisms determined for these earthquakes; consistent with Okal and Kirby (1998) who propose phase transformations in a detached slab segment as a trigger for these remote earthquakes.

GEOMETRY OF THE AUSTRALIAN SLAB

The northwest-trending volcanic island chain including the New Hebrides and south Solomon Islands formed as a result of east-dipping subduction of the now-fused Australian and South Fiji plates. The upper plate is the North Fiji Basin, which is a complex backarc composed of a series of subplates divided by active and fossil spreading centers. The subducting Australian slab exhibits a well-defined Wadati-Benioff seismic zone, highlighting a relatively steep-dipping slab to a maximum depth of 300–350 km. At its southern limit, the slab reaches a maximum depth of only 150 km where it terminates against the Hunter Fracture Zone (Figs. 1 and 2).

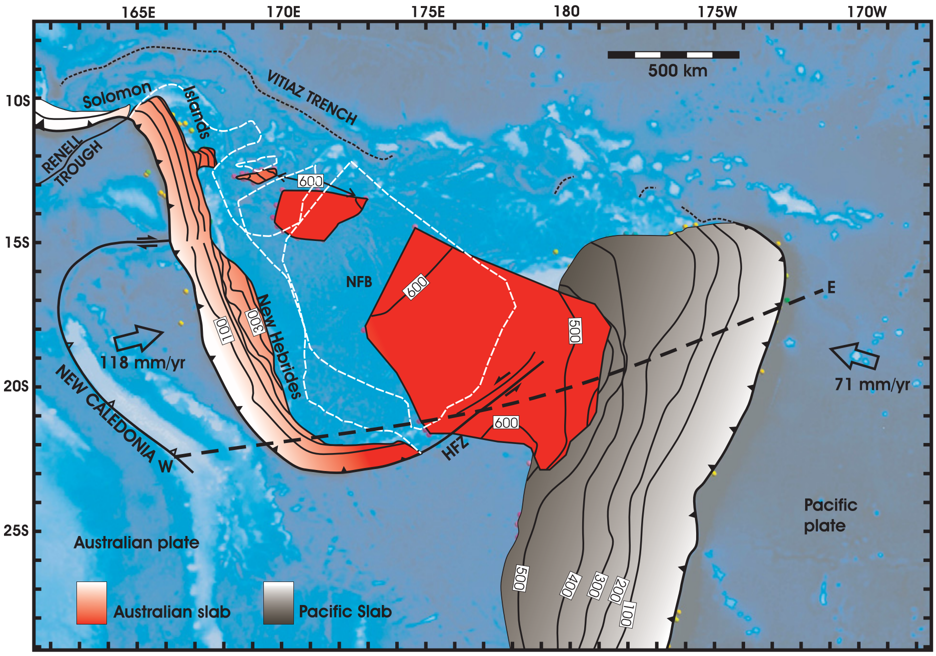

Figure 2. Map showing distribution of slab segments beneath the Tonga-Vanuatu region. West-dipping Pacific slab is shown in gray; northeast-dipping Australian slab is shown in red. Three detached segments of Australian slab lie below the North Fiji Basin (NFB). HFZ—Hunter Fracture Zone. Contour interval is 100 km. Detached segments of Australian plate form sub-horizontal sheets located at ~600 km depth. White dashed line shows outline of the subducted slab fragments when reconstructed from 660 km depth to the surface. When all subducted components are brought to the surface, the geometry closely approximates that of the North Fiji Basin.

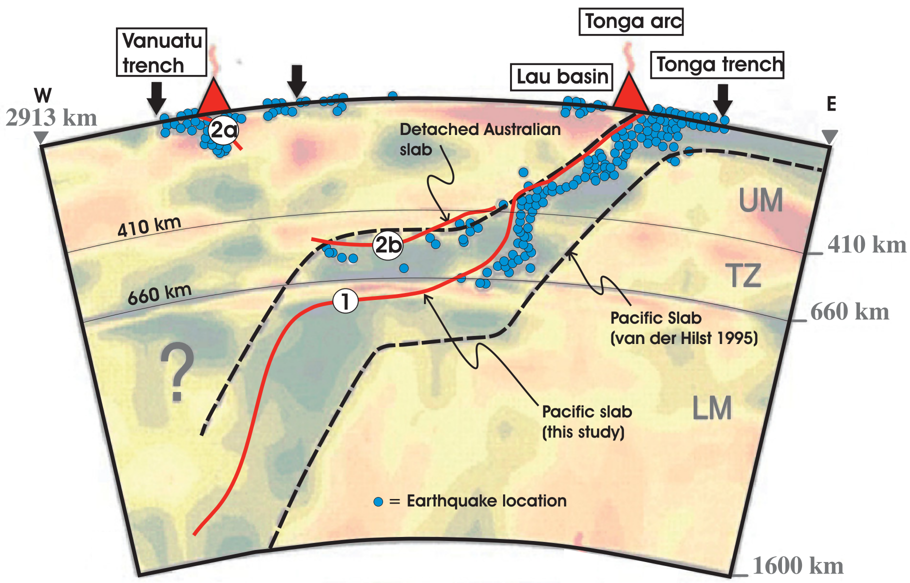

Figure 3. Previous interpretation of combined P-wave tomography and seismicity from van der Hilst (1995). Earthquake hypocenters are shown in blue. The previous interpretation of slab structure is contained within the black dashed lines. Solid red lines mark the surface of the Pacific slab (1), the still attached subducting Australian slab (2a), and the detached segment of the Australian plate (2b). UM—upper mantle; TZ—transition zone; LM—lower mantle.

To the northwest, the maximum depth of seismicity increases to ~250 km. Here, CMT solutions for earthquake hypocenters along the basal edge of the slab show T-axes that are generally plunging steeply to the northeast and are similar to those found in the actively detaching Tethyn slab beneath the Pamir area in the western syntaxes of the Himalaya (Lister et al., 2008). The northern limit of the subducting plate corresponds with the lack of seismicity beyond the sharp bend in the subduction trench hinge and the location of subduction of the Rennell trough (Fig. 2). The average downdip length of the subducted Australian slab is only 200 km.

Immediately below the central North Fiji Basin lie three distinct domains of seismicity. The western-most cluster is defined by 40 earthquakes located at 12.8°S and 169.4°E and at an average depth of ~640 km (Fig. 1). Although it is the smallest of the three clusters, it exhibits the highest density of earthquakes. The second, less dense cluster of 38 earthquakes lies immediately east and at a similar depth. A simple triangulated polygon is constructed in 3-D around these earthquakes to reveal a sheet-like zone extending toward the Pacific slab to the east (Figs. 2 and 3). Further east toward the Pacific slab, scattered earthquakes located at between 630 and 550 km depth define a surface that trends and shallows toward the Pacific slab. Earthquakes are shown in cross section in Figure 3. At its eastern edge, the zone of outboard earthquakes is interpreted to drape onto the subducted Pacific slab. Beneath this zone, the Pacific slab lies on the 660 km discontinuity (Fig. 3). Earthquakes within these isolated clusters never exceed magnitude 6.0, which contrasts with earthquakes at the same depth but located within the Pacific slab, where more than seven earthquakes are recorded with magnitudes >7.0.

EVOLUTION OF THE VANUATU AND TONGA ARC SYSTEM

Approximately 15 m.y. ago, westward motion of the Pacific plate was accommodated by WSW-directed subduction of the Pacific plate below the semi-continuous NW-trending Vitiaz (Melenesian) Arc (e.g., Hall and Spakman, 2002; Falvey, 1978). Collision of the Melanesian plateau at ca.12–13 Ma is interpreted to have terminated southwest-dipping subduction and simultaneously initiated northeast-dipping subduction of the Australian plate along the Vanuatu–New Hebrides subduction system, based on 12–14 Ma maximum seafloor ages in the North Fiji Basin (Pelletier et al., 1993).

Subduction along the Vanuatu trench is almost exclusively accommodated by subduction hinge rollback with minor northward motion of the Australian plate. Accordingly, the entire northeastern corner of the Australian plate has been subducted here. Thus an area the size of the North Fiji Basin must exist as subducted slab material beneath Vanuatu.

Since 4–5 Ma, the Tonga trench also underwent asymmetric hinge rollback to the east resulting in the opening of the Lau Basin between the Tonga trench and Fiji (Fig. 1) (Taylor et al., 1996).

INTERPRETATION

We interpret the seismicity beneath the North Fiji Basin described above as a segment of Australian slab that detached from the Vanuatu subduction zone; once detached, the slab slid eastwards and collided with the west-dipping Pacific slab. Seismic tomographic images of Hall and Spakman (2002) also show a distinct break in the fast wave speed anomaly at the base of the Australian slab Wadati-Benioff seismogenic zone, supporting an interpreted detached slab segment. Furthermore, the zone of anomalous deep seismicity described herein falls close to, or completely within, segments of the mantle exhibiting fast P-wave anomalies, suggesting that these unusual earthquakes below the North Fiji Basin are occurring within slab segments derived from surrounding subduction zones. Reconstructing the three detached slab segments back to the surface reveals that their combined surface area is almost equivalent to that of the present-day North Fiji Basin, which is also equivalent to the area of Australian plate subduction since 12 Ma (Fig. 2).

DISCUSSION AND MODEL

We have compiled a simple reconstruction in order to demonstrate the relationship between the two evolving subduction systems and to explain the source of deep seismicity below the North Fiji Basin (Figs. 4A–4E).

By 12 Ma (Fig. 4A), subduction hinge rollback along the Vanuatu trench began to consume the Australian plate (e.g., Meffre and Crawford, 2001; Schellart et al., 2002). At ca. 5 Ma (Fig. 4B), the basal section of the Australian slab detached, initially tearing in the east with the tear propagating to the northwest. Existing fractures on the subducting plate, like the d'Entrecasteaux fracture zone and the now-subducted northern part of the 40–30-m.y.-old North Loyalty Basin spreading center, may have contributed to the breakup of the detached slab into three independent segments. Rapid slab detachment is also supported by recent work by Burkett and Billen (2010) who show that complete detachment and segmentation can occur in as little as 1 m.y. Between 4 and 3 Ma (Fig. 4D), the completely detached slab segment collided with the west-dipping Pacific slab, resulting in the indentation of the Pacific slab. The Lau extensional backarc was also initiated at this stage (Taylor et al., 1996), which may have been triggered by initial slab collision. Between 3 Ma and the present, the Pacific slab must have subducted ~240 km (based on current subduction rates), and, given

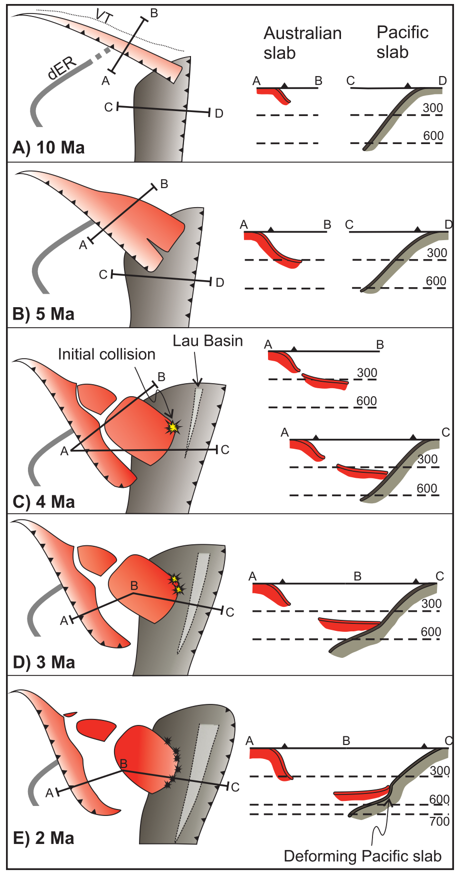

Figure 4. Simplified plate tectonic reconstruction showing the progressive geometric evolution of the Vanuatu and Tonga subduction systems in plan view and in cross section. Initiation of the Vanuatu subduction system begins by 10 Ma. Initial detachment of the basal part of the Australian slab begins at ca. 5–4 Ma and then sinking and collision between the detached segment and the Pacific slab occur by 3–4 Ma. Initial opening of the Lau backarc also occurred at this time. Between 3 Ma and the present, both slabs have been sinking progressively to their current position. VT—Vitiaz trench; dER—d'Entrecasteaux Ridge.

that the detached slab segment currently rests at ~600 km depth, initial collision may have occurred at depths of only 300 km.

The plethora of earthquakes exhibited by the Pacific slab between 550 and 600 km depth is interpreted here to be, at least in part, due to buckling and deformation of the Pacific slab at the point of collision and as the two segments collapse onto the 660 km discontinuity (Fig. 4E). Deformation may be enhanced within this region due to the resistance to slab subduction imposed by the buoyant Pacific superplume (Gurnis et al. 2000). The well-documented deep seismicity beneath Tonga is herein interpreted as the result of a combination of processes including, deformation of the slab, phase transformation, and deformation enhanced phase transformation.

In conclusion, we suggest that the unusual deep seismicity beneath the North Fiji Basin is constrained to within detached segments of the Australian slab. Slab detachment is interpreted to have occurred ca. 5 Ma, with collision occurring between the detached segment and the west-dipping Pacific slab at ca. 4 Ma. Collision between the two segments resulted in deformation of the Pacific slab and an associated increase in seismicity at ~500–600 km depth. The interpretations presented here also provide an explanation that is consistent with reconstructions and subduction-zone dynamics for the concentration of large-magnitude earthquakes beneath the North Fiji Basin; a source for the detached slab segment in which the earthquakes occur; a potential explanation for initiation of the opening of the Lau Basin; and finally, an explanation for the abundance of deep earthquakes located within the subducting Pacific slab.

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