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Concave slab out board of the Tonga subduction zone caused by opposite toroidal flows under the North Fiji Basin

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ABSTRACT

An alternative scenario is proposed for the origin of a concave NE-facing slab under the North Fiji Basin between the Tonga subduction slab and Vanuatu Arc. During rollback of the Australian Plate, Vanuatu Arc rotated clockwise, whereas Fiji Platform rotated counterclockwise from 12/10 Ma until 1.5 Ma ago. Thereafter, only Vanuatu Arc rotated until the present. During the period of opposite rotations, toroidal flows entered the mantle around the northwest slab edge of Vanuatu Arc and from the northeast slab edge of Fiji Platform. The latter lies close to the northern end of the Tonga slab where arc-parallel flows are shown by volcanic geochemistry and mantle anisotropy. Opposite toroidal flows with upwelling and downwelling components generate the concave form of the combined Vanuatu/Fiji Platform slab, match its extent to mapped deep seismicity, explain its position overlying the Tonga slab, provide a mechanism for high heat flow in the North Fiji Basin as well as enriched MORB and OIB basalts in the northern NFB, and obviate slab collisions invoked to produce slab curvature.

1. Introduction

The seismically-defined slab between the Vanuatu and Tonga slabs (Fig. 1) was considered part of the Vitiaz subduction zone (Chen and Brudzinski, 2001; Hamburger and Isacks, 1987), as detached from the Tonga slab (Bonnardot et al., 2009; Brudzinski and Chen, 2003), part Vitiaz and part Tonga (Okal and Kirby, 1998) or as detached from the Vanuatu slab (Chatelain et al., 1993; Richards et al., 2011).

Here I propose, following Richards et al. (2011), that the concave slab forms part of the Australian Plate. Whereas Richards et al. (2011) consider rollback only of the Vanuatu slab, the North Fiji Basin (NFB) developed via opposite rotations (Fig. 2) of the Vanuatu Arc and the Fiji Plateau from 12/10 Ma until 1.5 Ma (Martin, 2013).

Secondly, during rollback, toroidal flows around slab edges lead to a curved slab (Faccenna et al., 2010; Funiciello et al., 2006; Schellart, 2008). Such a model (Fig. 3) provides a mechanism for the shape of the concave slab underlying the NFB.

Thirdly, the evolution of this indented slab is described in terms of double saloon door tectonics in the NFB (Fig. 4). This generates the concave geometry of the slab, matches its extent to mapped deep seismicity, explains its existence under Fiji Platform but overlying the Tonga slab, provides a mechanism for high heat flow in the NFB and E-MORB and OIB basalts in the northern NFB, and obviates the slab collision invoked by Richards et al. (2011) to explain slab curvature.

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2. Revised model of North Fiji Basin development

The NFB developed with northeast-directed subduction of the Australian Plate 12/10 Ma ago. Single saloon door clockwise rotation of the Vanuatu Arc (Richards et al., 2011; Schellart et al., 2002) agrees with GPS data (Calmant et al., 2003). However, palaeomagnetic data (Taylor et al., 2000) show that Fiji Platform rotated counterclockwise while Vanuatu Arc rotated clockwise (Fig. 2) for most of the development of the NFB (Martin, 2013). The NFB developed via double saloon door tectonics from 12/10 Ma to 1.5 Ma, and then via single saloon door rotation of Vanuatu Arc. Lau Basin developed from 6 Ma, separating Lau and Tonga Ridges (Zellmer and Taylor, 2001). Reconstructions of the related subduction slabs (Fig. 4) are based on this scheme.

3. Development of a concave slab via toroidal flows into the mantle under North Fiji Basin

In the orthodox backarc model, gravitational pull of a sinking slab drives subduction rollback. Related deviatoric tensile stresses in the overlying plate and induced convection in the underlying mantle drive backarc extension and seafloor spreading (Schellart and Moresi, 2013; Shemenda, 1993). Opposite toroidal flows (Faccenna et al., 2010; Schellart, 2008) concentrate flow in a central location within the mantle wedge, generating opposite rotational torques (Fig. 3). The influence of slab curvature engenders the radiating flow geometry (Kneller and Van Keken, 2008). If slab pull is orthogonal to a curved slab, the force is no longer planar. Slab pull at one edge of a curved slab deviates from slab

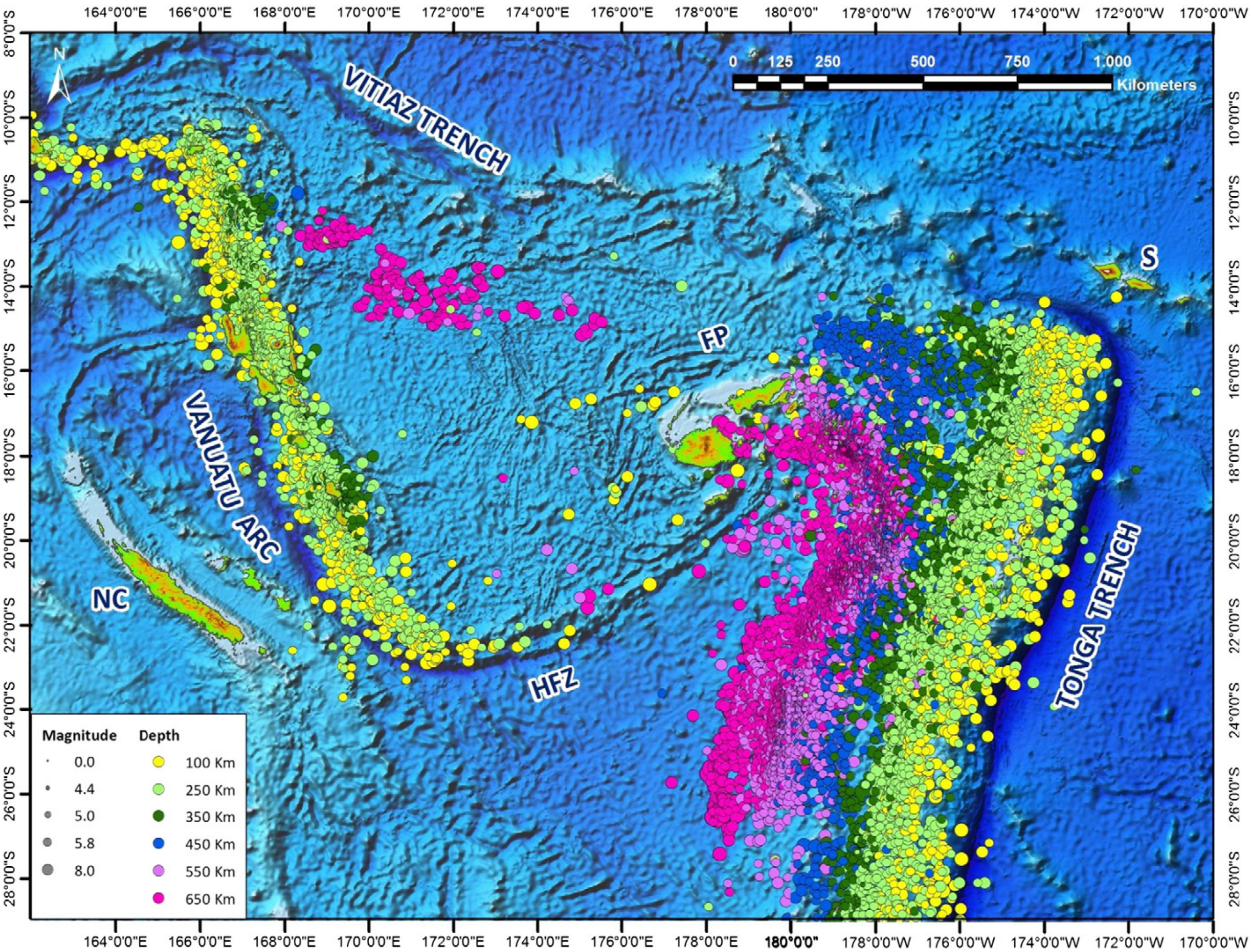

Fig. 1. Earthquake hypocentres from the USGS catalogue (earthquakes from 0 to 70 km depth excluded for clarity), overlain on shaded relief bathymetry showing tectonic elements of the Vanuatu/Tonga area. FP = Fiji Platform. HFZ = Hunter Fracture Zone. NC = New Caledonia. S = Samoa.

pull at the other slab edge, thereby augmenting the opposite rotational torques.

Geochemical markers in volcanic rocks (Gill and Whelan, 1989; Pearce and Stern, 2006; Turner and Hawkesworth, 1998) and anisotropy (Hall et al., 2000; Smith et al., 2001; Wiens et al., 2008) demonstrate flow around the north end of the Tonga Arc into the NFB and Lau Basin.

At its northwestern end, Vanuatu slab meets the EW-oriented Solomon slab. Richards et al. (2011) map these slabs to only 200 km, and 100 km respectively (cf Fig. 1). Tomographic depth slices (Hall and Spakman, 2002; Schellart and Spakman, 2012) suggest a gap at 200–500 km between the Vanuatu and Solomon slabs. Toroidal flows likely enter the mantle wedge above the Vanuatu slab from the northwest (Fig. 4).

4. Alternative geodynamic scenarios for the evolution of a concave slab under the NFB

4.1. Slab created during single-saloon-door opening of the NFB

In the Richards et al. (2011) scheme, part of the Vanuatu slab detaches, slides eastward and collides with the Tonga slab. Subsidence of the eastern end of the detached slab is slowed by the Tonga slab, whereas the central part continues subsiding, producing the concave-upward shape.

This model is flawed on several grounds. Firstly, no mechanism is given to explain the eastern motion and collision of the Vanuatu slab with the Tonga WBZ. Although motion of the Australian Plate and Vanuatu slab is towards the northeast (Calmant et al., 2003), the Tonga slab is retreating to the east even faster (Bevis et al., 1995). Secondly, in order to collide, Vanuatu slab has to subside faster than Tonga slab. The exact reverse is likely because Tonga slab comprises 100–120 Ma old cold lithosphere of the Pacific Plate (Van der Hilst, 1995), whereas 42–55 Ma old, less dense lithosphere subducts at Vanuatu (Schellart et al., 2002). Thirdly, Richards et al. (2011) envisage the collision at 500–600 km, whereas a slab west of Tonga slab may extend to only ~200 km. Although not resolved in tomographic cross-sections, depth slices (200, 320, 500 and 628 km — Hall and Spakman (2002); and 200, 400, 500, and 600 km Schellart and Spakman (2012)) show a possible slab under and southeast of Fiji, as do Vp/Vs tomographic images (Conder and Wiens, 2006). Chen and Brudzinski (2001) consider hypocentres as shallow as 350 km to be outboard of the Tonga WBZ (but see Fig. 4e). A shallow slab at only 200 km depth requires almost horizontal movement for the Vanuatu slab to collide with the Tonga slab, rendering slab collision implausible.

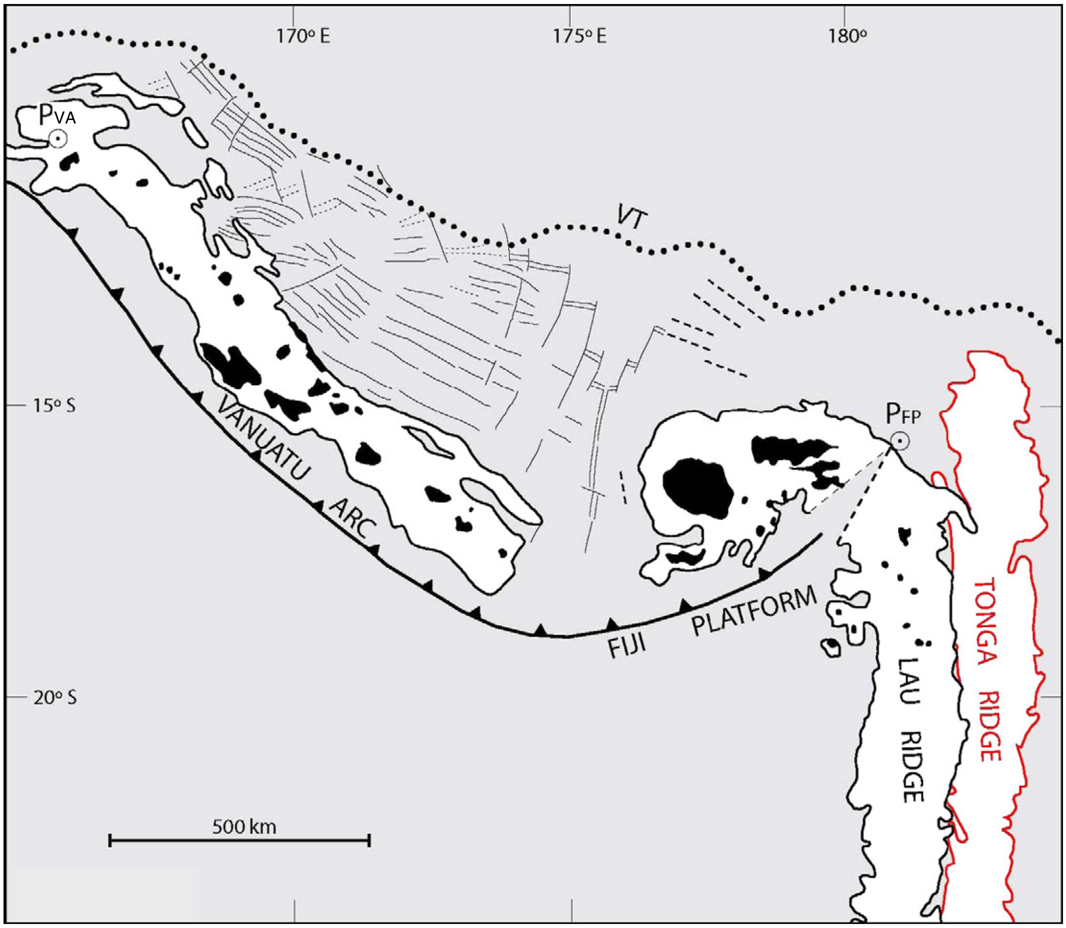

Fig. 2. 6 Ma reconstruction of North Fiji Basin (NFB) prior to Lau Basin opening, with Tonga and Lau Arcs juxtaposed (cf complementary reconstructions, Martin, 2013). VT = Vitiaz Trench. Vanuatu Arc and magnetic lineaments (thin solid and dotted lines) rotated clockwise about pole P VA, whereas Fiji Platform and lineaments (dashed lines) rotated counterclockwise about pole P FP. Paired thin lines represent an R–R–R triple junction which developed as opposite rotations cause WNW–ESE separation of Vanuatu Arc and Fiji Platform.

4.2. Slab generated during double-saloon-door opening of the NFB

Fig. 4 provides a revised scenario for the formation of the slab underlying the NFB. NNE-directed subduction initiates on the combined Vanuatu Arc/Fiji Platform trench 12/10 Ma ago (Fig. 4a). At its eastern end, no slab collision is required to form the curved slab underlying and southeast of the Fiji Platform, but overlying the Tonga slab. Rather, the slab develops a NE-facing concave bend as rollback proceeds (Fig. 4b–d) and toroidal flows enter the mantle wedge from both flanks (cf Fig. 3). The slab is asymmetric, the CCW rotated Fiji Platform is 510 km long whereas the CW rotated Vanuatu Arc is 1163 km in length. Before opening of the Lau Basin, toroidal flow entered the NFB (Fig. 4a and b). Given toroidal flows with radii of 700–800 km (Kneller and Van Keken, 2007; Schellart et al., 2007) or greater (Hall et al., 2000), flow around the Tonga slab edge likely influenced the NFB during opening of the Lau Basin, but with waning effect over time (Fig. 4c–e). At present, the northeastern tip of the Tonga slab (Fig. 1) is just over 700 km from the rotation pole of the Fiji Platform (Fig. 2). ENE–WSW-oriented fast splitting directions on Kadavu Island south of Fiji (Smith et al., 2001), are arc-parallel for the subduction zone southeast of Fiji Platform (Fig. 4b–d), and may relate to toroidal flows modified as in Fig. 3. Similar to Lau Basin, flow around the Tonga slab and influence of the Samoa hotspot have been interpreted in 3 Ma old alkalic volcanism in Fiji (Gill and Whelan, 1989; Smith et al., 2001). The upwelling components of opposite toroidal flows provide a mechanism for observed high heat flow in the NFB (Lagabrielle et al., 1997), while the flow cells (Fig. 3) may explain why enriched MORB and ocean island basalts (OIB) (Guivel et al., 1997) are restricted to the northern NFB (upwelling) rather than extending to the subduction zone (downwelling) (cf similar examples in Alaska and Calabria — Jadamec and Billen, 2010; Schellart, 2010). Tomographic images (Hall and Spakman, 2002; Schellart and Spakman, 2012) suggest that any slab tears may be less extensive than proposed by Richards et al. (2011). After Fiji Platform stopped rotating at 1.5 Ma, with continued Vanuatu Arc rotation, the Hunter Fracture Zone likely developed (Martin, 2013), possibly with a slab tear parallel to it (Fig. 4e). A similar tear may underlie the Epi Fracture Zone where Vanuatu Arc collides with D'Entrecasteaux Ridge and West Torres platform from 3.0–0.7 Ma to the present (Schellart et al., 2002).

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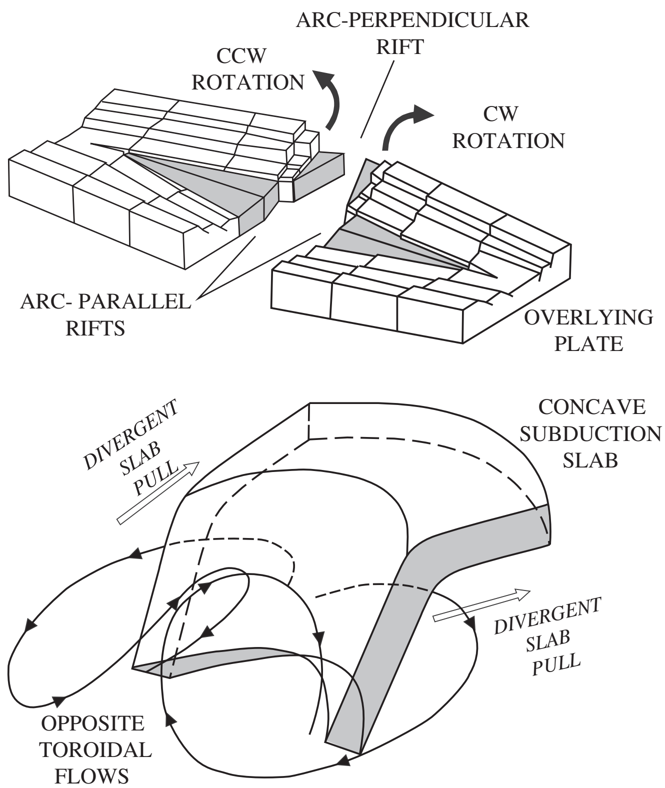

Fig. 3. Proposed geodynamic mechanism for concave slab under the NFB. Rollback induces slab curvature and opposite toroidal flows with upwelling and downwelling components (Faccenna et al., 2010; Funiciello et al., 2006; Schellart, 2008), the latter influenced by slab curvature (Kneller and Van Keken, 2008). Mantle flow is concentrated towards the slab in a central location (curved solid lines with arrows, shown dashed when seaward of the slab). Gravitational forces on either flank of curved subduction slab shown by open white arrows. Rifted island arc crust in overlying plate shown in white with fault block pattern. Oceanic crust lightly shaded.

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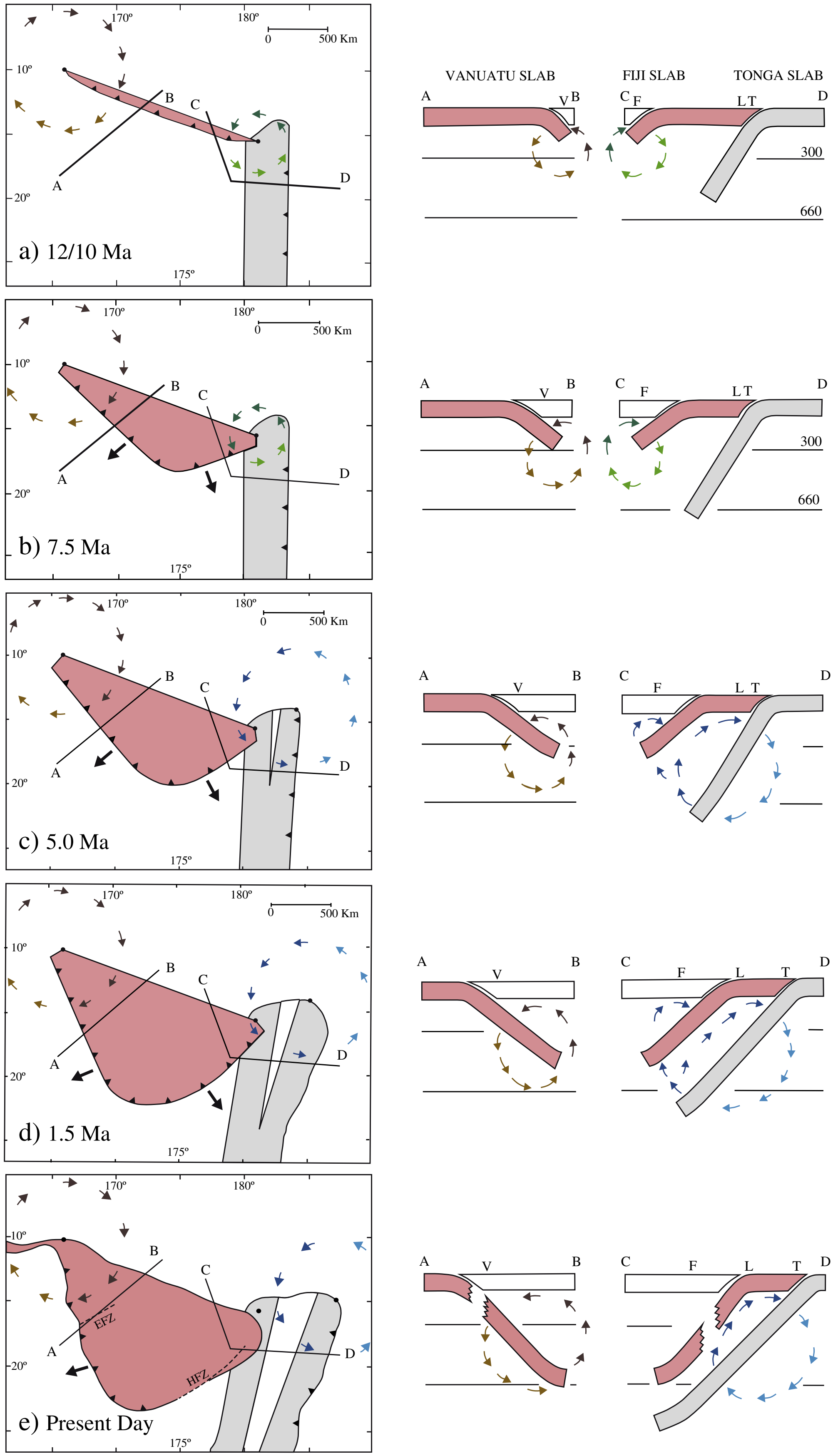
a) 12/10 Ma
b) 7.5 Ma
c) 5.0 Ma
d) 1.5 Ma
e) Present Day
170º
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A
B
C
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HFZ
VANUATU SLAB
FIJI SLAB
TONGA SLAB
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300
660

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Fig. 4. Evolution of slabs underlying the NFB in plan and two cross-sections, based on reconstructions of Martin (2013). Red = combined Vanuatu Fiji Platform slab. Grey = Tonga slab. Toroidal flows around the Vanuatu Arc rotation pole shown in brown arrows, around the Fiji platform rotation pole in green and around the northern end of Tonga slab in blue (lighter colours indicate flows below the slab). Cross-sections are intended to show upwelling and downwelling components of toroidal as opposed to poloidal flows. See Funiciello et al. (2006), Stegman et al. (2006), Schellart (2008) and Faccenna et al. (2010) for the full complexity of flows generated in analogue and numeric models.a) Vitiaz-parallel reconstruction when NE-directed subduction of the Australian Plate started 12/10 Ma ago. Toroidal flow radii shown as 500 km except around the Fiji Platform pole which is shown as 270 km because it may have been restricted by the northern end of the reconstructed Tonga slab (cf Fig. 2), whose hingeline was essentially stationary from 12/10 Ma to 6 Ma. F = Fiji Platform. L = Lau Ridge. T = Tonga Ridge. V = Vanuatu Arc.b) 7.5 Ma reconstruction. Thick black arrows show clockwise rollback of Vanuatu Arc and counterclockwise rollback of Fiji Platform, creating a concave slab (cf Fig. 3).c) 5 Ma reconstruction. Rollback of Tonga slab beginning 6 Ma ago (indicated in white, marking initial opening of overlying Lau Basin) initiates toroidal flow around northern end of Tonga slab (blue arrows). Separate flow cell around Fiji Platform rotation pole is omitted for clarity. Flow likely entered both NFB and Lau Basin mantle wedges.d) 1.5 Ma reconstruction when Fiji Platform stopped rotating (Martin, 2013), as it collided with Lau Ridge.e) Present day. Extent of the combined Vanuatu/Fiji Platform slab based on seismicity outboard of the Tonga slab in zones I and II of Bonnardot et al. (2009). Where Richards et al. (2011) show extensive slab tears, limited tears are shown based on tomography (Hall and Spakman, 2002; Schellart and Spakman, 2012), with gaps indicating possible tears under the Hunter and Epi Fracture Zones. The modelled slab (using rotations of Martin, 2013) extends SE to the Hunter Fracture Zone. Note that Chen and Brudzinski (2001) and Richards et al. (2011) include more hypocentres to the southeast, but these have alternatively been interpreted as extensional or compressional earthquakes related to the upper surface of a Tonga slab double seismic zone (Bonnardot et al., 2009). Lau Basin has expanded, northern Tonga slab is further east and flow into the NFB is reduced or curtailed.