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Mantle avalanche as a driving force for tectonic reorganization in the southwest Pacific

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Abstract

The mechanism responsible for the recent, dramatic reorganization of the tectonic plate boundary in the New Hebrides region of the southwest Pacific has remained elusive. We propose that an ongoing avalanche of cold, dense slab material into the lower mantle, imaged by high-resolution seismic tomographic methods, provides the necessary driving force for this enigmatic evolution. Numerical experiments demonstrate that the avalanche model reconciles a broad suite of observational constraints, including the change in polarity of plate subduction, the rapid migration of the New Hebrides arc and opening of the North Fiji Basin, and the present-day geometry of slabs associated with both active and extinct subduction zones.

Keywords: plate tectonics; subduction; New Hebrides; mantle convection; numerical modeling

1. Introduction

A growing body of evidence suggests that present-day tectonic plate boundaries are subject to a far more complex deformational history than would be expected from simple compressional, extensional or shear forcing. For example, while the overriding plate at oceanic subduction zones is commonly subject to extension, the rich diversity of such 'back-arc' environments suggests that a multitude of deformational mechanisms may be at play [1].

The recent evolution of the New Hebrides subduction boundary (Fig. 1) serves as an intriguing example of this complexity [2–6]. At 10 Ma, subduction of the Pacific plate beneath the Australian plate was occurring along the Solomon–Vitiaz–Tonga–Kermadec trench system [3,7] (Fig. 1A). Various stages of arc volcanism, beginning as early as ∼35 Ma, resulted in a series of island arcs on the Australian side of the subduction trench [8]. At 10 Ma, these island arcs comprised a continuous chain of the present-day Solomon–New Hebrides–Fiji–Lau–Tonga segments [9]. The highly oblique westward subduction at the Vitiaz

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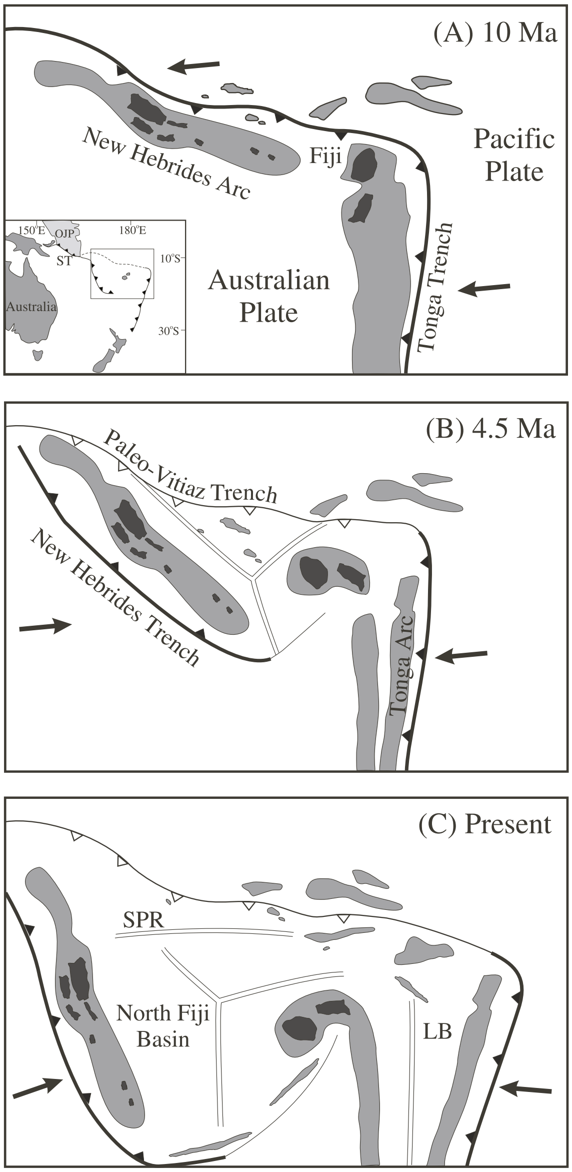


Fig. 1. Tectonic evolution of the Pacific–Australian plate boundary over the last 10 Ma (adapted from [3,4,7]). Solid black arrows are relative plate motion vectors, and the solid and open triangular teeth indicate the position of active and relic trenches, respectively (teeth point toward the overriding plate). Parallel thin lines are spreading centers. The light-shaded regions represent arc terranes, and the darker-shaded regions embedded within these areas are individual volcanic islands. The labels ST, OJP, SPR and LB denote the Solomon trench, Ontong Java Plateau, South Pandora Ridge and Lau Basin, respectively.

trench continued until ~5–7 Ma when the trench jumped across the New Hebrides arc and subduction of the Australian plate at the New Hebrides (Vanuatu) trench commenced [2,3,7,9,10]. Subsequently, the North Fiji Basin rapidly opened as the New Hebrides arc and trench rotated clockwise ~50° in just ~4–6 million years [11] (Fig. 1B, C); this is contemporaneous with a less pronounced clockwise rotation of the Tonga trench [3,7,12]. While plate reconstructions constrain the onset of New Hebrides subduction to be less than 8 Ma [3], geochemical evidence suggests that the main phase of North Fiji Basin opening and New Hebrides arc-trench migration may have occurred as recently as ~3 Ma [13,14]. In its current configuration, the southern tip of the New Hebrides arc-trench is ~1200 km from the fossil Vitiaz trench (Fig. 1C).

Seismic data indicate that the slab subducted at the New Hebrides trench is anomalously steep [1], indeed almost vertical, with a Wadati–Benioff zone extending to ~350 km depth. The North Fiji Basin is characterized by shallow, broadly distributed seismicity with a stress orientation that appears to rotate about an axis close to the southernmost edge of the New Hebrides arc [15]. Deep seismicity (to ~650 km depth) also occurs in the North Fiji Basin [3,16,17], and this has been attributed to detached fragments of lithosphere from fossil Vitiaz subduction [18]. In addition, the basin also exhibits an unusual spreading geometry. Back-arc regions are generally characterized by spreading ridges that are nearly parallel to the associated trench. The North Fiji Basin, in contrast, includes a complicated series of spreading centers, including a ridge–ridge–ridge triple junction (Fig. 1C) with segments oriented almost parallel and roughly perpendicular to the New Hebrides trench [4,6,19]. In addition, both heat flow [21] and seismic attenuation [20] measurements suggest that the basin overlies a relatively hot upper mantle.

What is the driving force responsible for the reorganization of the New Hebrides plate boundary? In this paper we propose that a flux, or 'avalanche', of slab material across the interface between the upper and lower mantle – recently imaged using seismic tomography – provides a geodynamic framework for reconciling both this evolution and the broad suite of observational constraints on present-day mantle, slab and lithospheric dynamics within the region.

2. A mantle avalanche beneath the southwest Pacific

The global endothermic phase transformation of olivine at ~660 km depth introduces buoyancy effects that may act to strongly hinder mass flux across the boundary (e.g., [22]). Indeed, numerical models of mantle convection over the last decade have led to the hypothesis of 'mantle avalanches'; that is, the argument that a primarily two-layered mantle convective regime was punctuated by dramatic episodes of mixing and whole mantle flow [23–26]. Subsequent numerical work has suggested that avalanche events were likely infrequent and less energetic than originally proposed [27,28]. Furthermore, new, lower estimates for the Clapeyron slope of the olivine system at 660 km depth [29], and the potential influence of additional mineral phases [30], introduce uncertainties regarding thermodynamic buoyancy effects near 660 km depth. Nevertheless, the phase transition, together with a viscosity contrast across the same interface, act as an effective, albeit temporary, impediment for slab penetration into the lower mantle [27,31,32]. Indeed, these effects are generally accepted as the explanation for the widespread deflection and accumulation of slab material within the transition zone imaged by seismic tomography (e.g., [33]).

In this regard, a series of seismic tomographic models provide a consistent image of present-day mantle conditions below the New Hebrides region [33,12] (Fig. 2). Specifically, these images indicate that the extensive Tonga slab, generally impeded from descending across the phase transition at ~660 km depth that marks the boundary between the upper and lower mantle, is actively 'avalanching' through this interface [12,34]. In particular, the flux of material is clearly localized to the geographic region centered under the present location of the southern edge of the New Hebrides arc and trench (Fig. 2B–D). Although this flux represents a localized descent of accumulated material through the 660 km depth phase change, rather than a global event, we adopt the term 'avalanche' to describe this flow regime.

Our hypothesis linking the seismically imaged mantle avalanche (Fig. 2) to the reorganization of the New Hebrides plate boundary is as follows. Long-standing subduction of the Pacific plate at Tonga (since at least the middle Eocene [9]) led to an accumulation of slab material above the 660 km boundary (i.e., within the transition zone) to the south of the Vitiaz trench (see Fig. 2A). Subsequently, shallow mantle flow coupled to a geographically localized avalanche of slab material propelled the buoyant island arc southward (i.e., toward the avalanche) in a clockwise fashion (Figs. 1, 2D). The avalanche-induced flow drove a reversal in the polarity of subduction across the arc and a rapid opening of the back-arc North Fiji Basin. This flow would also have contributed to the descent of the fossil Vitiaz slab and be responsible for the steep present-day subduction at the New Hebrides trench. The avalanche model appears to have the correct timing in relation to the observed plate reorganization: Specifically, the seismic model in Fig. 2 [34] indicates that the core of avalanche material is currently ~450 km below the phase boundary and mean extension rates within the basin [6] suggest characteristic flow velocities of ~6 cm/yr. These estimates imply that the avalanche initiated ~8 Ma, in accord with the tectonic reconstruction in Fig. 1.

3. Numerical model and results

We have developed an idealized two-dimensional crust–mantle model of Vitiaz–New Hebrides plate tectonics (Fig. 3A) in order to test our avalanche hypothesis against the observational constraints listed above. Our first simulation (Fig. 3B–D) was performed to model plate–slab–mantle evolution from the onset of the avalanche (Fig. 3A) in a vertical cross-section parallel to the Tonga trench (see profile B–B′ in Fig. 2). The model set-up consists of five heterogeneous regions:

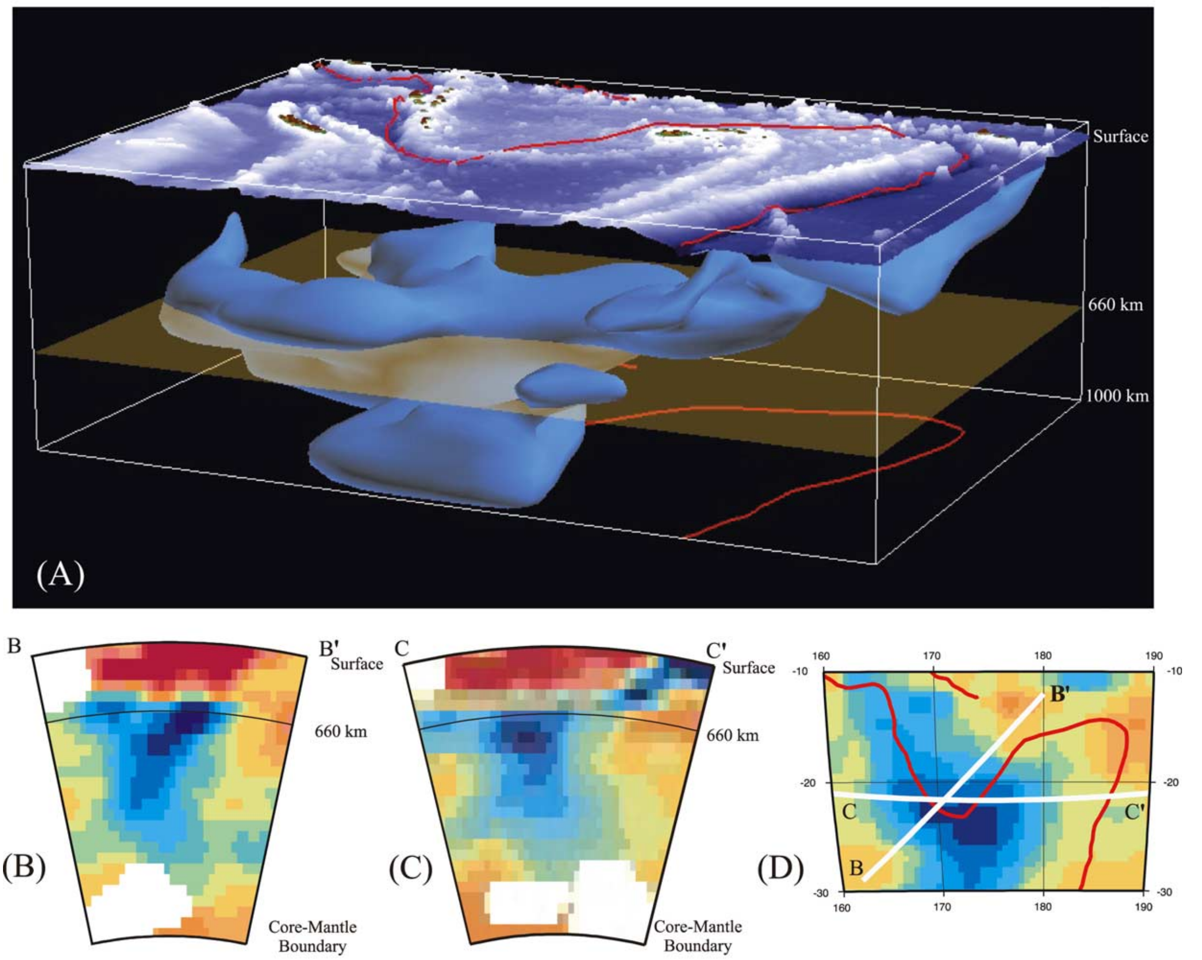


Fig. 2. Seismic tomographic images of mantle structure in the southwest Pacific. (A) Three-dimensional image of the compressional velocity anomaly of van der Hilst et al. [34] plotted under a surface region showing topography. The blue isosurface represents the +0.3% perturbation level relative to a reference Earth model. The solid red line on the top surface of the plot marks the location of the main boundary between the Pacific and Australian plates, while the dashed red line is the relic Vitiaz trench. These lines are copied onto the bottom surface (at 1000 km depth) to aid in visualizing the orientation of the deep slabs relative to the plate boundary structure. The beige horizontal plane is the boundary between the upper and lower mantle at 660 km depth. (B), (C) Vertical cross-sections through the seismic tomographic model along the profiles B–B′ and C–C′ (shown in frame D). (D) Horizontal cross-section through the tomographic model at a depth of 1500 km. Blue colors indicate regions of higher than average velocity (associated with cold material), and red colors indicate regions with lower than average velocity (hot material). Regions in white are areas where no velocity perturbation is available. For comparison of various tomographic models in this region, see [33].

(a) A sub-lithospheric zone with an upper mantle (Newtonian) viscosity of $\eta = 10^{20}$ Pa s and a jump in viscosity to $\eta = 1.4 \times 10^{21}$ Pa s in the shallow lower mantle [35]. (b) Two segments of dense ocean crust lithosphere, with a viscosity two orders of magnitude higher than the underlying mantle, representing the Australian and Pacific plates. These plate regions have a viscous rheology characterized by a factor of ~ 5 strain softening at high strain rates. This rheology permits the dynamic evolution of shear zones in the plates [36,37] as positive feedback of strain weakening causes progressive localization of deformation in the model [38]. The Pacific plate includes ~ 300

km of initial slab penetration (at the Vitiaz trench) into the upper mantle. (c) A 130 km wide region of buoyant lithosphere inserted between the two oceanic plates to model the New Hebrides island arc. (d) A weak zone ($\eta = 10^{20}$ Pa s) at the interface between the island arc and the model Pacific plate. (e) A dense, high-viscosity slab placed above the boundary at 660 km depth representing a cross-section through the Tonga slab prior to the avalanche event.

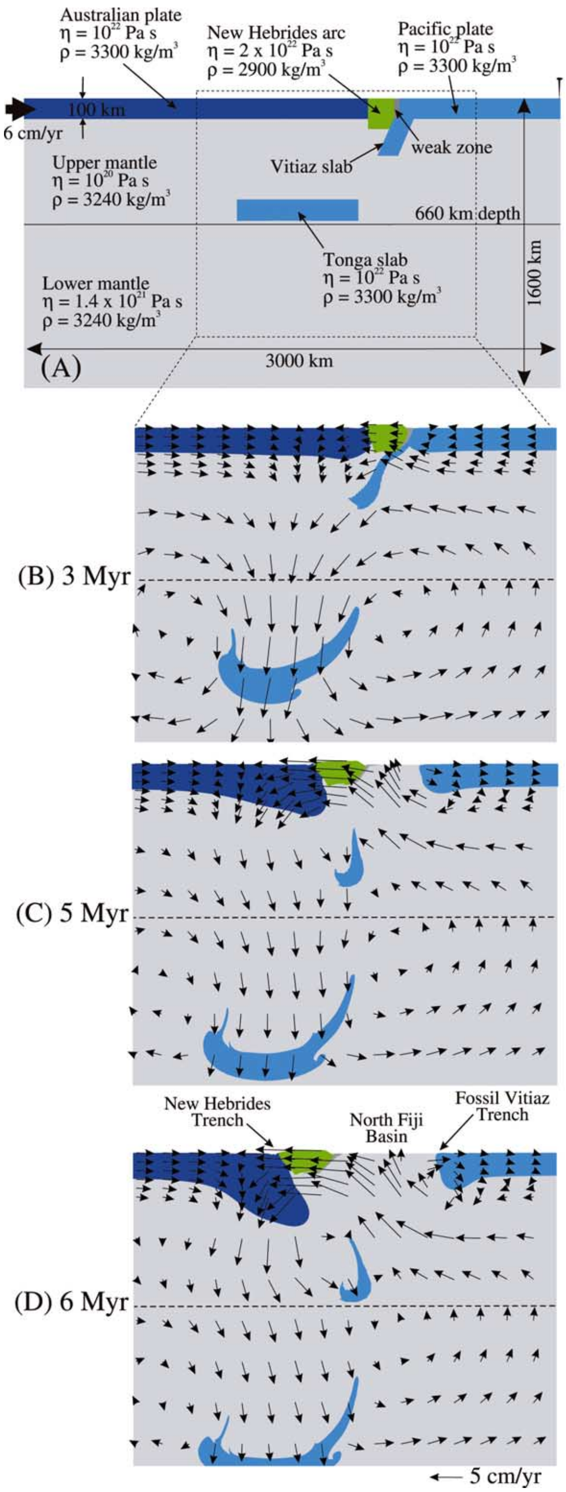
The inclusion of a weak zone between the New Hebrides arc and the Pacific plate is motivated by the tectonic setting of the Vitiaz trench during its phase of active subduction. Convergence along this segment was highly oblique [3,7] (Fig. 1A) and present-day plate boundaries of this type are commonly weakened by accumulated strain and 'slip partitioning' [39–41]. Indeed, plate boundary damage during oblique convergence at the Vitiaz trench is suggested by the analysis of paleomagnetic data from Fiji [42].

The oblique convergence makes it difficult to accurately infer the depth of slab penetration at the Vitiaz trench prior to the cessation of subduction. We have estimated, using present-day plate rotation vectors acting on the reconstructed (10 Ma) Vitiaz boundary geometry, a trench-perpendicular convergence of less than 1 cm/yr. The Vitiaz subduction began in the Eocene [43] and was active for ∼30 Myr [9], suggesting a slab penetration of roughly 300 km, as in Fig. 3A. However, we have found that the regional evolution of the model domain is largely unchanged from Fig. 3B–D for numerical simulations in which the penetration depth is varied from ∼0 to 300 km.

Three million years after the onset of the model avalanche (Fig. 3B) viscous flow coupled to the avalanche event has initiated a reversal in subduction polarity across the New Hebrides arc. Specifically, the downgoing slab at the Vitiaz trench has begun to pinch off from the Pacific plate and the margin of the Australian plate has thickened in response to a collision with the buoyant island arc. At this stage, the arc is being driven southward (left in the figure) and actively deformed by large scale avalanche-induced flow. In an additional 2 Myr (Fig. 3C) north-dipping subduction of the Australian plate has commenced at the new (New Hebrides) trench and the demise of Vitiaz subduction is marked by slab detachment and descent. At the same time, New Hebrides arc migration accelerates and overthrusting of the Australian plate margin is established along a discrete shear zone. The rapid back-arc extension between the New Hebrides arc and Pacific plate during this phase is accompanied by upwelling mantle flow. In the final model snapshot (Fig. 3D), 6 Myr after initiation of the avalanche, steep subduction of the Australian plate is well developed at the New Hebrides trench, and the distance between the two major oceanic plates has widened to ∼750 km despite the imposed convergence of 6 cm/yr. This gap develops by extension within the back-arc; in this regard, a relatively weak spreading center is active just south of the fossil Vitiaz trench. The slab that detached from the Vitiaz trench has descended to the transition zone at the base of the upper mantle. At this stage, the thickened, downgoing Australian slab acts in concert with the avalanche to intensify mantle flow.

Our 2-D model captures the broad evolution of the Vitiaz–New Hebrides system, including the switch in subduction polarity across the island arc and the non-uniform spreading history within the back-arc [13,14]. The success of the model is reinforced by interpreting Fig. 3D as a present-day snapshot and comparing the model predictions with available observational constraints. In particular, the model reconciles: the steepness and depth extent of the Wadati–Benioff zone at the New Hebrides trench [1]; the correlation between the southern edge of the New Hebrides arc and the epicenter of the seismically-inferred slab-avalanche (e.g., [12,34]; Fig. 2D); the development of an extensive back-arc environment [20]; the high heat flow [20] and seismic attenuation [21] in the North Fiji Basin; and even the presence of a detached slab fragment within the transition zone associated with paleo-Vitiaz subduction of the Pacific plate [18].

The location of the avalanche below the southern margin of the present-day New Hebrides arc-trench (Fig. 2D) may reconcile the complex spreading geometry within the North Fiji Basin (Fig. 1C), since the South Pandora Ridge lies roughly along a small circle about the avalanche



center, as well as the shallow seismicity and stress orientation within the basin [15]. Furthermore, the observed rotation of the New Hebrides arc (Fig. 1) appears to be consistent with the slab-avalanche mechanism, since the amount of arc migration is a linear function of the proximity to the avalanche epicenter (Figs. 1, 2).

4. Further discussion

If the slab-avalanche was responsible for the recent plate boundary reorganization within the New Hebrides region, then it is logical to ask why the impact of the event on the dynamics of subduction at the Tonga trench was more subdued. For example, the polarity of Tonga subduction (west-dipping, trench-perpendicular Pacific plate consumption) has, in contrast to the Vitiaz–New Hebrides system, remained stable for tens of millions of years. To explore this issue

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Fig. 3. Numerical simulation of plate–slab–mantle evolution corresponding to the profile B–B′ in Fig. 2B, D. (A) Numerical set-up just prior to the onset of the avalanche. The symbols η and ρ represent dynamic viscosity and density, respectively, within each of the regions defining the initial conditions of the model run. These regions are labeled according to their plate–mantle analogue. The solution space extends to a depth of 1600 km. Alternate experiments extending in depth to the core–mantle boundary showed little difference in the predicted style of slab descent and associated convective flow; thus, a depth of 1600 km was used for the model to optimize resolution within the lithosphere and upper mantle. The equations governing the thermo-mechanical behavior of incompressible viscous material within the model domain are solved using an arbitrary Lagrangian–Eulerian (ALE) finite element technique [51]. The solution space has a free top surface and a closed stress-free bottom boundary. New Australian lithosphere is introduced at the left side of the domain at a rate of 6 cm/yr, in accord with known relative plate velocities, while the Pacific lithosphere is held fixed. An outward flux of material is imposed evenly along sides characterized by sub-lithospheric mantle in order to balance the injected mass. Our numerical code has been benchmarked against several published simulations [52,53]. (B–D) Evolution of a subset of the complete model domain (given by the bounded box in frame A) 3 Myr, 5 Myr and 6 Myr from the onset of the slab-avalanche (i.e., model initiation). The arrows are instantaneous flow velocities (see scale at bottom right).

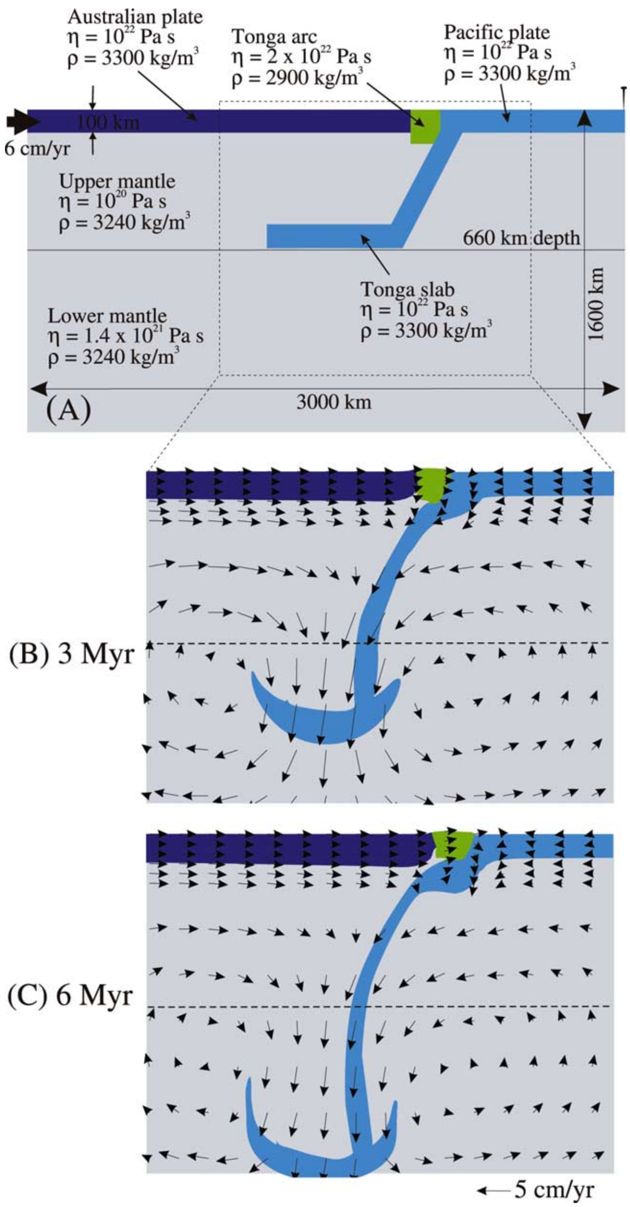

Fig. 4. Numerical model of plate–slab–mantle evolution corresponding to the profile C–C′ in Fig. 2C, D, oriented perpendicular to the Tonga trench. The simulation is initiated (A) just prior to an avalanche of the Tonga slab through the boundary at 660 km depth. The numerical formulation and boundary conditions are described in the caption to Fig. 3. The model is initiated with a mature Tonga slab resting, in part, on the 660 km boundary and results are shown 3 Myr (B) and 6 Myr after the onset of the slab-avalanche.

we modified the numerical simulation to consider plate–slab–mantle evolution in a vertical cross-section perpendicular to the Tonga trench (Fig. 4; see profile C–C′, Fig. 2). Accordingly, the new model was initiated with a more extensive slab penetration into the upper mantle and without a weak zone. In this case, subduction polarity does not reverse, in accord with observations, primarily because the downgoing Tonga slab does not detach and acts as a barrier for lateral flow.

This is not to suggest that the avalanche had no effect on subduction dynamics at Tonga. The simulation in Fig. 4 indicates that the avalanche contributed to the opening of the Lau Basin, which occurred at about the same time as the accelerated opening of the North Fiji Basin [13,14]. Analysis of topography, gravity anomalies and state of stress in the Tonga–Kermadec region suggests a low-viscosity, low-density wedge above the subducted slab [44]. Upwelling flow of mantle asthenosphere material induced by the slab-avalanche (Fig. 3D) and associated heating may be contributing significantly to these inferred wedge conditions.

The contemporaneous evolution of the nearby Solomon trench also raises several interesting issues. Subduction at the Solomon trench reversed polarity at approximately the same time as the cessation of Vitiaz subduction, and this reversal is commonly linked to the collision between the Ontong Java Plateau and the Solomon arc [45]. The temporal similarity has led some to suggest a causal connection between the Ontong Java–Solomon arc collision and the evolution of the Vitiaz–New Hebrides system [50]. However, this connection has several drawbacks. For example, the collision mechanism does not explain the simultaneous presence of back-arc extension within the North Fiji Basin and the absence of back-arc spreading near the Solomon arc (and the associated New Britain and San Cristobal trenches) [46]. Furthermore, the model does not appear to be consistent with the rapid rotation of the New Hebrides arc, the complex back-arc opening of the North Fiji Basin (in particular the existence of a triple junction and trench-perpendicular spreading centers within this basin), or the steepness of the present-day Wadati–Benioff zone for New Hebrides subduction. It is also unclear how the Ontong Java/Solomon collision would have significantly impacted the entire Vitiaz trench, whose eastern edge was ∼1000 km from the plateau. However, it is not unreasonable to assume that the collision played a role, in tandem with the slab-avalanche, in the recent tectonic evolution of this broad region of the southwest Pacific.

Three-dimensional simulations are clearly required to model the tectonic evolution of the entire region as well as observations such as the complex spreading geometry within the North Fiji Basin and the rotation of the New Hebrides arc. For example, there is compelling seismic [47–49] and geochemical [50] evidence for horizontal, trench-parallel upper mantle flow beneath the Tonga arc. The geometry of the slab-avalanche (Fig. 2) suggests that it may provide a driving mechanism for this trench-parallel flow; however, three-dimensional simulations of the plate–mantle system would be required to test this hypothesis. Nevertheless, our simulations, together with constraints on present-day mantle structure available from high-resolution seismic tomography, indicate that a geographically localized slab-avalanche played an important role in the recent, enigmatic evolution of the remarkably complex New Hebrides plate boundary region.

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