Rapid microplate rotations and backarc rifting at the transition between collision and subduction

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ABSTRACT

Using global positioning system velocities from convergent plate boundaries in Papua New Guinea, New Zealand, Tonga, Vanuatu, and the Marianas, we note a spatial correlation between rapid tectonic block rotations and the transition from subduction to collision. We present a mechanism for the block rotations, in which the change from collision of a buoyant indentor to normal subduction exerts a torque on the upper-plate microplate. This work improves our understanding of the causes of rapid vertical axis rotations, often observed in paleomagnetic studies. We also show how collision-induced rotations may lead to backarc rifting.

Keywords: GPS, global positioning system, collision, subduction, microplate rotation, backarc rifting, tectonics.

INTRODUCTION

The fastest modern-day tectonic block rotations, as much as 9°/m.y., occur in the forearcs of convergent plate margins (e.g., Calmant et al., 2003; Wallace et al., 2004a). It has been suggested that the bending and rotation of subduction-zone forearcs can be caused by collision of buoyant features with the subduction zone (e.g., Vogt et al., 1976; McCabe, 1984). Earlier studies of forearc block rotations were based on paleomagnetic declination anomalies that can provide the long-term vertical axis rotation rate, but cannot constrain the full angular velocity, so that the orientation of the spin axis is unknown. Using published global positioning system (GPS) velocities from five convergent margins around the world, we estimate the angular velocities of forearc blocks to reveal an apparent spatial relationship between the rotation of upper-plate microplates and the collisions of buoyant crustal masses (e.g., oceanic plateaus, seamount chains, or continental fragments) with the subduction zones. We suggest that the change from collision to subduction exerts a torque on the upper-plate microplate, causing the microplate to rotate rapidly (relative to the subducting plate) about a point near where the collision occurs. These rotations often result in backarc rifting. Our observations have implications for the knowledge of what drives rapid crustal block rotations, and the causes of backarc rifting.

KINEMATIC MODELING OF BLOCK ROTATIONS AT CONVERGENT PLATE BOUNDARIES

Estimates of tectonic block rotations at subduction margins from GPS velocities during the interseismic period are hampered by the effects of elastic strain due to locking on faults (particularly the subduction zone). To deal with this problem, we simultaneously invert GPS velocities, earthquake slip vector azimuths, transform fault orientations, and long-term geological fault slip rates (including seafloor spreading rates) for angular velocities of tectonic blocks and the degree of coupling on faults bounding the blocks (e.g., McCaffrey, 1995, 2002). Throughout this paper we refer to the point where the angular velocity intersects Earth's surface as the ''pole of rotation.'' We refer to the tectonic blocks or microplates (often coinciding with the forearc and/or arc) as ''convergent plate boundary microblocks.'' In all regions studied, we define the geometry of block boundaries (faults) based on earthquakes and geology. To place the regional GPS velocities into larger plate kinematic contexts, we use GPS velocities from sites on the bounding plates (e.g., Australian, Pacific, and Philippine Sea plates) given in Beavan et al. (2002) and Sella et al. (2002).

Papua New Guinea

Papua New Guinea forms the boundary zone between the obliquely and rapidly (~110 mm/yr) converging Australian and Pacific plates (Fig. 1). The southern boundary of the South Bismarck microplate changes (from west to east) from collision between the Finisterre Range and the underthrusting New Guinea Highlands to subduction of oceanic crust at the New Britain trench in the Solomon Sea. The northern boundary of the South Bismarck microplate is marked by the Manus and New Guinea backarc rifts, which are connected by left-lateral transform faults along the Bismarck Sea seismic lineation (e.g., Taylor, 1979). GPS velocities (Wallace et al., 2004a) show that the South Bismarck microplate rotates clockwise relative to the New Guinea Highlands microplate (the lower plate of the collision) at ~9°/m.y. about a pole where the

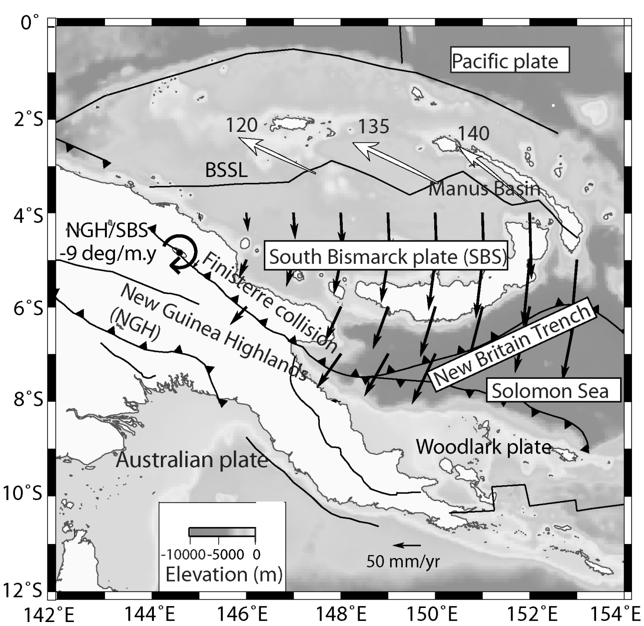

Figure 1. Tectonic setting of Papua New Guinea and vectors showing rotation of South Bismarck plate (SBS) relative to lower plate (see Wallace et al., 2004a, for details of modeling results). Pole of rotation for South Bismarck microplate relative to New Guinea Highlands (NGH) is shown by semicircular arrow, clockwise. Rates of rifting in Manus Basin (white arrows) are given in mm/yr. BSSL—Bismarck Sea seismic lineation. In best-fitting model, we obtain χ^2_n = 1.99, using 333 earthquake slip vectors and 66 global positioning system velocities to estimate 44 parameters.

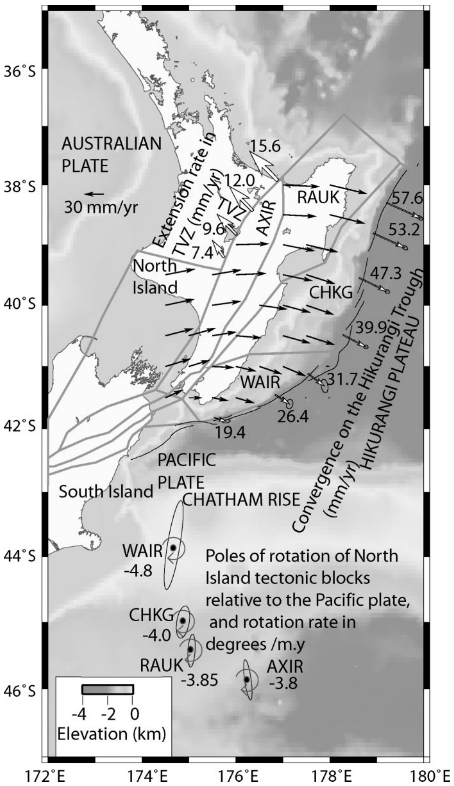

Figure 2. Rotation of New Zealand tectonic blocks relative to Pacific plate and tectonic setting (see Wallace et al., 2004b, for details of modeling results). Tectonic blocks and their respective poles of rotation are labeled (block names: WAIR—Wairarapa, RAUK—Raukumara, CHKG—Central Hikurangi, AXIR—Axial Ranges). White vectors are labeled with extension rates in Taupo volcanic zone (TVZ) and convergence rates at Hikurangi Trough (rates in mm/yr). Note: arrows in TVZ are not to scale. In our best-fitting model, we obtain χ_n^2 = 1.32 from 367 GPS velocities, 10 earthquake slip vectors, and 138 free parameters.

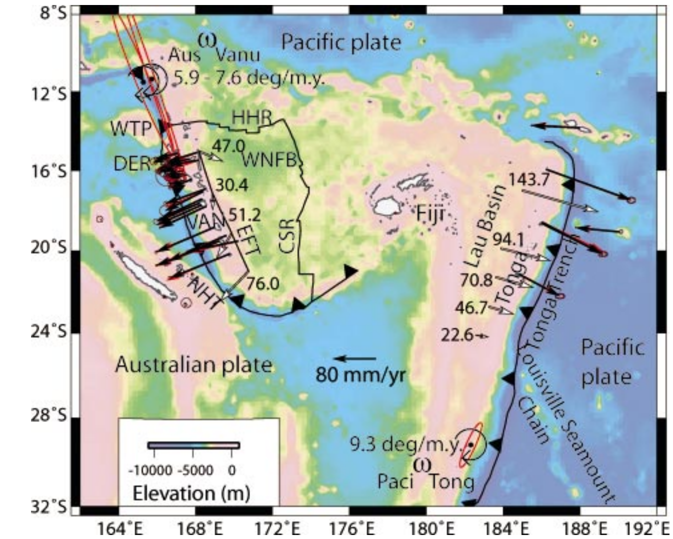

Figure 3. Tectonic setting of Tonga (Tong) and Vanuatu (Van), global positioning system (GPS) velocities (observed, black; model, red), and rotation poles of Vanuatu and Tonga tectonic blocks relative to subducting plate. GPS velocity vectors shown relative to Australian (Aus) plate. White vectors with rates next to them show relative motion in backarc (rates are in mm/yr, predicted from block model). For best model, we obtain χ_n^2 = 2.13, using 952 earthquake slip vectors, 4 spreading rates, and 83 GPS velocities to estimate 42 free parameters. NHT—New Hebrides Trench; EFT—Erromango-Futuna Trough; WTP—West Torres Plateau; DER—D'Entrecasteaux Ridge; VAN—Vanuatu; WNFB—western North Fiji Basin; HHR—Hazel Holme Ridge; CSR—central spreading ridge.

Finisterre collision is most advanced (Fig. 1). South Bismarck microplate rotation results in rapid rifting in the Manus and New Guinea Basins. Paleomagnetic evidence indicates that the South Bismarck microplate has been rotating clockwise at an average rate of 8°/m.y. since the Finisterre collision initiated (Weiler and Coe, 2000), consistent with the geodetic rates.

New Zealand

The plate boundary in the North Island, New Zealand, accommodates subduction of the Pacific plate beneath the North Island at the Hikurangi Trough (Fig. 2). Northeast of the North Island, oceanic crust is subducted at the Kermadec Trench (the northeastern continuation of the Hikurangi Trough). The subducting oceanic Pacific plate changes southward to the Hikurangi Plateau (an oceanic plateau), and eventually the Chatham Rise (a continental fragment) collides with the Hikurangi margin where subduction ceases. GPS velocities show that several crustal blocks in the eastern North Island rotate clockwise at 3.8°–5.0°/m.y. relative to the subducting Pacific plate (Wallace et al., 2004b). Paleomagnetic declinations and geological strain estimates also suggest clockwise rotation of the eastern North Island (e.g., Walcott, 1984; Beanland and Haines, 1998). Backarc rifting in the Taupo volcanic zone (central North Island) is related to eastern North Island rotation. The poles of rotation of the eastern North Island tectonic blocks relative to the subducting Pacific plate are located adjacent to where the buoyant Chatham Rise impinges upon the margin (Fig. 2).

Tonga

The Pacific plate subducts westward beneath the Australian plate (Fig. 3) at the Tonga Trench east of the Tonga Islands. West of Tonga, some of the highest documented rates of backarc rifting in the world are in the Lau Basin (e.g., Bevis et al., 1995; Taylor et al., 1996). The southern limit of rifting in the Lau Basin is near 26°S, adjacent to where the Louisville Seamount chain subducts, and rifting propagates south at ~100 mm/yr (Parson and Wright, 1996; Taylor et al., 1996) (Fig. 3). Much of the rifting history of the eastern Lau Basin is linked to the 128 mm/yr southward migration of the Louisville Seamount chain–Tonga Trench intersection (Pelletier et al., 1998; Ruellan et al., 2003).

GPS velocities from Tonga (Bevis et al., 1995) and 431 earthquake slip vectors on the Tonga Trench indicate that Tonga rotates clockwise (~9.3° ± 0.3°/m.y.) relative to the subducting Pacific plate about a pole just to the south of where the Louisville Seamount chain subducts beneath the margin (Fig. 3). This is comparable to the 6°–8°/m.y. clockwise rotation rate of Tonga estimated from paleomagnetic studies (Sager et al., 1994).

Vanuatu

Vanuatu straddles the Australia–Pacific plate boundary zone between the Tonga-Fiji region and New Guinea (Fig. 3). The major tectonic features in this region are the New Hebrides Trench, where Australia subducts beneath Vanuatu, and a complex series of rifts and transforms in the North Fiji Basin. Subduction of various buoyant features at the New Hebrides Trench (e.g., D'Entrecasteaux Ridge; West Torres Plateau) has influenced the recent deformation of the Vanuatu island chain (e.g., Pelletier et al., 1998; Calmant et al., 2003). Schellart et al. (2002) suggested that the North Fiji Basin is produced by asymmetric opening about a hinge point located near 11°S, 165°E, and that this asymmetric opening is produced by variation in the degree of rollback of the subducting Australian plate.

Following Calmant et al. (2003), we divide Vanuatu into central and southern tectonic blocks and include the western North Fiji Basin as a separate block (Fig. 3). The eastern boundaries of the southern and central blocks coincide with the zone of backarc thrusting and extension just to the east of the island chain. We invert GPS velocities (Calmant et al., 2003), spreading rates (Pelletier et al., 1998), and earthquake slip vectors for angular velocities of the blocks, and coupling on the subduction zone. The poles of rotation for central and southern Vanuatu relative to the Australian plate cluster near 165°E, 11°S, just to the north of D'Entrecasteaux Ridge and West Torres Plateau subduction, with a clockwise rotation rate of 6.0°–7.5°/m.y. (Fig. 3). These rates are comparable to paleomagnetic estimates of 28° of rotation (clockwise) of

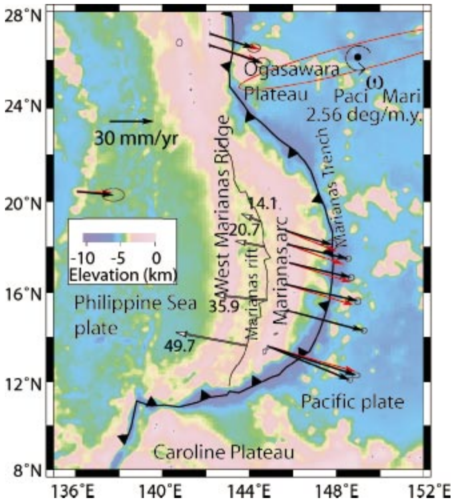

Figure 4. Tectonic setting of Marianas (Mari). Global positioning system (GPS) velocities (observed, black; model, red), and rotation pole of Marianas arc (all relative to Pacific [Paci] plate). White arrows with extension rates next to them (in mm/yr) are predicted relative motion in backarc. For this model, χ^2_n = 2.28, estimating 24 free parameters using 39 local and regional GPS velocities and 23 earthquake slip vectors.

much of Vanuatu since ca. 6 Ma (Falvey, 1978). The clockwise rotation of Vanuatu leads to rifting in the Erromango-Futuna Troughs (30–60 mm/yr) and shortening in the backarc region (north of 18°S) just to the east of Vanuatu (Fig. 3).

Marianas

The Marianas Islands are located between the active Marianas backarc rift and the Marianas Trench, where the Pacific plate subducts westward beneath the Philippine Sea plate (Fig. 4). The Marianas backarc began rifting in the late Miocene, separating the Mariana arc from the West Mariana Ridge (e.g., Karig et al., 1978), and propagated northward with time; the current rift tip is near 24°N (Stern et al., 1984). North of the Marianas, the Ogasawara Plateau collides with the trench, and to the south, the Caroline Plateau impinges upon the margin (Fig. 4). The collision point of the Ogasawara Plateau migrates northward at ~12 mm/yr, based on Pacific and Philippine Sea plate relative motion. McCabe and Uyeda (1983) suggested that the collision of the Ogasawara and Caroline Plateaus with the Marianas Trench explains the curvature and rotation of the Marianas arc.

We estimate the angular velocity of the Marianas arc microplate by inverting GPS velocities from sites in the Marianas Islands (Kato et al., 2003) and earthquake slip vectors on the Marianas Trench. The Marianas arc rotates counterclockwise (2.5° ± 0.8°/m.y.) relative to the subducting (Pacific) plate about a pole of rotation adjacent to where the Ogasawara Plateau collides with the subduction margin (Fig. 4). The GPS-derived kinematics of Marianas backarc rifting are largely consistent with marine geophysical studies, which suggest that opening rates increase from the northern end of the Marianas rift (20°N, ~10 mm/yr) to the southern end (30–45 mm/yr from 18°N to 14°N) (see Kato et al., 2003, for a review).

WHY DO CONVERGENT PLATE BOUNDARY MICROBLOCKS ROTATE RAPIDLY AT SUBDUCTION MARGINS WHERE A COLLISION OCCURS?

In the five areas discussed here, the poles of rotation for the convergent plate boundary microblocks relative to the subducting plate occur near where a buoyant crustal mass collides with the subduction zone (Figs. 1–4). Wallace et al. (2004a) suggested that in Papua New Guinea, the change from collision to subduction explains the rapid rotation of the South Bismarck microplate and subsequent rifting in the Manus Basin. This inference is based on three lines of evidence: (1) the South Bismarck microplate rotates relative to the underthrusting New Guinea Highlands about a pole where collisional resistance forces are expected to be highest (Fig. 1); (2) the Finisterre collision initiated at 3.5–4 Ma (Abbott et al., 1994), while rifting in the Manus Basin began simultaneously or soon afterward, ca. 3.5 Ma (Taylor, 1979); and (3) paleomagnetic studies indicate that the South Bismarck microplate has been rotating at ~8°/m.y. (consistent with the modern geodetic estimate) since Finisterre collision initiation (Weiler and Coe, 2000). Similar (but less complete) arguments can be constructed for the other regions addressed in this paper.

We suggest the following mechanism to explain the observed rapid microplate rotations at convergent margins (Fig. 5). Where a buoyant indentor enters a subduction zone, convergence is inhibited due to high collisional resistance forces, and the convergent plate boundary microblock is pushed into the upper plate as shortening is transferred from the trench into the backarc region. Where subduction of more negatively buoyant oceanic lithosphere occurs, the subducting slab may either roll back (e.g., Molnar and Atwater, 1978), or the position of the slab will remain stationary with respect to the surrounding mantle (e.g., Uyeda and Kanamori, 1979). The slab suction effect (caused by flow patterns induced in the mantle by the subduction process) causes the large upper plate to move toward the subduction zone, and requires the forearc to stay in contact with the subducting plate (e.g., Conrad and Lithgow-Bertelloni, 2004). These two competing effects (i.e., a landward push on the forearc at the collision point, and a trenchward pull where normal subduction occurs) exert a

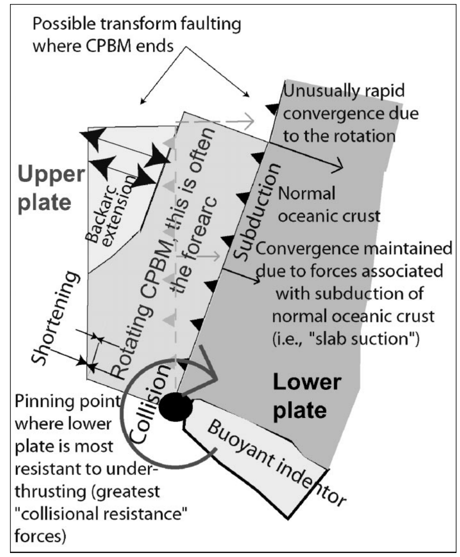

Figure 5. Schematic of our model for collision-induced rotation. CPBM—convergent plate boundary microblock.

torque on the convergent plate boundary microblock, causing it to rotate relative to the lower plate about a pole near where the buoyant indentor enters the subduction zone (Fig. 5). If slab rollback occurs, it will enhance the resulting rotation, although our mechanism does not require rollback of the slab. We must point out that there are some locations where a transition from collision to subduction occurs, yet rapid rotations are not apparent in modern geodetic data (e.g., Nazca Ridge subduction in South America, and Cocos Ridge subduction offshore Costa Rica).

CORRELATION OF COLLISION-INDUCED ROTATIONS WITH BACKARC RIFTING

In all our case study areas, there is a clear link between convergent plate boundary microblock rotation and extension in the backarc region (Figs. 1–5). Does the torque exerted on the microplate by an along-strike change in subducting plate buoyancy merely modify the rate of pre-existing backarc opening, or can it actually trigger localized extension in the backarc? Based on the Papua New Guinea case, we suggest that the latter is possible.

Any viable working hypothesis regarding the origin of backarc rifting must explain the episodic ephemeral nature of most backarc rift systems, the lack of rifting behind most subduction margins, and the rapid rotation of convergent plate boundary microblocks associated with many backarc rifts. Hence, it is likely that a special set of circumstances is required to initiate and maintain backarc rifting. Most proposed models for backarc rifting are two-dimensional, and involve extension as either actively driven by asthenospheric processes (e.g., corner flow and mantle diapir hypotheses), or passively responding to the kinematic boundary conditions (e.g., slab anchor and rollback hypotheses) (see Taylor and Karner, 1983, for a review). None of these can explain the lack of backarc rifting at most subduction zones, or its typically short duration (~10 m.y. or less). Our model of collision-induced rotations and backarc rifting incorporates some of the former mechanisms, but differs in that along-strike variations in the processes are paramount. Invoking collisions as the causative agent in the along-strike variations also satisfies the ephemeral nature of the backarc rifting. This mechanism may also influence backarc rifting in the Okinawa trough and southwest Japan (McCabe, 1984), and the Mediterranean. It is unlikely that our mechanism can explain rifting in the Scotia Basin or Havre Trough, although kinematic data in these locations are too sparse to test this possibility.

Subduction zones are complex systems, and it is likely that feedbacks between the various processes also contribute to the observed nature of rifting. For example, rifting initially induced by collision and rotation may influence flow patterns in the mantle wedge, and facilitate upwelling of molten material, adding to the total extension budget (a positive feedback). Alternatively, the mantle flow may require increasingly large stress, which may limit the deformation rates, or changes in the curvature of the subduction zone or fault orientations resulting from block rotation could affect the force balance of the system.

CONCLUSIONS

We document a correlation between rapid convergent plate boundary microblock rotations and the collision of buoyant features with a subduction margin. To explain this phenomenon, we suggest a mechanism in which the collision modifies the along-strike gradient in the convergence rate, which in turn causes the rapid microplate rotations. In some cases, these tectonic block rotations may lead to backarc rifting.

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