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Quantifying the forces needed for the rapid change of Pacific plate motion at 6 Ma

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ABSTRACT

Studies have documented several rapid changes along the Pacific-North American, Pacific-Antarctic and Pacific-Australian plate boundaries in latest Miocene to earliest Pliocene time consistent with a sudden clockwise rotation of Pacific plate velocity relative to hotspots during this period. We test the hypothesis that this change in plate motion was initiated by cessation of subduction along the northern Melanesian arc due to the collision between the arc and the Ontong Java plateau. This hypothesis has long been formulated but never tested quantitatively. We use a geomechanical model of the lithosphere to determine the changes in plate boundary forces that are necessary to obtain the observed change in the Pacific plate motion. Our model results show that the change in motion can be explained by a clockwise rotation of the slab-related (basal-strength) component of plate driving force. The change of slab-related force from a post-6 Ma to a pre-6 Ma setting is perpendicular to the arc and points towards the Australian plate. The force per unit length is in the range of currently accepted values for subduction zones. Since there have been no other relevant changes at subduction zones along the Pacific plate boundary during the latest Miocene, we relate this change in slab-related force to the former southward-dipping Pacific plate slab along the northern Melanesian arc system which is now detached. Our model results suggest that rapid changes in plate motion can be triggered by slab detachment, with consequences for plate boundary processes even at great distances from the event.

1. Introduction

Abundant evidence for a clockwise rotation of Pacific plate velocity relative to hotspots during the latest Miocene or early Pliocene has been found. *Cox and Engebretson* (1985) identified this change of motion to have occurred at 5 Ma visible in a slight bend in the Hawaiian-Emperor seamount chain at that time. Further investigations of geologic settings along almost the entire Pacific plate boundary as well as magnetic anomalies have supported this finding (*Bevis et al.*, 1995; *Cande and Stock*, 2004; *Harbert and Cox*, 1989; *King*, 2000; *Oskin et al.*, 2001; *Oskin and Stock*, 2003a, b; *Wessel and Kroenke*, 2000). It has been suggested that the change of plate motion was caused by cessation of southward-directed subduction of the Pacific plate along the northern Melanesian arc which was initiated by the collision of the Ontong Java Plateau (OJP) with the arc (*Cox and Engebretson*, 1985; *Harbert and Cox*, 1989; *Knesel et al.*, 2008; *Wessel and Kroenke*, 2000, 2007). *Bercovici et al.* (2000) and *Richards and Lithgow-Bertelloni* (1995b) stress the difficulty of explaining abrupt plate motion changes in terms of continuously evolving mantle buoyancy forces. They point out that perhaps the only way to explain short time-scale changes would invoke mechanisms that pertain to fracture or other rapid rheological responses (*Bercovici et al.*, 2000). Slab breakoff due to cessation of subduction might be such a mechanism as it includes rupture and strain-localization processes.

To test the hypothesis that subduction cessation can be linked to rapid kinematic changes of the Pacific plate we incorporate a geomechanical model of the lithoshpere using the numerical lithosphere code SHELLS (*Kong and Bird*, 1995). To quantify the forces that are related to the plate motion change we pose a tectonic inverse problem by using the change of Pacific plate motion as a boundary condition and investigate the consequent changes in plate driving and resisting forces. This allows us to calculate the changes in slab-related forces and to assess the importance of the plate boundary reorganization along the northern Melanesian arc.

We use a three-step approach: First, we reassess and identify timing by considering clearest and least controversial evidences around the Pacific plate. Second, we quantify the change of motion using Pacific-Antarctic spreading velocities and use the obtained plate velocities as boundary conditions. Third, we use a geomechanical model to calculate plate driving and resisting forces in a pre- and post-6 Ma setting and investigate their relation to a cessation of subduction.

2. Evidence for a clockwise rotation of Pacific plate motion at 6 Ma

In this section we discuss timing of events in the Gulf of California, New Zealand and its vicinity, the Tonga region and the Pitman fracture zone that indicate a change of Pacific plate motion at around 6 Ma.

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Pacific-North American contact was completed at the latitude of the southern Gulf of California at about 12 Ma (*Lonsdale*, 1989). *Atwater and Stock* (1998) used global plate circuit reconstructions to demonstrate that the Pacific plate has been transported 640-720 km to the northwest relative to stable North America since ca. 12.3 Ma. This relative displacement was partitioned into two deformation belts on either side of Baja California and occurred in two distinct kinematic phases of plate margin shearing (*Fletcher et al.*, 2007). The first phase from 12.3 to 6 Ma was accommodated west of Baja California with a total displacement of ca. 300-350 km (*Fletcher et al.*, 2007). At 6.5-6.3 Ma a sudden reorganization of the Pacific-North American plateboundary took place and the residual slip was accommodated in the Gulf of California (*Oskin et al.*, 2001; *Oskin and Stock*, 2003a, b). That means that nearly all of the dextral displacement between the Pacific and North American plates prior to 6.3 Ma took place outside of the Gulf region and just started to localize inside the Gulf prior to 6 Ma. Based on slickenlines on fault surfaces it is known that the orientation of regional extension in the Gulf of California rotated clockwise in the Late Miocene or Pliocene (*Umhoefer*, 2002). Furthermore, transform faults within the Gulf of California do not show any post-Miocene plate motion changes. Thus, the rotation most likely occurred just after the initiation of spreading in the Gulf region. Therefore, the best evidence for a change in motion at the Gulf of California is the clockwise change in extension orientation accompanying the localization of plate motion within the Gulf of California just prior to 6 Ma.

The Southern Alps of New Zealand is a prominent mountain range resulting from ongoing oblique thrusting of Pacific plate crust over the Australian plate along the Alpine Fault (*Sutherland*, 1996). Although this region was under compression for much of Miocene time, geological evidence shows that orogenic uplift initiated at various locations between 8-7 Ma and 5 Ma (*King*, 2000). Many tectonic changes at ca. 5 Ma have been linked to a plate motion change (see *King* (2000) and references therein). Comparison of the observed thermal history of the Southern Alps with that seen in models based on differing hypotheses of the tectonic evolution of the South Island (*Batt and Braun*, 1999) shows that the present tectonic regime of the orogen most probably developed in a single rapid reorganization at approximately 5 Ma with relative stability of the tectonic regime since that time. This situation resembles the plate boundary localization that occurred at ca. 6 Ma in the Gulf of California region.

Based on the analysis of magnetic anomaly and fracture zone data on the Southeast Indian Ridge, *Cande and Stock* (2004) suggested that the onset of the deformation of the South Tasman Sea and the development of the Macquarie microplate south of New Zealand were triggered by the subduction of young, buoyant oceanic crust near the Hjort Trench which is located north of the Australia-Pacific-Antarctic triple junction and attributed it to a clockwise change in Pacific-Australia motion around 6 Ma (see also *DeMets et al.*, 2010).

Drilling and marine geophysical surveys within the Tonga-Lau system have been used to constrain the history of the Lau basin which is located subparallel to and west of the Tonga trench (*Bevis et al.*, 1995). It is assumed that the Lau basin began opening around 6 Ma ago by diffuse Basin and Range style rifting followed by organized seafloor spreading initiating in the north no more than 4 Myr ago and subsequently propagating southwards.

Using magnetic anomaly data collected in conjunction with a multibeam survey of the Pitman fracture zone (*Cande et al.*, 1995), the change in trend of the fracture zone strike around chron 3Ay (6.04 Ma) is visible in the abyssal hill fabric adjacent to the fault (see Fig. 1). The fracture zone trend prior to this time was N60°W to N61°W. By chron 3o time (5.11 Ma) the trend was clearly stabilized at a more clockwise azimuth of N50°W to N48°W. From 6 Ma to 0.76 Ma we do not identify any further persistent change in trend of the Pitman fracture zone.

The uncertainty of all these age estimates varies widely depending on the method that is used. The intersection however, indicates a change at around 6 Ma.

3. Northern Melanesian arc system and the Ontong Java Plateau

A single, semi-continuous arc system existed in the southwest Pacific Ocean in Cenozoic time (*Mann and Taira*, 2004). The northern arm of the arc system, called the northern Melanesian arc system, includes the present-day areas of New Ireland, Solomon Islands, and Fiji (Fig. 2). The eastern arm (the Tonga-Kermadec arc system) includes the present-day areas of Tonga and the North Island of New Zealand. Throughout its history the northern Melanesian arc system went through complicated processes of back-arc opening, rotation and strike-slip faulting. The most important event affecting its evolution was the collision of the OJP with the arc. The OJP is the largest plateau in the world's oceans and together with the Solomon Islands arc has been the focus of many geological and geophysical studies (*Ben-Avraham et al.*, 1981; *Coleman and Kroenke*, 1981; *Hall*, 2002; *Hall and Spakman*, 2002; *Knesel et al.*, 2008; *Musgrave*, 1990; *Petterson et al.*, 1997, 1999; *Tejada et al.*, 2002).

Due to the tectonic complexity of this region timing for the collision between the OJP and the arc is highly debated. There are models with estimates ranging from 25 Ma (*Hall*, 2002; *Knesel et al.*, 2008) to 10 Ma (*Mann and Taira*, 2004). Also the style of collision and the delay between collision and slab breakoff is crucial and a matter of ongoing research (*Glen and Meffre*, 2009; *Petterson et al.*, 1999). Although the exact sequence of events remains uncertain to some extent it is unambiguous that the collision was followed by a subduction polarity reversal as the Australian plate began to subduct northeast at the newly-formed Vanuatu trench. Seismic tomography suggests that this was accompanied by a breakoff of the Pacific plate slab (*Hall and Spakman*, 2002).

4. Model for the change in Pacific plate motion

To quantify the forces that might have caused the change of Pacific plate motion at around 6 Ma, we set up a geomechanical model of the pre- and post-6 Ma setting. The general procedure is to impose an angular velocity vector for each plate, either through a velocity boundary condition on the slabs of subducting plates or through iterative adjustment of a traction boundary condition on nonsubducting plates, and then to solve the momentum equation with realistic lithosphere structure and rheology for the torques. This generates the three components of total torque (lithostatic-pressure, side-strength, and basal-strength) that are needed to obtain the imposed velocity. We do this for both settings and compare the resulting changes in torques (location and magnitude) with what would be expected from a cessation of subduction.

4.1. Determining the angular velocity vector for the change of Pacific plate motion

The angular velocity vectors that we use to model the post-6 Ma setting are given in Table 1 of *Bird* (2003). To model the pre-6 Ma configuration, two changes are made to the present day plate model: The angular velocity vectors for two plates (Pacific and Caroline plate) are changed as well as the subduction polarity along the northern Melanesian arc (see Fig. 2B). Hence, we need to identify an angular velocity vector of the Pacific plate relative to any convenient stable reference before the change in motion when the subduction south of the OJP was

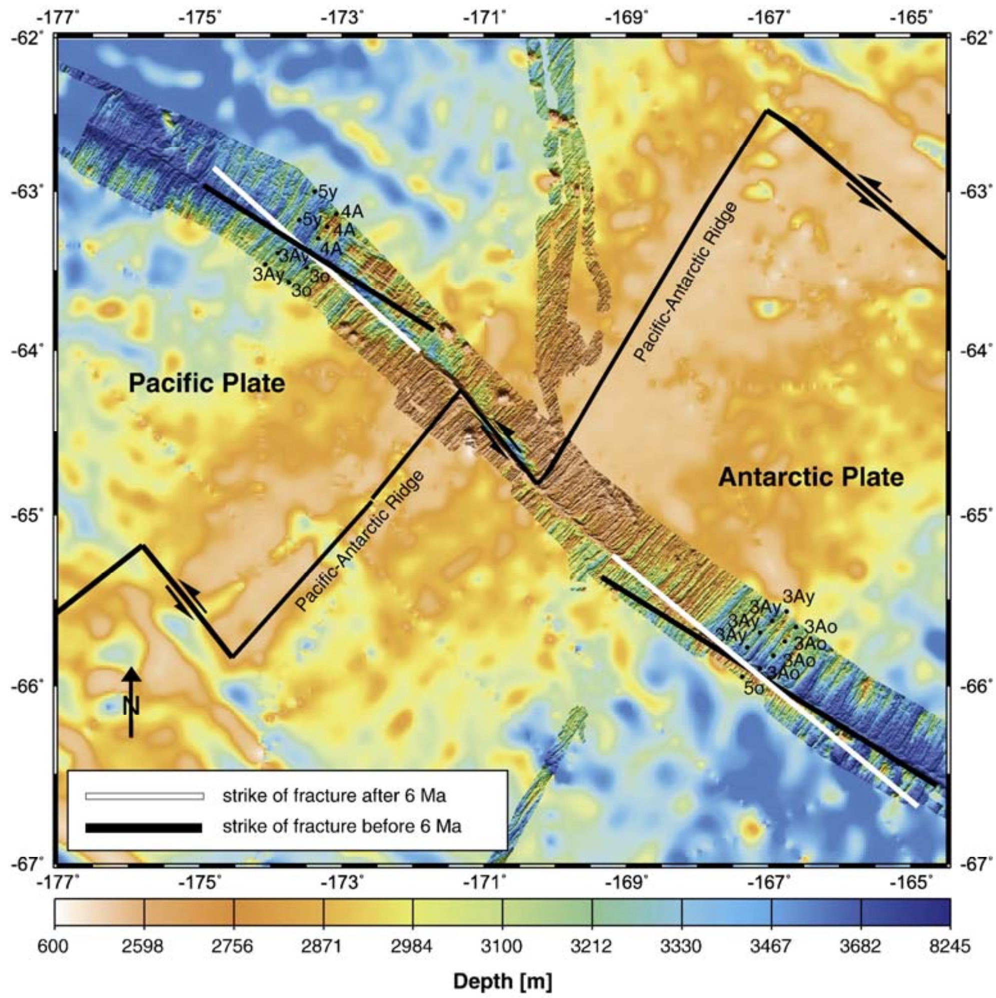

Fig. 1. Pitman fracture zone. Bathymetric map from multibeam data (cruises EW9513, NBP9802, NBP9605, NBP9604) with regional bathymetry derived from satellite gravity plotted with a histogram-equalized color scale. Black lines mark the strike of the fracture before 6 Ma, white lines the present strike. Ages corresponding to chrons are: 3o=5.11 Ma, 3Ay=6.04 Ma, 3Ao=6.71 Ma, 4A=8.86 Ma, 5y=9.74 Ma, and 5o=10.95 Ma (*Croon et al.*, 2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

still active. Antarctica is a convenient choice of reference.

A detailed set of rotation parameters for the Pacific-Antarctic plates since 40 Ma has been obtained using magnetic data from GPSnavigated cruises in the sector between New Zealand, Chile, and Antarctica, largely concentrated on several major fracture zones (*Croon et al.*, 2008). They are displayed in Fig. 3. The finite rotation poles show a major change in motion at the time of chrons 6c-10 (late Oligocene) and a minor change at the time of chron 3Ao (6.71 Ma) (see Fig. 3). The chrons 3o and 3y have slightly anomalous locations. Whereas *Croon et al.* (2008) stress the clockwise change in spreading direction starting around chron 5y we will focus on the later change at around chron 3Ao.

We choose chron 3Ay (6.04 Ma) for a separation between the preand post- change setting since it is the closest time to the postulated time of change at 6 Ma. To obtain stable "before" and "after" velocities we calculate stage rotations for time intervals of approximately 5 Myr before and 6 Myr after chron 3Ay. The stage rotation pole, in an Antarctica reference frame, for the setting before the change is located at 74°S and 107°E, with a rotation rate of 0.87°/Myr. For the setting after the change the stage rotation pole is located at 67°S and 99°E with a rotation rate of 0.86°/Myr. In the reference frame of Antarctica, the angular velocity vector for the change of Pacific plate motion is located at 24°S and 81°W with a rotation rate of 0.12°/Myr. This angular velocity vector is used for further calculations.

Doubrovine and Tarduno (2008) calculated finite rotations for the Pacific-North America plate boundary with a coarser resolution of approximately 3 Myr. Although these calculations are not entirely independent from *Croon et al.* (2008) since they use the East-West Antarctica plate circuit, they can be used for a first order test of consistency. From *Doubrovine and Tarduno's* (2008) finite rotations we obtain the angular velocity vector for the change in motion in a North America reference frame. The two estimates of the differential pole differ in position by 1.2° and in rotation by 0.01°/Myr. This indicates that the two reference frames are very similar and hence the change of motion was mainly accommodated by the Pacific and not the Antarctic or North-American plate. The change in plate motion can be seen in Fig. 4.

4.2. Description of the geomechanical model

The SHELLS code was initially developed by *Kong and Bird* (1995) and has experienced subsequent improvements and modifications. The version we use is contained in the auxiliary material of *Bird et al.* (2008). SHELLS is a finite element code and we use the global Earth5R grid of *Bird et al.* (2008) in contrast to its possible use for regional tectonic modeling (e.g., *Liu and Bird*, 2002). As a neotectonic code, SHELLS does not step through time nor make predictions of finite displacement or finite strain. It is a "thin shell" or "2.5-dimensional" code because it represents the horizontal velocity field of the top of the lithosphere as 2-D, but uses a 3-D model of lithospheric density and strength. The horizontal components of the momentum equation are vertically integrated through the

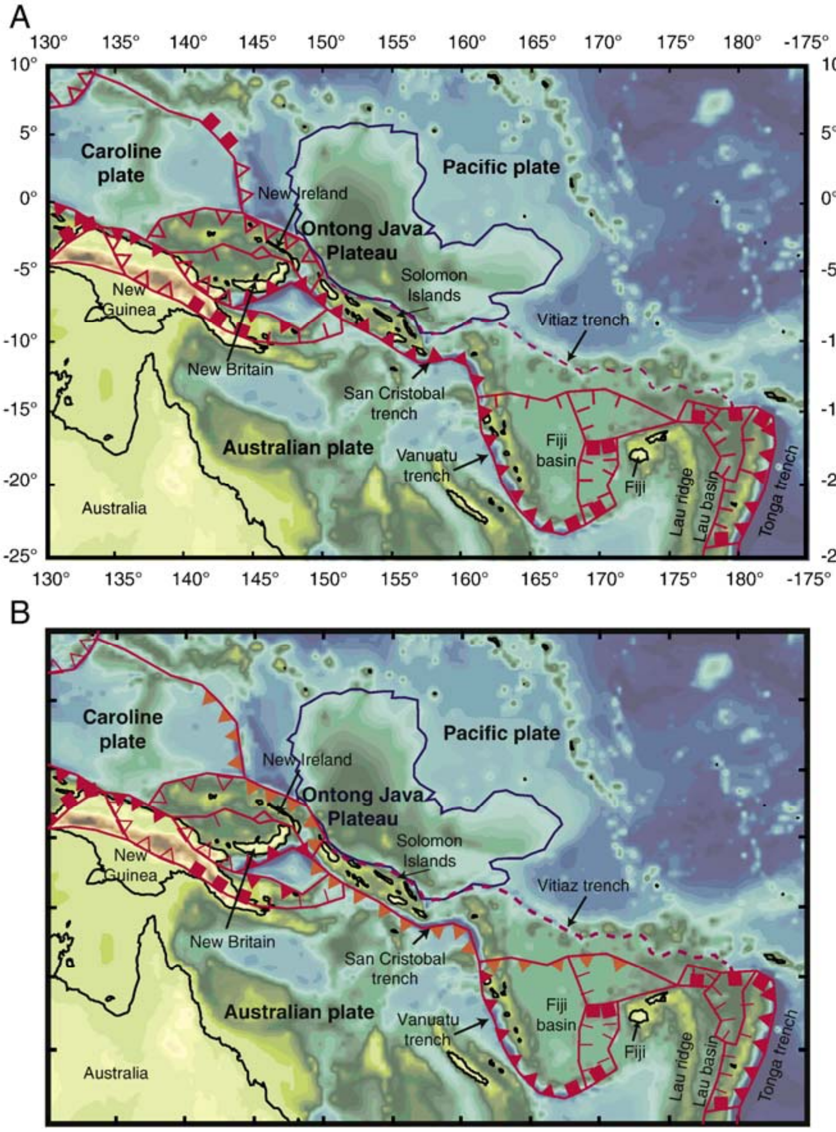

Fig. 2. Topographic map of the northern Melanesian arc system with plate boundaries. The Vitiaz trench (dashed trench) is inactive now and the OJP is outlined for better visualization. Plate boundaries are shown for the A) Earth5Now and B) Earth5Past model. The jump in position of certain subduction zones (relative to Australia) which has probably occurred at the time of their dip reversal has been neglected for simplicity. Also, the slow systematic drift in all plate boundary positions and topologies over the last 6 Myr has been neglected. Open triangles mark collision, solid triangles mark subduction, straight ticks mark spreading ridges, solid squares mark faults of oblique slip and lines without markers are transform faults. Plate boundary changes in panel B are colored orange. Elevations for this figure and Figs. 4 and 5 are from the global 5-min grid ETOPO5 (*NOAA*, 1988). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

plate, and solved in a "weak" or "Galerkin" form.

The model assumes an anelastic rheology and a strength that is limited by one of two competing processes: Mohr-Coulomb-Navier friction and power law dislocation creep. Further assumptions and approximations are given in *Bird et al.* (2008). The code uses a set of model parameters (Table 1 of *Bird et al.* (2008)) and assigns each node a topography, heat flow, and crust and lithosphere thickness. References for the sources of these parameters are given in *Bird et al.* (2008).

SHELLS computes stress and strength tensors and torques for each plate. The torques are divided into three parts: lithostatic pressure, side strength, and basal strength (as defined in *Bird et al.*, 2008). The lithostatic pressure torque represents all effects of lateral changes in gravitational potential energy such as ridge push, topographic trench pull and the topographic pressure part of continental collision resistance. The side strength torque is an integral of the strength over the sides of each plate, which results in resistant plate boundary forces such as transform resistance, trench resistance and the deviatoric stress part of continental collision resistance. The remaining integral of the strength over the base of each plate is described by the basal strength torque which comprises basal drag, net slab pull and slab suction. Assuming that plates are not accelerating at a significant rate these torques add up to zero for each plate since they represent a complete and mutually exclusive list of all torques present.

Since it is not practical or accurate to include subducting slabs within the 2D horizontal model domain, the slab pull forces are represented by velocity boundary conditions imposed on the trench-side edges of the surface portions of subducting plates (only). This follows the concept that subducting slabs are likely to regulate the velocities of their attached plates by exerting net slab-pull forces that depend on plate velocity relative to the deep mantle (*Conrad and Lithgow-Bertelloni*, 2002, 2004; *Forsyth and Uyeda*, 1975; *Richards and Lithgow-Bertelloni*, 1995a). Because the base of the model is arbitrarily taken as 200 km deep in subduction zones, strong subducting slabs pass through this arbitrary boundary. Deviatoric stresses (and more specifically "strength" as defined by *Bird et al.*, 2008) are large in these parts of the bottom boundary of the model domain, so net slab-pull is the major contributor of basal-strength torque for any plate which is

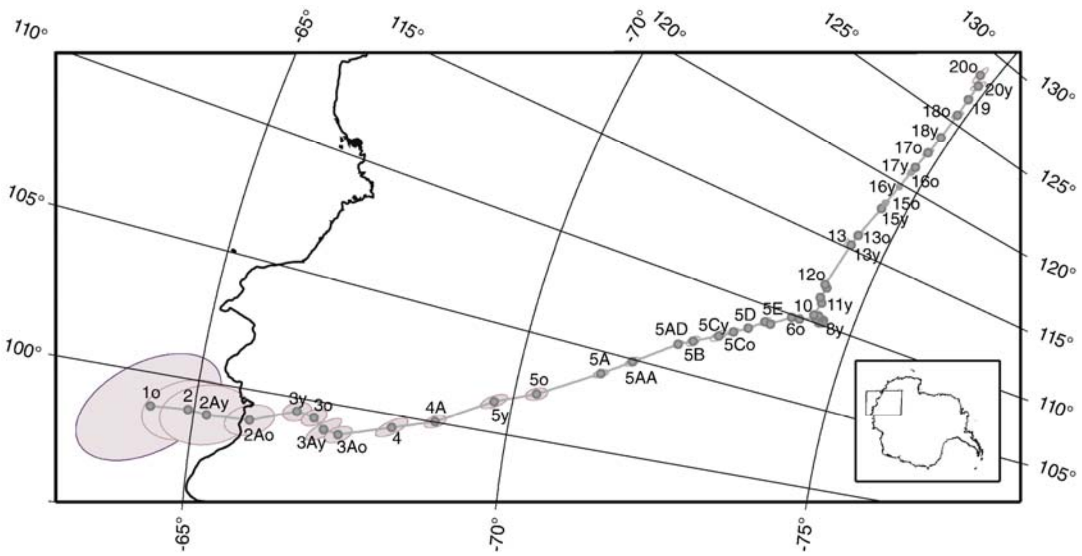

Fig. 3. Reconstruction poles for the Pacific-Antarctic Ridge from Croon et al. (2008). Shaded ellipses show 95% confidence regions. All poles are antipodal to those listed in the *Croon et al.* (2008) paper. Map projection is stereographic centered on 69°S, 180°W.
The figure is adapted from *Croon et al.* (2008). Reproduced/modified by permission of American Geophysical Union.

subducting, including the Pacific plate. However, basal strength torque also includes effects of any broadlydistributed shear tractions on the base of the plate. In practice, it is difficult to distinguish between these two sources of basal strength torque. To simplify the interpretation of models, we do not apply any broadly-distributed basal shear tractions to the bases of subducting plates.

To regulate the velocities of non-subducting plates (and keep them close to velocities inferred in models like PB2002 of *Bird*, 2003), a different kind of basal boundary condition is used. Basal shear tractions are applied across each non-subducting plate based on a "torque pole" (analogous to an Euler pole for horizontally-directed shear tractions, and defined in *Bird et al.*, 2008). Initially, velocity is also imposed at two or more strong points in the plate interior. Through iteration of the solutions, the fictitious resultant point forces at internal points (evaluated after each solution) are redistributed as basal shear tractions (contributing equal torque) so that all fictitious point forces can be removed in the final iteration of the solution. This method yields an Earth-like model (in the sense that all plates have approximately the "correct" rotation poles), plus a precise computation of the basal-strength torque that was required to achieve that rotation. For subducting plates, it is natural to infer that most of the basal-strength torque comes from net slab-pull applied at the trenches; for non-subducting plates, the basal-strength torque must come from distributed basal tractions whose resultant torque must be the same as in the model.

4.3. Model input and assumptions

For a reconstruction of the present plate setting we use plate geometries and material properties of the preferred model Earth5-049 of *Bird et al.* (2008). We will refer to this model as Earth5Now. As discussed above, there is much geologic evidence for a major change in plate motion at about 6 Ma. To obtain a plate setting that represents a pre-6 Ma configuration, some changes are made to the present day plate model: The angular velocity vector of the Pacific plate and the Caroline plate, and the subduction polarity along the northern Melanesian arc, are changed. We will refer to this model as Earth5Past. See Fig. 2(A) and (B) for plate boundaries in the Earth5Now and Earth5Past models.

Using the Earth5Past model to represent a setting just prior 6 Ma implies the following assumptions:

(1) The change in motion of the Pacific plate dominates motion changes of other plates. This can be justified by the following considerations. Major plates are driven by side boundary forces or viscous forces from the mantle. Viscous forces from the underlying mantle change over time scales >100 Myr (*Bercovici et al.*, 2000; *Bunge et al.*, 1998) if the motion of the plate is steady. Plates have therefore not changed their motions due to a change in viscous basal forces in the last 11 Myr. Boundary forces can change geologically fast (which is part of our hypothesis). The subduction reversal along the OJP is the dominant plate boundary change during the time period we consider. Other changes will therefore be neglected. The validity of this assumption is bolstered by the fact that the angular velocity vector that describes the change of motion of the Pacific plate deduced from the Pacific-Antarctic plate boundary and from the Pacific-North America plate boundary are consistent. Small plates on the other hand are generally driven by the balance of edge forces that can change quickly. Their impact on the torque balance of the Pacific plate is, however, limited due to their size. In order to confirm these statements we looked at the vertical integral of the greatest shear stress in the Earth5Past model and found no unrealistic high stress accumulations (such as could result from geometrically-incompatible boundary faults). We observe that all plate boundaries except for the plate boundary with the Caroline plate have reasonable stress values. Much of the boundary between the Caroline and Pacific plates in the Sorol Trough region is interpreted as a transform fault. If this is correct, then the component of Pacific plate velocity which is perpendicular to this transform fault cannot easily be changed without adjusting the velocity of the Caroline plate as well. In our model, we therefore applied the same increment angular velocity to both the Caroline plate and the Pacific plate. This results in plausible stress values along the Pacific-Caroline plate boundary.
(2) The model assumes furthermore that neither the positions of plate boundaries nor the types of plate boundaries have changed (except for the subduction reversal that we applied along the northern Melanesian arc). The plate boundary along the northern Melanesian arc underwent a location shift of approximately 250 km

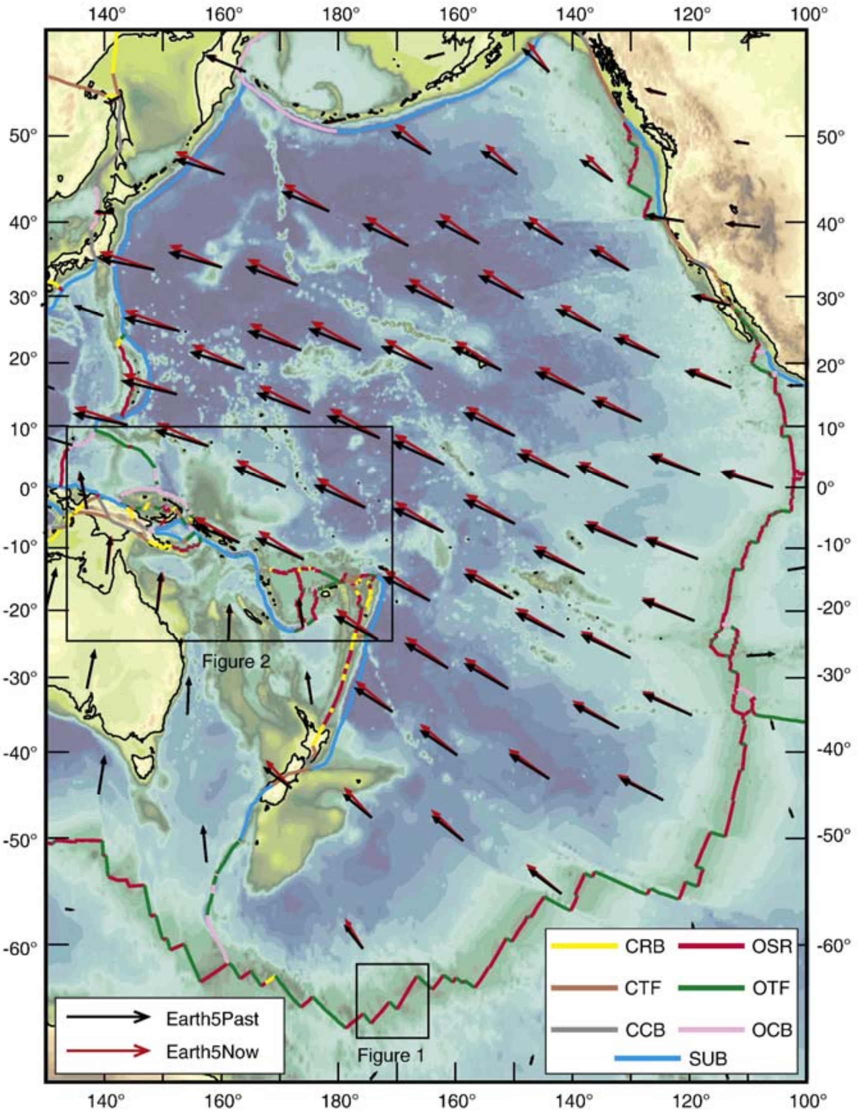

Fig. 4. Comparison between the current plate motion of the Pacific Plate from the Earth5Now model (*Bird et al.*, 2008) and the adjusted Earth5Past model that uses the plate motion before 6 Ma as boundary condition, both in a fixed Africa plate references system. Red arrows display the motion of the Pacific plate according to the plate model Earth5Now, black arrows are the result of the model Earth5Past. Boundary types are taken from *Bird* (2003) and described by its color: CCB continental convergent boundary, CTF continental transform fault, CRB continental rift boundary, OSR oceanic spreading ridge, OTF oceanic transform fault, OCB oceanic convergent boundary, SUB subduction zone. Rectangles refer to more detailed Figs. 1 and 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

from 6 Ma to now (*Mann and Taira*, 2004). We assume that other changes of plate boundary locations are of that order or less. Looking at effects on a global scale, these shifts can be neglected. Plate boundaries along the western Pacific and the Aleutian have been subduction zones for at least 40 Myr. The related slabs are visible on seismic tomography images (*van der Meer et al.*, 2010). *Levin et al.* (2005) proposed a slab detachment along the western Aleutian trench at 10-5 Ma. This change in boundary condition has not been applied in the model Earth5Past but it will be addressed in the discussion. No other major changes in type of plate boundary along the Pacific plate are present. Other plates will not directly interact with the Pacific plate and changes in their type of plate boundaries will therefore be neglected in this first order approach.

5. Results from the modeling approach

The velocity of the Pacific plate in the pre- and post-6 Ma configuration that is used as a kinematic boundary condition is displayed in Fig. 4. The two scenarios give different values of basal strength, side strength and lithostatic pressure torques for the Pacific plate (Table 1). Both cases involve a balance among these three contributions. Since the effect of these torques on the Pacific plate is hard to visualize we use a graphical substitute. Any torque about an axis through the center of the Earth is statically equivalent to a horizontal point force applied to the surface lithosphere along the great circle "equator" of that torque axis. Since the three kinds of torque on each plate add to zero, these three torque vectors are coplanar. This means that their surface great circles all intersect at two diametrically opposed surface points. We choose the surface intersection point inside of or nearest to the Pacific plate, and replace each kind of torque with its statically equivalent point force, using a color code (see Fig. 5 and Table 2). This makes it possible to display the balances of equivalent point forces. It is emphasized that these point forces are unphysical and do not actually exist, neither in the Earth nor in our finite element models.

The change of magnitude of the lithostatic pressure torque is less than 0.1% and the position of the torque changes only by 0.7°. These small deviations result from changes in the dips of certain subduction zones. This causes the down-dip integration

Table 1
Torques of the Pacific Plate in model Earth5Now representing today's plate setting and Earth5Past representing a setting before 6 Ma.

	Earth5Now			Earth5Past		
	Longitude (°E)	Latitude (°N)	Torque (N m)	Longitude (°E)	Latitude (°N)	Torque (N m)
Lithostatic pressure	100.28	−63.83	1.297E+26	99.20	−63.30	1.298E +26
Side strength	−81.08	53.25	2.787E+26	−52.03	67.46	2.362E +26
Basal strength	98.20	−44.29	1.531E+26	163.45	−64.65	1.130E +26

points at depth along some margins of the Pacific plate to be located beneath different topographic elevations where there is a different lithostatic pressure. Additional changes probably of similar small size due to changes in topography since the latest Miocene were neglected for lack of information.

The magnitude of the basal strength torque has increased by 35% from the Earth5Past to the Earth5Now model. The position of the torque has changed by 40.6° which results in a clockwise rotation of 57.8° for the statically equivalent point force from a southwest to a northwest direction. The basal strength torque contains both any basal drag and all slab forces on the Pacific plate. Basal drag and slab suction are both closely linked to mantle convection which only changes on timescales >100 Ma (*Bercovici et al.*, 2000; *Bunge et al.*, 1998). Net slab pull on the other hand might be able to change on much shorter timescales when rupture processes like slab detachment are involved. Our model supports this assumption. The significant change in net slab pull can be related to a former force pointing southwards that ceased from the Earth5Past to the Earth5Now model. The increase in magnitude supports the idea that there were forces acting in opposite directions in the Earth5Past model which resulted in a lower overall basal strength torque. The subduction along the Aleutian trench is opposite to the former subduction zone along the northern Melanesian arc and would have led to partial cancelation of the horizontal parts of net slab pull on the Pacific plate. With a cessation of net slab pull at the OJP, the remaining slab forces are more aligned (pointing in directions ranging from West to North) and therefore result in a higher

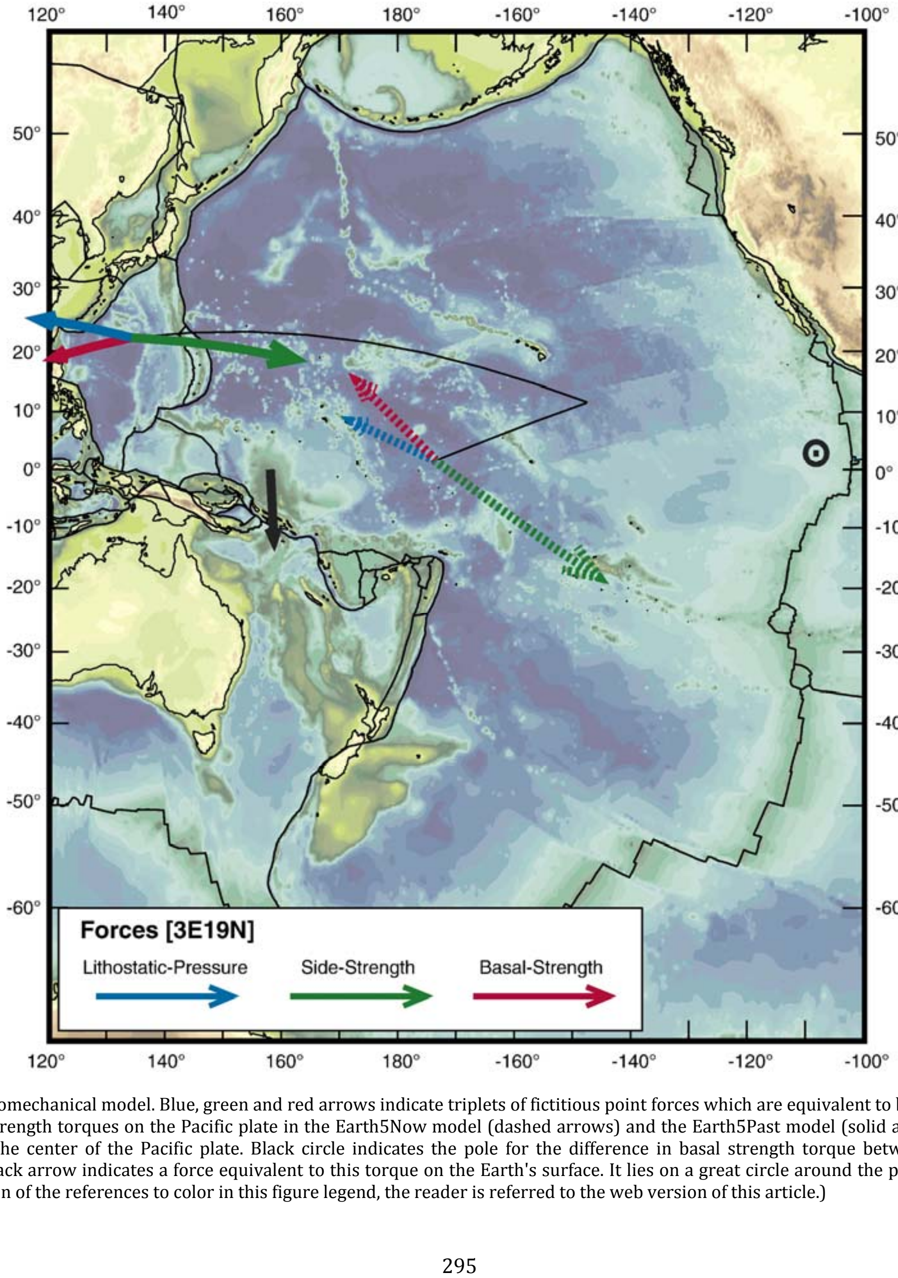

Fig. 5. Results from the geomechanical model. Blue, green and red arrows indicate triplets of fictitious point forces which are equivalent to balanced lithostatic pressure, side strength, and basal strength torques on the Pacific plate in the Earth5Now model (dashed arrows) and the Earth5Past model (solid arrows). The triplets are connected by black lines to the center of the Pacific plate. Black circle indicates the pole for the difference in basal strength torque between the Earth5Past and the Earth5Now model. The black arrow indicates a force equivalent to this torque on the Earth's surface. It lies on a great circle around the pole and is projected onto the equator. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Horizontal forces that correspond to the torques of Table 1 for the Earth5Now and Earth5Past model.

	Earth5Now		Earth5Past	
	Magnitude (N)	Azimuth	Magnitude (N)	Azimuth
Lithostatic pressure	2.036E +19	296.1	2.038E+19	284.9
Side strength	4.374E +19	126.7	3.707E+19	92.3
Basal strength	2.402E +19	315.7	1.774E+19	257.9

magnitude of the basal strength force.

The side strength torque can be formally understood as a torque component needed to balance the two other torque components and prevent unphysical accelerations. Like any SHELLS solution, the Earth5Past model has balanced torques, both on each individual plate, and globally. Changes (relative to Earth5Now) in plate boundary strength forces are communicated to neighboring plates, causing small adjustments in their individual balances, which in our calculations mostly occurred by changing their basal strength torques. These adjustments are too numerous and (mostly) too small to display graphically and therefore the torque balances for plates other than the Pacific plate are not shown in Fig. 5.

6. Discussion

The model results show a clockwise rotation of the basal strength force (Fig. 5) that we interpret as primarily resulting from a clockwise rotation of net slab pull due to the short timescale involved. This change can only be due to either a cessation of net slab pull pointing southwards or an equivalent increase in net slab pull pointing northwards. Along the western and northern Pacific plate boundaries, the Pacific plate has subducted northwestwards continuously for at least the last 40 Myr (*van der Meer et al.*, 2010). Seismic tomography along the Tonga-Kermadec subduction zone shows a continuous westward dipping slab that penetrates into the lower mantle (*Hall and Spakman*, 2002). Therefore subduction has been ongoing since more than 40 Myr. The only change concerning subduction during the latest Miocene and earliest Pliocene apart from the northern Melanesian arc system is postulated along the western Aleutian trench. *Levin et al.* (2005) suggest a slab breakoff between 5 and 10 Ma. This breakoff however cannot be responsible for a clockwise change in slab force rotation since it would result in exactly the opposite, an anticlockwise rotation. To reinforce this statement we modeled a pre-6 Ma scenario with a subduction zone along the western Aleutian trench. The resulting torques show no substantial differences from the torques obtained by the Earth5Past model. We therefore assume that the western Aleutian slab breakoff happened before 6 Ma and did not correlate with the cessation of subduction along the northern Melanesian arc. However, a coupling between those two regions prior to 6 Ma is possible. Taking all this into account, we conclude that the change in net slab pull can only be related to a sudden cessation of subduction along the northern Melanesian arc at around 6 Ma.

To test our hypothesis quantitatively, we analyze the amount of change of basal strength of the Pacific plate. The torque that describes the change in basal strength from the Earth5Past to the Earth5Now setting is located at 3°N, 108°W and has a magnitude of 10^{26} N m (see Fig. 5). To visualize the force that is related to this torque we projected it onto the crossing between the great circle corresponding to the torque and the equator. The force is located at 162°E at an azimuth of 177° and has a magnitude of 1.56×10^{19} N (see Fig. 5). The force points in the direction of past subduction. The northern Melanesian arc has a length of approximately 4000 km. This gives a force per unit length of 3.9×10^{12} N/m along the fault. Making a rough approximation of the thickness of oceanic lithosphere of 100 km due to its age, the implied change in strength is 39 MPa. The force per unit length related to a general slab force is not easy to quantify also because it depends on various parameters such as the dip angle, the plate velocity, the penetration depth and probably more. In a first approximation pure slab pull forces have been estimated to be in the range of $5\text{-}15\times10^{12}$ N/m (*Forsyth and Uyeda*, 1975; *Spence*, 1987; *Turcotte and Schubert*, 2002). More recent simulations however, have suggested that the net slab pull force is of order $4\text{-}6\times10^{12}$ N/m (*Bird et al.*, 2008; *Schellart*, 2004) which is in agreement with our results.

To assess the stability of the results and estimate the uncertainty involved we did the same calculations with the differential pole obtained from *Doubrovine and Tarduno* (2008) (see section 4.1). With this pole, the torque that describes the change in basal strength from the Earth5Now to the Earth5Past setting is located at 5°N, 106°W and has a magnitude of 9×10^{25} N m, i.e. it deviates by 3° in location and 10% in magnitude. This leads to a former net slab pull of 3.5×10^{12} N/m. We infer from this that the overall conclusion is robust with values for net slab pull uncertain by approximately ten percent.

7. Conclusion

Explaining sudden changes in plate motion poses a general challenge due to the long timescale of mantle convection. In this paper we have set up a geomechanical model to quantitatively relate changes in plate velocity to changes in plate driving torques and hence changes in plate boundary forces. This is a valid approach for investigating questions related to plate reorganizations.

The link between a change in Pacific plate motion and cessation of Pacific plate subduction at 6 Ma has been widely discussed qualitatively but few attempts of a quantitative formulation exist. From the modeling results we conclude that there was formerly a net slab pull on the Pacific plate which was pointing southwards before 6 Ma and is not present anymore in the post-6 Ma model. The results are uncertain by a few tens of percent, due to uncertainties in the finite rotations and the approximate plate boundary locations we used to model the pre-6 Ma tectonic setting. Still, the only tectonic event that is evidenced by numerous geological and geophysical observations that can be related to a force of that magnitude and direction even in the limits of uncertainty is a cessation of subduction along the northern Melanesian arc. Therefore, our conclusion is robust and supports the hypothesis that the Pacific plate motion changed due to a cessation of subduction along the northern Melanesian arc.

Our findings are also relevant to the debate about the origin of the ca. 40° bend in the Hawaiian-Emperor seamount chain at 43 Ma. Our results show that a cessation of subduction along an arc of length 4000 km can cause a rotation of plate motion of 5°-15°, i.e., this major geologic event had only a relatively small influence on the Pacific plate motion. This suggests that the bend at 43 Ma must have been either due to a substantial plate reorganization or at least partly due to a moving hotspot as suggested for example by *Tarduno et al.* (2003, 2009).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.epsl.2011.04.043.

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