Faccenna, C., Becker, T. W., Lallemand, S., Steinberger, B. (2012): On the role of slab pull and mid-Cenozoic changes in the motion of the Pacific plate. - Geophysical Research Letters, 39, L03305

DOI: 10.1029/2011GL050155

GEOPHYSICAL RESEARCH LETTERS, VOL. 39, L03305, doi:10.1029/2011GL050155, 2012

On the role of slab pull in the Cenozoic motion of the Pacific plate

Claudio Faccenna,[1,2] Thorsten W. Becker,[3] Serge Lallemand,[4] and Bernhard Steinberger[5,6]

Received 27 October 2011; revised 29 December 2011; accepted 3 January 2012; published 8 February 2012.

[1] We analyze the role of slab pull acting on the Pacific plate during its early Tertiary change in motion. Slab pull forces are estimated by integrating the negative buoyancy of a 700 km long slab along a revised subduction boundary model adopting the Müller et al. (2008) seafloor age reconstructions. Our results indicate that torques predicted from a simple slab pull model match the Pacific plate Euler vectors during the Tertiary fairly well. The change of the Pacific motion at ∼50–40 Ma appears to be driven by the onset of the Izu-Bonin-Mariana system and, soon afterwards, by the Tonga-Kermadec subduction zones. **Citation:** Faccenna, C., T. W. Becker, S. Lallemand, and B. Steinberger (2012), On the role of slab pull in the Cenozoic motion of the Pacific plate, *Geophys. Res. Lett.*, *39*, L03305, doi:10.1029/2011GL050155.

1. Introduction

[2] The motion of tectonic plates is generally considered to be driven by mantle convection, and the plates themselves can be viewed as the top thermo-chemical boundary layer of the mantle. However, it is nonetheless useful to evaluate the different force contributions separately [*Forsyth and Uyeda*, 1975] because this facilitates regional analysis and allows inferences on important parameters such as slab strength. Plates can be: (1) pulled directly into the mantle by the negative buoyancy of the attached, subducting oceanic lithosphere (slab pull [e.g., *Forsyth and Uyeda*, 1975; *Chapple and Tullis*, 1977]), (2) dragged at their base by mantle flow excited by density (thermal) anomalies (slab suction [e.g., *McKenzie*, 1969; *Turcotte and Oxburgh*, 1967; *Forsyth and Uyeda*, 1975; *Hager and O'Connell*, 1981]), (3) propelled by potential energy variations over the oceanic plate (ridge push [*Forsyth and Uyeda*, 1975]) or moved by a combination of some or all these forces [e.g., *Wortel et al.*, 1991; *Becker and O'Connell*, 2001; *Conrad and Lithgow-Bertelloni*, 2004]. Determining the mode of force transmission and discerning between the different contributions from resisting forces within the mantle is complicated by uncertainties such as those about lithospheric and mantle rheology [e.g., *Conrad and Lithgow-Bertelloni*, 2004; *Becker*, 2006]. One possible solution is to analyze the motion of the plate using plate reconstructions [e.g., *Lithgow-Bertelloni and Richards*, 1998; *Conrad and Lithgow-Bertelloni*, 2002, 2004].

[3] The Pacific plate represents a key site to analyze the different force contributions as it is the fastest plate on Earth and is half bounded by subduction zones. In addition, hot spot tracks record a sharp bend that is likely related to force re-organization. Along the Hawaiian-Emperor chain, this bend in the track from NNW to WNW direction (the Hawaiian-Emperor Bend, HEB) occurred between ∼50 and 43 Ma [*Steinberger et al.*, 2004; *Sharp and Clague*, 2006; *Whittaker et al.*, 2007]. Different hypotheses have been proposed to explain the Pacific plate reorganization and in turn related to different processes occurring in or around the Pacific during Cenozoic times [*Lithgow-Bertelloni and Richards*, 1998; *Conrad and Lithgow-Bertelloni*, 2004].

[4] Here, we revise the plate geometry and the tectonic event history in/around the Pacific plate, drawing extensively on the *Müller et al.* [2008] plate and seafloor age reconstructions and the compilation by *Gurnis et al.* [2012]. We compute simplified estimates of the expected slab pull force acting on the Pacific plate and show that the directions of Pacific plate motion are directly related to the slab pull acting on its boundary. Those forces increase rapidly during the inception of the Izu-Bonin-Mariana subduction, moving the Pacific to a more westerly direction.

2. Methods

[5] Several regional tectonic events took place in and around the Pacific during the early Tertiary: the onset of the volcanic arc in the Western Pacific along the Izu Bonin Mariana (IBM) trench at ∼55 Ma, the accretion of the Okhotsk and Aleutian terranes at the junction between Kamchatka and the Aleutians (∼65 to 55 Ma), the subduction of the Kula-Pacific Ridge beneath Kamchatka-Kuril-Japan and Ryuku (∼60 to 50 Ma), and the collision of India with Asia at ∼55–50 Ma [*Patriat and Achache*, 1984]. At least some of these events could have profound consequences on the force equilibrium on the plate.

[6] Here, we test the idea that the change in the plate-mantle force distribution that led to the plate reorganization is reflected in inferred seafloor ages and plate boundaries. The most direct consequence of changing plate configurations is represented by the variation of the slab pull torque acting on the Pacific. We compute the slab pull torque by integrating the inferred slab pull along the entire subduction zone. Following *Turcotte and Schubert* [1982], slab pull can be estimated as:

$$F_{sp} = 0.25\,\Delta\rho g l \cdot 2.32\,(kA)^{1/2} \qquad (1)$$

where l is slab length, assumed constant at 700 km considering the present mean slab dip of 55° of the western Pacific slab [*Lallemand et al.*, 2005], g is gravitational acceleration

[1]Dipartimento di Scienze Geologiche, Università degli Studi Roma Tre, Rome, Italy.
[2]IGAG, CNR, Rome, Italy.
[3]Department of Earth Sciences, University of Southern California, Los Angeles, California, USA.
[4]Laboratoire Géosciences Montpellier, Université Montpellier 2, CNRS, Montpellier, France.
[5]GeoForschungsZentrum Potsdam, Potsdam, Germany.
[6]PGP, University of Oslo, Oslo, Norway.

0094-8276/12/2011GL050155

($\approx$10 ms^{-2}), $\Delta\rho$ is the density contrast between the slab and the mantle, held constant at 70 kg m^{-3}. Slab thickness is estimated from half-space cooling using the square root of age of subducting lithosphere at trench (A), taken from *Müller et al.* [2008] for thermal diffusivity (k) equal to 10^{-6} m^2 s^{-1}. The coefficient 0.25 accounts for the decreasing of the excess mass due to conductive heating of the slab with depth [*Carlson et al.*, 1983]. We integrate the force F_{sp} along the convergent plate boundary segments to determine the total torque due to the subduction zone edge forces, and also express the torque as force per area evaluated at the Pacific plate centroid. Our reconstruction is based on the revised subduction zone geometry and on the geometry of *Gurnis et al.* [2012], and computed slab pull is compared to velocity reconstruction from *Müller et al.* [2008, hereinafter M08]. We considered the direction of subduction and detailed shape of the plate boundary based on a new updated reconstruction and computed forces as discussed below.

[7] For comparison, we also compute slab-pull estimated using subduction zones as compiled by the model of *Gurnis et al.* [2012], with ages of subducted plates as compiled by *Steinberger and Torsvik* [2010] (see auxiliary material) and compare to absolute plate motions from *Steinberger and Gaina* [2007, hereinafter SG07].[1] The *Müller et al.* [2008] model uses a global plate circuit to relate Pacific to African plate motion and, as a consequence, the direction of Pacific plate motion does not feature a sharp change corresponding to the HEB in that model. In contrast, in the *Steinberger and Gaina* [2007] model, which is only based on Pacific hotspots, plate motion changes sharply at ~47 Ma. However this model does not exactly correspond to the seafloor age grid used. Lastly, for comparison, we test the sensitivity of the model to: lithosphere age, positively buoyant contribution of a crustal layer and the approximate effect of conductive heating of the slab with depth.

3. Reconstructions and Slab Pull Estimates

[8] The evolution of the plate boundary as reconstructed here along with the velocity field at each stage is shown in Figure 1.

[9] At ~70 Ma, the Pacific plate is surrounded by ridges [*Whittaker et al.*, 2007]. Subduction was ongoing beneath western US and eastern Asia, as attested by volcanic belts of that age [i.e., *Zonenshain et al.*, 1984], pulling the Farallon or Kula plate, respectively. The plate velocity at this time was ~7 cm/yr in the M08 reference model and <2.4 cm/yr for SG07 (Figures 1, 2a, and S3a). Soon after, on the northwestern Pacific corner, the Okhotsk terrane was accreting. The cessation of the magmatic activity attests that the docking of the Okhotsk terrane against Asia occurred around ~65 Ma [*Zonenshain et al.*, 1990; *Kimura*, 1994; *Konstantinovskaya*, 2001]. At ~60 Ma, a segment of the Young Pacific ocean near the ridge was probably subducting beneath the Okhotsk terrane as constrained by the rapid subsidence of the island arc (called Ozernoy-Valagina) from ~62 to 53 Ma [*Konstantinovskaya*, 2011]. The structural analysis of the Kamtchatka orogen, which is located in the northern part of the Okhotsk accreted terrane, indicates that soon after the subsidence episode, the inactive arc was obducted onto the continental margin (53–50 Ma). Arc volcanism along the Kuril arc resumed then at ~46 Ma [*Konstantinovskaya*, 2011].

[10] The rest of the Kula-Pacific ridge southwest and northeast of the proto-Kuril trench reached the trenches also shortly before ~60 Ma. In the *Müller et al.* [2008] reconstruction, the Kula-Pacific ridges system in fact was almost parallel to trenches [*Whittaker et al.*, 2007]. Hence, an almost contemporaneous surge of volcanism is expected all along the Pacific margin. Previous models, conversely, suggested that a ridge subduction episode occurred 10–20 Myrs earlier [*Maruyama and Seno*, 1986; *Kinoshita*, 2002]. One other possible consequence of the arrival of the ridge into the subduction zone, northeast of the paleo-Kuriles at ~55 Ma, is the accretion of the Aleutia arc terrane. This terrane belonged to the former Kula plate and was accreted at ~50 Ma [*Scholl*, 2007; *Minyuk and Stone*, 2009]. A new subduction zone thus developed possibly along a Kula-Pacific ridge segment, becoming the proto-Aleutian arc, where the oldest volcanic rocks were dated at ~46 Ma [*Scholl*, 2007].

[11] At the same time ~55–50 Ma, several thousands of kilometers to the south near the paleo-equator, the proto-Izu-Bonin-Mariana (*IBM*) trench was initiating, probably along a former transform boundary [e.g., *Uyeda and Ben-Avraham*, 1972; *Stern and Bloomer*, 1992]. This new plate boundary has isolated the "nucleus" of the Philippine Sea plate that grew by spreading of several back-arc basins until present day [*Deschamps and Lallemand*, 2002]. The trench was initially oriented EW [*Hall et al.*, 1995; *Deschamps and Lallemand*, 2002]. Soon after its infant stage, the proto-IBM trench started rolling backward toward the North, with a counter-clockwise rotation pivoting on its eastern tip [*Hall et al.*, 1995; *Faccenna et al.*, 2009, and references therein]. Soon after, around 46 Ma, the proto-Tonga-Kermadec trench and the paleo-Vitiaz trench initiated [*Ewart et al.*, 1977; *Gaina and Müller*, 2007].

[12] Around ~50 Ma, the Pacific plate turned toward a WNW direction; this episode was completed by ~42 Ma [*Sharp and Clague*, 2006; *Wessel and Kroenke*, 2007; *Whittaker et al.*, 2007]. The velocity of the Pacific plate from ~40 Ma onward remained between a WNW and a NW direction (Figure 1). Increasing age of seafloor at the trench produced, around the Oligocene, an overall episode of trench rollback inducing back arc spreading from the Japan Sea, South China Sea, Shikoku and Parece-Vela Basins, Okhotsk Sea, and Commander Basin [*Sdrolias and Müller*, 2006]. The recent pattern of trench migration differs from the early Neogene one. The IBM trench inverted its migration sense from ~8–10 Ma, advancing toward the upper plate [*Faccenna et al.*, 2009, and references therein] while the Japan Sea started a compressional phase in the upper Pliocene [*Lallemand and Jolivet*, 1986]. During the same time, the Ontong-Java plateau collided with the northern Melanesian arc around 12 Ma producing a progressive subduction reversal from east to west [*Mann and Taira*, 2004; *Wessel and Kroenke*, 2000, 2007]. *Austermann et al.* [2011] show that the recent counter-clockwise rotation of 5–15° of the Pacific plate could be due to the cessation of subduction along the northern Melanesia arc. *Faccenna et al.* [2009] proposed that the inversion of the trench motion along the IBM could have contributed to this recent rotation episode.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL050155.

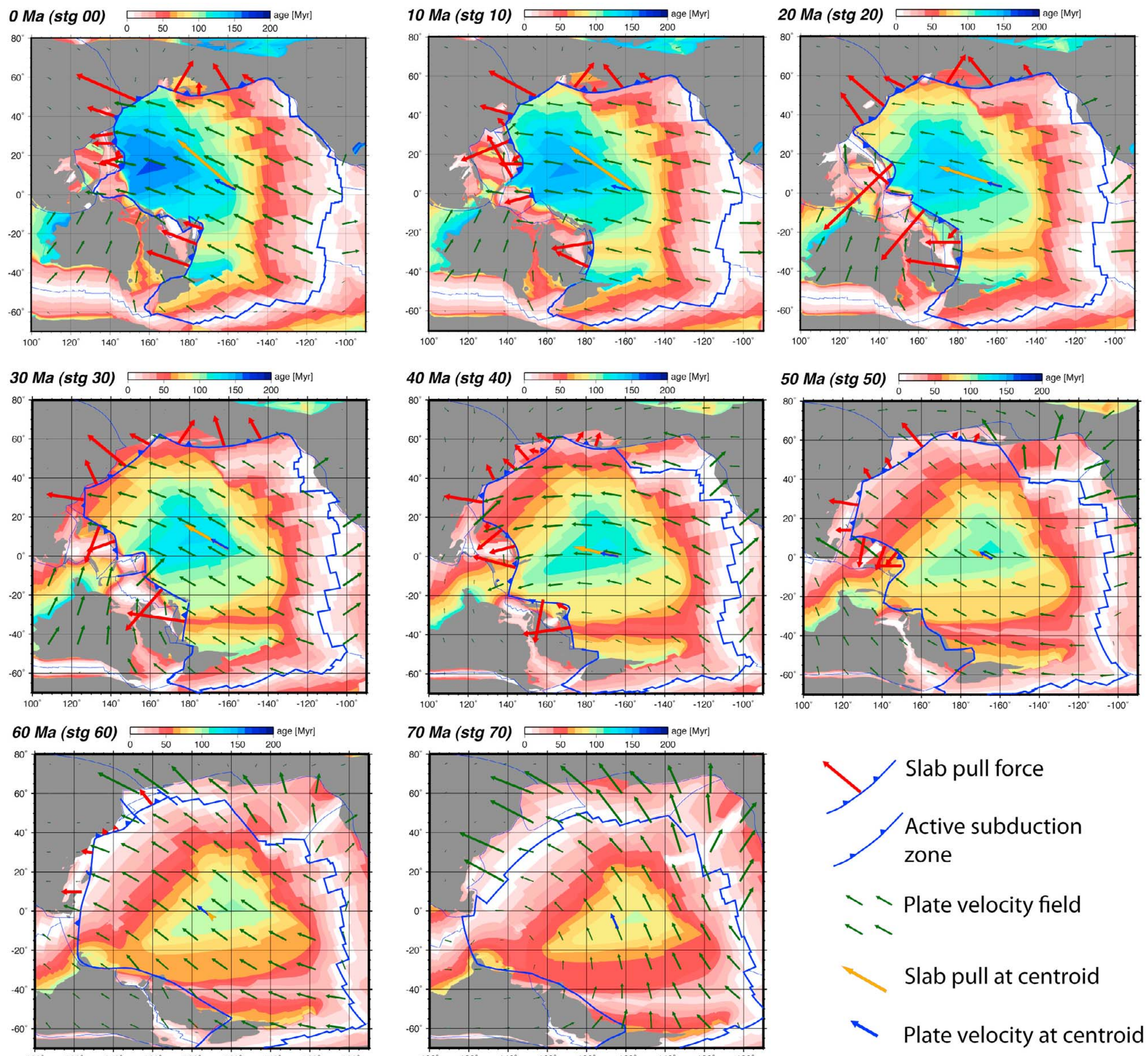

Figure 1. Reconstruction of the Pacific plate during the Tertiary, showing seafloor age, plate velocities (green arrows, both from *Müller et al.* [2008]), plate velocity at centroid (blue arrow), slab pull force along subduction zones (red arrows) as used for torque integration, and resulting slab pull force per area at the centroid (orange arrow). Thick blue lines indicate active plate boundaries along the Pacific plate, convergent when marked by blue triangle.

During this last episode, the velocity of the Pacific increased to ∼9 cm/yr.

[13] Figure 2 shows the estimates of slab pull orientation and intensity for the last 70 Ma, compared along with the velocity of the Pacific plate. During the first phase, at ∼70 Ma, the motion of the Pacific cannot be directly driven by any subducting slabs, hence the slab pull is zero. The value of the slab pull forces rises soon after the subduction of the Kula-Pacific ridge. At ∼60 Ma, slab pull is limited to the newly formed trench related to the accretion of the Okhotsk terrane and to the proto-Ryuku trench, with very low value after the consumption of the trench along the Japan trench. The direction of the slab pull vector is then oriented almost perpendicular to the Japan trench. Around ∼50 Ma, all trench segments around the northwest Pacific were actively pulling. To the west, the activation of the proto-IBM produced a relatively high slab pull directed toward WSW. This counter-balanced the effect of the N/NW directed pull coming from the proto-Japan-Kuril-Aleutian trenches. The resulting slab pull vector rotated by ∼20° counterclockwise toward a more WNW orientation. The onset of subduction around the Tonga-Kermadec trench around ∼40 Ma [*Gaina and Müller*, 2007] produced a supplementary rotation of slab pull of ∼15°.

[14] The activation of the southernmost Pacific subduction system, from paleo Vitiaz to Tonga and Kermadec, and the length increase of the IBM system reinforced the overall W-SW component of slab pull that counter-balances the Aleutian-Kuril system so that the resulting slab pull level is rotating toward a more WNW direction (N290°, Figure 2b). Overall, the mean slab pull level progressively increases, following the increase in the length of the subduction zone

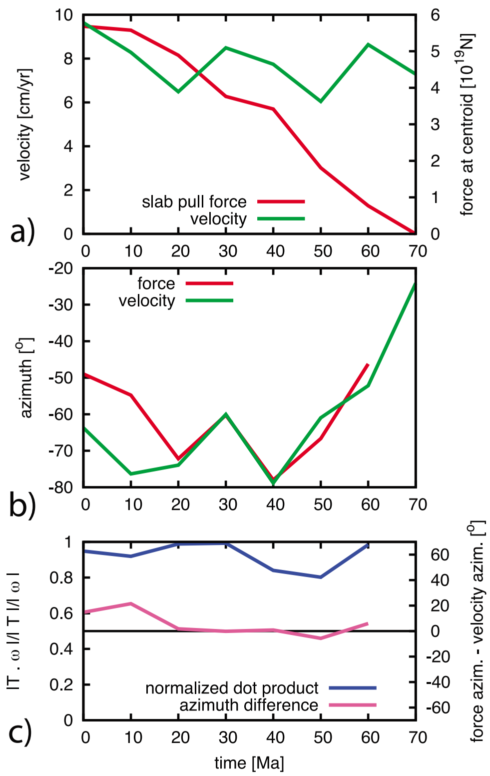

Figure 2. (a) Magnitude of slab pull as evaluated at the centroid from torque integration of the forces shown in Figure 1 and average velocity of the Pacific plate (original reference frame from *Müller et al.* [2008]) versus time. (b) Azimuth (clockwise from North) of the direction of the slab pull and plate velocity at the centroid, and (c) correlation between slab pull torque and Pacific Euler pole (normalized dot product) and azimuth difference between the direction of the slab pull and plate velocity at the centroid.

and the progressive increase of the seafloor age at the trench (Figure 2a).

[15] Figure 2c also shows the correlation between the slab pull torque and the plate Euler vector, which mainly tracks the behaviour seen in the azimuthal differences between the centroid force and velocities. Overall, the match between the slab pull torque and the plate Euler vector is good, showing the gradual rotation of the motion initiated at ~60–50 Ma and completed at ~40 Ma. Minor oscillations of ~10°–15° in the velocity vector at 30 Ma and 20 Ma are also rather well reproduced. The stage at ~10 Ma shows a mismatch of 20° decreasing to the present-day. This mismatch could be halved by considering that the pull of the Vitiaz trench, which is supposed to be terminated at ~12 Ma, is still actively pulling. Overall, the correlation between slab pull and plate velocity at the centroid ranges between 1 and 0.8 (Figure 2).

[16] Similar trends are also obtained by estimating the slab pull torque direction by the subduction zones of *Gurnis et al.* [2012], with ages of subducted plates as compiled by *Steinberger* and *Torsvik* [2010] (Figure S2b). Figure 2a also shows the magnitude of slab pull as evaluated at the centroid from torque integration of the forces shown in Figure 1 and the average velocity of the Pacific plate. The slab pull magnitude increases over time following the overall subducting seafloor ageing and the increase in subduction zone length [*Conrad and Lithgow-Bertelloni*, 2004]. This increase does not mirror an increase in plate speed as from M08, which is only oscillating between 9 and 6 cm/yr, increasing to >9 cm/yr at the present-day. A progressive increase in plate velocity during the Cenozoic is observed, conversely, in other absolute plate velocity models, such as SG07 (Figure S3a).

[17] Sensitivity tests show that the observed trend is robust independent of the adopted seafloor age model or force computation. Similar results are obtained assuming a constant age of 80 Ma at trench for all subduction zones or if slab pull is assumed to scale to the power 3/2 with age, as might be expected for certain conductive heating scenarios, where a stronger age dependence is expected (Figure S2). This indicates that the slab pull torque is mostly sensitive to the slab pull forces' directional distribution rather than their amplitude. Instead, the effect of a positively buoyant crustal and depleted lithospheric layer [e.g., *Davies*, 1992] decreases the slab pull for older stages (Figure S2).

4. Discussion

[18] The change in the Pacific plate motion represents a remarkable and fairly well recorded event for changes in global plate motions. It is reflected by the change of the hotspot tracks, as from the HEB, which was achieved probably over ten million years or less. The HEB is probably in part due to a slowdown in hotspot motion [*Steinberger*, 2000; *Tarduno et al.*, 2003; *Steinberger et al.*, 2004], however, this would likely lead to a smoother curvature of the track. Hence, we regard a change in Pacific plate motion, which is also reflected in a general reorganization of the plate system [*Wessel and Kroenke*, 2008; *Whittaker et al.*, 2007], as the main cause of the bend.

[19] Several mechanisms have been proposed to explain this reorganization. The collision of the India plate could have re-organized the overall plate system, but the force transmission from one plate to the other is probably not sufficient to turn Pacific motions [*Lithgow-Bertelloni and Richards*, 1998]. The avalanche of subducted materials into the lower mantle or a major plume event could potentially produce large scale re-organization (i.e., Réunion hotspot [*Cande and Stegman*, 2011]), but the timescale of the expected process is likely longer, in the order of some ten of Myrs, than the one registered by the Pacific motion. The sudden change of the Pacific-Australian margin from transform to subduction has been considered as the most efficient mechanism [*Richards and Lithgow-Bertelloni*, 1996], as the onset of arc volcanism along the IBM matches fairly well the change in the Pacific plate motion [*Whittaker et al.*, 2007]. None of the models proposed so far quantitatively predict the change in plate motion of the Pacific plate [*Lithgow-Bertelloni and Richards*, 1999]. *Conrad and Lithgow-Bertelloni* [2002, 2004] considered the mutual contribution between slab pull and slab suction and were able to reproduced the global pattern of plate motion, but could not reproduce the change in the Pacific plate.

[20] Here, we argue that the re-organization of the subduction system is able to turn Pacific plate motion toward a more westerly direction. Formally, this hypothesis can be translated into a calculation of slab pull, estimating the variation of the upper mantle portion of the slab around

the Pacific. For simplicity, we assume that all other forces are kept constant during this time interval, a hypothesis that is borne out by the approximate scaling of plate velocity with slab pull. Inspection of Figure 1 shows, for example, that ridge push during the 60, 50 and 40 Ma stages is approximately constant. In this time frame, it is plausible that the lower mantle driving forces, mainly related to a long-term subduction process, do not change much either.

[21] The slab pull force, conversely, does change rapidly in time due to cessation or initiation of subduction. The onset of the proto-IBM and, afterward, of the Solomon-Tonga-Kermadec subduction zones indeed produce a rapid pull directed toward west and south, turning the Pacific velocity by ~40°. This counterbalances the effect of the northern pull of the Aleutian and Kuriles.

[22] If we combine a speed of motion 8 cm/yr (approximate average since the HEB, from Figure 2) with a reasonable estimate of asthenosphere thickness 200 km [e.g., *Cammarano and Romanowicz*, 2007, Figure 2B] we arrive at associated strain-rates of $\varepsilon \sim 1.3 \cdot 10^{-14}$ s^{-1}. Integrating over the area of the Pacific plate A = $1.2 \cdot 10^{8}$ km^2 (approximate average size since the HEB) yields a total shear force of $F_S \sim \varepsilon\, \eta$ A. If we set this equal to the slab pull force of $\sim 4 \cdot 10^{19}$ N (approximate average since the HEB, from Figure 2), that causes this motion, we find a viscosity of $\eta \sim F_S/(A\ \varepsilon) \sim 4 \cdot 10^{19}$ N/($1.2 \cdot 10^{14}$ m$^2 \cdot 1.3 \cdot 10^{-14}$ s^{-1}) $\sim 2.6 \cdot 10^{19}$ Pas, which is a reasonable number for the suboceanic uppermost mantle.

[23] At ~70 Ma, the Pacific plate was not attached to any slabs. Therefore, its northerly motion should have been driven by other causes than slab pull, which is reflected in that the Euler pole is positioned within the plate during that time. The best candidate for the driving forces may be the overall mantle flow dragging the plate, perhaps related to past subduction (slab suction of *Conrad and Lithgow-Bertelloni* [2002]), or driven by lower mantle downwelling or upwellings [*Becker and O'Connell*, 2001; *Conrad and Lithgow-Bertelloni*, 2004; *Forte*, 2007]. Overall, the relationships between slab pull level and plate velocities is not simple (Figure 2a). The M08 plate velocity model, in fact, shows plate speeds remain similar since ~70 Ma, indicating that speed of the Pacific is mainly governed by other forces such as the overall mantle flow. However, this correlation gets more evident adopting other reference frames such as SG07 (Figure S3) or *Gordon and Jurdy* [1986]. The uncertainty in the absolute velocity models leaves unsolved the question if the driving force for plate velocity can be modulated by slab pull, if it is only driven by drag as suggested also by global circulation models [*Becker and O'Connell*, 2001; *Forte*, 2007], or if it is controlled by a correct mix of the two [*Conrad and Lithgow-Bertelloni*, 2004]. The correlation between slab pull torque and plate velocity, conversely, shows more clearly that rapid change in plate velocity direction can be directly correlated to upper mantle traction along subduction zones. The computed force azimuths are more similar to the velocity azimuths with the M08 velocity model, for which the Pacific plate velocity changes direction gradually between 70 and 40 Ma (Figure 2) than for SG07, where it changes more abruptly between 50 and 40 Ma. This could either indicate that Pacific plate motion has indeed changed gradually, but that would then require another explanation for the sharpness of the Hawaiian-Emperor bend, such as a rather abrupt cessation of rapid motion of the Hawaiian hotspot, which is also difficult to explain. Another possibility is that – through some non-linear feedback – Pacific plate motion only changed direction after the westward pull had exceeded a certain threshold. There is also a positive feedback, in that changing plate motions to a more westerly direction leads to more subduction to the west of the Pacific plate which will further increase westward pull.

5. Conclusion

[24] Changes in the Pacific plate motion during the Cenozoic can be explained by a simple model that accounts for the variation in the total upper mantle slab-pull, as predicted by variations in seafloor age at the trench and total active trench length. The model confirms that the onset of Western/Southern Pacific subduction (Izu-Bonin-Mariana and Tonga-Kermadec) plays a primary role in the Eocene Pacific re-organization. Our model matches the smooth change in plate direction as predicted by the *Müller et al.* [2008] model and the velocity increase as predicted by the *Steinberger and Gaina* [2007] plate model.

[25] **Acknowledgments.** We thank D. Müller, R. Wortel and E. Calais for the constructive criticisms, Clint Conrad and Laurent Husson for discussion, M. Gerault and M. Turner for help in extracting plate velocities from the GPlates dataset, and EarthByte Group, Caltech, and the Centre for Geodynamics at the Geological Survey of Norway for providing the GPlates software and plate reconstruction data.

[26] The Editor wishes to thank R. Dietmar Müller and an anonymous reviewer for their assistance evaluating this paper.

References

Austermann, J., Z. Ben-Avraham, P. Bird, O. Heidbach, G. Schubert, and M. J. Stock (2011), Quantifying the forces needed for the rapid change of Pacific plate motion at 6 Ma, *Earth Planet. Sci. Lett.*, *307*, 289–297, doi:10.1016/j.epsl.2011.04.043.

Becker, T. W. (2006), On the effect of temperature and strain-rate dependent viscosity on global mantle flow, net rotation, and plate-driving forces, *Geophys. J. Int.*, *167*, 943–957.

Becker, T. W., and R. J. O'Connell (2001), Predicting plate velocities with mantle circulation models, *Geochem. Geophys. Geosyst.*, *2*, 1060, doi:10.1029/2001GC000171.

Cammarano, F., and B. Romanowicz (2007), Insights into the nature of the transition zone from physically constrained inversion of long-period seismic data, *Proc. Natl. Acad. Sci. U. S. A.*, *104*, 9139–9144, doi:10.1073/pnas.0608075104.

Cande, S. C., and D. R. Stegman (2011), Indian and African plate motions driven by the push force of the Reunion plume head, *Nature*, *475*, 47–52, doi:10.1038/nature10174.

Carlson, R. L., T. W. C. Hilde, and S. Uyeda (1983), The driving mechanism of plate tectonics: Relation to age of the lithosphere at trench, *Geophys. Res. Lett.*, *10*(4), 297–300, doi:10.1029/GL010i004p00297.

Chapple, W. M., and T. E. Tullis (1977), Evaluation of the forces that drive the plates, *J. Geophys. Res.*, *82*, 1967–1984, doi:10.1029/JB082i014p01967.

Conrad, C. P., and C. Lithgow-Bertelloni (2002), How mantle slabs drive plate tectonics, *Science*, *298*, 207–209, doi:10.1126/science.1074161.

Conrad, C. P., and C. Lithgow-Bertelloni (2004), The temporal evolution of plate driving forces: Importance of "slab suction" versus "slab pull" during the Cenozoic, *J. Geophys. Res.*, *109*, B10407, doi:10.1029/2004JB002991.

Davies, G. F. (1992), On the emergence of plate tectonics, *Geology*, *20*, 963–966, doi:10.1130/0091-7613(1992)020<0963:OTEOPT>2.3.CO;2.

Deschamps, A., and S. Lallemand (2002), The West Philippine Basin: An Eocene to early Oligocene back arc basin opened between two opposed subduction zones, *J. Geophys. Res.*, *107*(B12), 2322, doi:10.1029/2001JB001706.

Ewart, A., R. N. Brothers, and A. Mateen (1977), An outline of the geology and geochemistry and the possible petrogenic evolution of the volcanic rocks of the Tonga-Kermadec – New Zealand island arc, *J. Volcanol. Geotherm. Res.*, *2*, 205–250, doi:10.1016/0377-0273(77)90001-4.

Faccenna, C., E. Di Giuseppe, F. Funiciello, S. Lallemand, and J. van Hunen (2009), Control of seafloor aging on the migration of the Izu–

Bonin–Mariana trench, *Earth Planet. Sci. Lett.*, *288*(3–4), 386–398, doi:10.1016/j.epsl.2009.09.042.

Forsyth, D., and S. Uyeda (1975), On the relative importance of the driving forces of plate motion, *Geophys. J. R. Astron. Soc.*, *43*, 163–200.

Forte, A. M. (2007), Constraints on seismic models from other disciplines—Implications for mantle dynamics and composition, in *Treatise on Geophysics*, vol. 1, *Seismology and the Structure of the Earth*, edited by G. Schubert and D. Berovici, pp. 805–858, Elsevier, Amsterdam, doi:10.1016/B978-044452748-6.00027-4.

Gaina, G., and D. Müller (2007), Cenozoic tectonic and depth/age evolution of the Indonesian gateway and associated back-arc basins, *Earth Sci. Rev.*, *83*, 177–203, doi:10.1016/j.earscirev.2007.04.004.

Gordon, R. G., and D. M. Jurdy (1986), Cenozoic global plate motions, *J. Geophys. Res.*, *91*, 12,389–12,406, doi:10.1029/JB091iB12p12389.

Gurnis, M., S. Zahirovic, M. Turner, L. Di Caprio, S. Spasojevic, R. D. Müller, J. Boyden, M. Seton, V. C. Manea, and D. J. Bower (2012), Plate reconstructions with continuously closing plates, *Comput. Geosci.*, *38*, 35–42, doi:10.1016/j.cageo.2011.04.014.

Hager, B. H., and R. J. O'Connell (1981), A simple global model of plate dynamics and mantle convection, *J. Geophys. Res.*, *86*, 4843–4867, doi:10.1029/JB086iB06p04843.

Hall, R., J. R. Ali, C. D. Anderson, and S. J. Baker (1995), Origin and motion history of the Philippine Sea plate, *Tectonophysics*, *251*, 229–250, doi:10.1016/0040-1951(95)00038-0.

Kimura, G. (1994), The latest Cretaceous-early Paleogene rapid growth of accretionary complex and exhumation of high-pressure series metamorphic rocks in northwestern Pacific margin, *J. Geophys. Res.*, *99*, 22,147–22,164, doi:10.1029/94JB00959.

Kinoshita, O. (2002), Possible manifestations of slab window magmatisms in Cretaceous southwest Japan, *Tectonophysics*, *344*, 1–13, doi:10.1016/S0040-1951(01)00262-1.

Konstantinovskaya, E. A. (2001), Arc-continent collision and subduction reversal in the Cenozoic evolution of the Northwest Pacific: An example from Kamtchatka (NE Russia), *Tectonophysics*, *333*, 75–94, doi:10.1016/S0040-1951(00)00268-7.

Konstantinovskaya, E. A. (2011), Early Eocene arc-continent collision in Kamtchatka, Russia: Structural evolution and geodynamic model, in *Arc-Continent Collision, Front. Earth Sci.*, edited by D. Brown and P. D. Ryan, pp. 247–277, Springer, Berlin, doi:10.1007/978-3-540-88558-0_9.

Lallemand, S., and L. Jolivet (1986), Japan Sea: A pull-apart basin?, *Earth Planet. Sci. Lett.*, *76*, 375–389, doi:10.1016/0012-821X(86)90088-9.

Lallemand, S., A. Heuret, and D. Boutelier (2005), On the relationships between slab dip, back-arc stress, upper plate absolute motion and crustal nature in subduction zones, *Geochem. Geophys. Geosyst.*, *6*, Q09006, doi:10.1029/2005GC000917.

Lithgow-Bertelloni, C., and M. A. Richards (1998), The dynamics of Cenozoic and Mesozoic plate motions, *Rev. Geophys.*, *36*, 27–78, doi:10.1029/97RG02282.

Mann, P., and A. Taira (2004), Global tectonic significance of the Solomon Islands and Ontong Java Plateau convergent zone, *Tectonophysics*, *389*, 137–190, doi:10.1016/j.tecto.2003.10.024.

Maruyama, S., and T. Seno (1986), Orogeny and relative plate motions: Examples of the Japanese islands, *Tectonophysics*, *127*, 305–329, doi:10.1016/0040-1951(86)90067-3.

McKenzie, D. (1969), Speculations on the consequences and causes of plate motions, *Geophys. J. R. Astron. Soc.*, *18*, 1–32.

Minyuk, P. S., and D. B. Stone (2009), Paleomagnetic determination of paleolatitude and rotation of Bering Islands (Komandorsky Islands) Russia: Comparison with rotations in the Aleutian Islands and Kamtchatka, *Stephan Mueller Spec. Publ. Ser.*, *4*, 329–348.

Müller, R. D., M. Sdrolias, C. Gaina, B. Steinberger, and C. Heine (2008), Long-term sea-level fluctuations driven by ocean basin dynamics, *Science*, *319*, 1357–1362, doi:10.1126/science.1151540.

Patriat, P., and J. Achache (1984), India–Eurasia collision chronology has implications for crustal shortening and driving mechanism of plates, *Nature*, *311*, 615–621, doi:10.1038/311615a0.

Richards, M. A., and C. Lithgow-Bertelloni (1996), Plate motion changes, the Hawaiian-Emperor bend, and the apparent success and failure of dynamical models, *Earth Planet. Sci. Lett.*, *137*, 19–27, doi:10.1016/0012-821X(95)00209-U.

Scholl, D. W. (2007), Viewing the tectonic evolution of the Kamchatka-Aleutian (KAT) connection with an Alaska crustal extrusion perspective, in *Volcanism and Subduction: The Kamchatka Region*, *Geophys. Monogr. Ser.*, vol. 172, edited by J. Eichelberger et al., pp. 3–35, AGU, Washington, D. C., doi:10.1029/172GM03

Sdrolias, M., and R. D. Müller (2006), Controls on back-arc basin formation, *Geochem. Geophys. Geosyst.*, *7*, Q04016, doi:10.1029/2005GC001090.

Sharp, W. D., and D. A. Clague (2006), 50-Ma initiation of Hawaiian-Emperor Bend records major change in Pacific Plate motion, *Science*, *313*, 1281–1284, doi:10.1126/science.1128489.

Steinberger, B. (2000), Slabs in the lower mantle—Results of dynamic modelling compared with tomographic images and the geoid, *Phys. Earth Planet. Inter.*, *118*, 241–257, doi:10.1016/S0031-9201(99)00172-7.

Steinberger, B., and C. Gaina (2007), Plate tectonic reconstructions predict part of Hawaiian hotspot track to be preserved in Bering Sea, *Geology*, *35*, 407–410, doi:10.1130/G23383A.1.

Steinberger, B., and T. H. Torsvik (2010), Toward an explanation for the present and past locations of the poles, *Geochem. Geophys. Geosyst.*, *11*, Q06W06, doi:10.1029/2009GC002889.

Steinberger, B., R. Sutherland, and R. J. O'Connell (2004), Prediction of Emperor-Hawaii seamount locations from a revised model of plate motion and mantle flow, *Nature*, *430*, 167–173, doi:10.1038/nature02660.

Stern, R. A., and S. H. Bloomer (1992), Subduction zone infancy: Examples from the Eocene Izu-Bonin-Mariana and Jurassic California arcs, *Geol. Soc. Am. Bull.*, *104*, 1621–1636, doi:10.1130/0016-7606(1992)104<1621:SZIEFT>2.3.CO;2.

Tarduno, J. A., et al. (2003), The Emperor Seamounts: Southward motion of the Hawaiian hotspot plume in Earth's mantle, *Science*, *301*, 1064–1069, doi:10.1126/science.1086442.

Turcotte, D. L., and E. R. Oxburgh (1967), Finite amplitude convective cells and continental drift, *J. Fluid Mech.*, *28*, 29–42, doi:10.1017/S0022112067001880.

Turcotte, D. L., and G. Schubert (1982), *Geodynamics: Applications of Continuum Physics to Geological Problems*, John Wiley, New York.

Uyeda, S., and Z. Ben-Avraham (1972), Origin and development of the Philippine Sea, *Nature*, *240*, 176–178.

Wessel, P., and L. Kroenke (2000), Ontong Java Plateau and the late Neogene change in Pacific motion, *J. Geophys. Res.*, *105*, 28,255–28,277, doi:10.1029/2000JB900290.

Wessel, P., and L. W. Kroenke (2007), Reconciling late Neogene Pacific absolute and relative plate motion changes, *Geochem. Geophys. Geosyst.*, *8*, Q08001, doi:10.1029/2007GC001636.

Wessel, P., and L. W. Kroenke (2008), Pacific absolute plate motion since 145 Ma: An assessment of the fixed hot spot hypothesis, *J. Geophys. Res.*, *113*, B06101, doi:10.1029/2007JB005499.

Whittaker, J., R. D. Müller, G. Leitchenkov, H. Stagg, M. Sdrolias, C. Gaina, and A. Goncharov (2007), Major Australian–Antarctic plate reorganization at Hawaiian–Emperor bend time, *Science*, *318*, 83–86, doi:10.1126/science.1143769.

Wortel, M. J. R., M. J. N. Remkes, R. Govers, S. A. P. L. Cloetingh, and P. T. Meijer (1991), Dynamics of the lithosphere and the intraplate stress field, *Philos. Trans. R. Soc. A*, *337*, 111–126, doi:10.1098/rsta.1991.0110.

Zonenshain, L. P., L. A. Savostin, and A. P. Sedov (1984), Global paleogeodynamic reconstructions for the last 160 million years, *Geotectonics, Engl. Transl.*, *18*(3), 181–195.

Zonenshain, L. P., M. I. Kuzmin, L. M. Natapov, and B. M. Page (Eds.) (1990), *Geology of the USSR: A Plate-Tectonic Synthesis*, *Geodyn. Ser.*, vol. 21, AGU, Washington, D. C.

T. W. Becker, Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089, USA.

C. Faccenna, Dipartimento di Scienze Geologiche, Università degli Studi Roma Tre, Largo S. Leonardo Murialdo 1, I-00146 Roma, Italy. (faccenna@uniroma3.it)

S. Lallemand, Laboratoire Géosciences Montpellier, Université Montpellier 2, CNRS, CC. 60, place E. Bataillon, F-34095 Montpellier CEDEX 5, France.

B. Steinberger, GeoForschungsZentrum Potsdam, Telegrafenberg, D-14473 Potsdam, Germany.