Feedback between mountain belt growth and plate convergence

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ABSTRACT

While it is generally assumed that global plate motions are driven by the pattern of convection in the Earth's mantle, the details of that link remain obscure. Bouyancy forces associated with subduction of cool, dense lithosphere at zones of plate convergence are thought to provide significant driving force, but the relative magnitudes of other driving and resisting forces are less clear, as are the main factors controlling long-term changes in plate motion. The ability to consider past as well as present plate motions provides significant additional constraints, because changes in plate motion are necessarily driven by changes in one or more driving or resisting forces, which may be inferred from independent data. Here we present for the first time a model that explicitly links global mantle convection and lithosphere models to infer plate motion changes as far back as Miocene time. By accurately predicting observed convergence rates over the past 10 m.y., we demonstrate that surface topography generated at convergent margins is a key factor controlling the long-term evolution of plate motion. Specifically, the topographic load of large mountain belts and plateaus consumes a significant amount of the driving force available for plate tectonics by increasing frictional forces between downgoing and overriding plates.

Keywords: plate convergence, mountain building, resistive stresses, plate motion.

INTRODUCTION

A central tenet of plate tectonics states that Earth's surface moves as rigid units, while most of the deformation occurs along plate margins (Morgan, 1968). At converging boundaries the deformation often generates large topography. Two prominent examples are the Tibet and Andes regions, where stress accumulation at the adjacent subduction zones produces lithospheric shortening and consequent uplift of high mountain plateaus in a process that in both cases is still active today (Molnar et al., 1993; Allmendinger et al., 1997).

Less certain is whether the resulting topography (4–5 km) in turn affects plate convergence and the dynamics of how plates move. There are important constraints on the dynamics of plate motion from the record of past plate velocities. Geologic plate reconstructions (Gordon and Jurdy, 1986; Lithgow-Bertelloni and Richards, 1998) reveal significant temporal variations in plate velocities for the Cenozoic period. These observations are augmented by a growing body of space geodetic data capable of mapping present-day plate velocities with unprecedented accuracy. For example, the Global Positioning System (GPS) measures relative plate velocities to a precision of a few millimeters/year or better (Dixon, 1991; Gordon and Stein, 1992).

In general, present plate motions are remarkably similar to models averaged over the past few million years such as NUVEL-1A (DeMets et al., 1994; Sella et al., 2002); however, the Nazca and South America plates are important exceptions. By comparing geodetic data with plate velocities predicted from NUVEL-1A, Norabuena et al. (1998) observed that present rates of Nazca–South America convergence are slower than their 3.2 m.y. average. The geodetic measurements constrain present-day relative motion between the Nazca and South America plates; at a point on the plate boundary, long 71.5°W, lat 25°S (all convergence rates herein are computed at this location), we obtain a convergence rate of 6.7 ± 0.2 cm/yr using the angular velocity vector of Sella et al. (2002); reconstructions of Gordon and Jurdy (1986) indicate a 10.3 ± 0.2 cm/yr convergence averaged over the past 10 m.y. (Figs. 1A and 1B).

The velocity reduction is also confirmed by long-term (40 m.y.) reconstructions of Nazca (Farallon)–South America plate motion (Somoza, 1998). The most significant tectonic change in the region for the past 25 m.y. is the growth of the high Andes along the western margin of South America, in particular the rise of the Altiplano and Puna plateau ~10 m.y. ago. Norabuena et al. (1999) suggested that Nazca–South America convergence slowed in response to Miocene–Pliocene uplift of the Andes, because the gravitational load of the mountain belt might increase the stress level on the dipping plate boundary.

The tectonic plates comprise the cold upper thermal boundary layer of mantle convection (Davies, 1999). In recent years there has been great progress in our ability to simulate three-dimensional (3-D) spherical mantle convection at high numerical resolution (Tackley et al., 1994; Bunge et al., 1997; Zhong et al., 2000). Combined with constraints on the history of subduction (Richards and Engebretson, 1992) one can exploit the computer simulations to construct mantle circulation models (MCMs) (Bunge et al., 1998). These time-dependent earth models map temporal variations of large-scale mantle flow. MCMs thus allow us to place first-order estimates on the internal mantle buoyancy forces that drive plate motion.

There have been great advances in the development of sophisticated global models of the lithosphere independent of the MCM development. One approach employs isostasy and vertical integration of lithospheric strength to reduce the 3-D problem to two dimensions in what is known as thin-shell tectonic modeling. Here we apply one such model (SHELLS; Kong and Bird, 1995) that includes driving forces from topography, a temperature-dependent viscous rheology, and faults at plate boundaries. Although the code reduces the geometry from 3-D to 2-D, it provides a realistic representation of the strength of rocks that accommodate Coulomb frictional sliding along faults in the cold upper brittle portion of the lithosphere and dislocation creep in the warm deeper ductile regions of the plates. Faults are implemented by means of finite-element interfaces where the fault dip angle is determined from seismological observations. We use the lithospheric model in conjunction with present-day plate driving forces from the MCM to explore the impact of high Andean topography on the velocity of the Nazca plate (methods are given in the GSA Data Repository[1]). In our approach, the asthenosphere velocities computed from the MCM are applied as boundary conditions at the base of plates in SHELLS. Plate driving tractions are then computed in SHELLS. The MCM parameters were described by Bunge et al. (2002); they account for radial variations in mantle viscosity (factor 40 increase from the upper to the lower mantle), internal heat generation from radioactivity, bottom heating from the core, and a history of subduction spanning the past 120 m.y.

[1]GSA Data Repository item 2006187, details about the technique, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

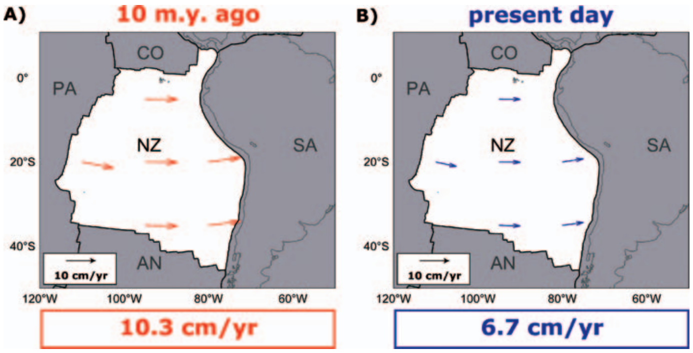

Figure 1. Nazca (NZ) plate motion relative to South America (SA) from Gordon and Jurdy (1986) (A) and Norabuena et al. (1999) (B). Plate boundaries are in black, coastlines are in gray. Reconstructions show convergence of 10.3 cm/yr at long 71.5°W, lat 25°S; geodetic data indicate 6.7 cm/yr at same position. Difference implies deceleration of Nazca plate relative to South America over past 10 m.y. PA—Pacific; CO—Cocos; AN—Antarctica.

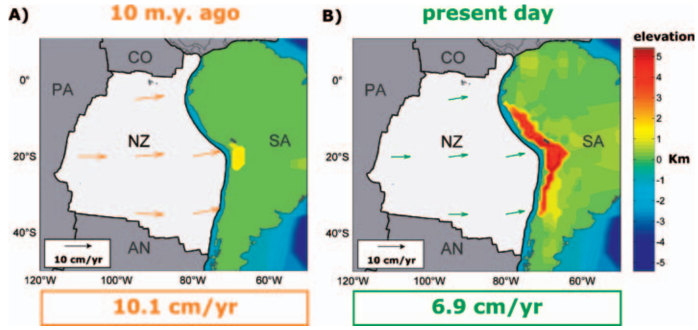

Figure 2. Computed Nazca (NZ) plate motion relative to South America (SA) from global plate motion simulations corresponding to assumed Andean paleotopography 10 m.y. ago (A) and present-day topography (B) from ETOPO 5 data set (National Geophysical Data Center, 1998). Abbreviations as in Figure 1. Plate boundaries are in black, coastlines and lakes are in gray. Assumed paleotopography 10 m.y. ago results in computed convergence of 10.1 cm/yr at long 71.5°W, lat 25°S; present-day topography results in convergence of 6.9 cm/yr at same position. Difference implies that deceleration of Nazca plate is due to topographic load of Andes (see text).

MODEL AND RESULTS

We compute global plate velocities with SHELLS assuming mantle shear tractions from the MCM and a fault friction coefficient of 0.03. This fault friction value is supported by experimental evidence (Hickman, 1991) and is consistent with a range of independent numerical modeling results (Hassani et al., 1997; Bird, 1998; Sobolev and Babeyko, 2005). To clearly isolate the effect of Andean topography, we perform two global plate motion simulations. First, our input topography is the one reported in the ETOPO5 data set (National Geophysical Data Center, 1998) with the Andes reaching an altitude of 4 km (Fig. 2B). This simulation is meant to represent present-day plate motions. We perform a second simulation with ETOPO5 elevation everywhere except for the Andes, where we use an estimate of paleotopography from published data (Gregory Wodzicki, 2000; Lamb and Davies, 2003) based on a range of botanic and geologic indicators (Fig. 2A). Plate velocities computed in this second scenario are meant to represent conditions at 10 m.y. ago.

To keep the modeling assumptions simple, mantle buoyancy forces are equal in both simulations. MCM modeling suggests that large-scale mantle heterogeneity evolves on a time scale of 50–100 m.y., comparable to a mantle overturn time and substantially larger than the 10 m.y. time period considered here. We also keep global plate geometry constant consistent with the reconstructions of Gordon and Jurdy (1986), who cast the global plate geometry of the past 10 m.y. into a single stage.

Figure 2 shows the computed Nazca plate velocity for the two cases in the South American reference frame. The case with topography corresponding to presumed conditions at 10 m.y. ago (Fig. 2A) results in a convergence of 10.1 cm/yr while the case corresponding to present Andean topography results in a 6.9 cm/yr plate convergence (Fig. 2B). These two values are in excellent agreement with the inferences, respectively, by Gordon and Jurdy (1986) (Fig. 1A) for Nazca–South America plate motion over the past 10 m.y. and with the geodetic constraints for present-day convergence (Fig. 1B). The computed Euler vectors from the two simulations agree with the observed rotation poles at the 68% confidence level in both position and rotation rate.

Could it be coincidence that the deceleration of the Nazca plate over the past 10 m.y. correlates with the assumed Andean uplift history? We address this question by considering two additional constraints to bear on our calculations. First, there is a large body of evidence to suggest that a significant portion of the current elevation of the Altiplano-Puna plateau was achieved prior to the past 5 m.y. Support for this comes from recent paleomagnetic work in the Peruvian Cordillera that demonstrates that rapid deformation and counterclockwise rotation occurred in geologic strata older than 9 Ma, while there is no evidence for such rotation in strata younger than 7 Ma (Rousse et al., 2002). Support comes from paleoaltimetry studies based on measurements of the abundances of ^{13}C-^{18}O bonds in soil carbonates that suggest that most of the Altiplano uplift took place between 10.3 and 6.7 m.y. ago (Ghosh et al., 2006). The tectonic deformation age is thus between 10 and 7 Ma. Second, there is further temporal information for relative Nazca–South America plate motion available from NUVEL-1A. De Mets et al. (1994) estimated the average Nazca–South America convergence at 8.0 $\pm$ 0.2 cm/yr for the past 3.2 m.y., less than the 10.3 $\pm$ 0.2 cm/yr value inferred by Gordon and Jurdy (1986) for the past 10 m.y., but still higher than the geodetic measure of current plate convergence (6.7 $\pm$ 0.2 cm/yr) from Norabuena et al. (1999). Thus it appears that the most rapid deceleration of the Nazca plate occurred during the period of the most pronounced Andean uplift. We test this notion explicitly in a third simulation. In accord with estimates for Andean paleotopography ~3 m.y. ago we assume a 3 km elevation for the central Andes (Fig. 3A) and find that this scenario results in a Nazca–South America convergence of 7.9 cm/yr (Fig. 3B). Note that this value is in excellent agreement with the NUVEL-1A model.

Our results beg an important question. Do large mountain belts like the Andes generate resistive fault stresses that are comparable to the driving forces of plate tectonics? We address this question in Figure 4, where we plot fault stresses and mantle shear tractions from our simulation for the present day beneath the Nazca and South America plates. Beneath the mountain belt, the subduction plane undergoes frictional stresses as high as 5 MPa, especially under highly elevated regions such as the Puna and Altiplano plateaus. These resistive stresses are comparable to the mantle shear tractions in our model.

In our global plate tectonic simulations it is logical to ask whether the effect of mountain belts is spatially confined to the plates sharing the convergent margin. We address this question in Figure 5A. Here we simultaneously plot the two sets of velocity directions corresponding, respectively, to our case with assumed conditions of Andean topography 10 m.y. ago and to our case with today's topography, both in the hotspot reference frame. We also show the absolute scalar magnitude of the velocity difference. Although there are some modest velocity differences, primarily for the African, North American, and Eurasian plates, the most important effect on plate motion from Andean uplift is focused at the velocity of the Nazca and South America plates.

Figure 5B is identical to Figure 5A, except that our calculation

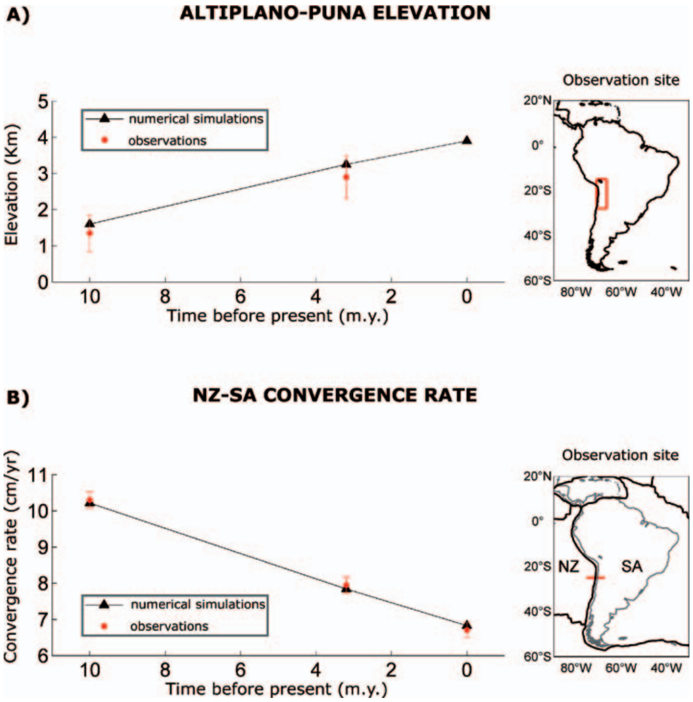

Figure 3. Published estimates of Andean paleotopography (A) and Nazca–South America (NZ-SA) plate convergence (B) for past 10 m.y. (see text) marked by red dots with error bounds. Black triangles—computed plate convergence and corresponding model topography for Andes. Observations show inverse correlation of plate velocity and elevation of Altiplano-Puna plateau, which is confirmed quantitatively by our simulations.

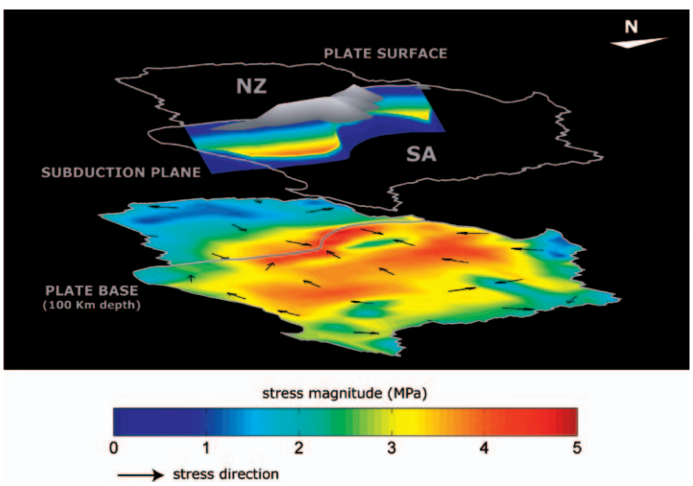

Figure 4. Subduction plane and plate base stresses at present day inferred from our simulation for Nazca (NZ) and South America (SA) plates. Color scale indicates stress magnitude (in MPa), arrows indicate stress direction. Plate boundaries (bottom) and Andes topographic contour lines (top) are in gray. Note that resisting stresses along subduction plane are comparable in magnitude to plate driving shear tractions from mantle, especially under highly elevated regions in the central Andes. Frictional forces at plate boundary are raised by 1 × 10¹³ N/m due to growth of the Andes.

corresponding to conditions 10 m.y. ago accounts for the inferred uplift of Tibet, which we model here in addition to the Andean uplift. A range of data supports a significant uplift of Tibet starting between 13 and 9 m.y. ago, coeval with age estimations for the major uplift phase in South America. In this case the velocity differences for the Nazca plate and South America (2 cm/yr) are the same that we found before,

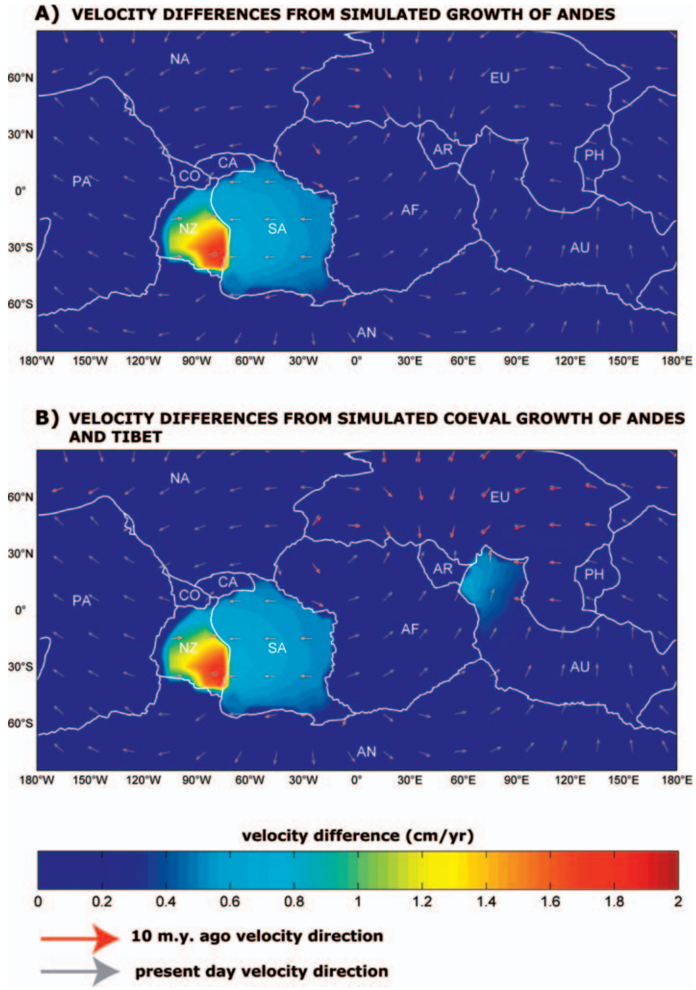

Figure 5. A: Difference of global plate velocities between model simulation with assumed Andean paleotopography 10 m.y. ago and calculation with present-day topography. Color scale is in cm/yr; arrows indicate velocity direction in hotspot reference frame. Plate boundaries are marked in white. Effect of topography on plate motion is spatially confined to plates sharing convergent margin. PA—Pacific; NA—North America; CO—Cocos; CA—Caribbean; AN—Antarctica; AF—Africa; AR—Arabia; EU—Eurasia; PH—Phillippine; AU—Australia. B: Same as A but for simulated coeval growth of Tibet. Growth of Tibet does not significantly alter our estimates for change in Nazca–South America (NZ-SA) convergence.

plus relatively smaller velocity differences, up to 0.6 cm/yr, in the Australian and the Eurasian plate. Thus the presumed growth of Tibet does not significantly alter our inference on Nazca–South America convergence, as expected from our results in Figure 5A.

DISCUSSION

Our modeling results are of great interest because an increasing number of plate kinematic constraints are now available on the temporal variations of how plates move. While there has been substantial but separate progress in the development of MCMs and tectonic models of the lithosphere, our simulations suggest that these models are beginning to achieve a level of maturity such that their joint application may prove useful to exploit these constraints and to test some first-order hypotheses on the dynamics of plate motion.

The strong influence of mountain belts on the velocity of plates may seem unexpected. We verified that the overburden pressure associated with 4 km relief in the high Andes raises the frictional forces along the main plate bounding fault plane by ~1 × 10^{13} N/m, a value that is significant compared to other key forces in plate tectonics. Recent 2-D geodynamic modeling (Husson and Ricard, 2004) of the Andean orogeny shows that the total transmitted force between subducting and overriding plate is $\sim 9 \times 10^{12}$ N/m. This value is consistent with our calculations and is supported by observations of large negative gravity variations along the Nazca–South America trench (Song and Simons, 2003). More important, the magnitude of frictional fault stresses is comparable to shear stresses in the mantle and implies that the topographic load of large mountain plateaus may consume a significant amount of the driving forces available for plate tectonics.

The latter observation may have profound implications. Raymo and Ruddiman (1992) suggested that Cenozoic climate change may have been caused by the uplift of Tibet; i.e., the rise of large mountain plateaus may affect climate. Lamb and Davis (2003) speculated that the reverse may be true for the Andes. Because these mountains act as an orographic barrier against moisture-bearing winds, they result in regional aridity and reduced erosion. Low erosion rates, however, have been implicated as a prerequisite for the creation of large plateaus such as the Altiplano (Sobel et al., 2003); i.e., climate may act as a force on plate tectonics.

We emphasize the large uncertainties associated with estimates of the Andean paleotopography. While our results are intriguing, a more robust relation between Andean topography and the velocity of the Nazca plate awaits improved constraints on the elevation history of the Andes.

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REFERENCES CITED

Allmendinger, R.W., Jordan, T.E., Kay, S.M., and Isacks, B.L., 1997, The evolution of the Altiplano-Puna plateau of the central Andes: Annual Review of Earth and Planetary Sciences, v. 25, p. 139–174, doi: 10.1146/annurev.earth.25.1.139.

Bird, P., 1998, Testing hypotheses on plate-driving mechanisms with global lithosphere models including topography, thermal structure, and faults: Journal of Geophysical Research, v. 103, p. 10,115–10,129, doi: 10.1029/98JB00198.

Bunge, H.-P., Richards, M.A., and Baumgardner, J.R., 1997, A sensitivity study of 3-D spherical mantle convection at 10^8 Rayleigh number: Effects of depth dependent viscosity, heating mode and an endothermic phase change: Journal of Geophysical Research, v. 102, p. 11,991–12,007, doi: 10.1029/96JB03806.

Bunge, H.-P., Richards, M.A., Lithgow-Bertelloni, C., Baumgardner, J.R., Grand, S.P., and Romanowicz, B.A., 1998, Time scales and heterogeneous structure in geodynamic earth models: Science, v. 280, p. 91–95, doi: 10.1126/science.280.5360.91.

Bunge, H.-P., Richards, M.A., and Baumgardner, J.R., 2002, Mantle-circulation models with sequential data assimilation: Inferring present-day mantle structure from plate-motion histories: Royal Society of London Philosophical Transactions, ser. A, v. 360, p. 2545–2567.

Davies, G.F., 1999, Dynamic Earth: Cambridge, Cambridge University Press, 455 p.

DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S., 1994, Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions: Geophysical Research Letters, v. 21, p. 2191–2194, doi: 10.1029/94GL02118.

Dixon, T.H., 1991, An introduction to the Global Positioning System and some geological applications: Reviews of Geophysics, v. 29, p. 249–276.

Ghosh, P., Garzione, C.N., and Eiler, J.M., 2006, Rapid uplift of the Altiplano revealed through ^{13}C–^{18}O bonds in paleosol carbonates: Science, v. 311, p. 511–515, doi: 10.1126/science.1119365.

Gordon, R.G., and Jurdy, D.M., 1986, Cenozoic global plate motions: Journal of Geophysical Research, v. 91, p. 12,389–12,406.

Gordon, R.G., and Stein, S., 1992, Global tectonics and space geodesy: Science, v. 256, p. 333–342.

Gregory-Wodzicki, K.M., 2000, Uplift history of the central and northern Andes: A review: Geological Society of America Bulletin, v. 112, p. 1091–1105, doi: 10.1130/0016-7606(2000)112<1091:UHOTCA>2.3.CO;2.

Hassani, R., Jongmans, D., and Chèry, J., 1997, Study of plate deformation and stress in subduction processes using two-dimensional numerical models: Journal of Geophysical Research, v. 102, p. 17,951–17,965, doi: 10.1029/97JB01354.

Hickman, S.H., 1991, Stress in the lithosphere and strength of active faults: Reviews of Geophysics, v. 29, p. 759–775.

Husson, L., and Ricard, Y., 2004, Stress balance above subduction: application to the Andes: Earth and Planetary Science Letters, v. 222, p. 1037–1050, doi: 10.1016/j.epsl.2004.03.041.

Kong, X., and Bird, P., 1995, SHELLS: A thin-shell program for modeling neotectonics of regional or global lithosphere with faults: Journal of Geophysical Research, v. 100, p. 22,129–22,132, doi: 10.1029/95JB02435.

Lamb, S., and Davies, P., 2003, Cenozoic climate change as a possible cause for the rise of the Andes: Nature, v. 425, p. 792–797, doi: 10.1038/nature02049.

Lithgow-Bertelloni, C., and Richards, M.A., 1998, The dynamics of Cenozoic and Mesozoic plate motions: Review of Geophysics, v. 36, p. 27–78, doi: 10.1029/97RG02282.

Molnar, P., England, P., and Martinod, J., 1993, Mantle dynamics, uplift of the Tibetan plateau, and the Indian monsoon: Review of Geophysics, v. 31, p. 357–396, doi: 10.1029/93RG02030.

Morgan, W.J., 1968, Rises, trenches, great faults, and crustal blocks: Journal of Geophysical Research, v. 73, p. 1959–1982.

National Geophysical Data Center, 1998, Digital relief of the surface of the Earth: Boulder, Colorado, National Oceanic and Atmospheric Administration Data Announcement 88-MGG-02.

Norabuena, E.O., Leffler-Griffin, L., Mao, A., Dixon, T.H., Stein, S., Sacks, I.S., Ocola, L., and Ellis, M., 1998, Space geodetic observations of Nazca–South America convergence across the central Andes: Science, v. 279, p. 358–362, doi: 10.1126/science.279.5349.358.

Norabuena, E.O., Dixon, T.H., Stein, S., and Harrison, C.G.A., 1999, Decelerating Nazca–South America and Nazca-Pacific plate motions: Geophysical Research Letters, v. 26, p. 3405–3408, doi: 10.1029/1999GL005394.

Raymo, M.E., and Ruddiman, W.F., 1992, Tectonic forcing of late Cenozoic climate: Nature, v. 359, p. 117–122, doi: 10.1038/359117a0.

Richards, M.A., and Engebretson, D.C., 1992, Large-scale mantle convection and the history of subduction: Nature, v. 355, p. 437–440, doi: 10.1038/355437a0.

Rousse, S., Gilder, S., Farber, D., McNulty, B., and Torres, V.R., 2002, Paleomagnetic evidence for rapid vertical-axis rotation in the Peruvian Cordillera ca. 8 Ma: Geology, v. 30, p. 75–78, doi: 10.1130/0091-7613(2002)030<0075:PEFRVA>2.0.CO;2.

Sella, G.F., Dixon, T.H., and Mao, A., 2002, REVEL: A model for recent plate velocities from space geodesy: Journal of Geophysical Research, v. 107, doi: 10.1029/2000JB000033.

Sobel, E.R., Hilley, G.E., and Strecker, M.R., 2003, Formation of internally drained contractional basins by aridity-limited bedrock incision: Journal of Geophysical Research, v. 108, doi: 10.1029/2000JB001883.

Sobolev, S.V., and Babeyko, A.Y., 2005, What drives orogeny in the Andes?: Geology, v. 33, p. 617–620, doi: 10.1130/G21557.1.

Somoza, R., 1998, Updated Nazca (Farallon)–South America relative motions during the last 40 My: Implications for mountain building in the central Andean region: Journal of South American Earth Sciences, v. 11, p. 211–215, doi: 10.1016/S0895-9811(98)00012-1.

Song, T.-R.A., Simons, M., 2003, Large trench-parallel gravity variations predict seismogenic behavior in subduction zones: Science, v. 301, p. 630–633, doi: 10.1126/science.1085557.

Tackley, P.J., Stevenson, D.J., Glatzmaier, G.A., and Schubert, G., 1994, Effects of multiple phase transitions in a three-dimensional spherical model of convection in Earth's mantle: Journal of Geophysical Research, v. 99, p. 15,877–15,902, doi: 10.1029/94JB00853.

Zhong, S., Zuber, M.T., Moresi, L., and Gurnis, M., 2000, Role of temperature-dependent viscosity and surface plates in spherical shell models of mantle convection: Journal of Geophysical Research, v. 105, p. 11,063–11,082, doi: 10.1029/2000JB900003.

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