Harper, J. R., 1975. On the driving forces of plate tectonics. *Geophysical Journal of the Royal Astronomical Society*, **40**, 465–474.
Jarvis, G. T., and Peltier, W. R., 1982. Mantle convection as a boundary layer phenomenon. *Geophysical Journal of the Royal Astronomical Society*, **68**, 385–424.
Karato, S-i., and Wu, P., 1993. Rheology of the upper mantle: A synthesis. *Science*, **260**, 771–778.
Karpychev, M., and Fleitout, L., 1996. Simple considerations on forces driving plate motion and on the plate-tectonic contribution to the long-wavelength geoid. *Journal of Geophysical Research*, **127**, 268–282.
Lithgow-Bertelloni, C., and Richards, M. A., 1998. The dynamics of Cenozoic and Mesozoic plate motions. *Reviews of Geophysics*, **36**, 27–78.
Lowman, J. P., Gait, A. D., Gable, C. W., and Kukreja, H., 2008. Plumes anchored by a high viscosity lowermantle in a 3D mantle convection model featuring dynamically evolving plates. *Geophysical Research Letters*, **35**, L19309, doi:10.1029/2008GL035342.
Malvern, L. E., 1969. *Introduction to the Mechanics of a Continuous Medium*. Englewood Cliffs: Prentice-Hall.
McKenzie, D. P., 1969. Speculations on the consequences and causes of plate motions. *Geophysical Journal of the Royal Astronomical Society*, **18**, 1–32.
Poirier, J. P., 1985. *Creep of Crystals*. Cambridge: Cambridge University Press.
Ricard, Y., and Vigny, C., 1989. Mantle dynamics with induced plate tectonics. *Journal of Geophysical Research*, **94**, 17543–17559.
Richardson, R. M., Solomon, S. C., and Sleep, N. H., 1976. Intraplate stress as an indicator of plate tectonic driving forces. *Journal of Geophysical Research*, **81**, 1847–1856.
Richter, F., 1973. Dynamical models for sea floor spreading. *Reviews of Geophysics and Space Physics*, **11**, 223–287.
Richter, F., 1977. On the driving mechanism of plate tectonics. *Tectonophysics*, **38**, 61–88.
Schellart, W. P., 2008. Kinematics and flow patterns in deep mantle and upper mantle subduction models: Influence of the mantle depth and slab to mantle viscosity ratio. Geochemistry. Geophysics Geosystems **9**, Q03014, doi:10.1029/2007GC001656.
Solomon, S. C., and Sleep, N. H., 1974. Some simple physical models for absolute plate motions. *Journal of Geophysical Research*, **79**, 2557–2567.
Tackley, P. J., 2000. Mantle convection and plate tectonics: Toward an integrated physical and chemical theory. *Science*, **288**, 2002–2007.
Turcotte, D. L., and Oxburgh, E. R., 1967. Finite amplitude convective cells and continental drift. *Journal of Fluid Mechanics*, **28**, 29–42.
Vigny, C., Ricard, Y., and Froidevaux, C., 1991. The driving mechanism of plate tectonics. *Tectonophysics*, **187**, 345–360.

Cross-references

Continental Drift
Earth's Structure, Global
Earth's Structure, Upper Mantle
Energy Budget of the Earth
Lithosphere, Oceanic
Lithosphere, Oceanic: Thermal Structure
Mantle Convection
Mantle Plumes
Seismic Structure at Mid-Ocean Ridges
Subduction Zones

PLATE MOTIONS IN TIME: INFERENCES ON DRIVING AND RESISTING FORCES

Giampiero Iaffaldano[1], Hans-Peter Bunge[2]
[1]Research School of Earth Sciences, The Australian National University, Acton, ACT, Australia
[2]Geophysics Section, Department of Earth and Environmental Sciences, Ludwig Maximilians University of Munich, Munich, Germany

Introduction

Plate tectonics is a remarkable theory. Its central tenet, which is widely known, states that the surface of the Earth moves in a piecewise coherent fashion via a number of rigid plates (Wilson, 1965; Morgan, 1968), with most of the deformation focused along plate boundaries (Stein, 1987). The underlying dynamic mechanism responsible for plate motions has been long identified in lateral buoyancy variations within the Earth mantle (Forte, 2010). However, 40 years after the acceptance of plate tectonics, the details of how these forces may vary in time to modify plate movements remain limited, and we still fail to answer basic questions of fundamental importance: *Why do plates change their motions as shown by the geologic and geodetic records? – What are the spatial and temporal patterns of forces responsible for such changes?* The main difficulty stems from our poor knowledge of the *force balance* in plate tectonics. It is widely agreed that plate motions are driven by convection in the Earth's mantle (Hager and O'Connel, 1981; Davies and Richards, 1992). But the influence of other driving and resisting mechanisms, especially along plate margins, remains unclear. Forces concentrated along plate margins are known as plate boundary forces (Forsyth and Uyeda, 1975) and it is likely that they play an important role in modulating plate motions (Humphreys and Coblentz, 2007).

A key component of plate boundary forces is the gravitational collapse associated with large mountain belts extending along plate margins. Climate-induced variations in topography, related to uplift and erosion in orogens, have been long recognized as possible controls in tectonics (Koeppen and Wegener, 1924), and may be therefore capable to initiate variations in plate motion on regional and global scales. Conversely, geodynamicists can use inferences on topography and plate motion variations as powerful probes into the underlying force balance of plate tectonics.

Temporal variations in plate motions provide significant constraints on the budget of forces acting upon plates. This is because by virtue of Newton's first law of motion any change in plate motion is necessarily driven by variations in one or more driving or resisting forces. With the advent of space geodetic techniques (Dixon, 1991), increasingly accurate estimates of global plate motions and their temporal variations are now available (Sella et al., 2002). While geodesy measures the current rates of plate motion, one can also glean long-term constraints

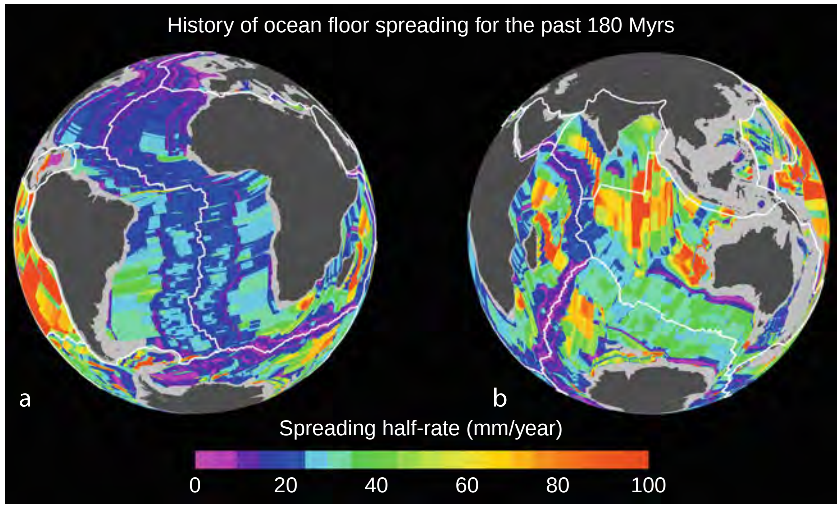

Plate Motions in Time: Inferences on Driving and Resisting Forces, Figure 1 Observed oceanic spreading half-rates for the past 180 Myrs after a recent global compilation by Müller et al. (2008). Plate boundaries are in white, continents in dark gray. Abrupt changes in spreading rates reveal short-term variations in global plate motions, particularly visible in the South Atlantic (**a**) as well as in the Indian Ocean (**b**). Such rapid variations are unlikely to originate from global changes in mantle driving forces, which occur on a longer time scale on the order of 50–100 Myrs as indicated by mantle circulation models. Instead, they are related to short-term variations in plate boundary forces caused, for example, by rapid growth of surface topography at convergent margins (see text). These observations point to the first-order importance of plate boundary forces in controlling global plate motions.

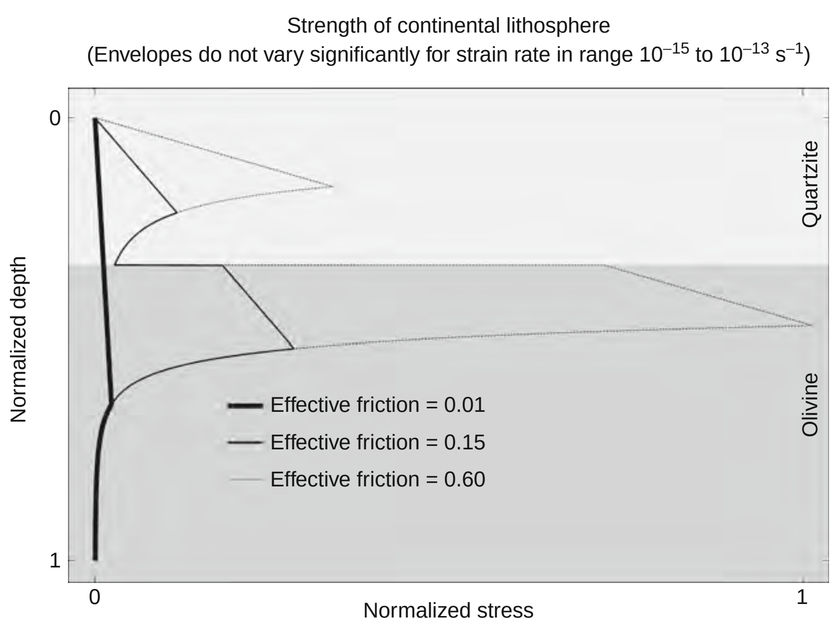

Plate Motions in Time: Inferences on Driving and Resisting Forces, Figure 2 Normalized strength/depth profiles for a simplified two-layer continental lithosphere, plotted for three different fault friction coefficients and a strain rate in the range of 10**–15 to 10**–13 1/s, typical of plate tectonics. Laboratory experiments performed mainly on quartzite and olivine (see text) indicate that lithosphere strength increases linearly with overburden pressure in the upper brittle part, and decreases exponentially with increasing temperature in the lower ductile part. Note that the brittle part contributes a significant portion (70–80%) of the total lithospheric strength, independently of the particular choice of friction coefficient and strain rate values. Experimental results suggest a friction coefficient around 0.6 (*dashed envelope*) for rocks under lithostatic pressure conditions, known as Byerlees law. However, various independent evidences for weak faults suggest much lower values between 0.01 and 0.15 (*solid envelopes*), so that plate boundaries experience considerably lower stresses even for high strain rates.

on plate motion from paleomagnetic observations derived from the magnetic isochron record of the ocean floor. In fact, recent paleomagnetic plate motion models approach temporal resolutions on the order of 1–2 Myrs and reveal a number of rapid *velocity-changes* (few cm/year) occurring over time-periods of a few Myrs or less (Müller et al., 2008). Some of these are particularly evident in the Southern Atlantic (Figure 1a) and in the Indian Ocean (Figure 1b). Their short duration makes it unlikely to attribute the changes to variations in the internal distribution of mantle buoyancies. In fact, these evolve globally on longer time scales on the order of 50–100 Myrs (Bunge et al., 1998), although locally changes may occur over some 10 Myrs (Forte et al., 2009). It is reasonable to link these rapid changes to variations in plate boundary forces.

Plate tectonics and the rheology of the lithosphere

The regime of plate tectonics requires high strain rates and low resistive stresses to coexist simultaneously along plate margins. But it is challenging to model this regime on a computer, because it is difficult to simulate shear failure along plate boundaries. To overcome this challenge some models of the lithosphere incorporate highly non-Newtonian, viscous creep, strain-rate weakening rheologies together with viscoplastic yielding. Moresi and Solomatov (1998) explored the effects of temperature-dependent viscosity in combination with a plastic yield stress: The former causes the cold upper boundary layer (lithosphere) to be strong, while the latter allows the boundary layer to fail locally in regions of high stress. The success, measured through a so-called plateness, is evident when extreme strain-softening rheologies, known as pseudo-stick-slip (Bercovici, 1995), are employed (Bercovici, 2003). Unfortunately, the rheological parameters required for pseudo-stick-slip agree poorly with laboratory experiments of ductile deformation performed on olivine (Kirby, 1983), particularly at the pressure and temperature conditions typical of the upper mantle (Karato and Jung, 2003). Figure 2 shows normalized strength envelopes of a simplified two-phase lithosphere. Depth-dependent strength is parameterized via empirical laws established through laboratory experiments performed on quartzite, abundant in the upper 20 km of continental lithosphere, and olivine, which dominates at greater depths. The laboratory results indicate that strength increases linearly with overburden pressure in the upper, brittle part of the lithosphere; it then decreases exponentially with increasing temperature in the lower, ductile part (Kohlstedt et al., 1995). High strength in the upper lithosphere reflects the resistance of rocks to failure at low temperature, or to sliding past each other when already faulted. Experimental results indicate a simple linear relationship to parameterize this behavior (Byerlee, 1978), with shear stress proportional to the normal pressure through a friction coefficient typically on the order of 0.6 (dashed envelope in Figure 2). There is, however, mounting evidence for significantly lower values (in the range 0.01–0.15, see solid envelopes in Figure 2) along faults and plate boundaries (Hickman, 1991; Bird, 1998; Suppe, 2007).

Computer models of the faulted lithosphere coupled with global mantle circulation models

Lithospheric faults exhibit low friction, as we have noted. In other words, they are mechanically weak and experience low stresses independently of the strain rate. It is therefore attractive to represent faults directly within the computational grid of numerical models of the lithosphere. This can be done, for instance, through the use of so-called contact-elements, in an approach known as neo-tectonic modeling. Neo-tectonic models have reached considerable sophistication. They solve the equations of mass and momentum conservation, and compute the instantaneous force balance and associated plate velocities. They implement empirical, depth-dependent rheologies of the

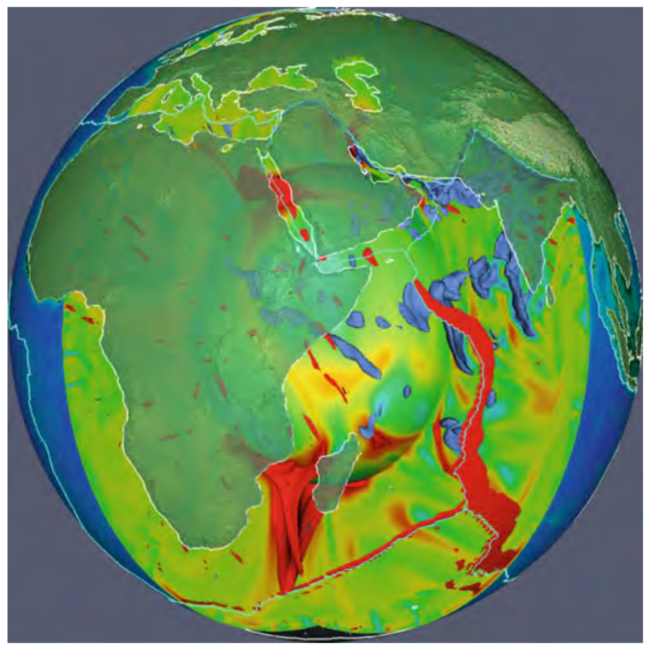

Plate Motions in Time: Inferences on Driving and Resisting Forces, Figure 3 Temperature distribution in the Earth's mantle from a recent, high-resolution 3-D global circulation model. *Blue* represents cold, denser material whereas *red* is hot and buoyant mantle. View is on Africa, coastline is in *white*, with continental topography in transparent *green color* scale. Present-day plate boundaries are outlined in *blue*. More than 100 million grid points discretize the Earth's mantle, equivalent to an average grid spacing of 20 km or less. Circulation models include 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 Myrs. A cold downwelling is visible beneath Tibet where the ancient Tethys Ocean subducted under Eurasia; a hot and buoyant upwelling is visible as well beneath the spreading triple-junction of the Antarctica, Africa, and Australia plates. The circulation model provides a realistic, first-order estimate of internal buoyancy forces driving global plate motions.

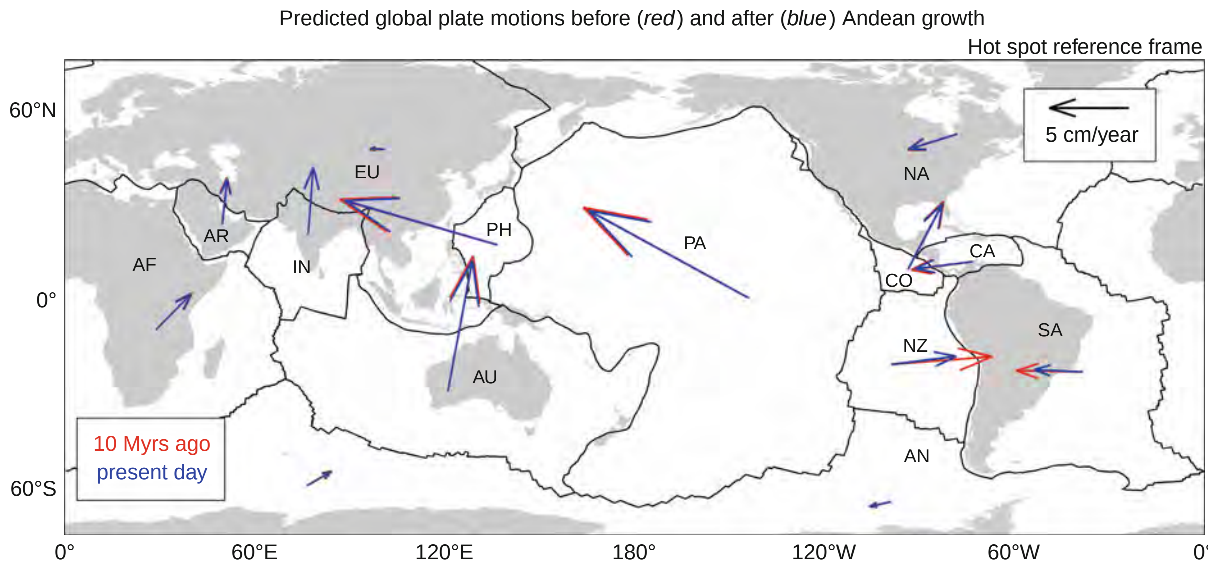

Plate Motions in Time: Inferences on Driving and Resisting Forces, Figure 4 Predicted plate motions in the Hot spot reference frame from coupled global mantle convection/lithosphere dynamics simulations, corresponding to assumed Andean paleotopography 10 Myrs ago (*red*) and present-day topography (*blue*). Plate boundaries are in *black*, continents in *gray*. AF Africa, AN Antarctica, AR Arabia, AU Australia, CA Caribbean, CO Cocos, EU Eurasia, IN India, NA North America, NZ Nazca, PA Pacific, PH Philippine, SA South America. IN and AU are treated as separate in the computational grid, based on recent evidences of plate separation (see text and Figures 6, 7). Note that a lower paleotopography assumed for the Andes 10 Myrs ago results in a predicted NZ/SA convergence of 10.1 cm/year at long 71.5°W, lat 25°S, whereas present-day topography results in a predicted convergence of 6.9 cm/year at the same position (see text). The rates compare remarkably well with observations inferred from a variety of data, which indicate a 30% reduction of NZ/SA plate convergence from 10.3 cm/year to 6.7 cm/year over the past 10 Myrs. The modeling results suggest that the reduction of NZ/SA convergence is caused by resisting plate-margin forces associated with the topographic load of Andes (see text). Similar numerical models moreover confirm that frictional variations along the boundary, arising from variations in trench sediment infill, are insufficient to explain the record of plate motion.

lithosphere and account for ductile deformation in the lower crust as well as brittle deformation along faults. In some cases, they take advantage of the so-called thin-sheet approximation to reduce the computational complexity from 3-D to 2-D (Kong and Bird, 1995) and to achieve greater computational efficiency.

Independent of advances in neo-tectonic models, there has been much progress in modeling the global circulation of the Earth's mantle (Tackley et al., 1994; Bunge et al., 1997; Zhong et al., 2000). Mantle circulation models (MCMs) account for the dynamic effects from a weak asthenosphere on the horizontal length-scales of the flow (Bunge et al., 1996), include internal heat generation from radioactivity, as well as a significant amount of heat from the core (Bunge, 2005; Quere and Forte, 2006; van der Hilst et al., 2007). Combined with constraints on the history of subduction, these models place first-order estimates on the internal mantle buoyancies driving plate motions. Figure 3 shows the temperature distribution in the mantle from one recent model with more than 100 million grid points (Oeser et al., 2006), equivalent to a grid point spacing of 20 km and less throughout the model mantle. MCMs provide first-order estimates of mantle buoyancy forces, but do not account for the complex processes in the lithosphere such the brittle failure. Similarly, neo-tectonic models include stresses originating within the lithosphere, and realistic plate boundary forces. But they rely on assumptions of the mantle buoyancy field to complete the force balance. The logical step is merging the two model classes to simulate the coupled global mantle convection/plate tectonics system. This makes it possible to account simultaneously for plate boundary forces and mantle-related components of lithospheric force balance, and to predict variations in global plate velocities that one may test explicitly against the geologic record. Several authors have recently undertaken such approach (Iaffaldano et al., 2006; Ghosh et al., 2008). Results are encouraging, and in the following, we review recent predictions of climate-related topography variations and their influence on plate velocities in the Southern Pacific, Southern Atlantic, as well as in the Indian Ocean that compare well with observations.

Recent plate motion changes

Kinematics of the Southern Pacific and Atlantic, and its relations to climate variations and topographic growth in the Andes

Paleomagnetic (Gordon and Jurdy, 1986; DeMets et al., 1994) and geodetic (Norabuena et al., 1999) data indicate a significant reduction (as high as 30%) of the Nazca/South America plate convergence over the

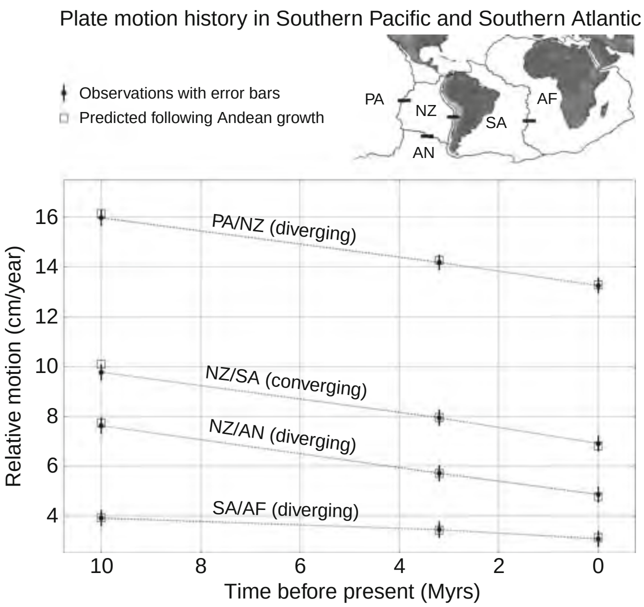

Plate Motions in Time: Inferences on Driving and Resisting Forces, Figure 5 Predicted and observed relative plate motions in the South Atlantic and South Pacific over the past 10 Myrs for a set of adjacent plate pairs: PA/NZ, NZ/SA, NZ/AN, and SA/AF (abbreviations as in Figure 6). *Black bold segments* in the small inset indicate positions along plate boundaries (*thin black*) at which relative motions have been computed. Observed plate motions (with *error bars*) inferred from paleomagnetic and geodetic data are represented by *black dots*, while *empty squares* indicate relative motions predicted from our simulations of the global coupled mantle/lithosphere system. The models explicitly account for the growth of the Andes over the past 10 Myrs, and demonstrate that the relative plate motion record can be entirely explained with the history of Andean orogeny. Our simulations thus point to the importance of far-field effects in plate tectonics, and imply that resisting plate margin forces due to Andean growth account for about 18% of global plate motion changes over the past 10 Myrs (see Figure 8).

past 10 Myrs. The timing of the slowdown is significant in that it is coeval with major growth of the Andes (Allmendinger et al., 1997) inferred from a variety of independent data (Gregory-Wodzicki, 2000). Iaffaldano et al. (2006) tested the effect of topography on plate convergence by computing plate velocities before and after Andean topography growth, assuming mantle shear tractions from a MCM, as well as a low fault friction coefficient of 0.03 for the tectonic model. They performed two separate simulations of global plate motions, in order to estimate the increase of horizontal deviatoric force in the frictional region of the Nazca/South America interface arising from the gravitational collapse of the Andean belt, and its effect on the convergence rate. One simulation was based on present-day topography from the ETOPO 5 data set, as high as 5 km in the central Andes, to compute global plate velocities. A second simulation accounted for a lower topographic relief of continental South America, based on a reconstruction of Andean paleo-elevation 10 Myrs ago (Gregory-Wodzicki, 2000).

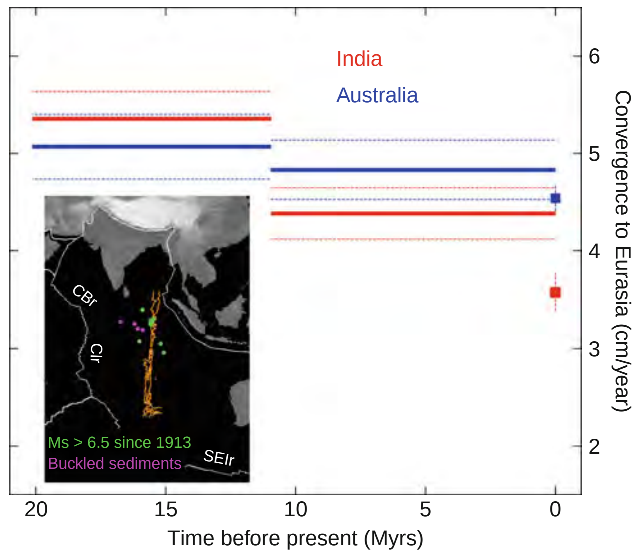

Plate Motions in Time: Inferences on Driving and Resisting Forces, Figure 6 Observed convergence of India (*red*) and Australia (*blue*) relative to fixed Eurasia over the past 20 Myrs. Convergence rates are computed through rigid-rotation Euler poles at long 86°E, lat 27°N of the India/Eurasia margin. Present-day values (*squares*) are derived from geodetic techniques while the paleomagnetic record (*solid lines*) is computed by averaging finite rotations of magnetic anomalies identified along the Carlsberg and South-East Indian ridges (labeled respectively, as CBr and SEIr in inset. CIr is Central Indian ridge). Note that convergence rates are very similar between 20 and 11 Myrs ago, when India and Australia appear to behave as one single plate with presumably little internal deformation. The convergence relative to Eurasia differs more distinctly over the last 11 Myrs, when India and Australia slowed down by almost 2 cm/year and 0.5 cm/year, respectively. Inset shows locations of identified unconformities of sediments (*magenta dots*) as well as great (Ms > 6.5) earthquakes (*green dots*) indicating left-lateral strike-slip motion in the northern portion of the Ninety East Ridge (*orange contours*). Those evidences suggest diffuse deformation in the Indian Ocean particularly pronounced during late Miocene, and have been interpreted as separation between the India and Australia. Plate boundaries are in *white*, continental topography in *gray color* scale.

Comparison of the two computed velocity fields predicts a 30% convergence reduction between the Nazca and South America plates (Figure 4), and agrees well with the record of present and past plate motions. More importantly, the contribution of the momentum from the gravitational collapse of the large plateau has been estimated to be of some 10**13 N/m along the central Andes. It should be pointed out that other mechanisms, such as temporal variations of friction along plate boundaries (Iaffaldano et al., 2008) and lateral buoyancy variations (Forte et al., 2009), may contribute to modify the convergence regime along the Nazca/South America margin to a minor extent. From Figure 4, it is evident that the total convergence reduction is unevenly partitioned between the Nazca and South America plates. This can be understood by recalling that mantle shear tractions exerted on the lithosphere-base scale to first order with the basal surface area of the plate times its velocity. Because the Nazca plate is smaller than South America, a higher velocity reduction is required in the momentum balance for mantle shear tractions to equilibrate topography-generated plate-boundary forces along the margin. Iaffaldano and Bunge (2009) took a step forward and used global models to predict the history of relative motion for plates adjacent to Nazca and South America (Pacific, Africa, Antarctica), which are shown in Figure 5. Agreement between models and observations is remarkable, implying that the resisting forces along the Nazca/South America plate boundary are responsible for driving plate motion changes also in the Southern Atlantic and Southern Pacific regions.

Plate motion changes in the Indian Ocean

While instantaneous calculations of the plate tectonic momentum balance cannot be taken to model the temporal evolution of plate boundaries, they do allow us to test the effects of variations in plate geometry on global plate motions, and in particular the creation of new plate boundaries. From the principle of inertia, it follows that any such event would invariably trigger plate motion changes due to repartitions in the budget of basal drag and plate boundary forces. A recent such episode is thought to have occurred in the Indian Ocean, where a variety of evidence has been interpreted as the generation of a diffuse boundary between the India and Australia plates, dated between 8 and 20 Myrs ago (Wiens et al., 1985; Gordon et al., 1998). Ocean-floor deformation at about 8 Myrs is documented from buckling of marine sediments (Weissel et al., 1980). Ongoing deformation in the Indian Ocean is also supported by pronounced (Ms > 6.5) and localized seismicity (Stein and Okal, 1978) along the northern portion of the Ninety East Ridge (see inset in Figure 6), suggestive of left-lateral strike-slip motion. Figure 6 shows the observed convergence history of India and Australia relative to Eurasia since early Miocene based on geodetic (Sella et al., 2002) as well as paleomagnetic (Cande and Stock, 2004; DeMets et al., 1994; Gordon and Jurdy, 1986; Merkouriev and DeMets, 2006) data collected along the Carlsberg and South East Indian ridges (labeled respectively as CBr and SEIr in the inset). Within error-bars, convergence rates are almost indistinguishable between 20 and 11 Myrs ago, suggesting that India and Australia behaved as one single plate with presumably little deformation occurring in between. Over the past 11 Myrs however their convergence to Eurasia differs distinctly. While India slowed down by almost 2 cm/year, convergence of Australia to Eurasia remained almost steady, with only some 0.5 cm/year of reduction. Timing of the India/Eurasia plate-motion change coincides reasonably well with the occurrence of diffuse deformation in the Indian Ocean. More relevant is the fact that Tibet had attained most of its current elevation (Tapponnier et al., 2001) prior to the slowdown of the Indian plate and prior also to the presumed formation of the India/Australia plate boundary, implying that resistive plate

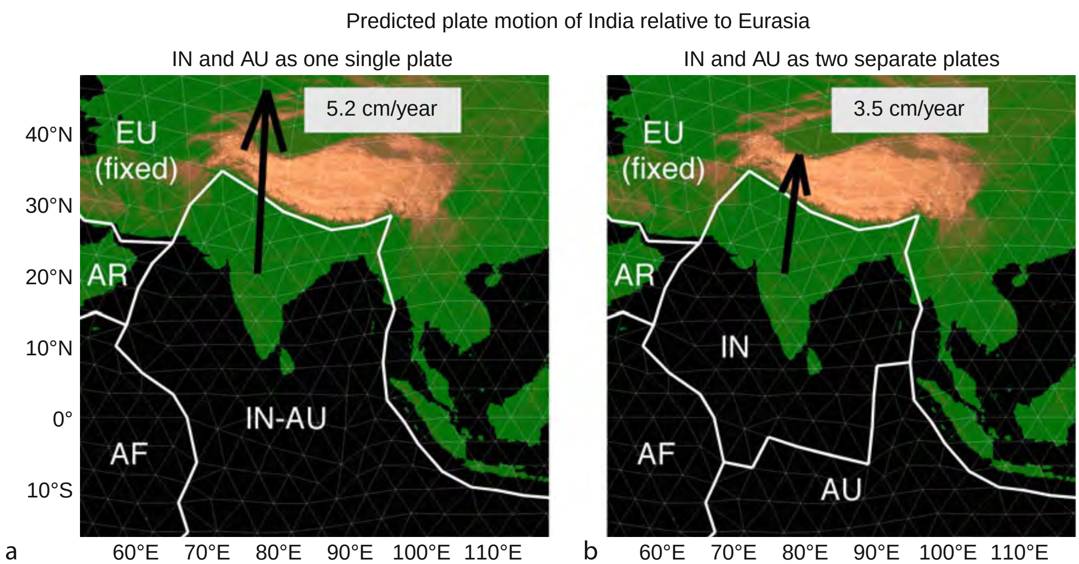

Plate Motions in Time: Inferences on Driving and Resisting Forces, Figure 7 Predicted India (IN) plate motion relative to Eurasia (EU) from two distinct simulations with India and Australia (AU) acting, respectively, (**a**) as one single and (**b**) as two separate plates, where plate boundaries in our computational mesh are shown in *bold white* and finite elements in thin white. Plate motions are computed at long 86°E, lat 27°N. Abbreviations of plate names as in Figure 6. Note that a single India/Australia plate results in a predicted convergence of 5.2 cm/year relative to EU, incompatible with the geodetic estimate (see Figure 12). Two separate plates result in a convergence of 3.5 cm/year of IN relative to EU, similar to the present-day observation. In the latter scenario, resisting forces from the gravitational load of Tibet act only against the smaller India plate, and are thus more effective in slowing the convergent motion.

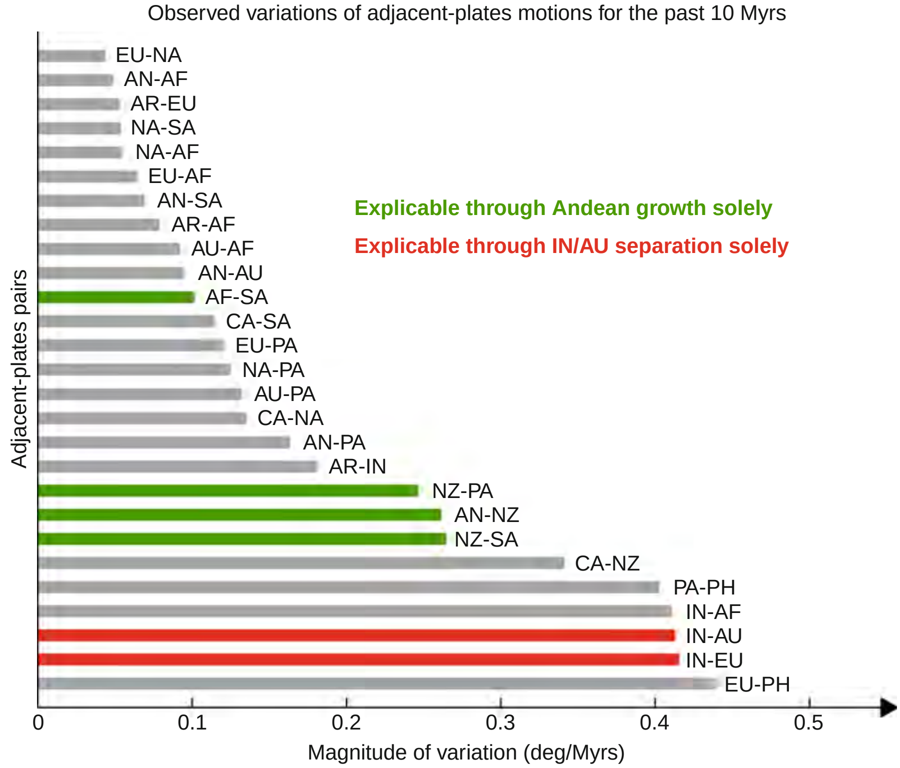

Plate Motions in Time: Inferences on Driving and Resisting Forces, Figure 8 Observed variations of adjacent-plates motions over the past 10 Myrs. Abbreviations of plate names as in Figure 6. For each couple of adjacent plates, variations are computed as magnitude of difference between relative rotation poles at 10 Myrs, derived from paleomagnetic reconstruction, and at present day, obtained through geodetic techniques (GPS). The Cocos oceanic plate is not considered, since a geodetic estimate for its rotation pole is not available. Variations of AF/SA, AN/NZ, NZ/SA, and NZ/PA adjacent-plates systems (*green bars*) can be entirely explained through the effect of Andean growth (see Figures 6 and 7). They amount to about 18% of the global relative motions changes over the past 10 Myrs. Variations of IN/EU as well as IN/AU relative motions (*red bars*) can be entirely explained through the effect of separation between India and Australia (see Figure 7). They amount to about 17% of the global relative motions changes over the past 10 Myrs. Thus, our models of mantle/lithosphere dynamics explicitly predict about 35% of the global plate motion changes observed over the past 10 Myrs from two well-identified tectonic variations.

boundary forces arising from the gravitational load of Tibet were already in place to act against convergence. Iaffaldano and Bunge (2009) tested explicitly whether plate-boundary forces from high Tibet are sufficient to explain the observed reduction of India/Eurasia plate convergence, once the former is separated from Australia by an additional plate boundary (Figure 7). Specifically, they performed two distinct simulations of global plate motions, one with India and Australia cast as one single plate and the other with two plates built into the computational finite-element grid. A single India/Australia plate results in a predicted convergence of 5.2 cm/year at long 86°E, lat 27°N (Figure 7a), whereas India being separated from Australia implies a convergence of 3.5 cm/year at the same position (Figure 7b). The latter prediction compares remarkably well with the geodetic estimate (see Figure 6). Finally, it is worth mentioning that simulations also predict an increased convergence between India and Australia, concentrated in the Indian Ocean, compatible with the aforementioned geologic and geodetic record.

Conclusions

Recent results indicate that joint modeling of the mantle/lithosphere system begins to achieve a level of maturity that allows explicit testing of a range of hypotheses on the force balance in plate tectonics, and identifying key controlling parameters. While buoyancy forces from MCMs contribute significantly to the dynamics of plate motion, it is clear that plate boundary forces are of sufficient magnitude relative to these driving forces to affect plate motions and plate deformation, and to initiate rapid plate motion changes. One key controlling parameter in regulating plate velocity is the elevation of large mountain belts, because their topographic load consumes a considerable amount of the driving forces available in plate tectonics, as much as 10**13 N/m. Along the Nazca/South America plate boundary these forces are sufficient to reduce the convergence rate over the past 10 Myrs by some 30%. This reduction is, however, not an isolated episode of a rapid plate motion slow down. Instead many such variations are documented from the global compilation of Müller et al. (2008), which points to the importance of topography and erosion in the global tectonic system (Cloetingh et al., 2007). The fact that models accurately predict the spreading history of the Pacific/Nazca, Nazca/South America, Nazca/Antarctica, and South America/Africa plate boundaries is of equal interest. The result is not entirely surprising, and arises from the kinematic constraints of plate tectonics on the sphere. This suggests that far-field effects cannot be neglected in the geologic record at least in some cases. The strong influence of mountain belts on the plate tectonic force balance could have important implications. In an influential paper, Raymo and Ruddiman (1992) advanced the notion that Cenozoic climate change may have been caused by the uplift of Tibet. In other words, the rise of large mountain plateaus may act as a tectonic force on climate (Strecker et al., 2007). Low erosion rates have been implicated as a prerequisite for the creation of large mountain plateaus (Sobel et al., 2003; Clift and Vannucchi, 2004). This implication suggests conversely that climate can act – through large topography – as a force in plate tectonics. Overall, a significant portion of recent changes in global plate motions can be attributed to topography-related forcing along plate boundaries rather than to mantle buoyancy. These findings are summarized in Figure 8, where the relative plate motion changes observed globally over the past 10 Myrs are plotted. Green and red bars show variations in plate motion that are related, respectively, to the growth of the high Andes or to the presumed recent separation between India and Australia, and amount to about 35% of the total change over the Earth surface. This remarkable first-order result clearly demonstrates the ability of plate boundary forces to affect the global plate velocity field. The level of maturity achieved by neo-tectonic simulations coupled with 3-D MCMs thus allows geodynamicists to make explicit predictions of the plate tectonic force balance that can be tested against the geologic record of present and past plate motions.

Bibliography

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*, **25**, 139–74.

Bercovici, D., 1995. A source-sink model of the generation of plate tectonics from non-Newtonian mantle flow. *Journal of Geophysical Research*, **100**, 2013–2030.

Bercovici, D., 2003. The generation of plate tectonics from mantle convection. *Earth and Planetary Science Letters*, **205**, 107–121.

Bird, P., 1998. Testing hypotheses on plate-driving mechanisms with global lithosphere models including topography, thermal structure, and faults. *Journal of Geophysical Research*, **103**, 10115–10129.

Bunge, H.-P., 2005. Low plume excess temperature and high core heat flux inferred from non-adiabatic geotherms in internally heated mantle circulation models. *Physics of the Earth and Planetary Interiors*, **153**, 3–10.

Bunge, H.-P., Richards, M. A., and Baumgardner, J. R., 1996. The effect of depth dependent viscosity on the planform of mantle convection. *Nature*, **379**, 436–438.

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*, **102**, 11991–12007.

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*, **280**, 91–95.

Byerlee, J. D., 1978. Friction of rocks. *Pure and Applied Geophysics*, **116**, 1189–1198.

Cande, S. C., and Stock, J. M., 2004. Pacific-Antarctic-Australia motion and the formation of the Macquarie plate. *Geophysical Journal International*, **157**, 399–414.

Clift, P., and Vannucchi, P., 2004. Controls on tectonic accretion versus erosion in subduction zones: implications for the origin and recycling of the continental crust. *Reviews of Geophysics*, **42**, RG2001.

Cloetingh, S. A. P. L., Ziegler, P. A., Bogaard, P. J. F., Andriessen, P. A. M., Artemieva, I. M., Bada, G., van Balen, R. T., Ben-Avraham, Z., Brun, J.-P., Bunge, H.-P., Burov, E. B., Carbonell, R., Facenna, C., Gallart, J., Green, A. G., Heidbach, O., Jones, A. G., Matenco, L., Mosar, J., Oncken, O., Pascal, C., Peters, G., Sli-aupa, S., Soesoo, A., Spakman, W. R. S., Thybo, H., Torsvik, T. H., de Vicente, G., Wenzel, F., Wortel, M. J. R., and the TOPO-EUROPE Working Group, 2007. TOPO-EUROPE: the geoscience of coupled deep earth – surface processes. *Global and Planetary Change*, **58**, 1–118.

Davies, G. F., and Richards, M. A., 1992. Mantle convection. *Journal of Geology*, **100**, 151–206.

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*, **21**, 2191–2194.

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

Forsyth, D. W., and Uyeda, S., 1975. Relative importance of driving forces of plate motion. *Geophysical Journal of the Royal Astronomical Society*, **43**, 163–200.

Forte, A. M., 2010. Plate driving forces. *Encyclopedia of solid earth geophysics*. Springer 2011.

Forte, A. M., Moucha, R., Rowley, D. B., Quere, S., Mitrovica, J. X., Simmons, N. A., and Grand, S. P., 2009. Recent tectonic plate decelerations driven by mantle convection. *Geophysical Research Letters*, **36**, L23301.

Ghosh, A., Holt, W. E., Wen, L., Haines, A. J., and Flesch, L. M., 2008. Joint modeling of lithosphere and mantle dynamics elucidating lithosphere-mantle coupling. *Geophysical Research Letters*, **35**, L16309.

Gordon, R. G., and Jurdy, D. M., 1986. Cenozoic global plate motions. *Journal of Geophysical Research*, **91**, 12389–12406.

Gordon, R. G., DeMets, C., and Royer, J.-Y., 1998. Evidence for long-term diffuse deformation of the lithosphere of the equatorial Indian Ocean. *Nature*, **395**, 370–374.

Gregory-Wodzicki, K. M., 2000. Uplift history of the central and northern Andes: A review. *Geological Society of America Bulletin*, **112**, 1091–1105.

Hager, B. F., and O'Connel, R. J., 1981. A simple global-model of plate dynamics and mantle convection. *Journal of Geophysical Research*, **86**, 4843–4867.

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

Humphreys, E. D., and Coblentz, D. D., 2007. North American dynamics and Western US tectonics. *Reviews of Geophysics*, **45**(2), RG3001.

Iaffaldano, G., and Bunge, H.-P., 2008. Strong plate coupling along the nazca/south america convergent margin. *Geology*, **36**, 443–446.

Iaffaldano, G., and Bunge, H.-P., 2009. Relating rapid plate-motion variations to plate-boundary forces in global coupled models of the mantle/lithosphere system: effects of topography and friction. *Tectonophysics*, **474**, 393–404.
Iaffaldano, G., Bunge, H.-P., and Dixon, T. H., 2006. Feedback between mountain belt growth and plate convergence. *Geology*, **34**, 893–896.
Karato, S., and Jung, H., 2003. Effects of pressure on high-temperature dislocation creep in olivine. *Philosophical Magazine*, **83**, 401–414.
Kirby, S. H., 1983. Rheology of the lithosphere. *Reviews of Geophysics*, **21**, 1458–1487.
Koeppen, W., and Wegener, A., 1924. *Die Klimate der geologischen Vorzeit*. Berlin: Borntraeger.
Kohlstedt, D. L., Evans, B., and Mackwell, S. J., 1995. Strength of the lithosphere: constraints imposed by laboratory experiments. *Journal of Geophysical Research*, **100**, 17587–17602.
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*, **100**, 22129–22132.
Merkouriev, S., and DeMets, C., 2006. Constraints on India plate motion since 20 Ma from dense Russian magnetic data: implications for Indian plate dynamics. *Geochemistry Geophysics Geosystems*, **7**, Q02002.
Moresi, L., and Solomatov, V., 1998. Mantle convection with a brittle lithosphere: thoughts on the global tectonic styles of the Earth and Venus. *Geophysical Journal International*, **133**, 669–682.
Morgan, W. J., 1968. Rises, trenches, great faults and crustal blocks. *Journal of Geophysical Research*, **73**, 1959.
Müller, R. D., Sdrolias, M., Gaina, C., and Roest, W. R., 2008. Age, spreading and spreading asymmetry of the world's ocean crust. *Geochemistry Geophysics Geosystems*, **9**, Q04006.
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*, **26**, 3405–3408.
Oeser, J., Bunge, H.-P., and Mohr, M., 2006. Cluster design in the earth sciences: TETHYS, high performance computing and communications – second international conference, HPCC 2006, Munich, Germany. *Lecture Notes in Computer Science*, **4208**, 31–40.
Quere, S., and Forte, A. M., 2006. Influence of past and present-day plate motions on spherical models of mantle convection: implications for mantle plumes and hotspots. *Geophysical Journal International*, **165**, 1041–1057.
Raymo, M. E., and Ruddiman, W. F., 1992. Tectonic forcing of late Cenozoic climate. *Nature*, **359**, 117–122.
Sella, G. F., Dixon, T. H., and Mao, A., 2002. REVEL: a model for recent plate velocities from space geodesy. *Journal of Geophysical Research*, **107**, 2081–2111.
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*, **108**, 2344.
Stein, R. S., 1987. Contemporary plate motion and crustal deformation. *Reviews of Geophysics*, **25**(5), 855–863.
Stein, S., and Okal, E., 1978. Seismicity and tectonics of the Ninetyeast Ridge area: evidence for internal deformation of the Indian plate. *Journal of Geophysical Research*, **83**, 2233–2246.
Strecker, M. R., Slonso, R. N., Bookhagen, B., Carrapa, B., Hilley, G. E., Sobel, E. R., and Trauth, M. H., 2007. Tectonics and climate of the Southern Central Andes. *Annual Review of Earth and Planetary Sciences*, **35**, 747–787.
Suppe, J., 2007. Absolute fault and crustal strength from wedge tapers. *Geology*, **35**(12), 1127–1130.
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*, **99**, 15877–15902.
Tapponnier, P., Zhiquin, X., Roger, F., Meyer, B., Arnaud, N., Wittlinger, G., and Jingsui, Y., 2001. Oblique stepwise rise and growth of the Tibet plateau. *Science*, **294**, 1671–1677.
van der Hilst, R. D., de Hoop, M. V., Wang, P., Shim, S.-H., Ma, P., and Tenorio, L., 2007. Seismostratigraphy and thermal structure of Earth's core-mantle boundary region. *Science*, **315**, 1813–1817.
Weissel, J. K., Anderson, R. N., and Geller, C. A., 1980. Deformation of the Indo-Australian plate. *Nature*, **287**, 284–291.
Wiens, D. A., DeMets, C., Gordon, R. G., Stein, S., Argus, D., Engeln, J. F., Lundgren, P., Quible, D., Stein, C., Weinstein, S., and Woods, D. F., 1985. A diffuse plate boundary model for Indian Ocean tectonics. *Geophysical Research Letters*, **12**, 429–432.
Wilson, J. T., 1965. A new class of faults and their bearing on continental drift. *Nature*, **207**, 343–347.
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*, **105**, 11063–11082.

Cross-references

Continental Drift
Geodesy, Ground Positioning and Leveling
Geodesy, Networks and Reference Systems
GPS, Tectonic Geodesy
Lithosphere, Oceanic
Plate Driving Forces
Plates and Paleoreconstructions

PLATE TECTONICS, PRECAMBRIAN

Y. J. Bhaskar Rao, E. V. S. S. K. Babu
National Geophysical Research Institute, Council of Scientific and Industrial Research, Hyderabad, India

Introduction

The plate tectonics paradigm, developed in the late 1960s, provides an excellent framework to explain the tectonics of the Earth's crust since the Cenozoic period. In general, the tectonic style reflects how the planets lose their internal heat and plate tectonics represent one of the at least three styles in which planets cool (Sleep, 2007). Intriguingly, Earth is the only planet that presently exhibits plate tectonics (Stevenson, 2003), an unusual mode of cooling. It is now widely appreciated that the excess density of the oceanic lithosphere that is sinking deeply in subduction zones drives the modern-style plate tectonics ("subduction tectonics," Stern, 2005). However, *why and when on Earth plate tectonics began* has been highly controversial and remains one of the most challenging unresolved problems in our understanding of the evolution of the planet (for a recent review on the subject see Condie and Pease, 2008 and articles therein; Ernst, 2009). While many authors propose that plate tectonics, in some form, operated since early Archaean times (Kroner, 1981; Ernst, 1983; Sleep, 1992; Parman et al., 2001; Smithies et al., 2003, 2005; Sleep, 2005; Condie, 2005; Cawood et al.,