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Episodic tectonic plate reorganizations driven by mantle convection

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Abstract

Periods of relatively uniform plate motion were interrupted several times throughout the Cenozoic and Mesozoic by rapid plate reorganization events [R. Hey, Geol. Soc. Am. Bull. 88 (1977) 1404–1420; P.A. Rona, E.S. Richardson, Earth Planet. Sci. Lett. 40 (1978) 1–11; D.C. Engebretson, A. Cox, R.G. Gordon, Geol. Soc. Am. Spec. Pap. 206 (1985); R.G. Gordon, D.M. Jurdy, J. Geophys. Res. 91 (1986) 12389–12406; D.A. Clague, G.B. Dalrymple, US Geol. Surv. Prof. Pap. 1350 (1987) 5–54; J.M. Stock, P. Molnar, Nature 325 (1987) 495–499; C. Lithgow-Bertelloni, M.A. Richards, Geophys. Res. Lett. 22 (1995) 1317–1320; M.A. Richards, C. Lithgow-Bertelloni, Earth Planet. Sci. Lett. 137 (1996) 19–27; C. Lithgow-Bertelloni, M.A. Richards, Rev. Geophys. 36 (1998) 27–78]. It has been proposed that changes in plate boundary forces are responsible for these events [M.A. Richards, C. Lithgow-Bertelloni, Earth Planet. Sci. Lett. 137 (1996) 19–27; C. Lithgow-Bertelloni, M.A. Richards, Rev. Geophys. 36 (1998) 27–78]. We present an alternative hypothesis: convection-driven plate motions are intrinsically unstable due to a buoyant instability that develops as a result of the influence of plates on an internally heated mantle. This instability, which has not been described before, is responsible for episodic reorganizations of plate motion. Numerical mantle convection experiments demonstrate that high-Rayleigh number convection with internal heating and surface plates is sufficient to induce plate reorganization events, changes in plate boundary forces, or plate geometry, are not required.

Keywords: mantle; convection; plate tectonics; movement; Emperor Seamounts

1. Introduction

Tectonic plate motions are the surface manifestation of thermal convection within the Earth's mantle. The negative buoyancy distributed throughout the cooling plates and cold, subducting slabs provides sufficient force to drive presently observed global plate motions [10–12]. Yet, surface deformation with piecewise uniform motion, which would approximate tectonic plates, is not easily obtained in mantle convection calculations [13]. Calculations of thermal convection with dynamically determined plate-like surface velocities

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have been produced using preexisting zones of weakness or faults [14–17], yield-stress or history-dependent rheologies [18–23], or by balancing forces on specified plate geometries [24–26]. Each method has its strengths and weaknesses. For example it is difficult, but not impossible, to create plate boundaries that move relative to one another with weak zone, fault, or force balance methods. On the other hand, the value of the yield-stress needed to generate plate behavior appears to be problem-dependent, and it can be difficult to maintain plate-like surface velocities for a billion years of model time evolution with yield-stress formulations. It is beyond the scope of this paper to address the strengths and limitations of each of these approaches in detail. The reader is referred to [17,27] and references therein for further discussion of plate generation methods.

While there have been significant advances in our knowledge of plate histories and the nature of mantle convection, one unexplained aspect of plate tectonics is the sudden changes in plate motions that have occurred intermittently in the past [1–9]. We propose that sudden changes in plate motion are a result of the interaction of internally heated mantle convection and mobile tectonic plates. This hypothesis is supported by a series of three-dimensional (3D) numerical models. We find that there are three elements necessary to observe this phenomenon: high-Rayleigh number convection with internal heating, mobile surface plates driven by convection, and long integration times.

Studies of two-dimensional (2D), infinite-Prandtl-number convection at high Rayleigh numbers have demonstrated that convection can be strongly time-dependent [28–34] and even episodic in certain cases [35–37]. Time-dependent convection has been previously observed in calculations with plates [29,32–34]. However, surface plates [38] and depth-dependent viscosity [39], both present in the calculations described here, have been shown to decrease the time-dependent behavior of convection.

The calculations reported here document a previously unrecognized regime of time-dependent plate motion and convection. In these calculations the direction of plate motion changes by angles that range from 30 to 180°, depending on the plate geometry and the location of convergent boundaries prior to the change in plate motion. More importantly, the time scale of the change in plate motion observed in these calculations is consistent with geophysical observations of the change in the motion of the Pacific plate at 43 Myr.

Plate motions appear to be uniform on 10–50 Myr time periods (stages). Transitions between stages occur over shorter time scales and involve plate reorganizations where plates change magnitude and direction of motion [3]. The strongest evidence for short transitions between stages is the sharp bend in the Hawaiian-Emperor seamount chain, which constrains the length of the associated stage transition to be as short as 5 Myr [3–6]. Other island chains in the Pacific record the same event but do not require such a short transition [5]. Plate boundary forces have been proposed to be the factor controlling stage transitions, primarily because transition times are shorter than the assumed characteristic time scales of mantle processes [8,9]. However, calculations using evolving plate boundaries that are constrained by geophysical observations have not succeeded in producing the dramatic change in plate motion recorded by the Hawaiian-Emperor chain [8,9]. These calculations use models of the location of subducting slabs for the buoyancy force that drives plate motion and do not explicitly solve the energy equation. Therefore, they do not include mantle heat (buoyancy) sources that are not related to plate-slab buoyancy. To evaluate factors controlling stage transitions not related to changing plate boundary forces, we studied 3D numerical experiments of mobile plates with invariant geometry driven by mantle convection.

2. Materials and methods

In the calculation presented here, mantle convection is modeled in a 3D Cartesian geometry with four mobile plates. 324 Fourier modes in each of the horizontal directions and 129 nodes in the vertical direction are used. The velocities are solved using a propagator technique and the energy equation is solved using a flux-corrected finite-difference formulation [24]. The Bénard–Rayleigh number is 5.0×10^7, the internal heating Rayleigh number is 7.5×10^8, and the viscosity at the base of the plate is the characteristic viscosity used in the definition of the Rayleigh number.

Plate motion remains in dynamic equilibrium with buoyancy forces throughout the calculations by balancing the integrated shear stresses on the base of each plate. The plate motion is determined by balancing stress on the base of the plate resulting from the buoyancy-driven flow with shear stress arising from purely plate-driven flow. The shear stress resulting from buoyancy-driven flow with a no-slip surface is integrated over the plate geometry at the base of the plate. The plate velocity is determined by the condition that the integrated shear stress due to the plate motion must equal the integral of the buoyancy induced driving shear stress. The superimposed buoyancy-driven and plate-driven flows result in plate motion that is in dynamic equilibrium with the buoyancy-driven flow. The only force acting on the plate is the integrated buoyancy within the plate and mantle. This method has been shown to produce plate velocities, Nusselt numbers, global kinetic energies, and dynamic topography profiles that are nearly indistinguishable from weak zone or power-law rheology methods of plate generation [27].

Plates are free to change velocity magnitude and direction in response to changes in the buoyancy distribution that drives the convection. Plate geometry and boundary locations remain constant. The plate geometry in the calculation is defined by plate boundaries that meet at triple junctions and a combination of large and small plates, as is observed on Earth. The model system has periodic side-boundary conditions, a $3\times3\times1$ horizontal to vertical domain size, and a depth-dependent viscosity characterized by a total increase in magnitude from the upper to lower mantle of a factor of 36 [40,41].

The model is heated both internally and from below (by a constant temperature bottom boundary condition). The ratio of the basal to the surface heat flux is approximately 40%. The initial condition is a temperature field from a statistically steady, 2D, high-Rayleigh number calculation with plates to which we add a 3D perturbation. When plates are introduced, there is a transient period, lasting several hundred million years, where the internal temperature changes in response to the new boundary conditions. The plate motions are recorded after this transient period when the mean temperature of the fluid has settled into a quasi-periodic state.

3. Results

A recurring feature in many calculations in our study is that relatively uniform plate motion is punctuated by reorganization events when plate speed and direction change rapidly over short time periods. Fig. 1 shows the plate geometry from one such calculation. The white region in the figure represents the computational domain and, due to periodicity imposed by the boundary conditions, the plate pattern is repeated as shown by the gray regions. Of particular note, Plate 3 appears on both the left- and right-hand sides of the computational domain; the computational domain boundary is not necessarily a plate boundary. Plate boundaries important to the discussion that follows are labeled A, B, C and D.

The motion of the plates during one reorganization event is illustrated by curves representing the trajectories taken by particles placed at the center of each plate shortly before the onset of reorganization. The plate motion depicted unfolds over a period of 1.5×10^{-3} from a calculation of 1.13×10^{-2} dimensionless time unit duration. This time interval is representative of several similar events that occur during the full calculation. Scaling these times to dimensional values, this is a 110 Myr interval from a 844 Myr calculation. The non-dimensional velocities and times from the calculations are converted to dimensional units using a depth of 3.0×10^6 m and a thermal diffusivity of 3.8×10^{-6} m^2/s. The value of the thermal diffusivity is a factor of 3.8 larger than generally assumed for the mantle. It is chosen by assuming the overturn time of the mantle is the relevant time scale for the calculations. For plate

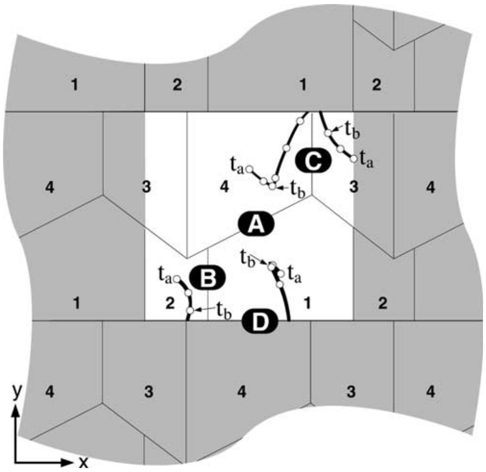

Fig. 1. The geometry of the plates is outlined by the thin black lines. A particle is placed at the center of each plate at time t_a. The heavy black lines illustrate particle paths for 110 Myr of the calculation with white circles along the curve every 18.75 Myr. Labels t_a and t_b denote times where isosurfaces are shown in Fig. 2. The model domain is shown in white and the plate boundaries are outlined in thin black lines. The shaded region illustrates the periodic nature of the domain. (Note that Plate 3 appears in both the upper left and upper right corners of the solution domain.)

velocities of 40 mm/yr, a particle will travel the depth of the mantle (approximately 3000 km) in 75 Myr. Thus, the dimensionless time interval that is required for a particle to travel the height of the box is assumed to be 75 Myr. Assuming the depth of the box is 3000 km, this constrains the thermal diffusivity.

The value of thermal diffusivity used in this scaling implies that the Rayleigh number used in these calculations is a factor of three to four lower than expected for the Earth. A conservative Rayleigh number was chosen to ensure that the calculations are numerically well resolved. More frequent changes in plate motion with shorter transitions between stages of stable plate motion are expected as the Rayleigh number increases. With this scaling the plate velocities are on the order of 40 mm/yr, consistent with observed tectonic plate velocities. (Throughout the text time is given in dimensionless values with dimensional values in parentheses.)

In Fig. 1, there is an abrupt transition in the motion of Plates 1 and 4. The change in motion of Plates 2 and 3 is gradual. Initially, Plates 1 and 4 converge along boundary A. After the reorganization, Plate 1 moves to the lower right (toward boundary D) and Plate 4 moves to the upper right. While Plate 1 appears to reverse direction, almost 180°, the motion of Plate 4 changes by approximately 120°. The time for this plate reorganization is 6.67×10^{-5} time units (5 Myr).

Snapshots of the temperature field taken at three times during the plate reorganization illustrated in Fig. 1 are shown in Fig. 2. The temperature distribution in the viscous plates has been removed for viewing purposes. The snapshots show: a stable period prior to the change in motion (Fig. 2a); a period during the change in motion (Fig. 2b); and a subsequent stable period after the plate reorganization (Fig. 2c). Prior to the plate reorganization (Fig. 2a), a downwelling sheet (blue isosurface) coincides with plate convergence at plate boundaries A, B and C. The plate velocity shows that cold, downwelling sheets (i.e. the subducting slab) are associated with convergent plate boundaries. In general, these cold sheets are stable throughout the stable period of plate motion except, as we describe below, preceding a transition period. Two regions of anomalously hot, buoyant fluid (orange isosurface), envelop the downwelling sheet sinking below the convergent boundary A. These buoyant regions develop because neither conductive nor advective heat transport through the old, thick plate is sufficient to locally remove the heat generated by internal heating in the interior of the long-wavelength, internally heated convection cell. Heat trapped below the plates is swept into the region around the downwelling sheets as the plates move toward the convergent boundary, entraining the warm upper mantle. This phenomenon creates an inherently unstable buoyant volume that eventually generates stress on the plates, overcomes the force due to downwelling cold surface boundary layer material, and leads to reorganization.

Without plates, the convective planform would evolve into a pattern characterized by a larger number of plume-like downwellings [42]. While at these Rayleigh numbers the flow without plates is time-dependent, large-scale flow reorganizations

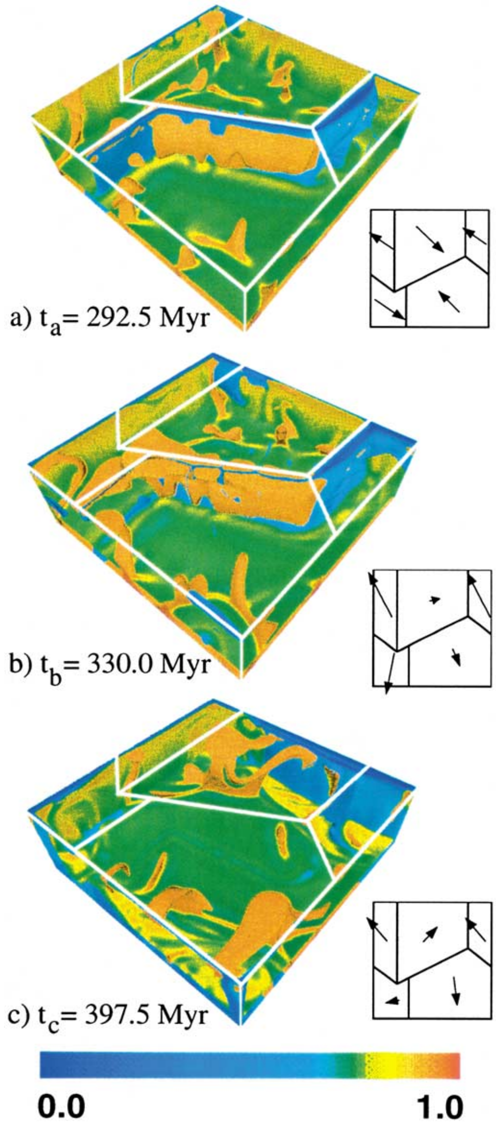

Fig. 2. Temperature isosurfaces below the viscous plate from three times surrounding plate reorganization (Fig. 1). (a) The beginning of the period illustrated in Fig. 1; (b) at the time of plate motion change; (c) after the end of the reorganization. Blue represents low temperatures and orange represents high temperatures. Plate geometry is outlined in white on the surface of the domain. Icons at the right show the instantaneous plate velocity.

have not been observed in flows without plates at the Rayleigh number and internal heating rate used in these calculations. In contrast, the large-scale planform instilled by the plate geometry allows large, isolated, poorly mixed regions to develop where heat builds up with time due to internal heat production distributed throughout the volume. As the system evolves, plate motion entrains warm upper mantle material into isolated regions that gradually grow to become unstable, at which time the plate motion changes.

At the time of the reorganization (Fig. 2b) hot, buoyant volumes of fluid near the downwelling sheet (orange isosurfaces) rise and spread out along the bottom of the plate. At the same time, the supply of cold material to the downwelling sheet below boundary A ceases. Plate 4 has nearly stopped moving while Plate 1 has reversed direction. Buoyancy in the hot, buoyant volumes reduces the 'slab pull' force on the plates from the mature, cold downwelling sheet and Plate 4 changes direction.

Following plate reorganization (Fig. 2c), a cold downwelling sheet forms below the convergent plate boundary D. Both the cold sheet and the warm regions associated with plate boundary A in Fig. 2a have disappeared. Plates 1 and 4 are moving toward the new downwelling sheet associated with a young subduction zone. Plate 1 is converging almost perpendicular to plate boundary D, while the motion of Plate 4 is oblique, driven by downwellings along the back-edge of the model (boundary D) and along boundary C.

A time series for the velocity of each plate for the period of the calculation (Fig. 3) suggests that at several times major changes in plate direction occur in less than 5.0×10^{-5} (3.75 Myr). Moreover, plate motions do not all change at the same time. This is apparent in the change in motion of Plates 1 and 4, which occurs just before time $t_b = 4.4 \times 10^{-3}$(330.0 Myr). During this event, the velocity arrows for Plate 1 change first followed by a change in the velocity of Plate 4. The motion of Plate 1 changes by almost 180° just before t_b, similar to a 'plate reversal' in a 2D calculation, and so the velocity drops to nearly zero (as it would have to in a 2D model) [26]. The velocity of Plate 4, the plate that abruptly changes direction by about 100°, decreases but does not go to zero. The velocity of Plate 2 changes prior to t_b while Plate 3 remains relatively stable throughout this time. Plate 3

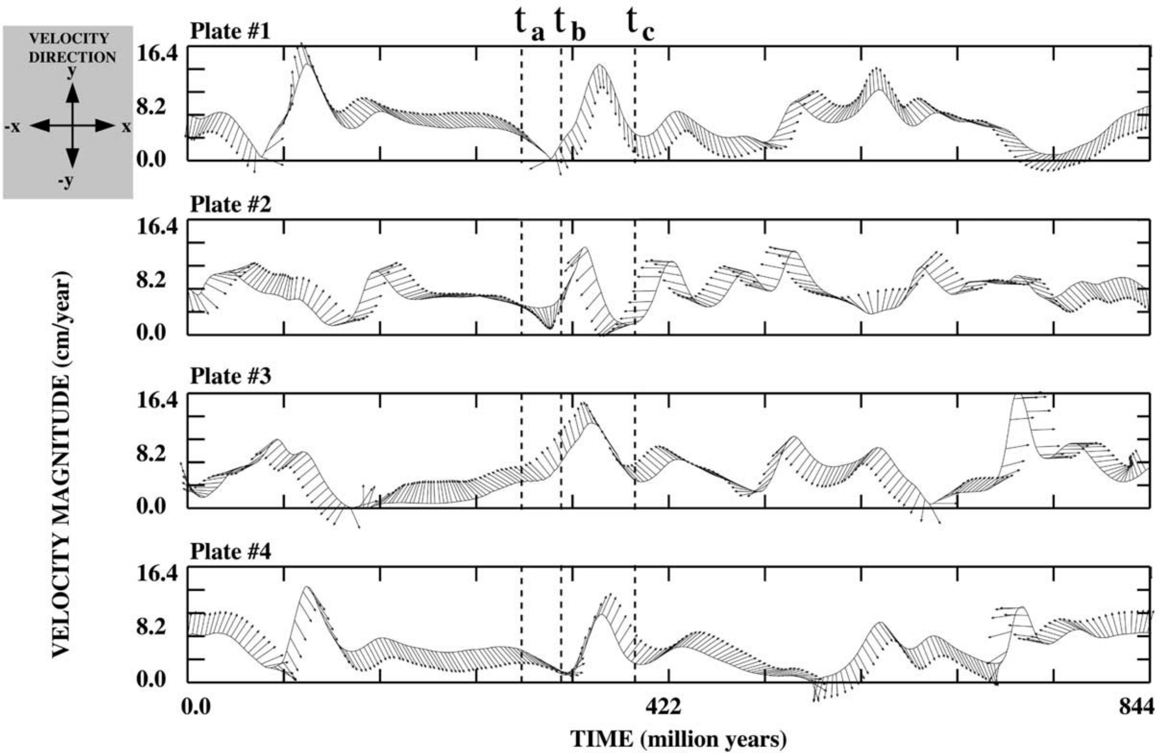

Fig. 3. Time-series plots of plate velocities for the four plates over the total period of the calculation. Velocity directions are illustrated by the arrows (see the coordinate system in the upper left) plotted at 5.0×10^{-5} (3.75 Myr) intervals and the magnitudes of the velocities are represented by the vertical scale of the time-series plot. A sudden change in the direction of plate motion is illustrated by the change in direction of neighboring arrows, which are plotted at 3.75 Myr intervals.

gradually changes direction later but has little effect on the other plates.

Over the time period shown in Fig. 3, four changes in plate motion involving more than one plate occur. These mark major plate reorganization events. Several instances exist where there is a change in the motion of a single plate.

Plate velocity magnitudes decrease significantly when plate directions change by more than 90° (e.g. Plate 1 at approximately 8.6×10^{-4} (65 Myr) and 4.0×10^{-3} (300 Myr); Plate 3 at approximately 2.0×10^{-3} (150 Myr) and 8.6×10^{-3} (650 Myr); Plate 4 at approximately 7.2×10^{-3} (540 Myr), because there is nearly a 180° change in plate motion (i.e. a reversal). Changes of less than 90° are also common (e.g. Plate 2 at 2.0×10^{-3} (150 Myr), 4.0×10^{-3} (300 Myr), 7.6×10^{-3} (570 Myr), 9.6×10^{-3} (720 Myr); Plate 3 at 9.2×10^{-3} (690 Myr); Plate 4 at 1.0×10^{-3} (80 Myr) and 9.6×10^{-3} (720 Myr)) and are not characterized by significant decreases in velocity.

4. Discussion

In the mechanism that we describe, plate reorganizations occur as a consequence of an instability that results from internal heat generation within the mantle and new subduction zones develop in response to the convergence of plates as the change in plate motion occurs. Hot regions enveloping mature slabs reduce the negative buoyancy 'pull' of the slab on the plate, allowing the plate to move toward a new subduction zone. It is generally accepted that the negative buoyancy of cold subducted slabs provides the major force driving plate motion. The suggestion by others that plates change direction in response to newly formed subduction zones lacks an explanation for the force driving the plate motion change. The negative buoyancy of a young slab must overcome the negative buoyancy of a mature slab.

Previous investigations focused on the hypothesis that evolving plate boundaries are responsible for the change in direction of plate motions [8,9]. However, using the best available plate geometry constraints throughout the Cenozoic and Mesozoic periods, the calculations fail to produce dramatic changes in plate motion consistent with the bend in the Hawaiian-Emperor chain [9]. The India–Asia collision has been proposed as the event responsible for the change in Pacific plate motion [43]. Yet, this change in plate geometry has no appreciable effect on the Pacific plate [9]. Thus, it appears that changes in plate geometry are not responsible for the dramatic change in the motion of the Pacific plate. It has been speculated that unmodeled effects related to the change in the Pacific–Australian margin from a transform boundary to subduction may be responsible for the change in Pacific plate motion [9]. Until the current study, the strongest evidence supporting this speculation was the assumed inability of mantle processes to reorganize plate motions on the necessary time scale.

It is interesting to note that Cenozoic plate calculations have the greatest difficulty reproducing the plate motions in the stages just before and after the bend in the Hawaiian-Emperor chain (e.g. the 25–43 and 10–25 Ma stages). Lithgow-Bertelloni and Richards [9] find that arbitrarily eliminating the lower mantle component of the slab driving force produces a better fit to the observed plate motions during these stages. While this does not prove that the mechanism we describe is applicable to the Earth, it is consistent with the calculations we describe – where hot regions enveloping a mature slab reduce the negative buoyancy of the slab. In the method used in previous studies [8,9], the only source of buoyancy in the mantle comes from the input subducting slab geometry. The mechanism we describe cannot occur in the calculations in [8,9] because the energy equation is not explicitly solved.

Based on a series of calculations similar to the calculation described above, several generalizations are apparent. First, the thermally induced buoyant instability responsible for plate reorganization is dependent on Rayleigh number; the higher the Rayleigh number the more likely, and the more frequent, changes in plate motion will be [26]. In the calculation described here, major changes in the direction of plate motion occur in less than 5.0×10^{-5} (3.75 Myr), consistent with the geological observations. Second, more symmetrical plate geometries suppress plate reorganizations. For example, reorganizations are infrequent or absent, even at high Rayleigh numbers, in calculations with symmetric plate geometries such as four square or two triangular plates. On Earth, plates vary in size and shape and the low symmetry in plate geometry on Earth supports plate reorganization driven by the thermal instability described above.

Plate geometries on Earth evolve with time, and it has been suggested that changes in plate geometry are an important factor in plate reorganization. If this were the case, calculations with geologically constrained plate boundary evolution [8,9] should have produced the dramatic change in the motion of the Pacific plate at 43 Myr. The fixed plate geometries in the calculations presented here focus on the interaction between internally heated convection and plate motions. Whether changes in plate boundary forces cause changes in plate motions or whether both changes in plate boundaries and plate motions are a response of the plate system to mantle convection, as we propose, is an important question. As the calculations demonstrate, the interaction between plate motions and the mantle is a dynamic process that exhibits rapid and episodic changes in plate motion. Changes in plate boundary forces or plate geometry are not necessary to trigger plate reorganization.

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References

[1] R. Hey, A new class of pseudofaults and their bearing on plate tectonics: a propagating rift model, Geol. Soc. Am. Bull. 88 (1977) 1404–1420.
[2] P.A. Rona, E.S. Richardson, Early Cenozoic global plate reorganization, Earth Planet. Sci. Lett. 40 (1978) 1–11.
[3] D.C. Engebretson, A. Cox, R.G. Gordon, Relative motion between oceanic and continental plates in the Pacific basin, Geol. Soc. Am. Spec. Pap. 206 (1985) 1–59.
[4] R.G. Gordon, D.M. Jurdy, Cenozoic global plate motions, J. Geophys. Res. 91 (1986) 12389–12406.
[5] D.A. Clague, G.B. Dalrymple, The Hawaiian-Emperor volcanic chain, part I, geological evolution, US Geol. Surv. Prof. Pap. 1350 (1987) 5–54.
[6] J.M. Stock, P. Molnar, Revised history of the early Tertiary plate motion in the southwest Pacific, Nature 325 (1987) 495–499.
[7] C. Lithgow-Bertelloni, M.A. Richards, Cenozoic plate driving forces, Geophys. Res. Lett. 22 (1995) 1317–1320.
[8] M.A. Richards, C. Lithgow-Bertelloni, Plate motion changes, the Hawaiian-Emperor bend, and the apparent success and failure of geodynamical models, Earth Planet. Sci. Lett. 137 (1996) 19–27.
[9] C. Lithgow-Bertelloni, M.A. Richards, The dynamics of Cenozoic and Mesozoic plate motions, Rev. Geophys. 36 (1998) 27–78.
[10] D.L. Turcotte, E.R. Oxburgh, Mantle convection and the new global tectonics, J. Fluid Mech. 28 (1967) 29–42.
[11] D. Forsyth, S. Uyeda, On the relative importance of the driving forces of plate motion, Geophys. J. R. Astron. Soc. 43 (1975) 163–200.
[12] B.H. Hager, R.J. O'Connell, A simple global model of plate dynamics and mantle convection, J. Geophys. Res. 86 (1981) 4843–4867.
[13] V.S. Solomatov, L.N. Moresi, Three regimes of mantle convection with non-Newtonian viscosity and stagnant lid convection on the terrestrial planets, Geophys. Res. Lett. 24 (1997) 1907–1910.
[14] M. Gurnis, B.H. Hager, Controls on the structure of subducted slabs, Nature 335 (1988) 317–321.
[15] S.D. King, B.H. Hager, The relationship between plate velocity and trench viscosity in Newtonian and power-law subduction calculations, Geophys. Res. Lett. 17 (1990) 2409–2412.
[16] S. Zhong, M. Gurnis, Mantle convection with plates and mobile, faulted plate margins, Science 267 (1995) 838–843.
[17] L. Han, M. Gurnis, How valid are dynamic models of subduction and convection when plate motions are prescribed?, Phys. Earth Planet. Int. 110 (1999) 235–246.
[18] S.A. Weinstein, P.L. Olson, Thermal convection with non-Newtonian plates, Geophys. J. Int. 111 (1992) 515–530.
[19] D. Bercovici, Generation of plate tectonics from lithosphere-mantle flow and void-volatile self-lubrication, Earth Planet. Sci. Lett. 154 (1998) 139–151.
[20] P.J. Tackley, Self-consistent generation of tectonic plates in three-dimensional mantle convection, Earth Planet. Sci. Lett. 157 (1998) 9–22.
[21] R. Trompert, U. Hansen, Mantle convection simulations with rheologies that generate plate-like behavior, Nature 395 (1998) 686–689.
[22] P.J. Tackley, Mantle convection and plate tectonics: Toward an integrated physical and chemical theory, Science 288 (2000) 2002–2007.
[23] S. Zhong, M.T. Zuber, L.N. Moresi, M. Gurnis, Role of temperature-dependent viscosity and surface plates in spherical shell models of mantle convection, J. Geophys. Res. 105 (2000) 110623–110682.
[24] C.W. Gable, R.J. O'Connell, B.J. Travis, Convection in three dimensions with surface plates: generation of toroidal flow, J. Geophys. Res. 96 (1991) 8391–8406.
[25] M. Monnereau, S. Quéré, Spherical shell models of mantle convection with tectonic plates, Earth Planet. Sci. Lett. 184 (2001) 575–587.
[26] J.P. Lowman, S.D. King, C.W. Gable, The influence of tectonic plates on mantle convection patterns, temperature and heat flow, Geophys. J. Int. 146 (2001) 619–636.
[27] S.D. King, C.W. Gable, S.A. Weinstein, Models of convection-driven tectonic plates: a comparison of methods and results, Geophys. J. Int. 109 (1992) 481–487.
[28] M. Gurnis, G.F. Davies, Numerical study of high Rayleigh number convection in a medium with depth-dependent viscosity, Geophys. J. R. Astron. Soc. 85 (1986) 523–541.
[29] M. Gurnis, Large-scale mantle convection and the aggregation and dispersal of supercontinents, Nature 332 (1988) 695–699.
[30] G.T. Jarvis, W.R. Peltier, Low-wavenumber signatures of time-dependent mantle convection, Phys. Earth Planet. Int. 59 (1990) 182–194.
[31] U. Hansen, D.A. Yuen, S.E. Kroening, Mass and heat transport in strongly time-dependent thermal convection at infinite Prandtl number, Geophys. Astrophys. Fluid Dyn. 63 (1992) 67–89.
[32] J.P. Lowman, G.T. Jarvis, Mantle convection flow reversals due to continental collisions, Geophys. Res. Lett. 20 (1993) 2087–2090.
[33] J.P. Lowman, G.T. Jarvis, Continental collisions in wide aspect ratio and high Rayleigh number two-dimensional mantle convection models, J. Geophys. Res. 101 (1996) 25485–25497.
[34] J.P. Lowman, G.T. Jarvis, Effects of mantle heat source distribution on supercontinent stability, J. Geophys. Res. 104 (1999) 12733–12747.
[35] P. Machetel, P. Weber, Intermittent layered convection in a model with an endothermic phase change at 670 km, Nature 350 (1991) 55–57.

[36] S.A. Weinstein, Catastrophic overturn of the Earth's mantle driven by multiple phase changes and internal heat generation, Geophys. Res. Lett. 20 (1993) 101–104.
[37] W.R. Peltier, L.P. Solheim, Mantle phase transitions and layered chaotic convection, Geophys. Res. Lett. 19 (1992) 321–324.
[38] S. Zhong, M.T. Zuber, L. Moresi, M. Gurnis, Role of temperature-dependent viscosity and surface plates in spherical shell models of mantle convection, J. Geophys. Res. 105 (2000) 11063–11082.
[39] H.P. Bunge, M.A. Richards, J.R. Baumgardner, A sensitivity study of three-dimensional spherical mantle convection at 10^8 Rayleigh number; effects of depth-dependent viscosity, heating mode, and an endothermic phase change, J. Geophys. Res. 102 (1997) 11991–12007.
[40] R.N. Pysklywec, J.X. Mitrovica, Mantle avalanches and the dynamic topography of continents, Earth Planet. Sci. Lett. 148 (1997) 447–455.
[41] A.M. Forte, J.X. Mitrovica, New inferences of mantle viscosity from joint inversion of long-wavelength mantle convection and post-glacial rebound data, Geophys. Res. Lett. 23 (1996) 1147–1150.
[42] F. Dubuffet, M. Rabinowicz, M. Monnereau, Multiple scales in mantle convection, Earth Planet. Sci. Lett. 178 (2000) 351–366.
[43] P. Patriat, J. Achache, India–Eurasia collision chronology has implications for crustal shortening and driving mechanism of plates, Nature 311 (1984) 615–621.