The temporal evolution of plate driving forces: Importance of "slab suction" versus "slab pull" during the Cenozoic

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[1] Although mantle slabs ultimately drive plate motions, the mechanism by which they do so remains unclear. A detached slab descending through the mantle will excite mantle flow that exerts shear tractions on the base of the surface plates. This ''slab suction'' force drives subducting and overriding plates symmetrically toward subduction zones. Alternatively, cold, strong slabs may effectively transmit stresses to subducting surface plates, exerting a direct ''slab pull'' force on these plates, drawing them rapidly toward subduction zones. This motion induces mantle flow that pushes overriding plates away from subduction zones. We constrain the relative importance of slab suction and slab pull by comparing Cenozoic plate motions to model predictions that include viscous mantle flow and a proxy for slab strength. We find that slab pull from upper mantle slabs combined with slab suction from lower mantle slabs explains the observation that subducting plates currently move ~4 times faster than nonsubducting plates. This implies that upper mantle slabs are strong enough to support their own weight. Slab suction and slab pull presently account for about 40 and 60% of the forces on plates, but slab suction only ~30% if a low-viscosity asthenosphere decouples plates from mantle flow. The importance slab pull has been increasing steadily through the Cenozoic because the mass and length of upper mantle slabs has been increasing. This causes subducting plates to double their speed relative to nonsubducting plates during this time period. Our model explains this temporal evolution of plate motions for the first time. *INDEX TERMS:* 8149 Tectonophysics: Planetary tectonics (5475); 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8157 Tectonophysics: Plate motions—past (3040); 8162 Tectonophysics: Rheology—mantle; 8168 Tectonophysics: Stresses—general; *KEYWORDS:* subduction, Cenozoic plate motions, plate-driving forces, slab pull, asthenosphere, mantle flow

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1. Introduction

[2] The Earth's tectonic plates are the fundamental surface expression of convection in the mantle. Plate motions are driven primarily by density heterogeneities in the mantle that are associated with convection [*Turcotte and Oxburgh*, 1967; *Richter*, 1977]. In a mantle largely driven by internal heating from radioactive decay, the most important source of buoyancy is the top thermal boundary layer of the convecting system, the plates [*Bercovici*, 2003]. Indeed, it is well accepted, and recent tomographic images of the mantle confirm [e.g., *Grand et al.*, 1997; *van der Hilst et al.*, 1997] that the most important density heterogeneities in the mantle are produced by the plates themselves as they dive into the mantle at subduction zones [e.g., *McKenzie*, 1969; *Richter and McKenzie*, 1978; *Hager*, 1984]. By contrast, density heterogeneity associated with lithospheric cooling, which generates the ''ridge push'' force, has been shown to represent only a small (less than ~10%) fraction of the net forces that drive plate motions [e.g., *Lithgow-Bertelloni and Richards*, 1998]. Thus the downward pull on subducted slabs is thought to be the dominant force that ultimately drives the motions of the surface plates [e.g., *Forsyth and Uyeda*, 1975; *Chapple and Tullis*, 1977; *Hager and O'Connell*, 1981; *Lithgow-Bertelloni and Richards*, 1998]. For this to be the case, the downward motion of slabs must be coupled to the horizontal motions of plates. The nature of this coupling has been the subject of some debate [e.g., *Becker and O'Connell*, 2001; *Conrad and Lithgow-Bertelloni*, 2002] and is the main focus of this work.

[3] Two mechanisms, referred to here and previously [*Forsyth and Uyeda*, 1975; *Conrad and Lithgow-Bertelloni*, 2002] as ''slab suction'' and ''slab pull,'' have been proposed to couple the motions of slabs and plates. The first, slab suction (Figure 1a), does not assume a direct physical attachment between slabs and plates, but instead arises from

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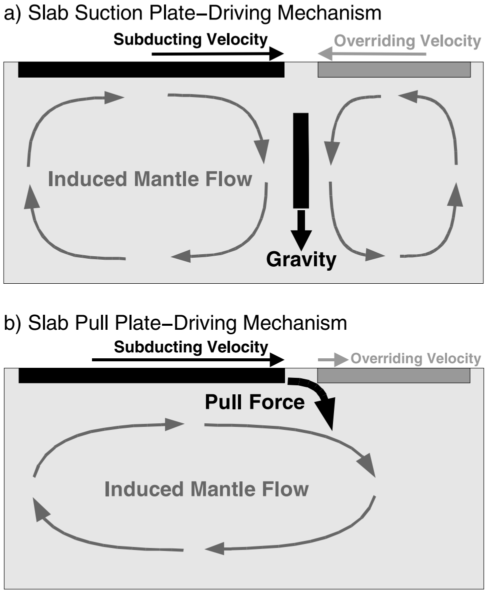

Figure 1. Cartoons showing two mechanisms by which subducted slab material can drive surface plate motions. If the slab is detached from the subducting plate, as in Figure 1a, the downward motion of the slab induces mantle flow that exerts tractions on the base of nearby plates, driving both subducting and overriding plates toward the subduction zone. If the slab remains attached to the subducting plate as it subducts, it exerts a direct pull force on the subducting plate, as in Figure 1b, drawing this plate rapidly toward the subduction zone. In this case the mantle flow induced by the motion of the subducting plate exerts shear tractions on the base of the overriding plate, driving it slowly away from the subduction zone.

the physics of convective flow in a viscous fluid [*Turcotte and Oxburgh*, 1967; *McKenzie*, 1969; *Sleep and Toksöz*, 1971]. In this view, the downward motion of dense slabs generates a circulation within the mantle that exerts shear tractions on the base of the surface plates. Because they are produced by mantle flow moving toward the downwelling material, these tractions cause nearby plates to move toward subduction zones. Slab suction has been parameterized directly as a driving force for plates [*Forsyth and Uyeda*, 1975; *Hager and O'Connell*, 1981] and is inherent to several studies that use models of mantle density heterogeneity to predict plate motions [*Ricard and Vigny*, 1989; *Deparis et al.*, 1995; *Lithgow-Bertelloni and Richards*, 1998; *Becker and O'Connell*, 2001; *Yoshida et al.*, 2001; *Zhong*, 2001].

[4] Although predictions of plate motions that consider only slab suction do reproduce the basic observation that plates generally move toward subduction zones, they typically predict that subducting plates move at about the same speed as overriding plates [*Lithgow-Bertelloni and Richards*, 1998]. By contrast, actively subducting plates are observed to move 3–4 times faster than plates that are not subducting [*Forsyth and Uyeda*, 1975; *Gripp and Gordon*, 1990; *Stoddard and Abbott*, 1996; *Zhong*, 2001; *Conrad and Lithgow-Bertelloni*, 2002]. The slab suction mechanism fails to reproduce this observation because, to first order, it operates on both the overriding and subducting plates equally. Because subducting material is downwelling between them, both overriding and subducting plates move toward the subduction zone at the same speed.

[5] One way of breaking this symmetry is to recognize that subduction involves a connection between a slab and a subducting surface plate [e.g., *Zhong*, 2001] and is an inherently asymmetrical process; one plate always subducts beneath another. If a plate remains mechanically strong as it subducts, then the subducting slab can act as a stress guide that transmits the downward pull of the dense mantle slab to the subducting boundary of a plate [*Elsasser*, 1969; *Spence*, 1987]. This mechanism, which we refer to here as slab pull (Figure 1b), has been estimated as one of several forces in a general force balance for each plate [*Forsyth and Uyeda*, 1975; *Chapple and Tullis*, 1977]. Such models, however, do not include a coupling of plates to the viscous flow beneath them. This coupling is important because the mantle flow induced by the motion of a plate driven by slab pull will exert shear tractions on the base of nearby plates, much as the flow generated by the slab suction force does. *Conrad and Lithgow-Bertelloni* [2002] showed that slab pull draws subducting plates rapidly toward subduction zones, and that this motion induces mantle flow that typically causes overriding plates to move *away* from subduction zones (Figure 1b). This overriding plate motion, when combined with the trenchward motion caused by the slab suction force, results in slow trenchward motion of overriding plates, as is observed for Earth. By estimating the slab pull force for each subduction zone from estimates of the upper mantle weight of each slab, *Conrad and Lithgow-Bertelloni* [2002] found that the combination of direct slab pull from the entire weight of upper mantle slabs and slab suction from slabs in the lower mantle reproduced the observation that subducting plates generally move 3 to 4 times faster than nonsubducting plates. This work uses the plate motions themselves as a constraint on the forces that drive plate motions.

[6] Coupling between mantle flow and plate motions may reduce the apparent effect of slab pull for certain flow geometries. For example, *Schellart* [2004a] found using laboratory experiments that a slab contributes only ~10% of its weight to pull the slab toward the subduction zones. This is because most of the slab's weight (~70%) is devoted to driving mantle flow associated with rapid trench rollback. *Schellart*'s [2004a] experiment is performed by subducting a plate of silicone putty into a shallow tank of glucose syrup. Because the trailing edge of the plate is near the tank wall and the tank depth is scaled to that of the upper mantle only, return flow generated by motion of the plate must travel around the slab, inducing strong slab rollback [*Schellart*, 2004b]. This type of focused return flow generally would not occur in an Earth-like geometry, which allows return flow to originate from elsewhere in the mantle, or to travel through the lower mantle. In addition, return flow traveling beneath the subducting plate may induce resisting shear tractions on the motion of that plate, slowing the plate. It is likely that these effects related to the constraints of the tank geometry combine to limit the effectiveness of the slab pull force for driving plate motions. They also highlight the importance of the coupling between plates and mantle flow in controlling plate motions. As a result, plate motions and

the spherical nature of mantle flow must be considered together in coupled models designed to investigate the forces that drive plate motions.

[7] *Conrad and Lithgow-Bertelloni* [2002] solve for mantle flow analytically in the spectral domain. These calculations sum the solution to the Stokes equation for each harmonic degree to obtain the net mantle flow field [*Hager and O'Connell*, 1979, 1981]. The spectral method provides a solution for the mantle flow field extremely rapidly, but it relies on the assumption of a radially symmetric viscosity structure for the mantle: layers with different viscosities are permitted, but lateral viscosity variations are not. Many mantle processes are sensitive to lateral viscosity variations [*Zhong et al.*, 2000; *Zhong*, 2001], particularly those occurring at plate boundaries [*Zhong*, 2001] where strength variations in lithospheric rocks are necessary for plate motions to occur [e.g., *Bercovici*, 2003]. For subducting lithosphere, a mechanically strong and coherent slab is required to transmit the slab pull force. Complete modeling of this pull force requires detailed modeling of asymmetrical subduction [e.g., *Conrad and Hager*, 1999a; *Billen et al.*, 2003; *Schellart*, 2004a, 2004b], which can be accomplished locally but is difficult to implement in a spherical, three-dimensional flow calculation. *Conrad and Lithgow-Bertelloni* [2002] circumvent this problem by including a parameterization of the slab pull force within the balance of forces on each plate. In doing so, these authors employ a proxy for the transmission of guiding stresses through a strong, coherent slab within the context of a radially symmetric flow model. Although this method does simulate the lateral viscosity variations necessary to transmit the slab pull force, it ignores other lateral viscosity variations that affect viscous flow in the vicinity of the subduction zone. For example, a strong, coherent slab will act as a barrier to flow that is not present if the viscosity structure is layered. Instead, a strong slab may induce flow around its edges, or mantle flow may induce trench rollback or flattening of the slab beneath the overriding plate [e.g., *Russo and Silver*, 1994; *Schellart*, 2004b]. *Billen et al.* [2003] found that the Tonga slab can support a significant fraction of its own weight if low viscosities in the mantle wedge allow for focused corner flow there [e.g., *Billen and Gurnis*, 2001, 2003]. The changes in flow patterns caused by viscosity variations near a subduction zone may affect the shear tractions exerted on the base of both the subducting and overriding plates. Although the tractions are likely to be important primarily near the subducting plate boundary, and thus for wavelengths that are generally shorter than those that dominate for global-scale flow they may be large enough to affect global predictions of slab-driven plate motions. We discuss some of the ramifications of lateral viscosity variations below but suggest that flow calculations that include the lateral viscosity variations inherent to subduction will be necessary to fully incorporate slab pull and slab suction into predictions of plate motions.

[8] In this work, we build upon *Conrad and Lithgow-Bertelloni*'s [2002] study by examining the temporal evolution of slab suction and slab pull through the Cenozoic, as well as the effect of the mantle viscosity structure on this evolution. Plate velocities and geometries have evolved significantly during the Cenozoic, giving rise to changes in the locations, sizes, densities, and geometries of slabs [*Lithgow-Bertelloni and Richards*, 1998]. The slab suction and slab pull forces exerted on the surface plates will evolve with the slabs, causing changes in plate motions. We may study changes in the temporal balance of plate driving forces by computing slab pull and slab suction through time using an evolving model of the history of subduction [*Lithgow-Bertelloni and Richards*, 1998]. By comparing model predictions to plate reconstructions in the Cenozoic, we may test whether the expected changes in the relative importance of slab suction and slab pull can explain the observed evolution in Cenozoic plate motions. A successful prediction of observed changes in plate motion will provide insight into the mechanism that causes plate motions to evolve with time, which has remained the subject of significant study [e.g., *Richards and Lithgow-Bertelloni*, 1996; *Lithgow-Bertelloni and Richards*, 1998; *King et al.*, 2002].

2. Predicting Plate Velocities

[9] To predict plate velocities driven by slab suction and slab pull, we follow the methods of *Conrad and Lithgow-Bertelloni* [2002] and *Conrad et al.* [2004]. This requires estimates of the locations and densities of slabs in the mantle, and the portion of each slab that excites the slab pull force. To calculate the slab suction force, we compute viscous flow driven by slabs that do not contribute to slab pull and sum the shear tractions that this flow exerts on the base of each plate. We predict plate motions by balancing the forces on each plate, and compare these predictions to observed plate motions. Each of these steps is described in more detail below.

2.1. Slab Heterogeneity Model

[10] We use a density heterogeneity model for the mantle that is determined from the Mesozoic and Cenozoic history of subduction [*Ricard et al.*, 1993; *Lithgow-Bertelloni and Richards*, 1998]. In this model, slab locations and densities are calculated by advecting oceanic lithosphere vertically downward into 20 equally spaced depth intervals at the rate of plate convergence in the upper mantle and at a rate 4 times slower in the lower mantle to account for its likely higher viscosity. Because the mantle density heterogeneity model is determined solely from Cenozoic and Mesozoic plate reconstructions, we also estimate models for past times, allowing us to predict plate motions throughout the Cenozoic [*Deparis et al.*, 1995; *Lithgow-Bertelloni and Richards*, 1995, 1998].

2.2. Connected Slab Models

[11] Following *Conrad and Lithgow-Bertelloni* [2002], we determine the slab pull force for a given time period by estimating the excess mass of the slab material that is physically attached to subducting plates, and multiplying by the acceleration due to gravity. We determine which previously subducted slabs are part of continuous subduction at each subduction zone (Table 1) and, following the method of *Conrad and Lithgow-Bertelloni* [2002], distribute their weight as a pull force on subducting plates, normal to subducting plate boundaries. For the present-day, we use the 10 subduction zones (Table 1) that we have defined previously [*Conrad et al.*, 2004]. For Cenozoic stages, we

Table 1. Geologic History of Continuous Subduction Used to Determine the Slab Connectivity for Present-Day Subduction Zones and for Subduction Zones Through the Cenozoic[a]

	Present-Day Subduction Zones										Past Subduction Zones		
Stage	CAM	PEC	CHL	JVA	NWH	TON	MIZ	ALT	JKK	PHL	FAR	AFR	KUL
0–10 Ma	CO/NA CO/CA	NZ/SA	NZ/SA	IN/EU	IN/PA	PA/IN	PA/PL	PA/NA	PA/EU PA/NA	PL/EU			
10–25 Ma	CO/NA[b] CO/SA[b]	NZ/SA[c]	NZ/SA[c]	IN/EU[d]	IN/PA[e]	PA/IN[f]		PA/NA[g]	PA/EU[h] PA/NA[h]	PA/EU[h]	FA/NA[i]		
25–43 Ma	NZ/NA[c] NZ/SA[c]	NZ/SA[c]	NZ/SA[c]	IN/EU[d]	AU/PA[j]			PA/NA[g]	PA/EU[h]	PA/EU[h]	FA/NA[i]	AF/EU[k]	
43–48 Ma	NZ/SA[c]	NZ/SA[c]	NZ/SA[c]	IN/EU[d]				PA/NA[g]	PA/EU[h]	PA/EU[h]	FA/NA[i]	AF/EU[k]	
48–56 Ma	FA/SA[i] FA/NA[i]	FA/SA[i] FA/NA[i]	FA/SA[i] FA/NA[i]	IN/EU[d]					PA/EU[h]	PA/EU[h]	FA/NA[i] FA/SA[i]		KU/NA[l]
56–64 Ma	FA/SA[i] FA/NA[i]	FA/SA[i] FA/NA[i]	FA/SA[i] FA/NA[i]	IN/EU[d]					PA/EU[h]	PA/EU[h]	FA/NA[i] FA/SA[i]		KU/NA[l]
64–74 Ma	FA/SA FA/NA FA/CA	FA/SA FA/NA FA/CA	FA/SA FA/NA FA/CA	IN/EU IN/PA IN/AF					PA/EU	PA/EU	FA/NA FA/CA FA/SA		KU/NA KU/EU
74–84 Ma	FA/NA	FA/NA	FA/NA	IN/EU IN/PA IN/AF					PA/EU	PA/EU	FA/NA		KU/NA KU/EU
84–94 Ma	FA/NA	FA/NA	FA/NA	IN/EU IN/IZA							FA/NA		FA/NA FA/EU
94–100 Ma	FA/NA	FA/NA	FA/NA	IN/EU							FA/NA		FA/NA FA/EU
100–119 Ma	FA/NA	FA/NA	FA/NA	IN/EU							FA/NA		FA/NA FA/EU

[a]Connected subducting/overriding plate pairs are shown as a function of time, where plate abbreviations are as given by *Lithgow-Bertelloni and Richards* [1998]. Present-day subduction zones [*Conrad et al.*, 2004] are for 0–10 Ma: Central America (CAM), Peru-Columbia (PEC), Chile (CHL), Java-Bengal (JVA), New Hebrides (NWH), Tonga (TON), Marianas-Izu-Bonin (MIZ), Aleutians (ALT), Japan-Kurile-Kamchatka (JKK), Philippines (PHL). Cenozoic subduction zones are denoted by superscripts and corresponding footnotes.
[b]Cocos Subduction Zone (10–25 Ma).
[c]Nazca Subduction Zone (10–48 Ma).
[d]Indian Subduction Zone (10–64 Ma).
[e]New Hebrides Subduction Zone (10–25 Ma).
[f]Tonga Subduction Zone (10–25 Ma).
[g]Aleutian Subduction Zone (10–48 Ma).
[h]Western Pacific Subduction Zone (10–64 Ma).
[i]Farallon Subduction Zone (10–64 Ma).
[j]Australian Subduction Zone (25–43 Ma).
[k]African Subduction Zone (25–48 Ma).
[l]Kula Subduction Zone (48–64 Ma).

use subduction zones defined for the major subducting boundaries of each subducting plate (Table 1). *Conrad and Lithgow-Bertelloni* [2002] found that present-day plate motions were best reproduced if nearly the entire weight of upper mantle slabs contribute to the slab pull force, but lower mantle slabs contribute to slab suction. Thus we exclude slab material deeper than 660 km when calculating the slab pull force. It is possible that some of a slab's upper mantle weight may be supported by the viscous mantle into which it descends, and thus contribute to slab suction instead of slab pull. Although *Conrad et al.* [2004] found that the fraction of a slab's weight that is transmitted as slab pull may depend on the degree of frictional interaction between the subducting and overriding plates, such variations between subduction zones cannot be constrained for past plate geometries. Thus we assume that this fraction does not vary between subduction zones for the purposes of this study.

2.3. Computation of Mantle Flow

[12] Both the slab suction and slab pull plate-driving mechanisms involve a coupling between plate motions and viscous mantle flow. We solve for mantle flow analytically in the spectral domain to harmonic degree 20 and use the propagator matrix method [*Hager and O'Connell*, 1979, 1981] to determine flow in each layer of the radially varying viscosity structure that yields the best fit to the geoid for the slab heterogeneity model [*Lithgow-Bertelloni and Richards*, 1998]. This structure includes a 130 km thick lithosphere that is 10 times more viscous than the upper mantle and a lower mantle below 660 km that is 50 times more viscous. Because it is inversely related to plate speeds, the absolute magnitude of the upper mantle viscosity can be tuned so that average predicted velocities match observed values [*Lithgow-Bertelloni and Richards*, 1998]. This is permitted because, although the average mantle viscosity is constrained by postglacial rebound studies, these constraints include an uncertainty of at least a factor of two [*Mitrovica*, 1996].

2.4. Computation of Plate Velocities

[13] Predicted plate velocities result from a balance between forces that drive and resist plate motions [e.g., *Solomon and Sleep*, 1974; *Lithgow-Bertelloni and Richards*, 1998]. We express the estimated slab pull force as a torque acting on each plate. The torques due to slab suction are determined by computing the viscous mantle flow induced by the slab heterogeneity model (with slab material that

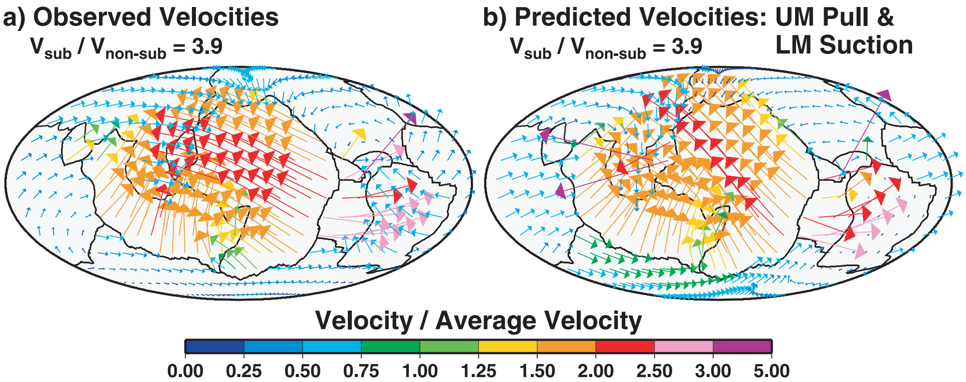

Figure 2. Comparison of (a) observed present-day plate motions with (b) predicted plate motions driven by a combination of direct slab pull from upper mantle slabs and slab suction from slabs in the lower mantle [*Conrad and Lithgow-Bertelloni*, 2002]. Velocity arrow lengths and colors are scaled to the average plate velocity.

generates slab pull removed), subject to a rigid surface boundary condition. The shear tractions acting on the base of this rigid surface are summed for the area covered by each plate to give the slab suction torque acting on each plate. Following *Lithgow-Bertelloni and Richards* [1998], we include mass variations of the oceanic lithosphere to account for the ''ridge-push'' force associated with thermal thickening of oceanic lithosphere. This force, however, is less than 5–10% of the slab pull and slab suction forces [*Lithgow-Bertelloni and Richards*, 1998], and thus its inclusion here does not significantly affect predicted plate velocities.

[14] Surface plate motions induce flow in the mantle that exerts shear tractions on the base of all plates. These tractions tend to resist the motions of the surface plates and are calculated by moving each plate a unit amount in each Cartesian direction while holding the others still. By finding the set of resistive torques that exactly balance the combined slab pull and slab suction plate-driving torques, we solve for the plate motions driven by those torques [*Ricard and Vigny*, 1989; *Lithgow-Bertelloni and Richards*, 1998]. Because the motion of one plate induces flow that exerts traction on every other plate (which allows the slab pull force to drive motion of the overriding plate), we solve for the motion of every plate simultaneously. For consistency, we subtract any net rotation of the lithosphere to present all results in a no-net-rotation reference frame.

2.5. Evaluation of Predicted Plate Velocities

[15] We evaluate models for the relative importance of the slab suction and slab pull forces based on their ability to predict observed plate motions. For the Cenozoic, we use the plate geometries and poles of rotation from *Gordon and Jurdy* [1986], and for the Mesozoic we use the compilations of *Lithgow-Bertelloni and Richards* [1998]. For the present-day, we used the plate motions (Figure 2a) used by *Conrad and Lithgow-Bertelloni* [2002], which are based on *Gordon and Jurdy*'s [1986] rotation poles for all plates except the African and South American plates, whose motion has been revised due to redating of South Atlantic seamounts [*O'Connor and le Roex*, 1992].

[16] To compare predicted and observed plate motions, we compute the ratio of plate speeds for plates with subduction zones (the Cocos, Indian-Australian, Nazca, and Pacific plates for the present-day) to those without (the African, Antarctic, Eurasian, North American, and South American plates). Average plate speeds are determined by taking the area-weighted average of local velocity magnitudes on a 1° by 1° grid. Small plates (the Caribbean, Arabian, and Philippine plates) are not included in this average because the degree of slab attachment to these plates is ambiguous, as is their observed plate motion. For a second measure of fit that includes information about the magnitude and direction of plate motions, we measured the area-weighted average magnitude of the vector difference between the predicted and observed velocity fields, as measured on a 1° by 1° grid [*Conrad et al.*, 2004]. Predicted velocities are first scaled to produce an average speed equal to that of the observed field.

3. Predicted Plate Velocities Through the Cenozoic

[17] *Conrad and Lithgow-Bertelloni* [2002] showed that present-day plate motions are best explained if lower mantle slabs drive plate motions by slab suction while upper mantle slabs drive plate motions by slab pull. This combination causes subducting plates to move about 4 times faster than nonsubducting plates (Figure 2b), as is observed (Figure 2a). This combined model can be applied to predict plate motions through the Cenozoic using estimates of slab locations during this time period. Following the work of *Lithgow-Bertelloni and Richards* [1998], we estimate past slab locations using geological reconstructions of subduction history through the Cenozoic and Mesozoic, but introduce slab pull from upper mantle slabs into their predictions of past plate motions. Because plate geometries and relative plate speeds during Cenozoic were different than they are today, comparisons between predicted and observed plate motions provide additional tests of the plate-driving model that combines lower mantle slab suction and upper mantle slab pull. Such comparisons also offer an opportunity to explain time-dependent changes in patterns of plate motions based on changes in the forces that drive these plates.

[18] Earth's tectonic plates experienced significant changes in directions and speeds during the Cenozoic. On a global scale, perhaps the most important change is the acceleration

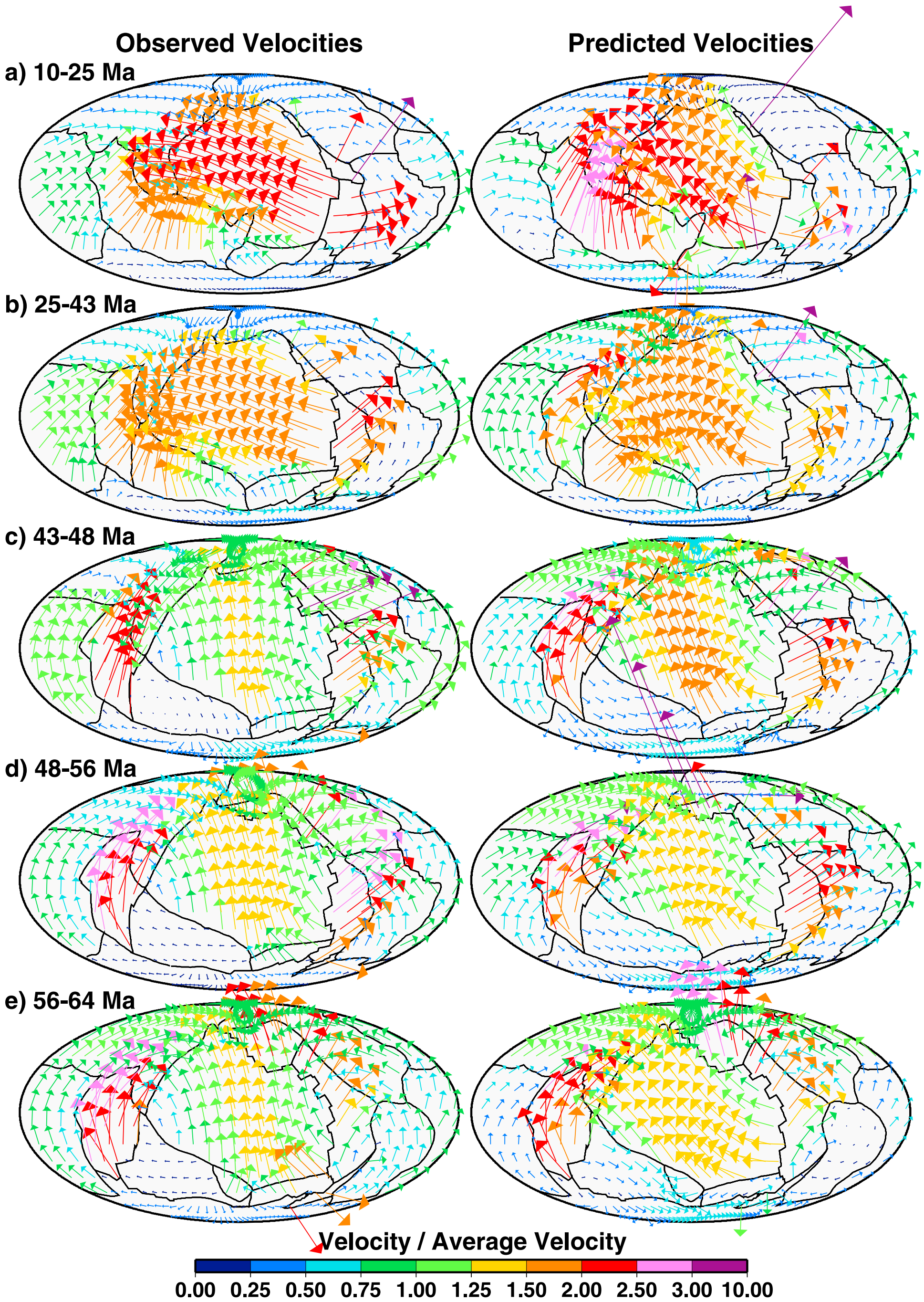

Figure 3. Comparison of (left) observed plate velocities and (right) predicted plate velocities for different stages during the Cenozoic. Predicted plate velocities are driven by direct pull from upper mantle slabs and slab suction from lower mantle slabs. Colors and arrow lengths correspond to velocity magnitudes relative to the average velocity.

of plates in the Pacific basin relative to the rest of the world during the second half of the Cenozoic. Before about 43 Ma, the Pacific plate was moving with speeds comparable to those of the nonsubducting Eurasian and North American plates, as shown by yellow and green colors in Figure 3 (left). During this time, only the Indian and Farallon plates subducting beneath Eurasia and the Americas moved at speeds significantly faster than average. Because of the small relative area of these plates, they do not contribute significantly to the global average of subducting plate speeds. As a result, the ratio of subducting to nonsubducting plate speeds was between 1.5 and 2.0 during the first half of the Cenozoic (Figure 4a, gray line), significantly smaller than the value of 3.9 observed for the present-day. During the second half of the Cenozoic, this ratio has increased as large subducting plates, particularly the Pacific plate, accelerated relative to the nonsubducting plates. This is shown by the orange/red and blue colors

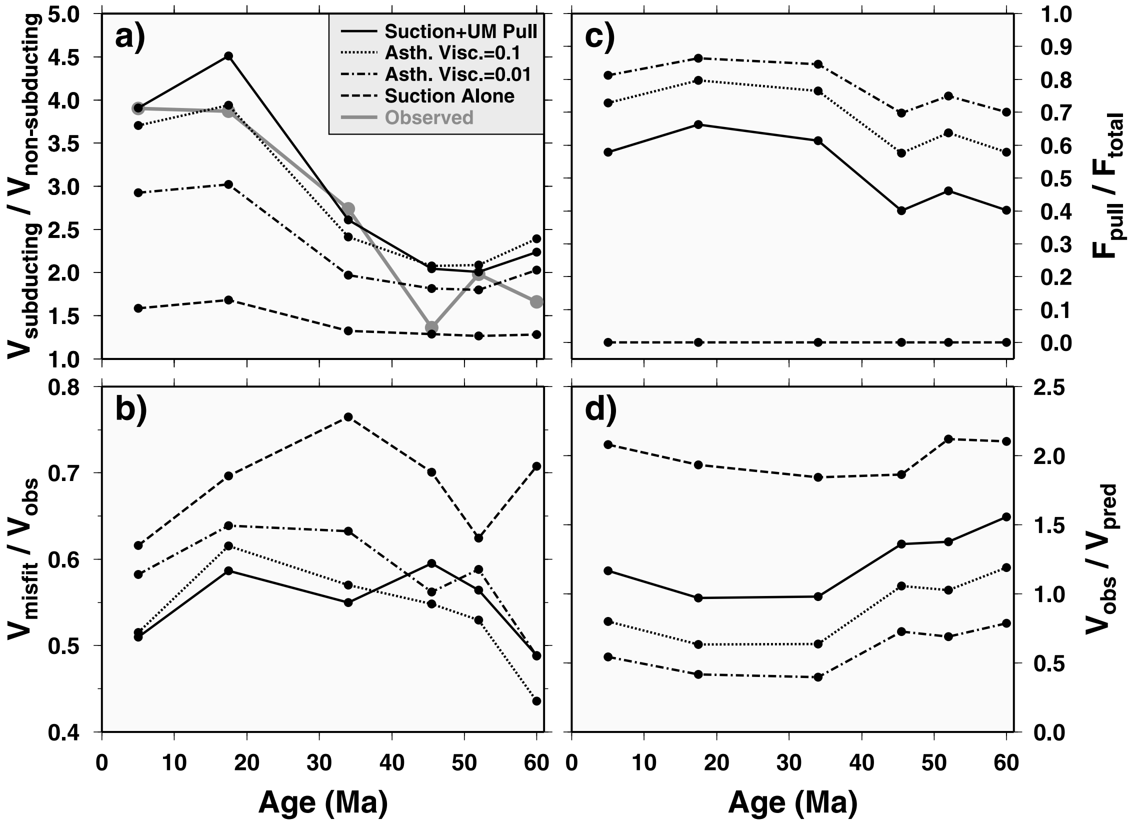

Figure 4. Comparison of diagnostics for different models of plate driving forces and viscosity structures, shown as a function of time through the Cenozoic. Shown at the midpoint of each stage is (a) the ratio of subducting to nonsubducting plate speeds, (b) the misfit between the predicted and observed plate velocities, (c) the fraction of the total force on plates that occurs as slab pull, and (d) the factor by which predicted plate velocities must be multiplied so that their average matches observed values. For an asthenosphere viscosity equal to that of the upper mantle, we show curves for slab suction operating alone (dashed line) and slab suction from lower mantle slabs operating along with slab pull from upper mantle slabs (solid line). For this combined model, we also include results using a low-viscosity asthenosphere for which viscosity is 0.1 (dotted line) or 0.01 (dash-dotted line) times that of the upper mantle. The legend in Figure 4a applies to all four panels.

that depict rapid subducting plates and sluggish non-subducting plates, respectively, during the latter half of the Cenozoic (Figures 2a, 3a, and 3b).

[19] This relative increase in subducting plate speeds during the Cenozoic provides a further test of our combined model of upper mantle slab pull and lower mantle slab suction. Plate motions predicted by this model show a reddening of the Pacific basins during the latter half of the Cenozoic, which indicates an acceleration of plate speeds relative to the rest of the globe (Figure 3, right). This acceleration is also shown by the predicted increase in the ratio of subducting to nonsubducting plate speeds (Figure 4a, solid line), which follows the same trend as the ratio obtained from plate reconstructions (Figure 4a, gray line). This acceleration is not apparent if plates are driven by slab suction alone, in which case the subducting to nonsubducting plate speed ratio remains close to 1.5 through the Cenozoic (Figure 4a, dashed line). The combined model also produces consistently lower velocity misfits to Cenozoic plate motions, compared to slab suction operating alone (Figure 4b). While most of this improvement is due to a better fit for the relative velocities of the Pacific plate, some is also due to improved fits for the smaller, rapidly moving plates such as the Indian and Farallon plates during the early Cenozoic. The slab pull force on these plates causes them to move rapidly toward subduction zones as is observed (Figures 3c, 3d, and 3e), which is not the case for studies that drive plates by slab suction alone [e.g., *Lithgow-Bertelloni and Richards*, 1998].

[20] The increase in the speed of subducting plates relative to nonsubducting plates during the mid-Cenozoic results from an increase in the importance of slab pull relative to slab suction (Figure 4c). During the first half of the Cenozoic, slab pull from upper mantle slabs accounts for about 40% of the total forces on plates, while slab suction from lower mantle slabs accounts for the remaining 60%. Later in the Cenozoic, the slab pull contribution is increased to 60% (Figure 4c). Because increased slab pull enhances the trenchward motion of subducting plates while mantle flow induced by slab pull retards the trenchward motion of overriding ones, the growing ratio of subducting to nonsubducting plate speeds during the Cenozoic can be explained by the increase in the importance of the slab pull force.

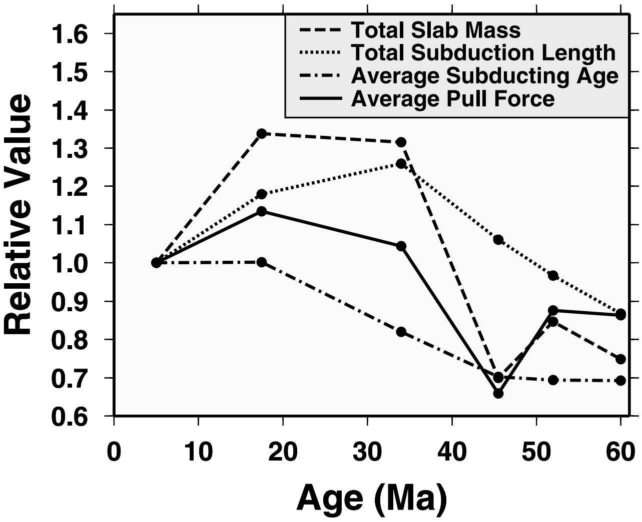

Figure 5. Variation of quantities affecting the slab pull force as a function of time through the Cenozoic. Shown at the midpoint of each stage is the total mass of upper mantle slab material that is connected to subducting plates (dashed line), the total length of subduction zones with attached slabs (dotted line), the average age of subducting material (dash-dotted line), and the average slab pull force (solid line). Each quantity is shown relative to its value during the present stage (0–10 Ma). This value is 1.3×10^{20} kg, 34,000 km, 66 Myr, and 3.8×10^{16} N/km for the total slab mass, total subduction length, average subducting age, and average pull force, respectively.

[21] The strengthening of the pull force results from the time-dependent nature of plate motions and geometries. For example, the average pull force that acts on subducting plates has increased during the Cenozoic (Figure 5, solid line) because the total mass of subducted slabs has increased (Figure 5, dashed line). The greater mass is primarily due to an increase in the average age, and thus thickness, of subducting material (Figure 5, dash-dotted line) as well a greater total length of subduction zones (Figure 5, dotted line). Increasing the average slab pull force does not lead directly to a corresponding increase in the subducting to nonsubducting plate speed ratio because the geometry and size of the plates on which this force acts determines its effect. For example, changes to the slab mass attached to the subducting Indian plate during the mid-Cenozoic may not significantly affect global averages of subducting plate speeds because the small Indian plate represents only a small fraction of the total subducting plate area. However, it is clear that changes in plate geometries during the Cenozoic changed the distribution and amplitude of slab pull forces, and thus changed the relative importance of slab pull and slab suction during this time.

[22] While radial viscosity variations affect predicted plate motion directions and relative speeds, the mantle's average viscosity affects only the magnitude of predicted plate speeds. Because the average mantle viscosity is, at best, known only to within a factor of 2 or 3 [e.g., *Mitrovica*, 1996], we scale predicted plate speeds so that their average values match average observed plate speeds for a given time period. This requires the scaling of mantle viscosities from their base structure, with an upper mantle viscosity of 10^{21} Pa s, by a reciprocal scaling factor. Thus an upper mantle viscosity of about 0.5×10^{21} Pa s is required for slab suction to reproduce average observed plate speeds, which are generally about twice as fast as those predicted using the base viscosity model (Figure 4d, dashed line). Because plate motions driven by slab pull are faster than those driven by slab suction, introducing slab pull allows a greater upper mantle viscosity of about 0.8×10^{21} Pa s (Figure 4d, solid line). All of these values are within the uncertainty associated with postglacial rebound estimates of average mantle viscosity, which, for the top 1000 km of the mantle, is thought to be about 10^{21} Pa s [*Mitrovica*, 1996]. The fact that the factor required to scale predicted velocities to observed velocities remains nearly constant for each model during the Cenozoic indicates that mantle viscosity should also remain nearly constant during this time, as is expected [*Conrad and Hager*, 1999b].

4. Effect of Mantle Viscosity: Present-Day Plate Motions

[23] The mantle's radial viscosity structure is constrained by postglacial rebound and geoid studies, but continues to be the subject of significant controversy [e.g., *Mitrovica*, 1996]. To examine how the time-dependent relative importance of slab suction and slab pull are affected by the mantle's viscosity structure, we compared observed velocities with velocities predicted from a model in which we varied the viscosity of each mantle layer by a given factor while keeping the viscosity of the other layers constant (Figure 6). There is some evidence that an asthenospheric layer with a viscosity 1 to 2 orders of magnitude smaller than that of the lower mantle lies beneath the lithosphere [e.g., *Hager*, 1991; *Mitrovica and Forte*, 1997] and might be an important enabler of plate motions [*Richards et al.*, 2001]. Thus we have added an asthenospheric layer between 130 and 230 km with an unperturbed viscosity equal to that of the upper mantle.

4.1. Lithosphere Viscosity

[24] In general, the forces acting on plates arise from mantle sources that are unaffected by lithospheric viscosity. This is shown by the nearly constant contribution of pull forces to plate-driving forces as lithospheric viscosities increase (Figure 6c). While the general pattern of plate motions does not change significantly for increased lithosphere viscosity, as shown by the only slightly increased misfit to observed velocities (Figure 6b), subducting plates tend to slow down slightly relative to the nonsubducting plates (Figure 6a). This is because a greater lithosphere viscosity inhibits relative motions between plates for a radially symmetric viscosity structure. Thus the rapid motion of a subducting plate toward an approaching overriding plate is diminished, which decreases the subducting to nonsubducting plate speed ratio. A model that includes lateral variations in lithospheric viscosity should more accurately include the increased viscosity of plate interiors while retaining the weak plate boundaries needed to accommodate the sharp changes in plate motions at these boundaries, particularly those at subducting plate boundaries [e.g., *Davies*, 1989; *King and Hager*, 1990; *Zhong and Davies*,

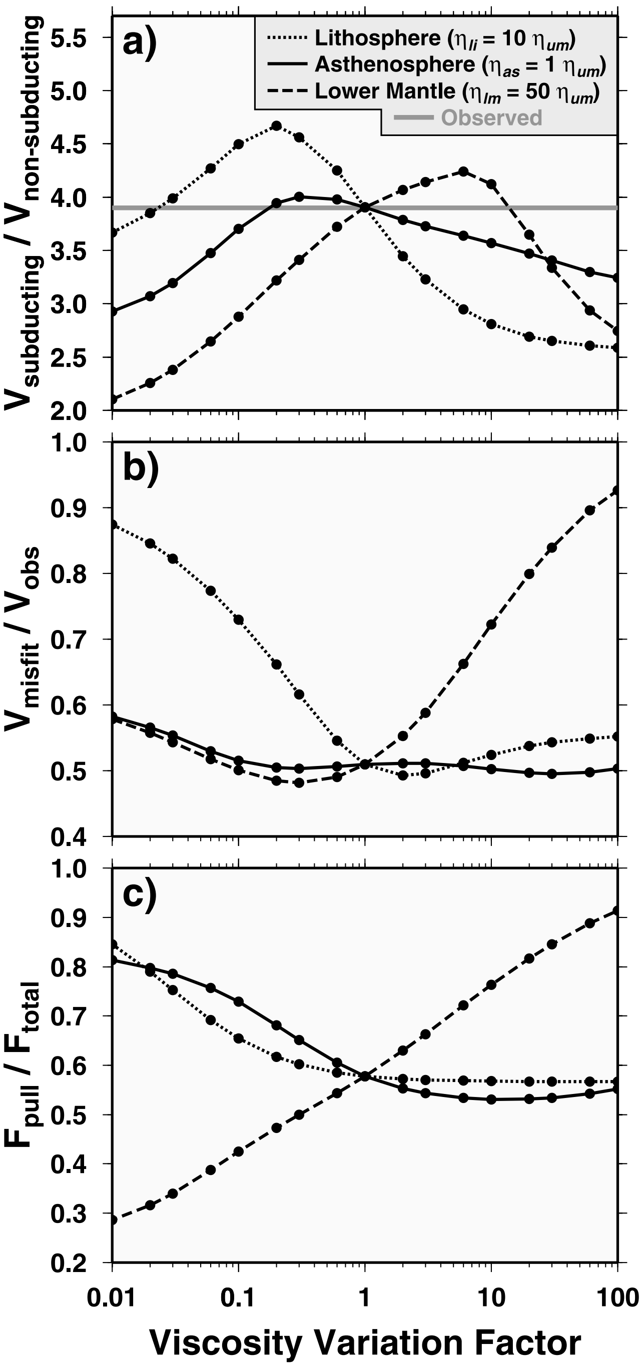

Figure 6. Comparison of present-day results for different viscosity structures. Here we vary the viscosity of a single layer of the base viscosity model (either the lithosphere (dotted line), asthenosphere (solid), or the lower mantle (dashed), base values are given in (a)) by a given factor (x axis). Shown are (a) the ratio of subducting to nonsubducting plate speeds, (b) the misfit between predicted and observed plate velocities, and (c) the fraction of the total force on plates that occurs as slab pull. The legend in (a) applies to all three panels.

1999; *Zhong*, 2001]. The moderate increase in lithospheric viscosity used in our base model acts as a compromise between the need for plate weak boundaries and strong plate interiors [*Lithgow-Bertelloni and Richards*, 1998].

[25] Diminished lithospheric viscosity, while unphysical for the earth, causes an increase in the contribution of slab pull relative to slab suction (Figure 6c) and leads to a sharp increase in the misfit to plate motions (Figure 6b). A low-viscosity lithosphere serves as a lubricating layer between mantle flow, which is the source of the forces on plates, and the Earth's surface, where we balance these forces to determine plate motions. Thus the slab suction force can not be effectively transmitted from the mantle to the surface through a low-viscosity lithospheric layer. This causes plates to be driven primarily by slab pull (Figure 6c), and leads to patterns of plate motions that are similar to those of an overly strong slab pull force [*Conrad and Lithgow-Bertelloni*, 2002].

4.2. Asthenosphere Viscosity

[26] Like the lithosphere, the asthenosphere is a near-surface layer through which mantle stresses must pass to reach the surface plates. Thus the changes in plate motions that result from increasing or decreasing asthenospheric viscosity are similar to those described above for lithospheric viscosity. An increase in asthenospheric viscosity, however, is unphysical while a low-viscosity asthenosphere is interesting for the earth. For the latter case, we again find an amplified role for slab pull relative to slab suction (Figure 6c) because a low-viscosity asthenosphere partially decouples mantle flow from the surface plates. If the asthenosphere is an order of magnitude less viscous than the upper mantle, then slab pull accounts for about 70% of the forces that drive plates (Figure 6c), the misfit to observed plate motions is only slightly increased (Figure 6b), and the subducting to nonsubducting speed ratio is slightly decreased (Figure 6a). These effects are slightly amplified if the asthenosphere is another order of magnitude less viscous.

4.3. Lower Mantle Viscosity

[27] Because the lower mantle is the layer in which slab suction forces are generated, rather than transmitted, changes in its viscosity generally have an opposite effect compared to those applied to the lithosphere or asthenosphere. For the lower mantle, a decreased viscosity causes the lower mantle to flow more rapidly for a given density heterogeneity model. This causes the slab suction force to increase in importance relative to the slab pull force (Figure 6c), which increases misfits slightly (Figure 6b) and causes subducting and overriding plates to move more symmetrically and at more similar speeds (Figure 6a). Increased lower mantle viscosity decreases the importance of slab suction in favor of slab pull (Figure 6c), which significantly increases misfits (Figure 6b), just as we observe for models with decreased lithosphere viscosity [*Conrad and Lithgow-Bertelloni*, 2002]. The base model's factor of 50 increase in lower mantle viscosity relative to that of the upper mantle is more well constrained by post-glacial rebound and mantle flow studies [*Hager*, 1984; *Hager and Richards*, 1989; *Ricard et al.*, 1993; *Mitrovica and Forte*, 1997; *Lithgow-Bertelloni and Richards*, 1998; *Steinberger*, 2000a] than are the factors for the asthenospheric or lithospheric layers [e.g., *Hager*, 1991; *Mitrovica and Forte*, 1997]. A lower mantle viscosity variation of half an order of magnitude causes only small changes in the fit to observed

plate motions (Figures 6a and 6b) or the relative importance of slab pull and slab suction (Figure 6c).

5. Mantle Viscosity Structure and Cenozoic Plate Motions

[28] Our predictions of Cenozoic plate motions depend on the mantle viscosity structure that we use. For the present-day, we have shown that lithosphere viscosity should not significantly affect predicted plate motions if weak plate boundaries are introduced. We have also shown that the uncertainty associated with the viscosity increase into the lower mantle is probably not sufficient to significantly affect plate motions. The viscosity of the asthenosphere, however, is not well constrained and possible ranges permit a more significant range of predicted plate motions. Thus we have predicted plate motions throughout the Cenozoic using a combination of upper mantle slab pull and lower mantle slab suction and a viscosity structure that includes an asthenosphere between 130 and 230 km depth with a viscosity that is 10 or 100 times less viscous than the upper mantle (Figure 4, dotted and dash-dotted lines). The presence of an asthenosphere that is 10 times less viscous than the upper mantle results in a subducting to nonsubducting plate speed ratio that is relatively unchanged (Figure 4a), and misfits to observed plate motions are also comparable (Figure 4b). As predicted by the present-day tests (Figure 6), subducting plates begin to slow compared to nonsubducting plates, and misfits rise slightly as the asthenosphere becomes 100 times less viscous than the upper mantle (Figures 4a and 4b). As discussed above, these changes result from a decreased importance of slab suction as a plate driving force due to the poor transmission of stresses from mantle flow through a low-viscosity asthenosphere. The slab pull force accounts for 60–80% or 70–90% of the forces on plates if the lithosphere viscosity is 10 or 100 times less viscous than the upper mantle (Figure 4c). The increased importance of slab pull increases average plate speeds compared to models without an asthenosphere (Figure 4d, dotted, dash-dotted lines). Given the comparable fits for models that either exclude or include a low-viscosity asthenosphere, it is difficult to verify the presence of an asthenosphere using these results. However, if an asthenosphere is present, it is probably not significantly more than about 10 times less viscous than the upper mantle.

6. Discussion

[29] The manner in which slabs drive plate motions and mantle flow depends on the rheological properties of both the slabs themselves and the viscous mantle into which they descend. As a result, we can use our constraints on the partitioning of slab weight between slab suction and slab pull to make inferences about the relative strengths of slabs and the surrounding mantle as a function of depth. For example, we have found that slabs in the upper mantle must drive plate motions primarily through slab pull. This implies that upper mantle slabs must be strong enough to support their own upper mantle weight, which requires the presence of extensional guiding stresses acting within the slab [*Elsasser*, 1969; *Spence*, 1987]. The presence of these guiding stresses has been inferred from slab seismicity [*Christova and Scholz*, 2003]. The viscous upper mantle material that surrounds the

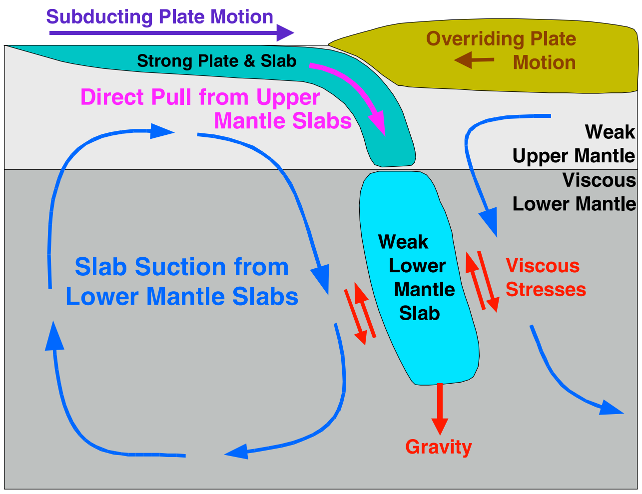

Figure 7. Cartoon summarizing the picture of the mantle developed in this work. We find that subducting plates must be pulled toward subduction zones with a force equivalent to the excess weight of the upper mantle portion of slabs. This suggests that slabs must remain physically intact as they subduct and strong enough to maintain guiding stresses that support the slab's upper mantle weight. Slabs in the lower mantle, however, must be detached from those in the upper mantle. Their excess weight is supported by the viscous mantle, which deforms and flows in response to this weight. This induced mantle flow exerts tractions on the base of the surface plates that draws both subducting and overriding plates toward subduction zones. These two mechanisms by which mantle slabs drive the surface plates cause subducting plates to move rapidly toward subduction zones while overriding plates move toward subduction zones more slowly.

slab must also be weak relative to the slab because otherwise the slab's weight would be supported by viscous stresses acting on its sides, which would excite the slab suction mechanism. This is expected because the slab is cold and its strength temperature-dependent [*Kohlstedt et al.*, 1995], so the slab should be significantly stronger than the surrounding mantle. Our results suggest that this strength increase is sufficient to cause upper mantle slabs to dangle in the mantle while supported from above by the slab itself, rather than by the strength of the viscous mantle (Figure 7).

[30] In order for slabs to support their own upper mantle weight, they must be capable of supporting up to 500 MPa of extensional stress for the heaviest slabs [*Conrad and Lithgow-Bertelloni*, 2002]. This value is much larger than estimates of stresses that are relieved by earthquakes, which are typically only about 1–10 MPa. Seismic stress drops, however provide only a lower bound on the background stress, and typically measure stress on weak plate-bounding faults [*Ruff*, 2002]. A coherent, slowly deforming, slab interior may be capable of supporting significantly larger stresses. In fact, stresses of 500 MPa are only about half of laboratory estimates of the expected maximum strength of oceanic lithosphere that is experiencing strain rates of 10^{-15} s^{-1} [*Kohlstedt et al.*, 1995]. Such strain rates will result from viscous stresses of 500 MPa if the effective viscosity of a deforming slab is about 2.5×10^{23} Pa s. This

value is within the range estimated by several authors [e.g., *De Bremaecker*, 1977; *Zhong et al.*, 1998; *Conrad and Hager*, 2001; *Billen et al.*, 2003], although non-Newtonian rheologies, such as plastic yielding, may decrease the slab's ability to support large stresses [e.g., *Pysklywec et al.*, 2000]. Thus subducting oceanic lithosphere appears to be marginally strong enough to support the upper mantle weight of slabs. The fact that the maximum pull force approaches the apparent maximum strength of the subducting slab may imply that the material strength of slabs limits the magnitude of the slab pull force. *Conrad et al.* [2004] found that the pull force at subduction zones with back-arc compression may be diminished because this compression also weakens the slab and diminishes its ability to transmit slab pull. This supports the notion that slab strength limits the maximum slab pull force.

[31] There is reason to believe that lower mantle slabs can not contribute to slab pull because of mechanical differences between upper and lower mantle materials. First, several slabs are observed to be horizontally deflected near the 670 km discontinuity [*Fukao et al.*, 2001], possibly because of the change in material properties there. This slab deformation may prevent the transmission of pull stresses from the lower to upper mantle slabs. Second, laboratory experiments show that the endothermic phase change at 660 km depth may cause significant weakening of the lower mantle portion of the slab [*Ito and Sato*, 1991], which may prevent transmission of pull stresses through the discontinuity [*Christensen*, 2001; *Conrad and Lithgow-Bertelloni*, 2002]. Third, the lower mantle is thought to be up to 2 orders of magnitude more viscous than the upper mantle [e.g., *Hager*, 1984; *Mitrovica*, 1996; *Mitrovica and Forte*, 1997]. This viscosity jump at 660 km should slow the descent of slabs as they enter the lower mantle because viscous tractions acting on the sides of slabs tend to support their weight instead of pull stresses transmitted through the slab from above. These side tractions induce viscous flow in the lower mantle (Figure 7) that excites the slab suction plate-driving mechanism. Thus the increased viscosity of the lower mantle, combined with possible weakening of slabs there, may explain why lower mantle slabs excite slab suction while upper mantle slabs excite slab pull.

[32] Slabs that are attached to surface plates at subduction zones should pull the Earth's surface downward, decreasing the geoid locally [*Moresi and Gurnis*, 1996]. This geoid constraint suggests that deep slabs must be detached from surface plates [*Zhong and Davies*, 1999], or that strong slabs must rest on a highly viscous lower mantle that partially supports the weight of the slab [*Moresi and Gurnis*, 1996]. Although these studies include rheologically strong descending slabs, they do not treat the asymmetrical nature of subduction, which may influence dynamically supported topography above the slab. Recent detailed modeling of the Tonga slab suggests that this slab remains coherent as it descends, and that the lateral viscosity variations inherent to asymmetrical subduction diminish the negative dynamic topography drawn downward by the descending slab [*Billen et al.*, 2003]. The resulting topography matches the observed trench topography [*Zhong and Gurnis*, 1994; *Billen et al.*, 2003] and decreases the short-wavelength geoid above subduction zones compared to predictions from less detailed models. The result is a predicted geoid that more closely matches observations near the subduction zone [*Billen et al.*, 2003]. Detailed global models for other subduction zones that include connected slabs and asymmetrical subduction may also satisfy global geoid constraints.

[33] Plate motions may also be affected by lateral viscosity variations in the mantle [e.g., *Zhong et al.*, 2000; *Zhong*, 2001]. For example, low viscosities associated with hot upwellings may affect global flow patterns [e.g., *Gurnis et al.*, 2000] and thus may alter the tractions that this flow exerts on the surface plates. High-viscosity slabs may introduce barriers to mantle flow that could divert the mantle around them [*Schellart*, 2004b], as is thought to occur around the Nazca slab subducting beneath South America [*Russo and Silver*, 1994]. Mantle flow may also push laterally on the plate itself, inducing trench rollback [*Schellart*, 2004b]. Alternatively, flow driven by the rapidly moving subducting plate, which would otherwise drive the overriding plate motion away from the trench, may push a strong, coherent, slab upward beneath the overriding plate. The rapidly moving Farallon plate is thought to have subducted shallowly beneath Western North America about 65 Myr ago [e.g., *Bird*, 1988]. Similarly, the Nazca slab subducting beneath central Chile may have experienced significant shallowing during the past 20 Myr [*Kay and Abbruzzi*, 1996], coincident with a period of increased subducting plate speeds for the Nazca plate [*Gordon and Jurdy*, 1986]. Because a flat-lying slab may not exert an effective slab pull force on the subducting plate, the subducting plate may slow down, decreasing the flow pushing the slab upward. Instead, the slab's own weight may draw it downward again until the slab begins to pull more effectively. The presently flat-lying Chilean slab may exert only a weak pull force [*Conrad et al.*, 2004], possibly for this reason, and may experience steepening in the future. In fact, the recent geodetic measurements of Nazca plate motion have indicated slowing of this plate relative to its average motion during the past 3 million years [*Norabuena et al.*, 1999]. Such slowing would be expected if recent slab flattening were to decrease the slab pull force.

[34] Our model of mantle density heterogeneity is based on slabs descending straight downward at locations and rates of plate convergence at the surface. Although this correctly approximates the total mass of slab material for each subduction zone, the distribution of this material will be affected by mantle flow as it descends [*Steinberger*, 2000b], causing the actual location of slabs to differ from those proposed in this model. Trench rollback or flat-lying subduction, which are not treated directly by the slab location model, may exacerbate this problem. Also, the slab location models are based on Cenozoic and Mesozoic plate reconstructions, which become increasingly uncertain as they get older [*Lithgow-Bertelloni and Richards*, 1998]. This is particularly a problem for slabs in the lower mantle and for the early Cenozoic, which are based on Mesozoic subduction, for which subducting plate ages are particularly uncertain. Errors in a slab's locations may be a problem for estimates of the slab suction force because the convergence of flow above a slab, and the shear tractions that this flow exerts on the surface plates, may be offset from the location of plate convergence at the surface. Finally, the slab heterogeneity model ignores seismically slow, and presumably light, regions of the mantle that are thought to cause upwelling mantle flow [e.g., *Conrad and Gurnis*, 2003]. Nevertheless, plate motions predicted using the slab heterogeneity model more closely match observed velocities than do those driven by densities inferred from

seismic tomography [*Becker and O'Connell*, 2001]. This suggests that tomography models do not image the structure and density of slabs completely. In addition, including the advection of slab material by mantle flow in the approximation of mantle slab heterogeneity [*Steinberger*, 2000b] only improves fits to observed plate motions slightly [*Becker and O'Connell*, 2001]. Thus including a more detailed model of mantle density structure may help improve plate motions slightly, but probably will not significantly alter our results.

[35] Although we have compared slab suction and slab pull and included the "ridge push" force within the slab suction force [*Lithgow-Bertelloni and Richards*, 1998], we have ignored several other forces that may contribute to the balance of forces acting on each plate. These include forces associated with plate-plate interactions at transform faults [e.g., *Hall et al.*, 2003], continent-continent collisions [e.g., *Richards and Lithgow-Bertelloni*, 1996; *Silver et al.*, 1998], and friction along plate-bounding faults at subduction zones [e.g., *Conrad and Hager*, 1999a]. These forces vary between plates and may be important in driving plates locally, but have not been shown to significantly improve fits to observed plate motions [*Becker and O'Connell*, 2001]. Because subducting plates are cold and therefore strong, the bending deformation required for subduction to occur may significantly resist plate motions [*Conrad and Hager*, 1999a]. Finally, compressive forces acting on slabs may also serve to diminish the slab pull force for some subduction zones [*Conrad et al.*, 2004].

[36] Lateral variations in viscosity, unmodeled forces, and potential variations between subduction zones may explain some of the differences between predicted and observed Cenozoic plate motions (Figures 2 and 3). Although the basic directions and relative speeds of plate motions are predicted by the combination of upper mantle slab pull and lower mantle slab suction, in detail there are several discrepancies. First, the motions of several slowly moving, nonsubducting plates are not well predicted during the Cenozoic (Figure 3). Slowly moving plates are especially susceptible to modeling uncertainties because small changes to the force balance of these plates can produce large changes in plate motion directions. Second, small plates are often predicted to move with speeds and directions that are different than is observed (Figure 3). Because they are driven by only a small length of attached slab and a small region of mantle flowing beneath them, small plates exhibit uncertainty in the pull and suction forces more strongly than do larger plates that tend to average out spatial variations in the forces acting upon them. Even large and rapidly moving plates, however, exhibit discrepancies between predicted and observed plate motions. For example, although the speedup of the Pacific plate during the latter half of the Cenozoic is predicted (Figure 3), the rapid northerly to westerly change in Pacific plate direction at about 43 Ma [*Gordon and Jurdy*, 1986] is not. Instead, the shift in plate motion direction gradually evolves during the entire Cenozoic, and is initially not as northerly and more recently not as westerly as is observed (Figure 3). Mantle flow models suggest that the plume that forms the Hawaii-Emperor hot spot track may have been moving southward due to mantle flow before 43 Ma [*Steinberger*, 2000a]. If so, the Pacific plate motion would be more westerly than is predicted by models based on a stationary mantle plume [e.g., *Gordon and Jurdy*, 1986]. Westerly motion during the Cenozoic is predicted by our model (Figure 3) and is also suggested by recent paleomagnetic work on Pacific seamounts [*Tarduno and Cottrell*, 1997] and by plate reconstructions not based on hot spot tracks [*Norton*, 1995]. Thus uncertainty in the "observed" plate velocities during the Cenozoic may also contribute to the net uncertainty associated with our results.

7. Conclusions

[37] We have shown that both slab pull and slab suction are required to drive the observed pattern of present-day plate motions in which subducting plates move about 3 to 4 times faster than overriding plates. The slab pull force arises from the direct pull of upper mantle slabs on the subducting surface plates to which they are attached (Figure 7) and causes subducting plates to move rapidly toward trenches while the flow induced by this motion causes overriding plates to move slowly away from trenches. Slab pull requires that slabs must be sufficiently strong to support their own upper mantle weight, while the viscous upper mantle that surrounds these slabs must offer little resistance to slab descent. Lower mantle slabs, by contrast, drive plate motions by exciting viscous flow that exerts tractions on the surface plates. This slab suction force drives both subducting and overriding plates toward subduction zones and requires that the lower mantle be sufficiently viscous so that slabs there are supported on their sides by viscous stresses associated with mantle flow, rather than from above by stresses transmitted within the slab (Figure 7).

[38] Increasing the viscosity of the lower mantle slows the speed of flow there and thus decreases the importance of slab suction. The increased role for slab pull leads to large misfits with observed plate motions. Conversely, decreased lower mantle viscosity increases the importance of slab suction and causes both subducting and overriding plates to move toward subduction zones at similar speeds, which is not observed. We find that a lower mantle that is between 1 and 2 orders of magnitude more viscous than the upper mantle provides the correct balance of forces in the upper and lower mantles, and produces the best fit to plate motions. This finding confirms the findings of several previous studies that use other observables to infer a viscosity jump of this magnitude. We also find that a low-viscosity asthenosphere beneath the lithosphere lubricates the interaction between mantle flow and plate motion, diminishing the plate-driving role of slab suction in favor of slab pull. This effect, however, only begins to diminish fits to plate motions if the asthenosphere is more than an order of magnitude less viscous than the upper mantle. In the absence of an asthenosphere, upper mantle slab pull and lower mantle slab suction account for about 60 and 40% of the forces on plates, respectively. An order of magnitude reduction of viscosity in the asthenospheric region changes the pull and suction fractions to 70 and 30%, respectively.

[39] Our model for plate-driving forces explains, for the first time, an observed change in the nature of plate motions with time. This change results from a change in the distribution of forces acting on plates. During the first half of the Cenozoic, slabs were shorter and less massive than they were during the second half. This caused the pull force to increase from about 40% of the total force on plates in the first half of the Cenozoic to about 60% during the second half. An

increase from about 60% to about 70–80% results if a low-viscosity asthenosphere is present. This increase in the relative strength of the slab pull force causes the speed of subducting plates to increase from about twice that of non-subducting plates early in the Cenozoic to about 4 times their speed recently. This observed increase in subducting plate speeds is predicted by models that drive plates using slab pull from upper mantle slabs and slab suction from lower mantle slabs, and thus confirms the importance of both of these forces for driving global plate motions.

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