Global Kinematics in the Deep Vs Shallow Hotspot Reference Frames

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Abstract

Plume tracks at the Earth's surface probably have various origins such as wet spots, simple rifts and shear heating. Since plate boundaries move relative to one another and relative to the mantle, plumes located on or close to them cannot be considered as reliable for a reference frame. Using only relatively fixed intraplate Pacific hotspots, plate motions in two different absolute reference frames, one fed from below the asthenosphere, and one fed by the asthenosphere itself, provide different kinematic results, stimulating opposite dynamic speculations. Plates move faster relative to the mantle if the source of hotspots is taken to be the middle-upper asthenosphere because hotspot tracks would not then record the entire decoupling occurring in the low velocity zone. A shallow intra-asthenospheric origin for hotspots would raise the Pacific deep-fed velocity from a value of 10 $\mathrm{cm\,yr^{-1}}$ to a faster hypothetical velocity of about 20 $\mathrm{cm\,yr^{-1}}$. In this setting, the net rotation of the lithosphere relative to the mesosphere would increase from a value of 0.4359 $^\circ\,\mathrm{Ma^{-1}}$ (deep-fed hotspots) to 1.4901 $^\circ\,\mathrm{Ma^{-1}}$ (shallow-fed hotspots). In this framework, all plates move westward along an undulated sinusoidal stream, and plate rotation

poles are largely located in a restricted area at a mean latitude of 58°S. This reference frame seems more consistent with the persistent geological asymmetry that suggests a global tuning of plate motions related to Earth's rotation. Another significant result is that along E- or NE-directed subduction zones, slabs move relative to the mantle in the direction opposed to the subduction, casting doubts on slab pull as the first order driving mechanism of plate dynamics.

1 Introduction

Absolute plate motions represent movements of plates relative to the mesosphere. To describe displacements of the lithosphere, two different absolute frameworks are used, the hotspots and the mean lithosphere. The first is based on the assumption that hotspots are fixed relative to the mesosphere and to one another (Morgan, 1972; Wilson, 1973). The second is defined by the no-net-rotation condition (NNR) (Solomon and Sleep, 1974), and it is assumed that there is uniform coupling between the lithosphere and the asthenosphere. Both absolute reference frames are referred to the mesosphere, and any difference between the mean-lithosphere and the hotspot frames is interpreted as a net rotation of the lithosphere with respect to the mesosphere (Forsyth and Uyeda, 1975). When plate motions are measured in the "classic" hotspot reference frame, the lithosphere shows a net "westward" rotation (Bostrom, 1971; O'Connell et al., 1991; Ricard et al., 1991; Gripp and Gordon, 2002; Crespi et al., 2006).

This so-called westward drift has been so far considered only as an average motion of the litho-sphere due to the larger weight of the Pacific plate in the global plate motion computation. But the westward drift persists also when plate motions are computed relative to Antarctica (Le Pichon, 1968; Knopoff and Leeds, 1972). Moreover, and more importantly, it is supported by in-dependent geological and geophysical asymmetries along subduction zones and rifts, sho-wing a global tuning and not just an average asymmetry (Doglioni et al., 1999; 2003). In order to check whether the westward drift is only an average casual component or a globally persistent signature, we analyze the different kinematics resulting from different hotspots reference frames.

Hotspot tracks have been used for computing the motion of plates relative to the mantle. For this purpose it is fundamental to know whether hotspots are i) fixed relative to the mantle, ii) if they are fixed relative to one another, and iii) from what depth they are fed. Hotspots have been used often uncritically, regardless of their real nature. Looking at maps of hotspots (e.g., Anderson and Schramm 2005), plumes occur both in intraplate settings, or close to or along plate boundaries. Hotspot reference frames have been used and misused possibly because their volcanic tracks have been considered monogenic and with similar source depths. A number of models have been produced to quantify the relative motion among hotspots and their reliability for generating a reference frame. Rejuvenating volcanic tracks at the Earth's surface may be a result of intraplate plumes (e.g. Hawaii), retrogradation of subducting slabs, migration of back-arc spreading, along strike propagation of rifts (e.g. East Africa), or propagation of transform faults with a transtensive component (Chagos?). All those volcanic trails may have different depths of their mantle sources and they should be differentiated (Fig. 1).

Plate boundaries are by definition moving relative to one another and relative to the mantle (e.g., Garfunkel et al., 1986; Doglioni et al., 2003). Therefore any hotspot located along a plate boundary cannot be used for the reference frame. For example, Norton (2000) grouped hotspots into three main families that have very little internal relative motion (Pacific, Indo-Atlantic and Iceland). In fact, he concluded that a global hotspot reference frame is inadequate because Pacific hotspots move relative to Indo-Atlantic hotspots and to Iceland. Since Indo-Atlantic hotspots and the Iceland hotspot are located along ridges, they do not satisfy the required fixity. In his analysis, Pacific plate hotspots are reasonably fixed relative to one another during the last 80 Ma, and they are located in intraplate settings. Therefore they are unrelated to plate margin processes and do not move with any margin. Screening of volcanic tracks to be used for the hotspot reference frame provides a very limited number of hot-lines and only the Pacific ones satisfy the requirements.

Hotspots may have short (<15 Ma) or long (>50 Ma) time gap between their emplacement and the age of the oceanic crust on which they reside. A shorter time frame suggests a closer relation with the formation of the oceanic crust, particularly when i) the location is persistently close to the ridge and ii) ridges form on both sides of the rifts (Doglioni et al., 2005). Therefore ridge-related plumes should move with a speed close to the absolute velocity of the plate boundary. Although moving relative to one another, hotspots always have a speed slower than plate motions and have been considered useful for a reference frame (e.g., Wang and Wang, 2001). However, the velocity of plate boundaries tends to be slower than the velocity of the relative plate motion among pairs of plates. For example the mid-Atlantic Ridge moves westward at rates comparable to the relative motion between the Pacific and Atlantic hotspots, but this intra-hotspot motion could be related to the absolute motion of the mid-Atlantic Ridge.

Moreover, assuming a deep source for the hotspots, a number of models have been computed to infer deep mantle circulation (e.g., Steinberger and O'Connell, 1998; Steinberger, 2000). These models argue that volcanic tracks move opposite to plate motions. However, this may be regarded again as a problem of reference. For example, in the no-net-rotation reference frame Africa moves "east", opposite relative to Ascencion and Tristan da Cunha, but in HS3-NUVEL1A (Gripp and Gordon, 2002) Africa moves in the same direction due "west", although at different velocity. Therefore the assumption that plates always move opposite to plate motions is misleading if not wrong.

In most of the models so far published on mantle circulation and hotspot reference frames two main issues are disregarded: i) plumes have different origins and different kinematic weights for the reference frames; ii) in the cases of plumes that are shallow asthenospheric features, this determines a different kinematic scenario with respect to the deep mantle circulation pattern.

Accumulating evidence suggests that hotspots are mostly shallow features (Bonatti, 1990; Smith and Lewis, 1999; Anderson, 2000; Foulger, 2002; Foulger et al., 2005). For example Atlantic hotspots might be interpreted more as wetspots rather than hot lines, as suggested by Bonatti (1990). An asthenospheric source richer in fluids that lower the melting point can account for the overproduction of magma. Propagating rifts (hot-lines, etc.) are shallow phenomena, which are not fixed to any deep mantle layer. The only hotspots that should be relevant to the reference frame are those located within plate. For a compelling petrological, geophysical and kinematic analysis on the shallow origin of plumes see Foulger et al. (2005). In this book a number of data are presented that support a shallow source depth for hotspots (upper mantle, asthenosphere, base lithosphere, etc.). Several theoretical models have been proposed to explain the different settings, such as rift zones, fluids in the asthenosphere, shear heating at the lithosphere-asthenosphere decoupling zone and lateral mantle compositional variations. All these models could be valid, but applied to different cases. Therefore we disagree in using uncritically all so-called hotspots because their different origin can corrupt the calculation of lithosphere-mantle relative motion.

In this paper, we present plate motions relative to a shallow hotspot framework, similar to Crespi et al. (2006). Moreover, since two fixed points are geometrically enough to construct a kinematic reference frame, we used only Pacific intraplate hotspots which are significantly fixed relative to one another (Gripp and Gordon, 2002). We obtained angular velocities that imply a different plate kinematics than the one obtained with the HS3–NUVEL1A plate kinematic model (Gripp and Gordon, 2002). Unlike Wang and Wang (2001), we find a much faster net rotation of the mean lithosphere with respect to HS3-NUVEL1A.

2 Decoupling in the asthenosphere

The asthenosphere is anisotropic, having the main orientation of crystals along the sense of shear (e.g., Barruol and Granet, 2002; Bokelmann and Silver, 2002). The asthenosphere is present all over the Earth (Gung et al., 2003), and shows an upper low-velocity zone that is more or less pronounced (Calcagnile and Panza, 1978; Thybo, 2006). This layer may have a viscosity far lower (Scoppola et al., 2006) than estimates for the whole asthenosphere (e.g., Anderson, 1989), and it should engineer the main decoupling between lithosphere and the underlying mesosphere.

The origin of intraplate Pacific magmatism is rather obscure, and its source depth and the mechanism of melting is still under discussion (Foulger et al., 2005). Since the Pacific is the fastest plate, shear heating along the basal decollement has been interpreted as a potential mechanism for generating localized hotspot tracks (Fig. 2b).

Kennedy et al. (2002) have shown how mantle xenoliths record a shear possibly located at the lithosphere-asthenosphere interface. This supports the notion of flow in the upper mantle and some decoupling at the base of the lithosphere as indicated by seismic anisotropy (Russo and Silver, 1996; Doglioni et al., 1999; Bokelmann and Silver, 2000). The fastest plate on Earth in the hotspot reference frame (i.e., the Pacific) is the one affected by the most widespread intraplate magmatism.

It is noteworthy that the fastest plate, the Pacific, overlies the asthenosphere with the mean lowest viscosity (5×10^{17} Pa s, (Pollitz et al., 1998)), and possibly the most undepleted mantle, and therefore prone to melt. Because of the melting characteristics of peridotite with minor amounts of carbon and hydrogen (lherzolite–(C+H+O) system), the asthenosphere is already partly molten (e.g., Schubert et al., 2001) and it is at a T of about 1430°C (e.g., Green and Falloon, 1998; Green et al., 2001). The rise of T of only few tens of degrees will increase the degree of melting which, in a deforming material, will migrate toward the surface. We postulate that locally, the viscosity of the asthenosphere can also increase (e.g., 10^{19} Pa s) due to refractory geochemical anisotropy, or decrease due to locally higher water activity. Shear stress could be irregularly distributed in such inhomogeneous materials, and consequently higher shear heating (Shaw, 1973) may be locally developed to generate punctiform magmatism. However, other models on the asthenospheric temperature can be devised (Foulger and Anderson, 2006).

Doglioni et al. (2005) modeled the shear heating between the lithosphere and asthenosphere as a possible source for Hawaii-type magmatism. In that model it was assumed the asthenosphere behaves as a Couette flow (Turcotte and Schubert, 1982). In such a channel, the maximum speed and the related shear heating are localized in the middle of the flow. For this reason it was assumed that the source of this type of hotspot could be positioned close to the half thickness of the asthenosphere. The asthenosphere has been shown to be an heterogeneous layer by a large number of geophysical and petrological models (e.g., Anderson, 2006; Thybo, 2006) where composition and viscosity may change laterally. Areas with viscosity higher than normal in the asthenospheric decollement should generate larger shear heating.

In such a model, punctuated and stiffer mantle sections would be able to generate sufficient extra T for asthenospheric melting. These mantle anisotropies, whenever shearing started, remained quite fixed relative to one another. According to Norton (2000) and Gripp and Gordon (2002), these intraplate Pacific plate hotspots satisfy the requirement of relative fixity, at least for the last few Ma.

3 Plate motions relative to the deep and shallow hotspots

Most of the hotspots used are neither fixed, nor do they represent a fixed reference frame because they are located on plate margins such as moving ridges (Galapagos, Easter Island, Iceland, Ascension, etc.), transform faults (Reunion), above subduction zones, or continental rifts (Afar), all features that are moving relative to one another and relative to the mantle.

In contrast, Pacific hotspots are reasonably fixed relative to one another and their volcanic tracks can be used for the hotspot reference frame. WNW-motion of the Pacific plate relative to the underlying mantle is inferred from the Hawaiian and other major intraplate hotspot tracks (Marquesas, Society, Pitcairn, Samoan, Macdonald), which suggest an average velocity of about 103–118 mm yr^{-1}, and also move along the same trend (290°–300°, WNW).

Following the hypothesis of deep-fed hotspots, after assuming that shear is distributed throughout the asthenospheric channel (Fig. 2a), and providing the velocity $\vec{V}_L$ of the Pacific lithosphere toward the ESE (110°-120°) is slower than that of the underlying sub–asthenospheric mantle $\vec{V}_M$ ($\vec{V}_M > \vec{V}_L$), the relative velocity $\vec{V}_O$ corresponding to the WNW delay of the lithosphere is:

$$\vec{V}_O = \vec{V}_L - \vec{V}_M \tag{1}$$

For the case of Hawaii, the observed linear velocity is $V_O = 103$ mm yr^{-1}, corresponding to the propagation rate of the Hawaiian volcanic track (Fig. 2a).

The HS3-NUVEL1A (Gripp and Gordon, 2002) absolute plate motion model is based on the deep-fed hotspot hypothesis. Gripp and Gordon (2002) compute absolute plate motions, estimating eleven segment trends and two propagation rates for volcanic tracks, presenting a set of absolute angular velocities consistent with the relative plate motion model NUVEL-1A (DeMets et al., 1990; 1994). Volcanic propagation rates used by Gripp and Gordon (2002) are those of Hawaii and Society, both on the Pacific plate, and they found a Pacific angular velocity of 1.0613 ° Ma^{-1} about a pole located at 61.467 °S, 90.326 °E (Table 1 and Fig. 3). Another simple way to reproduce the HS3-NUVEL1A angular velocities consists of adding the Pacific plate Euler vector, estimated by Gripp and Gordon (2002) to the relative plate motion model

NUVEL-1A (DeMets et al., 1990, 1994).

If the location of the Hawaiian melting spot is in the middle of the asthenosphere (Fig. 2b) instead of the lower mantle (Fig. 2a), this would imply that the shear recorded by the volcanic track at the surface is only that occurring between the asthenospheric source and the top of the asthenosphere, i.e. only half of the total displacement if the source is located in the middle of the asthenosphere.

Under this condition, the velocity recorded at the surface is:

$$\vec{V}_O = \vec{V}_L - \vec{V}_A \tag{2}$$

with

$$\vec{V}_A = \vec{V}_X + \vec{V}_M \tag{3}$$

where $V_O = 103\,\mathrm{mm\,yr^{-1}}$ is still the observed propagation rate of the volcanic track (for example Hawaii), $\vec{V}_A$ is the velocity recorded at the shallow source of the hotspot, and $\vec{V}_X$ is the velocity not–recorded, due to the missing shear.

Substituting equation (3) in equation (2), we have:

$$\vec{V}_O = \vec{V}_L - \vec{V}_M - \vec{V}_X \tag{4}$$

and

$$\vec{V}_O + \vec{V}_X = \vec{V}_L - \vec{V}_M \tag{5}$$

The observed velocity $V_O = 103$ mm yr^{-1} of Hawaii is the velocity of total displacement if the magmatic source is located in the deep mantle, whereas it represents only half of the whole shear if the source is located in the middle of the asthenosphere. In that case, to refer plate motions again with respect to the mesosphere, the velocity $\vec{V}_X$ has to be added to the observed velocity $\vec{V}_O$ (Fig. 2b), as shown in equation (5).

If the source of Pacific hotspots is in the middle of the asthenosphere, half of the lithosphere-sub-asthenospheric mantle relative motion is unrecorded, which means that, for example, the total relative displacement of the Hawaii would amount to about $V_O + V_X = 200$ mm yr^{-1} (Fig. 2b).

Under the hypothesis of a shallow source for Pacific hotspots, located in the middle of the asthenosphere, and referring to the HS3–NUVEL1A methods (Gripp and Gordon, 2002), Pacific plate rotation would occur about a pole located at 61.467 °S, 90.326 °E, but with a rate of 2.1226 °Ma^{-1}. Adding this Pacific Euler vector to the NUVEL-1A relative plate motion model (DeMets et al., 1990; 1994) results absolute plate motions with respect to the shallow hotspot reference frame (Table 1 and Fig. 4).

Moreover, referring to geometrical factors proposed by Argus and Gordon (1991), and using methods described by Gordon and Jurdy (1986) and Jurdy (1990), we computed net–rotation of the lithosphere relative to the mesosphere, that, under the shallow hotspot hypothesis, amounts about 1.4901 ° Ma^{-1} (Table 1), and is higher than that computed by Gripp and Gordon (2002) (0.4359 ° Ma^{-1}, deep hotspot condition, Table 1).

This faster velocity for the Pacific plate has these basic consequences: i) it extends westward drift of the lithosphere to all plates (Fig. 4), ii) the westward drift is more than double that of the deep hotspot reference frame, and iii) it increases the shear heating within the asthenosphere.

4 Shallow Hawaii plume

There is evidence that the propagation rate of Pacific "hotspots" or seamount tracks has varied with time, even with jumps back and forth and oblique propagation relative to "absolute" plate motions. This casts doubt on both the notion of absolute plate motions computed in the hotspot reference frame, and the nature of the magmatism itself (deep plume, or rather shallow plumes generated by cracks or boudins of the lithosphere (Winterer and Sandwell, 1987; Sandwell et al., 1995; Lynch, 1999; Natland and Winterer, 2003) filled by a mantle with compositional heterogeneity and no demonstrable thermal anomaly in hotspot magmatism relative to normal mid-oceanic ridges.

Janney et al. (2000) described a velocity of the Pukapuka volcanic ridge (interpreted as either a hotspot track or a leaky fracture zone), located in the eastern Central Pacific, between 5 and 12 Ma, of about 200–300 mm yr^{-1}. They also inferred a shallow mantle source for Pacific hotspots based on their geochemical characteristics.

Relative plate motions can presently be estimated with great accuracy using space geodesy data (e.g., Robbins et al., 1993; Heflin et al., 2004) refining the earlier NUVEL-1A plate motion model (DeMets et al., 1990, 1994).

The East Pacific Rise (EPR), separating the Pacific and Nazca plates, opens at a rate of 128 mm yr^{-1} just south of the equator (e.g., Heflin et al., 2004). At the same latitude shortening along the Andean subduction zone, where the Nazca plate subducts underneath South America, has been computed to about 68 mm yr^{-1}. When inserted in a reference frame where the Hawaiian hotspot is considered fixed and positioned in the sub-asthenospheric mantle, these relative motions imply that the Nazca plate is moving eastward relative to the sub-asthenospheric mantle at about 25 mm yr^{-1} (Fig. 7, option 1 of Doglioni et al., 2005). If we assume that the source of Pacific intraplate hotspots is rather in the middle asthenosphere and there is half of the lithosphere–sub–asthenospheric mantle relative motion missing in the Hawaiian track (Fig. 2b), the movement could rise to 200 mm yr^{-1}, as also suggested by some segments of the Pukapuka volcanic ridge (Janney et al., 2000). Note that in this configuration Nazca would rather move west relative to the mantle at 72 mm yr^{-1} (Fig. 7, option 2 of Doglioni et al., 2005) and therefore all three plates would move westward relative to the sub-asthenospheric mantle.

This last case agrees with the E-W-trending shear-wave splitting anisotropies beneath the Nazca plate, turning N-S when encroaching on the Andean slab, suggesting eastward mantle flow relative to the overlying plate (Russo and Silver, 1994). This flow could also explain the low dip of the Andean slab. Both suggest relative eastward mantle flow. Similar eastward mantle flow was proposed for the North American plate (Silver and Holt, 2002). The low dip of the Andean slab has alternatively been attributed to the young age of the subducting lithosphere. However the oceanic age has been proved not to be sufficient to explain the asymmetry between westerly–directed (steep and deep) vs. easterly–directed (low dip and shallow) subduction zones (Cruciani et al., 2005). In fact the geographically related asymmetry persists even where the same lithosphere (regardless oceanic or continental) subducts in both sides, such as in the Mediterranean orogens (Doglioni et al., 1999).

Another consequence of having a shallower source for Hawaiian magmatism is that the westward motion of the Pacific plate increases to a velocity faster than the spreading rate of the EPR (Fig. 7, option 2 of Doglioni et al., 2005). A shallow, intra-asthenospheric origin of Pacific hotspots provides a kinematic frame in which all mid–ocean ridges move westward. As a consequence, the ridge migrates continuously over a fertile mantle, which presents a possible explanation for the endless source of Mid-Ocean Ridge Basalts (MORB), which have a relatively constant composition. Moreover, the rift generates melting and consequently increases the viscosity of the residual mantle moving beneath the eastern side of the ridge, providing a mechanism for maintaining higher coupling at the lithosphere base, and keeping slower the plate to the east (Doglioni et al., 2003; 2005).

5 Discussion and Conclusions

We have computed absolute plate motions with respect to a shallow hotspot reference frame, making a comparison with the HS3-NUVEL1A results (Gripp and Gordon, 2002), and showing that shallow sources for hotspots produces different plate kinematics, i.e. new faster plate motions with respect to the mesosphere. Moreover in the deep hotspot frame, rotation poles are largely scattered and most of the plates move toward the west except for Nazca, Cocos and Juan de Fuca plates. On the contrary, relative to the shallow hotspot framework, all plates move westerly and rotation poles are mostly located in a restricted area at a mean latitude of 58 °S. Furthermore, we computed a faster net rotation of the lithosphere for the case of a shallow-fed hotspot, which is useful to compute plate motions in the mean-lithosphere reference frame (NNR) (Jurdy, 1990).

The mean-lithosphere is also the framework for space geodesy applications to plate tectonics (Heflin et al., 2004). Most of the geodesy plate motion models are referred to the NNR-frame (Sella et al., 2002; Drewes and Meisel, 2003). The International Terrestrial Reference Frame (ITRF2000) (Altamimi et al., 2002) is the framework where site velocities are estimated. The ITRF2000 angular velocity is defined using the mean-lithosphere. As suggested by Argus and Gross (2004), it would be better to estimate site positions and velocities relative to hotspots, continuing firstly to estimate velocity in the ITRF2000 and then adding the net-rotation angular velocity.

The deep and shallow hotspot interpretations generate two hotspot reference frames. In the case of deep mantle sources for the hotspots, there still are few plates moving eastward relative to the mantle (Fig. 3), whereas in the case of shallow mantle sources, all plates move “westward”, although at different velocities (Fig. 4). The kinematic and dynamic consequences of the shallow reference frame are so unexpected that it could be argued that they suggest that plumes are instead fed from the deep mantle. However, the shallow reference frame fits better observed geological and geophysical asymmetries which indicates a global tuning (i.e., a complete "westward" rotation of the lithosphere relative to the mantle) rather than a simple average of plate motions (i.e., where the westward drift is only a residual of plates moving both westward and eastward relative to the mantle).

In fact, geological and geophysical signatures of subduction and rift zones independently show a global signature, suggesting a complete net westward rotation of the lithosphere and a relative "eastward" motion of the mantle that can kinematically be inferred only from the shallow hotspot reference frame.

Plates move along a sort of mainstream depicting a sinusoid (Doglioni, 1990, 1993; Crespi et al., 2006) (Fig. 5), which is largely confirmed by present space geodesy plate kinematics (e.g., Heflin et al., 2004). Global shear-wave splitting directions (Debayle et al., 2005) are quite consistent with such undulate flow, deviating from it at subduction zones, which should represent obstacles to relative mantle motion. In fact, along this flow, west-directed subduction zones are steeper than those that are E– or NE–directed, and associated orogens are characterized by lower structural and topographic elevations, backarc basins, and on the other hand by higher structural and morphological elevation and no backarc basins (Doglioni et al., 1999). The asymmetry is striking when comparing western and eastern Pacific subduction zones, and it has usually been interpreted as related to the age of the downgoing oceanic lithosphere, i.e., older, cooler and denser on the western side. However these differences persist elsewhere, regardless the age and composition of the downgoing lithosphere, e.g., in the Mediterranean Apennines and Carpathians vs. the Alps and Dinarides, or in the Banda and Sandwich arcs, where even continental or zero-age oceanic lithosphere is almost vertical along west-directed subduction zones. Rift zones are also asymmetric, with the eastern side more elevated by about 100-300 m worldwide (Doglioni et al., 2003).

The westward drift of the lithosphere implies that plates have a general sense of motion and that they are not moving randomly. If we accept this postulate, plates move along this trend at different velocities toward the westrelative to the mantle along the flow lines of Fig. 5, which undulate and are not exactly E–W. In this view, plates would be more or less detached with respect to the mantle, as a function of the decoupling at their base. The degree of decoupling would be mainly controlled by the thickness and viscosity of the asthenosphere. Lateral variations in decoupling could control the variable velocity of the overlying lithosphere (Fig. 6). When a plate moves faster westward with respect to an adjacent plate to the east, the resulting plate margin is extensional; when a plate moves faster westward with respect to the adjacent plate to the west, their common margin will be convergent (Fig. 6).

The kinematic frame of shallow Pacific hotspots (Fig. 4) constrains plate motions as entirely polarized toward the west relative to the deep mantle. This framework provides a fundamental observation along E– or NE–directed subduction zones. In fact, with this reference frame, the slab tends to move out relative to the mantle, but subduction occurs because the upper plate overrides the lower plate faster. This argues against slab pull as the main mechanism for driving plate motions since the slab does not move into the mantle. In this view slabs are rather passive features (Fig. 7). This kinematic reconstruction is coherent with the frequent intra-slab down-dip extension earthquake focal mechanisms that characterize E- or NE-directed subduction zones (e.g., Isacks and Molnar, 1971). It is generally assumed that oceanic plates travel faster than plates with large fractions of continental lithosphere. However, Gripp and Gordon (2002), even in the deep hotspot reference frame, have shown that the South American plate is moving faster than the purely oceanic Nazca plate. Another common assumption is that plates move away from ridges, but again, still in the deep reference frame, Africa is moving toward the mid-Atlantic Ridge, although slower than South America. Moreover Africa is moving away from the Hellenic subduction zone. In the shallow reference frame these observations are accentuated and become unequivocal. Another typical assumption is that plates with attached slabs are move faster, but the Pacific plate moves at about 1.06 $^\circ$ Ma^{-1}, much faster in terms of absolute velocity than the Nazca plate (about 0.32 $^\circ$ Ma^{-1}). The Pacific and Nazca plates have roughly the same percentage of attached slab (37–34%).

Therefore, in the case of a shallow origin for Pacific hotspots, westward drift implies a generalized counterflow of the underlying mantle (Fig. 8). With such an asymmetric flow, upper mantle circulation would be constrained in this frame, but disturbed by subduction and rift zones (Doglioni et al., 2006a,b). The fertile asthenosphere coming from the west melts and deplets along the ridge. Continuing its travel to the east, the depleted asthenosphere is more viscous and lighter (Doglioni et al., 2005). Subduction zones directed to the east or north-northeast, along the mantle counterflow might refertilize the upper mantle, whereas west-directed subduction zones would rather penetrate deeper in the mantle.

The global scale asymmetry of tectonic features and the westward drift of the lithosphere supports a rotational component for the origin of plate tectonics (Scoppola et al., 2006). The westward drift could be the combined effect of three processes: (1) tidal torques acting on the lithosphere and generating a westerly directed torque decelerating Earth's spin; (2) downwelling of denser material toward the bottom of the mantle and in the core slightly decreasing the moment of inertia and speeding up Earth's rotation, only partly counterbalancing tidal drag; (3) thin (3–30 km) layers of very low viscosity hydrate channels in the asthenosphere. It is suggested that shear heating and mechanical fatigue self-perpetuate one or more channels of this kind, providing the necessary decoupling zone of the lithosphere (Scoppola et al., 2006) in the upper asthenosphere.

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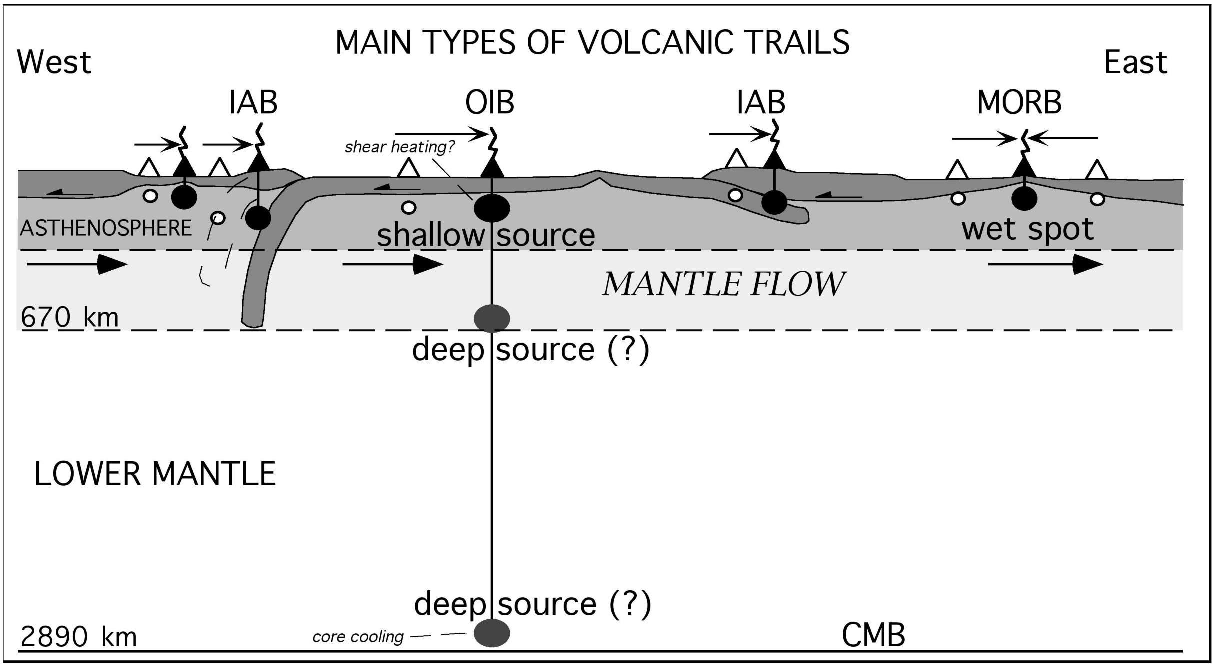

Figure 1: The main volcanic chains at the Earth's surface may have different origins and depths. The thin arrows indicate the direction of migration of volcanism with time. Filled triangles represent the youngest volcanic products. Volcanic trails originating on ridges may be wetspots (sensu Bonatti, 1990) and fed from a fluid-rich asthenosphere. The hotspots located on plate boundaries are not fixed by definition, since both ridges and trenches move relative to one another and with respect to the mantle. Pacific hotspots, regardless their source depth, are located within the plate and are virtually the only ones that can be considered reliable for a hotspot reference frame.

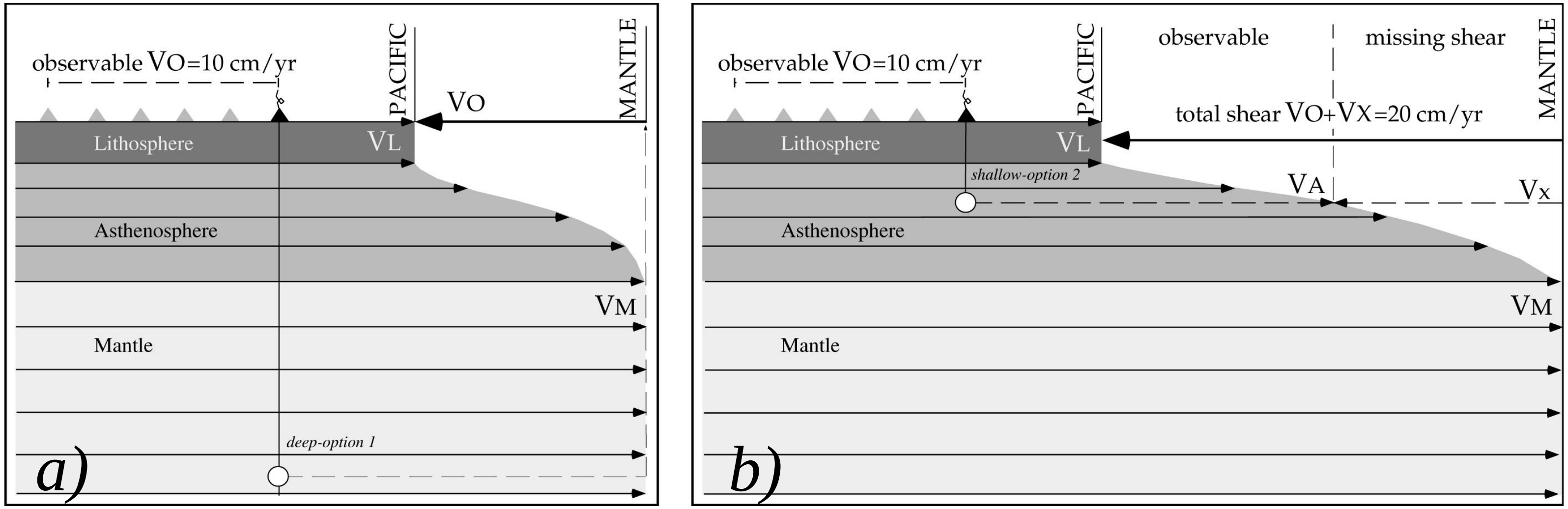

Figure 2: The Hawaiian volcanic track indicates that there is decoupling between the magma source and the lithosphere, which is moving relatively toward the WNW. a) If the source is below the asthenosphere (e.g., in the sub-asthenospheric mantle), the track records the entire shear between lithosphere and mantle. b) In the case of an asthenospheric source for the Hawaiian hotspot, the volcanic track does not record the entire shear between the lithosphere and sub-asthenospheric mantle, since part of it operates below the source (deep, missing shear). Moreover the larger decoupling implies larger shear heating, which could be responsible for the scattered, punctiform Pacific intraplate magmatism (after Doglioni et al., 2005).

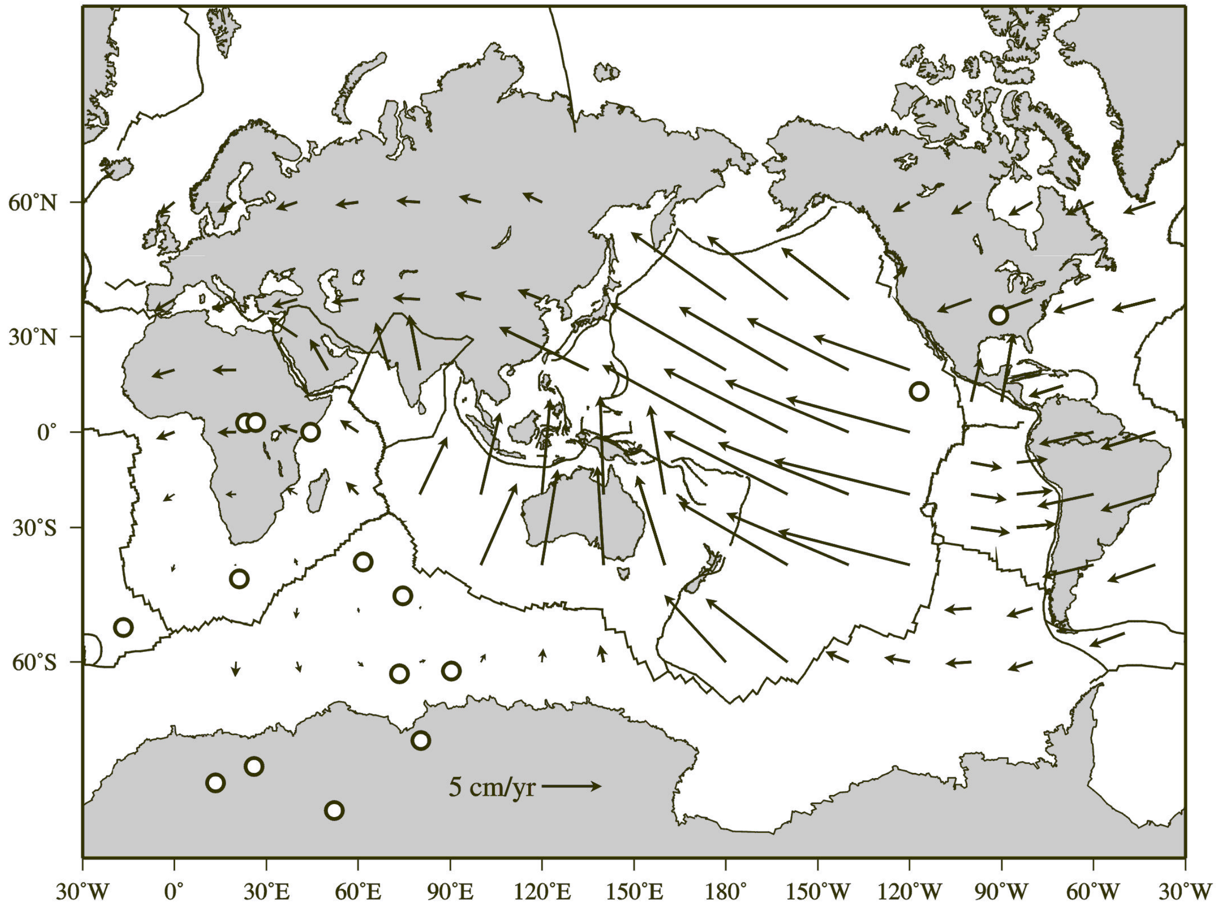

Figure 3: Current velocities with respect to the deep hotspot reference frame. Data from HS3-NUVEL1A (Gripp and Gordon, 2002). Open circles are the rotation poles.

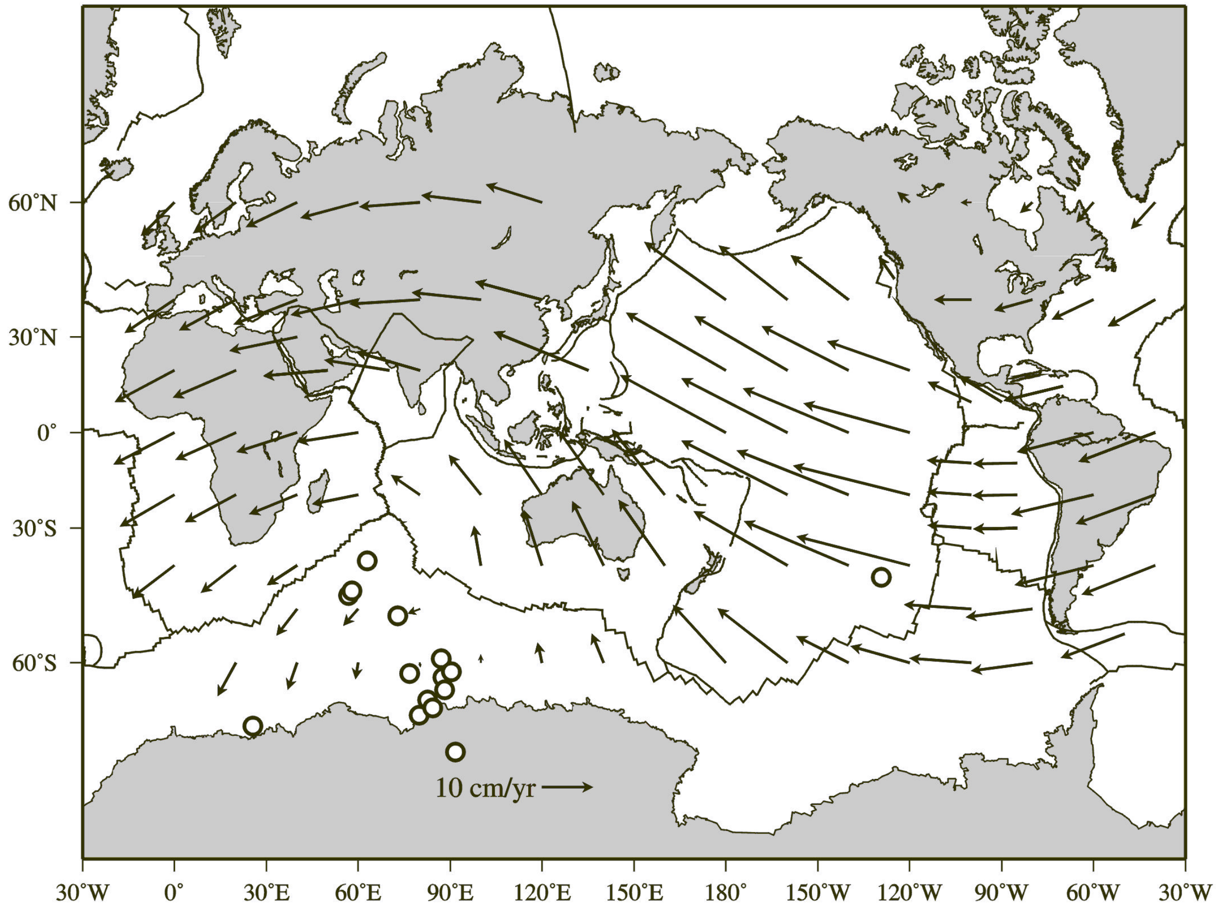

Figure 4: Present-day plate velocities relative to the shallow hotspot reference frame, incorporating the NUVEL1A relative plate motion model (DeMets et al., 1990; 1994). Note that in this frame all plates have a westward component. Open circles are the rotation poles.

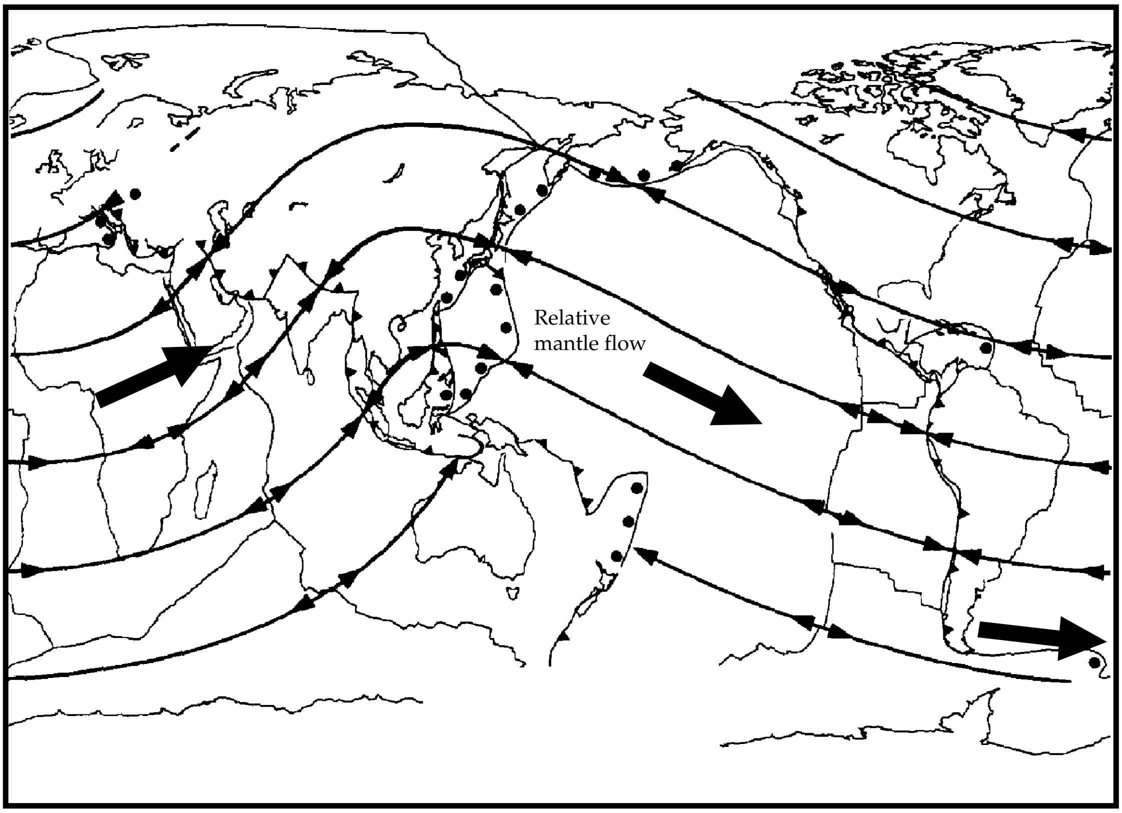

Figure 5: Connecting the directions of absolute plate motions that we can infer from large-scale rift zones or convergent belts from the past 40 Ma, we observe a coherent sinusoidal global flow field along which plates appear to move at different relative velocities in the geographic coordinate system (after Doglioni, 1993).

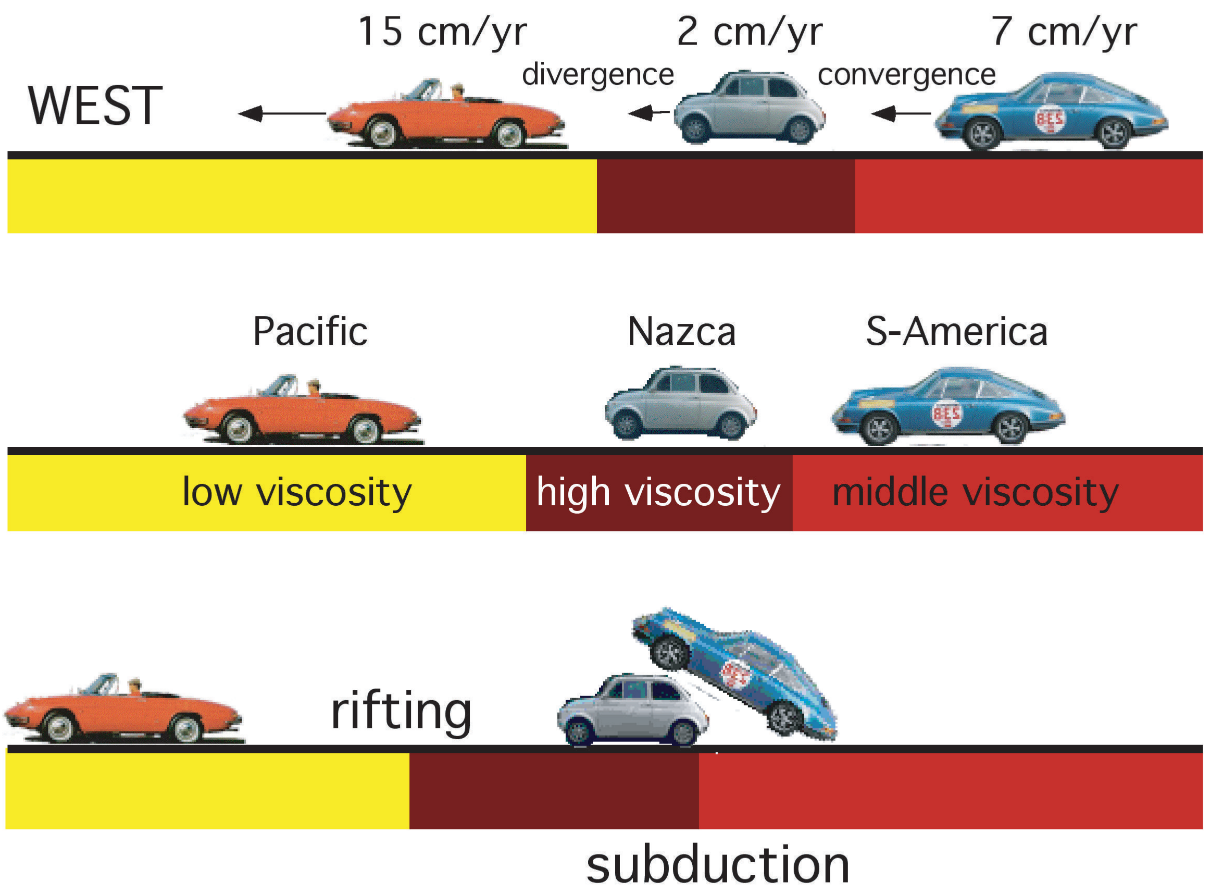

Figure 6: Cartoon illustrating that plates (cars) move along a common trail (e.g. the lines of Fig. 5) but with different velocities toward the west, as indicated by the westward drift of the lithosphere relative to the mantle. The differential velocities control the tectonic environment and result from different viscosities in the decoupling surface, i.e., the asthenosphere. There is extension when the western plate moves westward faster with respect to the plate to the east, while convergence occurs when the plate to the east moves westward faster with respect to the plate to the west. When the car in the middle is “subducted”, the tectonic regime switches to extension because the car to the west moves faster, e.g., the Basin & Range (after Doglioni, 1990).

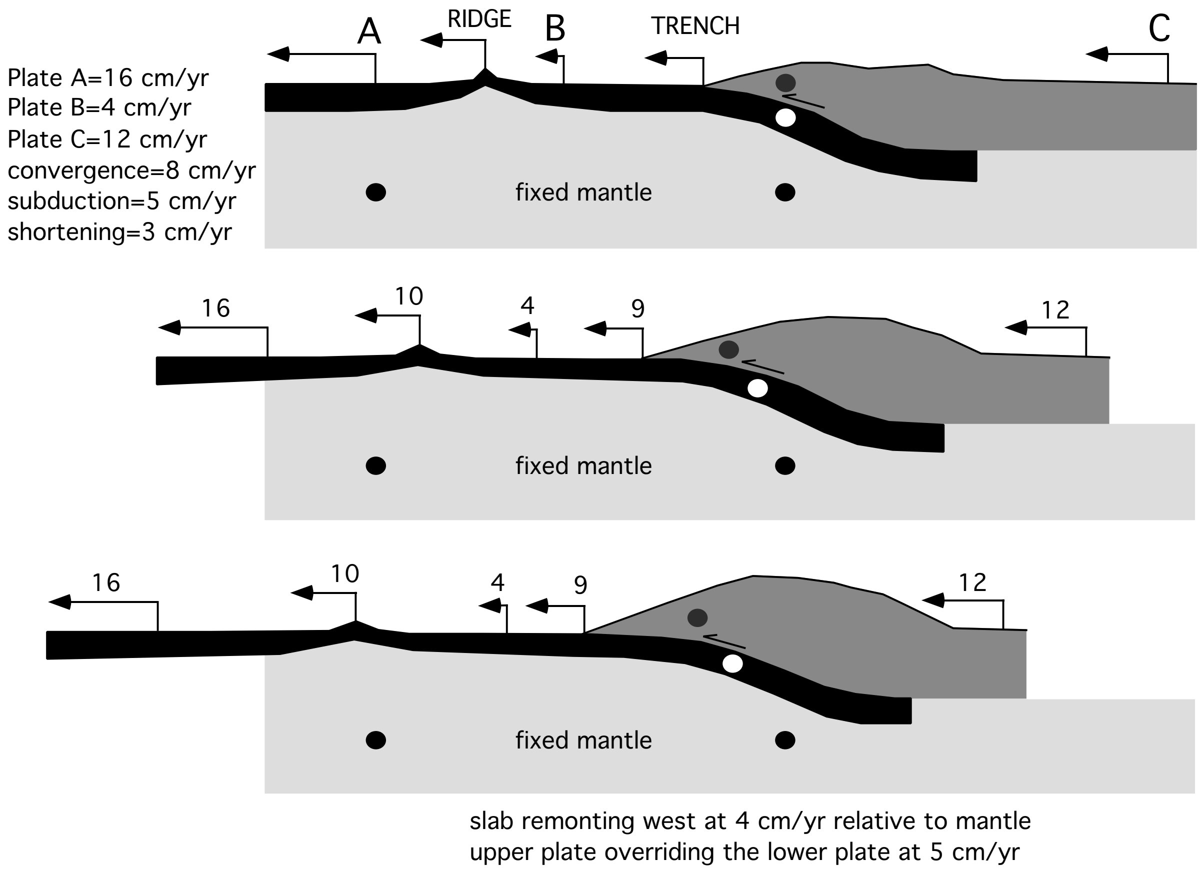

Figure 7: Cartoon assuming a Pacific plate (A) moving at 16 cm/yr. When plate motions are considered relative to the hotspot reference frame, the slabs of E- or NE-directed subduction zones may move out of the mantle. This is clearly the case for Hellenic subduction and, in the shallow hotspot reference frame, also for Andean subduction. This kinematic evidence for slabs moving out of the mantle casts doubt on slab pull as the driving mechanism of plate motions.

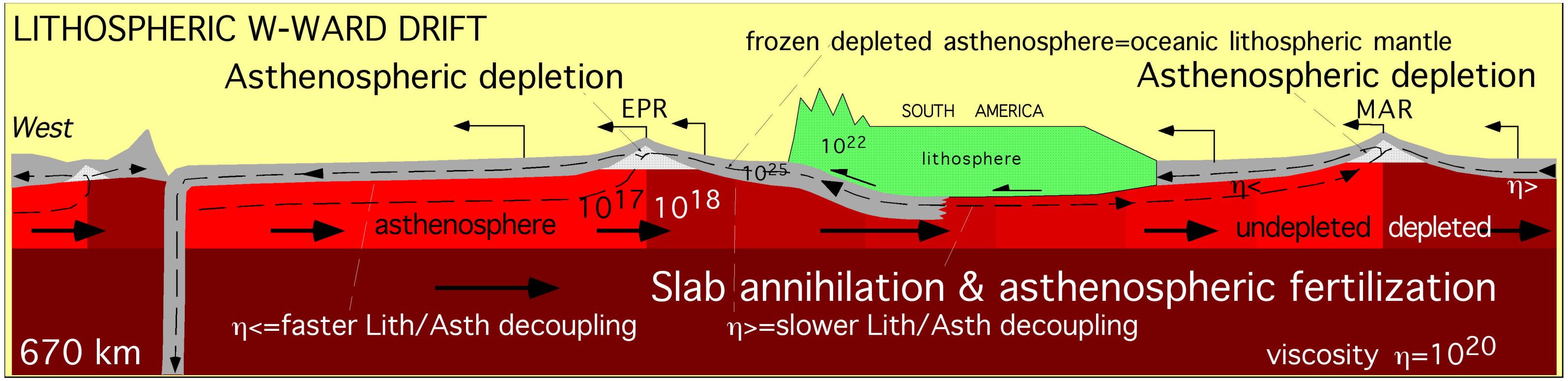

Figure 8: Model for the upper mantle cycle in the case of the shallow Pacific hotspot reference frame. The lower the asthenospheric viscosity, the faster the westward displacement of the overlying plate. The asthenospheric depletion at oceanic ridges makes the layer more viscous and decreases the lithosphere/asthenospheric decoupling, and the plate to the east is then slower. The oceanic lithosphere subducting eastward enters the asthenosphere where could partly melt again to refertilize the asthenosphere. West-directed subduction provides deeper circulation (after Doglioni et al., 2006a).

Table 1: Global plate motions with respect to the deep and shallow hotspot reference frame. Angular velocities of the deep-fed hypothesis come from the HS3-NUVEL1A absolute plate kinematic model (Gripp and Gordon, 2002).

		Deep Source[a]			Shallow Source		
PLATE		Euler Pole		ω	Euler Pole		ω
		°N	°E	$^\circ$ Ma^{-1}	°N	°E	$^\circ$ Ma^{-1}
AF	Africa	-43.386	21.136	0.1987	-61.750	76.734	1.2134
AN	Antarctica	-47.339	74.514	0.2024	-59.378	86.979	1.2564
AR	Arabia	2.951	23.175	0.5083	-46.993	56.726	1.2393
AU	Australia	-0.091	44.482	0.7467	-38.865	62.780	1.4878
CA	Caribbean	-73.212	25.925	0.2827	-65.541	82.593	1.3216
CO	Cocos	13.171	-116.997	1.1621	-42.844	-135.856	0.9818
EU	Eurasia	-61.901	73.474	0.2047	-62.352	87.511	1.2647
IN	India	3.069	26.467	0.5211	-46.051	57.930	1.2563
JF	Juan de Fuca	-39.211	61.633	1.0122	-51.452	72.836	2.0104
NA	N. America	-74.705	13.400	0.3835	-67.520	79.790	1.4094
NZ	Nazca	35.879	-90.913	0.3231	-71.733	91.649	0.7824
PA	Pacific	-61.467	90.326	1.0613	-61.467	90.326	2.1226
PH	Philippine	-53.880	-16.668	1.1543	-68.889	25.661	1.9989
SA	S. America	-70.583	80.401	0.4358	-64.176	88.125	1.4925
SC	Scotia	-76.912	52.228	0.4451	-66.654	84.271	1.4877
LS	Lithosphere	-55.908	69.930	0.4359	-60.244	83.662	1.4901

[a]Data from HS3-NUVEL1A (Gripp and Gordon, 2002)