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Global kinematics in deep versus 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. Because 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 establishing a reference frame. Using only relatively fixed intraplate Pacific hotspots, plate motions with respect to the mantle in two different 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 then not 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 cm/year to a faster hypothetical velocity of ~20 cm/year. In this setting, the net rotation of the lithosphere relative to the mesosphere would increase from a value of 0.4359°/m.y. (deep-fed hotspots) to 1.4901°/m.y. (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 east- or northeast-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.

Keywords: plate motions, reference frames, shallow hotspots, westward drift of the lithosphere

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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., 2007).

This so-called westward drift has been so far considered only as an average motion of the lithosphere, due to the larger weight of the Pacific plate in the global plate-motion computation. But the westward drift also persists when plate motions are computed relative to Antarctica (Le Pichon, 1968; Knopoff and Leeds, 1972). Moreover, and more importantly, it is supported by independent geological and geophysical asymmetries along subduction zones and rifts, showing a global tuning and not just an average asymmetry (Doglioni et al., 1999, 2003). 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 hotspot 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 (1) whether hotspots are fixed relative to the mantle, (2) whether they are fixed relative to one another, and (3) from what depth hotspots 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. Because 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 past 80 m.y., 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.

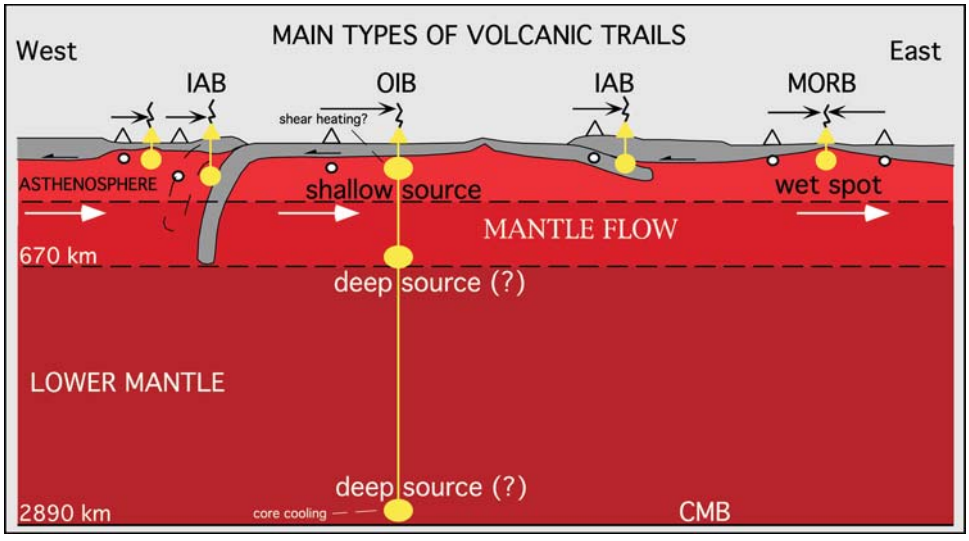

Figure 1. The main volcanic chains at the Earth's surface may have different origins and depths. The thin arrows indicate the direction of migration of volcanism with time. Filled triangles represent the youngest volcanic products. Volcanic trails originating on ridges may be wetspots (sensu Bonatti,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

Hotspots may have short (<15 m.y.) or long (>50 m.y.) time gaps 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 (1) the location is persistently close to the ridge and (2) ridges form on both sides of the rifts (Doglioni et al., 2005). Therefore, ridge-related plumes should move with a speed close to the velocity of the plate boundary relative to the mantle. 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 motion of the Mid-Atlantic Ridge.

Moreover, assuming a deep source for the hotspots, several 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 conclusion may be regarded again as a problem of reference. For example, in the NNR 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 seamounts in hotspot tracks 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: (1) plumes have different origins and different kinematic weights for the reference frames; and (2) in the cases of plumes that are shallow asthenospheric features, this second condition 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, some data are presented that support a shallow source depth for hotspots (e.g., upper mantle, asthenosphere, base lithosphere). 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 with the practice of using uncritically all so-called hotspots, because their different origin can corrupt the calculation of lithosphere-mantle relative motion.

In this article, we present current plate motions relative to a shallow hotspot framework, similar to Crespi et al. (2007). Moreover, because two fixed points are geometrically sufficient to construct a kinematic reference frame, we use only Pacific intraplate hotspots, which are significantly fixed relative to one another (Gripp and Gordon, 2002). We obtain 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.

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). Beause the Pacific is the fastest plate, shear heating along the basal décollement 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 observation 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), with T ~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 extent 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) because of refractory geochemi-

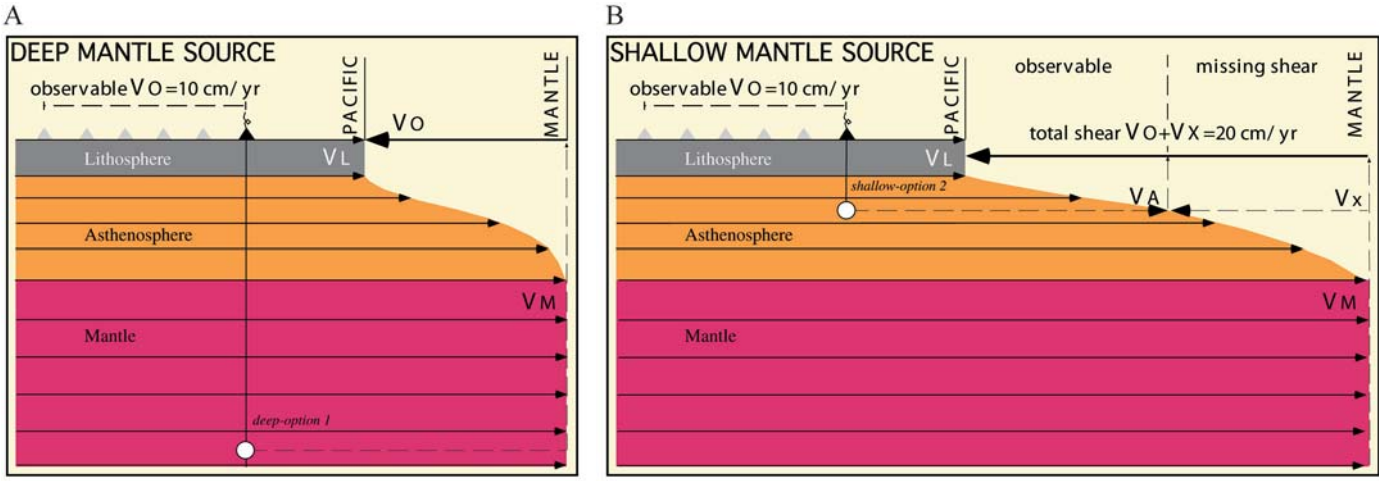

Figure 2. The Hawaiian volcanic track indicates that there is decoupling between the magma source and the lithosphere, which is moving relatively toward the WNW. (A) If the source is below the asthenosphere (e.g., in the subasthenospheric mantle), the track records the entire shear between lithosphere 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 subasthenospheric mantle, because part of it operates below the source (deep, missing shear). Moreover, the larger decoupling implies larger shear heating, which could be responsible for scattering the punctiform Pacific intraplate magmatism. After Doglioni et al. (2005). See text for definitions of the velocities VA, VL, VM, VO, and VX.

cal anisotropy, or decrease because of 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 for 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 Hawaiian-type magmatism. In that model, it was assumed the asthenosphere behaves as a Couette flow (Turcotte and Schubert, 2002). Following that model (i.e., the shear heating localized in the middle of the flow) we started from the assumption 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 a heterogeneous layer by a large number of geophysical and petrological models (e.g., Panza, 1980; Anderson, 2006; Thybo, 2006) in which composition and viscosity may change laterally. Areas with viscosity higher than normal in the asthenospheric décollement should generate greater 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 past few million years.

PLATE MOTIONS RELATIVE TO THE DEEP AND SHALLOW HOTSPOTS

Most of the hotspots used are not fixed; nor do they represent a fixed reference frame, because they are located on plate margins, such as moving ridges (e.g., Galapagos, Easter Island, Iceland, Ascension), transform faults (Réunion), 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, and Macdonald), which suggest an average velocity of ~103–118 mm/year, 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 $\mathbf{V_L}$ of the Pacific lithosphere toward the ESE (110°–120°) is slower than that of the underlying subasthenospheric mantle $\mathbf{V_M}$ ($\mathbf{V_M} > \mathbf{V_L}$), the relative velocity $\mathbf{V_O}$ corresponding to the WNW delay of the lithosphere is:

$$\mathbf{V_O} = \mathbf{V_L} - \mathbf{V_M}. \quad (1)$$

For the case of Hawaii, the observed linear velocity is V_O = 103 mm/year, corresponding to the propagation rate of the Hawaiian volcanic track (Fig. 2A).

The HS3-NUVEL1A (Gripp and Gordon, 2002) plate-motion model with respect to the mantle 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 and 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°/m.y. 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), as Cuffaro and Jurdy (2006) also did to incorporate motions of microplates in the deep-fed hotspot framework.

If the location of the Hawaiian melting spot is in the middle of the asthenosphere (Fig. 2B) instead of the lower mantle (Fig. 2A), it 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:

$$\mathbf{V_O} = \mathbf{V_L} - \mathbf{V_A}, \quad (2)$$

with

$$\mathbf{V_A} = \mathbf{V_X} + \mathbf{V_M}, \quad (3)$$

where V_O = 103 mm/year is still the observed propagation rate of the volcanic track (e.g., Hawaii), $\mathbf{V_A}$ is the velocity recorded at the shallow source of the hotspot, and $\mathbf{V_X}$ is that part of the velocity that is not recorded, due to the missing shear measurement.

Substituting equation 3 in equation 2, we have:

$$\mathbf{V_O} = \mathbf{V_L} - \mathbf{V_M} - \mathbf{V_X} \quad (4)$$

and

$$\mathbf{V_O} + \mathbf{V_X} = \mathbf{V_L} - \mathbf{V_M}. \quad (5)$$

The observed velocity V_O = 103 mm/year 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 total 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 $\mathbf{V_X}$ has to be added to the observed velocity $\mathbf{V_O}$ (Fig. 2B), as in equation 5. If the source of Pacific hotspots is in the middle of the asthenosphere, half of the lithosphere–subasthenospheric mantle relative motion is unrecorded, which means that the total relative displacement of the Hawaiian hotspot would amount to about $V_O + V_X$ = 200 mm/year (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°/m.y. 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, which, under the shallow hotspot hypothesis, amounts to ~1.4901°/m.y. (Table 1), and is higher than that computed by Gripp and Gordon (2002) (0.4359°/m.y., deep hotspot condition, Table 1).

This faster velocity for the Pacific plate has these basic consequences: (1) it extends westward drift of the lithosphere to all

TABLE 1. GLOBAL PLATE MOTIONS WITH RESPECT TO THE DEEP AND SHALLOW HOTSPOT REFERENCE FRAMES

	Deep source			Shallow source		
	Euler pole		ω	Euler pole		ω
Plate	°N	°E	(°/m.y.)	°N	°E	(°/m.y.)
Africa	–43.386	21.136	0.1987	–61.750	76.734	1.2134
Antarctica	–47.339	74.514	0.2024	–59.378	86.979	1.2564
Arabia	2.951	23.175	0.5083	–46.993	56.726	1.2393
Australia	–0.091	44.482	0.7467	–38.865	62.780	1.4878
Caribbean	–73.212	25.925	0.2827	–65.541	82.593	1.3216
Cocos	13.171	–116.997	1.1621	–42.844	–135.856	0.9818
Eurasia	–61.901	73.474	0.2047	–62.352	87.511	1.2647
India	3.069	26.467	0.5211	–46.051	57.930	1.2563
Juan de Fuca	–39.211	61.633	1.0122	–51.452	72.836	2.0104
North America	–74.705	13.400	0.3835	–67.520	79.790	1.4094
Nazca	35.879	–90.913	0.3231	–71.733	91.649	0.7824
Pacific	–61.467	90.326	1.0613	–61.467	90.326	2.1226
Philippine	–53.880	–16.668	1.1543	–68.889	25.661	1.9989
South America	–70.583	80.401	0.4358	–64.176	88.125	1.4925
Scotia	–76.912	52.228	0.4451	–66.654	84.271	1.4877
Lithosphere	–55.908	69.930	0.4359	–60.244	83.662	1.4901

Note: Angular velocities of the deep-fed hypothesis come from the HS3-NUVEL1A absolute plate kinematic model (Gripp and Gordon, 2002).

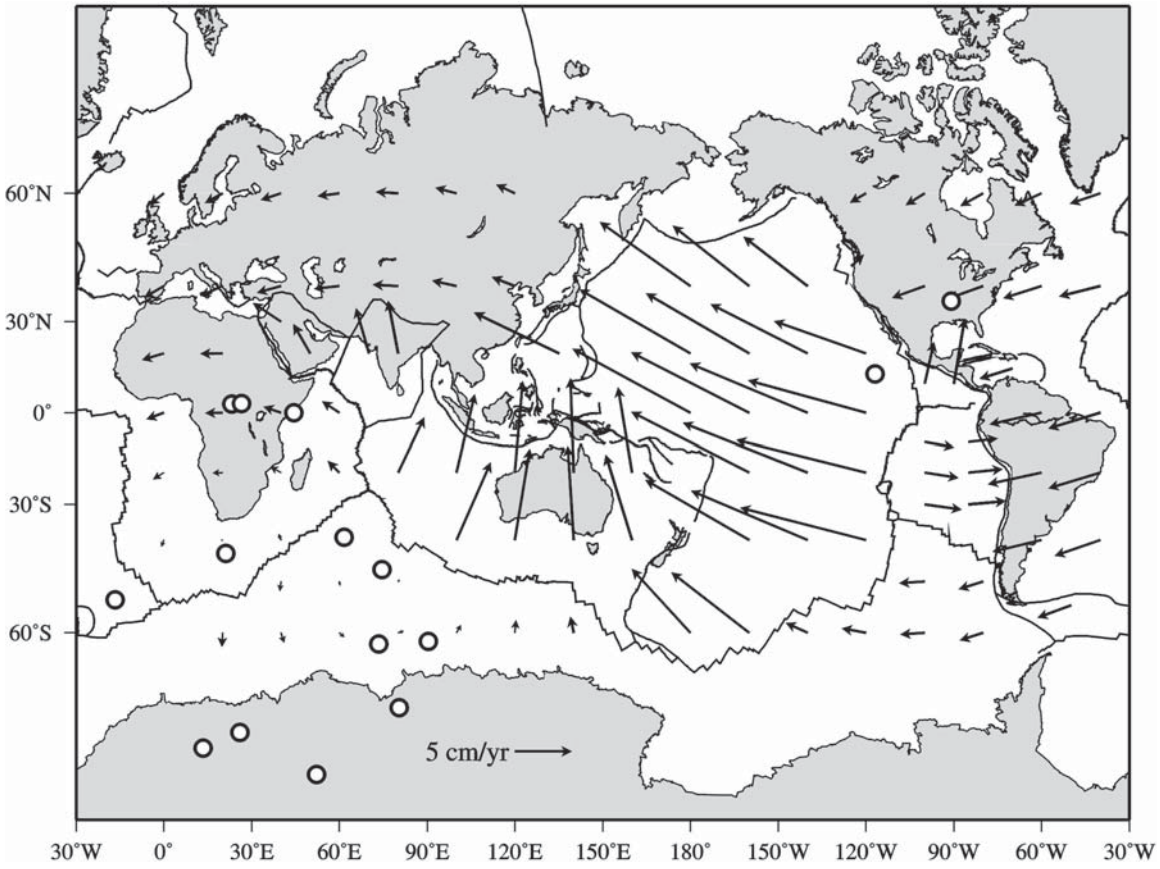

Figure 3. Current velocities with respect to the deep hotspot reference frame. Open circles are the rotation poles. Data from HS3-NUVEL1A (Gripp and Gordon, 2002).

plates (Fig. 4), (2) it more than doubles the westward drift compared to that of the deep hotspot reference frame, and (3) it increases the shear heating within the asthenosphere.

SHALLOW HAWAIIAN 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 plate motions with respect to the mantle. This variability casts doubt on both the notion of absolute plate motions computed in the hotspot reference frame and the nature of the magmatism itself, e.g., 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 m.y., of ~200–300 mm/year. 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, separating the Pacific and Nazca plates, opens at a rate of 128 mm/year 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 be ~68 mm/year. When inserted in a reference frame in which the Hawaiian hotspot is considered fixed and positioned in the subasthenospheric mantle, these relative motions imply that the Nazca plate is moving eastward relative to the subasthenospheric mantle at ~25 mm/year (Fig. 7, option 1 *in* Doglioni et al., 2005). If we assume that the source of Pacific intraplate hotspots is instead in the middle asthenosphere and half of the lithosphere–subasthenospheric mantle relative motion is missing in the Hawaiian track (Fig. 2B), the movement could rise to 200 mm/year, as also suggested by some segments of the Pukapuka volcanic ridge (Janney et al., 2000). Note that in this configuration,

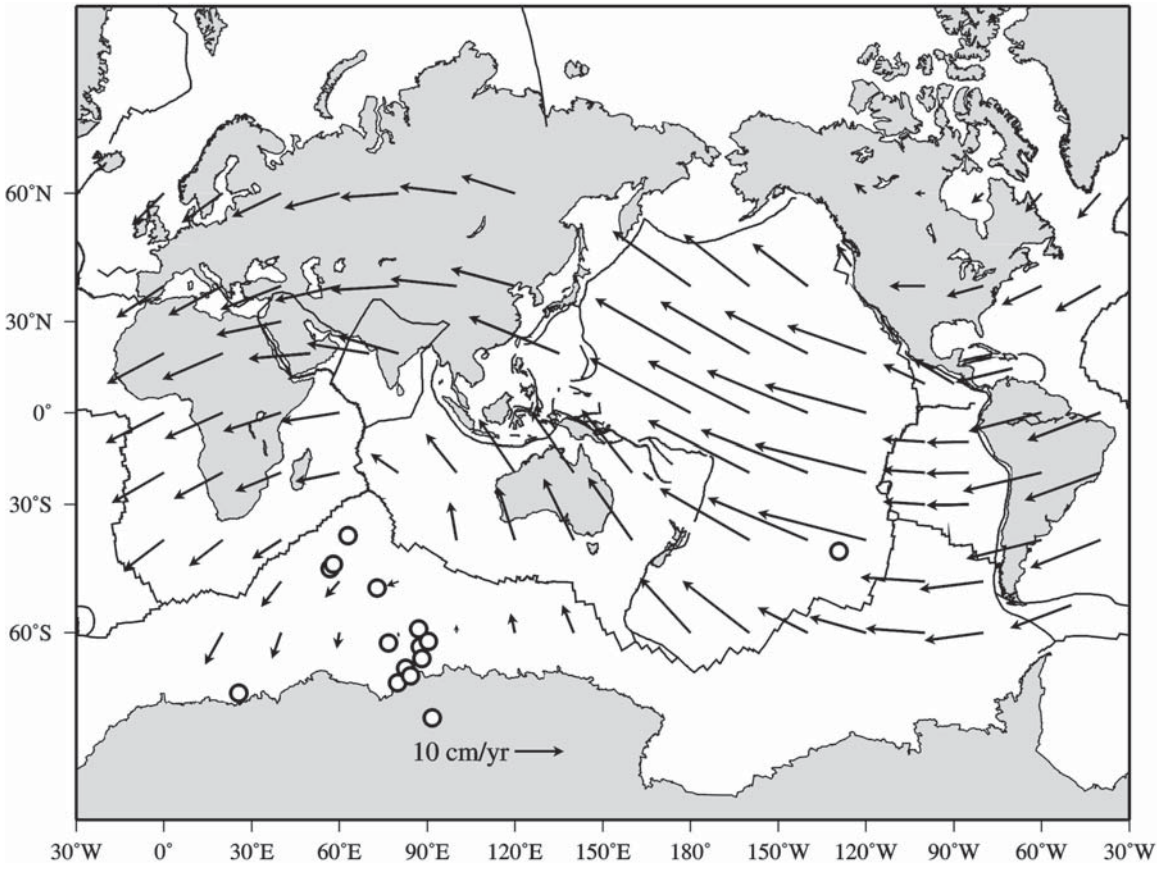

Figure 4. Present-day plate velocities relative to the shallow hotspot reference frame, incorporating the NUVEL-1A relative plate-motion model (DeMets et al., 1990, 1994). Note that in this frame, all plates have a westward velocity component. Open circles are the rotation poles.

Nazca would instead move west relative to the mantle at 72 mm/year (Fig. 7, option 2 *in* Doglioni et al., 2005), and therefore all three plates would move westward relative to the subasthenospheric mantle.

This last case agrees with the east-west–trending shearwave splitting anisotropies beneath the Nazca plate, turning north-south when encroaching on the Andean Slab, which suggests 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 factors 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) versus 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 East Pacific Rise (Fig. 7, option 2 *in* 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 retarding the plate to the east (Doglioni et al., 2003, 2005).

DISCUSSION AND CONCLUSIONS

We have computed 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 than those previously calculated. 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 in which 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 first 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., 2007; Fig. 5), which is largely confirmed by present space geodesy plate kinematics (e.g., Heflin et al., 2004). Global shearwave 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 east- or northeast-directed, and associated orogens are characterized by lower structural and topographic elevations, back-arc basins, or by higher structural and morphological elevation and no back-arc 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 of the age and composition of the downgoing lithosphere, e.g., in the Mediterranean Apennines and Carpathians versus the Alps and Dinarides, or in the Banda and

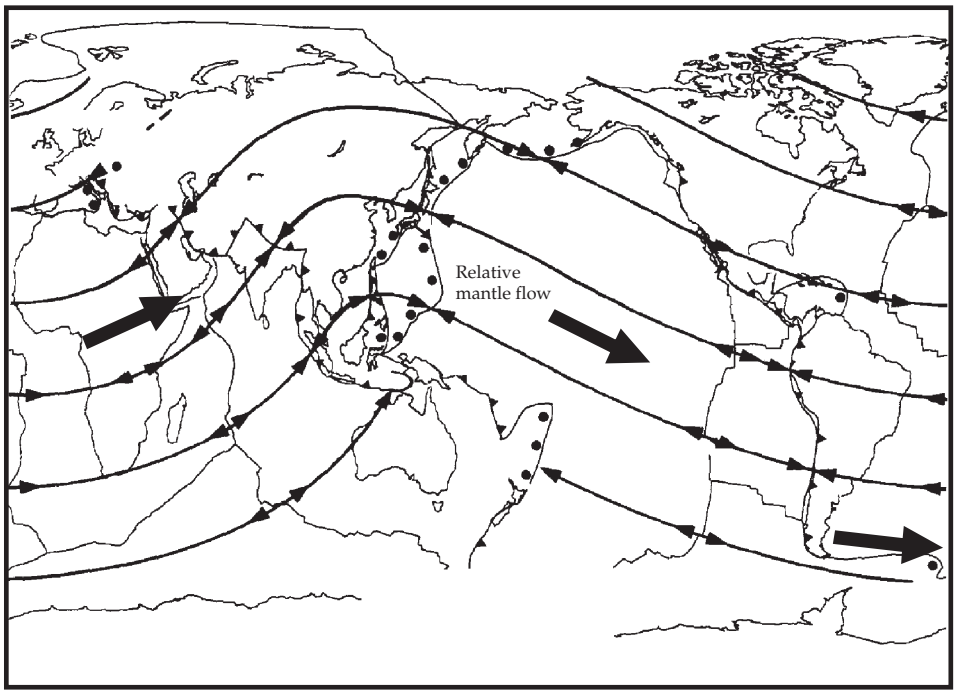

Figure 5. Connecting the directions of absolute plate motions that we can infer from large-scale rift zones or convergent belts from the past 40 Ma, we observe a coherent sinusoidal global flow field, along which plates appear to move at different relative velocities in the geographic coordinate system.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

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 ~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 west relative to the mantle along the flow lines of Figure 5, which undulate and are not exactly oriented east-west. 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 it 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 east- or northeast-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 scenario argues against slab pull as the main mechanism for driving plate motions, because 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 intraslab down-dip extension earthquake focal mechanisms that characterize east- or northeast-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,

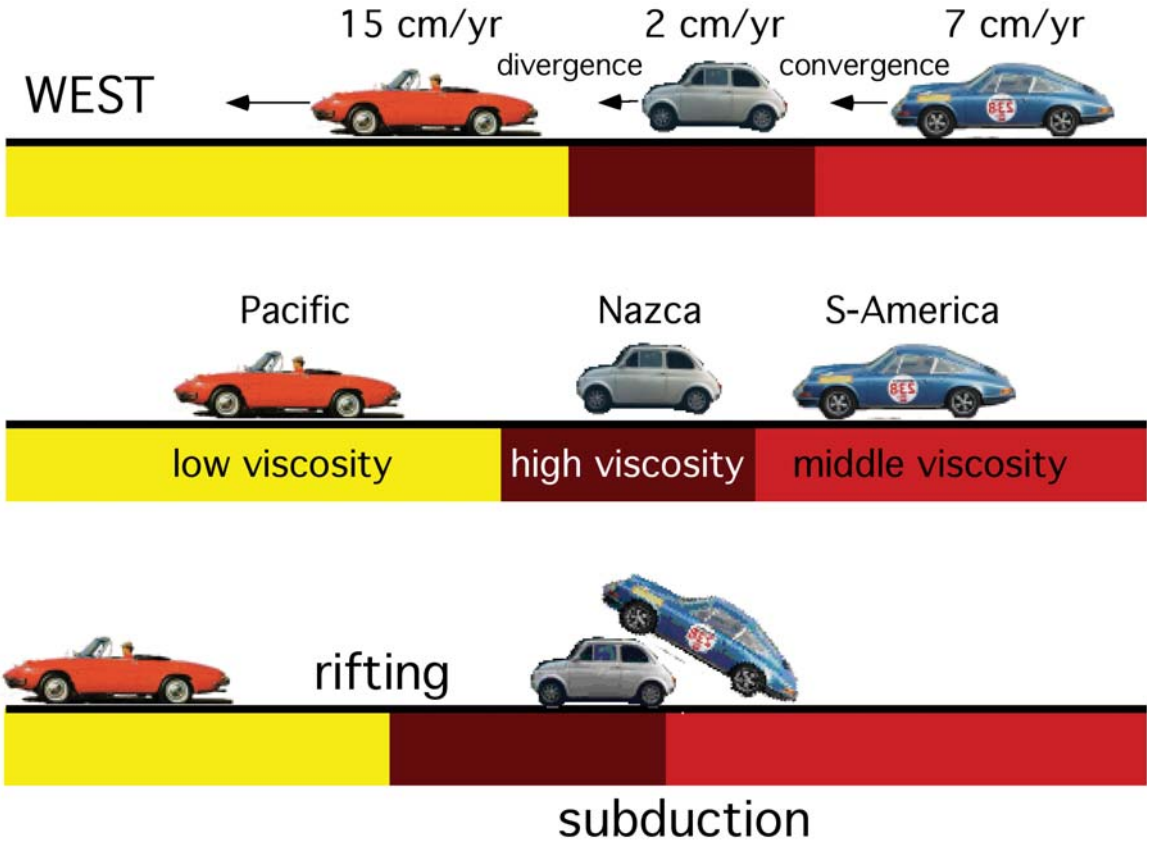

Figure 6. Cartoon illustrating that plates (cars) move along a common trail (e.g., the lines of Fig. 5) but with different velocities toward the west, as indicated by the westward drift of the lithosphere relative to the mantle. The differential velocities control the tectonic environment and result 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, whereas 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 and Range.

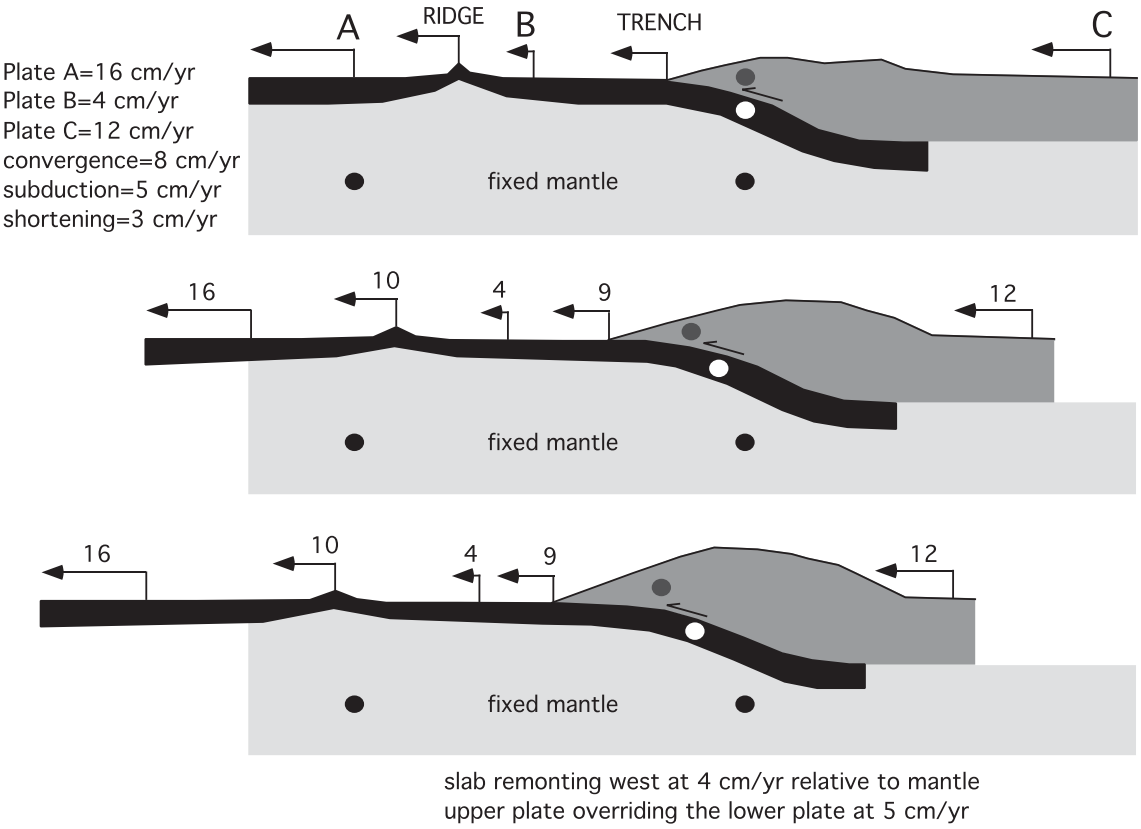

Figure 7. Cartoon assuming a Pacific plate (plate A) moving at 16 cm/year. When plate motions are considered relative to the shallow hotspot reference frame, the slabs of east- or northeast-directed subduction zones may move out of the mantle. This scenario is clearly the case for Hellenic subduction 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.

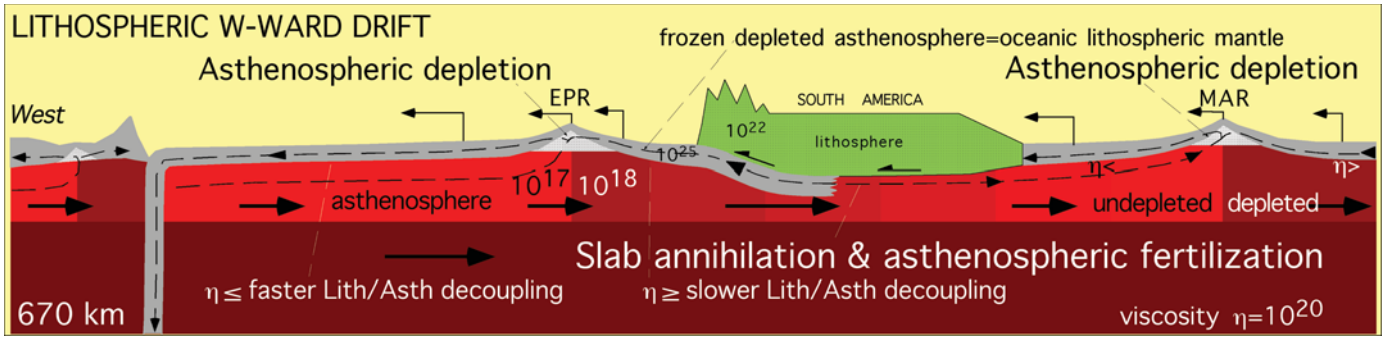

Figure 8. Model for the upper-mantle cycle in the case of the shallow Pacific hotspot reference frame. The lower the asthenospheric viscosity is, the faster the westward displacement of the overlying plate. The asthenospheric depletion at oceanic ridges makes the layer more viscous and decreases the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

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, in the deep reference frame, Africa is moving toward the Mid-Atlantic Ridge, although slower than is 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 move faster, but the Pacific plate moves at ~1.06°/m.y., much faster in terms of absolute velocity than the Nazca plate (~0.32°/m.y.). The Pacific and Nazca plates have roughly the same percentage of attached slab (37% and 34%, respectively).

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 depletes 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 NNE, along the mantle counterflow, might refertilize the upper mantle, whereas west-directed subduction zones would instead penetrate deeper into the mantle.

The global-scale asymmetry of tectonic features and the westward drift of the lithosphere support 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 that decelerates 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 and only partly counterbalancing tidal drag; and (3) thin (3- to 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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DISCUSSION

4 January 2007, Federica Riguzzi

The basic idea of this article is to analyze the impact of two different reference frames in plate kinematics and some consequent geodynamic implications. The definition of alternative absolute reference frames, including variable hotspot source depths, implicitly assumes variable net lithospheric westward rotations, and vice versa. Though not crucial in geodesy, in fact geodesists are concerned to define more rigorous lithospheric (terrestrial) reference frames (Dermanis, 2001). The question is significant in geodynamics, because it can reconcile some independent geological and/or geophysical evidence and open new and interesting questions.

From a geodetic point of view, the establishment of global geodetic networks aims to provide a unified way to describe the positions of points on the Earth's surface. Terrestrial Reference Frames (TRFs) are essentially conventional kinematic reference frames, because there is the need to overcome the variability due to Earth's rotation and to take into account plate motions. TRFs provided by the International Earth Rotation and Reference System Service consist of coordinates and velocities of the observing sites anchored to the NNR-NUVEL1A geodynamic model (Altamimi et al., 2002). They are no-net-rotation (NNR) or, in other words, strictly linked to the lithosphere, thus allowing accurate estimations only of surface relative motions.

When we want to represent absolute plate motions, the motion of the plates relative to the deep mantle, we assume the latter deforms slowly enough to constitute a reference independent from the plates themselves and the hotspot tracks recording the relative motion between lithosphere and mantle. Hotspot reference frame (HSRF) recent plate motion models (Gripp and Gordon, 2002) find a global westward rotation of the lithospheric NNR frame with respect to the absolute (or deep mantle) frame of up to 0.44° m.y.$^{-1}$.

Even if the transition from pure NNR to HSRF systems may be regarded as a simple linear transformation involving velocities $\vec{V}_{HSRF} = \vec{V}_{HNNR} + \vec{V}_{netrot}$, the estimation of net rotation depends somewhat on the assigned hotspot source depths. The article by Cuffaro and Doglioni (this volume) shows that the shallower the hotspot sources, the more polarized plate motion is expected to be, with respect to the mantle; assuming asthenospheric hotspot sources, all the plates have a westward component of motion reaching 1.49° m.y.$^{-1}$ and reconciling well with independent geological evidence (Doglioni, 1990, 1993).

In support of this view, it has been recently shown that a fast net rotation estimate (corresponding to shallow hotspot sources) matches, in a statistical sense, remarkably well with some large-scale geological constraints (Crespi et al., 2007).

30 January 2007, Warren B. Hamilton

Most Euler poles of current relative rotation between large lithosphere plates are at high latitudes, so a substantial part of present plate motion can be expressed as differential spin velocity. But do the motions sum to zero in a whole-Earth frame, or is there a net drift; and if the latter, is it a transient phenomenon (as, due to the evolving self-organization of plate motions; cf. Anderson, 2007), or is there a unidirectional spin term (tidal drag?) in plate motions? A net westward drift of lithosphere, with some retrograde motions, relative to the bulk Earth, is required by the popular hotspot reference frame for plate motions, but, as many papers and discussions in this volume and its predecessor (Foulger et al., 2005) show, the weak evidence cited in favor of fixed hotspots is contradicted by much else.

Doglioni and his colleagues (e.g., Cuffaro and Doglioni, this volume; Crespi et al., 2007) have speculated for many years that plate tectonics is a product of differential westward motion of lithosphere plates, decoupled across a very weak distributed-shear asthenosphere from the main mass of the mantle, in response to tidal drag. This mechanism is viewed as a substitute for, not a modification of, other proposed modes of plate propulsion. A gravitational drive by subduction is specifically rejected, and some apparently subducting plates are postulated to be rising from the mantle, not sinking into it. The present article by Cuffaro and Doglioni (this volume) seeks a reference frame wherein all plates move westward, and finds it by assuming that only Pacific hotspots are fixed, and in the low upper mantle rather than the deep mantle, and that the Hawaiian-hotspot-track velocity on the Pacific plate is only half the velocity of the plate over the source, the other half of the motion being smeared out

by shearing in the asthenosphere. (The embedding within unmoving low upper mantle of local sources of heat and melt to feed plumes for 50 m.y. is not addressed.) This assumption is termed the "shallow hotspot reference frame," and that space-geodesy vectors of relative motion can be transposed into this frame (as they can be into any frame) is wrongly claimed by Crespi et al. (2007) to validate the concept.

These westward-drift assumptions are derived from other assumptions. Doglioni and colleagues, including Cuffaro and Doglioni (this volume), have long claimed that, because of differential shear, west-dipping subducting slabs are steeper than east-dipping ones. Lallemand et al. (2005), not cited by Cuffaro and Doglioni (this volume), addressed this claim and disproved it in detail.

Were the model of Cuffaro and Doglioni (this volume) valid, westward-subducting slabs that penetrate below the asthenosphere (which most do, although this seems contrary to the model) should be overpassed by westward-moving lithosphere, and should appear geometrically as though dipping eastward at depth, and as plated down eastward onto the 660-km discontinuity. The opposite is the case; for example, lithosphere is plated down westward for as much as 2000 km under China from the lower limit of west-dipping western Pacific subduction systems (Huang and Zhao, 2006).

Other objections to the model can be raised on the basis of its incompatibility with geologically and geophysically observed features of subduction systems.

1 February 2007, Marco Cuffaro and Carlo Doglioni

We thank Warren Hamilton for his comment, which allows us to clarify a few issues in our article. First, we affirm that plumes should be differentiated by whether they are intraplate or steadily located close to plate margins, which are, by definition, moving relative to one another, and relative to the mantle (e.g., Garfunkel et al., 1986). Because practically all intraplate plumes are on the Pacific plate, we used those hotspot tracks (e.g., Norton, 2000; Gripp and Gordon, 2002) as a coherent reference frame. Starting from the idea that Pacific plumes are sourced from the asthenosphere (e.g., Smith and Lewis, 1999; Doglioni et al., 2005; Foulger et al., 2005), the consequence of this interpretation would be that westward drift of the lithosphere is not just an average rotation dictated by the Pacific plate, but is rather a global rotation relative to the mantle. This conclusion is more consistent with the geometric (Doglioni, 1994; Doglioni et al., 1999; Mariotti and Doglioni, 2000; Garzanti et al., 2007; Lenci and Doglioni, 2007), kinematic (Doglioni et al., 2006a; Crespi et al., 2007), and dynamic (Marotta and Mongelli, 1998; Doglioni et al., 2006b, 2007; Scoppola et al., 2006) observations of plate tectonics and subduction zones in particular. Subduction dip is just one parameter of subduction zones. There are a number of other observable features that have to be taken into account, such as morphological and structural elevation, metamorphism, magmatism, dip of the foreland monocline (Fig. D-1), the gravimetric and heatflow signatures, and the type of rocks involved in the prism or orogen. All these signatures support global systematics of the sort we describe.

However, because the aim of our article is not to discuss the differences between orogens and subduction zones as a function of their polarity, we did not quote the paper by Lallemand et al. (2005), and, contrary to Hamilton's statement of 30 January, Lallemand et al. (2005) accept the existence of global westward drift of the lithosphere. They only argue that slab dip is not sig-

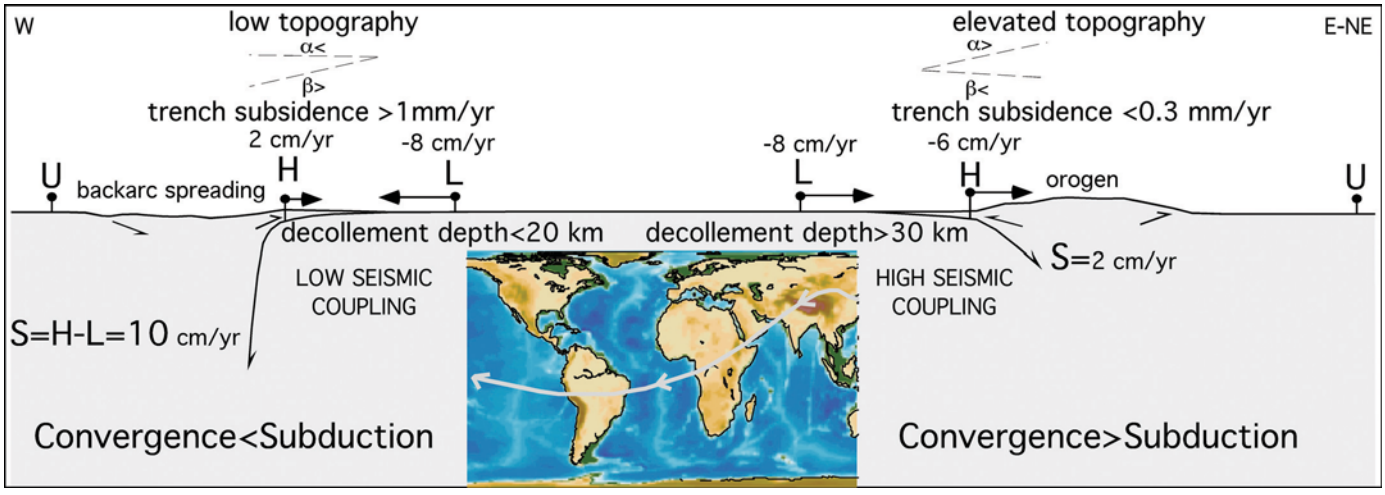

Figure D-1. Assuming point U is fixed the upper plate, along west-directed subduction zones, the subduction hinge H mostly diverges relative to U, whereas it converges along east-directed subduction zones. L—lower plate. Note that the subduction S is larger than the convergence along west-directed slabs, providing larger volumes for mantle recycling, whereas S is smaller for the east-directed case. The two end-members of hinge behavior are respectively accompanied on average by low and high topography, steep and shallow foreland monoclines, faster and slower subsidence rates in the trench or foreland basin, single and double verging orogens, and the like, highlighting a first-order worldwide subduction asymmetry along the flow lines of plate motions, as indicated in the inset (Doglioni et al., 2007).

nificantly influenced by the polarity of subduction. But their analysis is misleading and different from what is suggested in a number of alternative articles in which slab dip is measured not simply comparing east- versus west-directed subduction zones, but is measured along the undulated flow of absolute plate motions (e.g., Doglioni et al., 1999), and the definition of west- versus east- or northeast-directed is rather related to whether subduction accords with this flow. Moreover, their analysis subdivides the slab into a shallow (<125 km) and a deeper part (>125 km). This subdivision is ambiguous for a number of reasons. The east- or northeast-directed subduction zones have mostly continental lithosphere in the upper plate, and the dip of the shallowest 125 km is mostly constrained by the thickness and shape of the upper plate. Moreover, oblique or lateral subduction zones, such as the Cocos plate underneath Central America, are, from geometrical constraints, steeper (>50°) than frontal subduction zones (e.g., Chile), like the lateral ramp of a thrust.

In Cruciani et al. (2005) we reached similar conclusions to Lallemand et al. (2005) and find no correlation between slab age and dip of the slab. Our analysis stopped at about 250 km depth, because east- or northeast-directed subduction zones do not have systematic seismicity at deeper depth, apart from a few areas where seismicity notoriously appears to be concentrated between 630 and 670 km, close to the lower boundary of the upper mantle. The origin of these deep isolated earthquakes remains obscure (e.g., mineral phase change, blob of detached slab, higher shear stress), and therefore they cannot represent a simple geometric prolongation of the shallow part of the slab. Therefore, the deep dip of the slab based on seismicity cannot be compared between west- versus east- or northeast-directed subduction zones, simply because most of the east- or northeast-directed slabs do not show continuous seismicity deeper than 250 km. High-velocity bodies suggesting the presence of slabs in tomographic images often do not match slab seismicity.

Moreover, Lallemand et al. (2005) note that steeper slabs occur where the upper plate is oceanic, whereas shallower slabs occur where the upper plate is continental. However, the majority of east- or northeast-directed subduction zones worldwide have continental lithosphere in the upper plate, confirming the asymmetry we proposed. Apart from these issues, west-directed subduction zones, compared to east- or northeast-directed slabs, still maintain a number of fundamental differences, e.g., they are steeper, deeper (or at least they present more coherent slab-related seismicity from the surface down to the 670-km discontinuity), and they show opposite down-dip seismicity. Northern Japan is an exception, having a shallow dip; however, the subduction hinge there has started to invert, and it migrates toward the upper plate (Mazzotti et al., 2001). The back-arc basin is shrinking, and the system is losing the typical character of west-directed subduction zones in which the subduction hinge retreats relative to the upper plate.

In our article we do not address the problem of whether slabs penetrate into the lower mantle, because it is not relevant to our work. Slab pull is also not treated for the same reason. Moreover, we do not reject the negative buoyancy of the oceanic lithosphere as a fundamental component of plate tectonics, but we argue against considering slab pull to be the main driving force of plate tectonics. Apart from the kinematic counterarguments presented in our article, the inferred slab pull described in the literature is larger than the yield strength of the lithosphere under extension (i.e., the Pacific plate should have been broken by the pull) and is not sufficiently high to generate the observed slab rollback (Doglioni et al., 2006b).

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