Discussion of

Global kinematics in the Deep Vs Shallow Hotspot Reference Frame

by

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4th January, 2007, Federica Riguzzi

The basic idea of this manuscript 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 (HS) 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 since it can reconcile some independent geological/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, since there is the need to overcome the variability due to Earth 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 only accurate estimations 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 deform slowly enough to constitute a reference independent from the plates themselves and the HS tracks recording the relative motion between lithosphere and mantle. HSRF recent plate motion models (Gripp & Gordon, 2002) find a global westward rotation of the lithospheric NNR frame with respect to the absolute (or deep mantle) frame up to 0.44° Myr^{-1}.

Even if the transition from pure NNR to HSRF systems may be regarded as a simple linear transformation involving velocities $\vec{V}_{HSRF} = \vec{V}_{NNR} + \vec{V}_{netrot}$, the estimation of net rotation depends somewhat on the assigned HS source depths.

The paper by Cuffaro and Doglioni (this volume) shows that the shallower the HS sources the more polarized plate motion is expected to be, with respect to the mantle; assuming asthenospheric HS sources, all the plates have a westward component of motion reaching 1.49° Myr^{-1} and reconciling well with independent geological evidence (Doglioni, 1990; Doglioni, 1993).

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

30th 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.

Carlo Doglioni and his colleagues (e.g., Cuffaro and Doglioni, in 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 paper 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 million years 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 (in 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.

1st February 2007, Marco Cuffaro and Carlo Doglioni

We thank Warren Hamilton for his comment, that allows us to clarify a few issues in our chapter. First, we affirm that plumes should be differentiated 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). Since 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; Scoppola et al., 2006; Doglioni et al., 2006b; Doglioni et al., 2007) 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. 1), the gravimetric and heat flow signatures, and the type of rocks involved in the prism or orogen, etc.. All these signatures support global systematics of the sort we describe.

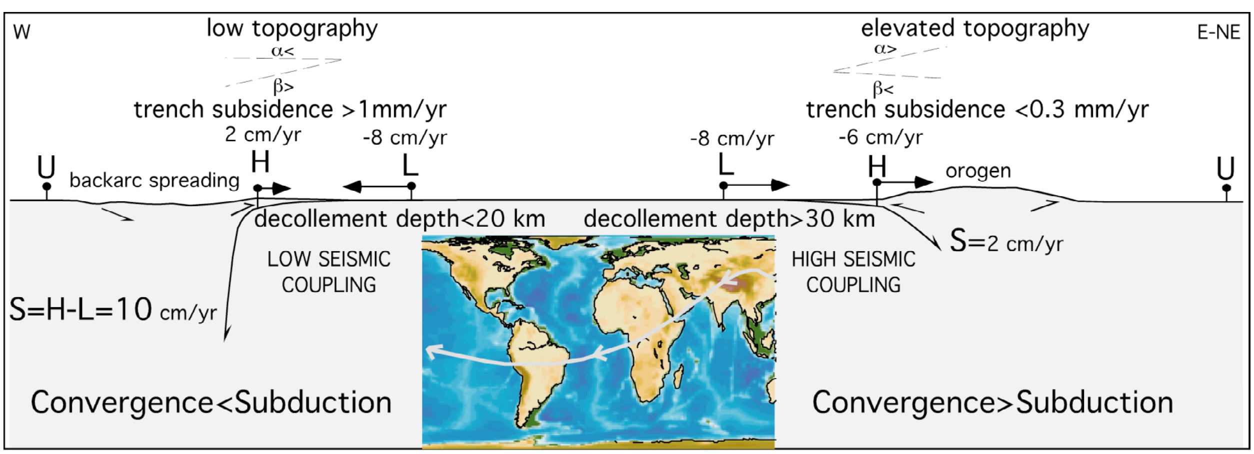

Fig. 1. Assuming point U is fixed the upper plate, along W-directed subduction zones the

subduction hinge H mostly diverges relative to U, whereas it converges along E-directed subduction zones. L, lower plate. Note that the subduction S is larger than the convergence along W-directed slabs, providing larger volumes for mantle recycling, whereas S is smaller for the E-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 vs. double verging orogens, etc., highlighting a first order worldwide subduction asymmetry along the flow lines of plate motions, as indicated in the inset (Doglioni et al., 2007).

However, since the aim of our chapter 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 30th January, Lallemand et al. (2005) accept the existence of global W-ward drift of the lithosphere. They only argue that slab dip is not significantly influenced by the polarity of subduction. But their analysis is misleading and different from what is suggested in a number of alternative articles where slab dip is measured not simply comparing E- vs. W-directed subduction zones, but is measured along the undulated flow of absolute plate motions (e.g., Doglioni et al., 1999), and the definition of W- vs. E- or NE-directed is rather related to whether subduction accords with this flow or not. 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 E- or NE-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 E- or NE-directed subduction zones do not have systematic seismicity at deeper depth, apart few areas where seismicity notoriously appears to be concentrated between 630- and 670-km depth, close 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 or 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 W- vs. E-NE-directed subduction zones, simply because most of the E- or NE-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, while shallower slabs occur where the upper plate is continental. However, the majority of E- or NE-directed subduction zones worldwide have continental lithosphere in the upper plate, confirming the asymmetry we proposed. Apart from these issues, W-directed subduction zones, when compared to E- or NE-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 backarc basin is shrinking, and the system is losing the typical character of W-directed subduction zones where the subduction hinge retreats relative to the upper plate.

In our paper we do not address the problem of whether slabs penetrate into the lower mantle or not 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 counter-arguments presented in our chapter, the inferred slab pull described in the literature is larger than the strength the lithosphere can sustain under extension (e.g., 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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