What moves slabs?

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ABSTRACT   When considering a migrating subduction hinge, the kinematics of convergent geodynamic settings shows that subduction zone rates can be faster or slower than convergent rates as a function of whether the subduction hinge migrates away or toward the upper plate. This opposite behaviour occurs in particular along W-directed and E- or NE-directed subduction zones respectively. Along W-directed slabs, the subduction rate is the convergence rate plus the slab retreat rate, which tends to equal the backarc extension rate. Along E- or NE-directed slabs, the subduction rate is decreased by the shortening in the upper plate. Relative to the mantle, the W-directed slab hinges are fixed, whereas they move west or southwest along E- or NE-directed subduction zones. Therefore, subduction zones appear as passive features controlled by the far field plate velocities and their motion relative to the underlying "eastward" mantle flow rather than by the negative buoyancy alone of the downgoing plate. Several observations cast doubts about the efficiency of the slab pull alone in triggering plate motions. For example, kinematically, the slab is moving out of the mantle along some E- or NE-directed subduction zones, i.e., moving in the direction opposite to the one predicted by the pull of the slab. Mantle convection is also inadequate to explain the Earth's surface kinematics. Plate motions driven by the Earth's rotation seem to be the simplest explanation for the asymmetry along the subduction zones and the aforementioned incongruence.

1. Introduction

Carlo Morelli's contribution to the knowledge of the geology and geophysics of the Mediterranean has been crucial for the development of researches throughout the basin. We are honoured to contribute to the volume dedicated to him with this article. The geophysical acquisitions of the last decades where Carlo Morelli (e.g., Morelli, 1970) injected lots of energy, allow a much more detailed view of the deep nature of our countries.

These new data sets permit us to better characterize the Alps and the Apennines, which, generally speaking, show geological and geophysical signatures that mimic the asymmetry between eastern and western Pacific subduction zones, although the Andes did not reach the collisional stage. The Alps (e.g., Dal Piaz *et al*. 2003; Panza *et al*., 2003) and the Apennines (e.g., Scandone, 1979; Calamita *et al*., 1994; Nicolich, 2001; Scrocca *et al*., 2003) are the result of two independent and opposite subduction zones (Laubscher, 1988; Doglioni, 1994). The Alps and the Apennines show, respectively, the following main differences (Doglioni *et al*., 1999): double verging orogen versus single vergent accretionary prism; elevated versus low topography; shallow versus deep foredeep (Doglioni, 1994); deep versus shallow rocks involved; shallow

versus steep foreland monocline dip (Mariotti and Doglioni, 2000); thickened versus thinned crust under the belt; thickened lithosphere versus shallow hangingwall asthenosphere; no backarc basin versus widespread hangingwall extension and well developed backarc basin with related alkaline-tholeiitic magmatism; scarce versus larger abundance of subduction-related volcanism; smooth vs. high amplitude gravity and heath flow anomalies (e.g., Carminati *et al.*, 2004a). These differences can be ascribed to the deeper lithospheric-rooted decollement occurring along "east"-directed subduction zones, with respect to the shallower upper crustal decollement typical of W-directed subduction zones. The asymmetry has been ascribed to the polarity of the subduction, i.e., following or opposing the relative "eastward" mantle flow implicit in the model of the westward drift of the lithosphere (Doglioni *et al.*, 1999). Within the two opposite end-members, a number of different settings can occur. For example along the E- or NE-directed subduction zones, there are oceanic slabs under continental lithosphere as the Andes, which may or may not evolve to continent-continent collision such as the Alps or Himalayas (Ernst, 2005). Along W-directed subduction zones there are also variable compositions of the lower plate (both oceanic and continental lithosphere, e.g., Marianas and Banda arc) and variable depth of the basal decollement plane determining the volume of the related accretionary prism (e.g., Bigi *et al.*, 2003; Lenci *et al.*, 2004).

Starting from these two end-member examples, here the gross kinematics of opposite subduction zones is briefly discussed, and the nature of the subduction in general is debated. Why does subduction occur? Why does the continental lithosphere also enter the underlying mantle (Dal Piaz *et al.*, 1972)? To decipher how and why the lithosphere subducts, means unravelling the engine of plate tectonics, which is still far from being entirely understood. Present models for plate tectonics are divided into plate motions dragged by mantle convection (e.g., Bokelmann, 2002; Bercovici, 2003), and plate motions energized by top-driven mantle convection, in which the negative buoyancy of the slab, i.e., the slab pull, drives plates (e.g., Anderson, 2001). However, we discuss these models suggesting they are both far from explaining the surface geology and kinematics and some counterarguments are pointed out too.

The kinematic analysis starts from the basic assumption that absolute motion of two adjacent plates should be described not only by their velocity, but also by the intervening margin. In fact, trenches, like all plate boundaries, migrate apart (e.g., Garfunkel *et al.*, 1986).

2. Basic kinematics of subduction zones

Hypothetically, assuming a plate moving west at 10 cm/yr, the subduction rate will be function of the migration rate of the hinge zone (Fig. 1). Therefore, a stationary hinge will generate a subduction rate equal to the plate velocity; if the hinge migrates in the same direction of the plate and at the same speed, the subduction rate will be null. When the hinge migrates in the opposite direction at the same speed, the subduction rate will double to 20 cm/yr. This last setting in which the slab retreats and the convergence rate is augmented by the migration of the hinge toward the foreland, is typical of W-directed subduction zones. Hinge or trench migration has been proposed as being sensitive to the viscosity stratification in the mantle (Enns *et al.*, 2005). Moreover, being stiffer a more viscous slab can penetrate more steeply the mantle.

Royden and Burchfiel (1989) have proposed that the opposite tectonic style between Alps and

Fig. 1 - Hypothetical kinematics of a subduction zone where the downgoing plate is moving left at 10 cm/yr. Changing the hinge migration direction and rate, the resulting subduction rate will vary. For example, a static subduction hinge clearly predicts a subduction rate equal to the plate motion (A). A forward migration of the hinge of the same amount of plate motion and in the same direction indicates null subduction rate, i.e., the slab only moves horizontally (B). The last case is where the hinge retreats in the direction opposed to the plate motion direction and with the same rate. Here the subduction rate is doubled (C). This scheme shows that a subduction accompanied by a hinge migrating toward or against the plate motion has respectively, slower and faster rates, with respect to the convergence rate. Examples of slower rates are the Andes, the Cascadia, the Himalayas, whereas examples of faster rates are the Marianas, Barbados and the Apennines.
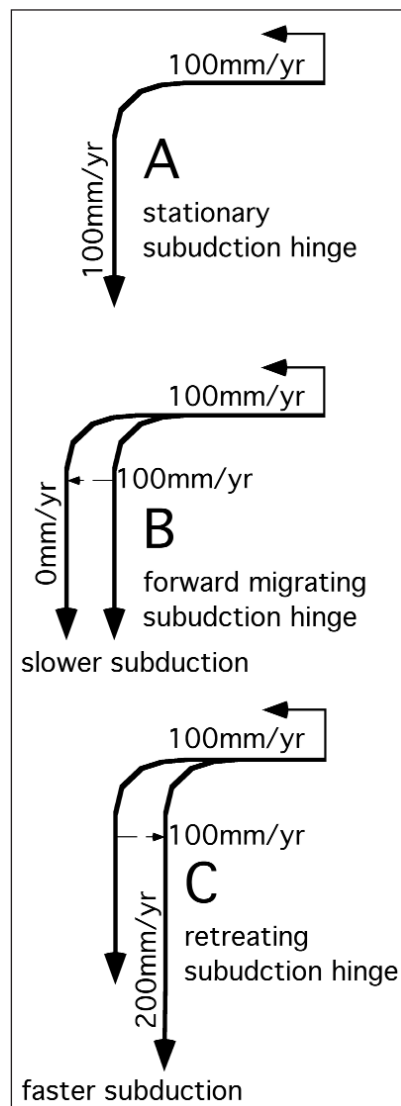
Apennines can be obtained by kinematic scenarios where the slab retreat is slower or faster than the convergence rate. Finite element models have clearly confirmed this relation (Waschbusch and Beaumont, 1996). In this paper we discuss the relation between convergence rate and subduction rate, which are different as a function of the subduction polarity.

Considering a fixed plate in the hangingwall of a subduction (U), and the subduction hinge (H) that is a point migrating over the downgoing lithosphere, we can observe an opposite behaviour along convergent margins (Fig. 2). Let us assume a fixed point in the footwall lower plate (L). The resulting subduction rate (S) can be calculated from the following simple relation, S = H-L, where H and L are the velocities of the hinge and of the lower plate relative to the fixed upper plate respectively. Movements converging relative to the upper plate are assumed as negative, and diverging positive.

As appears evident from Fig. 2, the subduction hinge H can migrate either in the direction of point U (upper panel a), or away from it (lower panel b). In the first case the UH is negative, whereas it is positive in the second case.

If we assume a fixed convergence rate of –8 cm/yr in both cases, and if the subduction hinge migrates toward the upper hangingwall plate at –6 cm/yr because part of the convergence is absorbed by the shortening of the orogen (a), the resulting subduction rate will be smaller, i.e., only 2 cm/yr.
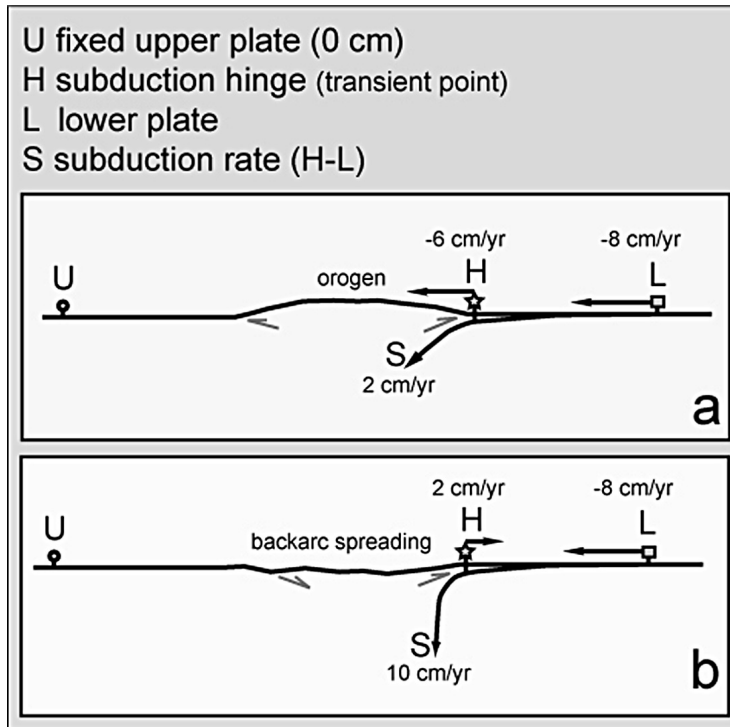
Fig. 2 - Basic kinematics of subduction zones, assuming a fixed upper plate. Movements converging relative to the upper plate are negative, and diverging positive. Upper panel: the trench is converging toward the upper plate and the resulting subduction rate is slower with respect to the convergence rate. That is because the shortening in the orogen decreases the subduction rate. Lower panel: the trench is diverging from the upper plate, and the subduction rate is faster than the convergence rate. In this case, the backarc extension increases the convergence rate. The two opposite cases fit with a lower and steeper dip of the slab (modified after Doglioni *et al.*, 2006).
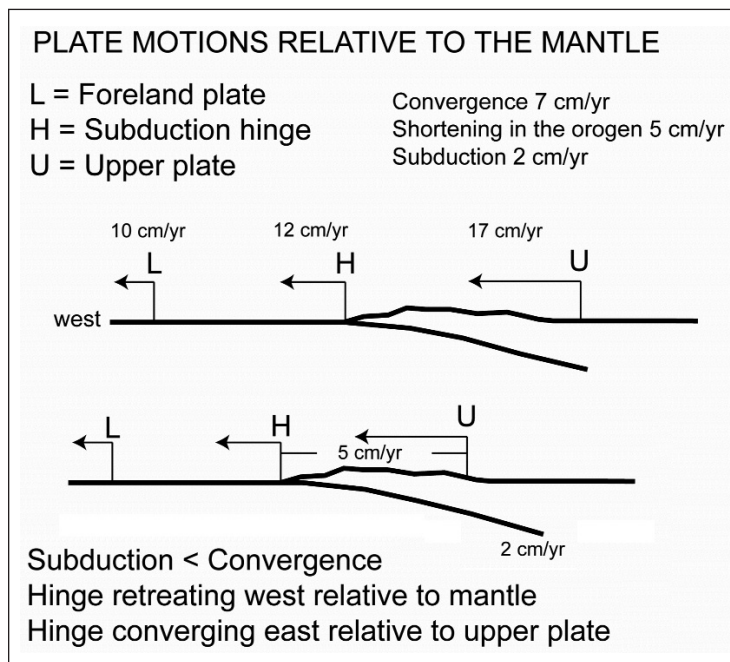

Fig. 3 - The absolute plate motions, e.g., relative to the mantle, show the same relationships as in the previous figure. The case of an E- NE-directed subduction shows a slower subduction rate with respect to the convergence rate. The trench or subduction hinge H is moving west relative to the mantle, but is moving east relative to the upper plate. The larger the shortening in the orogen, the lower the viscosity of the upper plate. The convergence/shortening ratio is 1.4 and is a function of the lithospheric viscosity. From this analysis, plate motions are not controlled by the subduction rate, but vice versa.

In case the subduction hinge migrates away from the upper plate at a rate of 2 cm/yr (b), the subduction rate will increase the convergence rate by the amount of slab retreat, i.e., the hinge migration, resulting in 10 cm/yr.

The two opposite settings are characterized, respectively, by a double vergent elevated orogen (a), and by a much smaller, single vergent accretionary prism, and the occurrence of a backarc basin (b). It is easy to apply these different kinematics to the Alps and the Apennines, or to the eastern and western Pacific subduction zones.

Therefore, the behaviour of the subduction hinge that can decrease or increase the subduction rate is crucial. This shows that the rate of subduction is not equal to the rate of convergence unless the subduction hinge does not migrate relative to the upper plate.

Let us assume another frame of reference for an E- NE-ward directed subduction, where both upper and lower plates move relative to the mantle (Fig. 3). The lower plate L moves westward at a rate of 10 cm/yr, while subducting eastwards. The subduction hinge H shifts westwards at 12 cm/yr, and the upper plate U also moves westwards at 17 cm/yr. Therefore, the convergence rate between upper and lower plate is 7 cm/yr. In this case the shortening (5 cm/yr) is computed as the difference in velocity between the subduction hinge migration rate and the upper plate velocity. The subduction rate would be 2 cm/yr, i.e., smaller than the shortening. Thus, the convergence rate is partitioned between superficial shortening and the subduction rate. It is worth noting that the subduction rate is smaller than the convergence rate. The subduction hinge retreats westwards relative to the mantle, while it converges eastwards relative to the upper plate.

When two plates interact, the less rigid, or less viscous one will undergo the larger deformation. The continental lithosphere is less viscous than the oceanic lithosphere. Looking at cross sections across the Chile trench, the Nazca oceanic lower plate is in fact much less deformed than the South American continental upper plate. In fact, very often, an erosional margin is depicted along this type of subduction zones (e.g., Ranero and von Huene, 2000). As an application, along the E- or NE -directed oceanic subduction zones, the higher the viscosity of the continental upper plate, the lower the shortening in the orogen; the subduction rate will also be relatively faster, but still slower than the convergence rate. Vice versa, a lower viscosity of the upper plate will allow a greater shortening in the orogen, and the subduction rate will be smaller. A screening of the convergence/shortening ratio is a further step for investigation of the different orogens in order to have average estimates of the upper plate viscosity. For example, in the central Andes, the convergence is 77 mm/yr, whereas the shortening is about 35 mm/yr (Liu *et al*., 2000). Therefore the convergence/shortening ratio is 2.2. The subduction rate should be 42 mm/yr.

Starting from the thin sheet model (England and McKenzie, 1982), and assuming a resistive drag at the base of the lithosphere, when computing the stress balance, the viscosity of the upper plate continental lithosphere in the Andes has been inferred as low as 3×10^{21} Pa s (Husson and Ricard, 2004). The viscosity of the oceanic lithosphere tends to be generally larger and decreases with depth. For example an oceanic lithosphere at a 25 km depth might have a range of viscosity between $10^{22} - 10^{27}$ Pa s, increasing with its age (Watts and Zhong, 2000). This may also explain why at oceanic-continental boundaries most of the deformation is absorbed by the upper plate, which is a softer continental lithosphere.

The higher the convergence/shortening ratio, the higher the viscosity of the upper plate (Fig. 4). The minimum value of this ratio for E- NE-directed subduction zones should be 1, where the
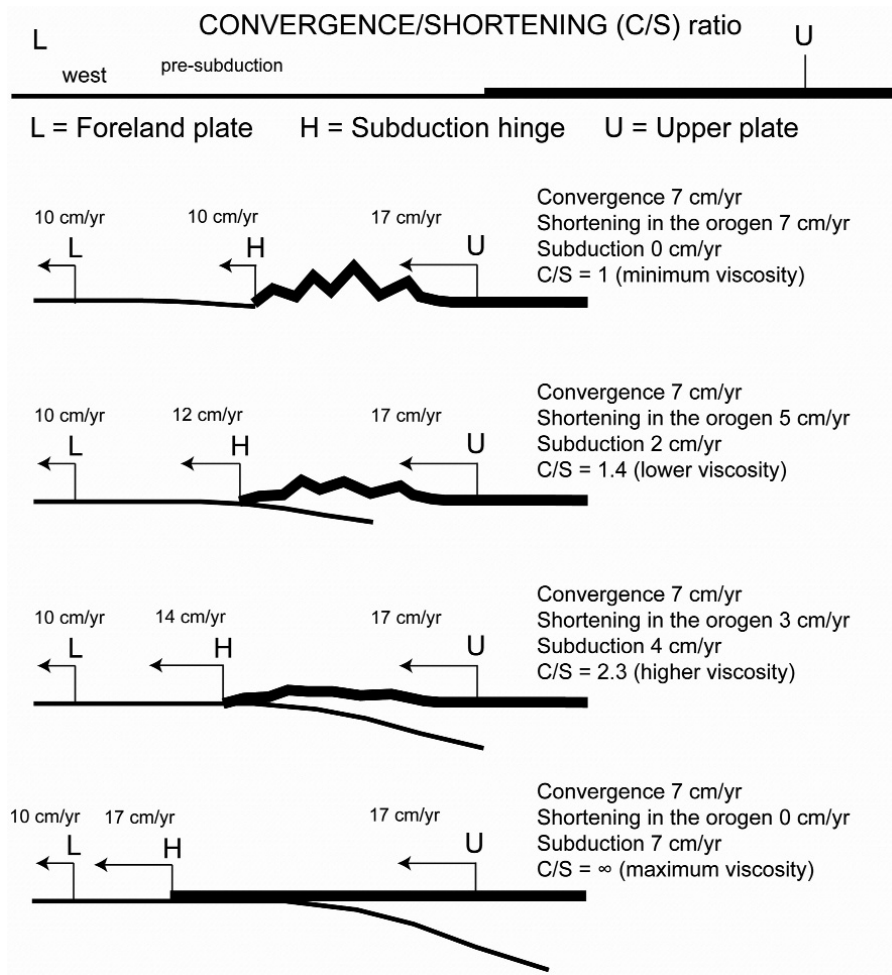
Fig. 4 - Four hypothetical cases of an oceanic subduction, where the shortening is confined to the continental upper lithosphere and varies as a function of its viscosity. The larger the shortening, the smaller the subduction rate, and the lower the viscosity (upper case). The convergence/shortening ratio can vary from 1 to ∞.

amount of convergence equals the amount of shortening in the belt, indicating very low viscosity, and virtually no subduction (Fig. 5).

Let us consider now the case of a W-directed subduction, where plate motions are still considered relative to the mantle (Fig. 6). The upper plate U moves westwards at 2 cm/yr. The hinge H is fixed relative to the mantle, but it is a transient point, shifting on the downgoing plate at the mantle velocity. The lower footwall plate L moves westwards at a speed of 11 cm/yr and the convergence rate is then 9 cm/yr. The backarc spreading, which is the rate of motion of U relative to H, is 2 cm/yr, and the subduction rate will be 11 cm/yr. The subduction rate is the sum of the convergence rate plus the backarc spreading. In this setting, the subduction rate is faster than the convergence rate, the hinge H is fixed relative to the mantle, and it is retreating eastwards relative to the upper plate. Along W-directed subduction zones, the convergence/shortening ratio can be smaller than 1 because the subduction rate is faster than the convergence rate, and the related accretionary prism peels off the downgoing lithosphere.
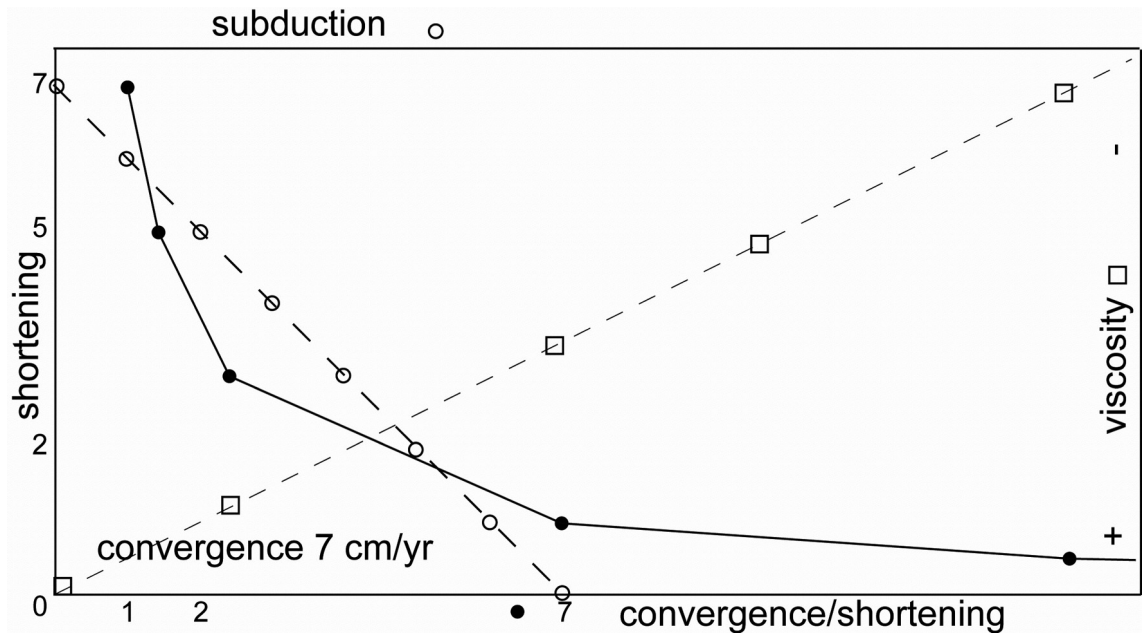
Fig. 5 - Diagram with the relations between shortening rate, convergence/shortening ratio, subduction rate and viscosity of the upper plate along an E- NE-directed subduction zone, at a convergence rate of 7 cm/yr.
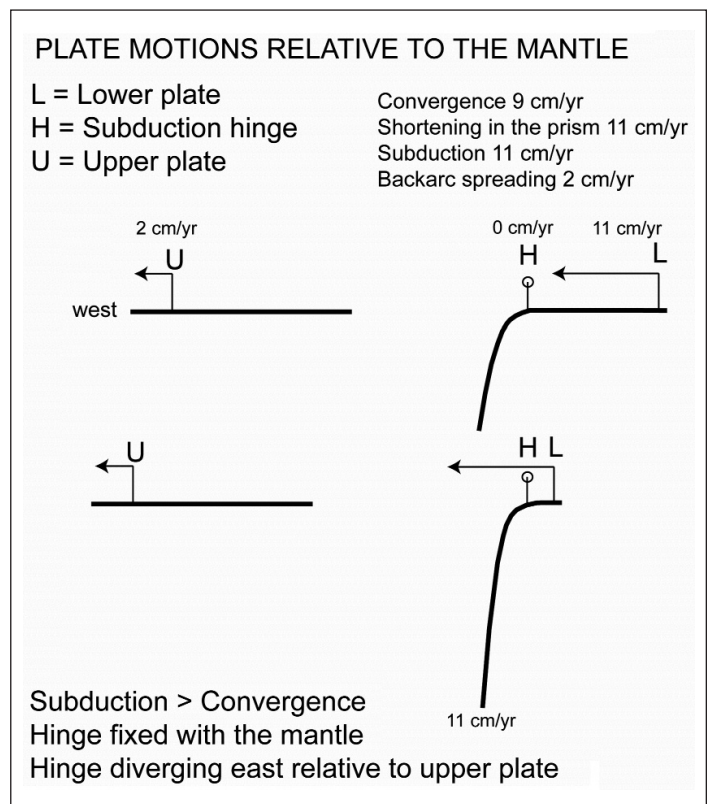

Fig. 6 - Absolute plate motions of a W-directed subduction zone. The slab is anchored to the mantle, and the subduction rate is faster than the convergence rate. The subduction hinge H is fixed relative to the mantle, but is moving east relative to the upper plate. Therefore, in both W- and E- NE-directed subduction zones, the hinge migrates eastwards relative to the upper plate.

Along both W- and E- NE-directed subduction zones, the hinge migrates eastwards relative to the upper plate. Therefore, along the W-directed subduction zones the hinge migrates away with respect to the upper plate, whereas the hinge migrates toward the upper plate along E- NE-directed subduction zones. In this interpretation, the far field velocities of the upper and lower plates control the subduction rate, and the subduction is a passive process. In fact, the rates of subduction do not determine plate velocities, but are rather a consequence of them.

As a conclusion, in eastern Pacific subduction zones, and in the E- or NE-directed subduction zones in general such as the Alps or Himalayas, the subduction rate should be lower than the convergence rate. On the other hand, along the western Pacific subduction zones, and the W-directed subduction zones in general such as the Apennines, the subduction rate has to be faster than the convergence rate since it is incremented by the hinge retreat and the related backarc extension. These opposite kinematics are determined by the westward drift of the lithosphere detected in the hotspot reference frame, generating different geodynamic settings as a function of the polarity of the subduction (Doglioni *et al.*, 1999). The shortening is mostly concentrated in the upper continental lithosphere in E- or NE-directed oceanic subduction zones (e.g., Andes), eventually involving the lower plate during later collisional stages (e.g., Himalayas). It is rather concentrated in the lower plate along W-directed subduction zones from the oceanic to the continental stage of subduction (e.g., Barbados, Apennines).

A kinematic puzzle arises from the absolute plate motions analyzed with respect to the hotspot reference frame. When describing the plate motions relative to the mantle, both Africa and Greece move SW-wards with respect to the mantle (Greece faster). This implies that the slab is moving in the opposite direction of the subduction when studied relative to the mantle, but it is sinking because the faster upper plate overrides it. When plate kinematics are studied relative to a shallow hotspots reference frame, then practically all E- or NE-directed subduction zones are moving W- or SW-wards faster than the mantle, i.e., moving out of it. The slab is foundering because the upper plate is moving westwards even faster than the lower plate. This observation indicates that the slab pull cannot be the only driving force of either the Hellenic subduction, or the E- or NE-directed subduction zones in general, because it is moving SW-wards or W-wards relative to the mantle, i.e., in the opposite sense of the supposed pull of the slab.

3. What drives subduction?

One paradigm of plate tectonics relates the dip of the slab to the buoyancy of the downgoing lithosphere along subduction zones, being the negative buoyancy proportional to the age of the oceanic lithosphere, length of the slab and length of the trench (Forsyth and Uyeda, 1975; Jarrard, 1986; Anderson, 2001; Conrad and Lithgow-Bertelloni, 2003). Several analogue modelling and finite element modelling have been carried out in order to reproduce subduction mechanisms (e.g., Shemenda, 1993; Regard *et al.*, 2003). However, the dip of the slab down to depths of 250 km shows no relation with the age of the downgoing lithosphere (Cruciani *et al.*, 2005; Lallemand *et al.*, 2005). In fact, there are slabs where moving along-strike the age of the downgoing lithosphere varies, but the dip remains the same (Barbados), or vice versa, the age remains constant but the dip varies (Philippines). There are cases where the age decreases and the dip increases (W-Indonesia), and other subduction zones where the age increases and the dip
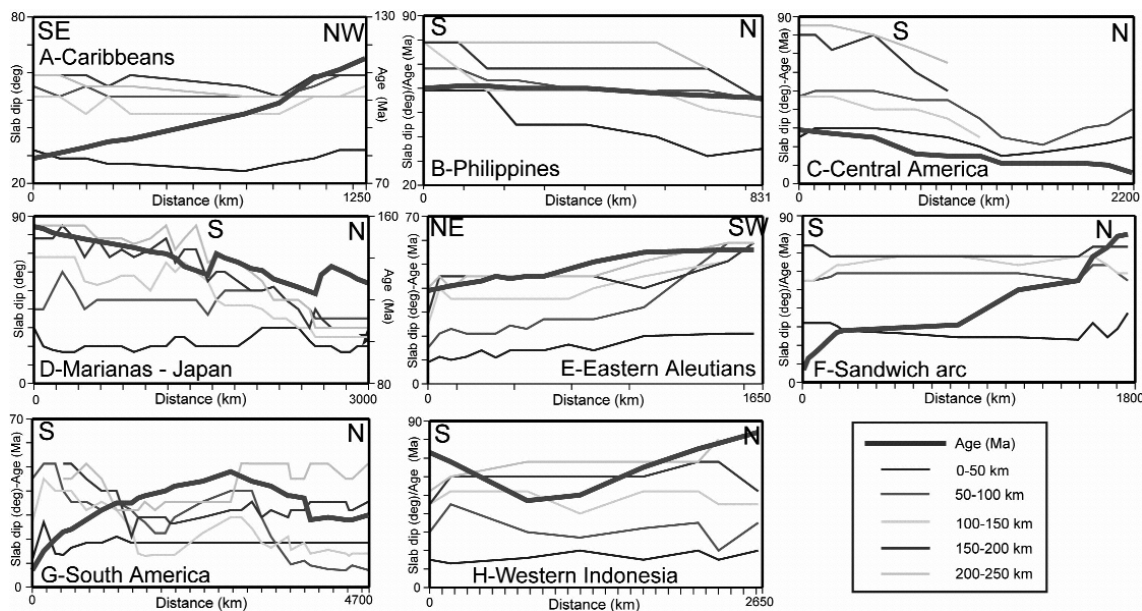
Fig. 7 - Dip variation along subduction zones at interval depths of 50-100-150-200-250 km. The thicker line indicates the age at the trench of the oceanic lithosphere of the downgoing plate (after Cruciani *et al.*, 2005). There is not a systematic correlation between slab dip and oceanic lithosphere age. For example, in the Caribbean, moving along strike, the dip remains constant but the age increases. In the Philippines, the dip decreases and the age remains almost constant. In S-America, the dip decreases and the age increases, or in western Indonesia the dip increases and the age decreases.

decreases (Sandwich). This shows that there is not a first order relationship between slab dip and lithospheric age (Fig. 7). This suggests that supplemental forces or constraints have to be accounted for, such as thickness and shape of the hangingwall plate, relative and absolute plate velocity, presence of lateral density variations in the hosting upper mantle, effects of accretion/erosion, subduction of oceanic plateaus and slab deformation due to the motion of the mantle relative to the subducting plate (Cruciani *et al.*, 2005). Seismicity illuminating the slab geometry is strongly influenced by the composition, thermal state and velocity of the downgoing plate (e.g., Carminati *et al.*, 2004b).

Plate motions in general, regardless of the tectonic setting (Fig. 8), have 10-100 times faster horizontal velocities with respect to vertical movements (Cuffaro *et al.*, 2006). This suggests that plate margins are passive features rather than active engines for plate tectonics.

In the following sections we will analyse the alternative mechanisms that have been proposed to drive plate tectonics, namely the slab pull, the mantle convection and the forces generated by the Earth's rotation.

4. On the efficiency of the slab pull

Is the slab pull the energetic source for plate motions? Is it large enough? Is it correctly calculated? Are the assumptions reliable? Most of the literature indicates that the slab pull is
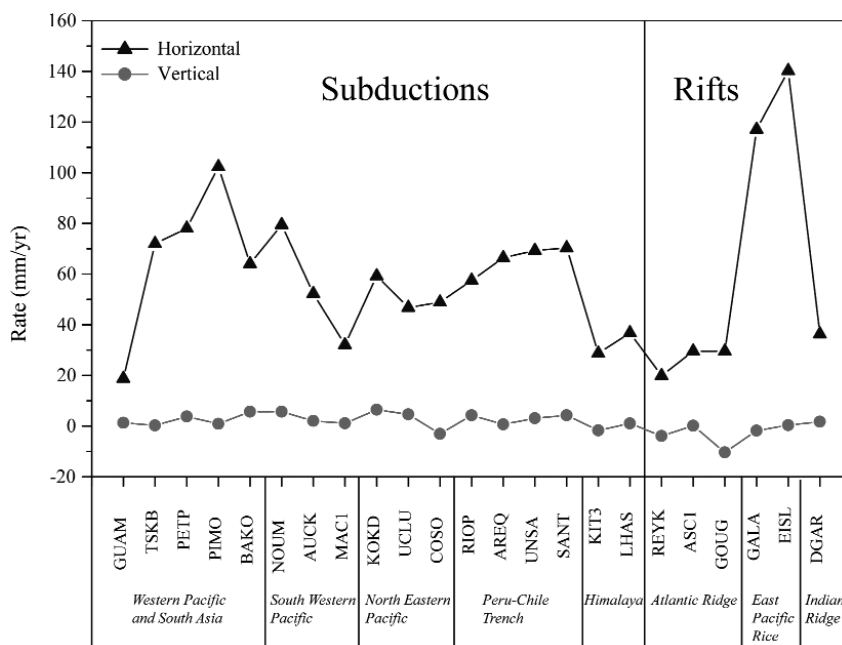
Fig. 8 - Present horizontal relative motions between pairs of plates (line with triangles) is 10-100 times faster than vertical movements at the intervening plate boundary (line with gray circles). These values are computed on the Nasa space geodesy database (http://sideshow.jpl.nasa.gov/mbh/series.html). GPS site locations are reported on same web site. This signal suggests that plate tectonics have a strong toroidal component, and that plate boundaries are passive features rather than the primary energetic source of plate motions (after Cuffaro et al., 2006)

about 3.3×10^{13} N m^{-1} (e.g., Turcotte and Schubert, 2002). This is a force per unit length parallel to the trench. However, this value is very small when compared to other energetic sources of the Earth, such as the energy dissipated by tidal friction, heat flow emission, and the Earth's rotation (e.g., Denis *et al.*, 2002). Moreover, the slab pull would be even smaller if chemical and mineralogical stratification are introduced in the upper mantle. Most of the Earth's volcanism is sourced from above 200 km: the subduction zones release magmatism at about 100-150 km depth (Tatsumi and Eggins, 1995); mid oceanic ridges are sourced by even shallower asthenosphere melting (100-30 km, e.g., Bonatti *et al.*, 2003); hotspots are also debated as potentially very shallow, and sourced by the asthenosphere (Bonatti, 1990; Smith and Lewis, 1999; Doglioni *et al.*, 2005; Foulger *et al.*, 2005). Since even xenoliths, in general, and kimberlite chimneys, originated at depth not deeper than the asthenosphere, we have no direct sampling of the composition of the standard lower part of the upper mantle. Therefore, we cannot exclude for example a more Fe-olivine fayalitic composition of the olivine, heavier and more compacted than the Mg-olivine forsterite, which is presently assumed as the more abundant mineral of the upper mantle. If more iron is present in the upper mantle olivine, the density of the ambient mantle would be slightly higher, making the slab pull smaller, if any. The slab pull concept is based on the hypothesis of a homogeneous composition of the upper mantle, with the lithosphere sinking only because it is cooler (e.g., Turcotte and Schubert, 2002). However, the oceanic lithosphere is a frozen shallow asthenosphere previously depleted beneath a mid-oceanic ridge. A depleted

asthenosphere is lighter than a normal deeper and undepleted asthenosphere [see Oxburgh and Parmentier (1977); Doglioni *et al*. (2003, 2005) for a discussion]. Therefore the assumption that the lithosphere is heavier only because it is cooler might not be entirely true, and the slab pull could be overestimated. Phase transitions within the subducting lithospheric mantle would enhance the slab pull in the transition zone [300-400 km: Stern (2002), Poli and Schmidt (2002)], but again, the occurrence of higher density country rocks due to chemical, and not only phase transitions could make the effect of the slab pull smaller and smaller. Moreover, the occurrence of metastable olivine wedges in fast subducting oceanic lithosphere is considered to create positive density anomalies that should counteract the effects of slab pull (Bina, 1996). A further density anomaly that is suggested to drive the slab pull is expected to come from the eclogitization of the subducting oceanic crust. This process involves only a thin layer (5-8 km thick) and not the entire downgoing lithosphere (70-90 km thick). Nevertheless, this type of metamorphic transition is often assumed to be able to determine the slab pull. The eclogites reach densities of about 3440-3460 kg/m^3 only at depths of about 100 km (Hacker *et al*., 2003; Pertermann and Hirschmann 2003). The density of the country mantle at comparable depths according to the PREM model is 3370 kg/m^3 (Anderson, 1989), i.e., only slightly lighter than the eclogitized oceanic crust. Both eclogite and mantle densities are quite speculative. The small density contrast between subducting crust and country mantle casts doubts on the potential effect of the negative buoyancy of the oceanic crust. Therefore, we do not have hard constraints on the depth at which the slab pull should turn on and at what depth it should turn off since the mineralogy of the slab and the hosting mantle is still largely unknown. Why then should a slab maintain its shape and coherence down to the 670 km discontinuity? The easiest explanation would be its higher stiffness. The high velocity of the slab detected by tomography could be related not to its higher density, but to its higher rigidity and viscosity. Certainly the slab becomes heavier during sinking for phase transformations, but is it an a priori denser or does it become heavier on the way down? Is it continuously reaching density equilibrium while moving down?

The main reasons why the slab pull is not considered here a good mechanism for moving plates and for triggering subduction are listed.

1) The dip of the slab is independent from the age of the oceanic lithosphere (Cruciani *et al*., 2005), considered to control the increase of the lithosphere's density and likely, therefore, to be the magnitude of the slab's pull forces.

2) Subduction involves even continental lithosphere even deeper than 100-150 km (Ampferer, 1906; Dal Piaz *et al*., 1972; Trümpy, 1975; Ranalli *et al*., 2000; van Hinsbergen *et al*., 2005), although the subducted average continental crust is most probably buoyant with respect to mantle rocks (Hermann, 2002).

3) The oceanic lithosphere is a frozen shallow (30-100 km deep) asthenosphere, previously depleted below ridges. Therefore, the oceanic lithosphere is the differentiated lighter upper part of the mantle: then why should it be heavier a priori than the undepleted deeper (100-300 km) asthenosphere lying beneath the old oceanic lithosphere where a pyrolite density of 3400 kg/m^3 (Jordan, 1988; Kelly *et al*., 2003) is inferred? Moreover, hydrothermal activity generates serpentinization of the mantle along the ridge that decreases the density even more.

4) If the oceanic lithosphere is heavier than the underlying mantle, why are there no blobs of LID falling in the upper mantle, below the western, older side of the Pacific plate?

DOWN-DIP COMPRESSION
Apennines slab

Tyrrhenian Sea

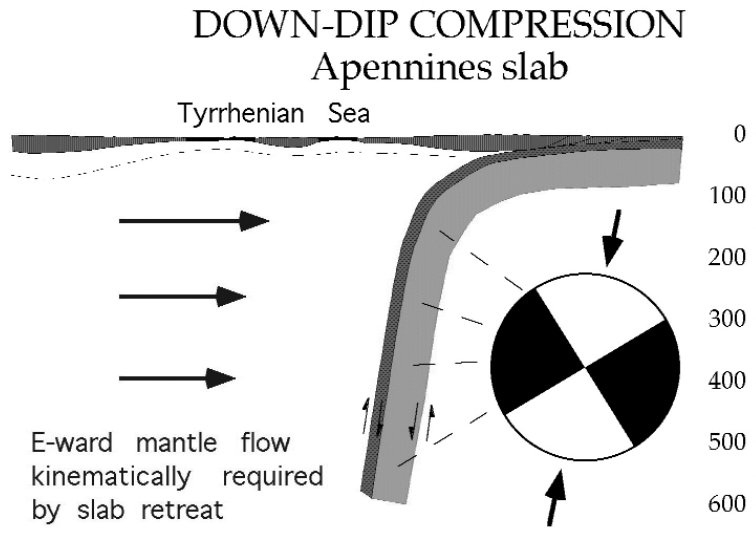E-ward mantle flow kinematically required by slab retreat

Fig. 9 - In the Tyrrhenian Sea, according to focal mechanisms, the slab is undergoing down-dip compression (Frepoli *et al.*, 1996). This is against an active pull of the slab. On the other hand, the slab retreat implies an eastward migration of the mantle, regardless of the fact that this is the cause or a consequence of it.

5) Down-dip compression (Fig. 9) affects most of the W-directed slabs, all below 300 km (Isacks and Molnar, 1971), and most of them at an even shallower depth (e.g., Frepoli *et al.*, 1996).

6) We do not have hard constraints of the real composition of the country's upper mantle: there could be more fayalite, making the upper mantle more dense and the slab's negative buoyancy smaller, or none.

7) The 700 km long W-Pacific slab, where only the upper 300 km show some potential down-dip extension seismicity [but it could be generated also by a horizontal shear in the mantle, Giardini and Woodhouse (1986)] should pull and carry the 10,000 km wide Pacific plate, 33 times bigger, winning the strong shear resistance at the plate base, and the opposing basal drag induced by the relative eastward mantle flow inferred from the hotspots migration (Fig. 10).

8) At the Earth's surface, the oceanic lithosphere has a low strength under extension [e.g., 8×10^{12} N m^{-1}, Liu *et al.* (2004)] and is able to resist a force smaller than that requested by the slab pull [3.3×10^{13} N m^{-1}, Turcotte and Schubert (2002)]. If the slab pull is the cause of
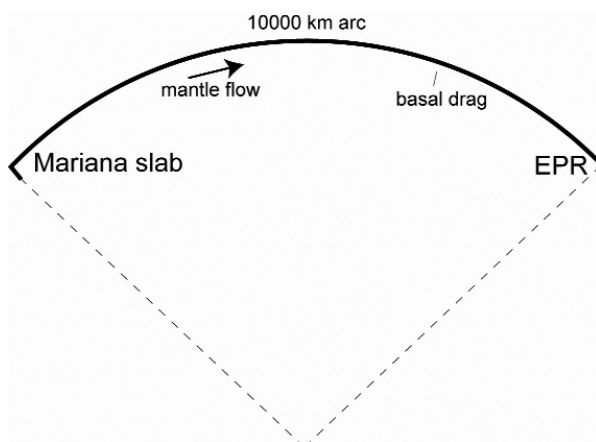

Fig. 10 - Sketch of vertical section of the Pacific plate from the Mariana subduction zone to the East Pacific Rise (EPR). Note the proportion of the slab length where there are some down-dip extension earthquakes (about 300 km), and the dimension of the plate. The negative buoyancy of the slab should be able to pull the 33-times-longer plate, and to win the basal drag of a mantle moving in the opposite direction according to the hotspots migration.

Fig. 11 - The slab pull maximum predicted force is larger than the strength of the lithosphere. Therefore, it is difficult to transfer the energy of the pull without breaking it. A smaller or even absent slab pull can occur in case of chemical upper mantle stratification.
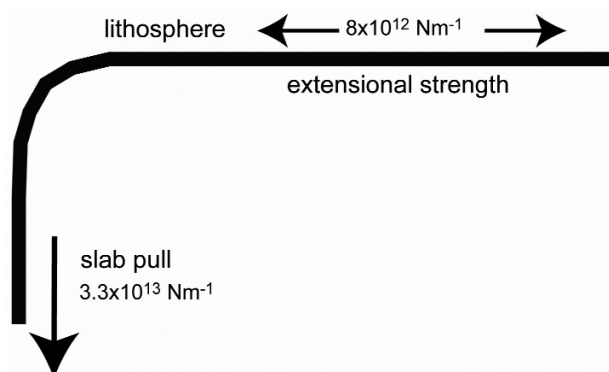
the motion of the Pacific plate, this observation argues in favour of a stretching of the Pacific lithosphere before the slab pull is able to move the plate. In other words, the plate cannot sustain the tensional stresses, that could eventually be due to slab pull (Fig. 11). The problem of low lithospheric strength could be, however, partly counterbalanced by the mantle flow and viscous tractions acting on the plates and induced by slab sinking (e.g., Lithgow-Bertelloni and Richards, 1998). Due to the low temperature and high pressure, the strength of the subducted oceanic lithosphere rises to some $2x10^{13}$-$6x10^{13}$ N m^{-1} (Wong a Ton and Wortel, 1997) and would make the eventual pull, induced by density anomalies related to phase changes at depth sustainable. In short, the subducted slab is probably able to sustain the load induced by the slab pull but probably, this load cannot be transmitted to the unsubducted portion of the plate without breaking it apart.

9) Faster plates surrounded by long slabs and trenches? It is a circular reasoning because long subduction zones might be a consequence of fast movements of plates. Moreover, plates are considered fast in the NNR reference frame (Conrad and Lithgow-Bertelloni, 2003). For example, measuring plate motions in the hotspot reference frame, i.e., relative to the mantle, Nazca is very slow relative to the mantle, so the relation plate velocity-slab age and length of the subduction zone (Fig. 12) is not true.

10) Plate velocities in the hotspot reference frame seem to be inversely proportional to the viscosity of the asthenosphere rather than to the length of the subduction zones and the age of the downgoing lithosphere. In fact the Pacific, which is the fastest westerly moving plate (Gripp and Gordon, 2002), has the lowest viscosity values (Pollitz et al., 1998).

Fig. 12 - The assumption that fast plates are such because they have long subduction zones is false. A clear example is the subduction of the Nazca plate under the Andes where the velocity in the no-net-rotation (NNR) reference frame is 4 cm/yr. However, this reference frame is an artefact, introduced only for geodetic needs, without geodynamic meaning. When looking at the same plate in the hotspot reference frame (HSRF), the velocity of Nazca is much smaller, regardless of the long subducting margin.
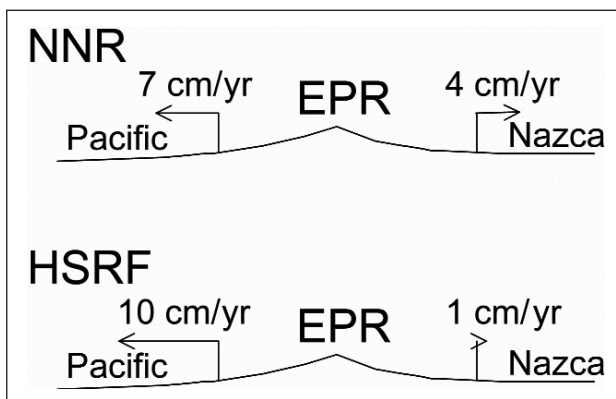
11) The horizontal velocity of plates is 10-100 times faster than vertical velocity (subduction related uplift or subsidence) suggesting that vertical motions are rather passive movements. Moreover, the kinematic analysis of section 2 shows that subduction rates appear controlled rather than controlling horizontal plate motions (Fig. 8).

12) The energy for compressing an orogen is probably larger than the one supposed for the slab pull.

13) Slab pull has been calculated to be potentially efficient only at a certain depth [e.g. 180 km, McKenzie (1977)]; and if it is shallower than that? How does subduction initiate?

14) Some plates in the hotspot reference frame move without any slab pulling them, e.g., the westward movements of N-America, Africa and South America (Gripp and Gordon, 2002).

15) There are rift zones formed between plates not surrounded by oceanic subduction to which one can attribute the pull for moving the lithosphere (e.g., the Red Sea).

16) Although the knowledge of the rheological behaviour of the subducted lithosphere is very poor it can be conjectured that the downgoing slab, being progressively heated, could potentially lose strength, diminishing the possibility of mechanically transfering the pull (Mantovani *et al.*, 2002).

17) Kinematically, subduction rollback implies that the volumes left in the hangingwall of the slab have to be replaced by a horizontal mantle flow, whether this is a consequence or the cause of the retreat (Doglioni *et al.*, 1999). However, in order to allow the slab to move back, the slab retreat needs the mantle in the footwall of the slab to also move away in the direction of the slab retreat, regardless whether this motion is generated by the slab pull or is an independent mantle horizontal flow. But the energy required to push the mantle forward is much greater than the slab pull can effort.

18) When describing the plate motions relative to the mantle, e.g. in the hotspots reference frame, along E- or NE-directed subduction zones the slab might move out of the mantle, e.g., in the opposite direction of the subduction. It is sinking because it is overridden by the faster upper plate (Fig. 13).

19) Within a slab, eclogitization is assumed to make the lithosphere denser. However, eclogitization is concentrated in the 6-8 km thick oceanic crust, whereas the remaining 60-80 km thick lithospheric mantle does not undergo the same transformation. Therefore only 1/10 of the slab is apparently increasing density, but the main mass of the slab (90%) does not change significantly.

20) The density increase due to eclogitization is in contrast with the exhumation of the eclogitic prism that is usually detached with respect to the "lighter" lithospheric mantle (G.V. Dal Piaz, pers. comm.).

21) Why should the lithosphere start to subduct? This crucial point arises particularly when considering an oceanic hydrated and serpentinized lithosphere that has not yet been metamorphosed by the subduction process, and consequently it is still less dense (G.V. Dal Piaz, pers. comm.).

This long list casts doubts on the possibility that the slab pull can actually trigger subduction, slab rollback, and drive plate motions. Density anomalies due to phase changes occurring at depth within the slab could enhance the sinking of the slab. However, the slab pull alone, even if efficient at some depth, is apparently unable to explain the initiation of the subduction, and the mechanism perpetuating plate motions in general.
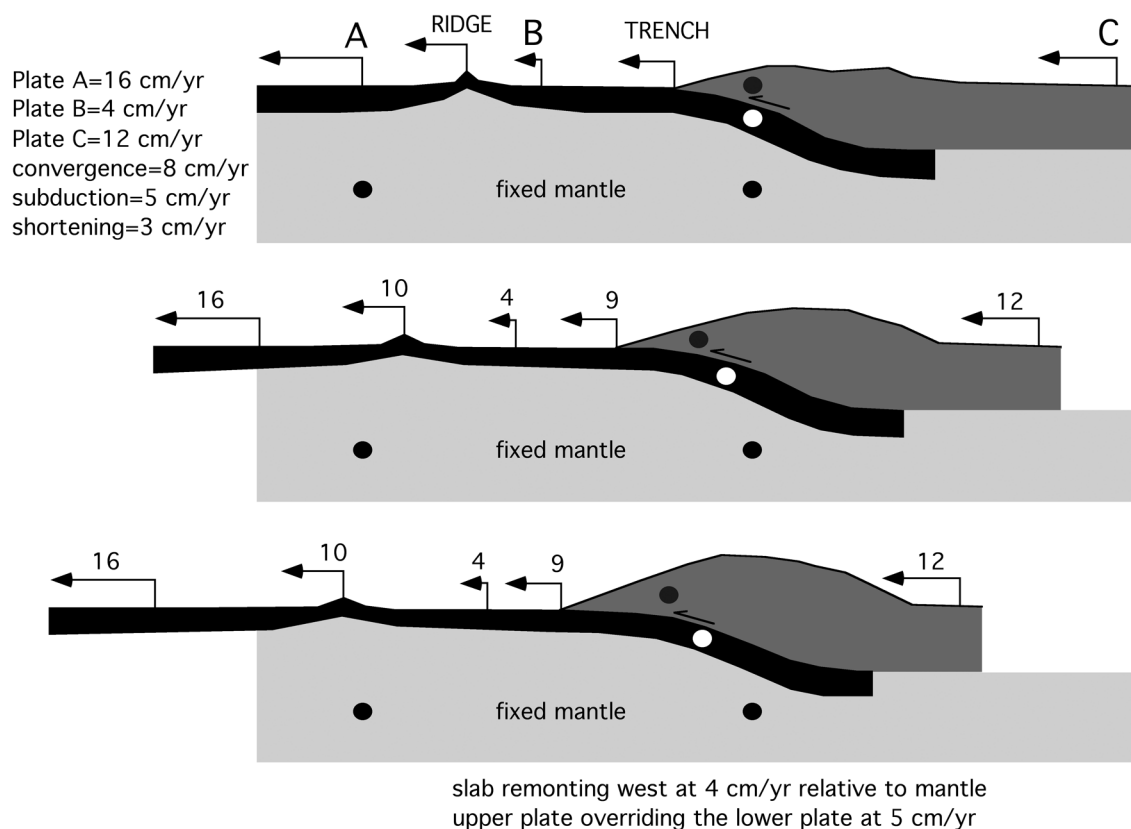
Fig. 13 - When plate motions are considered relative to the hotspot reference frame, the slabs of E- or NE-directed subduction zones may move out of the mantle. This is clearly the case for Hellenic subduction and, in the shallow hotspot reference frame, also for Andean subduction. This kinematic evidence of slabs moving out of the mantle casts doubts on slab pull as the driving mechanism of plate motions.

The slab detachment model is conceived as a consequence of the negative buoyancy of the slab and has been invoked many times to explain the supposed rupture of the slab in tomographic images (e.g., Wortel and Spakman, 2000) and to fit the geochemistry of magmatism (e.g., Lustrino, 2005). However, tomographic images are based on velocity models that often overestimate the velocity of the asthenosphere where the detachment is usually modelled. Therefore, the detachment disappears when using slower velocity for the asthenosphere in the reference velocity model or generating regional tomographic images with better accuracy (e.g., Piromallo and Morelli, 2003). Recently, Rychert *et al*. (2005) have shown how the base of the lithosphere – top of the asthenosphere is characterized by unexpected extremely low velocities beneath northwestern North America, far from subduction zones. This implies a revision of the velocity models used for mantle tomography, particularly in areas characterized by strong lateral variations in composition of the subducting lithosphere (e.g., continental vs. oceanic) that cannot be 3D modelled with a 1D velocity model.

5. Mantle convection

It is obvious that convection occurs in the mantle, not only from modelling, but also from the kinematics of plate boundaries, where mantle uprises along ridges and the lithosphere sinks along subduction zones. It is also evident that the oceanic lithosphere circulates in the mantle much more easily than the continental lithosphere, since only relatively young (180-0 Ma) oceans cover the Earth's surface compared to the much older cratons, where a much older (>3000 Ma) and continental lithosphere is buoyant over the mantle.

The mantle is considered compositionally quite homogeneous. However, this is very unlikely, since the whole Earth is intensely stratified both in density and chemistry from the topmost atmosphere down to the core. The supposed convection cells are probably be made of an uprising warmer buoyant mantle, laterally accompanied by down-welling cooler currents. From the view point of convection modellers, the surface expression of cells are the plates. But the Atlantic, E-Africa and Indian rifts do not have intervening subductions; there are also several cases of paired subduction zones without rifts in between: this shows the inapplicability of the convection cells to the simple superficial plate tectonics.

In most of the convection models, uprising and down-welling mantle currents are stationary, but we know that all plate margins rather migrate. Convection styles frequently generate poligonal shapes of cells, but plate margins can be very linear e.g., the Atlantic ridge, by contrast with the typical mushroom shape of mantle plumes.

The fastest W-ward moving plate relative to the mantle (the Pacific plate) has the lowest asthenosphere viscosity value (Pollitz *et al.*, 1998), and it is the most decoupled plate, but mantle convection should rather predict that faster moving plates are more coupled (higher viscosity) with the mantle.

The Hawaii hotspot volcanic chain indicates that the underlying mantle is moving E-SE-wards. Beneath the East Pacific Rise, an eastward migrating mantle has been modelled by Doglioni *et al.* (2003) and Hammond and Toomey (2003). An eastward migrating mantle has been suggested also beneath the Nazca plate by Russo and Silver (1994) through shear wave splitting analysis. An eastward relative mantle flow beneath the South America plate is imposed by the hotspot reference frame (Van Hunen *et al.*, 2002). A relatively eastward moving mantle flow has been proposed also beneath North America (Silver and Holt, 2002) and beneath the Caribbean plate (Negredo *et al.*, 2004). Beneath the Tyrrhenian Sea a similar west to east flow of the mantle can be inferred from mantle anisotropy (Margheriti *et al.*, 2003). A global reconstruction of the anisotropy in the asthenosphere (Debayle *et al.*, 2005) fits the sinusoidal flow of plate motions quite well (e.g., Doglioni *et al.*, 1999), apart from along subduction zones where the shear wave splitting anisotropy shows orthogonal trends compatible with the re-orientation of a flow encroaching an obstacle.

Trampert *et al.* (2004) have recently demonstrated that low velocity volumes of the mantle detected by tomography can be due to lateral variations in composition rather than to temperature, i.e., they can be areas of even higher density rather than hotter, lighter, buoyant material as has been so far interpreted. In fact, considering the main low velocity zones in the mantle such as the asthenosphere or the liquid core, their decrease, in speed, of the P waves is related to their lower rigidity or viscosity (e.g., Secco, 1995) either generated by CO_2 content in the asthenosphere, or higher density – low viscosity iron alloys in the liquid core. As extreme examples, gold or lead

have high density but low seismic velocity. Therefore, the interpretation of tomographic images of the mantle where the red (lower velocity) areas are assumed as lighter, hotter rocks can simply be wrong, i.e., they may even be cooler and denser (Van der Hilst, 2004). With the same reasoning, blue (higher velocity) areas, which are assumed as denser, but cooler rocks may even be warmer and lighter.

Trampert *et al*. (2004) also suggest that the low velocity in the lower mantle could for example be due to higher concentrations of iron. Minerals containing more iron are more conductive, and at that depth the coefficient of thermal expansion must be very low. Both factors decrease the Rayleigh number, making the convection very sluggish (e.g., Anderson, 2002). The onion structure of the Earth with compositionally homogeneous shells [e.g., the PREM, see Anderson (1989)] is a misleading oversimplification, since the occurrence of lateral heterogeneities in the whole of the Earth's layers has been widely demonstrated.

6. The Earth's rotation

The lithosphere is decoupled relative to the mantle, as indicated, for example, by the hotspots tracks. The anisotropy detected by shear wave splitting, supports a shear zone active in the asthenosphere (Gung *et al*., 2003). Sheared asthenospheric xenoliths confirm decoupling at that depth (Kennedy *et al*., 2002), and the migration of plate boundaries in general (Garfunkel *et al*., 1986; Doglioni *et al*., 2003). But what is forcing the lithosphere relative to the mantle? Moreover, the decoupling is polarized towards the west (Rittmann, 1942; Le Pichon, 1968; Bostrom, 1971; Wang, 1975), although it is along a sinusoidal flow (Doglioni *et al*., 1999). A net rotation of the lithosphere toward the "west" of about 4.9 cm/yr has been computed in the hotspot reference frame (Gripp and Gordon, 2002).

Scoppola *et al*. (2006) recently proposed a combined model where the net westward rotation of the lithosphere relative to the underlying mantle is a combined effect of three processes: 1) tidal torques act on the lithosphere generating a westerly-directed torque decelerating the Earth's spin; 2) the downwelling of the denser material toward the bottom of the mantle and in the core, decreasing the moment of inertia and speeding up the Earth's rotation, only partly counterbalancing the tidal drag; 3) the development of thin (3-30 km) layers of very low viscosity hydrate melt rich channels in the asthenosphere. Scoppola *et al*. (2006) suggested that shear heating and the mechanical fatigue self-perpetuate one or more channels of this kind that provide the necessary decoupling zone for the lithosphere. This can account for the geological and geophysical asymmetry characterizing W- versus E- or NE-directed subduction zones and related orogens (Marotta and Mongelli, 1998; Doglioni *et al*., 1999). The fastest westerly moving plate (Pacific) is the slowest eastward moving possibly due to the more effective decoupling in the asthenosphere generated by the Earth's rotation.

7. Conclusions

Surprisingly, along W-directed slabs, the rate of subduction is faster than the convergence rate, whereas along E- or NE-directed slabs, the rate of subduction is slower than the convergence rate. The two opposite kinematics predict a subduction hinge migrating away from (W-directed

subduction), or toward the (E-NE-directed subduction) upper plate. The kinematics described above suggest that subduction zones are passive features relative to far-field plate velocities, since the subduction rates can be even smaller than relative plate motions along E- or NE-directed subduction zones.

The convergence/shortening ratio is regularly higher than 1 in E- NE-directed subduction zones (Fig. 4). This value is sensitive to the viscosity of the upper continental lithosphere. Higher ratio means higher viscosity of the lithosphere, i.e., it is stiffer and sustains the convergence, while most of the convergence is absorbed by subduction (Fig. 5). The observation that the convergence is faster than the shortening, supports the notion that the plate boundary (subduction and related orogen) is a passive feature, and does not provide the driving energy of plate motions. A kinematic counterargument for the slab pull is the observation that the slab is moving out of the mantle along E- or NE-directed subduction zones when plate motions are analyzed relative to the hotspots reference frame.

What is moving the lithosphere relative to the mantle? The only feasible mechanisms are either the slab pull or the tidal friction. However, the slab pull model is affected by a number of inconsistencies, which have briefly been described here. Slab pull does not seem able to determine plate motions in general, although it could enhance subduction once started. An alternative or complementary model would be the tidal drag exerted by the Moon and the Sun while the Earth rotates.

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