

## Simple Kinematics of Subduction Zones

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### Abstract

Two main types of subduction zones can be distinguished: (1) those where the subduction hinge migrates away from the upper plate; and (2) those in which the subduction hinge migrates toward the upper plate. Apart from a few exceptions, this distinction seems to apply particularly for W-directed subduction zones and E- or NE-directed subduction zones, respectively. Moreover, the rate of subduction is larger than the convergence rate along W-directed subduction zones, whereas it is smaller along E- or NE-directed subduction zones. Along W-inclined 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-dipping slabs, the shortening in the upper plate decreases the subduction rate, and no typical backarc basin forms.

Relative to the mantle, the W-directed slab hinges are fixed, whereas they move west or south-west along E- or NE-directed subduction zones. The single vergent accretionary prism related to W-directed subduction zones is formed at the expenses of the shallow layers of the lower plate. The orogens generated by E- and NE-dipping subductions are double vergent since the early stages, and upper plate rocks mostly compose them until continental collision takes place, eventually involving the rocks of the lower plate more extensively. The convergence/shortening ratio in this type of orogens is higher than 1 and is inversely proportional to the viscosity of the upper plate. The higher the viscosity, the smaller the shortening and faster the subduction rate. The convergence/shortening ratio along W-directed subduction zones is instead generally lower than 1.

W-directed subduction zones provide larger volumes of lithospheric return into the mantle than the opposite E- or NE-directed subduction zones. The latter may contribute to refertilize the shallow upper mantle. These observations suggest that subduction zones are passive features with respect to the far-field velocity of plate motions and the relative “eastward” mantle flow, implicit with a net “westward” rotation of the lithosphere.

### Introduction

THE SUBDUCTION PROCESS is a vital ingredient of plate tectonics (Anderson, 1989, 2001; Stern, 2002; Conrad and Lithgow-Bertelloni, 2003). Most of the oceanic lithosphere is recycled into the mantle, but also some continental lithosphere can subduct (Ampferer, 1906; Ranalli et al., 2000; Hermann, 2002). There still are doubts on the initiation of the subduction process (Spence, 1987; Niu et al., 2003), but once activated, it may work for several tens of million years. Subduction zones have a related accretionary prism or orogen, a subduction hinge that can migrate (Garfunkel et al., 1986), and a large variety of geophysical, magmatological and geological signatures (Isacks and Molnar, 1971; Jarrard, 1986; Royden and Burchfiel, 1989; Tatsumi and Eggins, 1995; Hacker et al., 2003; Carminati et al.,

2004; Ernst, 2005). In this article we only discuss the most striking asymmetries among subduction zones and their kinematics.

Subduction zones and related orogens show significant differences as a function of their polarity. W-directed slabs are generally very steep (up to 90°) and deep, they have a cogenetic backarc basin; the related single-vergent accretionary prism has low elevation, it is mostly composed of shallow rocks, and has a frontal deep trench or foredeep (Doglioni et al., 1999). The E- or NE-directed subduction zones are less inclined (30–60°), and seismicity generally dies at about 300 km, apart some deeper clusters close to the upper-lower mantle transition (Omori et al., 2004). The related orogens have high morphological and structural elevation, wide outcrops of basement rocks, and two shallower trenches or foredeeps at the fronts of the double-vergent belt, i.e., the forebelt and the retrobelt. These differences can be ascribed to shallower upper-crustal decol-

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ments typical of W-directed subduction zones with respect to the deeper lithospheric-rooted decollements occurring along E- and NE-directed subduction zones. The asymmetry can be recognized not simply comparing W- versus E-directed subduction zones, but subductions along the sinusoidal flow of absolute plate motions that undulates from WNW in the Pacific, E-W in the Atlantic and NE to NNE from eastern Africa, the Indian Ocean, and the Himalayas. In the hotspot reference frame a “westward” rotation of the lithosphere can be observed (Gripp and Gordon, 2002). The origin of this net rotation of the lithosphere (Bostrom, 1971) is still under debate (Scoppola et al., 2006), but it amounts to about 4.9 cm/yr at his equator (Gripp and Gordon, 2002). This implies that the plate motion flow is significantly polarized toward the “west”, i.e., following or opposing the “eastward” relative mantle flow (Doglioni et al., 1999).

Regional foreland monoclines also show a signature such as steep dip and fast subsidence rates for W-directed subduction zones, and shallow dip and slow subsidence rates for E- or NE-directed subduction zones (Doglioni, 1994; Mariotti and Doglioni, 2000). This is a paradox because, along the highest mountains such as the Andes and Himalayas, we should expect the deepest trenches and foredeeps, but we rather observe these features along the opposite subduction zones where there is not a significant lithostatic load, like the Marianas trench, the Apennines, and Carpathians foredeep. The relative “eastward” mantle flow could favor the bending of the slab and the superficial subsidence along the hinge of W-directed subduction zones. The mantle counterflow rather should contrast to the subsidence along the opposite subduction zones, providing a force sustaining the slab (Doglioni, 1994). Although W-directed subduction-related prisms have low-grade metamorphism, the E or NE subduction-related orogens at the collisional stage may exhibit UHP rocks (Doglioni et al., 1999). Metallogenesis also appears to be controlled by subduction style (Mitchell and Garson, 1981). The Mariana type subduction is characterized by Kuroko or similar volcanogenic sulfide deposits (Nishiwaki and Uyeda, 1983). Porphyry copper deposits are instead concentrated in collisional settings and Andean-type subduction zones.

Within the two opposite end-members, a number of different settings can occur. For example along the E- or NE-directed subduction zones, oceanic slabs underlie continental lithosphere such 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 also are variable compositions of the lower plate (both oceanic and continental lithosphere, e.g., Marianas and Apennines, Banda arc) and variable depth of the basal decollement plane, resulting in variations in the volume of the related accretionary prism (e.g., Bigi et al., 2003; Lenci et al., 2004).

Royden and Burchfiel (1989) have proposed that the opposite tectonic style between Alps and Apennines can be obtained by kinematic scenarios in which the slab retreat is slower or faster than the convergence rate. Finite element models have confirmed this relation (Waschbusch and Beaumont, 1996). However, these differences appear to be more sensitive to the geographic direction of the subduction (Doglioni et al., 1999). Based on the two end-member subduction zones, i.e., W- versus E- or NE-directed slabs, the first-order kinematics of the opposite subduction zones are briefly outlined. In this paper, we discuss the relation between convergence rate and subduction rate, which are different as a function of the subduction polarity, and the crucial behavior of the subduction hinge that can migrate away or toward the upper plate (Heuret and Lallemand 2005; Lallemand et al., 2005).

### Basic Kinematics of Subduction Zones

Considering a fixed plate in the hanging wall of a subduction zone (U), and the subduction hinge (H) that is a point migrating over the downgoing lithosphere, we can observe an opposite behavior along convergent margins (Fig. 1). Let us assume a fixed point in the lower plate (L). The resulting subduction rate (S) can be calculated from the following simple relation,  $S = HL + UL$ , where HL and UL are the rates of relative motions, respectively, between H and L, and U and L. In this frame,  $HL = UH - UL$ . Movements diverging relative to the upper plate are assumed as positive, and converging negative.

As evident from Figure 1, the subduction hinge H can migrate away from point U (upper panel a), or toward it (lower panel b). In the first case, the UH is negative, whereas it is positive in the second case. In other words, the subduction hinge can either diverge from the upper plate, or approach it. This bipolar behavior is generally observable when comparing W-directed subduction zones versus E- or NE-directed subduction zones.

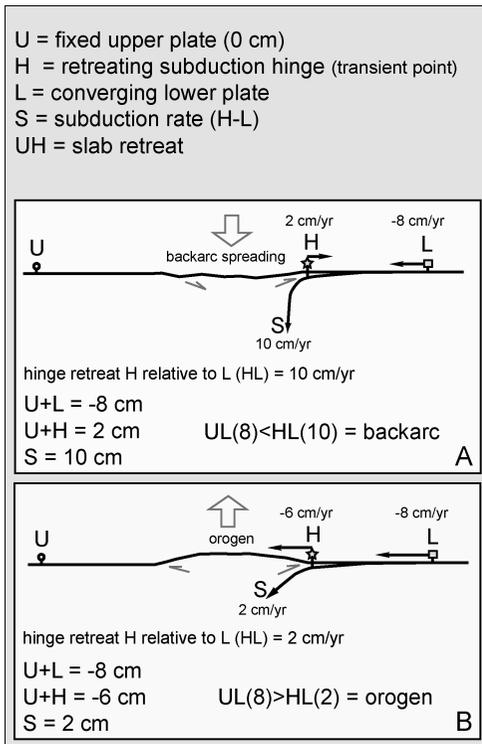


FIG. 1. Basic kinematics of subduction zones, assuming a fixed upper plate U. Movements diverging relative to the upper plate are positive, whereas they are negative when converging. A. The trench diverges from the upper plate, and the subduction rate is faster than the convergence rate. In this case, the backarc extension increases the convergence rate. B. The trench converges 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.

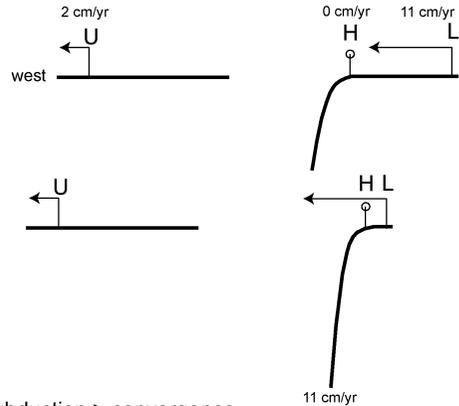
Assuming a fixed convergence rate of 8 cm/yr in both cases, in case the subduction hinge migrates away from the upper plate at a rate of 2 cm/yr (A), the subduction rate will increase the convergence rate by the amount of slab retreat, i.e., the hinge migration, resulting in 10 cm/yr. If the subduction hinge migrates toward the upper hangingwall plate at -6 cm/yr because part of the convergence is absorbed by the shortening in the orogen (B), the resulting subduction rate will be smaller, i.e., only 2 cm/yr.

The two opposite settings are characterized respectively by a much smaller, single-vergent accretionary prism, and the occurrence of a backarc basin (A), whereas in the opposite case there forms a double-vergent elevated orogen (B). This differ-

Plate motions relative to the mantle

L = lower plate  
 H = subduction hinge  
 U = upper plate

Convergence 9 cm/yr  
 Shortening in the prism 11 cm/yr  
 Subduction 11 cm/yr  
 Backarc spreading 2 cm/yr



Subduction > convergence  
 Hinge fixed with the mantle  
 Hinge diverging east relative to upper plate

FIG. 2. Absolute plate motions of a W-directed subduction zone. The slab is anchored in 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 eastward relative to the upper plate.

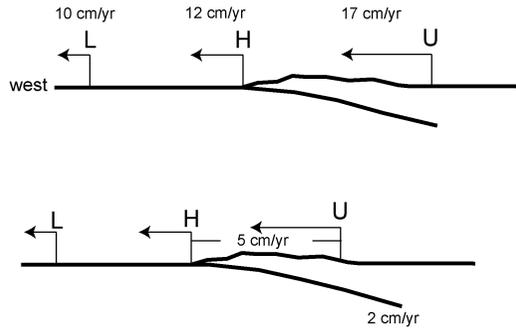
ence in kinematics can be applied to a comparison of the Apennines and Alps (Carminati et al., 2004), or to the western versus eastern Pacific subduction zones. Therefore, behavior of the subduction hinge that can decrease or increase the subduction rate is crucial. This shows that the rate of subduction is not equal to the rate of convergence unless the subduction hinge is fixed relative to the upper plate.

Let us assume another frame of reference for subduction zones—e.g., not relative to the upper plate, but with respect to the mantle. In the example of a W-directed subduction (Fig. 2), the upper plate U moves westward 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 plate L moves westward at a speed of 11 cm/yr and the convergence rate between upper and lower plates 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 resulting subduction rate is

## Plate motions relative to the mantle

L = lower plate  
 H = subduction hinge  
 U = upper plate

Convergence 7 cm/yr  
 Shortening in the orogen 5 cm/yr  
 Subduction 2 cm/yr



Subduction < convergence  
 Hinge retreating west relative to mantle  
 Hinge converging east relative to upper plate

FIG. 3. Absolute plate motions, e.g., relative to the mantle, show the same relationships as in the previous figure. The case of E- or NE-directed subduction exhibits 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 greater 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.

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 eastward relative to the upper plate. An example can be the Tonga subduction zone (Bevis et al., 1995), where in the northern segment the convergence rate between upper and lower plate is about 8 cm/yr, the backarc spreading and the hinge migration amount 16 cm/yr, and the convergence plus hinge retreat that is the subduction rate should be 24 cm/yr; this is the velocity of the volcanic arc close to the subduction hinge and migrating relative to a fixed Pacific plate (Bevis et al., 1995).

In the opposite model of an E- or 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 eastward. The subduction hinge H shifts westward at 12 cm/yr, and the upper plate U also moves westward 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. In this case the convergence rate is partitioned between the superficial shortening and the subduction rate. It is worth noting that the subduction rate is smaller than the convergence rate. The subduction hinge retreats westward relative to the mantle, while it converges eastward relative to the upper plate. From this comparison it is evident that at a given convergence rate, W-directed subduction zones in general transfer larger lithospheric volumes into the mantle with respect to the opposed E- or NE-directed subduction zones. Heuret and Lallemand (2005) made an accurate worldwide analysis of the migration of the subduction hinge, showing in 92% cases a motion in the range of  $\pm 50$  mm/yr.

### Convergence versus Shortening and Subduction Rates

As discussed above, the convergence rate can differ with respect to the subduction rate, and the

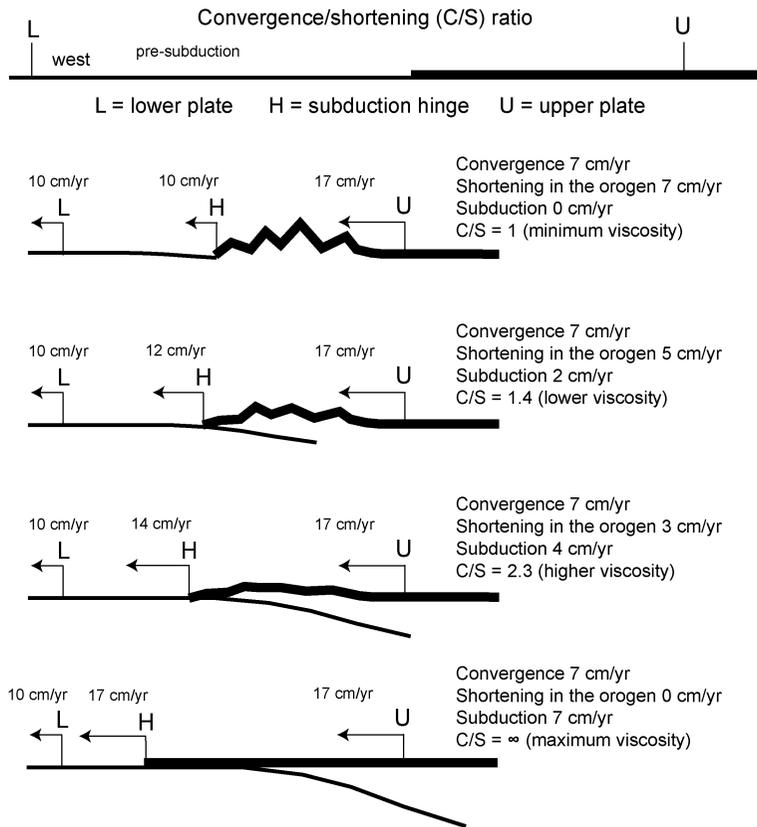


FIG. 4. Four hypothetical cases of oceanic subduction, where the shortening is confined to the continental upper lithosphere and varies as a function of mantle viscosity. The greater the shortening, the smaller the subduction rate, and the lower the viscosity (upper case). The convergence/shortening ratio can vary from 1 to  $\infty$ .

shortening rate in the orogen. We can analyze the relation between convergence and shortening. Their ratio is clearly 1 if they coincide.

Along W-directed subduction zones, the convergence/shortening ratio tends to be smaller than 1 because the convergence rate is slower than the subduction rate when the subduction hinge migrates eastward relative to the upper plate, incrementing the subduction rate, but not the upper-lower plate convergence. The related accretionary prism peels off the downgoing lithosphere, generating a shortening equal to the subduction amount.

The convergence rate is generally faster than the shortening rate, particularly along E- or NE-directed oceanic subduction zones, and their ratio has to be greater than 1. In this setting, the higher the viscosity of the continental upper plate, the lower will be the shortening in the orogen; the sub-

duction 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 (Fig. 4). A screening of the convergence/shortening ratio could therefore be an indirect way to infer the upper plate viscosity in the different orogens. For example, in the central Andes, the convergence is 73 mm/yr, whereas the shortening is about 40 mm/yr (Liu et al., 2000). Consequently, the convergence/shortening (C/S) ratio is about 1.8, and the subduction rate should be 33 mm/yr. Computing the stress balance, the viscosity of the upper plate continental lithosphere in the Andes has been inferred as low as  $3 \times 10^{21}$  Pa s (Husson and Ricard, 2004). The viscosity of oceanic lithosphere tends to be generally larger, and it decreases with depth. For example, an oceanic

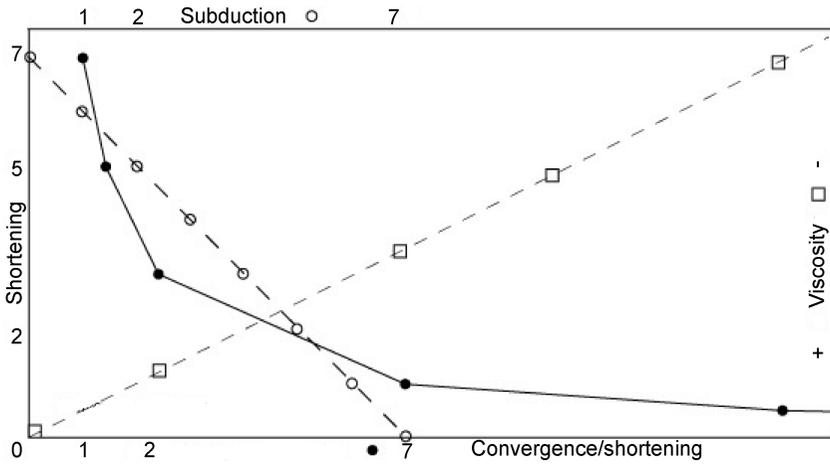


FIG. 5. Diagram depicting the relations between shortening rate, convergence/shortening ratio, subduction rate, and viscosity of the upper plate along an E- or NE-directed subduction zone, at a convergence rate of 7 cm/yr.

lithosphere at 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 the upper plate made by softer continental lithosphere absorbs most of the deformation. The higher the convergence/shortening ratio (C/S), the higher the viscosity of the upper plate (Fig. 5). The minimum value of this ratio for E- or NE-directed subduction zones should be 1, where the amount of convergence equals the amount of shortening in the belt, indicating very low viscosity, and virtually no subduction. Subduction is inversely proportional to the amount of shortening, and the convergence/shortening ratio increases exponentially with the decrease of shortening, and the increase of the subduction rate (Fig. 5). An attempt to compute the C/S along the Andes using REVEL (Sella et al., 2002) is shown as Figure 6, where it is decreasing, moving southward. This signifies that the northern lithosphere of the Andes has a slightly higher viscosity. During collision, convergence rate slows down, and the shortening is propagating more pervasively into the lower plate. Therefore the C/S decreases during the final stages of the orogenic life.

Therefore, along the western Pacific subduction zones, and the W-directed subduction zones in general, such as the Apennines and Barbados, the subduction rate is faster than the convergence rate inasmuch as it is augmented by hinge retreat and the related backarc extension. Paradoxically, once

subduction is activated, the slab can continue to sink even with no convergence, or even with extension between upper and lower plate; examples could be the Apennines, the Carpathians, and the Banda arc. For example, the Barbados subduction hinge retreats about 2 cm/yr (Weber et al., 2001), in spite of no apparently active convergence. A kinematic model of active subduction without convergence is shown in Figure 7, where the shortening is determined not by an actively thrusting upper plate, but by the eastward-moving mantle, peeling off the superficial layers of the downgoing lower plate (Doglioni et al., 2004). On the other hand, in the eastern Pacific subduction zones, and in the E- or NE-directed subduction zones such as the Alps or Himalayas, the subduction rate is lower than the convergence rate, but subduction does not occur without convergence.

Along both W- and E-/NE-directed subduction zones, the hinge migrates eastward relative to the upper plate, apart from a few exceptions like Japan. Therefore, most frequently 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- or NE-directed subduction zones. In this interpretation, the far-field velocities of the upper and lower plates control the subduction rate, and subduction is a passive process. In fact, rates of subduction do not determine plate velocities, but are rather a consequence of them.

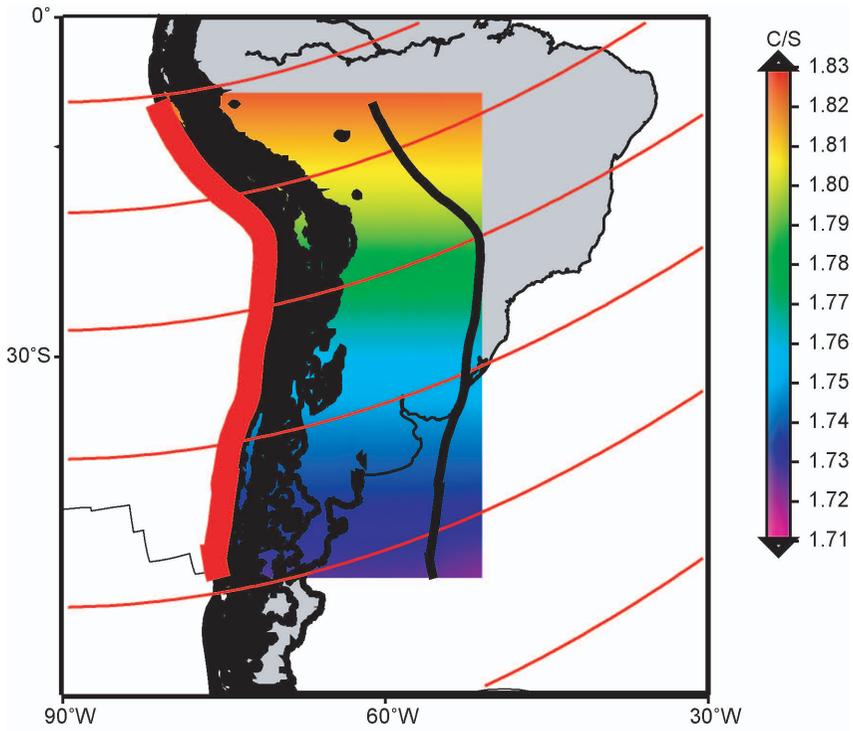


FIG. 6. Convergence/shortening ratio along the Andes. The black line is assumed as a fixed reference in the stable upper plate, and the red line as the subduction hinge that is relatively converging, but more slowly than the Nazca-South America convergence rate. Thin red lines are circles of the pole of the Nazca-South America motion. The higher the  $C/S$ , the higher the viscosity of the South American lithosphere.

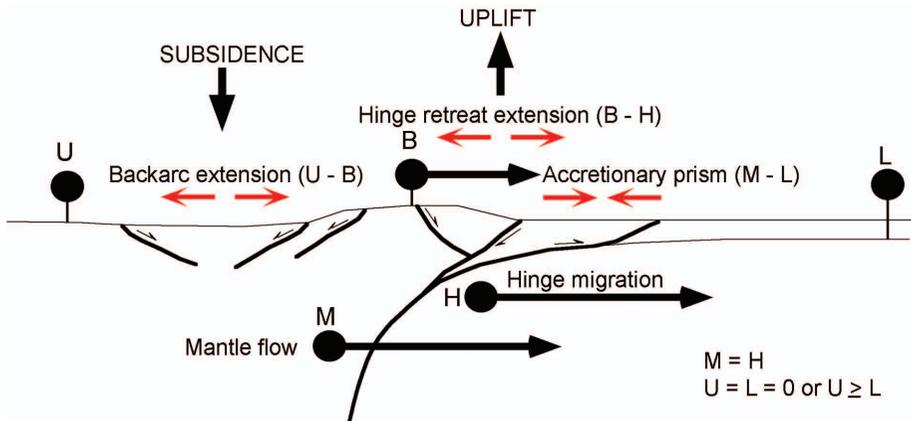


FIG. 7. Kinematic model of a W-directed subduction where the system can be active even without convergence. Relative motions are shown in red. Shortening in the accretionary prism occurs because the mantle  $M$  moves eastward relative to  $U$ , peeling off the shallow layers of the lower plate. Abbreviations:  $U$  = upper plate;  $B$  = belt;  $L$  = lower plate. Modified after Doglioni et al. (2004).

### W- versus E-/NE-Directed Subduction and Orogens

The shortening in prisms of W-dipping subductions can be larger than the convergence rate, whereas it is in general smaller than the convergence in orogens of E- or NE-related subductions. This occurs because along W-directed slabs the shortening is confined to the lower plate and directly equivalent to the amount of subduction, which is larger than the convergence rate. In the E- or NE-directed slabs, the shortening is smaller than the convergence because the convergence is partitioned partly in the subduction rate, and partly in the contraction of the upper plate. While W-subduction-related prisms have a forebelt and a backarc basin, E-NE-subduction-related orogens have a forebelt and a widely developed retrobelt dating from the very early stages.

The opposite kinematics between the opposite subduction zones can be explained by the westward drift of the lithosphere detected in the hotspot reference frame (Gripp and Gordon, 2002), generating different geodynamic settings as a function of the polarity of the subduction (Doglioni, 1993). The net "westward" rotation of the lithosphere provides two main tectonic consequences: (1) the mantle is relatively shifting "eastward" along a sinusoidal flow; and (2) the decollement planes at the base and within the lithosphere are polarized toward the "west" (Doglioni et al., 1999). The result of this asymmetry is that along W-directed subduction zones, only the shallow rocks on the subduction hinge are accreted because the accretionary prism basal decollement is traveling at the top of the subduction, without an actively thrusting upper plate. In the opposite E- or NE-directed subduction hinge, the lithosphere basal decollement is ramping upwards, providing a mechanism to uplift deep-seated rocks (Doglioni, 1992).

As a consequence, the shortening is concentrated in the shallow layers of the lower plate along W-directed subduction zones, both during the oceanic and the continental stages of subduction (Fig. 8), providing small volumes to the orogen and maintaining a low elevation of the critical taper (e.g., Bigi et al, 2003; Lenci et al., 2004).

In contrast, shortening is mostly concentrated in the upper continental lithosphere in E- or NE-directed oceanic subduction zones (Fig. 9). Andean-type trenches are in fact often characterized by tectonic erosion (e.g., von Huene and Lallemand,

1990; Ranero and von Huene, 2000), rather than accretion. However, accretion is documented along the Cascadia, Indonesia, and several other segments of this type of subduction zone (e.g., Hyndman et al., 1993), thus providing a transfer of shallow rocks from the lower to the upper plate. However, it is only at a collisional stage that the lower plate is eventually entirely involved and shortened. During this final stage, the lower plate contributes significantly to the volume increase of the orogen because shear zones and decollement planes enter much deeper into the continental crust of the footwall plate (Fig. 9).

A number of exceptions occur to these two end members. For example, Japan has low elevation and other characteristics of W-directed subduction zones, such as the backarc basin and an accretionary prism mostly composed of shallow rocks (von Huene, 1986). However, the slab has low dip of the subduction plane (Jarrard, 1986) and there is no active hanging wall extension, despite an onshore morphology suggesting widely distributed structural depressions. GPS data confirm that the Japan Sea backarc is not opening anymore, but rather is closing (Mazzotti et al., 2001). This indicates that the system possibly has arrived at an end, and its inversion started. Unlike other living W-directed subduction zones, the slab hinge is moving toward the upper plate (Fig. 10).

W-directed subduction zones on Earth appear to be short lived. If the Marianas or Japan subductions were active since the Cretaceous with a steady-state eastward hinge retreat, they should be now in the middle of the Pacific. Backarc spreading in the hanging wall of W-directed subduction zones are mostly Cenozoic, pointing out that the related subduction should have a similar age. Backarc basins probably arrive to a critical opening stage, and then they become closed, until a new subduction starts. The non-standard Japan subduction in fact shows scattered intermediate deep seismicity, unlike what typically occurs along similar slabs (e.g., Omori et al., 2004).

Another apparent discrepancy to the W versus E/NE asymmetry is the occurrence of backarc basins also in the hanging wall of E- or NE-directed subduction zones. However, these types of rifts rarely arrive to oceanic spreading, as W-directed subduction do in their hanging wall. Moreover, they may be post-subduction (e.g., Basin and Range; Doglioni, 1995), or accommodating differential advancement of the upper plate over the lower plate (Fig. 11). Examples are the Aegean and the Andaman

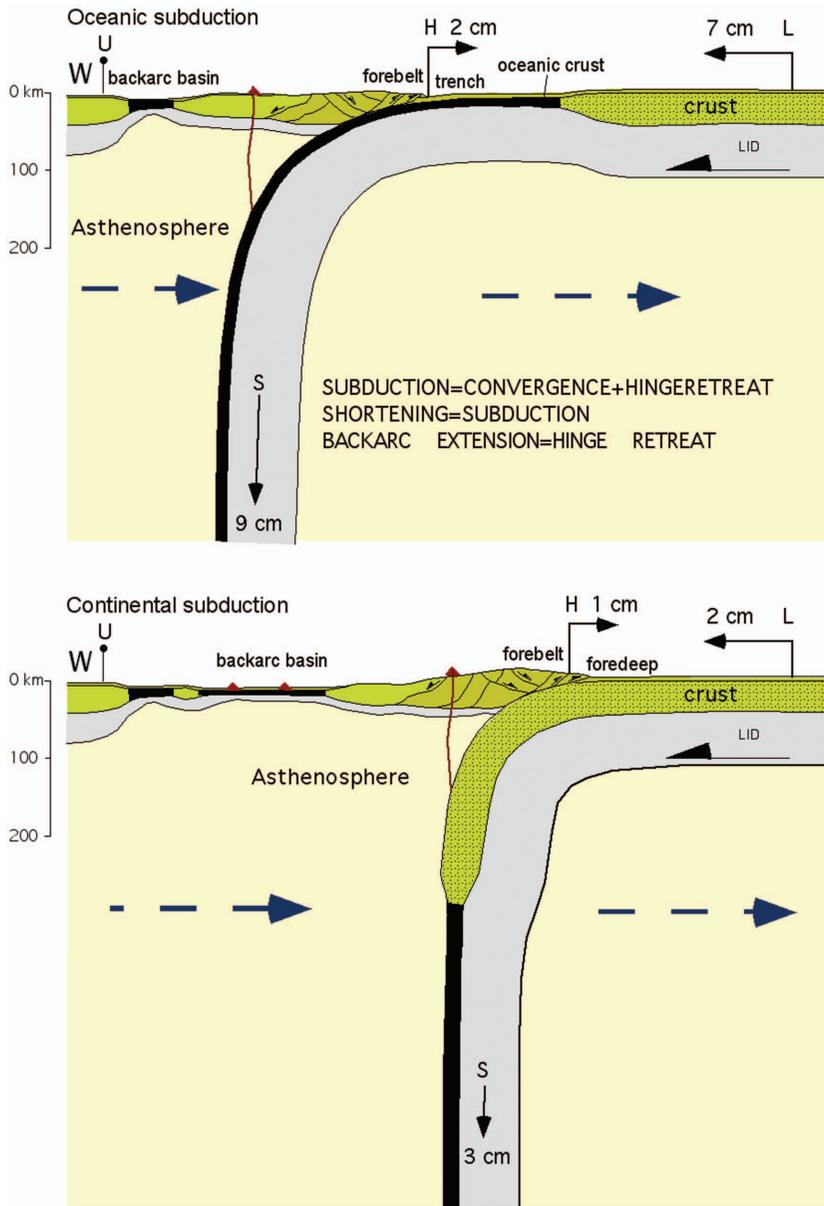


FIG. 8. W-directed subduction zones have in general the subduction hinge migrating away from the upper plate U, here considered fixed. The retreat of the slab hinge allows extension in the hanging wall and the opening of a backarc basin. The accretionary prism is mainly composed of shallow rocks offscraped from the top of the downgoing lower plate, apart from basement slices of inherited orogens to the west. The sum of convergence and hinge retreat determines the subduction rate. The arrival of continental lithosphere (green) at the trench slows down the subduction, but the continental lithosphere can subduct at least to 150–200 km. The involvement of the continental crust allows a deeper decollement depth of the accretionary prism, generating a thicker belt. This setting might remain active even when the convergence rate is null. In this case, the subduction rate will be the same as the hinge retreat.

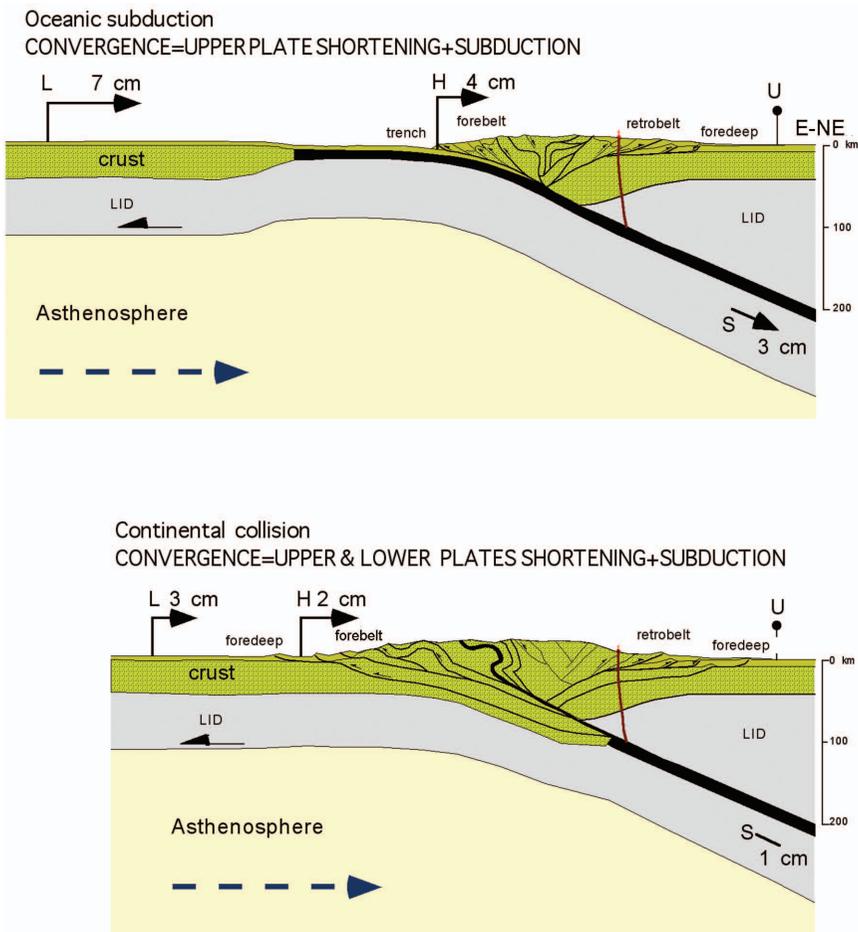


FIG. 9. E- or NE-directed subduction zones have typically faster convergence rates when oceanic lithosphere (black) is subducting. During oceanic subduction (upper panel), the convergence is partitioned both in the upper plate shortening and in the subduction rate. The subduction hinge H moves toward the relatively fixed upper plate, and its velocity represents the upper-plate shortening. The orogen in the upper plate is double vergent, and no backarc basin forms. At the collisional stage (lower panel), the lower plate is also extensively shortened, and the western deformation border (H) is shifted westward. The convergence rate is partitioned between upper and lower plate shortening, and the subduction rate.

rifts. The extension in western Turkey, Aegean Sea, Greece, and Bulgaria can be interpreted as a result of the differential convergence rates between the NE-directed subduction of Africa relative to the hanging wall—disrupted Eurasian lithosphere (Doglioni et al., 2002). Considering fixed Africa, the faster southwestward motion of Greece relative to Cyprus-Anatolia determines the Aegean extension. The differences in velocity can be ascribed to differential decoupling with the asthenosphere. Unlike west Pacific backarc basins where the asthenosphere replaced a subducting and retreating slab,

the Aegean rift represents a different type of extension associated with a subduction zone, where the hanging wall plate overrode the slab at different velocities, implying internal deformation. While W-directed subductions occur with the rollback of the lower plate relative to the upper plate, the Aegean setting needs three plates—i.e., a common lower plate, and two plates overriding at different velocities. Analogously, assuming only few mm/yr of relative motion between the Indian and Australian plates (e.g., Bird, 2003), along the Himalayas collision, the Indo-Australian plates converge relative to

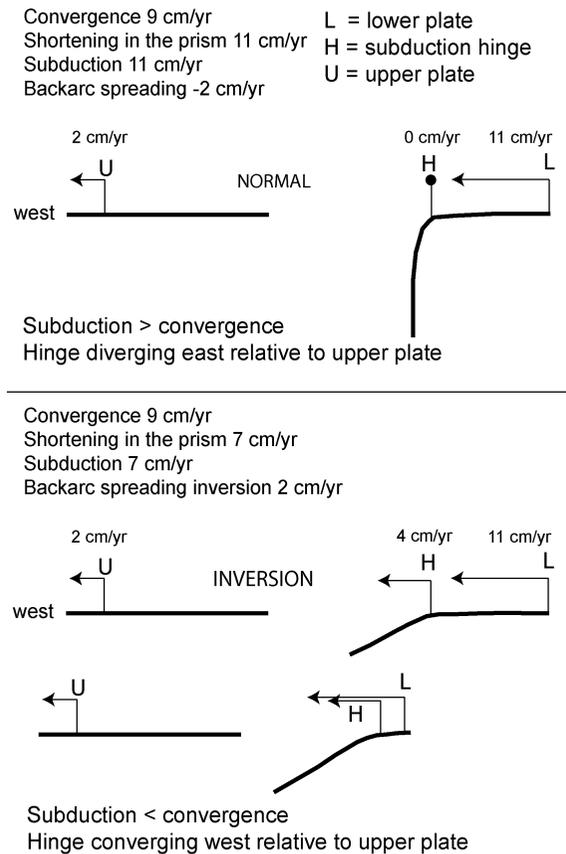


FIG. 10. A W-directed subduction zone is generally short lived (30–50 m.y.). In the normal state (upper panel), the backarc is opening. When the backarc stop widening, the subduction hinge moves back, inverting the basin (lower panel). The westward motion of the subduction hinge diminishes the subduction rate, and possibly its slab dip. This could be the present kinematics of the Japan subduction zone. Velocities are relative to the mantle.

Asia at about 36 mm/yr, while the same Indo-Australian plates along their oceanic northern part are overridden by the Sumatra-Burma plate at around 64 mm/yr (Sella et al., 2002). Therefore, assuming a relatively coherent lower plate, the hanging wall plates move SSW-ward at different velocity, this gradient being responsible for the extension between Asia and Sumatra-Burma, and generating the Andaman rift. In this type of geodynamic setting, the subduction hinge still moves toward the upper plate, as in the normal E- or NE-directed subduction zones.

### Upper Mantle Circulation

Along oceanic ridges, melting produces a residual depleted asthenosphere that is also more viscous

than the undepleted one. Braun et al. (2000) have shown that water extraction during melting determines higher viscosities up to 2 orders of magnitude in the residual mantle. The mantle, once depleted during the transit beneath the ridge, should be cooler, less dense, and more viscous. The most shallow, depleted asthenosphere will eventually become lithospheric mantle with the progressive cooling, shifting away from the ridge. In this view, moving horizontally within the asthenosphere, the viscosity could be due more to lateral compositional variations than to temperature gradients.

The Pacific plate is the fastest “westward”-moving plate and it has the lowest viscosity of the underlying asthenosphere (Pollitz et al., 1998). Therefore there seems to be a positive correlation between asthenospheric viscosity and plate velocities.

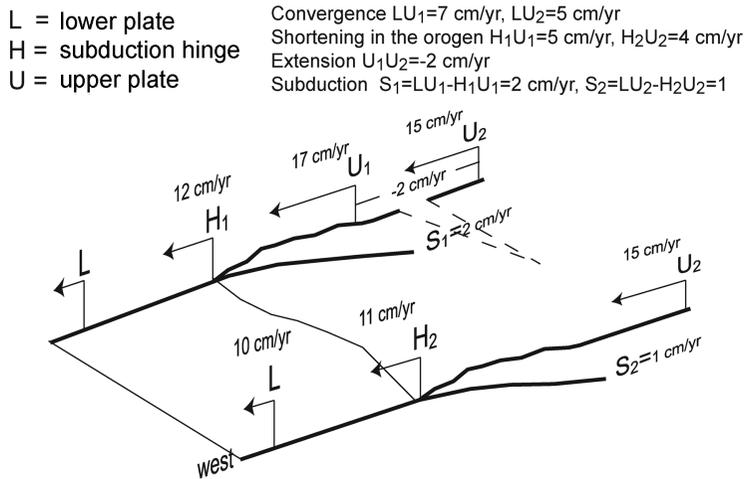


FIG. 11. Along E- or NE-directed subduction zones, the upper plate can have variable convergence rates with respect to the lower plate, being divided into two subplates ( $U_1$  and  $U_2$ ), and variable hinge velocity ( $H_1$  and  $H_2$ ). Extension can occur in the hanging wall for these velocity gradients. Examples could be the Aegean Sea or the Andaman Sea.

The question of hotspot source depth, i.e., shallow versus deep mantle, is under debate (Foulger et al., 2005). In the event that they are shallow, all plates move “westward” relative to the hotspot reference frame because the net rotation rises to about 9 cm/yr (Doglioni et al., 2005). Plate-variable velocities appear to be controlled by the lithosphere-asthenosphere decoupling, which is a function of asthenospheric viscosity. Subduction zones and oceanic ridges contribute to upper mantle convection. The W-directed subductions clearly reach the lower boundary of the upper mantle. The E- or NE-directed subduction zones are rather shallower and less inclined. Most of their seismicity terminates in the asthenosphere, except for a few deep earthquakes at the upper-lower mantle transition. Most of the Earth’s subduction-related magmatism is sourced from a top slab depth range of 65–130 km (England et al., 2004). As shown in the previous section, the Andean subduction rate should be slower than the convergence rate. Moreover, the slab along some segments of the Andes becomes almost flat, indicating the insertion of the plate into the asthenosphere. At that depth, the slab shares the pressure and temperature that allow partial melting of the asthenosphere. Therefore the oceanic lithosphere might re-enter the source mantle, becoming ductile, and gradually melting, refertilizing the mantle that generated it (Fig. 12). Note that in the mantle reference frame, assuming shallow hotspots

and the faster westward drift of the lithosphere, the Nazca plate is coming out of the mantle, but subduction occurs because the South America plate moves westward faster than Nazca.

W-directed subduction zones are penetrating and geochemically modifying the lower upper mantle. E- or NE-directed subduction zones are more suitable for regenerating the shallow upper mantle that is the most favorable candidate for sourcing MORB along mid-oceanic ridges (e.g., Bonatti et al., 2003).

### Discussion and Concluding Remarks

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-inclined subduction), or toward (E-NE-dipping subduction) the upper plate, apart from a few exceptions. The kinematics described above suggest that subduction zones are passive features relative to far-field plate velocities, inasmuch as subduction rates can be even smaller than relative plate motions along E- or NE-directed subduction zones. The convergence/shortening ratio is regularly smaller than 1 in W-directed subduction zones. Because the shortening is concentrated in the accretionary prism consisting of the shallow crust of the

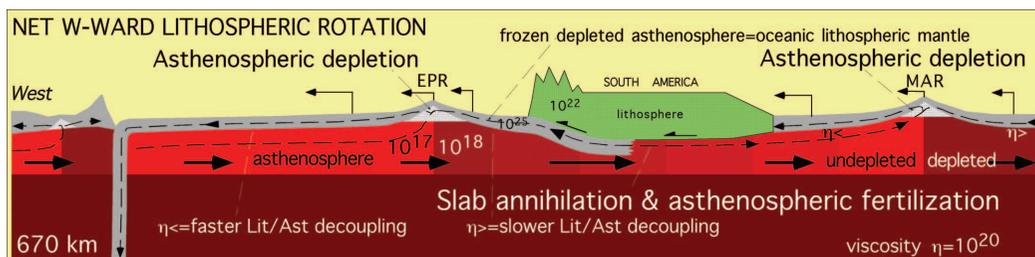


FIG. 12. Model for the upper mantle cycle. The lower the asthenospheric viscosity, the faster the westward displacement of the overlying plate. The asthenospheric depletion at oceanic ridges makes the layer more viscous and decreases the lithosphere/asthenospheric decoupling, and the plate on the east is then slower. The oceanic lithosphere subducting eastward enters the asthenosphere, where it is molten again, to refertilize the asthenosphere. W-directed subductions provide deeper circulation. Note that the E-directed subduction (the Andes) tends to escape from the mantle, but it is overridden by the upper plate (South America).

lower plate (Fig. 8), and the shortening equals the subduction, the convergence/shortening ratio is opposed and smaller with respect to the E-NE-directed subduction zones.

The convergence/shortening ratio is regularly higher than 1 in E- and NE-directed subduction zones (Fig. 4). This value is sensitive to the viscosity of the upper continental lithosphere. Higher ratios mean higher viscosities of the lithosphere, i.e., it is stiffer and sustains the convergence, while most of the convergence is absorbed by subduction (Fig. 5). Lower ratios indicate larger values of upper-plate shortening, faster motions of the subduction hinge toward the upper plate, and lower subduction rates. During the earlier oceanic subduction, the related orogen is composed of upper-plate doubly-vergent shortening, whereas only at the collisional stage does the lower plate more widely contribute to the orogenic growth (Fig. 9). The few exceptions can be explained either by inversion and closure of an earlier W-directed subduction-related backarc basin, as in Japan (Fig. 10), or upper-plate variable W- or SW-ward velocity generating a sort of backarc basin in the hanging wall of E- or NE-directed subduction zones, as in the New-Hebrides, Hellenic, and Western Indonesia subduction zones (Fig. 11).

W-directed subduction zones provide larger volumes of lithospheric return to the mantle than the opposite subduction zones that may instead refertilize the shallow upper mantle (Fig. 12). The “westward” drift of the lithosphere seems to be the most favorable mechanism for the aforementioned tuning. Moreover, the observation that the convergence differs both negatively and positively from shortening supports the notion that plate boundaries (subduc-

tion and related orogen) are passive features, and do not provide the first-order driving energy of plate motions.

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