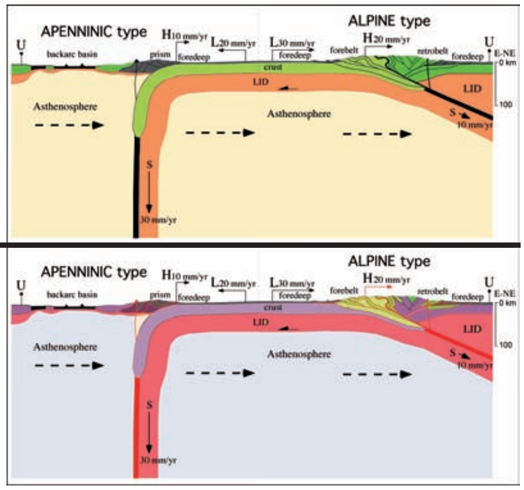
7. Geodynamic framework of subduction zones



The kinematics of subduction zones shows a variety of settings that can provide clues for dynamic understandings. Two reference frames are used here to describe simple 2D kinematics of subduction zones (fig. 144). In the first, the upper plate is assumed fixed, whereas in the second frame upper and lower plates move relative to the mantle.
Relative to a fixed point in the upper plate U, the transient subduction hinge H can converge, diverge, or be stationary. Similarly, the lower plate L can converge, diverge or be stationary. The subduction rate VS is given by the velocity of the hinge VH minus the velocity of the lower plate VL (VS=VH-VL). The subduction rate 1) increases when H diverges, and 2) decreases when H converges.
Combining the different movements, at least 14 kinematic settings can be distinguished along the subduction zones. Variable settings can coexist even along a single subduction zone, as for the 5 different cases occurring along the Apennines subduction zone (DOGLIONI *et alii*, 2007). Apart from few exceptions, the subduction hinge converges toward the upper plate more frequently along E- or NE-directed subduction zone, whereas mainly diverges from the upper plate along W-directed subduction zones accompanying backarc extension.
Before collision, orogen growth occurs mostly at the expenses of the upper plate shortening along E- NE-directed subduction zones, whereas the accretionary prism of W-directed subduction zones increases at the expenses of the shallow layers of the lower plate.
Backarc spreading forms in two settings: along the W-directed subduction zones it is determined by the hinge divergence relative to the upper plate, minus the volume of the accretionary prism, or, in case of scarce or no accretion, minus the volume of the asthenospheric intrusion at the subduction hinge. Since the volume of the accretionary prism is proportional to the depth of the decollement plane, the backarc rifting is inversely proportional to the depth of the decollement. On the other hand, along E- or NE-directed subduction zones, few backarc basins form (e.g., Aegean, Andaman) and can be explained by the velocity gradient within the hangingwall lithosphere, separated into two plates.
When referring to the mantle, the kinematics of subduction zones can be computed either in

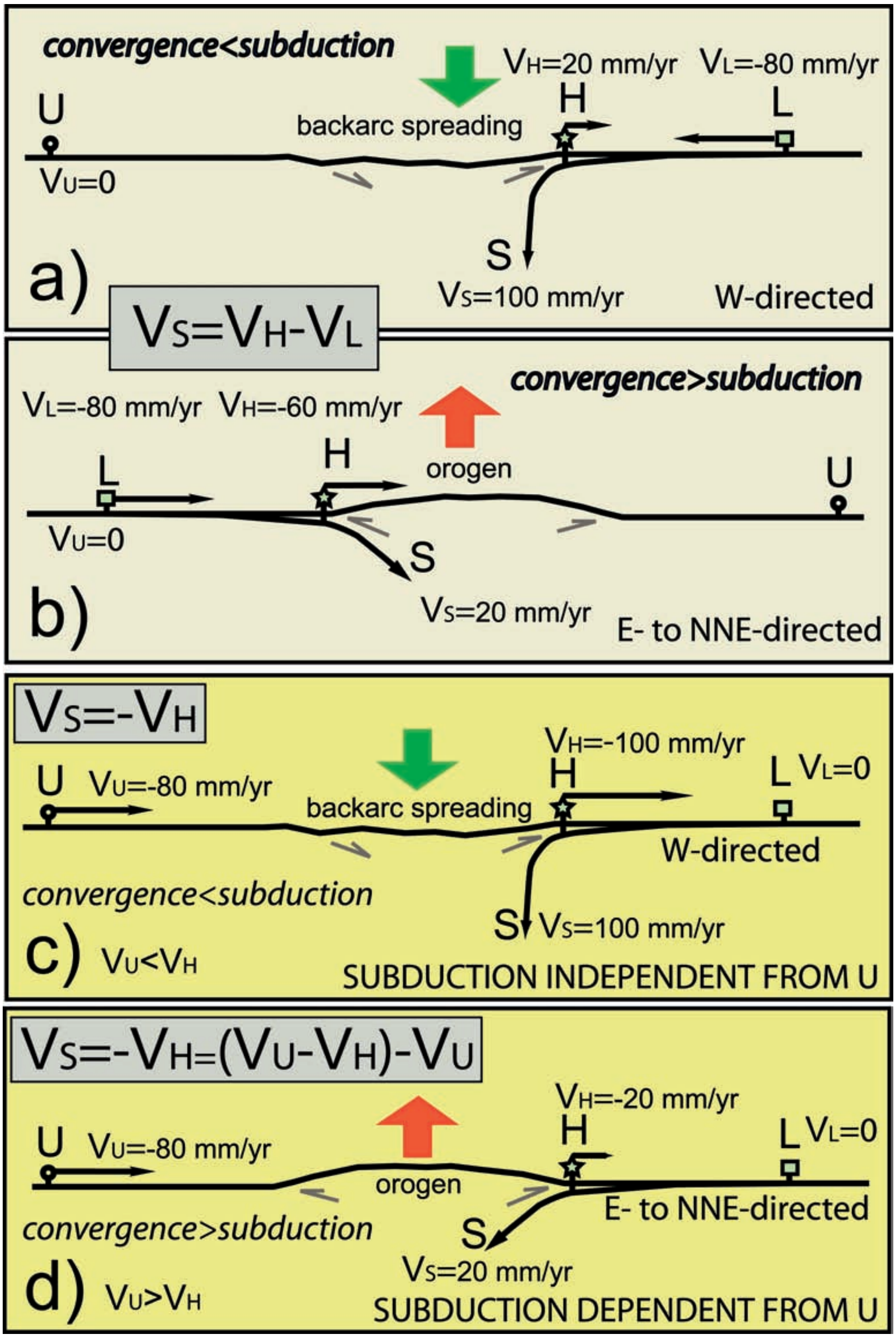


Fig. 144 - Upper panels a) and b): Basic kinematics of subduction zones, assuming a fixed upper plate U, a converging lower plate L, and a transient subduction hinge, H. The subduction rate S is given by $V_S=V_H-V_L$. Values are only as an example. S increases when H diverges relative to the upper plate (a), whereas S decreases if H converges (b). The movements diverging from the upper plate are positive, whereas they are negative when converging. The case a) is accompanied by backarc spreading, a low prism and is typical of W-directed subduction zones, whereas in case b) double verging and elevated orogens form and is more frequent along E- to NNE-directed subduction zones. Note that in both W- and E- NE-directed subduction zones, the hinge migrates eastward relative to the upper plate, suggesting a global tuning in subduction processes. Lower panels c) and d): kinematics of subduction zones assuming fixed the lower plate. Note that the velocity of the hinge equals the velocity of the subduction in both cases. In case c) the subduction is independent from the upper plate velocity, whereas in case d) is a function of it. These opposite kinematic settings indicate different dynamic origin of the subduction, i.e., slab/mantle interaction for c), and upper/lower plates interaction for case d).

the deep or in the shallow hotspot reference frames. The subduction hinge is mostly stationary being the slab anchored to the mantle along W-directed subduction zones, whereas it moves W- or SW-ward along E- or NE-directed subduction zones. Surprisingly, along E- or NE-directed subduction zones, the slab moves "out" of the mantle, i.e., the slab slips relative to the mantle opposite to the subduction direction. Kinematically, this subduction occurs because the upper plate overrides the lower plate, pushing it down into the mantle. As an example, the Hellenic slab moves out relative to the mantle, i.e., SW-ward, opposite to its subduction direction, both in the deep and shallow hotspot reference frames. In the shallow hotspot reference frame, upper and lower plates move "westward" relative to the mantle along all subduction zones.

This kinematic observation casts serious doubts on the slab negative buoyancy as the primary driving mechanism of subduction and plate motions.

W-directed subduction zones rather provide about 2-3 times larger volumes of lithosphere re-entering into the mantle, and the slab is pushed down. This opposite behavior is consistent with the down-dip extension seismicity along E-NE-directed subduction zones, and the frequent down-dip compression along the W-directed subduction zones.

Subduction kinematics show that plate velocity is not dictated by the rate of subduction. Along the W-directed subduction zones, the rate of subduction is rather controlled i) by the hinge migration due to the slab interaction with the "easterly" trending horizontal mantle wind along the global tectonic mainstream, ii) by the far field plate velocities, and, iii) by the value of negative buoyancy of the slab relative to the country mantle.

Alternatively, E-NE-NNE-directed subduction zones have rates of sinking chiefly determined i) by the far field velocity of plates, and ii) by the value of negative buoyancy of the slab relative to the country mantle. Along this type of subduction, the subduction hinge generally advances E-NE-ward toward the upper plate decreasing the subduction rate, but it moves W-SW-ward relative to the mantle.

All this indicates that subduction zones have different origin as a function of their geographic polarity, and the subduction process is more a passive feature rather than being the driving mechanism of plate motions. A rotational component combined with mantle density and viscosity anisotropies seems more plausible for generating the global tuning in the asymmetry of subduction zones.

Subduction zones and related orogens show significant differences as a function of their polarity. It is referred here as polarity the direction of subduction with respect to the tectonic mainstream, which is not E-W, but undulates around the Earth. Therefore, the asymmetry can be recognized not simply comparing W-directed 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, Indian Ocean and Himalayas. In the hotspot reference frame a "westward" rotation of the lithosphere can be observed. The origin of this net rotation of the lithosphere (BOSTROM, 1971) is still under debate (SCOPPOLA *et alii*, 2006), but it should range between 4.9 cm/yr (GRIPP & GORDON, 2002) and 13.4 cm/yr (CRESPI *et alii*, 2007) at its equator. This implies that the plate motions flow is significantly polarized toward the "west" (Doglioni et al., 1999), and subduction zones follow or oppose the relative "eastward" relative mantle flow. Subduction zones following the flow are: North and South America cordilleras, Dinarides, Hellenides, Caucasus, Zagros, Makran, Himalayas, Indonesia-Sunda arc, Taiwan, New Guinea, New Hebrides, southern New Zealand. Subduction zones opposing the flow are: Barbados, Sandwich, Apennines, Carpathians, Banda, Molucca, Tonga, Kermadec, Marianas, Izu-Bonin,

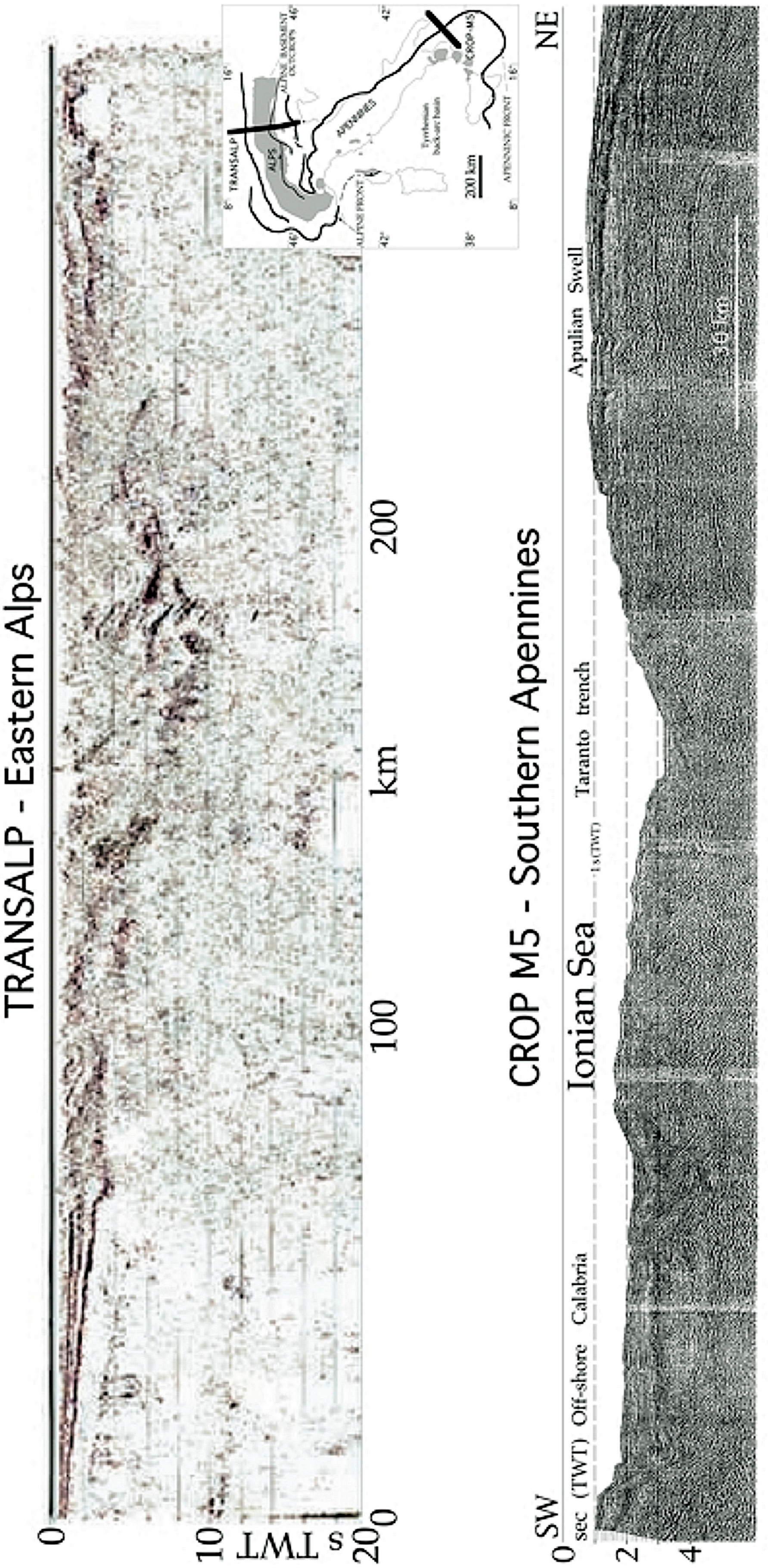


Fig. 145 - Seismic sections of the Alps (Transalp, 2002) and of the Apennines (Scrocca *et alii*, 2003).

Nankai, Philippine, Kurili, Aleutians. The Japan subduction appears as a transitional subduction zone.

Since many subduction zones have undulations or arcs along strike, their dip and strike can be oblique or parallel to the proposed tectonic mainstream. For example, in the transfer zone between Makran and Himalayas NNE-directed subduction zones, along the Chaman left-lateral transpressive system, the tectonic mainstream is about parallel to the belt. Another emblematic case is the Aleutians arc, here considered as a subduction opposing the flow (W-directed). Along their western termination, they almost parallel the Pacific subduction direction (WNW), where the slab is a right-lateral ramp of the subduction, and it dips to the NNE.

The W-directed slabs are generally very steep (up to 90°) and deep, apart few cases as Japan. They have a co-genetic backarc basin, and the related single verging accretionary prism has low elevation (e.g., Barbados, Sandwich, Nankai), is mostly composed of shallow rocks, and has a frontal deep trench or foredeep (DOGLIONI *et alii*, 1999). The E- or NE-directed subduction zones are less inclined (15-70°), and the seismicity generally dies at about 300 km, apart some deeper clusters close to the upper-lower mantle transition. The related orogens have high morphological and structural elevation (e.g., Andes, Himalayas, Alps), wide outcrops of basement rocks, and two shallower trenches or foredeeps at the fronts of the double verging belt, i.e., the forebelt and the retrobelt. The retrobelt decreases its development when the upper plate is subject to extension (e.g., Central America, Aegena and Andaman Seas).

But, even more striking, surface geology and topography of the orogens contrast dramatically with a number of differences between the opposite subduction zones such as shallow vs. deep rocks, steep vs. shallow dip of the foreland monocline, low vs. higher inclination of the topographic and structural envelop, small vs. wider area above sea-level, etc., respectively for W- vs. E- or NE-directed subduction zones (e.g., LENCI & DOGLIONI, 2007).

Moreover backarc spreading occurs mostly in W-directed subduction zones. Two counterexamples are proposed as proofs that this statement is not correct, i.e., the Aegean and the Andaman Seas, which are related to NE- to NNE-directed subduction zones. However these two cases have a different kinematics and geodynamic setting with respect to the W-directed subduction zones, where upper plate extension is concomitant to subduction hinge migrating away with respect to the upper plate, being the lithospheric deficit due to subduction, compensated by mantle replacement. Along the Aegean and Andaman rift zones the extension rather accommodates only the differential velocity within the upper lithospheric plate, which is split into two plates overriding the subduction (e.g., DOGLIONI *et alii,* 2002). Along the Andaman-Sunda-Indonesia arc for example, the flow of plates is NE- to NNE-directed. Extension or "backarc" spreading is not diffused along the entire arc, but rather concentrated at the western margin, along the transfer zone between the SW-ward faster advancing of Indonesia upper plate over the lower oceanic plate (about 60 mm/yr) with respect to the slower velocity of Eurasia upper plate in overriding the continental Indian lithosphere along the Himalayas belt (about 40 mm/yr). Where upper plate extension occurs along these settings, the retrobelt of the orogen is poorly developed and narrower. Another example seems the Central America subduction zone (e.g. Guatemala, El Salvador, Nicaragua, Costa Rica), in which the upper plate extension accommodates the faster westward motion of North America relative to South America.

DOGLIONI *et alii* (2006) rather suggested that the subduction system is primarily sensitive to the behavior of the subduction hinge, i.e., moving toward or away from the upper plate, regardless the convergence rate. The resulting subduction rate is faster than the convergence rate where the hinge migrates away from the upper plate, whereas it is slower than the convergence where the hinge converges or advances toward the upper plate. The two end members appear sensitive to the geographic polarity of the subduction zones, being the asymmetry not among E-W subduction zones, but following or opposing an undulated "westerly" directed lithospheric flow (DOGLIONI, 1993), recently validated by space geodesy and statistical analysis (CRESPI *et alii*, 2007). This tectonic mainstream implies a relative mantle undulated counterflow, "easterly" directed.

The result of the asymmetry among opposite subduction zones (figs. 145 - 147) is that along the W-directed subduction zones only the shallow rocks on the subduction hinge are accreted (sedimentary cover and slices of the topmost basement) because the accretionary prism basal decollement is located 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 for uplifting deep-seated rocks. 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, providing small volumes to the orogen and maintaining a low elevation of the critical taper. The shortening is rather mostly concentrated in the upper continental lithosphere in E- or NE-directed oceanic subduction zones. Andean type trenches are in fact often characterized by tectonic erosion, rather than accretion. It is unclear how deep is transported the material offscraped by the tectonic erosion. It could eventually be re-transferred to the upper

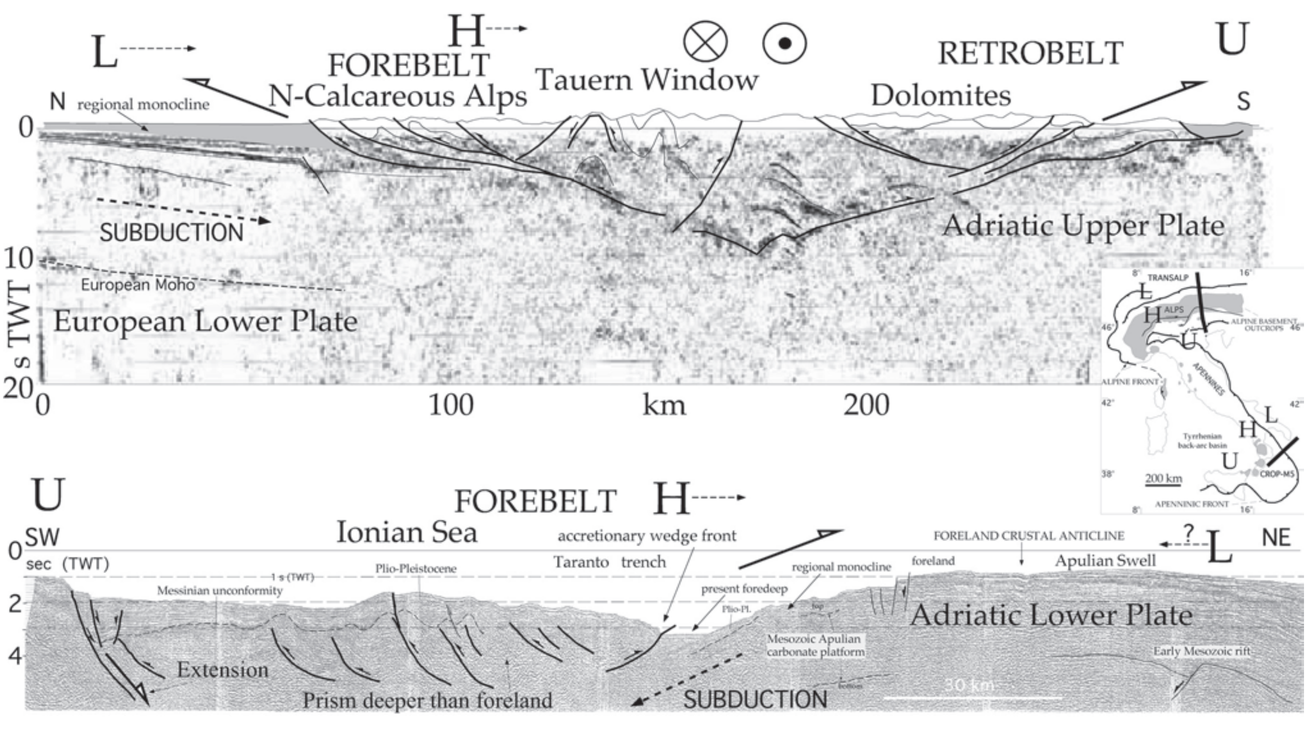


Fig. 146 - Same sections as in the previous figure with some interpretation (modified after TRANSALP, 2002; DOGLIONI *et alii*, 1999c). Note the Alpine double vergence versus the single Apennines vergence, where the prism is even deeper than the foreland and followed by extension to the left. L, lower plate, H, subduction hinge, U, upper plate. In the Alps H migrated toward the upper plate, whereas it moves toward the lower plate in the Apennines. The Adriatic plate is the upper plate U in the Alps, while it is the lower plate L in the Apennines. The E-W segment of the Alps formed under right-lateral transpression (After DOGLIONI *et alii*, 2007).

plate in the lower crust or upper mantle, and later re-exhumed during shortening progression.

However, accretion is documented along the Cascadia, Indonesia and several other segments of this type of subduction zones, thus providing a transfer of shallow rocks from the lower to the upper plate. But 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 in the continental crust of the footwall plate.

The term accretionary prism is often confused with the term forearc, which is the region between the subduction trench and the volcanic arc, having not always a unique tectonic meaning. The arc is also a misleading term used both to define a volcanic belt or a structural undulation of a thrust system. Moreover in the so-called forearc, extension can be widespread, without active accretion.

The shortening in prisms of W-directed 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 in 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 since the very early stages.

The different rock exhumation in the different subduction settings is highlighted by peculiar petrography of transported sediments (GARZANTI *et alii*, 2007). Regional foreland monoclines at the accretionary prism fronts also show steep dip and fast subsidence rates along W-directed subduction zones, and shallow dip and slow subsidence rates for E- or NE-directed subduction zones. This is a paradox because if the foredeep subsidence is generated only by the mountain load, along the highest mountains 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 foredeep fast subsidence along the hinge of W-directed subduction zones. The mantle counter flow should rather contrast the subsidence along the opposite subduction zones, providing a force sustaining the slab. While W-directed subduction-related prisms have low-grade metamorphism, the E- or NE-subduction-related orogens at the collisional stage may exhibit UHP rocks. Metallogenesis appears also controlled by subduction style. The Mariana type subduction is characterized by Kuroko or similar volcanogenic sulphide deposits. Porphyry copper deposits are instead concentrated in collisional settings and Andean type subduction zones.

The seismicity of the slabs is mostly characterized by down-dip compression along W-directed subduction zones, whereas it is quite often down-dip extensional along E- or NE-directed subduction zones. Japan subduction shows a different case, having two separate layers of slab seismicity, i.e., an upper one characterized by down-dip compression, and a lower one where down-dip extension prevails. However, Japan seems an intermediate case of subduction, where the Neogene W-directed subduction system is presently initiating to flip, having the backarc basin started to shrink. The seismicity is frequently down-dip extensional all along the subduction hinges of both subduction polarities, possibly related to

the bending of the lithosphere.
Within the two opposite end-members, a number of different settings can occur. For example along the E- NE-directed subduction zones there are oceanic slabs under continental lithosphere as in the Andes, which may or may not evolve to continent-continent collision such as the Alps or Himalayas. 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, determining variations in the volume of the related accretionary prism.
The vertical and lateral growth of orogens is strongly asymmetric. In fact prism or orogens related to W-directed subduction zones mostly generate an E-ward migrating wave, never reaching high structural and morphologic elevation, where the volumes and elevation rates of the prism are constrained by the subduction rate and the depth of the basal decollement plane of the accretionary prism. On the other hand, orogens related to E- or NE-directed subduction zones are much more elevated and their growth occurs both vertically and horizontally.
As prototypes of different subduction zones, the Alps and the Apennines are orogens formed above opposite slabs. Along the first belt, since the Cretaceous, the European plate subducted SE-ward underneath the Adriatic plate, whereas along the second belt, since the Late Oligocene, the Adriatic plate subducted W-ward below the European plate, with fast slab rollback and backarc spreading in the western Mediterranean. The Alps, unlike the Apennines, have double vergence, high structural and morphologic elevation, and no backarc basin. The Alps have two shallow foreland monoclines at the base of two foredeep basins, whereas the Apennines have a single deep foredeep, with steeper monocline and faster subsidence rates. Beneath the Alps the crust is about doubled, and the lithosphere base is deeper than 100 km. Below the Apennines, a new shallow Moho formed in the western backarc side, and the asthenosphere is very shallow (30-40 km, PANZA *et alii*, 2003). The new Moho is kinematically required by the replacement of the original Moho, now subducted, on which the present surface thrust sheets were originally lying, being part of a pre-existing passive margin section. A new mantle section from west has replaced the subducted crustal section, the pre-subduction Moho and the lithospheric mantle of the lower plate, since the slab is eastward retreating (DOGLIONI, 1991).
The Alps have widespread outcrops of basement rocks. In fact along the Alpine belt, thrusts are deeply rooted, cross-cutting the whole crust and upper mantle (DAL PIAZ *et alii*, 2003). Seismic tomography shows large involvement of continental lithosphere in the subduction system (MUELLER & PANZA, 1986). In the Apenninic belt, the prism is rather mostly composed of shallow (mostly sedimentary) crustal rocks of the lower plate because the decoupling surface is traveling atop the downgoing lithosphere (BALLY *et alii*, 1986).
The different structural settings of Alps and Apennines suggest different dynamic and consequently kinematic evolution of the related subduction zones. These asymmetries are diffused worldwide in the orogens, and appear controlled by the polarity of the subduction, i.e., following or opposing the polarized undulated flow of plate motions.
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. However the slab has low dip of the subduction plane, and there is no active hangingwall extension, in spite of an onshore morphology suggesting widely distributed structural depressions. The GPS data confirm that the Japan Sea backarc is not opening anymore, but it is rather closing. This

indicates that the system possibly arrived at an end, and its inversion started. Unlike other living W-directed subduction zones, the slab hinge in Northern Japan is moving toward the upper plate.

W-directed subduction zones formed mostly along the retrobelt of pre-existing E-NE-directed subduction zones, provided that oceanic lithosphere was present in the foreland to the east. This would explain why, for example, the Barbados and Sandwich arcs formed only where the Northern and Southern America continental lithospheres narrow, and slices of Cordillera type are boudinaged and scattered in the backarc setting. Similarly, the Japanese W-directed subduction, developed during the Neogene, to the east of a retrobelt of an earlier Cretaceous Andean type orogen, generated by an E-directed subduction. This is also supported by the outcrops of Andean type co-genetic porphyry copper deposits in Japan and Chorea.

W-directed subduction zones on Earth appear as short lived. If the Marianas or Japan subductions were active since the Cretaceous with a steady state E-ward hinge retreat, they should be now positioned in the middle of the Pacific. Backarc spreading in the hangingwall 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 it typically occurs along similar slabs.

Another apparent discrepancy to the W-directed versus E-NE-directed slabs asymmetry is the occurrence of backarc basins also in the hangingwall of E- or NE-directed subduction zones. However these types of rifts rarely arrive to oceanic spreading as W-directed subduction do in their hangingwall. Moreover they may be post-subduction (e.g., Basin and Range, DOGLIONI, 1995), or sin-subduction but accommodating differential advancement of the upper plate over the lower plate.

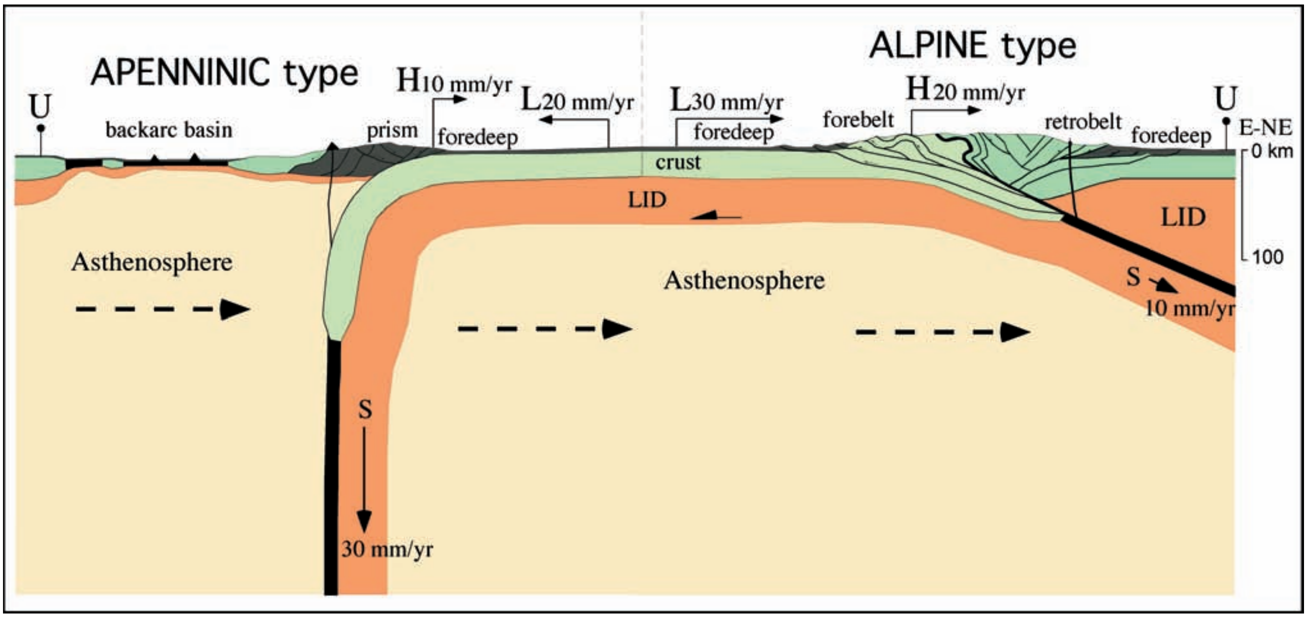


Fig. 147 - Schematic sections showing how in an Alpine setting, the subduction rate is decreased by the migration of the hinge H toward the upper plate U, and the orogen in the final collisional stage is composed both by the upper and lower plate L rocks. In the opposed Apenninic setting, the subduction rate is rather increased by the migration of H away from U, and the accretionary prism is made of shallow rocks of the lower plate. Note also the shallower asthenosphere in the hangingwall, which is typical of W-directed subduction zones (after DOGLIONI *et alii*, 2007).

Examples of this type are the aforementioned Aegean and the Andaman 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-ward directed subduction of Africa relative to the hangingwall disrupted Eurasian lithosphere (DOGLIONI *et alii*, 2002). Considering fixed Africa, the faster SW-ward 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 replaces a subducted and retreated slab, the Aegean rift represents a different type of extension associated to a subduction zone, where the hangingwall 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, along the Himalayas collision, the Indo-Australian plates converge relative to 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. Therefore, assuming a relatively coherent lower plate, the hangingwall 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.

There are belts that are apparently not following the global trend of plate motions, like orogens that are E-W trending, and related to N-S convergence (e.g., the Pyrenees, Venezuela-Colombia belt). They have Alpine character and may kinematically be explained as related to subrotation of plates (CUFFARO *et alii*, 2004). The Atlas is not directly related to a subduction zone, but has been interpreted as an intraplate inversion structure, while the E-W-trending Maghrebides (FRIZON DE LAMOTTE *et alii*, 2000) are rather the right-lateral prolongation in northwestern Africa of the arcuate Apennines-Maghrebides subduction system. Along this segment of the belt, the right-lateral transpression coexisted with an about 5 times slower roughly N-S component of Africa-Europe convergence (GUEGUEN *et alii*, 1998). The E-W-trending Himalaya is instead almost perpendicular to the global tectonic mainstream (DOGLIONI, 1990).

Mantle convection could satisfy a steady state speed of the lithosphere, assuming low or no decoupling at the asthenosphere interface. However, mantle convection is kinematically problematic in explaining the migration of plate boundaries and the occurrence of a decoupling surface at the lithosphere base. Although a combination of all forces acting on the lithosphere is likely, the decoupling between lithosphere and mantle suggests that a torque acts on the lithosphere independently of the mantle drag. Slab pull and ridge push are candidates for generating this torque, but, unlike these boundary forces, the advantage of the Earth's rotation and related tidal drag is to be a volume force, acting simultaneously and tangentially on the whole plates. Tidal drag maintains the lithosphere under a permanent high frequency vibration, polarized and sheared toward the "west". Earth's rotation and the break exerted by the lag of the tidal bulge (BOSTROM, 1971) can be efficient only if very low viscosity occur at the lithosphere-asthenosphere transition (JORDAN, 1974), but growing evidences are emerging on the presence of an ultra-low viscosity layer at the very top of the asthenosphere, possibly related also to higher fluids concentration in the mantle. Lateral variations in the low-velocity layer viscosity could control the different velocity of plates.