On the origin of west-directed subduction zones and applications to the western Mediterranean

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Abstract: West-directed subduction zones show east-verging arcs of 1500–3000 km. They are usually younger than 50 Ma and are characterized by a frontal accretionary wedge and a back-arc basin propagating together toward the east. The accretionary wedge scrapes off superficial layers of the downgoing plate (thin-skinned tectonics) whereas the back-arc extension cross-cuts the entire subduction hanging wall (thick-skinned tectonics). The slab of this type of subduction is steep to vertical and the hanging wall of the subduction has a mean elevation of 1000 m below sea level. Trenches and foredeeps are the deepest basins of the Earth and the mean depth is of 5000 m below sea level. West-directed subduction occurs both in case of the highest E–W convergence rates among plates (e.g. W Pacific examples) and no or very low convergence (e.g. Carpathians). Following Atlantic W-directed subduction examples, the W-directed subductions seem to develop along the back-thrust belt of former E-directed subduction zones, where oceanic lithosphere occur in the foreland to the east with the narrowing of the American continents. This could be applied to the onset of the Apennines subduction along the back-thrust belt of the Alpine–Betic orogen where Tethys oceanic crust was present. The Alpine orogen was stretched and scattered in the Apennines back-arc basin. The back-arc extension is internally punctuated by necks (sub-basins) and boudins (horsts of continental lithosphere). Asymmetric extension in the back-arc basin appears controlled by differential drag between the eastward mantle flow and the overlying passively transported crustal remnants. Compression in the accretionary prism may be interpreted as the superficial expression of the shear occurring between the downgoing lithosphere and the horizontally moving mantle which compensates the slab roll-back. The area of the Apennines appears lower than the area of the sedimentary cover before subduction: this favours the idea that not significant crustal slices have been involved in the Apenninic accretionary prism, and the basement thrust sheets included in the western part of the belt are mainly relicts of the Alpine–Betic orogen.

This paper aims to underline the peculiar characters of W-directed subduction zones which present strong differences particularly when compared to the other settings such as the classic Alpine or Andean subduction zones. The main known, presently active or preserved W-directed subduction zones of the world are the Apennines, Carpathians, Barbados, Sandwich, Aleutians, Kurile, Japan, Nankai, Ryukyu, Izu–Bonin, Marianas, Tonga, Kermadec, Banda, Philippines. We prefer to use the term W-directed rather than W-dipping because the west is the mean direction of an arcuate slab which may dip for example to the southwest (Northern Apennines), or to the northwest (Calabria), or even to the north (Sicily and Maghrebides). The Aleutian slab dips northwestward, but the Pacific plate travels WNW oblique to the trench. West-directed subduction zones are here differentiated because they present a number of peculiarities such low elevation in the hanging wall, back-arc spreading to the west, high-amplitude gravimetric signatures, short life, etc. Moreover their accretionary prisms have a dominant vergence to the east and they are followed by a wave of extensional faults. The accretionary prisms are mainly composed of sedimentary rocks off scraped from the top of the foreland subducting plate and basement relicts of former orogens related to E- or NE-directed subduction zones (Doglioni 1991, 1992). The western Mediterranean system is used here as the main example for the description of the main traits of the W-directed subduction zones.

Main characters of west-directed subduction zones

West-directed subduction zones have generally arcuate shape, with the convexity verging mainly toward the east (Fig. 1). It was proposed that any subduction on a sphere generates an arc (e.g. Fowler 1990). However this geometric observation does not explain why E- or NE-directed

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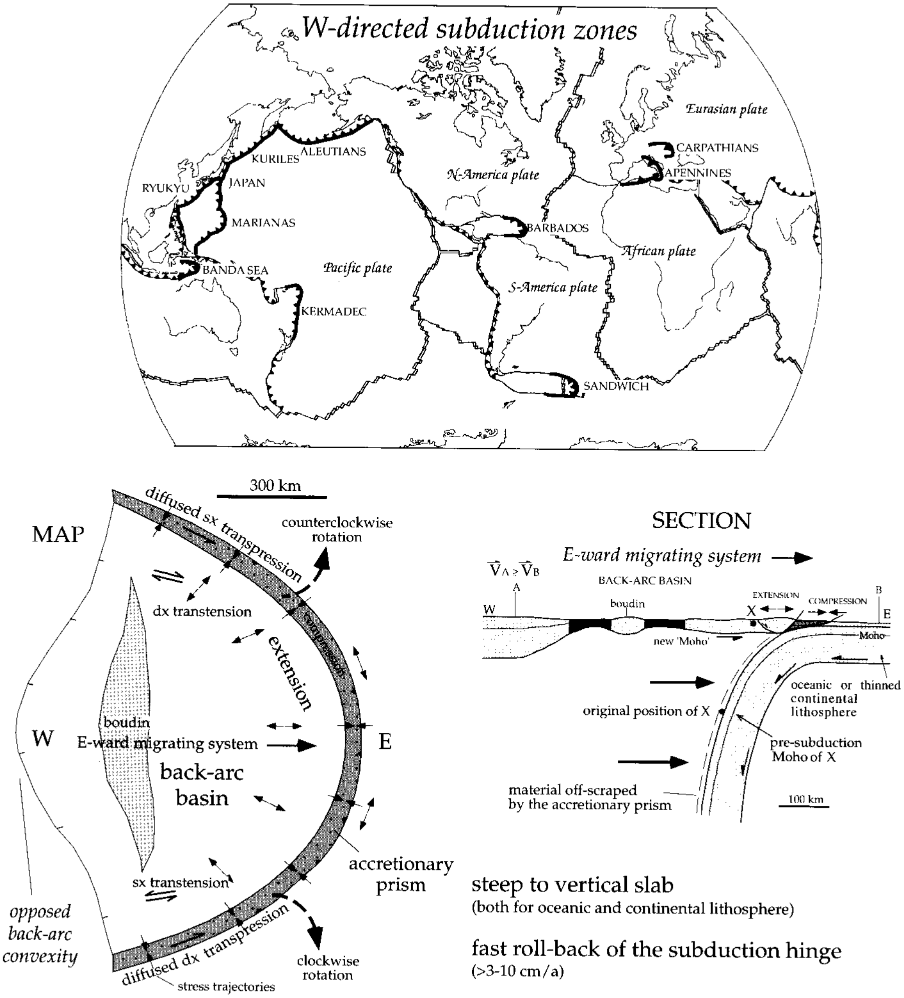

arcuate shape
(arc length 2000-3000 km)

arc migrating eastward
(along-strike extension)

younger than 50 Ma
(usually less than 30 Ma)

always back-arc basin
(migrating in the same direction)

lithospheric boudinage in the back-arc basin
(asymmetric extension, mainly E-dipping normal faults)

western margin of the back-arc basin with convexity opposed to the the subduction arc

steep to vertical slab
(both for oceanic and continental lithosphere)

fast roll-back of the subduction hinge
(>3-10 cm/a)

fast subsidence rates
(foredeep or trench 1 mm/a; back-arc basin 0.6 mm/a)

low elevation of the subduction hanging wall
(average 1000 m below sea-level)

deep trenches
(average 5000 m below sea-level)

thin crust in the hangingwall of the subduction
(20-30 km thick, lying on a new 'Moho' and a new mantle section)

magmatic pair
(sourced by the slab and the back-arc asthenosphere)

thin-skinned compressive tectonics at the front and thick-skinned extensional tectonics in the back-arc

Fig. 1. Summary of the main characteristics of west-directed subduction zones. Plate boundaries in the upper figure are after Fowler (1990).

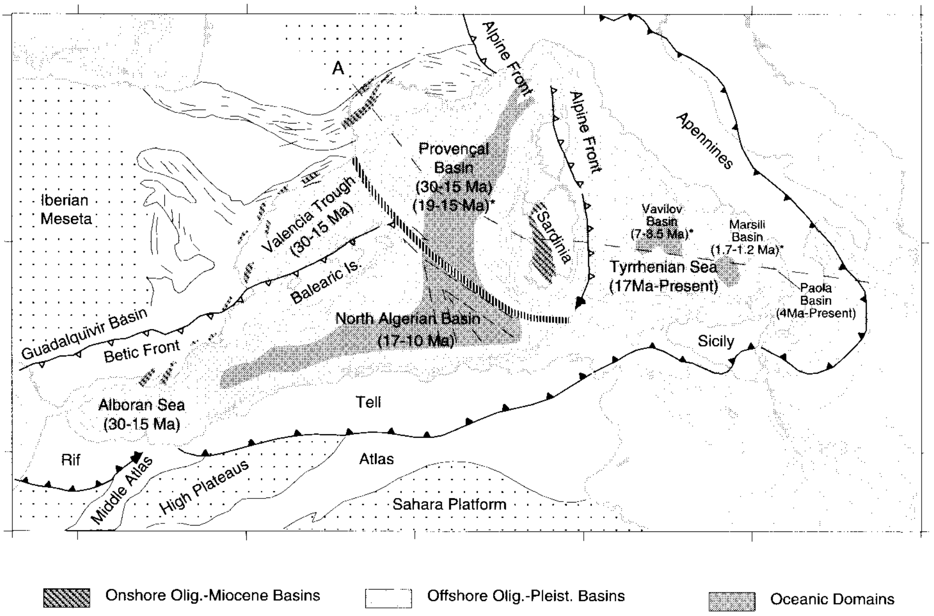

Fig. 2. The western Mediterranean is composed by sub-basins that show an age progression from west to east. They developed in the hanging wall of the eastward retreating Apenninic subduction as back-arc basins. The sub-basins show triangular shapes. A shows the location of the section shown in Fig. 3. Ages with the asterisk indicate the age of the oceanic crust (after Gueguen *et al.* 1997).

subduction zones do not show such a shape (e.g. Cordillera, Himalayas). The arc of the W-directed subduction zones has average length of 1500–3000 km both in the Pacific and in the Mediterranean (Fig. 2). West-directed subductions occur both in case of the highest convergence rates among plates (e.g. W Pacific examples, with rates even higher than 10 cm a^{-1}) and no or very low rates of convergence (e.g. W Atlantic examples, Apennines, Carpathians, with rates of 0–2 cm a^{-1}). There are W-directed subductions where the slab retreats eastward without any convergence along margins of plates travelling independently toward the NE (e.g. the Banda arc at the northwestern Australian margin, and the Apenninic arc at the western margin of the Adriatic–African plate, Fig. 3).

Thrust belts associated with W-directed subductions have a shallow new Moho beneath the thrust belt with respect to the deeper and pre-subduction Moho of the foreland (Fig. 1). The recent age of this 'new' Moho is constrained by the age of the back-arc spreading and by the kinematics of the subducting foreland pre-subduction Moho. In fact, the so-called 'new' Moho below the belt shows lower velocities (7.7–8.0 km s) than the foreland Moho (7.9–8.2 km s). Compare the Apennine data with those of the Alps where notoriously the crust is thicker (Locardi & Nicolich 1988; Kissling 1993; Scarascia *et al.* 1994). Moreover the accretionary wedges have only one main vergence (generally speaking eastward) and only one foredeep, in contrast with Alpine or Andean orogens which are characterized by double vergence and two foredeeps or trenches. Double vergence of such belts are only related to external geodynamic settings overprinting the W-directed subduction, like the N–S compression of the Southern America plate due to its clockwise rotation which is deforming the southern arm of the Barbados subduction zone and the Caribbean back-arc.

The accretionary wedges of W-directed subductions are mainly composed of sedimentary rocks scraped off the top of the subducting plate; basement rocks occur as pre-existing structural highs of the foreland truncated by the advancing thrusts or inherited in the hanging wall from earlier orogenic belts. In some sections of such belts the main crystalline basement and crust may be missing due to subduction. These peculiarities could be explained by the behaviour of the décollement zones of the W-directed subduction

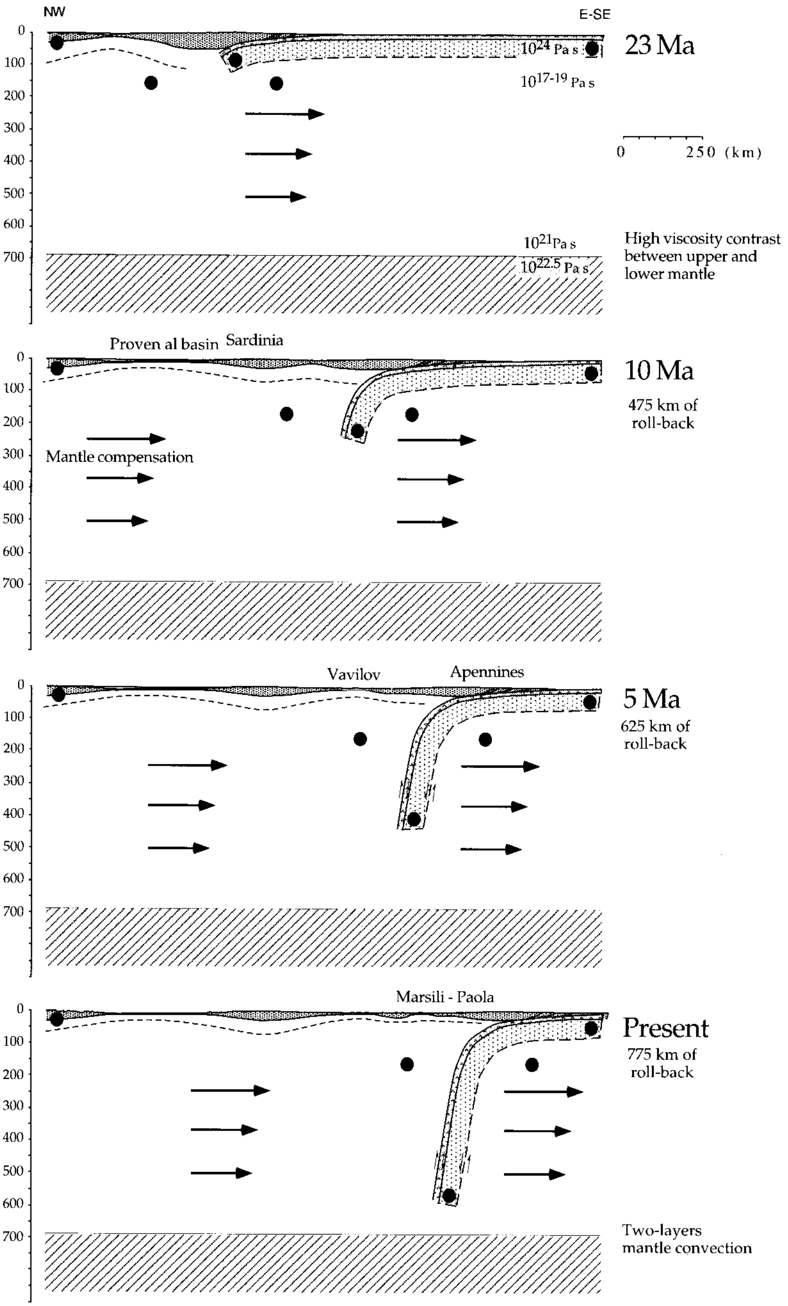

Fig. 3. Kinematic model of the Apennines subduction using an area balancing method. The back-arc extension in the hanging wall of the Apenninic subduction is characterized by lithospheric necking progressively moving to the east. It opened first in the Provençal basin, then it jumped to the east of Sardinia and developed the Tyrrhenian extension with the Vavilov and Marsili sub-basins. This appears to indicate a discontinuous process of extension in the hanging wall of the W-directed subduction where large slices of lithosphere are boudinated and dragged eastward, including the Alpine orogen. While the back-arc extension appears punctuated, the subduction roll-back seems to be a more continuous process. About 800 km of subduction roll-back are calculated in the area of maximum subduction and arcuature of the Apennines. The eastward retreat of the slab implies an eastward relative motion of the mantle to compensate the slab retreat at the west, and to allow the slab retreat to the east. Note the relative motions among the black reference points. Location of the section on Fig. 2. Viscosity values after B. Romanowicz and R. Sabadini (pers. comm.).

zones which are polarized by the westward drift of the lithosphere relative to the asthenosphere (Ricard *et al.* 1991). In fact the basal décollement of the downgoing lithosphere is warped and subducted along W-directed subduction zones (Doglioni 1992). Without the possibility of uplifting deep-seated crustal rocks of the foreland, only shallow upper layers of the lithosphere are accreted (Fig. 1).

The accretionary wedge is accompanied by right-lateral transpression and clockwise rotations of the thrust sheets in the southern arm of the arc associated to a W-directed subduction zone, whereas the northern arm is characterized by diffuse left-lateral transpression and counterclockwise rotation of the thrust sheets (Fig. 1). Opposed versus of transtension is recorded in the extensional area to the west: right-lateral transtension in the northern arm of the back-arc basin and left lateral transtension in the southern arm of the arc. No significant rotations are described in the back-arc transtensional areas. This may be ascribed also to the interpretation of the depth of the décollements: the accretionary wedge is characterized more by thin-skinned thrust-tectonics where the lithostatic load is low. On the other hand the extensional belt to the west is cross-cut by thick-skinned normal faulting cross-cutting the entire crust; this could inhibit large rotations of the hanging wall due to the higher lithostatic load operating on the décollement planes of the lower crust.

Foredeeps and trenches are also very pronounced along W-directed subduction zones. They show the highest subsidence rates of any basin on Earth in the order of 1600 m Ma^{-1} (e.g. Apennines and Carpathians). This observation enables us to interpret the slow filling of foredeeps with huge flysch deposits (Apennines) or poor deposition (Marianas trough). In fact the cross-sectional area of thrust belts associated with W-directed subduction is smaller in comparison with the area of the foredeep or trench. All these observations appear to maintain their general validity both in the case of subduction of oceanic lithosphere and of thin continental lithosphere. Along the W-directed subduction zones the origin of the foredeep and trench appears to be mainly controlled by the eastward roll-back of the subduction hinge resulting from the eastward mantle push (Doglioni 1994). The subsidence is so fast in those foredeeps that the fold growth along the frontal part of the accretionary wedge can be negative when the regional subsidence exceeded the single fold uplift rate. In these cases, the envelope to the folds crest may dip toward the hinterland (Doglioni & Prosser 1997).

Associated with a W-directed subduction there always occurs a back-arc basin, with fast eastward propagation (30–50 mm a^{-1}, e.g. the Tyrrhenian Sea). The subducted lithosphere is replaced by new asthenospheric material in the back-arc. The main geometric and kinematic characters of the W-directed subduction zones are summarized in Fig. 1. The thickness and shape of the accretionary wedge along the trench or foredeep is controlled by the depth of the décollement, which is also a function of the thickness and rheology of the sedimentary cover arriving at the subduction hinge. Thin or absent sedimentary cover on top of the oceanic crust will inhibit the development of appreciable accretionary wedge like in the Marianas trough where the basal décollement is almost at the earth surface. The calcalkaline to shoshonitic and alkaline to tholeiitic magmatic suite pairs mark the W-directed subduction settings as indicators of the subduction plane and the back-arc asthenospheric spreading sources.

Most of these peculiarities have been so far explained in terms of slab pull and age of the subducting oceanic lithosphere, or rates of convergence between plates (e.g. Royden & Burchfiel 1989). However, in the Mediterranean, the Adriatic continental lithosphere and the Ionian oceanic lithosphere (de Voogd *et al.* 1992) are subducting both under the Apennines (steep W-directed subduction, Selvaggi & Chiarabba 1995) and under the Dinarides–Hellenides (shallow NE-directed subduction, Christova & Nikolova 1993). The two related thrust belts follow the east and west Pacific rules, without age and thickness variations of the subducting lithosphere. In the Pacific itself, the W-directed subductions are the fastest in the world and the slab is steep, while the Andean subduction is active since the Mesozoic and the slab is shallow. Those examples are clearly in contradiction with an age of the subduction, and the age and thickness of the subducting lithosphere as first order controls of the tectonic style. The westward drift of the lithosphere relative to the mantle could better explain these asymmetries.

Focal mechanisms of intermediate and deep events are an important tool in understanding subduction processes and in delineating slab geometry. In particular W-directed slabs have dip angles ranging from 40° of the fastest Western Pacific slabs to verticality of the blocked Carpathians slab. The Pacific slabs are characterized by active convergence (4–10 cm a^{-1}) as well as slab retreat, conversely the Atlantic and European slabs have slab retreat as dominant mechanism. The difference in dip of the two groups is probably due to the fact that the induced flow (e.g. Turcotte & Schubert 1982) in the first one is much higher than in the second one causing an uplift of the slab. An analysis of deep earthquakes shows us that their activity in the Atlantic and European slabs is much less prominent that in the Pacific slabs. In particular the Sandwich slab has recorded events up to a depth of about 140 km, the Barbados down to about 170 km, the Carpathians down to 180 km (e.g. Oncescu 1984, 1987), and the Tyrrhenian slab down to 450 km (e.g. Frepoli *et al.* 1996). Conversely all the Pacific slabs show deep earthquake activity almost to the 670 km discontinuity. Moreover in the Atlantic and European slabs there is a prevalence of compressional events; within the Pacific slabs we observe an alternation of compressional and tensional mechanisms, combined with horizontal shear flow. On the base of this observation, Frepoli *et al.* (1996) question the role of the slab pull for the Tyrrhenian slab. In fact slowly subducting slabs reach a state of thermal equilibrium at shallower depth; the density difference between the slabs and the surrounding mantle becomes less relevant and might be the reason because the slabs apparently do not sink.

In the Apennines the seismicity appears located along the northwestward palaeogeographic prolongation of the Ionian Mesozoic oceanic lithosphere; the shortening in the Apenninic accretionary wedge is maximum in northern Calabria and southern Apennines and decreases along the opposite arms of the Apenninic arc. However the shortening which is appreciable in the accretionary prism suggests that subduction has occurred all along the Apenninic arc. Moreover the Mesozoic shallow-water facies piled up in the belt indicate that they were lying on a continental crust at least 25 km thick. The missing crust in the Apennines and the shortening in the belt support the subduction of those volumes of continental lithosphere. The latter has lower temperature of brittle–ductile transition and therefore the paucity of deep seismicity along northern segments of the Apenninic arc could be attributed to the different rheology of the quartz-feldspar rich Adriatic continental lithosphere with respect to that of the olivine-pyroxene rich Mesozoic oceanic Ionian sea. These differences are supported also by the magmatism that shows clearly different sources (Peccerillo 1985; Serri *et al.* 1993). Recent tomographic investigations of the Apenninic slab show a much more continuous cold body underneath the Apennines than so far imaged (Amato *et al.* 1996).

The map view and the section of an arc associated to a W-directed subduction zone shows how the stress trajectories follow the arc and compression in the accretionary wedge can occur without relative motion between the foreland and the hinterland plates (Fig. 1). Therefore the seismicity associated to the offscraping of the sedimentary cover due to slab retreat along the arc of W-directed subduction zones is not a reliable indicator of relative plate motion among footwall and hanging wall plates (e.g. Barbados or Apennines arcs). In this frame, the Africa–Europe relative motion that has been interpreted on the basis of the northern Africa seismicity (e.g. McKenzie 1972), can also be interpreted as due to the migration of the subduction hinge in a context of no or low convergence. The observed compression–extension wave is generated by the 'eastward' roll-back of the subducting Adriatic–Ionian–African lithosphere and only marginally deformed by the relative Africa–Europe convergence.

It is commonly believed that the extension determining the opening of the western Mediterranean developed in a context of relative convergence between Africa and Europe. However the direction of relative motion is still under debate. Most of the reconstructions (Albarello *et al.* 1995; Dewey *et al.* 1989; Mazzoli & Helman 1994; Campan 1995) show an amount of shortening of 150 km during the all Tertiary in the western Alboran area. The main difference between these models is the increase of convergence further east ranging from 300 km (Dewey *et al.* 1989) to 250 km (Campan 1995) in Tunisia. The amount of shortening in the two areas diminishes when computed for the last 20 Ma to 70–80 km in the Alboran and 100–165 km in Tunisia (Dewey *et al.* 1989; Campan 1995). It appears that the amount of relative N–S Africa Europe relative motion was in any case five to eight times slower with respect to the eastward migration of the Apenninic arc which migrated eastward about 800 km during the last 23 Ma (Fig. 3), i.e. 4–7 mm a^{-1} v. 30–50 mm a^{-1}. (Patacca & Scandone 1989; Doglioni 1991; Gueguen *et al.* 1997). Recent geodetic data (Lageos, VLBI, GPS) confirm this main frame (Smith *et al.* 1994; Ward 1994). Therefore the Apenninic arc migrated eastward faster than the N–S convergence related to the counterclockwise rotation of Africa relative to Europe. A similar setting may be observed in the Caribbean region (Westbrook & McCann 1986; Mascle *et al.* 1986) where the arc due to the Barbados subduction zone migrated eastward faster than the N–S convergence of the South America with the Caribbean back-arc basin owing to the clockwise rotation of the South America plate.

Geologically, W-directed subductions are less known because they are mainly below sea level. Average low topography and pronounced gravimetric anomalies characterize them. A narrow arc-chain in the hanging wall of the subduction (about 200–300 km in section) typically rises to 2000–3000 m over the mean plate height. The subducting plate is generally only 1000–2000 m lower than the overriding one. If the subducting plate is oceanic, there is always a pronounced trench, whereas for continental plates, the trench may be filled (e.g., Carpathians) or partly filled (Banda) by sediments. The associated volcanic arc is usually well defined. West-directed subductions are characterized by strong negative free-air gravimetric anomalies with an asymmetric shape (150–200 mgal) along the trench, by a prominent positive signature (over 100 mgal) corresponding to the arc-chain, and similar gravimetric values on both plates immediately off the trench–arc system. The minimum gravimetric values are located along the trench or foredeep, displaced from the mountain range in the hanging wall (e.g. the Apennines, Mongelli *et al.* 1975). For further details and comparison with E-directed subductions see Harabaglia & Doglioni (1998).

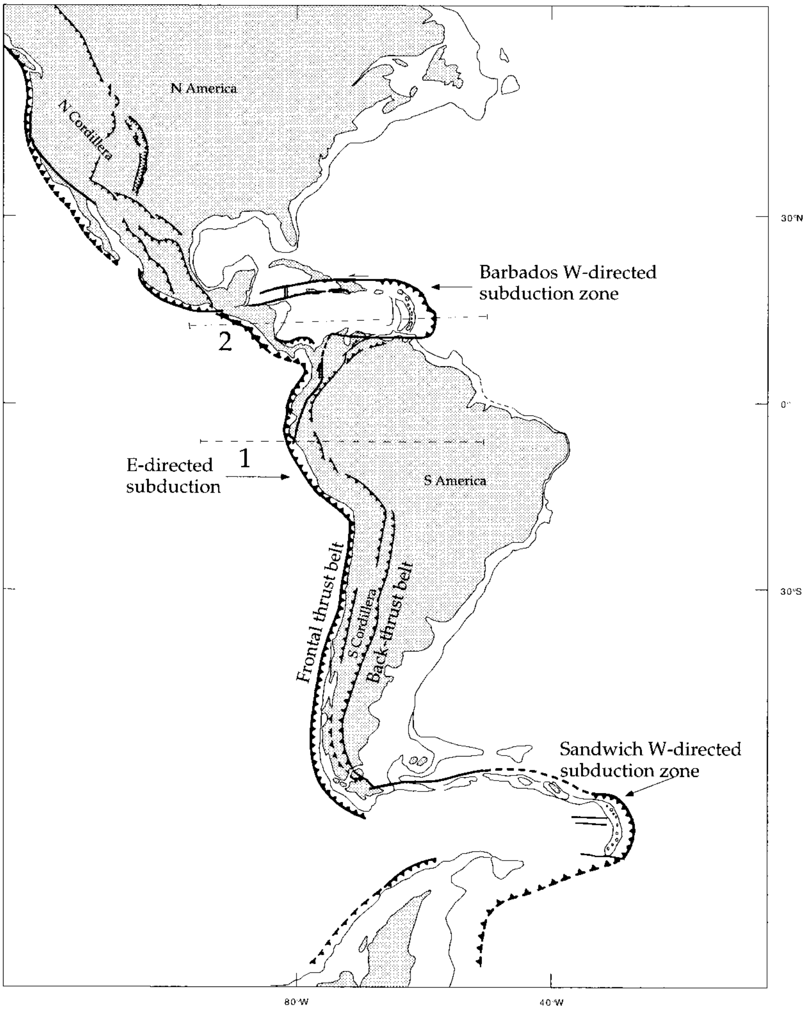

Fig. 4. Note that Barbados and Sandwich arcs formed only where the American continents narrow. Their W-directed subduction zones evolved only where there was Atlantic oceanic lithosphere in the foreland of the back-thrust belts of the E-directed subduction zones of the northern and southern Cordillera. Lines 1 and 2 refer to Fig. 5.

Initiation of west-directed subduction zones

West-directed subduction zones appear to nucleate along back-thrust belts of former E-directed subductions, if oceanic or thinned continental lithosphere was present in the foreland of the E-verging back-thrust belt (Fig. 4). This seems the indication coming from the Atlantic W-directed subduction zones. Those two subductions, i.e. Barbados and New Scotia arcs, developed along the front of the E-verging cordillera back-thrust belt (e.g. Rocky Mountains, Sub-Andean thrust belt) only where there was Atlantic oceanic lithosphere in the foreland to the east of the back-thrust belt. The W-directed subductions did not develop where to the east of the back-thrust belts of the E-directed subduction there was thick continental lithosphere like in the Western Interior of North America or in Brazil and Argentina in the South America continent. Therefore W-directed subductions developed only in central America and south of Patagonia, where the Northern and Southern American continents narrow (Fig. 4). The two subduction zones developed during Tertiary and Quaternary times, and they have arcuate shapes and a length of about 2000 km. In order to explain the W-directed Atlantic subduction zones, Russo & Silver (1994) proposed an eastward mantle flow in the back-arc of the Barbados and Sandwich arcs, laterally deviated from the Andean subduction zone.

From the aforementioned indications, it appears that W-directed subductions, which are world-wide Tertiary and Quaternary features, possibly form only in the presence of particular geodynamic constraints, i.e. (1) along the back-thrust belt of earlier E-directed subduction zones, and (2) in the presence of oceanic or thinned continental lithosphere in the foreland of the related back-thrust belt (Fig. 5).

In this paper we propose that similar geodynamic constraints favoured the Neogene–Quaternary Apennines development, i.e. the Apennines W-directed subduction formed where Mesozoic oceanic Tethys lithosphere (Bernoulli & Lemoine 1980) was present in the foreland of the back-thrust belt of the pre-existing E-directed subduction-related Alpine orogen (Figs 6 & 7). Remnants of the former Alpine orogen were passively incorporated into

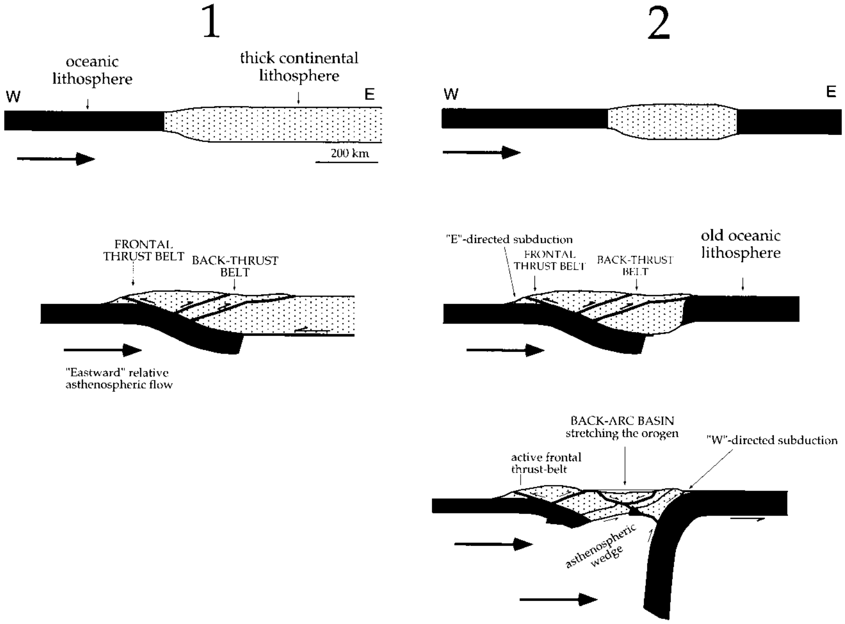

Fig. 5. The E-directed subduction forms where there is convergence between two plates and oceanic or thin continental lithosphere is in the footwall of the subduction (1, e.g. Andes). The W-directed subduction develops along the back-thrust belt of the former E-directed subduction-related orogen, where the continent narrows and oceanic lithosphere is present in the foreland of the orogen to the east (2, e.g. Barbados). The back-arc extension of the W-directed subduction stretches the internal parts and the back-thrust belt of the pre-existing orogen (e.g. early stages of the Central Americas and Barbados opposite subduction zones which are scattered in Cube, Haiti and Caribbean islands). 1 and 2 refer schematically to Fig. 4.

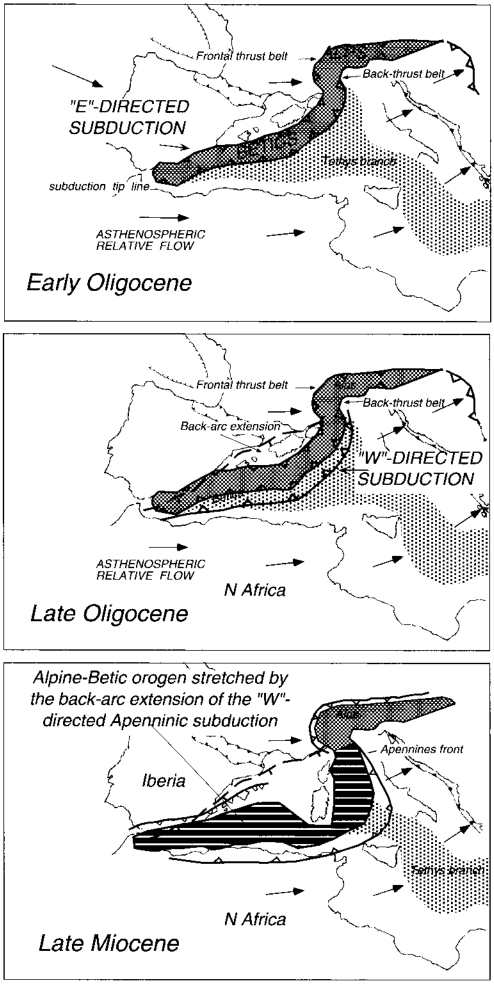

Fig. 6. Palaeogeographic reconstruction of the Western Mediterranean since the Late Oligocene, and application of the Atlantic example of Fig. 4 for the initiation of the Apenninic subduction zone. The W-directed subduction might have developed along the back-thrust belt of the Alpine–Betic orogen where a pre-existing Mesozoic oceanic relict of the Tethys should have been present. The back-arc basin of the Apenninic subduction stretched and scattered into the segmented basins the Alpine–Betic orogen.

the internal parts of the accretionary wedge, boudinaged and cross-cut by the back-arc extension related to the younger W-directed subduction (Figs 8 & 9). A similar geodynamic evolution has been proposed for the W-directed Japanese subduction, which apparently formed during the Neogene to the east of an earlier Andean type orogen related to an E-directed subduction (Sillitoe 1977; Cadet & Charvet 1983).

Geodynamic setting of the western Mediterranean and back-arc settings

The western Mediterranean basin (Auzende *et al.* 1973; Boccaletti & Guazzone 1974; Scandone 1980; Réhault *et al.* 1984; Stanley & Wezel 1985; Malinverno & Ryan 1986; Kastens *et al.* 1988; Robertson & Grasso 1995) consists of a series of V-shaped sub-basins (Fig. 2) which developed from late Oligocene on in the context of back-arc extension contemporaneous to the eastward roll-back of the westerly directed Apenninic subduction zone (Gueguen *et al.* 1997). Figure 3 shows jumps in the thinning process and rejuvenation of the basins toward the east or southeast. The jumps in the thinning process are responsible for a boudinage of the crust and the lithosphere which show large lateral thickness variations (Calcagnile & Panza 1981; Banda & Santanach 1992; Blundell *et al.* 1992; Torné *et al.* 1992; Scarascia *et al.* 1994; Fernàndez *et al.* 1995). Therefore the western Mediterranean has to be viewed as a whole basin dismembered into sub-basins by the heterogeneous stretching of the back-arc setting. The isolation of boudins indicates a discontinuous process in the back-arc area. The large scale lithospheric boudinage shows a range of 100–400 km wavelength. The Sardinia–Corsica continental block represents the largest lithospheric boudin of the western Mediterranean. The boudinage arrived to complete thinning of the continental lithosphere with formation of new oceanic crust in the Provençal, Algerian, Vavilov and Marsili basins. This is also supported by the back-arc magmatism that does not show a regular spatial and temporal evolution. It rather shows moments of larger manifestations located in the western side of the boudins (e.g. the Early Miocene western Sardinia and Valencia trough magmatism). The Neogene–Quaternary magmatism of the western Mediterranean back-arc setting regularly shows paired calc-alkaline and alkaline suites, the first usually being older in every single magmatic province (e.g. Martí *et al.* 1992). The back-arc extension and the related magmatism are younger moving eastward (e.g. in the Tyrrhenian, Savelli 1984). Gravity profiles across the central western Mediterranean (Cella *et al.* 1998) also support the evidence of an asymmetric boudinage of the lithosphere.

The evidences for the Apenninic subduction have been extensively documented in the last decades by geophysical, geological and volcanological data that indicate W-directed subduction of the Adriatic plate underneath central and southern Italy (Mongelli *et al.* 1975; Peccerillo 1985; Royden *et al.* 1987; Channell &

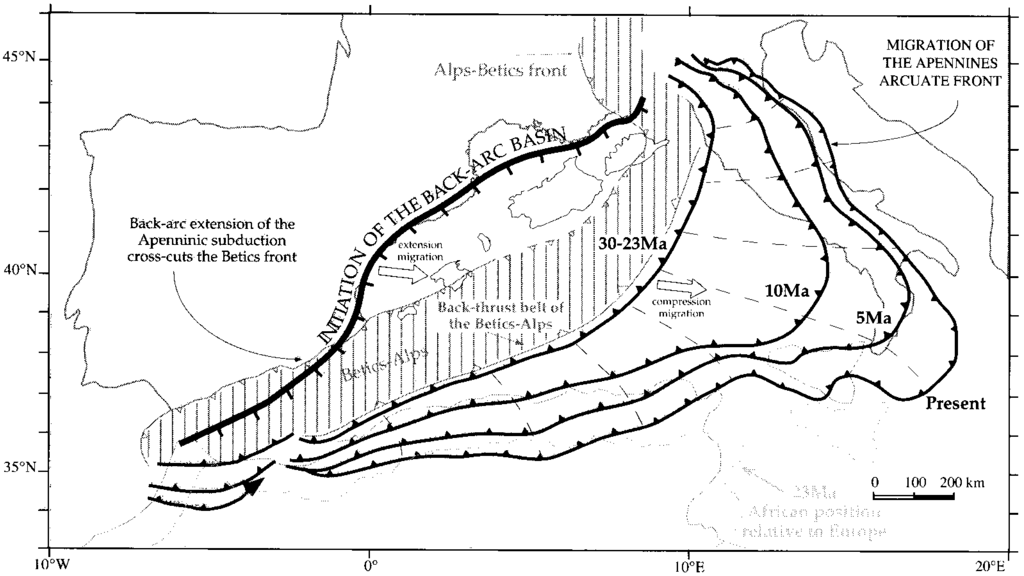

Fig. 7. W-directed Apenninic subduction started in the western Mediterranean in the Late Oligocene along the back-thrust belt of the Alpine–Betic orogen. Its arc migrated eastward up to the present position due to the eastward slab retreat. The western Mediterranean back-arc basins developed in the hangingwall of this retreating slab. Note the lengthening of the arc which should generate along arc extension. The back-arc initiation cross-cuts the Alpine–Betic front (Doglioni *et al.* 1997), suggesting that the extension is not simply the collapse of the Alpine–Betic orogen.

Mareschal 1989; Beccaluva *et al.* 1989; Spakman 1989; Doglioni 1991; Amato *et al.* 1993; Serri *et al.* 1993; Selvaggi & Chiarabba 1995; Faccenna *et al.* 1996). The subduction retreated 'eastward' and the associated back-arc basins have ages progressively younger (30 Ma to present) moving from west (Valencia, Provençal, Alboran and Algerian basins), to east (Tyrrhenian sea) (Fig. 2). Roll-back of the slab likely caused loss of lithosphere which should have been replaced by asthenosphere (Fig. 3) responsible for the high heat flow values (>100 mW m^{-2}) measured in the western Mediterranean.

The W-directed Apenninic subduction started to the east of the pre-existing Cretaceous to Miocene Alpine–Betic orogen. The back-arc extension in the hanging wall of the Apenninic subduction stretched and deformed the inherited Alpine–Betic orogen related to an 'E'-directed subduction. Remnants of the Alpine–Betic thrust belt have been dispersed throughout the western Mediterranean (Alvarez *et al.* 1974), both in the basins and in the swells. Relicts of metamorphic rocks emplaced by Alpine thrusts have been dragged in the Tyrrhenian (Kastens *et al.* 1988) and are scattered around the back-arc basins (e.g. the Kabylie in northern Africa and the Aspromonte and Peloritani in southern Italy). The subduction underneath the Apennines consumed inherited Tethyan domains (Dercourt *et al.* 1986; Ziegler 1988). Similarly, boudinage of the pre-existing Alpine–Dinaric orogens occurred in the Pannonian basin, which is the Miocene–Pliocene back-arc basin related to the coeval W-directed Carpathian subduction zone which retreated during the Miocene and Pliocene (Oncescu 1984; Royden & Horváth 1988; Horváth 1993; Tomek 1993; Tomek & Hall 1993; Linzer 1996). In the Pannonian basin the extension isolated boudins of continental lithosphere thickened by the earlier Dinaric orogen, like the Apuseni mountains which separate the Pannonian basin *s.s.* from the Transylvanian basin to the east. The western Mediterranean back-arc setting is comparable with Atlantic and western Pacific back-arc basins that show similar large scale lithospheric boudinage, where parts of earlier orogens have been scattered in the back-arc area, like the central America Cordillera relicts that are dispersed in the Caribbean domain (Donnelly 1989).

Back-arc basins are typical features forming in

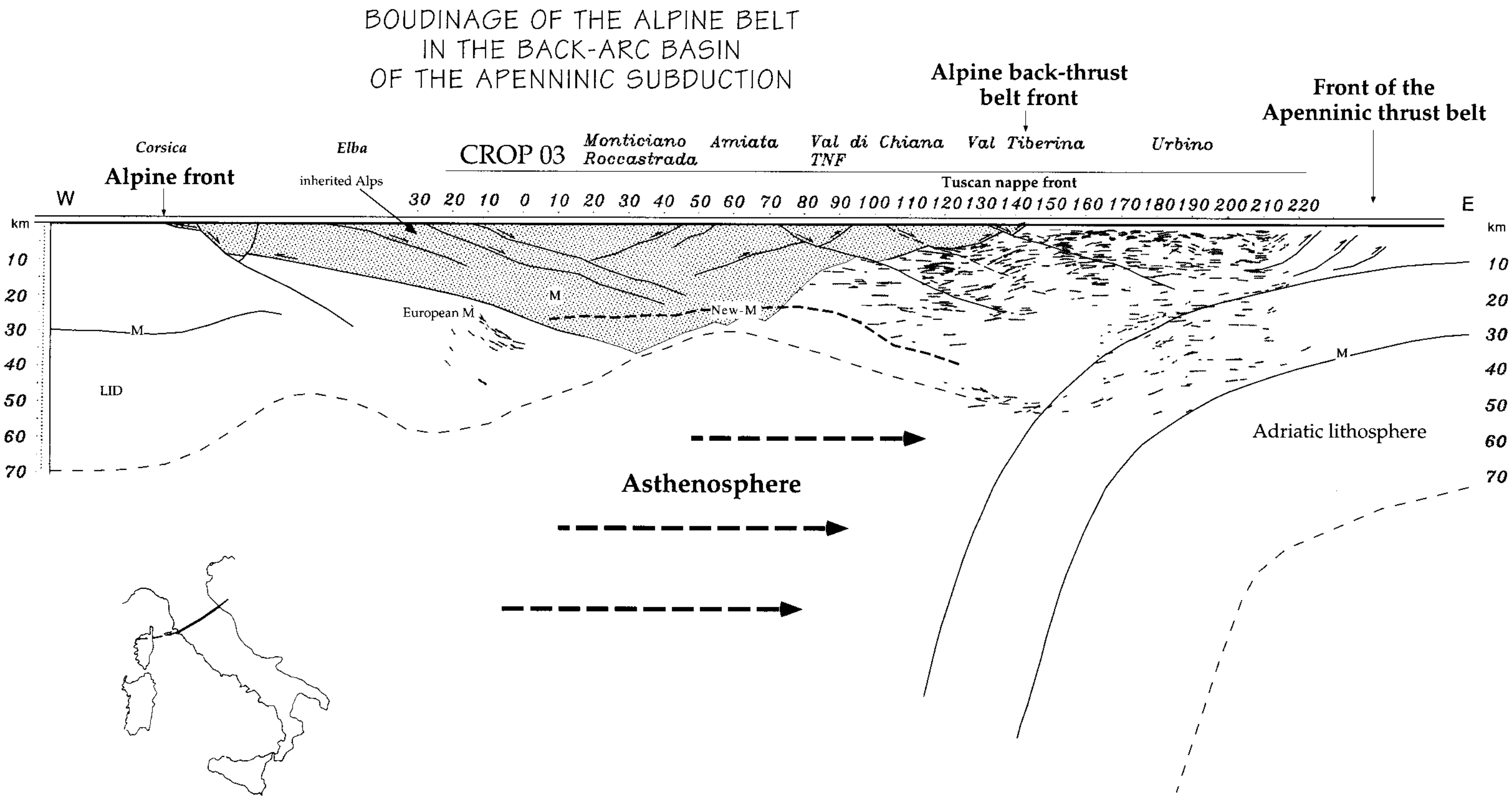

Fig. 8. Line drawing and interpretation of the Crop 03 seismic reflection profile. In shadow is the Alpine orogen stretched by the back-arc extension of the W-directed Apenninic subduction (after Doglioni *et al.* 1998).

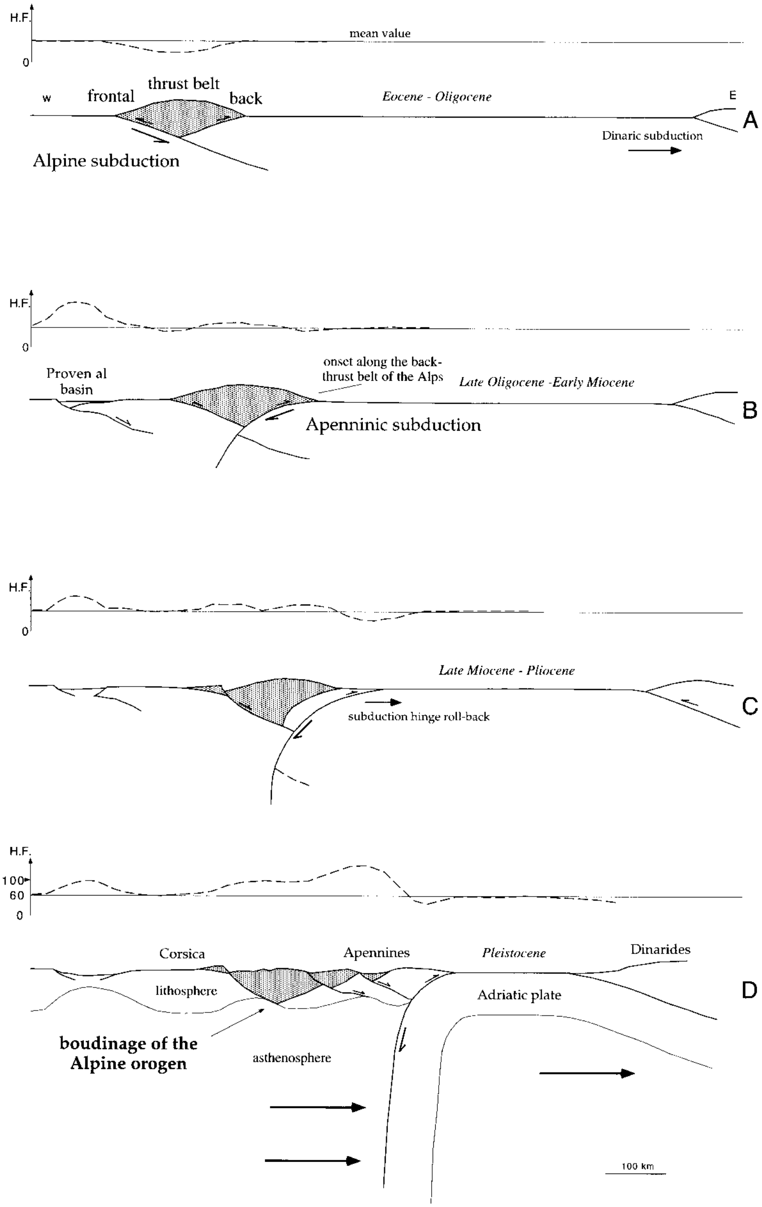

Fig. 9. Kinematic reconstruction of the gross evolution of the Northern Apennines. The back-thrust belt of the Alpine orogen is interpreted as the seat for the development of the west-directed Apenninic subduction. The Alpine belt was progressively boudinated and deformed by the back-arc extension of the Apenninic subduction. H. F. is the speculated (A–B–C) and observed (D) heat flow evolution across the area at the different times (after Doglioni *et al.* 1998).

the hanging wall of subduction zones. They are notably well developed in the western Pacific (Karig & Sharman 1975; Zonenshain & Savostin 1981; Honza 1995), and they are particularly associated with west-directed subduction zones (Uyeda & Kanamori 1979; Doglioni 1991). The back-arc basins have shape, subsidence rates and timing which strongly differ from linear, Atlantic type, rift zones. They are characterized by semicircular or triangular shape (Fig. 1), the highest subsidence rates for extensional environments (up to 600 m Ma^{-1}), and they have ages ranging mainly from early Tertiary to Recent (Doglioni 1995; Honza 1995). West-directed subduction zones are always associated with a back-arc basin in the hanging wall of the subduction to the west. The extension in the back-arc propagates eastward like the roll-back of the subduction zone. The basins are often floored of oceanic crust which is also rejuvenating toward the east (e.g. Parece Vela basin, Caribbean sea and western Mediterranean, Westbrook & McCann 1986; Honza 1995).

The western margin of the back-arc basin has a convexity opposed to that of the subduction arc, i.e. toward the west (Fig. 1). In other words the shape of the back-arc in some way mirrors the one of the main arc. The re-entrance of the western margin of the back-arc basin is particularly visible on the Asian margins of the Japan sea and the South China sea, and the Cordillera margin of the Caribbean sea. The westernmost initiation of the back-arc extension probably corresponds to the latitude of the location of the first onset of the W-directed subduction to the east and in the end to the largest amount of subducted slab and the widest back-arc extension.

Back-arc basins have maximum width variable between 800 and 1500 km. The maximum and minimum widths of the back-arc basin correlate to the west at the maximum and minimum amount of subduction present to the east. For instance the largest opening of the Tyrrhenian sea corresponds to the deepest part of the Apennines slab.

During back-arc spreading, blocks moved eastward and rotated both clockwise (southern arm) and counterclockwise (northern arm). See the well described counterclockwise rotation of the Sardinia–Corsica continental block (Montigny *et al.* 1981; Vigliotti & Kent 1990), and the clockwise rotation of the Balearic promontory (Parés *et al.* 1992). Moreover the increasing length of the arc (Fig. 7) should be responsible for an extensional stress parallel to the arc direction (Doglioni 1991). This should have generated along strike boudinage of the lithosphere like for instance in the Balearic promontory which is stretched both in NW–SE direction (main back-arc boudinage) and along the NE–SW direction (boudinage along the strike of the arc). The southern back-arc settings of the western Mediterranean are characterized by diffuse left-lateral transtension, whereas the associated North African accretionary wedge developed in a context of right-lateral transpression. On the other side, the Provençal and northern Tyrrhenian sea were controlled by a diffuse right-lateral transtension while the frontal Apenninic accretionary prism formed in a regime of left-lateral transpression. These tectonic settings regularly occur in W-directed subduction systems (Fig. 1).

There is more and more evidence that the eastward migration of the back-arc extension is accommodated by asymmetric rifting, with low-angle normal faults dipping to the east. These faults have been recognized in the western Mediterranean back-arc setting, e.g. in the western margin of the Provençal basin (Benedicto *et al.* 1996), along the eastern margin of Corsica–Sardinia (Jolivet *et al.* 1990), in the northern Apennines (Barchi *et al.* 1997) and in other western Pacific back-arc basins. East-dipping normal faults are usually spaced (10–50 km) and sometimes they isolate large boudins of thicker continental crust generating a lithospheric boudinage both in the Pacific, Atlantic and Mediterranean back-arc basins (Daniel *et al.* 1996; Gueguen *et al.* 1997).

Back-arc spreading associated with the W-directed subductions may develop both within the former orogen or even far into the foreland of the frontal thrust-belt of the earlier E-directed subduction zone, probably as a function of the width of the orogen (e.g. Japan Sea, Valencia trough). Part or the entire orogen of the former ‘E’-directed subduction zone is stretched and boudinated in the hanging wall of the W-directed subduction, in the back-arc region. HT–LP metamorphism associated with asthenospheric wedging in the back-arc underneath the former orogen commonly overprints HP–LT metamorphic assemblages (Jolivet 1993, and references therein). The western Mediterranean back-arc basins associated with the W-directed Apenninic subduction provide a complete set of these variations even along strike in the opening of the back-arc basins oblique to the former Alpine orogen.

Lifetime of west-directed subduction zones

Present W-directed subduction zones developed during the Neogene. Some of them started during the Palaeogene (e.g. Barbados). Generally speaking, they are younger than 50 Ma (usually less than 30 Ma). This does not imply that W-directed subduction zones did not exist before the Tertiary, but simply that they have a fast and short evolution in the geological record, and they may have been overprinted and incorporated by later tectonic settings. A Mid-Palaeozoic analogue of this type of subduction zone could be the Antler orogeny in the western US which has been compared to the Apennines arc (Burchfiel & Royden 1991) or to the Banda arc (Carpenter *et al.* 1994). A short life of the Mid-Palaeozoic Antler orogen has been proposed by Johnson & Pendergast (1981). They have shown that the main deformation occurred during Early Mississippian type. The short life of the W-directed subduction zones is striking when compared to the Andean type of subduction which has been active for hundreds of millions of years. There may be two simple reasons why W-directed subduction zones terminate.

(1) The encroachment of the arc with thick continental lithosphere in the foreland to the east is one case in which the subduction stops due to the high buoyancy values of a thick continental lithosphere which is no subductable. Modification of the subduction retreat might also occur with the arrival of an oceanic volcanic plateau at the subduction hinge (e.g. Ontong–Java). This is the reason for the termination of E-directed subduction zones as well, but in this last case we may observe a real collision between upper and lower plate, collision which does not occur along the arc of W-directed subduction zones because the upper plate always remains westward of the arc, with an eastward motion slower than the roll-back of the subduction hinge. Slowing or termination of W-directed subduction zones due to the presence of thick continental lithosphere in the foreland are the Carpathians, the Antler orogen, and some segments of the Apennines where the heterogeneity of the foreland controlled the different rates of slab retreat (Doglioni *et al.* 1994). The forebulge uplift in the foreland is more developed where the lithosphere decreases its subduction rates along segments of thick continental lithosphere.

(2) The second reason for the end of a W-directed subduction zone or the switch to an E-directed subduction zone of the system is implicit in the kinematics of W-directed subduction zones (Doglioni 1991, 1993). In fact the generation of a back-arc basin introduces two new important lateral discontinuities in the lithosphere at the margins of the basin in the hangingwall of the subduction. Those weak zones are observed to be the main areas of initiation of subduction zones. The presence of those discontinuities can trigger the change in the subduction polarity, e.g. the eastern margin of a back-arc basin with thin or oceanic lithosphere to the west might become the seat for the development of an E-directed subduction zone, like it occurred in the eastern margin of the South China sea. The South China sea is the back-arc basin of the W-directed Philippine subduction, and since late Miocene it developed along its eastern margin an E-directed subduction zone from Taiwan in the north, to western Borneo in the south.

The self generation of those discontinuities in the back-arc basin seems to control the early self destruction of the W-directed subduction zones which alternate repetitively like a yo-yo from W- to E-directed subduction polarity, as it occurred in the western Pacific subduction zones during the Phanerozoic (Doglioni 1993). The young age of the western Pacific W-directed subduction zones is also suggested by the close location of the subduction zones to the Asiatic continental margin: if the subduction zones were older than the Tertiary, considering the high velocity of the eastward retreat of the subduction, they should be positioned far in the middle of the Pacific ocean.

West-directed subduction zones and the westward drift of the lithosphere

On the basis of the hot-spot reference frame a 'westward' drift of the lithosphere relative to the asthenospheric mantle has been suggested (Le Pichon 1968; O'Connell *et al.* 1991; Ricard *et al.* 1991; Cadek & Ricard 1992). Summing the vectors of plate motions in the hot spot reference frame a westward component of the lithospheric motion of a few centimetres per year remains. This 'westward' drift implies that plates have a general sense of motion and that they are not moving randomly. If we accept this kinematic frame, plates are moving along this trend at different velocities toward the 'west' relative to the asthenospheric mantle. Rather than exactly west it would be better to say moving generally 'westward' (SW, WWN, etc.) along flow lines, which undulate and are not E–W parallel (Doglioni 1993).

The roll-back of the slab along W-directed subduction zones implies a substitution of the lithosphere by the mantle. Since the retreat of the subducting lithosphere is eastward directed, an equivalent amount of mantle should move eastward to replace the lithospheric loss. We might argue that vertical motions of the mantle could compensate this loss without to invoke the lateral eastward migration of the mantle, but the steep attitude of the W-directed subduction zones and the strong increase of the viscosity value at the 670 km discontinuity between upper and lower mantle (Hager 1990) make the mantle adjacent to the seismically detectable slab as an isolated system, with inhibited communication among eastern and western sectors of the slab, and the upper and lower mantle underneath. This supports the notion that since the slab retreats vertically toward the east, we should kinematically expect a contemporaneous migration of the mantle located to the east of the slab toward the east as well. This does not exclude that the eastward moving mantle is the cause for the eastward slab retreat and not a consequence of it, but nevertheless a relative eastward mantle flow is kinematically unavoidable. An actively eastward pushing mantle agrees with the westward drift of the lithosphere relative to the asthenosphere detected in the hot-spot reference frame (Ricard *et al.* 1991), and it supports an eastward-oriented push at depth on the slab in order to generate the arcuate shape of the W-directed subduction zones like an obstacle does in a river (Fig. 4). Marotta & Mongelli (1997) demonstrated that the combination of slab-pull, induced flow and eastward relative mantle flow can account for the observed asymmetry among steep W-directed and shallow E-directed subduction zones. The Margheriti *et al.* (1996) seismic polarization data indicate an east–west anisotropy in the Tyrrhenian area. The anisotropy deviates to an Apenninic trend underneath the belt: these data might be an indication of an eastward mantle flow underneath the Tyrrhenian back-arc where the crystals should parallel the direction of mantle movement, and the encroachment with the subduction zone underneath the Apennines where the crystals should reorient due to the obstacle of the subduction.

Thermal state of west-directed subduction zones

The W-directed subduction zones present among the lowest and the highest heat-flow values of the Earth respectively in the foredeep or trench and in the back-arc basin. The low values in the foredeep (down to 30 mW m^{-2}) are due to the deflection of the isotherms with the subduction and to the sediments filling the foredeep, whenever they occur. The accretionary wedge is generally formed of superficial thrust sheets and piggy-back basins mainly made of sedimentary cover and therefore a low thermal gradient is expected. A rapid increase of heat-flow is observed from the foredeep toward the back-arc basin (e.g. in the Southern Apennines, up to 80 mW m^{-2}, Doglioni *et al.* 1996). Back-arc basins are sites of very high surface heat flow, up to 150 mW m^{-2}, which is the consequence of the thinning of the lithosphere. This has generally been so far considered as due to pure-shear extension and therefore characterized by a dome-shaped symmetrical structure (e.g. McKenzie 1978, and later literature). Wernicke (1985) and Lister *et al.* (1991) proposed also an alternative asymmetrical thinning of the lithosphere. A more careful examination of the distribution of the heat-flow in a back-arc basin reveals two important features: (1) the maximum value is not located in the central sector of the basin, but it is laterally displaced eastward, toward the subduction hinge; (2) the heat flow distribution follows that of the sub-basins and boudins with a series of highs and lows. This confirms the hypothesis that the extension of the lithosphere and the upwelling of the asthenosphere is a pulsating phenomenon which occurs following the roll-back of the subducting slab. Probably each sub-basin may open by pure-shear or simple-shear extension. An example is represented by the back-arc basin related to the Apenninic subduction, which is in fact the entire western Mediterranean, where clearly heat-flow data and thermal modelling show that the maximum heat-flow values are encountered in the sub-basins: 120 mW m^{-2} in the eastern Alboran (Polyak *et al.* 1996), 90–100 mW m^{-2} in the Valencia trough (Foucher *et al.* 1992), and more than 200 mW m^{-2} in the Tyrrhenian sea (Réhault *et al.* 1990; Mongelli *et al.* 1991). The eastward migration of the accretionary wedge and the extension following to the west implies that the heat flow continuously propagated with time during the migration of the tectonic fields, generating waves able to create alternances of relative ‘cold’ and ‘hot’ moments in the same areas.

Coexisting compression and extension along west-directed subduction zones

The active accretionary wedge is followed by an extensional wave cross-cutting the thrusts and folds previously formed in the accretionary wedge. The Apennines are a natural laboratory where to study the interplay between compression and extension (see for example Fig. 8). The extension has been very well described in the deep seismic profile Crop 03 of the northern Apennines (Barchi *et al.* 1998) and it shows an asymmetric character with mainly E-dipping undulated normal faults. It has always been a task to interpret the coexistence of this tectonic pair (Lavecchia *et al.* 1994). Here we propose a kinematic interpretation based on the shape and kinematics of the W-directed subduction zones. Back-arc extension develops as soon as the subduction starts, suggesting prevalent mechanical controlling factors. The subduction induces a mantle motion around the slab that enhances the shear stress and the mantle drag at the base of the lithosphere. This shear has a strong decrease moving westward away from the subduction hinge and it could explain why east-dipping normal faults in the hanging wall of the subduction nucleate on top of the mantle wedge at the subduction hinge (Fig. 10). This shear stress can be viewed either as a resistive force or as a driving force in plate dynamics depending

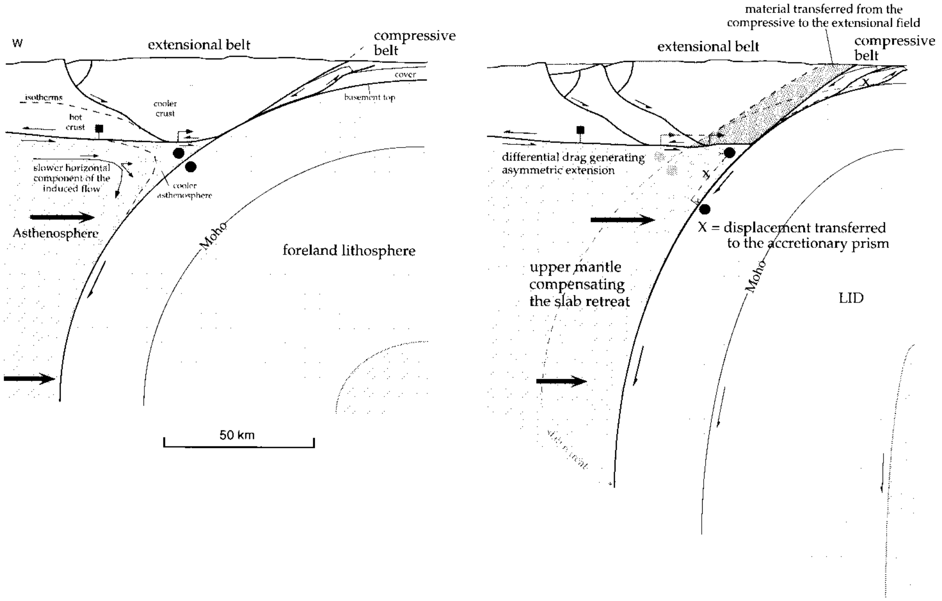

Fig. 10. Kinematic model for the association compression–extension of W-directed subduction zones as the Apennines. The extension in the hangingwall of a W-directed subduction may be attributed to the differential drag between the eastward intruding asthenosphere and the overlying relict crust. The differential drag may be controlled by the slower horizontal component of the mantle flow induced by subduction near the mantle wedge, and by thermal constraints. The shortening in the accretionary wedge can be explained as related to the shear between the downgoing and retreating lithosphere and the eastward compensating upper mantle. The displacement is transferred upward and peels-out the cover from the foreland lithosphere. Note the different trajectory of the two black spots in the asthenosphere and at the top of the slab.

on its magnitude and direction with respect to plate motion. In case of a W-directed subduction, the relative eastward relative asthenospheric flow would add its effect to that of the induced flow in the back-arc region while in case of an E- or NE-directed subduction it would counteract the induced flow effect.

On the other hand, the shortening in the accretionary wedge can be explained as related to the shear between the downgoing and retreating lithosphere and the eastward compensating mantle. This displacement is transferred upward to the east and peels off the cover from the foreland lithosphere (Fig. 10). This kinematic model for the eastward migrating compression–extension pair is triggered by the subduction roll-back and by the simultaneous asthenospheric replacement (Fig. 10).

Volume of the accretionary prism

According to the proposed evolution, the Apennines developed to the east of the former Alpine–Betic orogen. We tried to compute the amount of crust involved in the accretionary prism. The thickness of the Apenninic crust is paradoxically often smaller than the thickness of the foreland crust. In Calabria the crust can be 17 km thick (Scarascia *et al.* 1994). Assuming a roll-back of about 800 km and an average of 4.5 km of the sedimentary cover of the downgoing lithosphere, an area of about 3500 km^2 results for the cover alone. The present crustal area of the Apennines along the same transect is about 2900 km^2 (Fig. 11). In other words, the crustal area is smaller than the area predicted for the sedimentary cover, which suggests that the accretionary wedge cannot contain significant involvement of the crystalline basement since the cover itself is not reaching the entire expected area (Fig. 11). It can correctly be argued that part of the Apennines have been eroded, but the amount of area eliminated by the erosion has to be very little in this belt where the vitrinite reflectance data indicate that the Apennines were never significantly overburden (Corrado 1995). Part of the Apenninic volume might have been lost by along strike extension. Still the crustal thickness of the Apennines remains too small to invoke large slices of

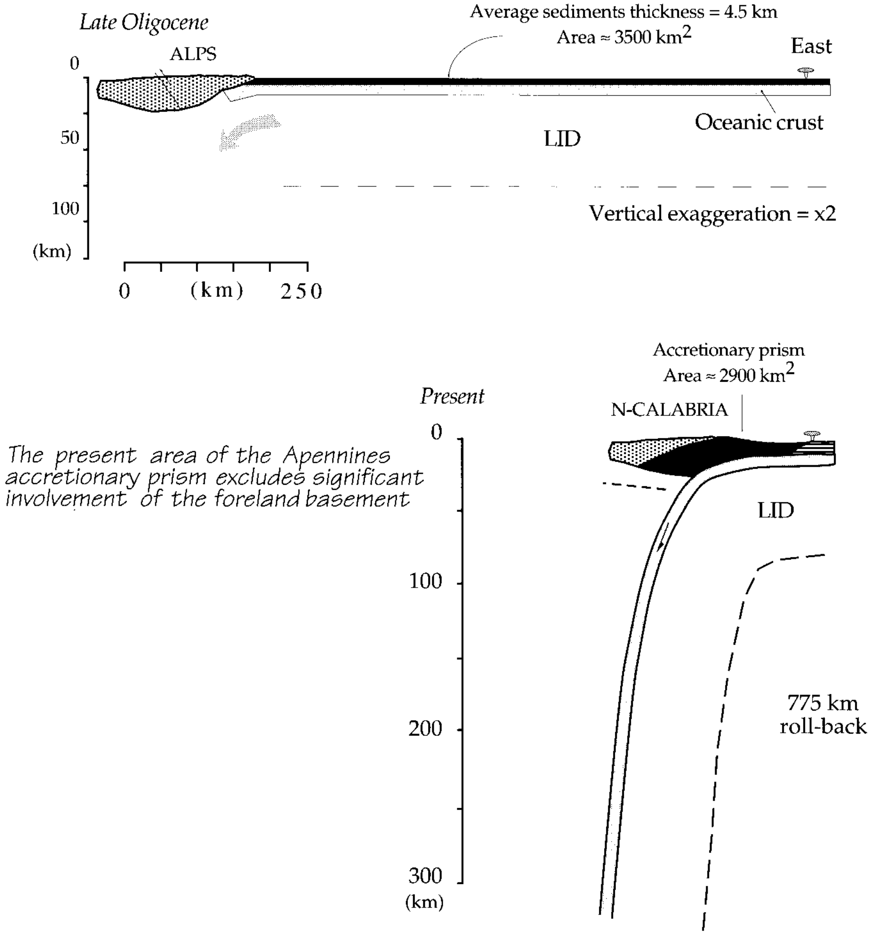

Fig. 11. The area of the Apennines accretionary prism is smaller than the area calculated for the sedimentary cover originally present on the subducted plate. Erosion and along strike extension contribute to this decrement. However the small area of the accretionary prism excludes significant involvement of the foreland basement. The thickness of the pre-subduction sedimentary cover is computed conservatively as a mean value of the different paleogeographic domains such oceanic, platform and basinal facies on the continental passive margin of the Apulia plate.

basement involved in the accretionary wedge. See Fig. 10 for an interpretation of the kinematics of the main basal décollement zone of the accretionary wedge which shows the absence of a classic 'vertical' back-stop. The compression can be generated by the shear between the mantle moving horizontally and the downgoing lithosphere (Fig. 10). Unlike the delamination model, this model indicates that not only the lithospheric mantle is subducted in a west-directed subduction, but also the largest part of the crust, apart the main body of the sedimentary cover (Doglioni 1991), as also supported by the geochemical signatures in the calkalcaline magmas of the volcanic arc (e.g., Peccerillo 1985; Serri *et al.* 1993).

Conclusions

West-directed subduction zones are peculiar geodynamic settings that should be differentiated from the other subduction zones. They form very fast and are short lived. They have an internal kinematics shaped by the particular behaviour of the décollement zones, probably due to the global polarity generated by the westward drift of the lithosphere with respect to the asthenosphere. The so-called upper plate may not actively thrust the footwall plate, particularly in those W-directed subduction zones that developed without E–W convergence.

The Apenninic W-directed subduction zone nucleated along the east-verging back-thrust belt of the earlier Alpine–Betic orogen, where a flip in the subduction polarity from E- to W-directed took gradually place probably during the Early Miocene. During the Neogene and Quaternary, the Apenninic arc migrated up to about 800 km on its most advanced northern Calabrian parts. With this scenario, the about 100 km N–S Africa–Europe relative convergence during the same time appears to be of about eight times lower importance with respect to the E- or W-directed subductions in shaping the western Mediterranean. The western Mediterranean is the Apenninic subduction-related back-arc basin formed during the eastward retreat of the W-directed slab. Boudins of continental lithosphere were dispersed and stretched in the back-arc setting (Fig. 6). The boudinage occurred from the late Oligocene in the westernmost parts (Alboran, Valencia and Provençal basins) up to now to the east (eastern Tyrrhenian sea). These observations indicate the back-arc area is punctuated by jumps in the spreading position (Fig. 3) which have also been recorded by the magmatic suites.

The westernmost basins of the Mediterranean developed obliquely to the Alpine–Betic orogen because the extension nucleated both within the pre-existing Betic cordillera (e.g. Alboran sea) and in its foreland (Valencia and Provençal troughs), being the direction of grabens oblique to the partly coeval orogen and showing its structural independence from the orogenic roots (Fig. 7). The kinematics imposed by the slab retreat can account for the tectonic pair thin-skinned compression in the accretionary wedge and thick-skinned extension in the belt to the west following and cross-cutting the accretionary wedge (Fig. 10). The small amount of relic crust now observable in the hangingwall of the subduction suggests that the largest part of the foreland crust has been subducted (Fig. 11).

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