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Arc-trench-back arc systems in the Mediterranean area: examples of extrusion tectonics

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Abstract: The hypothesis that trench-arc-back arc migrating systems in the Mediterranean area developed as extrusion processes, driven by the convergence of the confining plates, i.e. Africa, Arabia and Eurasia is discussed. This kind of process occurs in the zones where an accretionary belt obliquely collides with a strong buoyant block. This collision induces in the belt a compressional regime parallel to its main trend, which is accommodated by an outward extrusion/bending of the belt (arc), at the expense of an adjacent low buoyancy domain. In the zone where the bending arc separates from the overriding plate, crustal extension occurs, with the generation of a back arc basin. It is argued that the dynamic and structural conditions implied by the proposed mechanism may be recognized in the Mediterranean tectonic contexts which led to the strong distortion and migration of orogenic systems, both in the western and eastern Mediterranean regions, and to the consequent generation of the Balearic, Tyrrhenian, Aegean and Pannonian basins, in the wake of the respective migrating arcs. The proposed interpretation allows to find simple, coherent and plausible explanations for the complex space-time distribution of tectonic events observed in the study area. It is also argued that the implications of the most quoted alternative explanation of back arc opening, i.e. the slab pull model, cannot easily be reconciled with several major features of the observed deformation pattern.

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Introduction

The Tertiary evolution of the Mediterranean region has been characterized by the large migration of orogenic belts (arcs) and by the opening of basins in the wake of the migrating arcs (e.g. Biju-Duval et al., 1977; Dewey and Sengor, 1979; Le Pichon and Angelier, 1979; Dercourt et al., 1986; Royden, 1993 a,b; Sengor, 1993; Mantovani et al., 1997, 2000a). This complex of interconnected tectonic processes is generally called trench-arc-back arc (T-A-BA) system. Numerous hypotheses have been advanced about the dynamics of this phenomenon, but none of them is widely accepted. Two main types of interpretations may be recognized. One postulates that arc-trench migration and back arc extension are driven by subduction-related forces, with particular regard to the negative buoyancy (slab pull) of the subducted lithosphere (e.g. Malinverno and Ryan, 1986; Royden, 1993a,b). The other type of model suggests that T-A-BA systems are closely connected with extrusion processes, induced by the interaction of buoyant structures in constrictional tectonic contexts (Tapponier, 1977; Mantovani et al., 1997, 2000a).

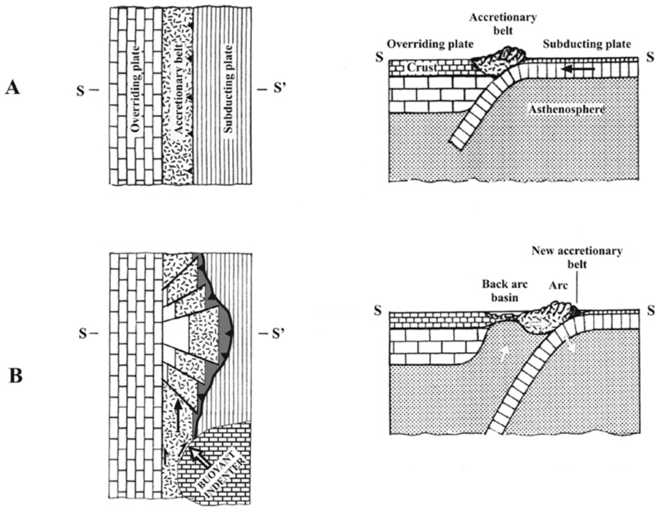
The outstanding problems created by the adoption of subduction-related models in the world have been pointed out in several papers (e.g., Uyeda and Kanamori, 1979; Taylor and Karner, 1983; Uyeda, 1986; Mantovani et al., 1997, 2000a, 2001a; Flower et al., 2001). In particular, it has been argued that this kind of mechanism cannot easily provide plausible explanations for a number of basic features, as e.g. the fact that back arc extension occurs in some subduction zones and not in others, that in a number of consuming boundaries subduction is still active while back arc extension ceased several My ago, that back arc basins only develop along a limited sector of the convergent plate boundary and that arcs are often characterized by a considerably arcued shape. Furthermore, the attempts at quantifying subduction-related forces by numerical and analogue modelling suggest that slab pull forces are too weak to produce extensional deformation in the overriding plate, unless it has been previously weakened and its mechanical coupling with the subducting plate is very weak (Shemenda, 1993; Hassani et al., 1997). Even in the case that the above conditions are fulfilled, a minimum slab length (about 300 km) is required to initiate the slab roll back and the consequent back arc extension (Hassani et al., 1997).

As regards the Mediterranean area, we have argued in previous papers (Mantovani et al., 1997, 2000a, 2001a) that the slab pull model cannot easily explain the space-time distribution of deformation observed in this region and that the extrusion model offers much better chances to achieve such result. However, none of our previous attempts provides a definitive proof of the reliability of the proposed model, since most of the supporting arguments are necessarily qualitative and the nature and timing of the observed deformation are affected by considerable uncertainty. Not even the quantitative arguments we have provided in support of our viewpoint, by numerical modelling (Mantovani et al., 2000b, 2001b), may overcome this problem, since they are obtained by procedures based on a number of tentative assumptions about the properties of the model adopted. Thus, the way towards a satisfactory understanding of the Mediterranean geodynamics must be patiently developed through a series of attempts, involving a progressive improvement of the recognition of the most significant tectonic events and of their consistency, as concerns timing and location, with the implications of the proposed interpretational scheme. This work describes a further effort in this direction. With respect to previous attempts, we try to provide a clearer explanation of the proposed genetic mechanism of T-A-BA systems and of the possibility to recognize its implications in the Mediterranean zones where the major back arc basins opened up. We also report new arguments about the (poor) compatibility between the expected consequences of the slab pull model and the observed deformations in the Mediterranean area.

Extrusion model

The mechanism we propose (Fig.1) generally occurs along a sector of a consuming border, where the accretionary belt, under the action of a longitudinal compression, undergoes a trenchward extrusion and partly separates from the overriding plate. This separation is accommodated by crustal stretching in the back arc zone. Simultaneously, the outward migration of the deforming belt (arc) causes the roll back of the slab lying in front of it (Fig.1). The tectonic context which produces the deformation of the arc may be quite different from case to case. Most often, this phenomenon occurs when a mechanically strong and buoyant structure enters a sector of the consuming border, with a direction of motion not perpendicular to the trench. In this oblique constrictional context, the accretionary belt undergoes a longitudinal compression, which is accommodated by its outward extrusion/bending, at the expense of the adjacent lithospheric domain. The occurrence of this mechanism requires that the buoyancy of the accretionary belt is significantly higher than that of the lithospheric domain lying in front of it. For instance, the lateral extrusion of the arc is strongly favoured when it faces a very old oceanic lithosphere, since this kind of structure, as the Ionian and Levantine oceanic domains, is presumably characterized by very low, or even negative, buoyancy (e.g., Cloos, 1993). Another basic condition for the formation of a back arc basin with this mechanism is the brittle behavior of the belt, which allows the formation of relatively large crustal wedges, decoupled by major strike slip faults (Fig. 1). If this condition is not fulfilled, the extruding material would tend to occupy the entire space available and, thus, it would not allow the separation of the arc from the overriding plate and the consequent back arc opening. The above property may be found, for instance, in a accretionary belt, since this kind of structure is entirely constituted by a buoyant and brittle upper crustal material, scraped off a subducting lithosphere.

Figure 1. Sketch of the extrusion model



Sketch of the extrusion model here proposed as genetic mechanism of back arc extension. Up) Structural/tectonic setting which may precede the opening of a back arc basin. Subduction (black arrows) occurs along a convergent plate border leading to the formation of an accretionary belt. Down) Dynamic conditions required for the generation of a back arc basin. Due to oblique collision with a buoyant indenter, the belt is stressed parallely to its main trend (black arrow). The related shortening is accommodated by the lateral expulsion of crustal wedges, which results in a outward bending of the arc, at the expense of the adjacent low buoyancy lithosphere. The divergence between the arc and the overriding plate causes crustal stretching in the back arc zone. The geodynamic framework which may induce a longitudinal compression in the belt may be quite variable from case to case, as discussed in the text. The trenchward migration of the arc and the consequent roll back of the slab attract asthenospheric material from the surrounding mantle. (Click for enlargement)

The importance of extrusion processes in the generation of back arc basins has already been stressed by a number of authors (e.g. Tapponnier, 1977; McCabe, 1984; Tapponnier et al., 1986; Uyeda, 1986; Lavé et al., 1996; Mantovani et al., 1997, 2000a, 2001a). The physical plausibility of this kind of mechanism has been demonstrated by analitical computations and by analogue and numerical modelling (Tapponnier et al., 1982; Peltzer and Tapponnier, 1988; Ratschbacher et al., 1991; Faccenna et al., 1996; Mantovani et al., 2000b, 2001b).

As argued by Mantovani et al. (2001d), the extrusion model may provide plausible explanations of the major features of T-A-BA systems in the world and may help to overcome the outstanding problems of subduction-related interpretations.

In the next sections we discuss on how the conditions required for the occurrence of this mechanism may be recognized in the Mediterranean zones where T-A-BA systems developed. To help the identification of the structural/tectonic elements mentioned in the discussion, with respect to their paleotectonic contexts, the evolutionary reconstruction proposed for the study area is reported in Figs.2 and 3.

Western Mediterranean T-A-BA system

Around the late Eocene-early Oligocene the border zone between the western European foreland and the western Apulian region was constituted by an orogenic/metamorphic belt (Iberian, in Fig.2a) built up by the consumption and closure of the Tethyan oceanic domain (Cohen, 1980; Dercourt et al., 1986; Finetti et al., 2001). Around the early Oligocene, the central sector of this belt, along with a fragment of the European foreland (the Corsica-Sardinia microplate), detached from Western Europe, and extensional tectonics began in the Balearic basin (Fig.2b). After this detachment, the Balearic arc underwent a long east to SEward migration and a considerable bending, up to reach the final configuration shown in Fig.2c. The major features of the kinematic reconstruction of this T-A-BA system shown in Fig.2 are widely recognized (e.g. Cohen, 1980; Rehault et al., 1984; Dercourt et al., 1986).

Figure 2 Tentative reconstruction of the Mediterranean evolution for the period Oligocene-middle Miocene. This evolutionary phase has been characterised by a profound tectonic reorganisation of both the western and eastern Mediterranean regions, where the Balearic and Pannonian basins opened up. Extensional tectonics also occurred in the Northern Aegean and northwestern Anatolian zones. 1,2,3,4) Eurasian and African-Apulian domains, reported with the present size (corresponding to that reported in Fig. 3c, 1) and 2) respectively identify the continental and thinned parts of the Eurasian domain, 3) and 4) the continental and thinned parts of the African/Apulian domain. 5) Parts of the Eurasian and African margins which will be consumed during the successive evolution. 6) Zones affected by moderate (a) or intense (b) crustal thinning. 7) Orogenic belt built up by the closure of the Tethys Ocean, constituted by oceanic remnants, metamorphic bodies and crystalline massifs. 8,9) Accretionary belts constituted by units of the European and African domains respectively. 10) Compressional features. 11) Transcurrent fault, active (a) and inactive (b). 12) Normal faults. A) Oligocene paleogeographic setting. B) Lower Miocene: SC= Sardinia-Corsica block, V=Vardar zone. C) Middle Miocene. A=Albanides, Ca=Calabria, DSF=Dead Sea Fault, WG=Western Greece.

The kinematic patterns of Africa and Arabia adopted in the maps are based on the evidence and arguments given by Dercourt et al. (1986), Hempton (1987), Albarello et al. (1995), Mantovani et al. (1997, 2000a,b, 2001b). Motion rates are only indicative. Present geographical contours and the paleoposition of the African, Sardinia and Corsica coastal line are reported for reference in each evolutionary phase. (Click for enlargement)

Here we hypothesize that the detachment of the Iberian belt from Western Europe was driven by the SW-NE Africa-Europe convergence, after the collision of the southwestern edge of this belt with the African continental domain (Fig.2a), roughly connected with Morocco (Le Pichon et al., 1988; Sengor, 1993). The arc parallel compression induced by this oblique plate convergence implied a longitudinal shortening of the belt, which was accommodated by its outward bending/extrusion, at the expense of the Western Apulian domain, recognized as an oceanic low buoyancy zone (Beccaluva et al., 1994; Doglioni et al., 1999). Extensional tectonics developed in the wake of the extruding arc, with the formation of the Balearic back arc basin. This process progressively slowed down and ceased as more and more eastern sectors of the southern migrating arc (Iberian-Maghrebian belt) collided with the African continent, along the Algero-Tunisian sector (Fig.2b,c). Extension in the Balearic basin finally ceased around the middle Miocene (12-13 My), when the Corsica-Sardinia microplate underwent a complete stop. At the end of this evolutionary phase (Fig.2c), the western Mediterranean region was characterized by a structural/tectonic setting not much different from the present one (e.g. Rehault et al., 1987; Dercourt et al., 1986; Vigliotti and Langenhein, 1995).

To evaluate the reliability of the driving mechanism here proposed and to understand if it can offer better chances to explain the observed deformation with respect to the slab pull model, it may be useful to make some considerations about the expected differences between the deformation patterns implied by these two types of interpretation. The most evident differences are expected in the migrating arc, since the extrusion model (Fig.1) predicts a shortening of the arc in the direction of the driving stress, whereas the slab pull model implies the lengthening and disruption of the original belt. Another important difference is expected in the back arc basin, since the slab pull model predicts a pure extensional, trenchward oriented, strain regime, whereas the extrusion model involves a transtensional tectonics due to the simultaneous action of dominant trenchward extension and perpendicular compression (e.g. Philip, 1987). Minor differences are expected, instead, in the external part of the arc, where both models predict slab roll back under the advancing arc and consequent accretionary activity along the trench.

Here, we argue that the major features of the arc deformation pattern observed in the western Mediterranean area (Fig.2b,c) can more easily be reconciled with the implications of the extrusion model on the basis of the following evidence and arguments:

- The tectonic structural setting of the Balearic basin, reconstructed by seismic surveys (see, e.g., Rehault et al., 1984, Fig.3) is characterized by a series of crustal wedges, decoupled by strike slip faults, as shown in Fig. 2c, with an overall geometry of the arc very similar to that predicted by the extrusion model (Fig. 1). It is hard to believe that the migration of such a fractured arc, while maintaining the ordered distribution and close contact of wedges shown by the present configuration (Fig. 2c), may have been produced by a driving mechanism not involving any longitudinal compression of the belt, as the one implied by the roughly eastward roll-back of the Apulian slab.

• The strong bending that the Balearic arc underwent during its migration, changing from a more or less straight configuration (Fig.2a) to the final shape characterized by two almost perpendicular sectors (Fig.2c), could be seen as a shortening process able to accommodate the SW-NE convergence between Africa and Europe. Instead, to interpret such bending as an effect of slab pull forces, one should explain why the rate of trench retreat was higher in the central part of the arc with respect to its peripheral segments. This explanation must necessarily invoke a peculiar distribution of densities in the roll backing slab or other ‘ad hoc’ structural/geometrical conditions of the subduction process, which should be supported by observational evidence. Other considerations about this last problem are given by Mantovani et al. (2001d).

• A sinistral transpressional deformation is recognized in the Iberian belt during the collisional phase which preceded the detachment of this belt from Western Europe (Marroni and Treves, 1998; Finetti et al, 2001). This kind of strain regime is consistent with the oblique Africa-Europe convergence suggested by our interpretation. This agreement between predicted and observed features is also corroborated by the fact that the successive extensional phase along this plate border was characterized by a sinistral transtensional regime (Finetti et al, 2001). This kind of deformation is not predicted by the slab pull driving mechanism, which would only involve a trenchward extensional regime.

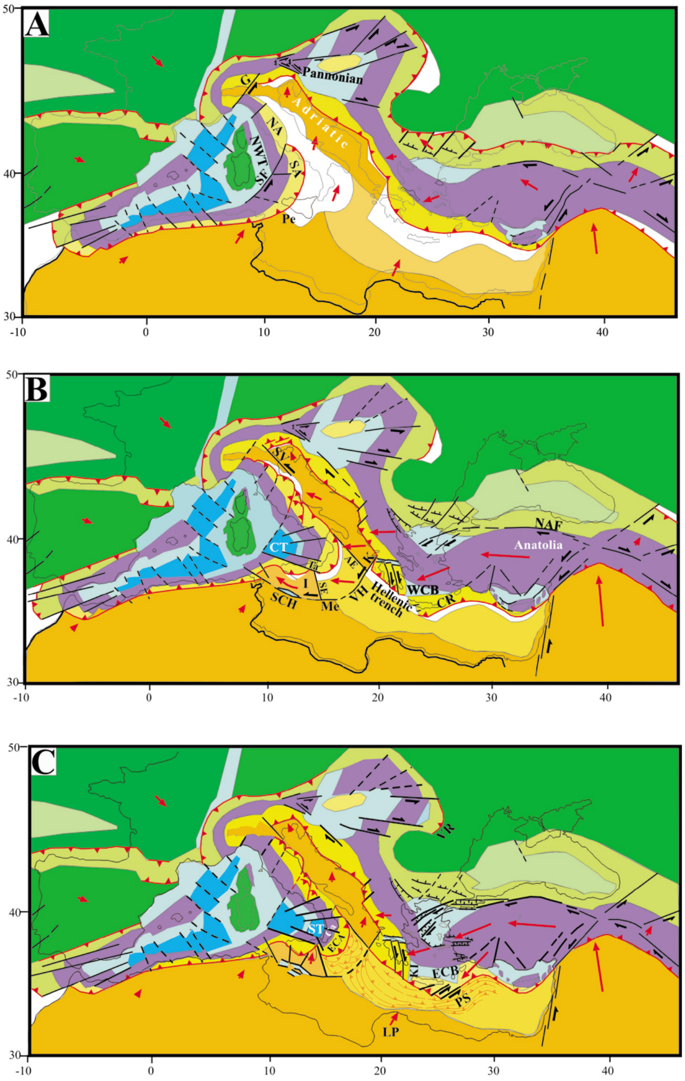
A severe difficulty for the slab pull model, in this T-A-BA system, is the fact that the development of the Apulian slab (i.e. the one which formed during the opening of the Balearic basin) began simultaneously with the onset of arc migration in this area. In fact, on the basis of geological and petrological evidence, a number of authors suggested that the previously active consuming process at this plate border involved the subduction of the northern European domain under the southern Apulian one (Cohen, 1980; Rehault et al., 1984; Doglioni et al., 1999). This would mean that the starting of back arc extension in the Balearic basin coincided with an inversion of the subduction vergence at that plate border and, that, consequently, the new embrional NWward dipping slab could not certainly induce back arc extension by a slab pull mechanism.

Another significant feature of the Balearic arc is the strong curvature that it shows in the segment comprised between the western Alps and Corsica (Fig.2c). To explain such strong distortion, it seems necessary to assume a roughly northward displacement of the belt, in line with the evidence mentioned in the previous point and with the proposed arc parallel compression.

Carpatho-Balkan-Pannonian T-A-BA system

Most evolutionary reconstructions of this zone (e.g., Burchfiel, 1980; Burtman, 1986; Royden and Burchfiel, 1989; Fodor et al., 1998) suggest a progressive outward migration of the Carpathian arc (35-6 My), at the expense of a low buoyancy zone of the European foreland through a deformation pattern similar to that shown in Figs.2 and 3. In the internal part of this arc, trans-tensional tectonics took place, with the generation of the Pannonian basin. During the Oligocene-early Miocene (35-17 My), major shear zones allowed the east to northeastward displacement of crustal wedges in the northern part of the Pannonian area, while during the middle-upper Miocene (16-6 My) eastward migration of crustal wedges mainly occurred in the southern Pannonian region (e.g. Royden and Burchfiel, 1989; Fodor et al. 1998).

Figure 3. Tentative reconstruction of evolution of the Mediterranean



Tentative reconstruction of evolution of the Mediterranean since the late Miocene, characterised by a profound reorganisation of the central and eastern regions, which respectively led to the formation of the Tyrrhenian and Aegean basins. Symbols as in Fig.2. A) Late Miocene: G=Giudicarie trans-pressional fault system, NA, SA=Northern and Southern Apennines, NWT=Northwestern Tyrrhenian, Pe=Pelagian zone, SF=Selli fault. B) Late Pliocene: AE=Apulian escarpment, CR=Crete-Rhodes, CT=Central Tyrrhenian (Magnaghi-Vavilov basin), K=Kefallinia fault, I=Iblean-Ventura microplate, Me = Medina fault, NAF=North Anatolian fault system, SCH=Sicily channel fault system, SE=Siracusa escarpment, SV=Schio-Vicenza Line, Ta=Taormina fault zone, WCB=Western Cretan basin. C) Present: Ca=Calabrian wedge, ECA=External Calabrian Arc, ECB=Eastern Cretan basin, KI=Kithira trough, LP=Lybian promontory, PS=Pliny and Strabo trenches, ST=Southern Tyrrhenian (Marsili basin), VH = Victor-Hensen fault, VR=Vrancea zone. See text and the caption of fig.2 for plate kinematics. (Click for enlargement)

We advance the hypothesis that the development of this T-A-BA system was connected with an extrusion process, induced by the indentation of the Arabian plate (moving faster than Africa, since the lower Miocene, Hempton, 1987) against the wide orogenic system built up by the closure of the Tethyan ocean and by the consumption of the adjacent African and Eurasian margins. This system was constituted by three parallel belts (Fig.2a): a northern accretionary chain with European affinity (Carpathians-Balkanides-Pontides) and a southern one with African affinity (Dinarides-Hellenides-Taurides), separated by an inner zone (Tethyan belt) constituted by oceanic remnants, metamorphic bodies and crystalline massifs (i.e. the Pelagonian, Aegean and Anatolian) as suggested by a number of authors (e.g. Brunn, 1976; Biju-Duval et al., 1977; Boccaletti and Dainelli, 1982; Burtman, 1986; Royden and Burchfiel, 1989).

It is widely recognized that the indentation of Arabia caused the lateral escape of Anatolia (e.g., Mckenzie, 1972; Dewey and Sengor, 1979). However, we think that this extrusion process did not only involve Anatolia, since this zone still constituted an integral part of the long orogenic system mentioned above. Thus, the overall effect of this extrusion involved the migration and distortion of the whole Tethyan belt and of the adjacent chains, from the eastern Anatolia to the Carpathians, as tentatively reconstructed in Fig.2. This hypothesis is suggested by the fact that the Tethyan belt has maintened its original continuity till to the present (Fig.3c), in spite of the considerable deformation it underwent. In the first phase (Fig.2b), the lateral escape of Anatolia was oriented roughly NWward , guided by a system of major dextral shear zones (Dercourt et al.,1986; Hempton, 1987; Finetti et al.,1988). This displacement of Anatolia and of the whole Tethyan system was accommodated by the lateral NEward extrusion of orogenic wedges in the Carpathian arc, at the expense of a low buoyancy sector of the European foreland, and by a SWward bending of the Aegean arc, at the expense of the Ionian-Levantine old oceanic lithosphere. In the wake of the outward migrating crustal wedges in the Carpathian arc, transtensional deformation took place in the Pannonian area (Figs.2b,c).

During this phase, longitudinal shortening also occurred in the Balkanides, accommodated by the NEward lateral escape of crustal wedges, at the expense of the southern Moesian margin (e.g. Stanishkova and Slejko, 1991). Since the proposed pattern (Fig.2b) provides that the NWward displacement of the Balkanides-Carpathian belt is greater than that of the inner Pelagonian massifs, one should expect a left lateral decoupling between these belts. The imprints of this decoupling might be represented by the sinistral shear deformation recognized in the Vardar zone for the period involved (e.g. Brunn, 1960, 1976; Burtman, 1986; Zeilinga de Boer, 1989).

The development of the Carpathian T-A-BA system underwent slowdown/cessation as the arc collided with the continental European domain, with a progressive evolution of this stop from north to south (e.g. Royden, 1993b). At present, minor tectonic activity in this arc only occurs in its southernmost corner, in the Vrancea zone.

The deformation pattern of the Carpathian-Pannonian system appears to be consistent with the dynamic implications of the extrusion model, since the overall shape of the Carpathian arc strongly resembles that of a large crustal wedge, extruded in response to a SE-NW compression. Also, one could note that the outer part of this arc is longer than the internal one, in line with the deformation pattern predicted by the simulation of extrusion processes (e.g., Ratschbacher et al., 1991; Faccenna et al., 1996; Keep, 2000; Sokoutis et al., 2000). The presence of a system of strike slip faults in the Pannonian area is consistent with the proposed driving mechanism, which implies the simultaneous action of a SE-NW compression and of a perpendicular extension.

Instead, the above deformation cannot easily be reconciled with the pure SW-NE extension predicted by the slab pull mechanism. Furthermore, one should consider that arc migration driven by slab pull would imply fragmentation and longitudinal interruption of the initial orogenic belt. Instead, the present configuration of this arc (Fig.2) clearly shows that its various segments have remained in close contact during the evolution.

The timing of this T-A-BA system (e.g., Royden, 1993b) can be plausibly related with the proposed driving mechanism, i.e. the indentation of Arabia. In fact, the most intense tectonic activity in the Carpatho-Balkan-Pannonian area just followed the activation of the tectonic zones which allowed the decoupling of the Arabian promontory from Africa, with particular regard to the Red Sea rifting zone and the Dead Sea fault system (e.g., Hempton, 1987). Instead, the implications of the slab pull mechanism do not provide any precise justification for the onset of slab roll back in the Carpathian arc around the late Oligocene-early Miocene. The consuming process under the Carpathian belt seems to have begun much earlier, at least in the Paleocene (Royden and Baldi, 1988; Dercourt et al., 1986), and thus one should explain why slab roll back has not occurred prior to the Miocene.

Furthermore, we think, on the basis of the arguments already pointed out in the discussion of the Western Mediterranean T-A-BA system, that the remarkable bending that the Carpathian arc underwent cannot easily reconciled with a slab pull driving mechanism.

Miocene Aegean T-A-BA system

As argued earlier, another effect of the extrusion of the Tethyan, in front of the Arabian indenter, was the westward displacement and southward bending of the Aegean arc (Fig.2b,c). Due to this deformation, the Aegean massifs (Cyclades) and the Hellenides belt separated from the Balkanides, causing extensional deformation in the north Aegean and northwestern Anatolian regions (Fig.2b,c), as indicated by geological and volcanological evidence (Fitykas et al., 1985; Sengor et al., 1985; Mercier et al., 1989; Jolivet et al. 1994; Seyitoglu and Scott, 1996), which suggests a progressive south to SWward migration of extension. The southward bowing of the Aegean arc and the consequent consumption of the Ionian-Levantine lithosphere, is testified by the Miocenic accretionary activity recorded along the Hellenic trench zone (e.g; Finetti, 1976; Le Pichon and Angelier, 1979; Le Pichon et al., 1988; Mercier et al., 1989).

The westernmost edge (and hinge zone) of the Aegean arc roughly corresponded to the Albanides, i.e. the transition zone between the Dinaric sector of the belt, where the Adriatic plate was already sutured to the Tethyan system, and the Hellenic sector, where the consumption of the last part of the pre-Apulian zone was still going on (e.g., Mercier et al., 1989). This interpretation is suggested by geological, morphological and paleomagnetic data (Kissel et al., 1995) which indicate a clockwise rotation of the Albanides-Western Greece zone with respect to the Dinarides, since the lower-middle Miocene.

Some authors (e.g., Le Pichon and Angelier, 1979; Jolivet et al., 1994; Le Pichon et al., 1995) argued that the occurrence of extensional strain in the Aegean region during the lower-middle Miocene demonstrates that the tectonic evolution of this region cannot be taken as an effect of the westward escape of Anatolia, since at that time the western segment of the North Anatolian fault (NAF) was not formed yet. However, we think that this argument could be uncorrect since the kinematic reconstruction reported in Fig.2 shows that even the Miocenic extension in the Aegean zone may causally be linked with the lateral escape of Anatolia (and of the Tethyan belt). In fact, during this phase the westward motion of Anatolia did not require any decoupling from the northern domain (Pontides), since this last chain was participating the migration of the whole Tethyan belt. The activation of the western NAF, as right-lateral guide of the westward escape of Anatolia, became instead unavoidable around the late Miocene, when the mobility of the Pontides decreased considerably after the continental collision of the Carpathian arc with Eurasia (Sengor, 1993).

Tyrrhenian T-A-BA system

The structural evolution of this basin and of the surrounding Apenninic belt (Fig.3a-c) may be subdivided in three main phases, well differentiated in space and time (e.g. Kastens et al., 1988; Sartori, 1990; Sartori and Capozzi, 1998).

From the Tortonian to the middle Messinian (roughly 9-6 My), crustal stretching, with a nearly E-W to ENE-WSW extensional trend, only occurred in the northwestern Tyrrhenian zone, lying north of the Selli fault (Fig.3a). Negligible, or minor, accretionary activity developed in the adjacent belt (Northern Apennines) during this phase (e.g. Vai, 1987; Sgrosso et al., 1988; Borsetti et al., 1990; Castellarin et al., 1992).

From the middle Messinian to the late Pliocene (6-2 My), intense crustal stretching, with a roughly E-W extensional trend, only occurred in the central Tyrrhenian zone (Magnaghi-Vavilov basin), while intense accretionary activity affected the whole Apenninic belt, with particular regard to the southern arc, comprising the Southern Apennines and Calabria (e.g. Patacca et al., 1993). During this phase, the Northern Apennines began to be affected by thrust activity along their external front and tensional deformations in the internal zone (e.g. Elter et al., 1975; Castellarin and Vai, 1986; Vai, 1987; Bigi et al., 1989; Bartole, 1995).

Around the late Pliocene (2 My), crustal stretching ceased in the central Tyrrhenian basin and started, with roughly NW-SE extensional trend, in the southernmost Tyrrhenian zone, leading to the formation of the narrow and elongated Marsili basin. Accretionary activity ceased in the Southern Apennines (e.g. Cinque et al., 1993) and accelerated in the external Calabrian arc and Northern Apennines (e.g. Boccaletti et al., 1985; Finetti and Del Ben, 1986; Castellarin and Vai, 1986; Bartole, 1995).

In the following, we discuss on how the above deformation pattern may be interpreted as an effect of the proposed extrusion mechanism.

Northwestern Tyrrhenian

The fact that the opening of this basin was not accompanied by accretionary activity at the related trench zone, i.e. the Northern Apennines, implies that no lithosphere subduction has occurred during this extensional event. This inference is corroborated by the fact that the Adriatic domain, which lays in front of the Northern Apennines, was characterized by a continental crust (e.g. Boccaletti et al., 1980; Serri et al., 1991) and, thus, its consumption would have certainly left clear imprints, in terms of accretionary material, at the trench zone. This evidence implies that the formation of the northwestern Tyrrhenian basin was not connected with the development of a T-A-BA system and, thus, it does not represent an example to be discussed in this work.

A possible explanation of this extension and of the lack of coeval subduction in the Northern Apennines has been proposed by Mantovani et al. (1997), who interpreted this event as a consequence of the divergence between the confining blocks, i.e. the fixed Corsica-Sardinia microplate and the NEward drifting Adriatic promontory, triggered by the activation of the Giudicarie decoupling fault system.

On the other hand, it must be pointed out that the opening of the Northern Tyrrhenian basin cannot be explained by the slab pull model, since the lack of coeval lithosphere consumption at the trench zone contradicts one of the basic implications of the above model, i.e. the roll back of the slab.

Central Tyrrhenian

The boundary conditions which determined the opening of this basin developed around the upper Messinian (5-6 My), when the pre-Apulian low buoyancy zone was completely consumed and a continental collision occurred between the Adriatic and the Aegean-Balkan systems, roughly in correspondence to western Greece (e.g. Mercier et al., 1989). This last event caused the suture of the above consuming boundary and the subsequent efficient transmission of the westward push of the Tethyan orogenic system on the Adriatic promontory. After this event, the Adriatic plate undertook a clockwise rotation around a pole roughly located in the northern Pannonian area (Mantovani et la., 1997, 2000a). The proposed kinematic pattern of this block is illustrated in Fig.3b. This kinematic change was allowed by the decoupling of the Adriatic plate from the surrounding regions, with particular regard to the African block. This decoupling was most probably achieved by the formation of a left lateral shear zone, the Victor Hensen-Medina fault, located in the central Ionian area along the prolongation of the Kefallinia fault (Fig.3b). Post late Miocene tectonic activity, with a transtensional regime, has been recognized in the Victor Hensen (Hieke and Wanninger, 1985; Hieke and Dehghani, 1999) and Medina faults (Rossi and Zarudzki, 1978; Ryan, 1978; Della Vedova and Pellis, 1989).

Another important tectonic event which allowed the change of the Adriatic kinematics was the detachment of the Iblean-Ventura microplate from the African block. This event was a consequence of the roughly E-W convergence between the Adriatic/northern Ionian block and the continental African margin (Tunisia), which caused the detachment and NWward escape of an African fragment, i.e. the Iblean-Ventura microplate (Fig. 3b,c). The strike-slip lateral guides of this extrusion were the Taormina fault, to the East, and the Sicily Channel fault system, to the West. This last fault, being characterized by a leaky transform geometry in its central sector, became the site of localized extensional deformation in a pull-apart style, with the opening of some troughs (e.g. Finetti and Del Ben, 1986; Reuther, 1987; Argnani, 1993; Mantovani et al.,1997).

On its turn, the lateral escape of the Iblean-Ventura microplate caused other secondary extrusion processes in the Tyrrhenian area. In particular, the NWward indentation of the Iblean-Ventura microplate into the orogenic zone which lay in front of it, and east of Sardinia, caused the eastward expulsion of crustal wedges, at the expense of the western Apulian and Ionian zones. The oceanic-like character of the litosphere subducted during this phase is suggested by petrological evidence (Serri et al., 1993; Francalanci and Manetti, 1994; Beccaluva et al., 1994). The above extrusion process may explain the renewal of orogenic activity that occurred around the late Miocene in the southern Apenninic arc, after some My of relative tectonic quiescence (Bigi et al., 1989; Patacca and Scandone, 1989). In the wake of the westward extruding wedges, crustal stretching occurred in the central Tyrrhenian area, with the formation of the Magnaghi-Vavilov basin (Sartori and Capozzi, 1998).

The reactivation of vertical movements along the Siracusa and Apulian escarpments, representing the borders between the Ionian oceanic lithosphere and the adjacent continental zones, i.e. the Iblean block to the West and the Adriatic plate to the East (Carbone et al., 1982; Auroux et al., 1984; Finetti and Del Ben, 1986) could be interpreted as an effect of the downward flexure of the Ionian lithosphere beneath the extruding southern Apenninic arc.

Another major tectonic event which could be associated with the late Miocenic change of the Adriatic kinematics was the activation of a major SE-NW shear zone, the Schio-Vicenza fault (Cantelli and Castellarin, 1994). This discontinuity allowed a new decoupling of the main Adriatic block from its Padanian sector, this time compatible with the post Late Miocene Adriatic kinematic pattern, induced by the push of the Anatolian-Aegean system (Fig. 3b). This change of motion trend in the northern Adriatic zone is also testified by the evidence that the trend of the compressional axis in the sector of the Alps lying East of the Schio-Vicenza line changed from SW-NE to SE-NW (Cantelli and Castellarin, 1994).

The opening of the central Tyrrhenian basin has been alternatively interpreted as an effect of slab pull forces (e.g. Malinverno and Ryan, 1986; Royden, 1993a,b). However, this interpretation can not easily provide convincing explanations for the timing of this extensional event (late Miocene – late Pliocene) and for the peculiar geometry of the stretched zones. At the end of the Western Mediterranean arc-trench migration, around the upper Miocene (12-13 My), a well developed slab was presumably present under the N-S segment of the Iberian-Apenninic belt and the Corsica-Sardinia microplate (Fig.2c), as indicated by volcanological evidence (Bellon, 1981; Beccaluva et al., 1994). It is not clear why this large slab did not undergo roll back in the time interval spanning from 12-13 to 5-6 My and why slab roll back just started around the late Miocene and only occurred under the Southern Apennines and the Calabrian arc, notwithstanding that well developed subducted lithosphere also existed to the north and to the south of this sector.

Another evidence which can hardly be explained as an effect of a slab pull mechanism is the formation of several oroclinal arcs in the Apenninic belt and the counterclockwise rotation of the Southern Apennines with respect to the northern part of the belt (e.g. Bigi et al., 1989; Sartori, 1990).

One must also consider that, to avoid the need of several driving mechanisms, any geodynamic interpretation of the Tyrrhenian-Apennines system should also account for the major tectonic events occurred in the surrounding regions, as, for instance, the complex time-space distribution of tectonic activity in the Pelagian zone and in the Alps (Fig. 3b,c). No attempts in this sense have been so far made by assuming the slab pull model as driving mechanism.

Southernmost Tyrrhenian

Around the late Pliocene, the arrival of the continental part of the Adriatic foreland at the Southern Apennines consuming boundary determined the stop of subduction (e.g. Patacca et al., 1993). After this event, the convergence between the Iblean-African domain and the Adriatic plate, no longer accommodated by lithosphere consumption beneath the Southern Apennines, caused the lateral expulsion of the Calabrian wedge, at the expense of the Ionian domain (Fig.3c). The effects of this extrusion process might be recognized in the contemporaneous acceleration of tensional (opening of the Marsili basin) and of compressional (accretionary activity in the external Calabrian Arc) deformation respectively along the internal and external sides of the Calabrian wedge. The roughly SW-NE compressional regime that the Calabrian Arc underwent during this phase might explain the acceleration of tectonic activity with the formation of several troughs and sphenocasms, and uplift in this zone (e.g. Barone et al., 1982; Sartori, 1990; Sagnotti, 1992; Del Ben, 1993; Bordoni and Valensise, 1998).

If the formation of the narrow Marsili basin (Fig.3c) had been an effect of a slab-pull mechanism, the sinking slab should have been confined to a very narrow slice of the Ionian domain. In this case, however, one should find the decoupling zones between the sinking Ionian slice and the lateral non subducting parts of this zone. Two discontinuities which could have played such a role are the Apulian and Siracusa escarpments (Carbone et al., 1982; Finetti and Del Ben, 1986; Sartori et al., 1989; Reuther et al., 1993). However, these features are separated by a distance of several hundreds of km, i.e. much larger than the width of the presumed sinking Ionian slice.

As said before, during this phase the Calabrian Arc was affected by a fast uplift and a significant increase of its curvature. If this deformation pattern was an effect of slab-pull forces, one might wonder why a comparable uplift and disruption did not also affect the Southern Apennines in the previous phase (Messinian-late Pliocene), i.e. during the formation of the Magnaghi-Vavilov back arc basin. Some authors (e.g. Westaway, 1993; Cinque et al., 1993) suggested that the Quaternary uplift in Southern Italy might represent the isostatic response of the shallow structure to the detachment of the underlying slab. However, this hypothesis cannot be advanced for the Calabrian Arc, where the distribution of deep earthquakes (e.g. Anderson and Jackson, 1987), the results of tomographic analysis (e.g. Spakman, 1990; Selvaggi and Chiarabba, 1995; Piromallo and Morelli, 1997; Giardini and Velonà, 1991) and the study of high-frequency seismic wave propagation (Mele, 1998) indicate the presence of a continuous subducted body from shallow depths to about 500 km of depth.

Plio-Quaternary Aegean T-A-BA system

A number of major tectonic events indicate that around the late Miocene (5-6 My), the Hellenic Arc accelerated its southward buckling:

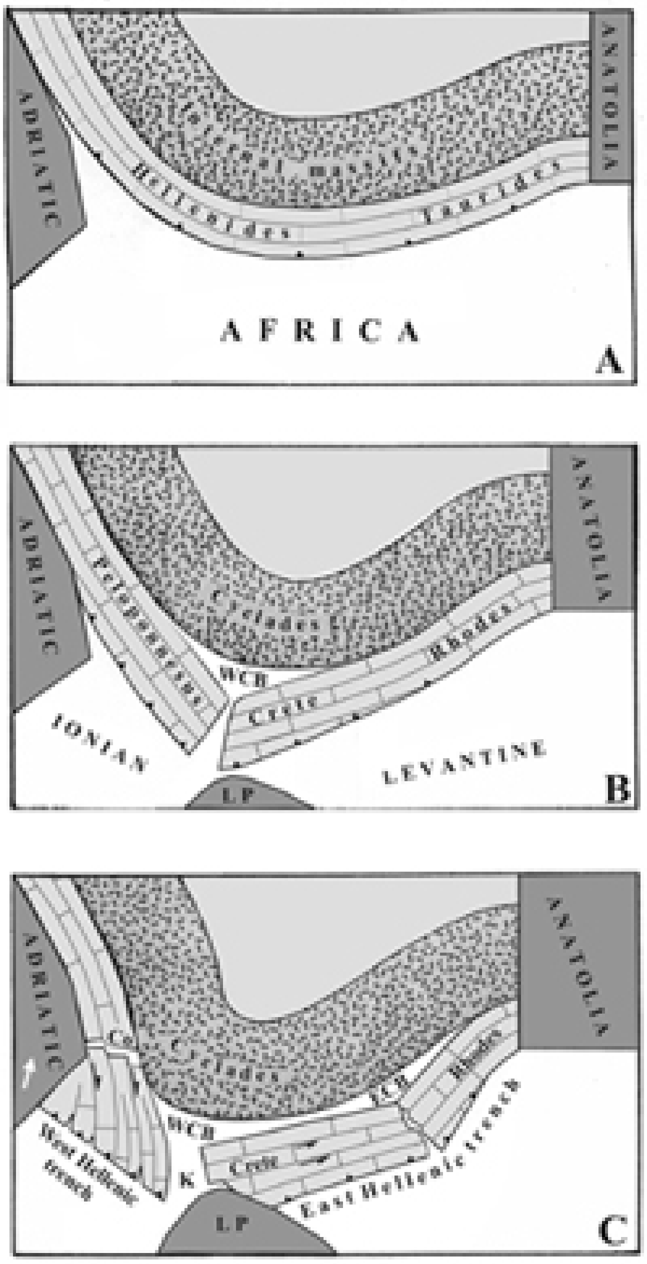
- The most intense accretionary activity along the external front of the Aegean Arc, i.e. the Hellenic trench, occurred in the Pliocene, leading to the formation of the so called "Mediterranean ridge" (e.g. Finetti, 1976; Underhill, 1989; Mascle and Chaumillon, 1997).
- The north Aegean and northwestern Anatolian regions were affected by a significant acceleration of transtensional tectonics, associated with a system of SW-NE strike slip faults (Sengor et al., 1985; Hempton, 1987; Yilmaz, 1989; Mercier et al., 1989; Zanchi et al., 1990; Taymaz et al., 1991; Barka, 1992).
- Crustal thinning, with a dominant S-N extensional trend, occurred in the Western Cretan basin (WCB) which almost reached its present configuration around the late Pliocene (Buttner and Kowalczyk, 1978; Angelier et al., 1982; Mercier et al., 1989; Meulenkamp et al., 1994).

The fact that crustal stretching only occurred in such a limited zone, with an almost triangular shape (Fig.3b), and only developed during the Pliocene, imposes important constraints on the driving mechanism of this extensional event.

- The Cyclades arc was affected by intense E-W compressional deformation and by uplift, which generated plurikilometric sized faults and the first deposition of continental facies, after the Miocene marine sedimentation (Buttner and Kowalczyk, 1978; Durr et al., 1978; Mercier et al., 1987, 1989; Avigad et al., 2001).

The deformations listed above may be interpreted, in our opinion, as effects of the continental collision between the Adriatic block and the Tethyan orogenic system at western Greece. After this collision, the convergence between the eastern Anatolia and the Adriatic plate, no longer accommodated by the consumption of the pre-Apulian zone, emphasized E-W stresses on the Aegean arc, accelerating its southward bending/extrusion. We advance the hypothesis that this bending and the different mechanical behavior of the external accretionary belt (Hellenides) with respect to the inner massifs (Cyclades) was responsible for the generation of the WCB, through the mechanism sketched in Fig. 4. Due to its high rigidity, the Hellenides belt did not resist the tensional stress induced by bending and broke up in two arcs, the Peloponnesus to the West and the Crete-Rhodes to the East. After this break, the two Hellenic arcs diverged from the Cyclades massifs, causing crustal extension in a roughly triangular zone, the WCB.

Figure 4. Proposed driving mechanism



Proposed driving mechanism of the deformation pattern of the Aegean arc and of the consequent generation of the Western (WCB) and Eastern (ECB) Cretan basins. Under the E-W compression between the Anatolian and Adriatic blocks, the Aegean arc undergoes a roughly southward bending (A). Due to its high rigidity (see text), the Hellenides-Taurides belt did not resist the stress induced by bending and broke up in two sectors (B), the Peloponnesus to the west and the Crete-Rhodes to the east. After this break, an angular divergence occurred between the Cyclades massifs and the two sectors of the Hellenic arc, causing the opening of a roughly triangular zone, the WCB. Boundary conditions underwent a significant change around the late Pliocene (C), due to the incipient continental collision between the Lybian promontory (LP) and the central Hellenic arc (Crete). After this event, compressional stress increased considerably in the eastern Hellenic arc (Crete-Rhodes), causing its extrusion/bending at the expense of the Levantine zone. In the wake of this arc, extensional deformation, with a NW-SE trend, occurred, forming the Eastern Cretan basin. This mechanism also determined the land interruption between Crete and Rhodes. The clockwise rotation and internal deformation of the Peloponnesus, due to its oblique collision with the southermost edge of the Adriatic continental plate, caused the formation of the Corinthian trough (Co). The divergence between the Peloponnesus and Crete produced the formation of N-S trending extensional features, as the Kithira trough (K).

Around the late Pliocene–early Pleistocene, the tectonic setting in the southern Aegean region changed considerably. Crustal stretching ceased in the WCB and began in the Eastern Cretan basin (ECB) , with a roughly NW-SE extensional trend. Tectonic activity in the eastern Hellenic Arc (Crete-Rhodes) underwent a significant acceleration, with the formation of several discontinuities and the land interruption between Crete and Rhodes (e.g. Buttner and Kowalczyk, 1978; Armijo et al., 1992). This tectonic change might be a consequence of the incipient collision of African continental domain (Libyan promontory) against the central sector of Hellenic consuming boundary, just southwest of Crete (e.g. Ryan et al., 1982; Lyon-Caen et al., 1988; Armijo et al., 1992; Mascle and Chaumillon, 1997). After this continental collision, the compressional stress field induced by the westward push of southern Anatolia concentrated in the eastern Hellenic Arc, causing its SEward bending/extrusion, accompanied by a considerable fragmentation (Fig.4c). In the wake of the outward migrating eastern Hellenic arc, NW-SE extensional tectonics occurred, with the formation of the ECB. The above mechanism and the related deformation pattern are still going on in the southeastern Aegean area and eastern Hellenic Arc, as indicated by neotectonic, seismological and geodetic data (Mercier et al., 1989; Armijo et al., 1992; Papazachos and Kiratzi, 1996; McClusky et al., 2000; Viti et al., 2001).

The above space-time distribution of tectonic events in the Aegean zone cannot easily be explained by the slab pull model. Here we report some considerations about the major outstanding problems.

• It is widely recognized that the Ionian-Levantine lithosphere has subducted roughly NNE to NEward, along a trench zone extending from the Kefallinia fault system to Crete (Fig.2), while the easternmost sector of the Hellenic trench (Pliny and Strabo) is instead recognized as a sinistral transpressional border (e.g. McKenzie, 1978; Le Pichon and Angelier, 1979; Mercier et al., 1989; Armijo et al., 1992). Given this geometry of the slab, one could expect that SW-NE back-arc extension induced by its roll back mainly affected the Peloponnesus and the Aegean internal zone (the present Aegean sea). Instead, since the late Miocene the most evident extensional deformation with a roughly S-N trend has occurred in a limited and peculiarly shaped zone of the southern Aegean area, i.e. the WCB, as indicated by geological and geophysical observations (Berckhemer, 1977; Le Pichon and Angelier, 1979; Angelier et al., 1982; Gautier and Brun, 1994) and by the fact that, at present, the crust in the above zone is significantly thinner, roughly 20 km, than that in the surrounding Aegean zones, roughly 30 km (e.g. Makris, 1978; Meissner et al., 1987).

• It has been suggested that Crete during its separation from the central Aegean zone (Cyclades massif) moved roughly southward, (Buttner and Kowalczyk, 1978: Angelier et al., 1982; Mercier et al., 1987, 1989; Armijo et al., 1992). Contemporaneously, the Peloponnesus experienced a significant clockwise rotation, roughly 30° (e.g. Kissel and Laj, 1988). This heterogenous kinematic behavior of the various sectors of the arc, with the consequent separation between the Peloponnesus and Crete (Armijo et al., 1992), cannot easily be reconciled with the presumed cylindrical SWward roll-back of the Hellenic slab.

• Geological evidence indicates that the starting of the more recent extensional phase in the Southern Aegean zone (Pliocene) was more or less coeval with the starting of outward migration of the Hellenic Arc (e.g. Le Pichon and Angelier, 1979; Angelier et al., 1982; Mercier et al., 1989). This would imply that the driving mechanism of this T-A-BA system can not easily be related with the pull of the Pliocenic-Quaternary slab, since in the early Pliocene this slab was not yet sufficiently developed to undergo gravitational instability. Thus, the presumed slab-pull force could only be related to the sinking of a pre-existing subducted lithosphere. In this case, however, one should explain why gravitational instability just occurred in a limited sector of a considerably laterally extended consuming boundary, ranging from the Dinarides to Anatolia (Mercier et al., 1987, 1989).

• Around the late Pliocene-early Pleistocene, the deformation pattern in the internal Aegean area underwent a considerable change. S-N crustal stretching almost ceased in the WCB (e.g. Armijo et al., 1992) and began to develop in the ECB, with a roughly NW-SE extensional trend, and in the western Aegean area between the Peloponnesus and Crete, with a dominant E-W extensional trend (e.g. Mercier et al., 1989; Armijo et al., 1992). If extensional activity in the Aegean back-arc zone was driven by slab-pull forces, one could expect that the observed drastic change of strain pattern around the early Pleistocene was associated with important changes in the Hellenic subduction process. However, there is no clear evidence of any significant change, in subduction rate and geometry, of the above consuming process since the upper Miocene-early Pliocene (e.g. Le Pichon and Angelier, 1979).

- The sinking of the Hellenic slab and the related SWward trench suction can hardly be assumed as the driving mechanism of the Quaternary extensional activity, i.e. the NW-SE extension in the southeastern Aegean zone and of the roughly E-W extension between the Peloponnesus and Crete.

Conclusions and discussion

It is argued that the large migration and distortion of orogenic belts and the opening of several back arc basins observed in the Mediterranean region are the results of extrusion processes, driven by the convergence of the confining plates, i.e. Africa, Arabia and Eurasia. In support of this hypothesis, it is pointed out that the tectonic contexts within which the major T-A-BA systems developed were characterized by the dynamic and structural conditions implied by the extrusion mechanism (Fig.1).

As argued in the text, the proposed evolutionary reconstruction, based on the extrusion model, allows to find plausible and coherent explanations for the very complex time-space distribution of tectonic events in the study area, while such possibility is not provided by the most popular alternative model, i.e. the slab pull mechanism.

Some objections have been reported in literature about the applicability of the extrusion model to the Mediterranean back arc basins. For instance, Gueguen et al. (1997) and Jolivet et al. (1998) suggested that this model cannot be applied to the Tyrrhenian-Apennines T-A-BA system since it cannot account for the fact that the rate of trench retreat under the Southern Apennines and Calabrian Arc was considerably higher, 3-5 cm/y (e.g. Patacca et al., 1990), than the convergence rate between Africa and Eurasia, lower than 1 cm/y. However, this argument does not take into account the very important influence of the Adriatic westward motion on the formation of the Tyrrhenian basin (Mantovani et al., 1997, 2000a). Furthermore, simple geometrical arguments suggest that the velocity of an extruding wedge becomes higher than the convergence rate of the confining blocks when the lateral decoupling faults of crustal wedges form high angles with respect to the main trend of the belt. In the geodynamic context which led to the southern Tyrrhenian extension, the formation of high angle decoupling shear zones for the extruding Calabrian wedges may have been favoured by the small size of the lateral weak boundary (Ionian oceanic domain) which lay in front of the stressed Calabrian Arc. The presence of such high angle lateral guides for the extension of wedges in the southern Apennines and Calabrian arc is suggested by the results of seismic surveys (Finetti and Del Ben, 1986).

Other doubts about the feasibility of the extrusion model have been expressed for the Aegean-Hellenic T-A-BA system on the basis of the velocity field in the Aegean-Anatolian regions inferred from space geodetic data (e.g. McClusky et al., 2000). The major evidence on which these objection are based is the fact that the Aegean Arc is moving faster (roughly 30 mm/y) than the Anatolian block (roughly 24 mm/y), apparently in contrast with the hypothesis that the deformation pattern of the Aegean zone is driven by the Anatolian westward push. However, Mantovani et al. (2001c) and Cenni et al. (2001) have shown, by numerical modelling experiments, that the kinematic pattern indicated by geodetic data can also be explained as an effect of post seismic relaxation processes, triggered by the sequence of very strong earthquakes occurred along the North Anatolian fault system since 1939 (e.g. Barka, 1992). This result, along with other evidence and arguments (e.g. Anderson, 1975; Rydelek and Sacks, 1990), points out that the short-term kinematic behavior of blocks may be very different with respect to the long-term (geological) one. This possibility is also suggested by the fact that the Plio-Quaternary slip rate along the North Anatolian fault, estimated by the analysis of fault offsets and long-term seismicity pattern (Barka, 1992), is lower than 10 mm/year.

Arguments against the extrusion model in the Mediterranean area are also based on numerical and analogue modelling (Faccenna et al., 1996; Meijer and Wortel, 1997; Lundgreen et al., 1998; Wortel and Spakman, 2000). In particular, the above attempts suggest that the observed strain patterns in the Aegean and Tyrrhenian zones cannot be reproduced if a trench suction force is not assumed in the Hellenic and Calabrian arcs, respectively. However, one must consider that the results of the above experiments may be strongly influenced by the oversimplified models assumed in computations, with particular regard to the fact that only very few tectonic discontinuities, with respect to the large amount of active features recognized in the study area, have been included in models. This possibility is suggested by the fact that a satisfactory match of the strain field in the central-eastern Mediterranean area, deduced by a large amount of geological and geophysical information can be obtained adopting more realistic models, which take into account lateral heterogeneities of mechanical properties and major tectonic discontinuities in the zones considered, and assuming the convergence of the confining blocks (Africa, Arabia and Eurasia) as the only driving mechanism (Mantovani et al., 2000b, 2001b).

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