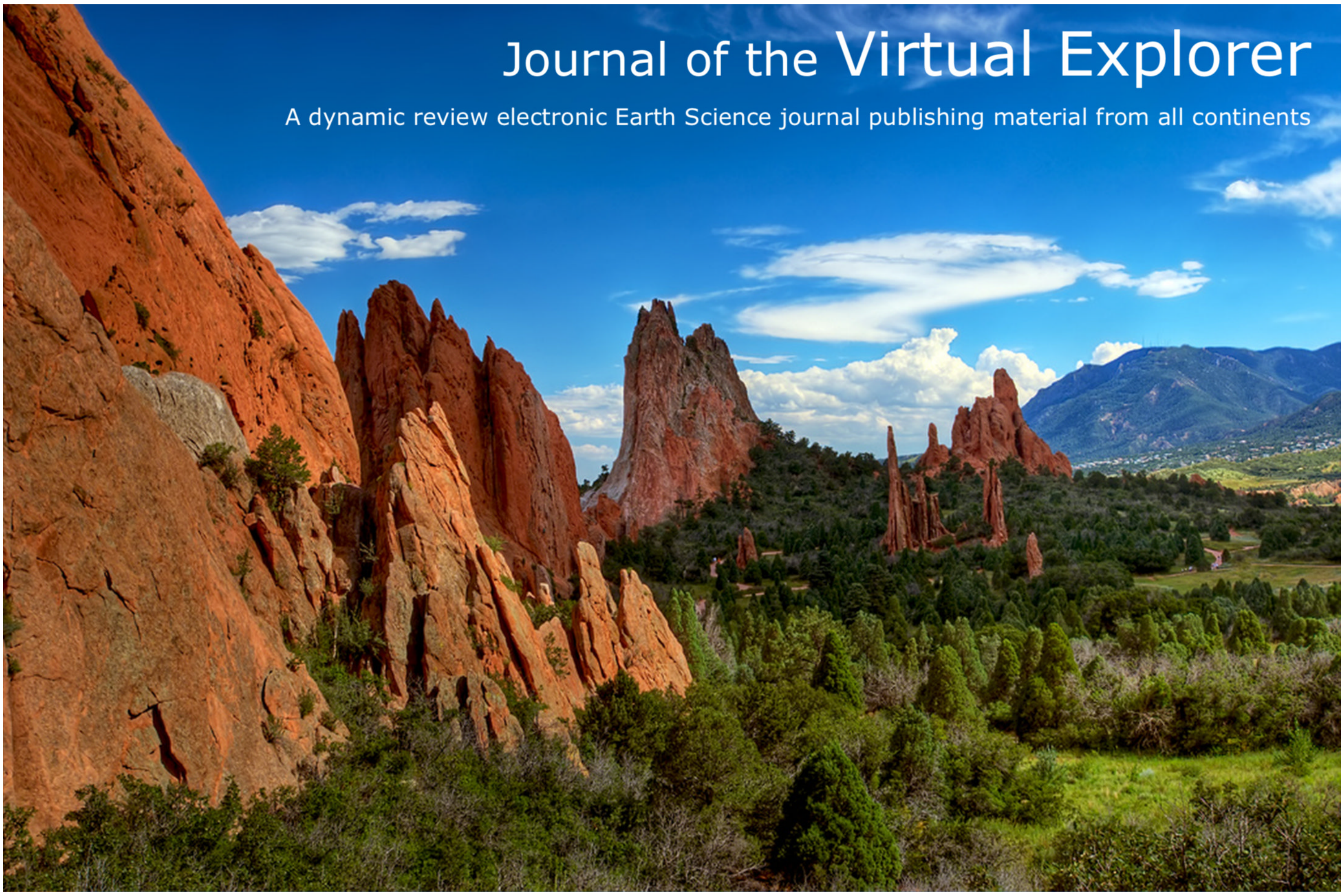

Reconstruction of the tectonic evolution of the western Mediterranean since the Oligocene

Gideon Rosenbaum, Gordon S. Lister, Cecile Duboz

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Abstract: We present a tectonic synthesis and an animation of the tectonics of the western Mediterranean since the Oligocene. This work is based on data derived from different geological datasets, such as structural geology, the distribution of metamorphic rocks, magmatic activity, sedimentary patterns, palaeomagnetic data and geophysics. Reconstruction was performed using an interactive software package (PLATYPLUS), which enabled us to apply rotational motions to numerous microplates and continental terranes involved in the evolution of the western Mediterranean basins. Boundary conditions are provided by the relative motions of Africa and Iberia with respect to Europe, and the Adriatic plate is considered here as an African promontory.

The reconstruction shows that during Alpine orogenesis, a very wide zone in the interface between Africa and Europe underwent extension. Extensional tectonics was governed by rollback of subduction zones triggered by gravitational instability of old and dense oceanic lithosphere. Back-arc extension occurred in the overriding plates as a result of slow convergence rates combined with rapid subduction rollback. This mechanism can account for the evolution of the majority of the post-Oligocene extensional systems in the western Mediterranean. Moreover, extension led to drifting and rotations of continental terranes towards the retreating slabs in excess of 100-800 km. These terranes - Corsica, Sardinia, the Balearic Islands, the Kabylies blocks, Calabria and the Rif-Betic - drifted as long as subduction rollback took place, and were eventually accreted to the adjacent continents. We conclude that large-scale horizontal motions associated with subduction rollback, back-arc extension and accretion of allochthonous terranes played a fundamental role during Alpine orogenesis.

http://virtualexplorer.com.au/article/2002/53/evolution-of-the-western-mediterranean

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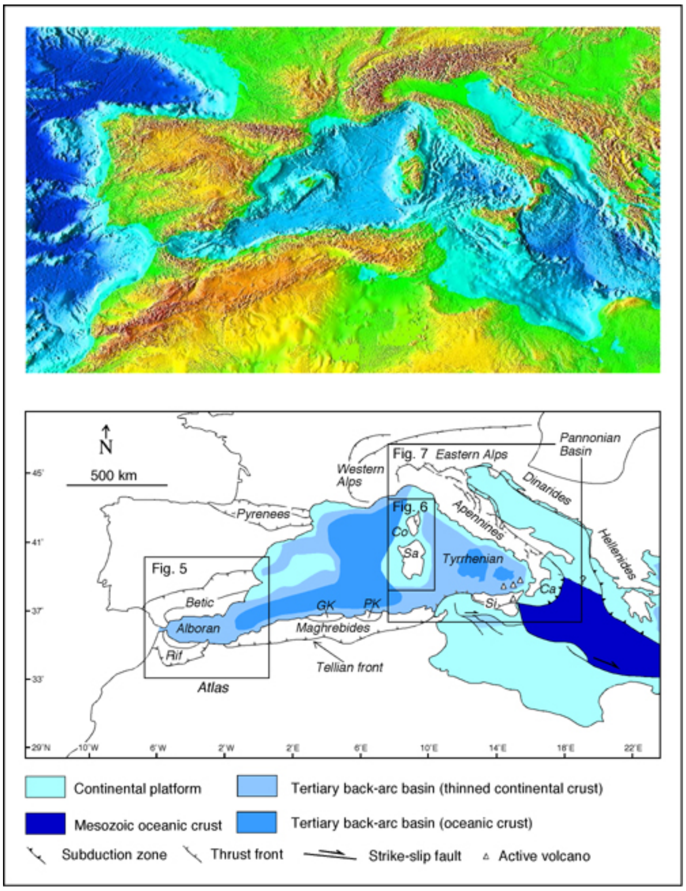
Introduction

The geological evolution of the western Mediterranean exhibits complicated interactions between orogenic processes and widespread extensional tectonics. The region is located in a convergent plate margin separating Africa and Europe, and consists of marine basins - the Alboran Sea, the Algerian-Provençal Basin, the Valencia Trough, the Ligurian Sea and the Tyrrhenian Sea (Figure 1) - which formed as back-arc basins since the Oligocene. The evolution of these basins, simultaneously with ongoing convergence of Africa with respect to Europe, has been the subject of numerous studies (e.g., Stanley & Wezel 1985, Durand et al. 1999). Widespread extension associated with the formation of these basins led to considerable thinning of the continental crust (i.e., in the Alboran Sea and the northern Tyrrhenian) or to the local initiation of sea floor spreading (i.e., in the southern Tyrrhenian and Provençal Basin). Furthermore, extensional tectonism in the western Mediterranean was coeval with orogenesis in the adjacent mountain chains of the Rif-Betic cordillera, the Maghrebides of northern Africa and Sicily, the Apennines, the Alps and the Dinarides (Malinverno & Ryan 1986, Crespo-Blanc et al. 1994, Tricart et al. 1994, Cello et al. 1996, Azañón et al. 1997, Frizon de Lamotte et al. 2000, Faccenna et al. 2001)(Figure 1).

Figure 1. Regional Map



(a) Topography of the western Mediterranean region; (b) tectonic setting of the western Mediterranean basins and the Alpine orogen (only Mediterranean marine basins are coloured). Ca = Calabria; Co = Corsica; GK = Grand Kabylie; PK = Petite Kabylie; Sa = Sardinia; Si = Sicily.

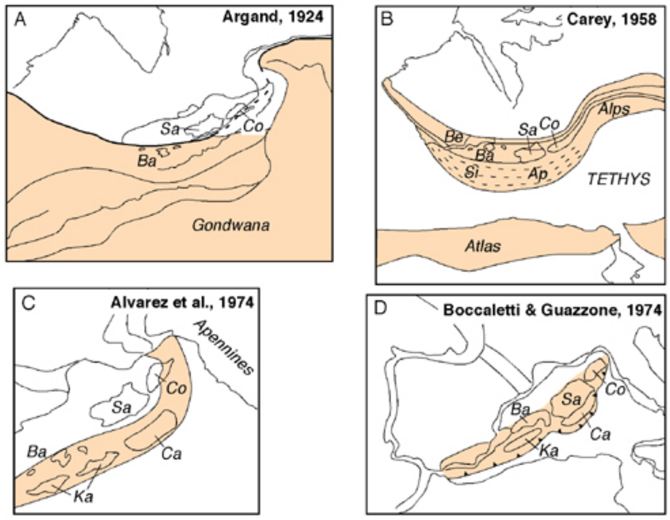
The simultaneous formation of extensional basins together with thrusting and folding in adjacent mountain belts has led to several tectonic models that acknowledge the role of large-scale horizontal motions associated with the retreat of the subduction trench (hereafter termed subduction rollback) (Malinverno & Ryan 1986, Royden 1993a, Lonergan & White 1997). These provide an explanation for the origin of allochthonous terranes, which drifted great distances to their present locations (e.g., Calabria). However, some issues are yet to be resolved and have been the subject of considerable debate. Different models have been proposed to explain the evolution of the Alboran Sea, namely, as a back-arc basin associated with a retreating slab (Lonergan & White 1997), or as the result of an extensional collapse of thickened lithosphere (Platt & Vissers 1989, Housman 1996). The evolution of the Tyrrhenian Sea is also controversial, with some fundamental problems in the current explanations of the evolution of this basin.

In this work, we aim to develop a coherent visual reconstruction that will best explain the large-scale tectonics of the western Mediterranean region. We use a wealth of accumulated knowledge as published in the literature, as well as a new software package that provides the ability to perform an interactive reconstruction. The reconstruction is presented as an animation, which clearly demonstrates some fundamental features seen in convergent plate margins. It shows the complex interactions between subduction processes, horizontal extension, block rotations and accretion events, and it emphasises the roles of subduction rollback and the episodic accretion of allochthonous terranes during orogenesis.

Summary of previous works

Over the course of the last century, and particularly since the emergence of the modern plate tectonics theory, numerous studies have aimed to reconstruct the evolution of the Mediterranean basins in the context of the Alpine orogeny. The main concepts used in these reconstructions (as well as in the present study) correspond to continental drift, microplate rotations and migration of subduction zones. They were introduced as early as 80 years ago in the outstanding tectonic synthesis of Argand (1924) (Figure 2a). In an early attempt to reconstruct the tectonic evolution of the Mediterranean region, Carey (1958) has demonstrated that the unbending of arcuate mountain belts throughout the western Tethys yielded the reassembly of Spain, Balearic Islands, Corsica, Sardinia, Sicily and Italy in the northwestern margin of the Tethys Ocean (Figure 2b). Subsequent reconstruction models have generally followed Carey's ideas concerning the palaeo-position of these terranes (Smith 1971, Alvarez et al. 1974, Boccaletti & Guazzone 1974, Biju-Duval et al. 1977, Cohen 1980) (Figure 2c,d), although the significance of the Cenozoic deformation was not always recognised (e.g., Smith 1971).

Figure 2. Examples of earlier reconstructions



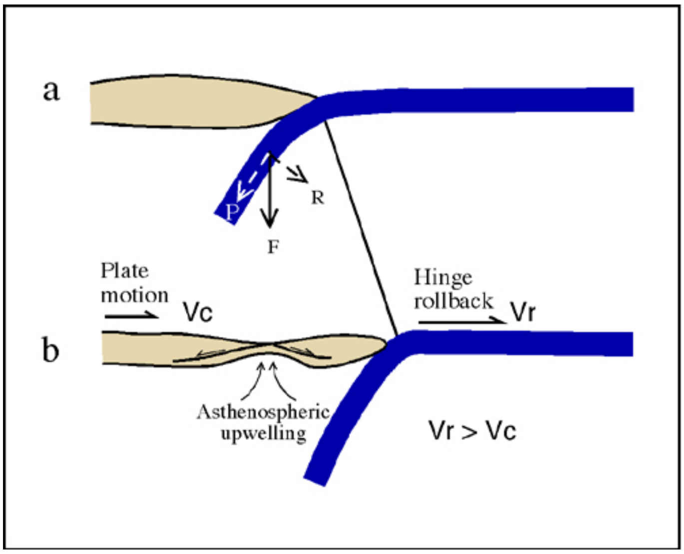
Examples of earlier reconstructions showing the western Mediterranean prior to the opening of Late Cenozoic extensional basins. (a) Argand (1924); (b) Carey (1958); (c) Alvarez et al. (1974); (d) Boccaletti and Guazzone (1974). Ap = Apennines; Ba = Balearic Islands; Be = Betic; Ca = Calabria; Co = Corsica; Ka = Kabylies; Sa = Sardinia; Si = Sicily.

During the 1970s, it was suggested that the western Mediterranean basins are relatively late tectonic features formed progressively since the Late Oligocene (Dewey et al. 1973, Alvarez et al. 1974, Biju-Duval et al. 1977). Since then this conclusion has been strongly supported by evidence of Oligocene and Miocene extensional deformation and syn-rift deposits on the margins of the western Mediterranean basins (e.g., Cherchi & Montadert 1982, Rehault et al. 1985, Bartrina et al. 1992 and many others). Thus, the western Mediterranean basins are essentially different from the Eastern Mediterranean; where the remnants of Mesozoic oceanic crust (Neotethys) are probably preserved below the sediments (de Voogd et al. 1992, Ben-Avraham et al. 2002). Mesozoic oceanic crust is not found on the floor of the western Mediterranean basins. However, the existence of consumed oceanic basins in this region is implied by reconstruction models (e.g. Dercourt et al. 1986, Ricou et al. 1986) and by the occurrence of ophiolitic complexes within the adjacent fold-and-thrust belts (Ricou et al. 1986, Knott 1987).

The configuration of extensional basins surrounded by continuous mountain belts has been commonly interpreted as the result of back-arc extension (Boccaletti & Guazzone 1974, Biju-Duval et al. 1977, Cohen 1980, Ricou et al. 1986). In most reconstructions, it has been stressed that back-arc extension led to drifting of continental blocks and to large-scale block rotations (Dewey et al. 1973, 1989, Alvarez et al. 1974, Biju-Duval et al. 1977). Corsica and Sardinia underwent counterclockwise rotations during the opening of the Ligurian Sea, whereas the opening of the Valencia Trough was accompanied by clockwise rotations of the Balearic Islands (Montigny et al. 1981, Pares et al. 1992). The Kabylies and the Calabrian blocks, which had been deformed and metamorphosed in the Alpine orogen, migrated to their present locations during the opening of the Algero-Provençal Basin and the Tyrrhenian Sea, respectively (Alvarez et al. 1974, Cohen 1980, Dewey et al. 1989). Boccaletti and Guazzano (1974) have further suggested a southward and eastward migration of subduction arcs during the formation of the western Mediterranean basins. Similar ideas explained the existence of extensional back-arc basins in convergent margins (Dewey 1980). In the western Mediterranean, it led to the recognition of subduction rollback as an important driving mechanism in the tectonic evolution of the region (Rehault et al. 1985, Malinverno & Ryan 1986, Royden 1993a, Lonergan & White 1997).

The mechanism of subduction rollback has been discussed by Elsasser (1971) Molnar and Atwater (1978), Dewey (1980) and Royden (1993b). These authors have suggested that subduction rollback is the result of a negative buoyancy of the subducting slab relative to the asthenosphere (Figure 3), obtained when the subducting slab is cold and dense, as in the case of oceanic slabs older than ~50 Ma (Molnar & Atwater 1978). It results in a vertical sinking of the subducting lithosphere beneath the asthenosphere, which can lead to a regressive motion of the subduction hinge (Lonergan & White 1997) (Figure 3). As rollback occurs, it produces a potential vacant region, which can either be supported by convergence that matched or exceeds the rates of the retreating hinge, or by back-arc extension in the overriding lithosphere (Royden 1993b). In the works of Rehault et al. (1985), Malinverno and Ryan (1986), Royden (1993a) and Lonergan and White (1997), the evolution of the western Mediterranean basins has been mainly attributed to the rollback of a NNW dipping subduction zone. We note that our reconstruction largely reflects ideas previously presented in these works.

Figure 3. Simplified cross section

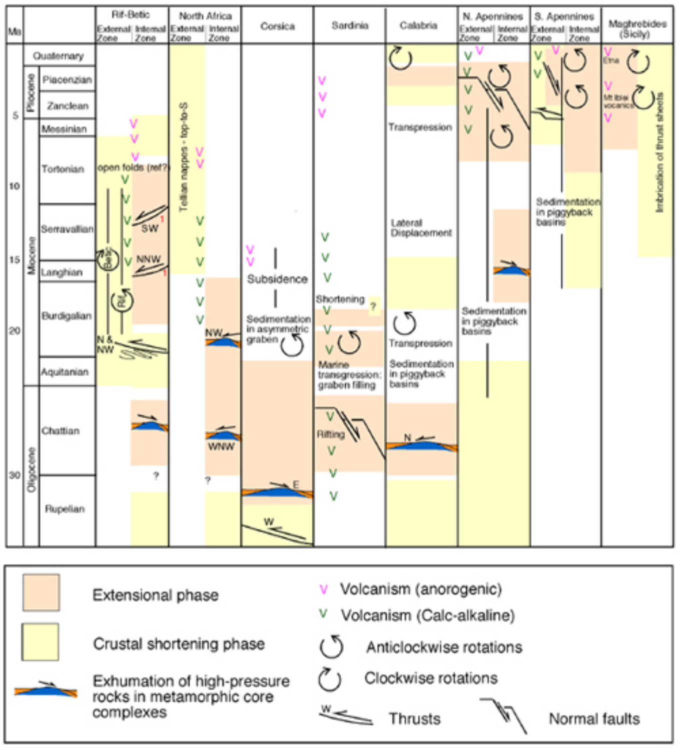


Simplified cross section showing the evolution of subduction rollback (modified after Lonergan & White 1997). (a) P and R are two components of the vertical negative buoyancy (F) of the subducting slab. If the subducting slab is cold and dense, the component R cannot be supported by the mantle asthenosphere, and the subduction zone is pulled backward; (b) back-arc extension forms when the rate of subduction rollback (Vr) exceeds the rate of convergence (Vc).

The geology of the western Mediterranean region

In this section, we briefly discuss the main characteristics of geological terranes that were incorporated in the post-Oligocene evolution of the western Mediterranean. Time relationships between the different terranes are presented in Figure 4.

Figure 4. Time-space diagram

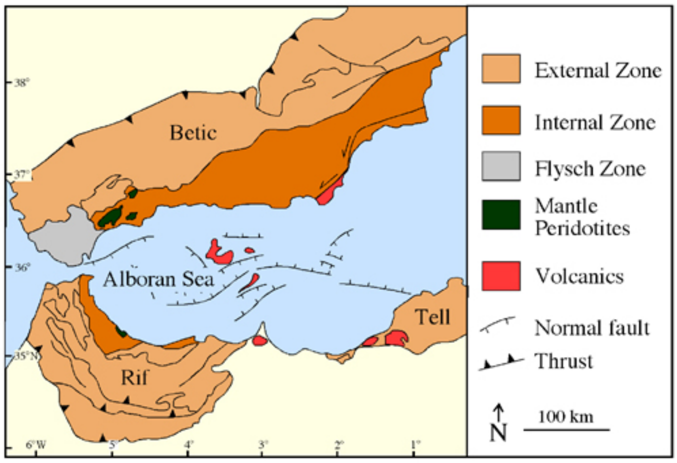


Time-space diagram of the tectonic activity in the western Mediterranean (time scale after Palmer 1983). Data compiled from Boccaletti et al. (1990), Oldow et al. (1990), van Dijk & Okkes (1991), Caby & Hammor (1992), Carmignani et al. (1994), Crespo-Blanc et al. (1994), Ferranti et al. (1996), Saadallah & Caby (1996), Azañon et al. (1997), Sowerbutts (2000) and Crespo-Blanc & Campos (2001).

Rif-Betic cordillera

The mountains of the Betic in southern Spain and the Rif in northern Morocco surround the Alboran Sea to form an arc shape orogenic belt in the westernmost Mediterranean (Figure 5). This belt marks the western terminus of the Alpine orogen. The rocks of the Rif-Betic cordillera are usually divided to three main zones: the Internal Zone, the External Zone and the Flysch Zone. The Internal Zone consists of allochthonous Paleozoic to Early Miocene rocks, which were thrust onto the External Zone during the Miocene (Crespo-Blanc et al. 1994, Crespo-Blanc & Campos 2001). Alpine deformation and metamorphism affected the Internal Zone during the Cretaceous and the Tertiary, and crustal rocks were buried to great depths and underwent high-pressure metamorphism (de Jong 1990). The External Zone consists of Mesozoic to Tertiary rocks, which represent the passive margin of Africa and Iberia deforming during Alpine orogeny. The Flysch Zone mainly consists of Early Cretaceous to Early Miocene deep marine clastic deposits (Wildi 1983).

Figure 5. Alboran Sea and the Rif-Betic cordillera



Geological map of the Alboran Sea and the Rif-Betic cordillera (after Platt & Vissers 1989).

Structural and metamorphic relationships in the Rif-Betic cordillera, particularly from the Internal Zone, show that several contractional and extensional episodes took place. The earliest extension was probably associated with rapid isothermal exhumation of the high-pressure rocks in the Late Oligocene – Early Miocene, and probably commenced at ~30 Ma (Azañón et al. 1997, Platt et al. 1998). Few authors have demonstrated that coeval with crustal shortening in the External Zone, earlier thrust faults in the Internal Zone were rejuvenated as extensional detachments (Azañón et al. 1997, Martínez-Martínez & Azañón 1997). Extension led to vertical thinning and isothermal exhumation of high-pressure rocks now exposed beneath low-angle normal faults (Platt et al. 1983, Azañón et al. 1997, Balanya et al. 1997). Furthermore, during the Early Neogene, a slab of diamond-bearing mantle peridotites was exhumed and juxtaposed amidst crustal rocks of the Internal Zone (Van der Val & Vissers 1993). Radiometric dating of the high-pressure rocks suggests a rapid exhumation during the Late Oligocene - Early Miocene (27-18 Ma) (Monie et al. 1994, Platt et al. 1998).

The floor of the Alboran Sea consists of rocks similar to those found in the Rif-Betic cordillera, and covered by Early Miocene syn-rift deposits and post-rift marine sediments (Comas et al. 1992, Platt et al. 1998). It is therefore evident that the region was subjected to widespread extension during the Middle Miocene that led to the formation of the Alboran Sea. However, contemporaneously with extension in the Alboran Sea, thin-skinned thrusting and folding took place in the External Zones of the Rif-Betic cordillera (Platt & Vissers 1989, Platzman et al. 1993, Crespo-Blanc & Campos 2001). This deformation was accompanied by a considerable amount of block rotations around vertical axes, with clockwise rotations in the Rif and counterclockwise rotations in the Betic (Allerton et al. 1993, Platzman et al. 1993, Lonergan & White 1997).

The Maghrebides and Kabylies

The mountain chain of the Maghrebides in Northern Africa and in Sicily consists of a stack of south-verging thrust sheets that bridges the Apennines of Italy with the Rif Mountains of Morocco (Figure 1). Most rocks exposed in the Maghrebides are non-metamorphic sedimentary units of Mesozoic to Early Miocene age deposited on the southern margin of the Tethys Ocean (Wildi 1983). The southern boundary of the Maghrebides is a low-angle thrust fault (the Tellian Front) that delimits the Maghrebides nappes from the autochthonous terranes of the Atlas chain (Wildi 1983). More internal zones of the orogen are found in northern Algeria and Tunisia (Grande and Petite Kabylies), as well as in a submerged fold-and-thrust belt between Sicily and Tunisia (Compagnoni et al. 1989, Tricart et al. 1994). These internal terranes originated in the Alpine orogen and were overthrust onto the Maghrebides during the opening of the western Mediterranean basins (Cohen 1980).

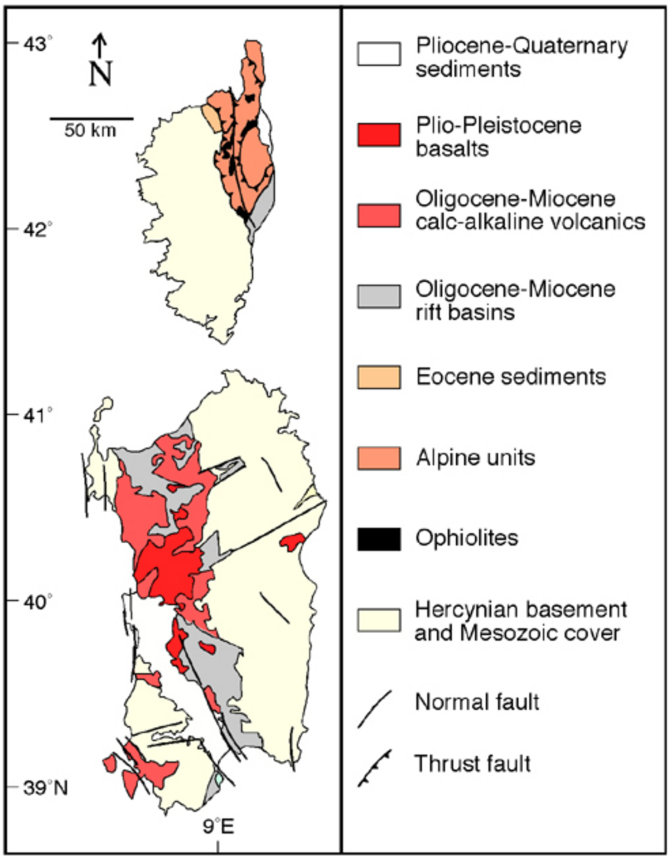
The Kabylies consist of a Hercynian basement and Mesozoic sediments, metamorphosed and strongly deformed during Alpine orogenesis. Alpine metamorphism took place during the Cretaceous and the Tertiary (Peucat & Bossière 1981, Monié et al. 1984; 1988; 1992, Cheilletz et al. 1999), and involved metamorphism at high-pressure conditions. High-pressure rocks are presently exposed in metamorphic core complexes, and are directly overlain by rocks that did not suffer Alpine metamorphism (Caby & Hammor 1992, Saadallah & Caby 1996). Their exhumation seems to be associated with horizontal extension accommodated along low-angle-normal faults (Caby & Hammor 1992, Saadallah & Caby 1996). Deformation along these faults is usually associated with flat lying foliations and mylonitic shear zones with top-to-the-NW sense of shear (Caby & Hammor 1992, Saadallah & Caby 1996). Radiometric dating indicates that extensional deformation probably occurred at 25-16 Ma (Moniéet al. 1984, 1988, 1992).

Thrusting in the External Maghrebides commenced at the Early/Middle Miocene and was generally directed southward and southeastward (Frizon de Lamotte et al. 2000 and references therein). Since the Tortonian, the locus of major crustal shortening has migrated southward until a ~400 km wide area was structured as a fold-and thrust belt (Tricart et al. 1994).

Corsica and Sardinia

The islands of Corsica and Sardinia consist of a Hercynian basement and a Mesozoic-Tertiary cover which are overthrust (in northern Corsica) by slivers of Alpine origin (Mattauer et al. 1981)(Figure 6). The External Units probably originated in the southern margin of Europe, and are usually reconstructed to a position adjacent to southern France or northeast Spain (Figure 2). The separation of these terranes from Europe is attributed to the post-Oligocene rifting in the Gulf of Lion and the opening of the Ligurian Sea, in which the islands underwent ~30-° of counterclockwise rotations (Montigny et al. 1981).

Figure 6. Corsica and Sardinia



Geological map of Corsica and Sardinia after Cherchi and Montadert (1982) and Jolivet et al. (1990).

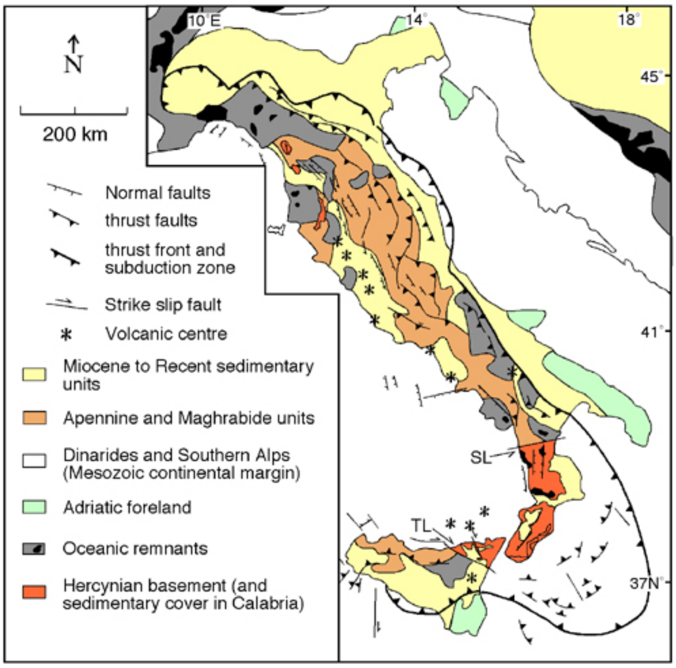
In the nappe stack of Alpine Corsica, high-pressure ophiolitic rocks and non-metamorphic rocks are overthrust on top of external (mainly granitic) units. Radiometric ages of the high-pressure rocks in Alpine Corsica indicate that metamorphism took place during the Late Cretaceous and Tertiary (Jolivet et al. 1998, Brunet et al. 2000 and references therein), at the same time when high-pressure metamorphism occurred in the western Alps. Structural evidence shows that Alpine Corsica was thrust over the Hercynian basement with a westward sense of movement and that these structures are overprinted by younger extensional structures with eastward sense of shear (Fournier et al. 1991). Extensional deformation occurred at greenschist-facies conditions and is defined in localised shear zones along extensional detachments (Fournier et al. 1991, Daniel et al. 1996). This style of extension led to isothermal exhumation of the metamorphic core complex now preserved in northeast Corsica (Jolivet et al. 1990, Fournier et al. 1991). An age of ~32 Ma has been estimated as the commencement of extensional deformation in Corsica (Brunet et al. 2000).

The island of Sardinia consists of a Hercynian basement and a Mesozoic to Eocene sedimentary cover, overlain by syn and post-rift sediments and volcanics (Cherchi & Montadert 1982)(Figure 6). The island is transected by a N-S striking rift that forms a succession of tilted blocks filled with Oligocene-Miocene continental to marine sediments (Cherchi & Montadert 1982). Rifting probably commenced in the middle Oligocene (~30 Ma), and at the end of the Oligocene the trough was deep enough to allow invasion by sea (Cherchi & Montadert 1982). The latest syn-rift sediments are Aquitanian in age, indicating that rifting ceased at 23-24 (Cherchi & Montadert 1982). A second phase of extension that postdated the formation of the Sardinian rift took place at mid-Aquitanian to early Burdigalian (23-20 Ma) (Sowerbutts 2000). Letouzey et al. (1982) have reported Burdigalian (21-17 Ma) NE-SW contractional structures, which seemed to occur simultaneously with a third extensional phase associated with the reactivation of N to NNW trending normal faults (Sowerbutts 2000).

Calabria

Calabria is a nappe-structured belt in the southernmost part of the Italian Peninsula and the northeastern corner of Sicily connecting the Apennines and the Maghrebides (Figure 7). The northern and the southern boundaries of the Calabrian block are major strike-slip faults, the sinistral Sagiento Line and the dextral Taormina Line; their sense of motion indicates that the whole Calabrian block underwent eastern displacement relative to the Apennines and Maghrebides (van Dijk & Scheepers 1995). The rocks in Calabria are remarkably different from those in the Apennine-Maghrebide belts indicating prolonged tectono-metamorphic evolution associated with Alpine orogenesis.

Figure 7. Italian Peninsula and Sicily



Geological map of the Italian Peninsula and Sicily, modified after Channell et al. (1979) and Patacca et al. (1993). SL = Sagiento Line; TR = Taormina Line.

The Calabrian nappes are divided into three major tectonic units (Amodio-Morelli et al. 1976). The lowermost unit consists of a Mesozoic carbonate platform that belongs to the margin of Adria. It is overlain by two ophiolitic nappes composed of Mesozoic and Cenozoic sedimentary and ophiolitic rocks partly metamorphosed under high-pressure conditions (Knott 1987, Cello et al. 1996). The uppermost unit consists of a Paleozoic Hercynian basement and a Mesozoic to Cenozoic sedimentary cover with a strong Alpine signature (Knott 1987). The latter allochthonous terrane, thereafter referred as the Calabrian block, was progressively empvVan Dijk & Okkes 1991).

The age of high-pressure metamorphism in the Calabrian block is ambiguous and varies between 60-35 Ma (Schenk 1980, Rosseti et al. 2001). During the Oligocene and the Miocene, isothermal exhumation of the high-pressure rocks took place (Rosseti et al. 2001). This led to the emplacement of weakly metamorphosed and non-metamorphosed rocks on top of high-pressure rocks in tectonic contacts of low-angle extensional detachments (Platt & Compagnoni 1990, Rosseti et al. 2001). The commencement of extensional tectonics has been inferred as ~30 Ma from 40Ar/39Ar data (Rosseti et al. 2001).

The Apennines

The Apennine belt is a Late Cenozoic fold-and-thrust belt striking parallel to the Italian peninsula from Calabria to the western Alps (Figure 7). The nappes of the Apennines predominantly consist of non-metamorphic or weakly metamorphosed Late Triassic to Neogene marine sediments probably deposited on the passive margin of the Adriatic foreland. The autochthonous crystalline basement is rarely exposed and is only found in the area of Alpi Apuane tectonic windows (northern Apennines). In these outcrops, low-angle normal faults juxtaposed the allochthonous cover above a Hercynian basement, which was metamorphosed at high-pressure conditions at ~25 Ma (Carmignani & Kligfield 1990, Carmignani et al. 1994, Jolivet et al. 1998, Brunet et al. 2000). Extensional tectonics during the Oligocene-Miocene has been considered to play an important role in the exhumation of the Hercynian basement (Carmignani et al. 1994, Jolivet et al. 1998).

Deformation in the Apennines commenced in the Oligocene in the Northern Apennines (Boccaletti et al. 1990) and has propagated southward since the Late Miocene. During deformation, the front of the Apennine thrust system migrated eastward and is presently located predominantly in the Adriatic Sea (Jolivet et al. 1998, Brunet et al. 2000). While ongoing thrusting took place in the (eastern) external Apennines, the (western) internal domain was subjected to crustal extension (e.g. Carmignani et al. 1994, Ferranti et al. 1996) forming extensional sedimentary basins that become younger towards the east (Patacca et al. 1990).

Methods and data

PLATYPLUS

Reconstruction has been performed using PLATYPLUS, a software package developed in the Australian Crustal Research Centre at Monash University (for more information about the PLATYPLUS project see: http://www.virtualexplorer.com.au/PlatyPlus/). The program provides an interactive platform for tectonic reconstruction on a Unix machine. It enables the user to rotate and translate polygons on a spherical Earth. Polygons are chosen based on geological criteria, and their boundaries are digitised and recorded in ASCII files. The objects' hierarchy is then defined in another file. Once motions are projected on the PLATYPLUS platform, they can be rotated and translated. This can be done either by reading a previously prepared motion file that contains sets of Euler poles of rotations, or by using a manual dragging. Thus, known motions are defined in a motion file and applied accordingly, whereas unknown motions are found by trial-and-error experiments using the best available kinematic constraints. This method provides a continuous updating of the motion file during the reconstruction process. Finally, the resulting reconstruction can be viewed in a movie format.

Magnetic isochrons

The most robust data used in plate reconstructions are obtained from the existence of magnetic anomalies in the Atlantic Ocean. Anomalies of similar ages (isochrons) are recognised on both sides of the spreading ridge. Thus, fitting of these isochrons can provide the relative motion of the two diverging plates. However, this method cannot be used for convergent plate margins, and is therefore of little importance in the Mediterranean region. In this reconstruction, the only motions constrained by magnetic isochrons are the relative motions of Africa versus Europe and Iberia versus Europe (Table 1). These data are based on plate circuit calculations described in Rosenbaum et al. (in press).

Figure Table 1. Table 1

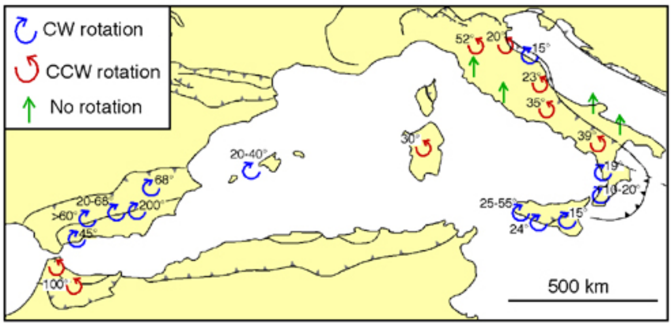
Time (Ma)	Africa/Europe			Iberia/Europe		
	Lat.	Long.	Rot.	Lat.	Long.	Rot.
5	-13.99	158.23	0.55	0.00	0.00	0.00
10	-13.91	158.94	1.09	78.26	58.40	0.00
15	-14.77	162.89	1.53	78.10	58.72	0.13
20	-17.27	164.31	2.13	63.16	133.18	0.19
25	-24.32	161.90	3.57	-21.55	163.26	0.65
30	-27.24	161.11	5.04	-29.42	165.91	1.31
35	-28.89	160.77	6.41	-30.21	165.32	1.72

The motions of Africa and Iberia relative to Europe used in the reconstruction (after Rosenbaum et al. in press).

Palaeomagnetism

Constraints on the kinematics of deformed allochthonous terranes are obtained from palaeomagnetic studies, which can theoretically provide information about the role of block rotations around vertical axis. However, the regional significance of these rotations in deformed rocks can be ambiguous because of the effect of local deformation. In this reconstruction, we refer only to palaeomagnetic studies that considered the effect of local deformation and provided regional tectonic implications. The amount and timing of block rotations associated with different terranes are presented in Figure 8 and summarised in Appendix 1.

Figure 8. Rotations inferred from palaeomagnetic studies



Rotations inferred from palaeomagnetic studies throughout the western Mediterranean. References and time constraints are summarised in Appendix 1.

The role of post-Oligocene block rotations in the western Mediterranean is presented in Figure 8. The rotation of Corsica and Sardinia is relatively well established by palaeomagnetic constraints that indicate ~30° of counterclockwise rotations after the Late Eocene and prior to the Middle Miocene (De Jong et al. 1973, Montigny et al. 1981, Vigliotti & Langenheim 1995, Speranza 1999). It has therefore been concluded that Sardinia and Corsica rotated to their present position during the opening of the Ligurian Sea in the Late Oligocene – Early Miocene. Likewise, the Balearic Islands underwent approximately 25° of clockwise rotation during the opening of Valencia Trough (Freeman et al. 1989, Pares et al. 1992).

Post-Oligocene rotations also occurred in allochthonous terranes of the Rif-Betic cordillera and in the deformed External Zones of the African and Iberian margins. In the Betic cordillera, palaeomagnetic studies implied large amount of clockwise rotations (130° -200°) that gradually decrease towards the distal parts of the thrust belt (Lonergan & White 1997, Platzman 1992, Allerton et al. 1993). At the same time, rocks in the Rif were subjected to counterclockwise rotation in magnitude of approximately 100° (Platzman et al. 1993). In the following reconstruction, we adopt Lonergan and White's (1997) explanation for the opposite rotational directions on both sides of the arcuate Rif-Betic orogen, which is associated with back-arc extension and a westward subduction rollback.

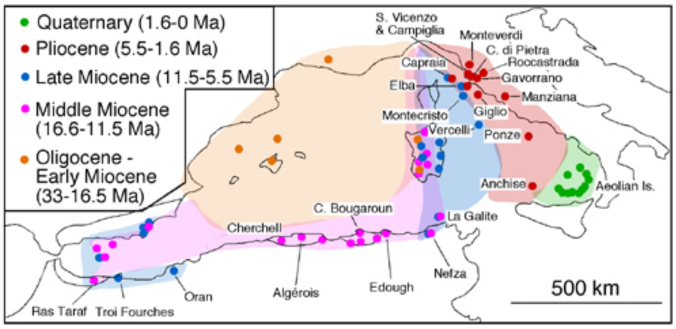
Most palaeomagnetic results from peninsular Italy show a counterclockwise rotation of the allochthonous Apennines (Lowrie & Alvarez 1974, 1975, Channell 1992, Dela Pierre et al. 1992, Scheepers & Langereis 1994, Iorio et al. 1996, Speranza et al. 1998, Muttoni et al. 2000, Sagnotti et al. 2000). However, clockwise rotations have also been reported in post-Messinian sediments in the Northern Apennines (Speranza et al. 1997). Palaeomagnetic results from the Apennines are probably biased by the effect of local deformation (Sagnotti 1992, Scheepers et al. 1993, Mattei et al. 1995), and it is therefore extremely difficult to constrain the kinematics of these terranes. It seems likely, however, that the motion of Apennine nappe thrusts was dominated by counterclockwise rotations during the opening of the Tyrrhenian Sea (ca. 9-5 Ma in the northern Tyrrhenian and 5-0 in the southern Tyrrhenian).

Palaeomagnetic studies from the Calabrian block suggest a counterclockwise rotation in Early – Middle Miocene, followed by ~15-20° clockwise rotations, probably during the Pleistocene (van Dijk & Scheepers 1995, Speranza et al. 2000 and references therein). In the Maghrebide belt of Sicily, post-Miocene deformation has been dominated by clockwise rotations, which decrease towards the distal part of the belt (Speranza et al. 1999 and references therein).

Volcanism

The distribution of calc-alkaline magmatism in the western Mediterranean is summarised in Appendix 2 and presented in Figure 9. Calc-alkaline magmatism was probably produced during subduction processes, and the nature of subduction systems can thus be implied from the spatial and temporal distribution of the volcanic rocks (Figure 9). Calc-alkaline volcanics show a general younging trend from southern France towards the Apennines, North Africa and the Alboran Sea, suggesting migration of volcanic arcs during subduction rollback. They are locally superimposed by younger alkaline volcanics and oceanic basalts, which were emplaced in the back-arc region.

Figure 9. Distribution of volcanic rocks



Map showing the distribution of volcanic rocks in the western Mediterranean.

Evidence for an Oligocene volcanic arc is found in southern France and Sardinia. In southern France, calc-alkaline magmas erupted between the Oligocene and the Middle Miocene (33-20 Ma)(Bellon 1981). Based on geochemical criteria, it has been suggested that volcanism took place in a north-dipping subduction system (Rehault et al. 1985). The volcanic arc continued southwestward in Sardinia and Valnecia Trough, although in the latter, volcanism commenced only at 25-24 Ma (Marti et al. 1992).

During the Lower – Middle Miocene, extension took place in the Ligurian Sea and Valencia Trough, and the volcanic arc migrated with accordance of the retreating slab. In Sardinia, ongoing volcanism occurred until 14 Ma (Savelli 1988). The largest amount of Middle Miocene volcanism is found in the North African coast and in the Alboran Sea (Lonergan & White 1997, El Bakkali et al. 1998, Maury et al. 2000, Zeck et al. 2000, Fourcade et al. 2001 and references therein). Calc-alkaline volcanism occurred in North Africa between 16.5-8 Ma, following the accretion of the Kabylies blocks to the African margin at ~18-15 Ma (Lonergan & White 1997). Volcanic activity in the Alboran Sea and the Betic-Rif cordillera has been dated to 15-7 Ma, and was probably associated with an east-dipping subduction zone that retreated westward towards Gibraltar during Middle-Late Miocene (Lonergan & White 1997).

Since the Late Miocene, the majority of volcanism in the western Mediterranean has been concentrated in the Tyrrhenian Sea (Savelli 1988, 2000, Serri et al. 1993, Argnani & Savelli 1999)(Figure 9). In this region, calc-alkaline volcanics become younger from west to east, and show a geochemical polarity that resulted from a west dipping subduction (Savelli 2000). The existence of magmas younger than ~7 Ma eastward of the Sardinia-Corsica axis suggests commencement of eastward slab rollback at 10-7 Ma. It can also be recognised that arc migration first occurred in the northern Tyrrhenian, and only later (~5 Ma) occurred in the southern Tyrrhenian. The youngest calc-alkaline volcanics, found in the Aeolian Islands, mark the present location of the volcanic arc associated with a Benioff Zone beneath Calabria.

Seismicity

Deep structures in the Mediterranean region have been studied from the analysis of seismic data, and particularly from seismic tomography images (Wortel & Spakman 1992, Spakman et al. 1993, Carminati et al. 1998, Wortel & Spakman 2000). Seismic tomography is based on the contrast between seismic velocities produced by the existence of relatively cold subducting lithosphere within the surrounding hot asthenosphere. It thus provides an insight to the three-dimensional structures of subduction systems long after the generation of earthquakes has ceased (Wortel & Spakman 1992).

Seismic tomography results strongly support the existence of subduction systems throughout the western Mediterranean. A well-defined Benioff Zone is found in the Calabrian Arc, where active subduction of the Ionian plate is taking place. It is associated with deep (>500 km) earthquakes (Anderson & Jackson 1987), and is clearly recognised in tomographic images that show a northwest dipping lithospheric slab subducting beneath Calabria, and flattened in the upper/lower mantle boundary (Lucente et al. 1999). In other localities, such as the Apennines and the Alboran Sea, the seismic tomography images show subducting slabs detached from the lithosphere at the surface (Wortel & Spakman 2000). Beneath the Apennines, a detached lithospheric slab is recognised at 150-670 km depth. It is dipping towards the southwest, and indicates the remnant subduction system that existed during the opening of the Tyrrhenian Sea (Lucente et al. 1999). In the Alboran Sea, a detached lithospheric slab at depths of more than 600 km has been deduced from deep seismicity and tomographic images (Buforn et al. 1991, Seber et al. 1996, Calvert et al. 2000). However, the tectonic significance of the detached slab has been ambiguously interpreted as evidence for east dipping subduction (Lonergan & White 1997), lithospheric delamination (Seber et al. 1996, Calvert et al. 2000), and a convective removal of thickened lithosphere (Platt & Vissers 1989). In the North African margin, tomographic anomalies have not been clearly recognised due to a relatively poor spatial resolution (Spakman et al. 1993). However, it has been suggested that existing anomalies below Algeria indicate remnants lithospheric mantle ruptured and segmented from the Tyrrhenian and the Alboran subduction systems (Carminati et al. 1998).

Reconstruction

Figure 10. Computer animation

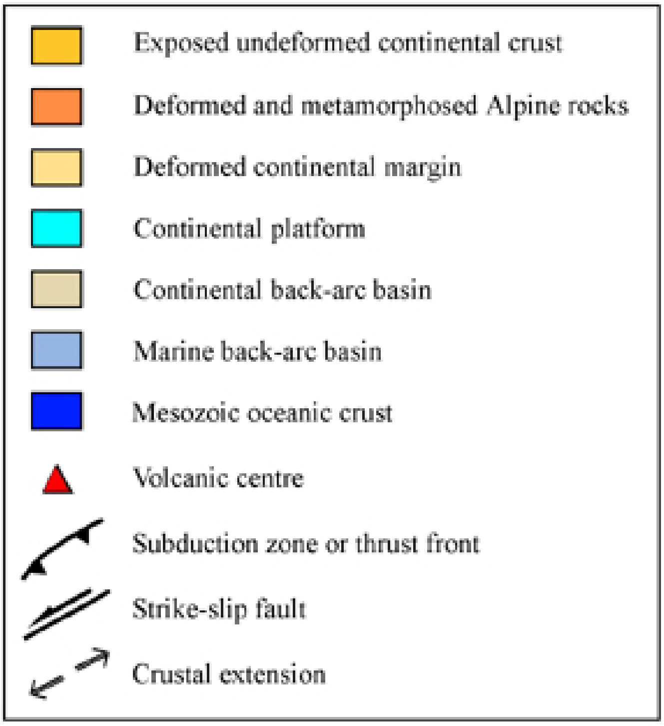


Figure 10 is a movie showing the reconstruction of the western Mediterranean since the Oligocene. The main tectonic characteristics are discussed below. Figure 10a Key to principal colours and symbols used in the reconstruction movie and in Figures 11-18. Figure 10b Reconstruction movie of the tectonic evolution of the western Mediterranean since the Oligocene. (Select image to view animation)

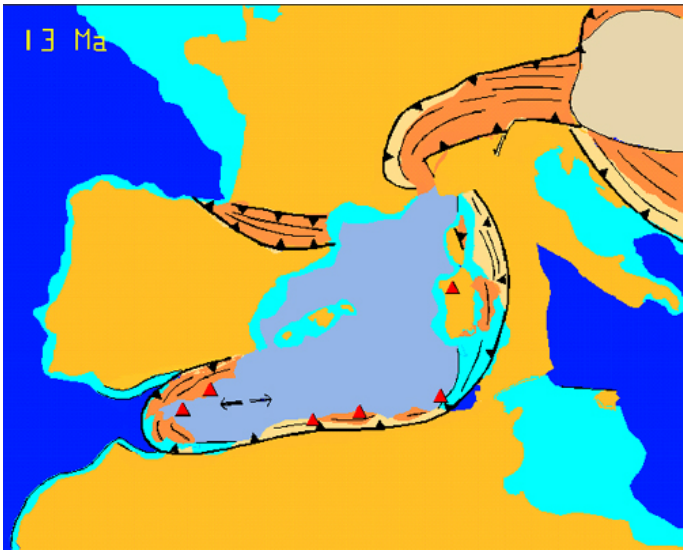
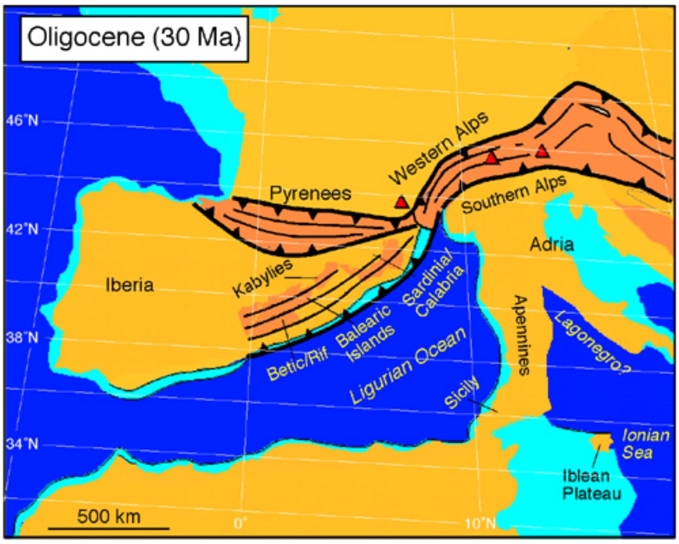


Figure 10 is a movie showing the reconstruction of the western Mediterranean since the Oligocene. The main tectonic characteristics are discussed below. Figure 10a Key to principal colours and symbols used in the reconstruction movie and in Figures 11-18. Figure 10b Reconstruction movie of the tectonic evolution of the western Mediterranean since the Oligocene. (Select image to view animation)

Tectonic setting of south Europe in the Oligocene

During the Oligocene, the area between the Iberian Peninsula and southern France consisted of several terranes, which are now located hundreds of kilometres away. Among these are the internal zone of the Betic-Rif Cordillera, the Balearic Islands, the Kabylies, Corsica, Sardinia, and Calabria (Ricou et al. 1986, Lonergan & White 1997)(Figure 11). Most of these terranes consist of a Hercynian basement and a Mesozoic cover, which largely underwent deformation and metamorphism during Alpine orogenesis. The origin of these terranes is not entirely clear, but they were possibly attached to the Iberian plate before being incorporated in the Alpine orogeny (Stampfli et al. 1998). Since the Middle Miocene, no rotations occurred in Corsica, Sardinia and the Balearic Islands, and their palaeo-positions can be inferred by applying opposite rotations to those obtained from palaeomagnetic studies. Prior to the opening of the western Mediterranean basins, Calabria was located adjacent to Sardinia (Alvarez et al. 1974, Dewey et al. 1989, Minzoni 1991). An alternative hypothesis is that during the Oligocene, Sardinia and Calabria overlapped each other, forming the upper (Sardinia) and the lower (Calabria) units of a metamorphic core complex. This hypothesis, however, requires further research. The largest uncertainty in the Oligocene reconstruction is the position of the Internal Zone of the Rif-Betic cordillera, which is here placed southeast to the Balearic Islands after Lonergan and White (1997). This configuration forms a continuous orogenic belt during the Oligocene, from the Rif-Betic to Calabria, Corsica and the western Alps.

Figure 11. Oligocene reconstruction



Oligocene reconstruction (30 Ma).

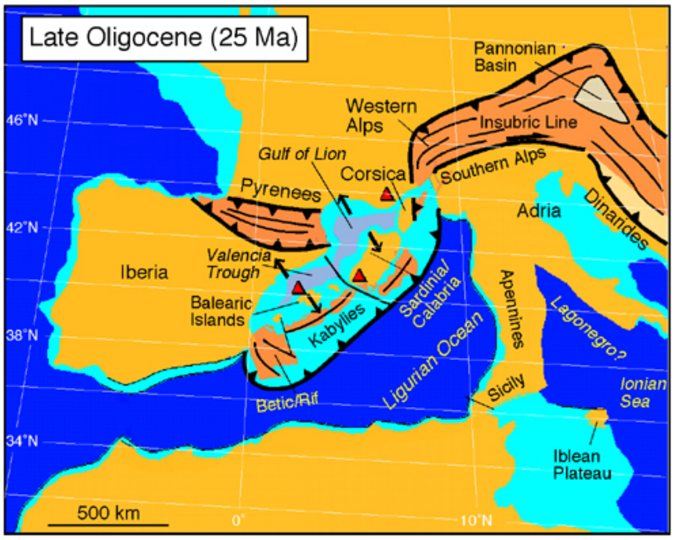
The tectonic setting in the Late Oligocene was characterised by a switch in the vergence of subduction systems and by the occurrence of widespread extension in the Alps (termed ‘the Oligocene Lull’ by Laubscher (1983)) and in the western Mediterranean region. In the Early Oligocene, the Alpine orogen underwent a major orogenic episode, indicated by ~35 Ma ages of high-pressure and ultra-high-pressure rocks exposed in the Internal Crystalline Massifs of the western Alps (Gebauer 1996, Gebauer et al. 1997, Rubatto & Gebauer 1999). The present structural configuration of the Alpine sutures in western Alps and in northeast Corsica suggests that, prior to continental collision, the area had been controlled by a southeast-dipping subduction system (Figure 11). In the Late Oligocene, however, the polarity of the subduction system changed, and a new northwest-dipping subduction system developed in the southern margin of west Europe, producing calc-alkaline volcanism in Provence and Sardinia (Figure 11).

The initiation of a new northwest-dipping subduction system was possibly triggered by continental collision in the Alps at 35 Ma. This collision could block the existing subduction system by the arrival of thick crustal material at the subduction zone. Thus, a new subduction system developed in a more southerly location, where relatively old (Jurassic) oceanic lithosphere was found. Thus, at 30 Ma the subducting oceanic lithosphere was relatively old (>110 Ma) and cold enough to create a gravitational instability, which would cause rollback of the subduction hinge towards the SE. In addition to slab rollback, the motion of Africa relative to Europe has been considerably slow since 30 Ma, and particularly since 25-20 Ma (Jolivet & Faccenna 2000, Rosenbaum et al. in press). Thus, with the absence of sufficient convergence to support subduction rollback, extension commenced in the overriding plate, forming the foundations of the western Mediterranean basins.

Valencia Trough, Gulf of Lion and the Ligurian Sea

Earlier rifting is inferred from syn-rift Late Oligocene sediments deposited on Early Oligocene grabens and half grabens in the margins of Valencia Trough, the Gulf of Lion and the Ligurian Sea (Cherchi & Montadert 1982, Burrus 1989, Bartrina et al. 1992). Rifting probably commenced in the early Late Oligocene (~30 Ma) in the Gulf of Lion (Séranne 1999), and in the latest Oligocene (~25 Ma) in Valencia Trough (Roca et al. 1999). A right lateral strike-slip fault (North Balearic Transfer Zone) separated the Valencia Trough from the Gulf of Lion (Séranne 1999)(Figure 12). Structural observations from the extended margins suggest that horizontal extension was partitioned in different crustal levels, forming rift valleys in the upper crust (e.g., in Sardinia)(Cherchi & Montadert 1982), and low angle extensional detachments in deeper crustal levels (e.g., Corsica and Calabria)(Jolivet et al. 1990, Rosseti et al. 2001). Ductile extensional deformation in Corsica and Calabria has been dated at 32-25 Ma (Brunet et al. 2000, Rosseti et al. 2001), that is, before subduction rollback commenced.

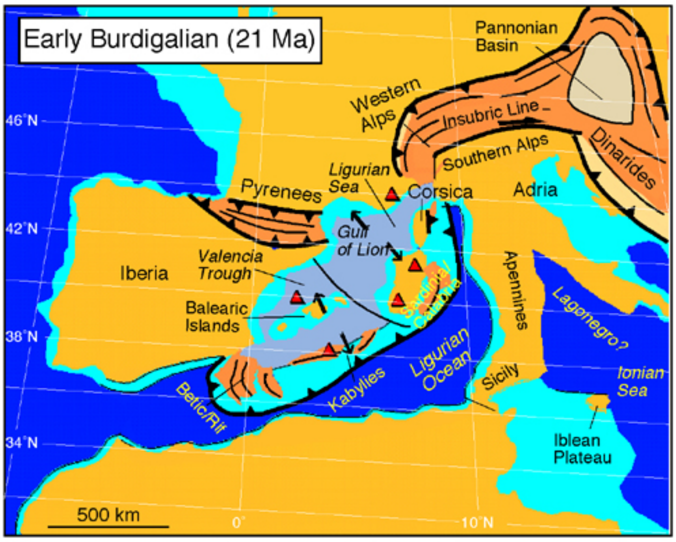
Figure 12. Late Oligocene reconstruction



Late Oligocene reconstruction (25 Ma).

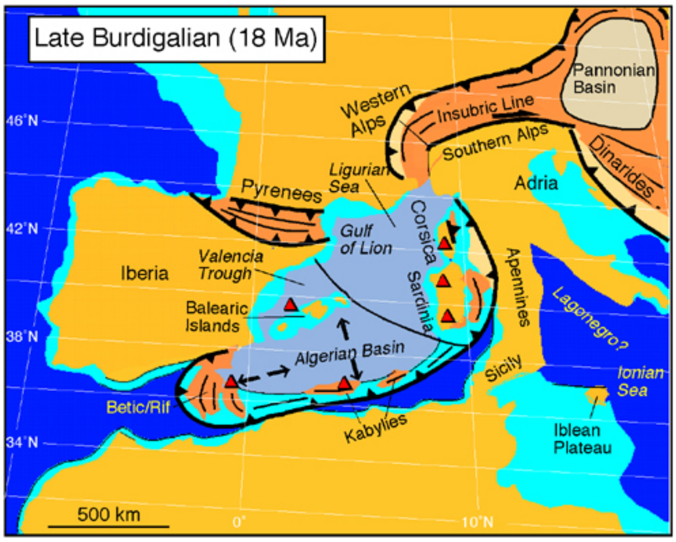
As a result of subduction rollback, Extension in the Early Miocene led to the breakup and drifting of continental fragments formerly attached to southern France and Iberia. Thus, during the opening of the Ligurian Sea and the Valencia trough, the Balearic Islands, Corsica, Sardinia and Calabria were subjected to block rotations. Extension in Valencia Trough ceased in early Burdigalian (21-20 Ma) before it was sufficient to form oceanic crust (Bartrina et al. 1992, Watts & Torné1992). However, ongoing southward rollback of the subduction hinge led to the formation of a new rift system between the Balearic Islands and the Kabylies blocks, and further extension resulted in the formation of the Provençal Basin (Séranne 1999)(Figure 13). In the Gulf of Lion, tectonic activity ceased in Aquitanian/early Burdigalian (20-18 Ma) (Cherchi & Montadert 1982, Burrus 1989), possibly due to the collision of Corsica, Sardinia and Calabria with the Apennines (Figure 14). Following collision, Apennine units arrived at the subduction system and impeded rollback, which in turn, led to the cessation of back-arc extension in the Ligurian Sea.

Figure 13. Early Burdigalian reconstruction



Early Burdigalian reconstruction (21 Ma).

Figure 14. Late Burdigalian reconstruction



Late Burdigalian reconstruction (18 Ma).

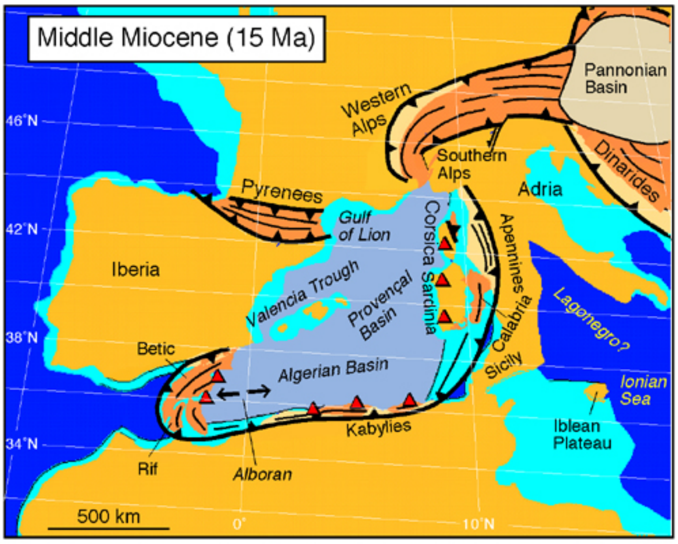
North Africa

During the Early-Middle Miocene, intense tectonic activity took place in North Africa due to the opening of the Provençal, Algerian and Alboran basins, and the subsequent emplacement of the Kabylies block and the Internal Rif onto the African margin. Extension in the Provençal Basin commenced after rifting in Valencia Trough had failed. In early Burdigalian (~21 Ma), continental breakup occurred between the Balearic Islands and the Kabylies blocks, and a new basin developed. Extension was probably governed by a rapid southward rollback and subsequently led to sea floor spreading and formation of a new oceanic crust in the Algerian-Provençal Basin (Rehault et al. 1985)(Figure 13 & Figure 14).

Evidence for extensional fabrics associated with the opening of the Algerian-Provençal Basin are found in the Kabylies metamorphic core complexes, which are now accreted to the African margin. These complexes are characterised by the occurrence of low-angle extensional detachments, which juxtaposed upper crustal rocks on top of high-grade metamorphic rocks (Caby & Hammor 1992, Tricart et al. 1994, Saadallah & Caby 1996). The occurrence of core complexes implies that a considerable amount of crustal thinning was made possible by non-coaxial shearing along extensional detachments. Based on 40Ar/39Ar dating, it has been suggested that extensional deformation occurred at 25-16 Ma (Monié et al. 1984, 1988, 1992).

The Kabylies blocks drifted southward in response to the southward rollback of the subduction zone until they collided and accreted to the African margin (Cohen 1980, Tricart et al. 1994)(Figure 15). Collision occurred when the Mesozoic oceanic lithosphere, which had previously separated the Kabylies from the African margin, was totally consumed by subduction. The collision occurred between 18-15 Ma, based on the cessation of extensional tectonics in the Algerian-Provençal Basin and the Kabylies core complexes, and the commencement of thrusting in the External Maghrebides (Frizon de Lamotte et al. 2000). The accretion of the Kabylies block and the final consumption of old oceanic lithosphere in this region permanently terminated southward subduction rollback. South-directed thrust systems propagated southward after accretion (Frizon de Lamotte et al. 2000), but subduction processes were impeded and eventually halted with the presence of the relatively buoyant continental crust at the subduction zone. The Middle Miocene cessation of subduction processes in North Africa resulted in the segmentation of the western Mediterranean subduction system, with an eastward dipping subduction in the Alboran region, and a westward dipping subduction in the Tyrrhenian region (Lonergan & White 1997)(Figure 15).

Figure 15. Middle Miocene reconstruction



Middle Miocene reconstruction (15 Ma).

The Alboran Domain

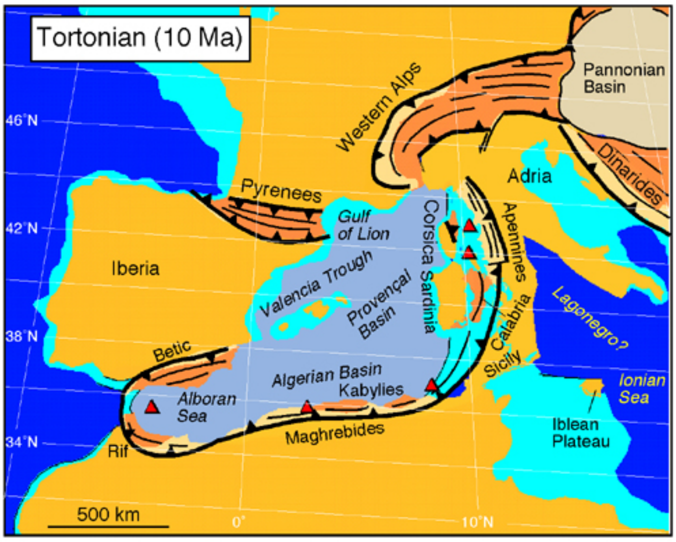
The tectonic evolution of the Alboran Sea is a matter of controversy, and several different models have been proposed. This reconstruction follows Royden (1993a) and Lonergan and White (1997), who suggested a slab rollback model for the opening of the Alboran Sea. Alternatively, it has been suggested that extension in the Alboran Sea developed as a result or an extensional collapse of a thickened continental crust and its underlying lithospheric mantle (e.g. Platt & Vissers 1989, Housman 1996). These models are not entirely supported by field observations from the Rif-Betic cordillera, which imply episodic alterations from crustal shortening to extension (Azañón et al. 1997, Balanya et al. 1997, Martínez-Martínez & Azañón, 2002). Neither are such models supported by the block rotations inferred from palaeomagnetic data.

According to our model, the origin of the Internal Zone of the Rif-Betic cordillera is similar to the origin of Corsica, Sardinia, Calabria and the Kabylies (Figure 11). Thus, the Rif-Betic in its Oligocene position formed a continuous orogenic belt together with the Kabylies, Calabria, Corsica and the western Alps that underwent high-pressure metamorphism during Alpine orogeny (Figure 11). As mentioned before, these terranes (excluding the western Alps) were part of an overriding continental slab above a northwest dipping subduction zone, which started to retreat oceanward during the Oligocene. Once rollback of the subduction hinge commenced, rocks of the Rif-Betic Internal Zone were subjected to an extensional regime leading to the formation of metamorphic core complexes and exhumation of high-pressure metamorphic rocks below extensional detachments (Platt et al. 1983, Azañón et al. 1997, Balanya et al. 1997).

Westward rollback of the subduction hinge in the westernmost Mediterranean was probably triggered by an original curvature of the subduction zone in its western terminus. Rollback, therefore, led to southwestward migration of the subduction hinge accompanied by southwestward drifting of the extended continental fragments of the overriding plate. Southerly migration, however, could not proceed after the subduction zone reached the passive margin of Africa (see previous section). Rollback continued only in areas where the existence of oceanic lithosphere still permitted oceanward retreat of the subducting lithosphere (Figure 15). Thus, in the Middle Miocene (16-15 Ma), the western east-dipping segment of the subduction zone rolled back in the direction of the oceanic lithosphere.

The formation of the Alboran Sea occurred during the westward migration of the subduction hinge. Rapid rollback was compensated by wholesale extension in the overriding continental crust, which was thinned to ~15 km between 23-10 Ma (Lonergan & White 1997). Contemporaneously, fragments of continental crust were thrust onto the passive margin of Africa and Iberia (the External Zone), forming rotation patterns consistent with oblique thrusting derived by the westward rollback of the subduction zone. Final accretion of the Rif-Betic Cordillera occurred at ~10 Ma, when the subduction zone rolled back as far as Gibraltar (Figure 16). Subduction rollback then ceased, together with the cessation back-arc extension in the Alboran Sea (Lonergan & White 1997).

Figure 16. Tortonian reconstruction



Tortonian reconstruction (10 Ma).

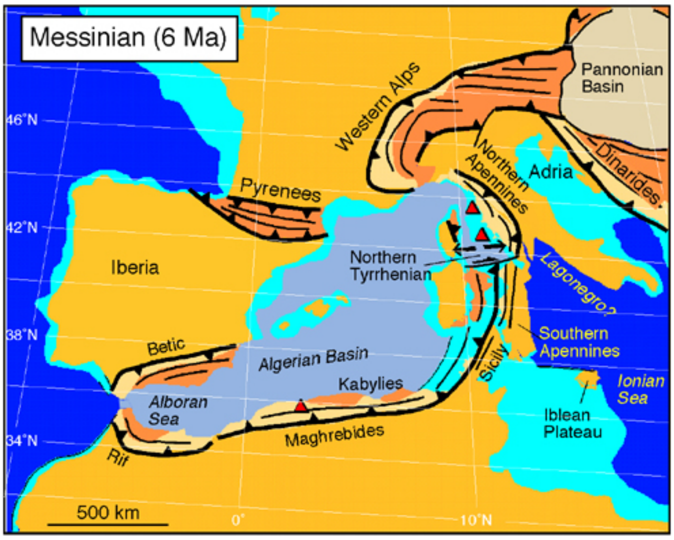
Tyrrhenian Sea

The Tyrrhenian Sea is the youngest basin in the western Mediterranean, forming since the Tortonian (~9 Ma). It was opened, according to this reconstruction, as a result of a southeastward rollback of subduction systems near the margins of the Adriatic plate (Malinverno & Ryan 1986).

We suggest that the collision of Corsica and Sardinia with the Apennines at ~18 Ma led to a relative quiescence in back-arc extension between 18-10 Ma (Figure 14-Figure 16). During this period, continental crust of Apennine units incorporated in the subduction zone, and impeded further eastward subduction rollback. Thus, considerable crustal shortening occurred in the Apennines accompanied by thrust systems that propagated eastward.

The opening of the Tyrrhenian Sea occurred in two stages: an early (9-5 Ma) opening of the northern Tyrrhenian Sea (Figure 17), and a late (5-0 Ma) opening of the southern Tyrrhenian Sea (Mantovani et al. 1996)(Figure 18). It was accompanied by coeval crustal shortening in the Apennines (Malinverno & Ryan 1986) and counterclockwise rotations of nappe stacks. The reason for the opening of the northern Tyrrhenian is not entirely clear. It may be associated with subduction of oceanic crust located between the Apennine belt and the Adriatic foreland, which promoted lithospheric gravitational instability during Late Miocene, and further eastward subduction rollback. It is possible that deep-sea sediments of the Lagonegro and Molise formations are remnants of these intra-Adriatic basins (Sengör 1993). At this stage, the subduction zone was oriented ~N-S, that is, roughly parallel to the direction of convergence. Therefore, the rate of convergence at the trench was very low, and consumption of oceanic lithosphere was mostly driven by the negative buoyancy of the subducting slab (Faccenna et al. 2001).

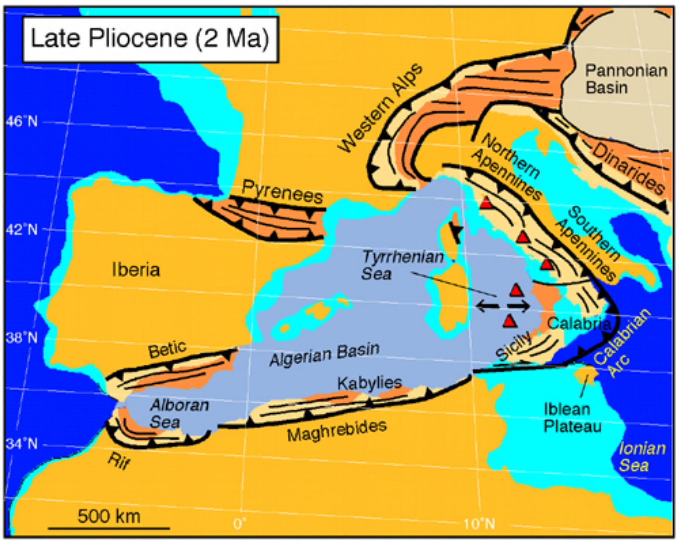
Figure 17. Messinian reconstruction



Messinian reconstruction (6 Ma).

During the latest Miocene or the Early Pliocene (5 Ma) extension ceased in the northern Tyrrhenian Sea and migrated southward to the southern Tyrrhenian Sea (Figure 18). This stage was characterised by considerable extension that culminated during the Pliocene-Pleistocene, when new oceanic crust formed. Contemporaneously, crustal shortening occurred in the Southern Apennines and Sicily accompanied by counterclockwise block rotations in the former and clockwise rotations in the latter. These processes have been controlled by rapid rollback of oceanic Ionian lithosphere beneath the Calabrian arc.

Figure 18. Late Pliocene reconstruction



Late Pliocene reconstruction (2 Ma).

Discussion

The reconstruction of the western Mediterranean since the Oligocene emphasises the role of subduction rollback in convergent plate margins. It shows that a widespread extension took place in the convergent interface separating Africa and Europe, forming marine back-arc basins and new spreading centres. Subduction rollback was probably controlled by the gravitational instability produced during subduction of cold and dense oceanic lithosphere. Back arc extension was likely to occur when the velocity of the slab retreat overcame the absolute motion of the overriding plate (Molnar & Atwater 1978, Dewey 1980, Royden 1993b, Lonergan & White 1997). In the evolution of the western Mediterranean these processes have played a fundamental role since the Oligocene. Subduction rollback was made possible by the consumption of Mesozoic oceanic lithosphere at the subduction zone. This oceanic lithosphere was probably old and cold enough to be gravitationally unstable relative to the surrounding asthenosphere. The subduction zone has therefore progressively retreated from its Oligocene position near the southern margin of Europe to its final configuration in the Calabrian arc, North Africa and the Alboran arc. In the western Mediterranean, subduction rollback occurred during a period of relatively slow convergence between Africa and Europe (Jolivet & Faccenna 2000, Rosenbaum et al. in press). As convergence alone could not compensate the vacant area formed by subduction retreat, back-arc extension occurred in the overriding plate. Thus, a period of relatively slow convergence was actually characterised by large-scale horizontal motions of smaller microplates and allochthonous terranes.

The dispersion of continental terranes, which drifted and rotated during subduction rollback, is clearly seen in our reconstruction. In the Alpine orogen, this process led to the fragmentation of a continuous belt into continental terranes, which in turn, collided with the passive margins of the surrounding continents. We stress that this mechanism may have profound tectonic implications on the way orogens work. Orogens may be subjected to switches from crustal shortening and extension, controlled by the processes of subduction rollback, rifting in the back-arc region and the subsequent accretion of allochthonous terranes onto adjacent passive margins. Thus orogenesis cannot be oversimplified to subduction followed by collision of two continental plates, but includes accretion of numerous continental terranes. Following collisional events, reorganisation of the plate boundaries occurs, associated with termination, jumping or segmentation of subduction zones. A Similar style of orogenesis has been proposed by Nur and Ben Avraham (1982) based on numerous examples of allochthonous terranes throughout the Circum-Pacific (excluding the Andes) and the Alpine Himalayan belts. These authors have suggested that continental slivers and microcontinents could actually migrate great distances before colliding with the continents.

In summary, the style of tectonism suggests that the role of horizontal motions during orogenesis cannot be disparaged. Fragments of continental crust were possibly subjected to large amount of horizontal transportation, block rotations on vertical axes, and episodic alterations from crustal shortening to extension.

Concluding remarks

Extension in the western Mediterranean commenced at 32-30 Ma and was primarily controlled by subduction rollback. The rapid rollback of the subduction hinge was accompanied by a relatively slow convergence between Africa and Europe. Therefore, convergence could not support the rate of subduction rollback, and extension occurred on the overriding plate.

During back-arc extension, marine basins progressively formed from north to south, floored either by thinned continental crust or new oceanic crust. The earliest basins began to form in Late Oligocene in the Gulf of Lion, the Ligurian Sea and Valencia Trough. In Early Miocene, back-arc extension propagated to Provençal, Algerian and Alboran basins, and in the Upper Miocene, extension in the Tyrrhenian Sea commenced.

Rifting led to breakup of continental terranes, which drifted and rotated as long as the subduction zone continued to rollback. Subduction rollback temporally or permanently ceased when continental crust arrived at the subduction zone, impeding subduction processes. The continental terranes have then been accreted to the continents and considerable crustal shortening occurred.

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Appendices

Appendix 1 Appendix 2

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