Chapter 5
The Rif Belt

A. Chalouan, A. Michard, Kh. El Kadiri, F. Negro, D. Frizon de Lamotte, J.I. Soto and O. Saddiqi

This chapter is dedicated to the memory of our friend Pr. Ahmed Ben Yaïch, whose promising scientific activity has been interrupted too early, and of Gabriel Suter, the father of the Rifian geological mapping, just disappeared after a long Moroccan career.

5.1 General

References: Considering only the most recent and general references, we may cite Frizon de Lamotte et al. (1991), Martínez-Martínez & Azañón (1997), Chalouan et al. (2001), Platt et al. (2003a), Chalouan & Michard (2004), Frizon de Lamotte

A. Chalouan
Department of Earth Sciences, Mohammed V-Agdal University, Faculty of Sciences, BP 1014, Rabat-Agdal, Morocco, e-mail: chalouan@yahoo.com

A. Michard
Université de Paris-Sud (Orsay) and Ecole Normale Supérieure (Paris), 10 rue des Jeûneurs, 75002 Paris, e-mail: andremichard@orange.fr

Kh. El Kadiri
Abdelmalek-Essaadi University, Faculty of Sciences, BP. 2121, M'Hannech II, 93003 Tetouan, Morocco, e-mail: khkadiri@fst.ac.ma

F. Negro
Institut de Géologie et d'Hydrogéologie, Université de Neuchâtel, 11, rue Emile Argand, CP 158, 2009 Neuchâtel, Suisse, e-mail: francois.negro@unine.ch

D. Frizon de Lamotte
Université de Cergy-Pontoise, Dépt. Sciences de la Terre et de l'Environnement, (CNRS, UMR 7072) 95 031 Cergy cedex, France, e-mail: dfrizon@u-cergy.fr

J.I. Soto
Departamento de Geodinámica e Instituto Andaluz de Ciencias de la Tierra (CSIC-Univ. Granada) Campus Fuentenueva s/n 18071, Granada (Spain), e-mail: jsoto@ugr.es

O. Saddiqi
Université Hassan II, Faculté des Sciences Aïn Chok, Laboratoire Géodynamique et Thermochronologie, BP 5366 Maârif, Casablanca, Maroc, e-mail: o.saddiqi@fsac.ac.ma

A. Michard et al., *Continental Evolution: The Geology of Morocco*. Lecture Notes in Earth Sciences 116,

et al. (2004), Crespo-Blanc & Frizon de Lamotte (2006), and Michard et al. (2006). The most recent offshore campaigns in the Alboran Sea, Gulf of Cadiz, and Algerian Basin are reported by Chalouan et al. (1997), Comas et al. (1999), Maldonado et al. (1999), and Mauffret et al. (2004, 2007). The role of the Gibraltar Arc tectonics on the Messinian salinity crisis is considered by Jolivet et al. (2006), Loget & Van Den Driessche (2006), and Maillard et al. (2006). Further geophysical references are given in Sect. 5.3. An historical review of the concept of Gibraltar Arc has been published by Durand-Delga (2006).

5.1.1 The Rif Belt, a Segment of the Mediterranean Alpine Belts

The Rif Belt belongs to a much larger orogen, i.e. the Betic-Rif-Tell orogen, which itself is part of the still larger Mediterranean Alpine belts (Fig. 5.1; see also Chap. 1.1, Fig. 1.2). The Rif Belt occupies a key position in this orogenic system. On the one hand, it forms the westernmost part of the *Maghrebide belt*, which extends along the North African coast, and continues eastward to Sicily and Calabria in southern Italy. On the other hand, it forms the southern limb of the Gibraltar Arc, the northern limb of which corresponds to the Betic Cordilleras (Fig. 5.2).

The Gibraltar Arc is one of the tighter orogenic arcs (oroclines) worldwide. It also corresponds to the western tip of the Alpine belts. The Gibraltar Arc closes almost completely the Mediterranean to the west (Fig. 5.3), and exemplifies the

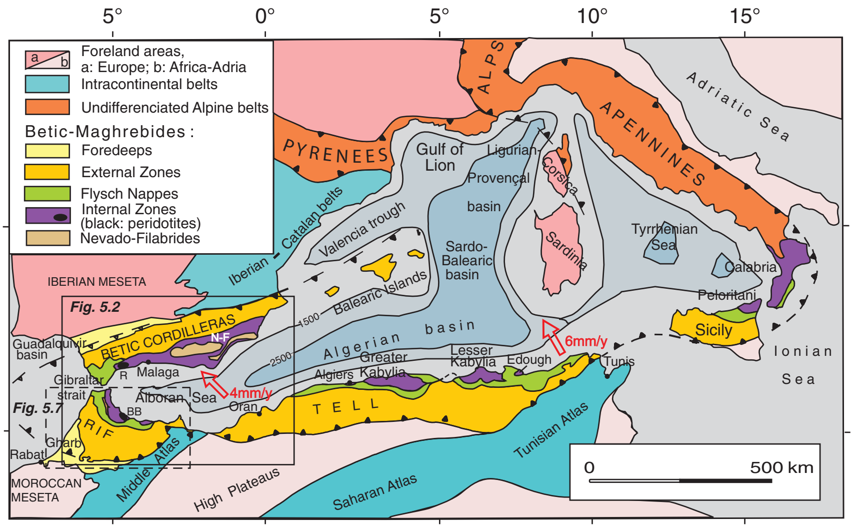


Fig. 5.1 The Rif Belt in the frame of the West Mediterranean Alpine belts. *Empty arrows*: direction and rate of recent Africa-Europe convergence (NUVEL 1A model, DeMets et al., 1994; Morel & Meghraoui, 1996). BB: Beni Bousera; N-F: Nevado-Filabrides; R: Ronda

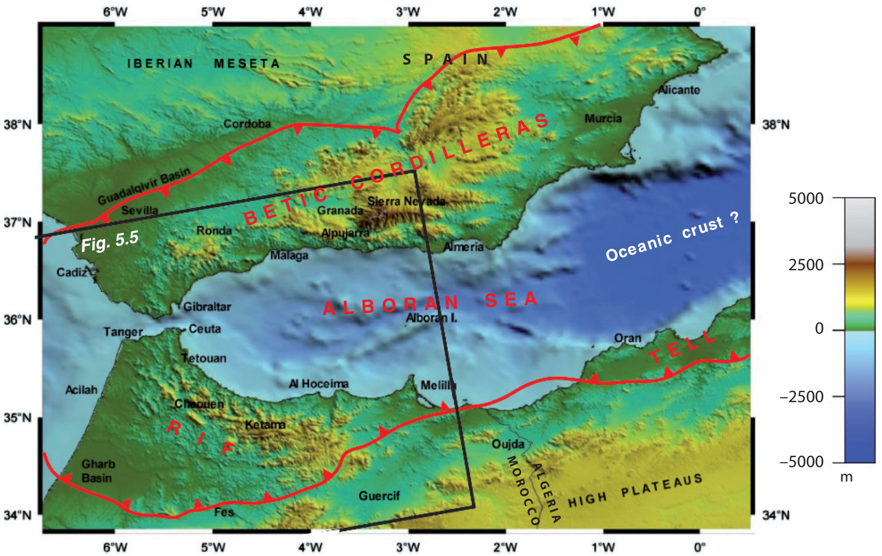


Fig. 5.2 Elevation map of the Gibraltar Arc and Alboran Sea area from ETOPO2 Global Data Base (Courtesy of F. Negro). For location, see Fig. 5.1. *Red line* with teeth: External front of the Betic and Maghrebide orogens

intimate association of two opposite processes, i.e. mountain building and subsequent collapse. The latter process formed the Alboran Sea in the core of the system while thrusts and folds propagated towards the external zones. The Gibraltar Arc has a counterpart at the eastern end of the Maghrebides, i.e. the Calabrese Arc. Both arcs originate from the same geodynamic process, which resulted in the closure of the Ligurian-Maghrebian Tethys and opening of the West Mediterranean

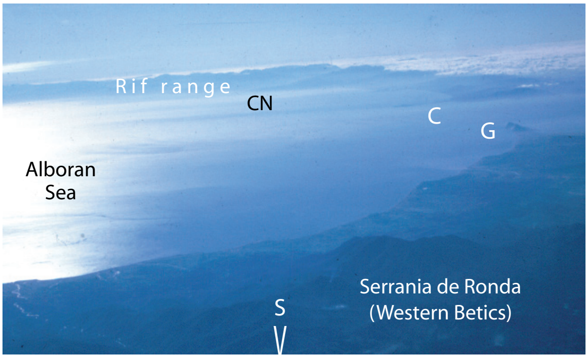


Fig. 5.3 Aerial view looking southeast-ward on the Alboran Sea surrounded by the Gibraltar Arc. The plane is crossing the Serrania de Ronda. G: Gibraltar; C: Ceuta; CN: Cabo Negro. The Strait of Gibraltar passes between G and C. The clouds from the Atlantic Ocean are stopped by the Dorsale range of the Haouz, south of Ceuta

Sea. Paradoxically, this evolution started from the Late Eocene and lasted for about 30 million years while the Africa-Europe convergence was going on (see Chap. 1, Fig. 1.12). This is explained by the roll-back of the Tethyan subduction beneath the European lithosphere (Sect. 5.7).

Due to its position between the Atlantic Ocean and the Mediterranean Sea, the Gibraltar Arc played a major role in the evolution of the famous Messinian salinity crisis (5.9–5.3 Ma), which deeply marked the morphology of the Mediterranean areas and the coeval sedimentation. Folding in the External Zones related to plate convergence during the Messinian (~6 Ma) contributed to the closure of the *South-Rif Corridor*, i.e. the last gate for the Atlantic waters entering in the Mediterranean. Closure of the seaway was ensured by the regional uplift related to the development of the Trans-Moroccan Hot Line (Chap. 4), also responsible for the Trans-Alboran magmatism. By the early Pliocene, the opening of the Strait of Gibraltar allowed the cool, low-salinity Atlantic waters to enter again the Mediterranean Basin (Fig. 5.4). This event can be ascribed either to normal fault activity within the Strait, or to a general downthrow of the whole Arc due to westward roll-back of the underlying subduction (see Sect. 5.7), or to both causes. Moreover, during the late Messinian when the Mediterranean Sea level was at its lower stand, the Gibraltar threshold has been incised by a deep canyon where Atlantic waters finally rushed.

5.1.2 Structural Domains

Three main structural domains form the Gibraltar Arc, from inside to outside and bottom to top, (i) the *Internal Zones*, or *Alboran Domain*; (ii) the *Maghrebian Flyschs*, and (iii) the *External Zones* (Fig. 5.5). Each domain consists of tectonic complexes of stacked units or nappes with similar lithologies within a given complex, but contrasting from one complex to the other. This results in different surface morphologies and spectral signatures (Fig. 5.6). The structural map (Fig. 5.7) and associated cross-section (Fig. 5.8) highlight the principal structural lines of the Rif Belt based on extensive, integrated studies and mapping at scale 1:50000.

5.1.2.1 Internal Zones (Alboran Domain)

The Internal Zones consist of continental units displaced westward over several hundreds of kilometres, thus representing a genuine exotic terrane. Considering the grade of Alpine metamorphic recrystallization in these units, we can recognize two complexes, which respectively form the upper and lower plates of a metamorphic core complex. In the Rif and western Betics, the lower plate corresponds to the *Sebtide* and *Alpujarride* units, respectively, both dominantly consisting of relatively deep crustal rocks such as mica-schists, migmatites and granulites associated with mantle peridotites (Beni Bousera, Ronda). Another deep complex occurs in Central and Eastern Betics beneath the Alpujarrides, namely the *Nevado-Filabride* complex,

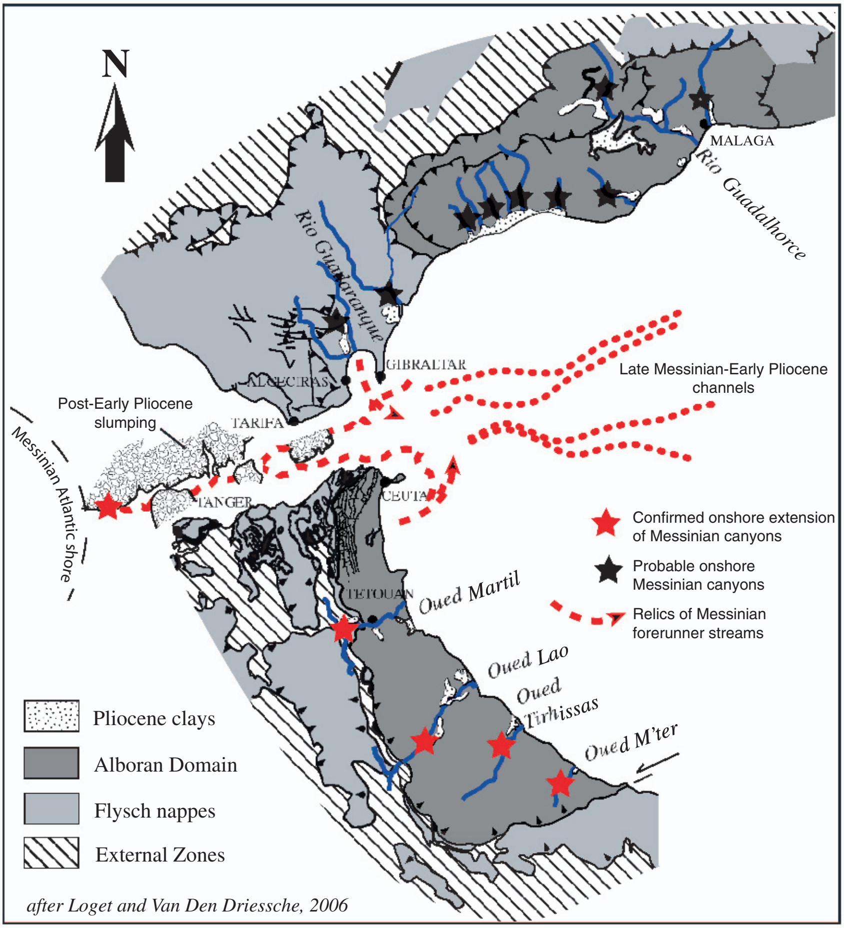


Fig. 5.4 Distribution of the Pliocene deposits in the Messinian canyons of the internal part of the Gibraltar Arc, after Loget & Van Den Driessche (2006), modified. The canyon of the Strait of Gibraltar, now filled with breccias, was used by the Atlantic waters 5.3 Ma ago to rush into the Mediterranean Basin

which displays meta-ophiolites at its top. The upper plate consists of the *Ghomaride* (Rif) and *Malaguide* (Betics) complexes, which overlie the Sebtide-Alpujarride through a regional detachment. They include Paleozoic rocks affected by a Variscan metamorphism partly superimposed by weak Alpine recrystallization, and relicts of their Mesozoic-Cenozoic cover.

Sebtide-Alpujarride rocks were cored in the Alboran Basin (Fig. 5.5), which fully justifies the name of "Alboran Domain" given to the Internal Zones. A similar metamorphic structure can be recognized in the Algerian Kabylides, Peloritan Mountains of Sicily, and Calabria. Thus, these varied exotic terranes were admittedly parts of the same continental domain *AlKaPeCa* (Bouillin, 1984), including the "Alboran

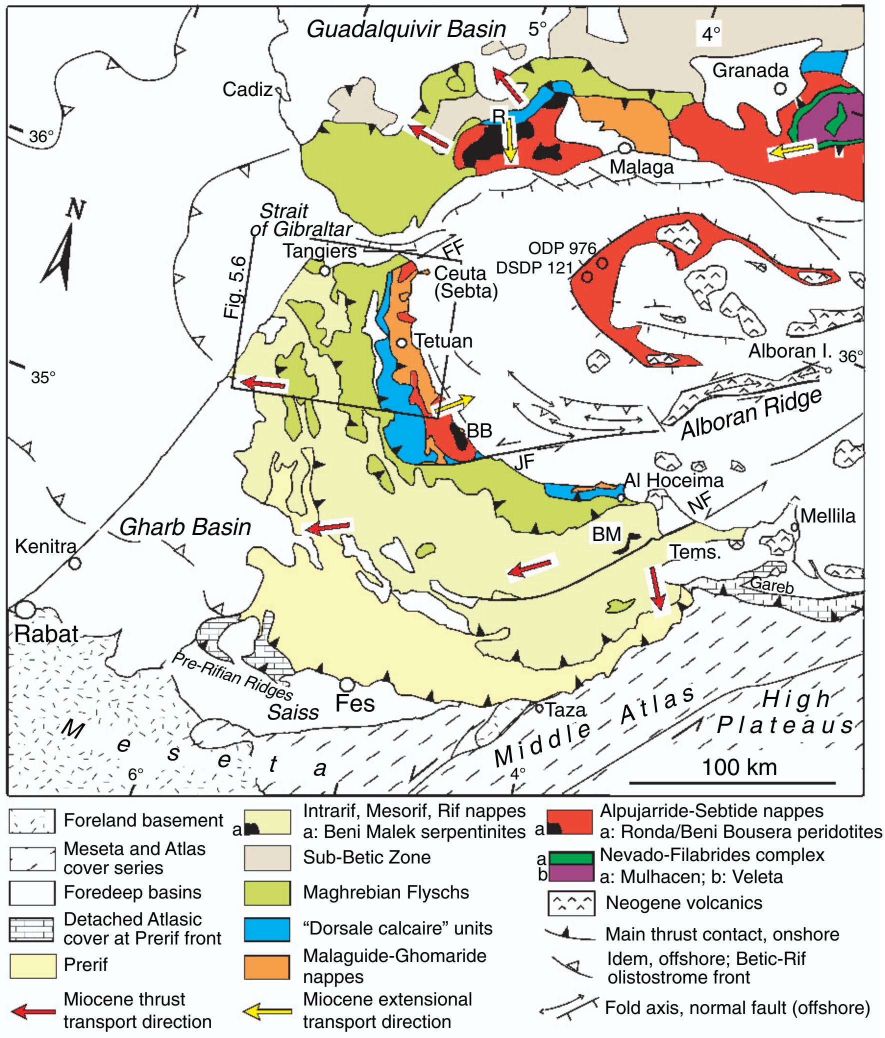


Fig. 5.5 Structural map of the Gibraltar Arc, modified from Chalouan & Michard (2004). Alboran Basin after Comas et al. (1999); Gulf of Cadiz after Maldonado et al. (1999); Miocene kinematics after Frizon de Lamotte et al. (1991) and Martínez-Martínez & Azañón (1997). BB: Beni Bousera; BM: Beni Malek; FF: Fahies Fault; JF: Jebha Fault; NF: Nekor Fault; R: Ronda; Tems.: Temsamane

microplate" of Andrieux et al. (1971), before being deformed and dispersed. The initial location of AlKaPeCa is controversial as this domain may correspond either to a distal part of the Iberian margin or to an isolated microcontinent within western Tethys (Sect. 5.7). Note that the name of "Mesomediterranean Block", sometimes used instead of AlKaPeCa, is misleading since the Mediterranean Sea developed after the AlKaPeCa split.

The Alboran Domain and its eastern equivalents include also a complex of Mesozoic-Cenozoic thrust sheets dominated by Triassic-Liassic carbonates. This is the *Dorsale Calcaire*, which appears as discontinuous ranges at the front of, and generally below the more internal crustal units. The Dorsale Calcaire units represent remnants of the former southern passive margin of AlKaPeCa. These units can be traced northward around the Gibraltar Arc up to the Granada meridian.

5.1.2.2 Maghrebian Flyschs

The Maghrebian Flyschs nappe complex originates from the Ligurian-Maghrebian Ocean, which connected the Central Atlantic and Alpine Oceans from Jurassic to Paleogene (see Chap. 1, Figs. 1.5, 1.8). The final suturing of the Maghrebian Ocean between AlKaPeCa and Africa by the Late Oligocene-Early Miocene resulted in the formation of a nappe stack consisting of the dominantly turbiditic sediments ("flyschs") accumulated within the oceanic basin. These nappes root beneath the Internal Zones and overlie the External Zones (Figs. 5.7, 5.8). Part of the Flysch nappes has been back-thrust over the northern Ghomarides (J. Zemzem and Riffiene massifs south of Ceuta).

The Flyschs nappes are exposed widely in western Betics (Campo de Gibraltar; Fig. 5.5), up to the Granada transect. According to Algerian nomenclature

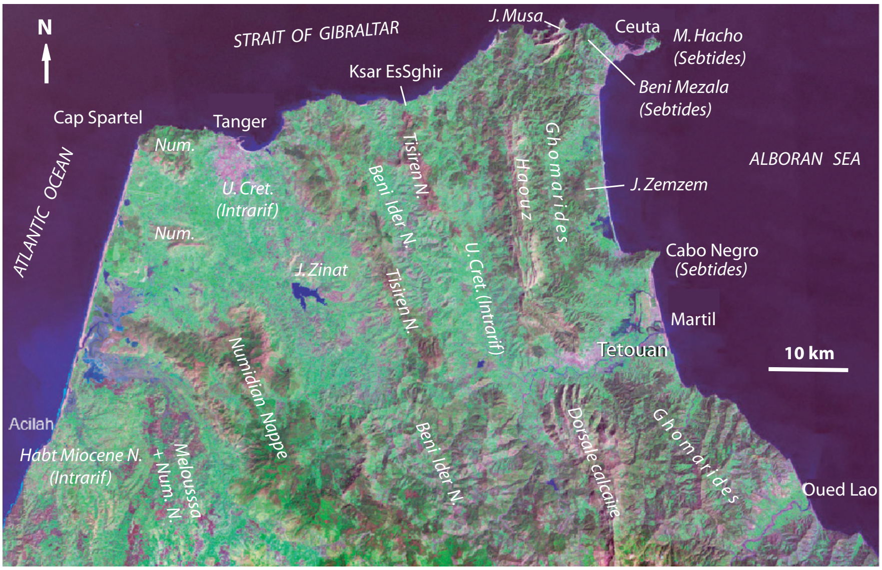


Fig. 5.6 Landsat image of northern Rif. Location: see Figs. 5.5 and 5.7. The different structural zones shown here are (from E to W) the Internal Zones (Sebtides, Ghomarides, Dorsale calcaire), the Flysch Nappes (Tisiren, Beni Ider, Meloussa, Numidian), and the underlying External Zones (restricted to their internal part, i.e. Intrarif from Tanger and Habt). Num. N: Numidian Nappe. Basically, the image shows a collapsed accretionnary prism in front of a partly collapsed and immerged buttress

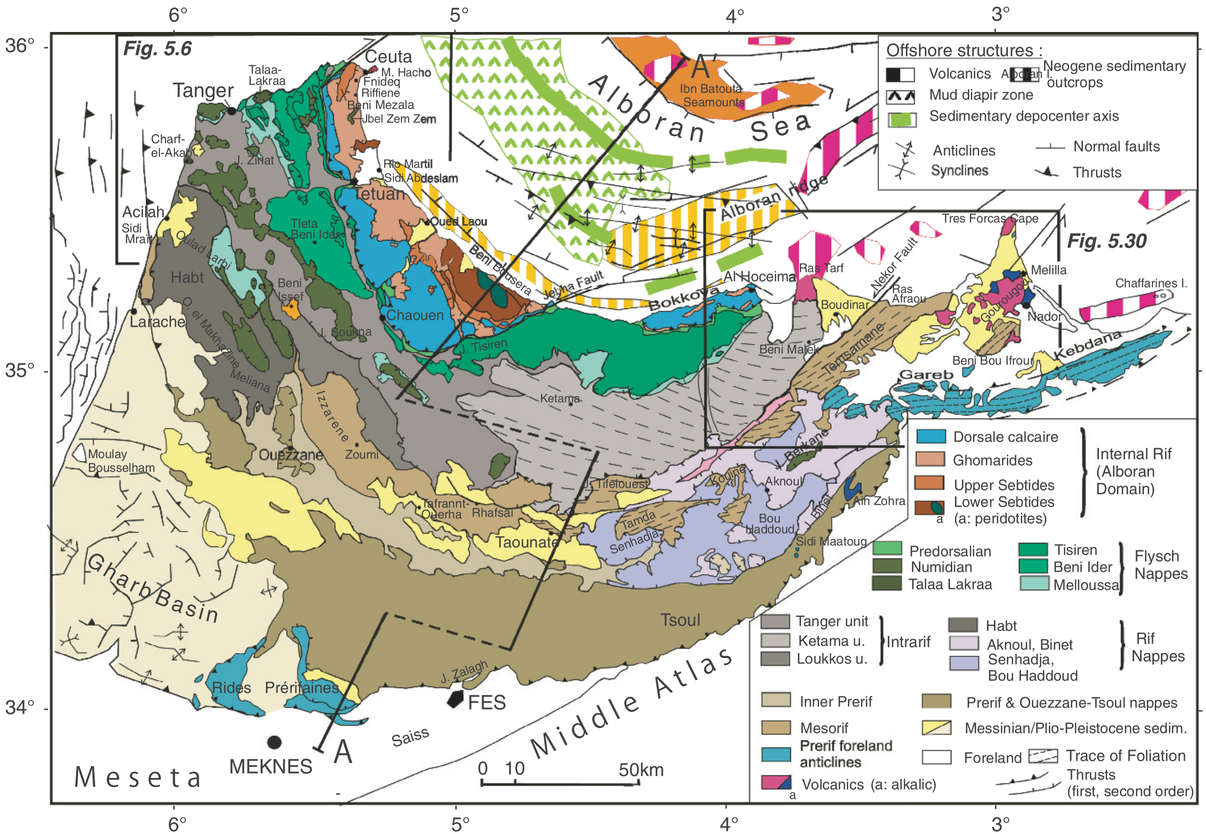


Fig. 5.7 Structural map of the Rif Belt, after Suter (1980a, 1980b) and Chalouan et al. (2001), modified. Alboran Basin after Chalouan et al. (1997) and Comas et al. (1999). Gharb and Atlantic margin after Flinch (1996). AA': trace of cross-section shown in Fig. 5.8

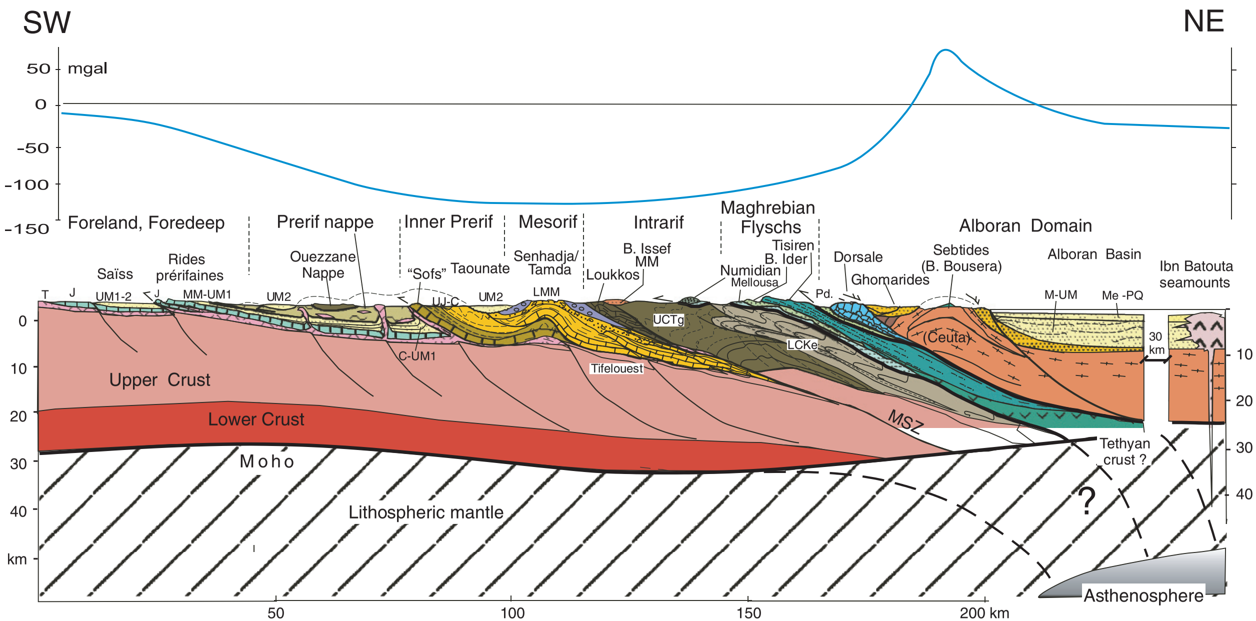


Fig. 5.8 Crustal cross-section of the Rif Belt, modified from Chalouan et al. (2001), and corresponding Bouguer anomaly after Favre (1995). Moho and base of lithosphere depth after Favre (1995), Torné et al. (2000), Frizon de Lamotte et al. (2004), Fullea Urchulutegui et al. (2006). Location in Fig. 5.7. Abbreviations: B.: Beni; C: Cretaceous; J: Lower-Middle Jurassic; LCKe: Lower Cretaceous of Ketama; LMM: Lower-Middle Miocene; MM: Middle Miocene; MSZ: Mesorif Suture Zone; Pd: Predorsalian; T: Triassic; Tg: Tanger Unit; UM: Upper Miocene (1: Tortonian "pre-nappe"; 2: Upper Tortonian-Pliocene "post-nappe"); UJ-C: Upper Jurassic-Cretaceous. Conventional lithologic signatures (schematic)

(cf. Sect. 5.3), the more internal and higher units are referred to as the *Mauretanian nappes* (in the Rif, J. Tisiren and Beni Ider nappes), whereas the more external and lower units are named the *Massylian nappes* (Chouamat-Melloussa and Numidian nappes). All these nappes of oceanic origin mark a suture zone beneath the Alboran terrane (Fig. 5.8), although ophiolitic remnants are lacking along the suture, except in Algeria and, more significantly, in Calabria.

5.1.2.3 External Zones

The External Zones of each limb of the Gibraltar Arc originate from two distinct paleomargins of Africa and Iberia, respectively. Therefore, contrary to the Internal Zones and Flyschs nappes, the Rif and Betic External Zones do not display any stratigraphic/structural continuity across the Strait of Gibraltar, except in the uppermost and youngest units of the accretionary prism located offshore in the Gulf of Cadiz. The *Subbetic Zone* proceeds from a starved paleomargin and displays a thin-skinned tectonics, whereas the more complex Rif-Tell Externides proceed from an abundantly sedimented margin and display both thick-skinned and thin-skinned structural styles.

In the External Rif (Figs. 5.7, 5.8), we may distinguish three structural zones, from north to south and top to bottom, the *Intrarif, Mesorif* and *Prerif*, which derive from more and more proximal parts of the African paleomargin, respectively. Within each of these zones, we may again distinguish deep rooted, parautochthonous units (more or less detached from their original basement), and diverticulated, superficial gravity-driven nappes. Metamorphic recrystallizations reaching the chloritoid-bearing greenschist-facies conditions occur in the deep Intrarif (Ketama) and eastern Mesorif (North Temsamane) units, on both sides of the Nekor fault. Serpentinite and metabasite slivers (Beni Malek) crop out along the latter fault, which likely corresponds to a segment of an intracontinental (intra-margin) minor suture recognisable eastward up to Algeria (Sect. 5.4).

Two major, ENE to NE-trending left-lateral faults, namely the Jebha Fault, south of the Northern Rif Internal Zones, and the Nekor Fault in the Eastern Rif, give evidence, at the map scale, of the obliquity of the movement of the Alboran Domain relative to Africa. The tectonic structures observed in the External units and overlying Flysch outliers all show an externalward displacement, i.e. toward the Neogene *Prerif foredeep*. The foredeep is widely developed and poorly deformed in the west, i.e. in the Gharb (Rharb) Basin, equivalent to the Guadalqivir Basin (Betic foredeep). In contrast, the foredeep changes to a deformed, narrow corridor south of Eastern Rif, and finally vanishes east of Taza, where the Mesorif outliers directly overlie the Middle Atlas foreland.

5.1.2.4 Alboran Basin and Trans-Alboran Magmatism

The *Alboran Basin* opened at the rear/east of the belt during the latest Oligocene-Early Miocene. This is a synorogenic basin with a thinned continental crust, which incorporates stretched elements of the orogen. Up to 8 km of turbidites and muds accumulated in the western sub-basin where numerous mud diapirs occur. In the central and eastern parts of the basin, as well as on its southern and northern borders, an important calc-alkaline magmatism developed during the Middle-Late Miocene. This is the *Trans-Alboran magmatic province*, i.e. the western part of the Maghrebian magmatic province, which includes numerous granitic massifs in Algeria (Sect. 5.6).

The Alboran sediments are affected by open folds and strike-slip faults (Alboran Ridge) dated from the Late Miocene (Messinian) and resulting from the ongoing Africa-Europe convergence.

5.1.3 Lithospheric Structure

References: The crustal structure of the African margin was described by Favre (1995). Overall descriptions of the Gibraltar Arc lithosphere, based mainly on seismological data and geophysical modeling, have been published by Seber et al. (1996), Calvert et al. (2000), Gurría & Mezcua (2000), Torné et al. (2000), Gutscher et al. (2002), Spakman & Wortel (2004), Frizon de Lamotte et al. (2004), Fullea Urchulutegui et al. (2006), Bokelman & Maufroy (2007). The thermal structure is described by Polyak et al. (1996) and Rimi et al. (1998). Concerning the Eastern Alboran Basin and next Algerian-Balearic Basin, see Mauffret et al. (2004), Domzig et al. (2006), and Schettino & Turco (2006).

The continental crust north and especially south of the Alboran Basin is rather poorly known due to lack of deep seismic survey. However, the varied geophysical methods already used indicate great thickness variations in the crust and heterogeneities in the mantle.

In the Rif foreland, seismic refraction studies image a 30 km thick continental crust, with a 9–10 km thick lower crust (Chap. 1, Fig. 1.20; cf. Fig. 5.8 above). Modelling of crustal and lithospheric thickness or density variations that integrates both elevation and geoid anomalies yields evidence (assuming local isostasy) of a poorly marked orogenic root beneath Central Rif (Moho at 34 km depth), followed by a quick Moho rise toward the Alboran Basin. In the western sub-basin where the water depth does not exceed 1 km (Figs. 5.2, 5.8), the Moho is located at about 18–20 km, associated with a thinned, 15–18 km continental crust. East of the Alboran Ridge, water depth increases up to 2.5 km, and the crust thickness decreases to ~12 km: the eastern Alboran sub-basin is transitional toward the Algerian-Balearic Basin the crust of which is likely oceanic.

The mantle lithosphere thickness is less constrained. Taking into account the high thermal gradients observed in the basin axis, Torné et al. (2000) inferred a thickness of about 20–30 km. In contrast, seismic studies led Calvert et al. (2000) to suggest that asthenosphere comes in contact with the Alboran thinned continental crust, and even penetrates as a wedge between the Gibraltar Arc crust and underlying lithospheric mantle (delamination). The latter hypothesis is neither confirmed nor contradicted by the more recent geophysical studies (Sect. 5.7). Fullea Urchulutegui et al. (2006) modelling leads to rather greater thicknesses beneath the western sub-basin (Fig. 1.18). In the cross-section (Fig. 5.8), we schematically delineate the depth to the asthenosphere at shallow level beneath the Alboran Sea and assume that it crosscuts the subducting African lithosphere, consistent with the slab break-off hypothesis. The latter hypothesis is supported by the geochemistry of the Trans-Alboran magmatism (Sect. 5.6) and by the 3D seismic tomography imaging (Sect. 5.7). Waveforms of body waves that traverse the Alboran Sea confirm the presence of an anomalous mantle underlying the basin (Bokelman & Maufroy, 2007).

North of the Alboran Sea, the continental crust again thickens beneath the Betic Cordilleras, following a roughly symmetrical pattern as described above in the Rif. Below the Strait of Gibraltar, the crust is up to 30–32 km thick (Fig. 1.18). This is consistent with the current concept of an orogenic arc above an active east-dipping subduction zone (Sect. 5.7).

5.2 Internal Zones (Alboran Domain)

The following sections describe the stratigraphy and structure of the Rif Internal Zones, i.e. of the Moroccan part of the Alboran Domain. However, we will also refer frequently to Betic data, as they complement usefully the geological data on this exotic terrane.

5.2.1 Sebtides

References: Most of the recent literature concerning the Sebtide complex deals with its metamorphic structure and petrology: see Bouybaouene (1993), Saddiqi et al. (1995), Bouybaouene et al. (1998), Montel et al. (2000), El Maz & Guiraud (2001), Haissen et al. (2004). Negro et al. (2006) consider both the Sebtides and their Betic counterparts (Alpujarrides). The Beni Bousera peridotites were repeatedly studied: see Reuber et al. (1982), Saddiqi et al. (1988), Pearson et al. (1989), Kornprobst et al. (1990), Kumar et al. (1996), Tabit et al. (1997), Pearson et al. (2004), and Downes (2007). Their Betic equivalents (Ronda), even more frequently investigated, are recently considered by Sánchez-Gómez et al. (2002), Platt et al. (2003b), Tubía et al. (2004), Cuevas et al. (2006), and Downes (2007), with references therein. The isotopic ages reported below are from Platt & Whitehouse (1999), Argles et al. (1999), Montel et al. (2000) and Sánchez-Rodriguez & Gebauer (2000). Kabylian data are summarized by Michard et al. (2006), with references therein.

The Sebtide complex crops out in four tectonic windows beneath the Ghomaride nappes (Figs. 5.7, 5.9), i.e. from N to S, the Beni Mezala anticline, Ceuta-Monte Hacho massif, Cabo Negro promontory, and eventually the much larger Beni

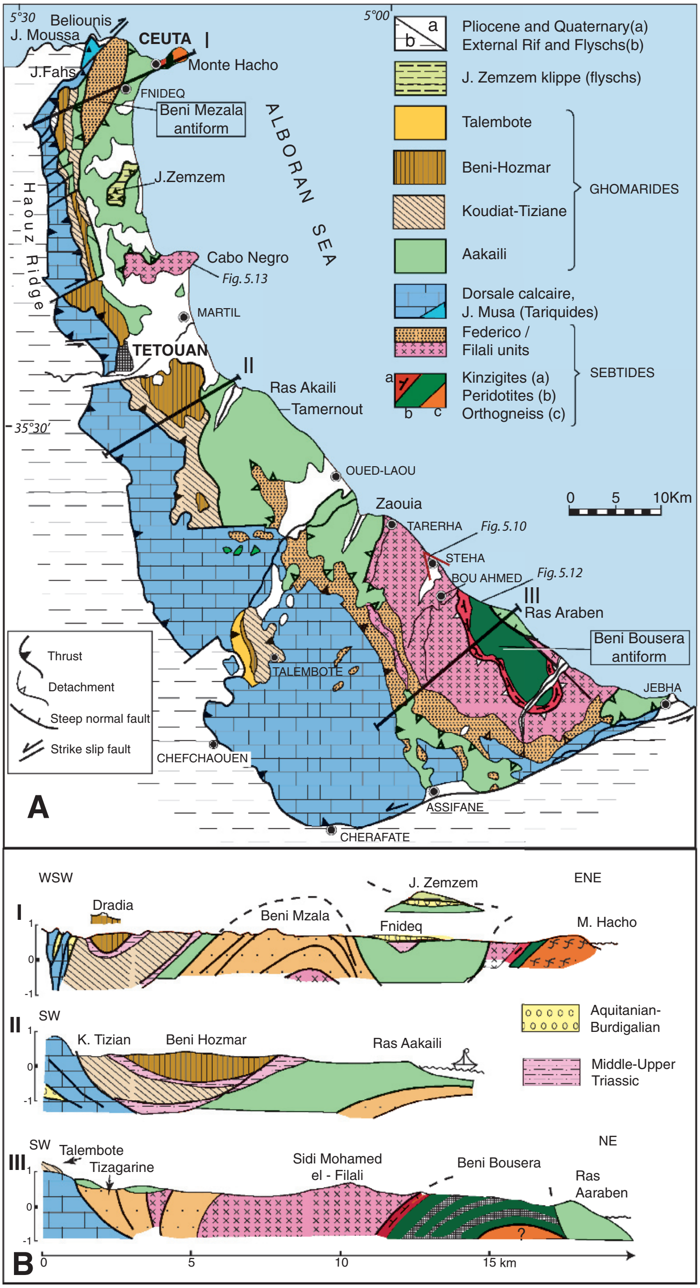


Fig. 5.9 Structural map (**A**) and cross-sections (**B**) in the Northern Rif Internal Zones, after Chalouan & Michard (1990), modified. The Ghomaride-Sebtide nappe stack was folded before and after the unconformable onlap of the "post-nappe" formations (e.g. at Fnideq in Sect. B-I). The J. Zemzem and Haouz backthrusts occurred during the second shortening event

Bousera antiform. Each of these windows, except Cabo Negro, consists of a stack of nappes with different pre-Alpine protoliths and contrasted metamorphic grades (Sect. 5.4.2).

5.2.1.1 Basement Units

The oldest rocks, likely Paleozoic in age or even Precambrian, crop out in the Beni Bousera antiform (Fig. 5.10). This large antiformal structure deforms a stack of two thick basement units, from bottom to top, the *Beni Bousera* and *Filali* units, and their more or less detached metamorphic cover units, referred to as the *Federico* imbrications (Fig. 5.11A).

The Beni Bousera unit consists of a huge peridotite body, at least 2 km thick, topped by discontinuous slivers of granulites (kinzigites). Together with their Alpujarride counterpart (Ronda peridotites of the Los Reales nappe), the Beni Bousera peridotites are among the largest infracontinental mantle massif worldwide (Figs. 5.10, 5.12). The dominant lithology is a spinel lherzolite including pyroxenite layers which yielded graphitized diamond pseudomorphs. This indicates an early equilibration at more than 140 km depth followed by a retromorphic evolution at about 50 km depth. The metagabbroic pyroxenite and garnet pyroxenite layers interbedded within the ultrabasites are deformed by isoclinal folds associated with a high temperature foliation. Only some of these pyroxenites display geochemical evidence of being related to recycled oceanic crust, whereas the others are best explained by crustal accumulation in mantle-derived magmas (Downes, 2007). Intensely foliated harzburgites occur close to the top of the ultrabasite massif, some of them including garnet crystals whose origin is controversial. Serpentinization increases toward the sheared envelope of the peridotite body.

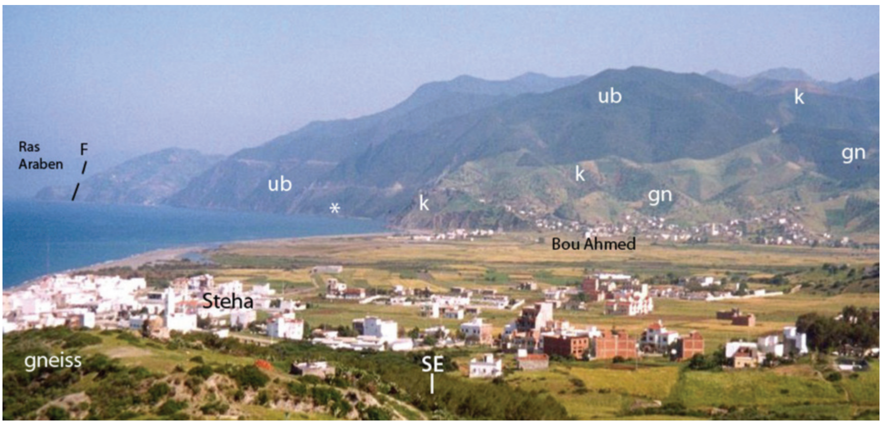


Fig. 5.10 View of the Beni Bousera massif looking SE-ward. See Fig. 5.9A for location. ub: ultrabasites (*: location of Fig. 5.12); k: kinzigites (top of Beni Bousera unit); gn: gneisses (base of Filali unit). The Ras (Cape) Araben is made of a downthrown element of the Aakaili nappe (Ghomaride). Photo by O. Saddiqi

The crustal rocks immediately above the peridotites consist mainly of acidic granulites (kinzigites) with garnet-sillimanite±kyanite-graphite assemblages (Sect. 5.5). Some basic granulites are interbedded within the acidic ones, such as the Ichendirene HP-granulites, which exhibit mineral assemblage including pyrope-rich garnet, jadeite-rich clinopyroxene and rutile, indicative of an equilibration at $P > 16$ kbar, 760–820 °C. The latter P-T conditions are closely similar to those of the garnet-bearing peridotite equilibration.

It is worth noting that the Beni Bousera and Ronda peridotites have become disconnected with the mantle as they were thrust over a deeper Sebtide-Alpujarride crustal unit, which corresponds to the migmatitic orthogneiss of Monte Hacho

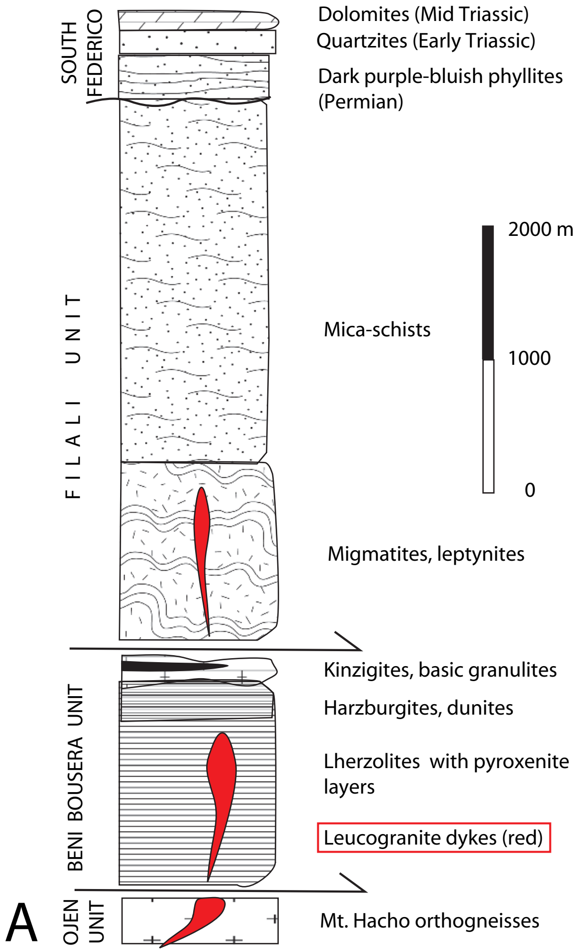


Fig. 5.11 Synthetic litho-stratigraphy of the pre-Triassic series of the Alboran Domain in the Rif Belt. (**A**): Sebtides, after Bouybaouene (1993), Saddiqi (1995), Negro (2005); (**B**–**D**): Ghomaride nappes, after Chalouan & Michard (1990), modified

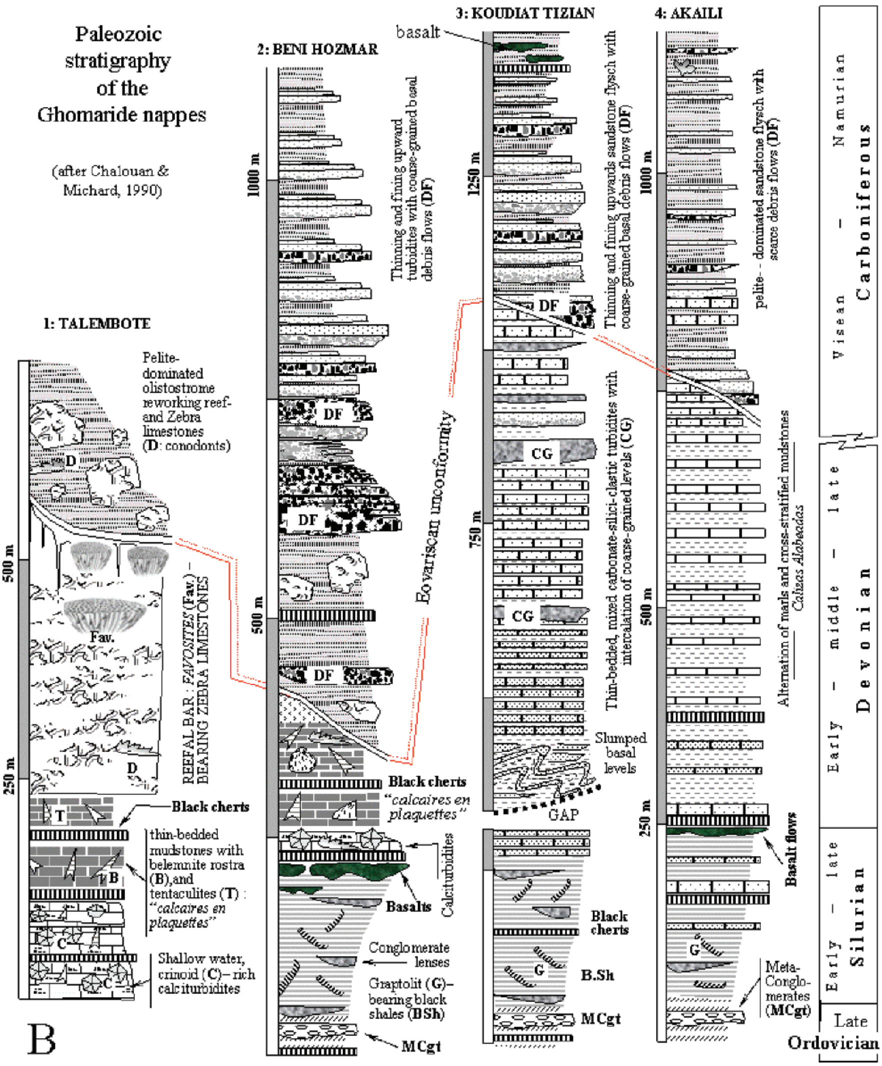


Fig. 5.11 (continued)

(Ceuta) and Ojen (Betics), associated with thick marbles in Andalucia (Sierra Blanca). Partial melting within this deep crustal material resulted in the intrusion of cordierite-andalusite-bearing granite dykes across both the northern and southern peridotite massifs.

The age and emplacement mechanisms of the Ronda and Beni Bousera peridotites have been repeatedly questioned. Some authors assume that they originate from a Miocene hot asthenospheric diapir coeval with the opening of the Alboran Sea, whereas others argue that they formed during the Paleozoic, being uplifted first during the opening of the Tethys Ocean, then during the Alpine orogeny

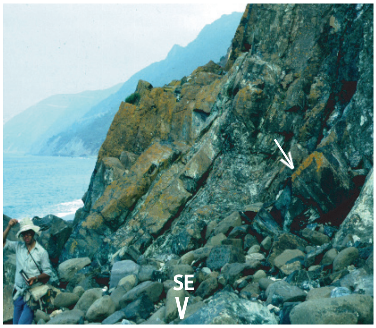


Fig. 5.12 Lherzolite outcrops along the Beni Bousera shoreline east of Bou Ahmed (see Figs. 5.9 and 5.10 for location). *Arrow*: pyroxenite layers. The steep, NE-dipping fractures are likely related to the Ras Araben normal fault (*background left*)

(Sect. 5.7.4.4). The latter hypothesis is supported by a great variety of isotopic datings such as: the ages close to 300 Ma obtained on relict minerals from the kinzigites (U-Pb on zircon cores, and garnet-armoured monazite grains); the garnet-whole rock Sm-Nd isochron age of 235.1 ± 1.7 Ma obtained from Ronda pyroxenites; the 286 ± 5 Ma U-Pb age from oscillatory-zoned domains from the euhedral zircon fraction in Ronda garnet pyroxenites; and the U-Pb zircon core ages from the same rocks, 178 ± 6 Ma, 143 ± 16 Ma, 131 ± 3 Ma recording successive steps of cooling during the Triassic-Early Cretaceous Tethyan rifting.

The Filali unit overlies the Beni Bousera unit through a subtractive ductile shear zone, as the migmatites at the bottom of the Filali (Fig. 5.13) are equilibrated under 8 kbar, 780 °C, i.e. at much lower pressure than the underlying granulites. Above the gneisses, the Filali unit is made of mica-schists the mineral assemblages of which change more progressively upward, from garnet-biotite-sillimanite to garnet-biotite-staurolite-kyanite, and finally chlorite-chloritoid-muscovite±biotite±kyanite. Andalusite is ubiquitous in these metapelites, and the coexistence of the three Al silicates suggests a polycyclic metamorphic history with an Alpine evolution (Sect. 5.5) superimposed on a Variscan one. Indeed, Variscan to Jurassic ages were obtained from some high-grade Alpujarride rocks, such as the Torrox gneiss (equivalent to the Monte Hacho gneiss), dated at 285 ± 5 Ma (U-Pb zircon), and the eclogite included in the Ojen gneisses (183 ± 3 Ma, U-Pb on magmatic zircon core).

5.2.1.2 Metamorphic Cover Units

The *Upper Sebtides* or *Federico units* consist of metasediments, affected only by Alpine recrystallizations. They form thrust imbrications where the same lithostratigraphic sequence is repeated several times with downward increasing metamorphic grade. In the Beni Mezala antiform (Figs. 5.9, 5.14), four superimposed, relatively thin units (500–1000 m) are folded together forming an antiformal stack beneath the Ghomarides units. Each unit displays the three main formations ascribed from bottom to top, to Permian-Triassic, Lower Triassic and Middle-Upper Triassic Alpine-type sequences (Fig. 5.15A1). The Permian-Triassic deposits consist of red pelites in the uppermost unit (Tizgarine), purple phyllites in the intermediate unit (Boquete

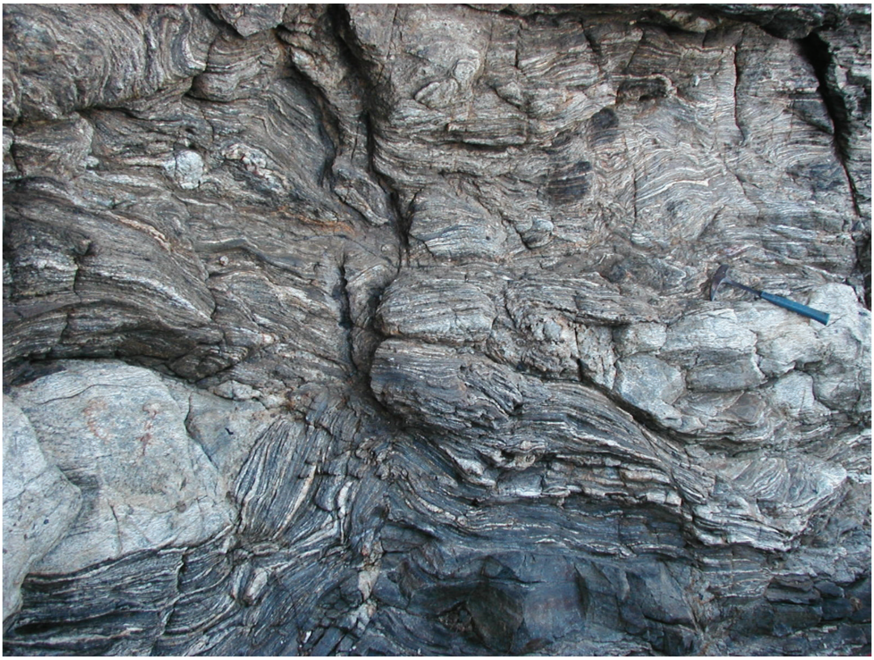


Fig. 5.13 Migmatitic gneiss from the Filali unit, with a pervasive boudinage fabric affecting a dyke of garnet-bearing meta-aplite (below the hammer). Note the complex, polyphase structure of these rocks (superimposed Variscan and Alpine deformations). Cabo Negro south cliffs (see Fig. 5.9A for location). Photo by O. Saddiqi

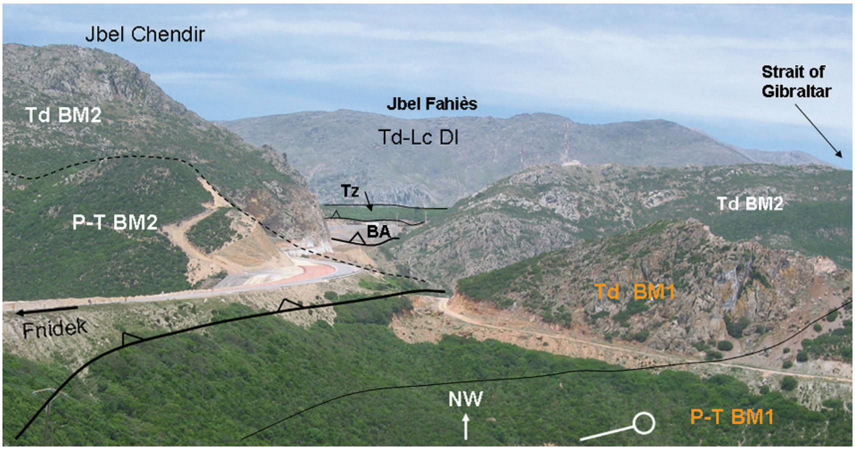


Fig. 5.14 The Beni Mezala (BM) massif along the Fnideq-Ksar Es-Sghir road, 3 km NW from Fnideq (see Fig. 5.9 for location). Note the duplication of the stratigraphic levels of the lowest BM1 and BM2 Federico units in the foreground: P-T, Permian-Triassic metapelites and quartzites; Td: Middle Triassic dolomites. Background: Upper Federico units (BA: Boquete Anjera; Tz: Tizgarine), dominated by the Jebel Fahs Dorsale unit (DI), which includes Upper Triassic dolomites and Hettangian limestones (Td-Lc). The post-nappe fold axis plunges SSW

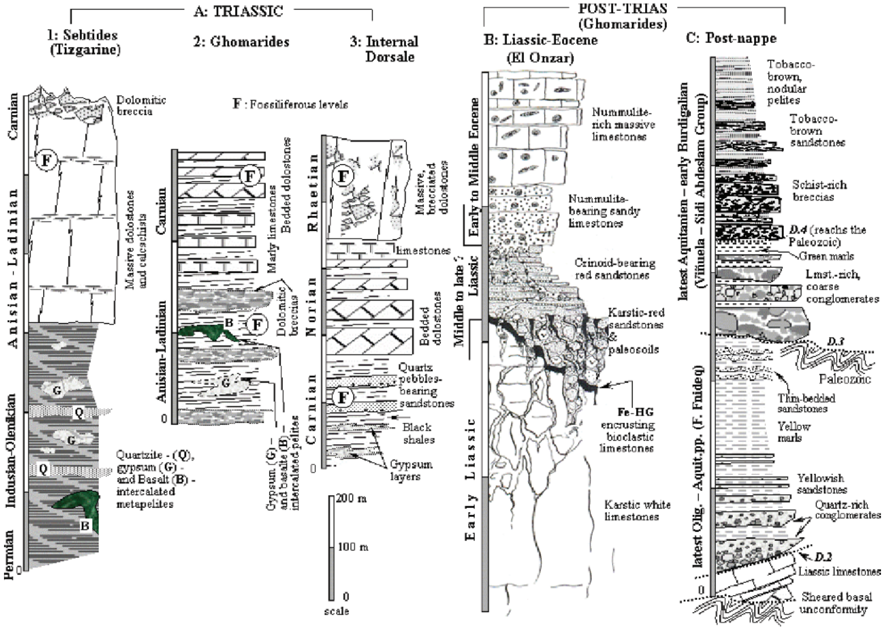


Fig. 5.15 Detail stratigraphy of the cover sequences from representative units of the Alboran Domain in the Rif Belt. (**A**): Triassic series, after Chalouan (1996). (**B** and **C**): Liassic-Eocene and "post-nappe" séries of the Ghomarides, after El Kadiri et al. (1992) and Serrano et al. (2006), respectively

Anjera), and of dark ("color de humo", smokg) quartz-phyllites in the lowest units (Beni Mezala 2 and 1). This color evolution can be correlated with change in metamorphic grade (Sect. 5.5). Light-colored quartzites are placed in the Lower Triassic, and compare with the Briançonnais quartzites of Western Alps. They are overlain by Middle-Upper Triassic dolomitic marbles, which locally yielded *Gyroporella* (Dasycladaceae) of Middle Triassic age. Remarkably, no younger stratigraphic level was ever recognized in the Sebtides or the Alpujarrides, which is possibly related to a tectonic detachement of the upper units (Sect. 5.7.4.3). By contrast, the stratigraphic sequence of the upper Federico unit is completed downward by probable Upper Carboniferous greywacke formations. The base of the Beni Mezala unit is made of the Benzu mica-schists, closely similar to the Filali ones.

On top of the Beni Bousera antiform, similar metamorphic imbrications occur. However, in this southern region the lowest Federico unit, here labelled the *Souk-el-Had unit*, seemingly remained in stratigraphic contact over the Filali mica-schists, as similar metamorphic assemblages are found on both sides of their common limit (Sect. 5.5). Note that similar Permian and Triassic imbrications also occur on top of the Los Reales nappe of western Betics (Casares units, Benarraba imbrications).

5.2.2 Ghomarides

References: The Paleozoic stratigraphy of the Ghomaride–Malaguide Complex has been described by Herbig & Mamet (1985) and Herbig (1989) in Spain, and by Chalouan & Michard (1990) in Morocco. The pre-Alpine relationships of this complex, and of the Alboran microplate in general with the other Hercynian segments of Western Mediterranean have been discussed by von Raumer et al. (2003), Trombetta et al. (2004), Helbing et al. (2006), Sanz de Galdeano et al. (2006), Micheletti et al. (2006).

The Triassic unconformable deposits have been described by Baudelot et al. (1984), Chalouan (1996), and Diez (2000). On the other hand, Feinberg et al. (1990), El Kadiri et al. (1992), Durand-Delga et al. (1993), Maaté (1996), Martín-Martín et al. (1997, 2006), Martín-Algarra et al. (2000), El Kadiri et al. (2001), Serrano et al. (2006) described the post-Triassic deposits. Concerning the late orogenic basins of eastern and central Betics (i.e. the youngest deposits which overlie the Ghomarides as well as the deeper nappes complexes), see Weijermars et al. (1985), Montenat et al. (1987), Weijermars (1991), García-Dueñas et al. (1992), Orozco et al. (1999).

The Ghomaride complex includes four nappes (Fig. 5.9) with different Paleozoic stratigraphy (Fig. 5.11B1–4). The nappes are separated from each other by relics of their Mesozoic-Cenozoic cover, mostly Triassic in age. The larger nappes, i.e. from bottom to top, Aakaili, Koudiat Tizian, and Beni Hozmar nappes crop out in northern Rif and partly in the Bokkoya. The highest, Talembote nappe forms a large tectonic klippe over the Dorsale in the Oued Lao area and some small outcrops in the Bokkoya (Fig. 5.7).

5.2.2.1 Paleozoic Formations

The Ghomaride Paleozoic formations are folded and recrystallized (Fig. 5.16), contrary to their Mesozoic-Cenozoic cover deposits. Therefore, they must be regarded as Variscan chips in the Rif Alpine belt.

The Lower Paleozoic sequences are rather homogeneous from one nappe to another, contrary to the Devonian (Fig. 5.11B2–4). The terrigeneous Ordovician deposits consist of phyllites with interleaved quartzite and meta-conglomerates. Carbonate layers first appear in the Silurian sequence, which contains black Graptolith-bearing cherts (Llandovery). This sequence is followed upward by a trilogy pillow basalts-lydites-micrites with *Orthoceras*, Tentaculites and Conodonts, all indicating the Lochkovian. These pelagic limestones are substituted by much thicker *Orthoceras* limestones in the Talembote nappe, with incipient reef buildings: this is the beginning of a strong paleogeographic differenciation. In the Aakaili nappe, the Devonian sedimentation continues with distal calci-turbidites ("calizas alabeadas" = "tortuous limestones": cf. Fig. 5.16) where Famennian levels are dated near the top of the sequence. In the Koudiat Tizian nappe, a proximal, terrigeneous flysch (greywackes and pelites) is found. In the Beni Hozmar nappe, the latter deposits are substituted

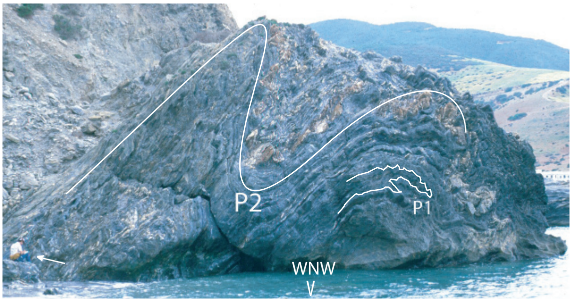


Fig. 5.16 Superimposed Eovariscan folds in the Upper Devonian calciturbidites of the Aakaili nappe (Lower Ghomarides) at Tamernout beach (see Fig. 5.9 for location). Scale is given by the person sitting on the left (*arrow*). A tight syn-metamorphic P1 fold is deformed by the P2 folds, which are associated with a SE-dipping crenulation cleavage

by thinner Tentaculite-bearing marls and limestones. Eventually, massive limestones ("calcaires zébrés") with *Favosites* reef-mounds occur in the Talembote nappe.

The Lower and Middle Paleozoic formations are affected by an Eovariscan folding phase associated with greenschist-facies metamorphism prior to the transgression of the unconformable Carboniferous sediments. The earliest Carboniferous levels are dated from the late Tournaisian in the Malaguides, which indicates a late Famennian-early Tournaisian age of the Eovariscan phase. The Carboniferous deposits begin with a lower sequence of proximal, turbiditic greywackes ending (at least in the Beni Hozmar and Talembote nappes) with coarse olistotromal conglomerates and boulders of Late Visean shallow water limestones. This lower, proximal sequence is followed upward by a more distal sequence interleaved by limestones with Late Visean-lower Namurian microfossils. Conglomeratic mass flows toward the bottom of this upper sequence contain pebbles reworked from the earlier Carboniferous sediments, the Silurian – Devonian deformed series, and even from a granitic and metamorphic basement, which is unknown in the Ghomaride-Malaguide complex, but occurs in the Kabylides.

The Aakaili Carboniferous sedimentation ends at Ceuta with coarse conglomeratic deposits comparable to the early Late Carboniferous Marbella Conglomerates in the Malaguides. Both conglomerates include peraluminous granite pebbles and resemble coeval conglomerates from Menorca (Balearic Islands), likely sourced from Central Iberia (Sanz de Galdeano et al., 2006). Likewise, the Early Carboniferous sediments of both the Ghomarides and Malaguides strongly recall those from Menorca. However, they also resemble the coeval deposits from the Moroccan Eastern Meseta, and contrast with those of Western Meseta where the Eovariscan phase is virtually lacking (Chalouan & Michard, 1990). Both cases support an eastern origin for the Ghomaride-Malaguide Complex in the Alpine, pre-collisional setting (cf. Sect. 5.7.4.3).

The restoration of the initial position of these Variscan chips, and more generally of the AlKaPeCa basement (Alboran microplate), at the beginning of the Paleozoic evolution is hindered by the superimposed effects of both the Variscan and Alpine orogenic cycles. Recent attempts of restoration have been based on

U-Pb zircon datings of the orthogneisses from the Alboran microplate elements. The Lesser Kabylia orthogneisses and the Peloritan porphyroids yielded Mid-Ordovician magmatic ages, which compare with the age obtained from the Sardinia gneisses (Trombetta et al., 2004; Helbing et al., 2006), suggesting relationships with the Variscan segments of south-western Europe. Contrastingly, Micheletti et al. (2006) obtained Late Neoproterozoic-Early Cambrian magmatic ages from the Calabrian augen gneisses, suggesting relationships with the high-K granitoid suite of the Anti-Atlas. The latter authors assume that the "Alboran microplate" – or, at least, its Calabrian part, detached from Gondwana after the early rifting and drifting of the Avalonian-Cadomian terranes (Raumer et al., 2003). Accordingly, the AlKaPeCa basement appears to be composed of different terranes whose collage resulted from the Variscan orogeny. The position of this complex after the western Tethys opening is discussed in Sect. 5.7.4.3.

5.2.2.2 Mesozoic-Cenozoic Cover

The post-Variscan sedimentation begins with Middle-Upper Triassic unconformable red beds (Fig. 5.15A2). These are thick, mainly fresh water deposits such as channelled quartzose conglomerates, arkosic sandstones, and gypsum intercalated ferrugineous clays. Paleogeographically, the entire succession evokes a mostly emergent continental shelf. Palynological data indicate the late Anisian-Ladinian (Baudelot et al., 1984) or Ladinian-Carnian (Diez, 2000). Locally, the clastic sequence is followed upward by dolomitic carbonates dated from the Carnian. Extensional tectonics related to the Tethyan opening is recorded by frequent synsedimentary faults and some alkaline basalt flows.

The remainder of the cover sequence occurs only in discrete strips. North of Tetuan, the El Onzar strip (Fig. 5.15B) overlies the Koudiat Tizian nappe, whereas two other strips (Belouazene, Kellalyine) occur beneath the latter nappe and overlie the Aakaili one through a tectonic contact which partly or totally cuts out the Triassic sandstones. Further to the north and west of Fnideq, the truncated Dradia strip lies on top of Beni Hozmar Paleozoic sediments (Fig. 5.9B).

In the most representative outcrops, the Triassic red beds are followed upward by Upper Triassic dolomites, passing up into massive limestones of Early Liassic age. This is a typical shelf sequence of the pre-rift stage. A possible emersion is suggested by karst-like structures formed during the Early-Middle Liassic: at that time, the area would correspond to the Tethyan rift shoulder or to the head of some large tilted block. However, the area is certainly submerged during the Toarcian as ammonites from that stage are reworked within breccias topping the deeply fractured Liassic limestones. The breccias are in turn topped by *Microcodium* limestones (Dradia) followed upward by whitish, bioclastic sandy limestones with Nummulites, Alveolines, and Discocyclines of Ypresian, Lutetian and Bartonian age. These Lower-Middle Eocene layers are, in turn, locally topped (Jebha, Fig. 5.9) by Upper Eocene conglomerates, which contain Hercynian granite pebbles (Iberian or Kabylian basement-sourced?)

The lack of any post-Toarcian sedimentary record up to the Late Cretaceous can be interpreted as being the result of a long-lasting emersion, or alternatively as the consequence of the Late Cretaceous-Eocene erosion of a thin Jurassic-Cretaceous sedimentary veil (Sect. 5.7). Indeed, some Malaguide sections show preserved Mesozoic deposits. In such sections, Martín-Martín et al. (2006) describe the following events: (i) emersion of the Triassic-Liassic platform before the Domerian (karst); (ii) rifting and submersion of the platform during the Middle-Upper Liassic (Toarcian – Dogger cherts and micrites); (iii) break-up unconformity at the bottom of Upper Jurassic pelagic limestones, either nodular or not; (iv) Cretaceous marls/calcschists deposited during thermal subsidence of the rifted area. These data allow us to correlate the Malaguide-Ghomaride domain with the Internal Dorsale one (Sect. 5.3.2).

5.2.2.3 Oligocene-Miocene "Post-Nappe" Cover

The youngest levels of the late orogenic, deeply unconformable Ghomaride-Malaguide cover, include two groups of formations (Fig. 5.15C), defined at the Betic-Rif scale, i.e. from bottom to top, (i) the late Oligocene-Aquitanian *Ciudad Granada Group*, and (ii) the Burdigalian *Viñuela Group* (Serrano et al., 2006). The *Fnideq Formation* and its Betic counterpart the *Alozaina Fm.* both belong to the Ciudad Granada Group. They begin with quartzose conglomerates passing upward to alternating sandstones and marls with benthic and pelagic fossils of Late Oligocene and Aquitanian age. These deposits are diachronous, being dated from the latest Rupelian (~29 Ma) in Eastern Betics (Sierra Espuña), and from the Aquitanian near Malaga (Western Betics).

The *Sidi-Abdeslam Fm* (Viñuela Group) outcrops are usually separated from those of the Fnideq Fm. For example, the Beni Maaden coarse conglomerates belonging to the Sidi Abdeslam Fm directly overlie the Paleozoic sediments. However, at Talembote (Fig. 5.15C), the Fnideq Fm. is unconformably overlain by conglomerates and green siliceous marls with Radiolaria and Foraminifera from the latest Aquitanian-earliest Budigalian. Thus, these levels can be correlated with the *Viñuela* (*Las Millianas*) *Fm.* defined around the Malaga basin. Their pebbles and boulders originate from local sources (Paleozoic and Triassic-Eocene units of the Ghomaride-Malaguide nappes). Cordierite migmatites, orthogneisses and phyllites comparable to the Kabylides upper plate basement or to the Sebtides-Alpujarrides crustal rocks can also be observed. However, in Andalucia, the Viñuela Fm. clearly contains Alpujarride rocks such as peridotites, kinzigites and garnet gneisses. Therefore, parts of the previously buried Alpujarride units have been exposed as early as 20–19 Ma ago.

Again at Talembote, the upper levels of the Viñuela Group correspond to brown-tobacco pelites, which yield nannoplankton assemblages of Early-Middle Burdigalian age. These levels contain sandstone intercalations comparable to the Numidian layers ("Neonumidian" of Andalucia), as well as olistostromes carrying rocks from the whole Internal complexes and locally from the Flysch nappes. By that time (~19–18 Ma), the Sebtide-Alpujarride units are totally exhumed, and the slopes inside the Gibraltar Arc are directed toward the Alboran Basin.

The latter formations are referred to as “post-nappe” formations as they unconformably overlie the varied Ghomaride-Malaguide nappes, and are never pinched in between. The Late Eocene uplift of the Paleozoic basement (granite pebbles at Jebha) and the deep erosion prior to the Oligocene-Aquitanian onlap suggest strong compressional deformations during the Late Eocene-Oligocene. In the eastern Malaguides (Sierra Espuña), some of the cross-sections constrain the age of nappe emplacement in the “middle” Oligocene (i.e. ~28 Ma ± 1 Ma). The Ciudad Granada deposits postdate this phase, being coeval with the beginning of the mountain belt collapse. The Viñuela deposits accumulate under the same extensional regime, and are contemporaneous with the opening of the Alboran Sea. Since the late Burdigalian (~18–17 Ma), these internal “post-nappe” formations are affected by major tectonic events, which cause the Dorsale and Flyschs to be thrust onto the more external domains, with backthrusting of parts of the Dorsale (Haouz range) and Flysch units (J. Zemzem) over the Ghomarides. Therefore, the so-called “post-nappe” formations of the Alboran Domain are indeed synorogenic deposits.

In Central and Eastern Betic Cordilleras, transgressive deposits of Serravallian, Tortonian and Messinian age unconformably overlie the “post-nappe” formations and underlying terranes, including the Nevado-Filabrides. They occupy large synclines, which can be regarded as emerged parts of the Alboran Basin itself, and formed through two main stages, before and after the Messinian. They represent late- to post-orogenic deposits: the exhumation of the Nevado-Filabride domes from 14 to 9 Ma controlled the depocentre evolution between 12 and 8 Ma. In the internal Rif, the post-Burdigalian deposits are restricted to Pliocene marls and conglomerates accumulated within the canyons formed during the Messinian salinity crisis (Fig. 5.4).

5.2.3 Dorsale Calcaire and Predorsalian

References: The most important and more or less recent works concerning the Dorsale are those by Wildi et al. (1977), Wildi (1979), Nold et al. (1981), Baudelot et al. (1984), Ben Yaïch et al. (1986, 1988), El Hatimi et al. (1991), El Kadiri et al. (1992), Maaté et al. (1993), El Kadiri (2002a, 2002b), El Kadiri et al. (2005). The neptunian dykes from the Algerian Dorsale (Djurdjura), Sicily and Calabria are described by Bouillin & Bellomo (1990) and Bouillin et al. (1999). Concerning the Predorsalian units, see Mourier et al. (1982), De Wever et al. (1985), Durand-Delga & Olivier (1988), El Hatimi et al. (1988), Olivier (1990), El Kadiri et al. (1990), Hlila et al. (1994), Durand-Delga & Maaté (2003), Durand-Delga et al. (2005, 2007). The Jebha Fault is described by Olivier (1981–1982) and Leblanc & Olivier (1984).

5.2.3.1 General

The Dorsale calcaire (Calcareous Range) is a complex tectonic domain, but its Mesozoic-Paleogene paleogeographic evolution is well constrained by a wealth of paleontological and sedimentological data. There, the deformed relics of the south paleomargin of the Alboran Domain may be observed, as exposed below (see also Sect. 5.7.4.3). However, the initial relative location of the ca. 30 elementary units or "nappes", which compose the Dorsale from the Strait of Gibraltar to Jebha and the Bokkoya (Fig. 5.17) is controversial. As for the Predorsalian, it consists of highly

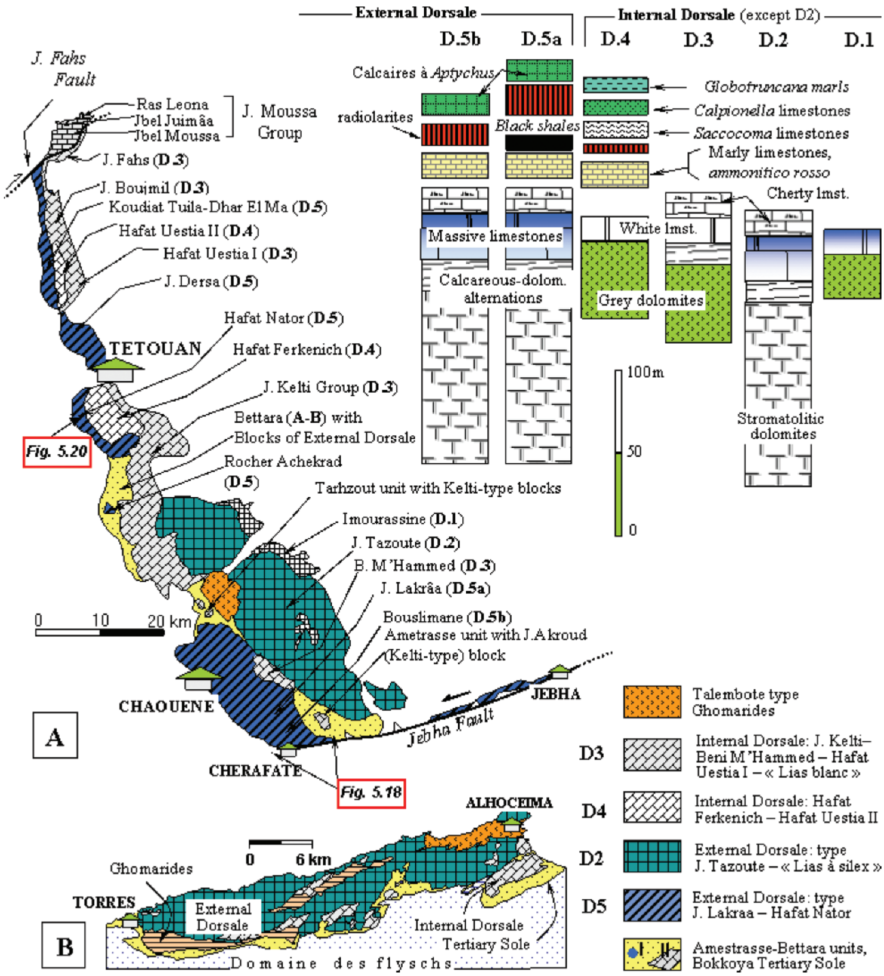


Fig. 5.17 Structural map of the "Dorsale calcaire" from Northern Rif (**A**) and Bokkoya area (**B**), and synthetic stratigraphic columns of the units, classified as Internal and External Dorsale units according to their stratigraphy. The Liassic strata are white massive limestones ("Lias blanc") in the Internal Dorsale, whereas they are dark cherty limestones ("Lias à silex") in the External Dorsale. The Internal-type unit D2 is intercalated within the External domain, either due to paleogeographic variations or out-of-sequence thrust. The maps also show the syntectonic formations of Late Oligocene-Aquitanian age (Ametrasse-Bettara units, Bokkoya Tertiary Sole) at the front of the nappe stack. Note that the town of Chaouen is frequently referred to as Chefchaouen

disrupted stratigraphic sections pinched within the narrow suture zone beneath the Alboran continental block, and admittedly corresponds to a former transition zone toward the Maghrebian Flyschs oceanic basin.

The two regions where the Dorsale units crop out in the Rif range, i.e. the Northern Rif and Bokkoya, are separated one from each other by the Jebha Fault, which extends offshore beneath the Alboran Ridge (Fig. 5.7). The geometry of the Jebha Fault is that of a sinistral lateral ramp with respect to the Internal Zone main thrust. The fault likely developed as a tear fault in the Internal Zone allochthon in front of a transverse structure of the underlying African margin. Due to an accessory vertical throw, the fault exposes a beautiful section across the Dorsale nappes and underlying units (Fig. 5.18). From there to the Tetouan valley, the Dorsale corresponds to a stack of moderately dipping imbrications, thrust over the Predorsalian, the Flyschs and the External Zones, and overlain either by the Ghomarides (Talembote) or the Sebtides (lower Oued Lao valley). This suggests a complex evolution of the main Alboran thrust (out-of-sequence thrust, and late extensional inversion; see Sect. 5.7). By contrast, in the Haouz range (north of Tetouan, Fig. 5.6) the varied Dorsale imbrications are nearly vertical and show a fan-like structure.

The Dorsale and Predorsalian stratigraphy corresponds to three contrasting sequences, which encompass the Triassic – Miocene time interval. The oldest, Late Triassic – Liassic sequence forms the competent part of the nappes, and on the other hand, allowed the authors to classify the varied nappes into "Internal Dorsale" and "External Dorsale" although, in some cases, this traditional classification does not correspond to the actual position of the nappes. The intermediate, Liassic–Paleocene sequence records the evolution of a Tethyan paleomargin, and finally the youngest, Eocene-Miocene sequence records that of the Alpine orogeny.

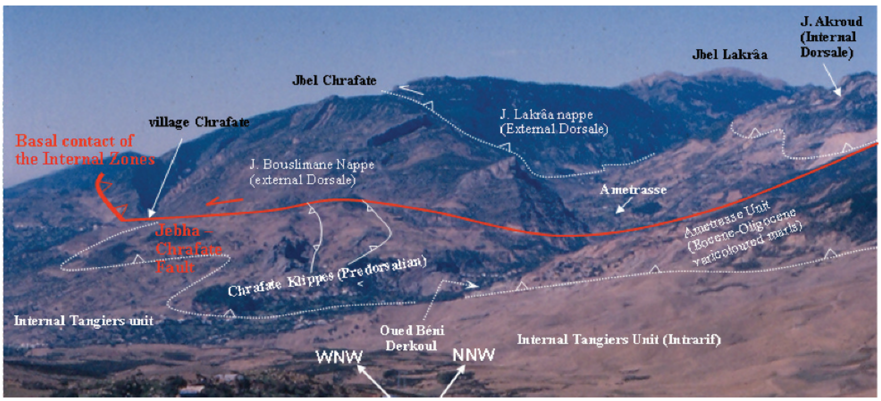


Fig. 5.18 Southwest corner of the Northern Rif Dorsale, looking NW-ward from the Ketama-Bab Taza road. Location: see Fig. 5.17. Note the lack of any Flysch Nappe outcrop between the Predorsalian and Intrarif (Tanger) units along the Jebha-Cherafat wrench fault. A huge rock fall slid recently from J. Akroud down to the Ametrasse houses

5.2.3.2 Triassic-Liassic Massive Carbonates

Triassic-Liassic massive carbonates characterize the Dorsale range. In some cases these calcareous slabs overlie upper Carnian evaporites (Fig. 5.19A), which clearly compare with the corresponding levels of the Ghomarides (Fig. 5.15A2, A3), and

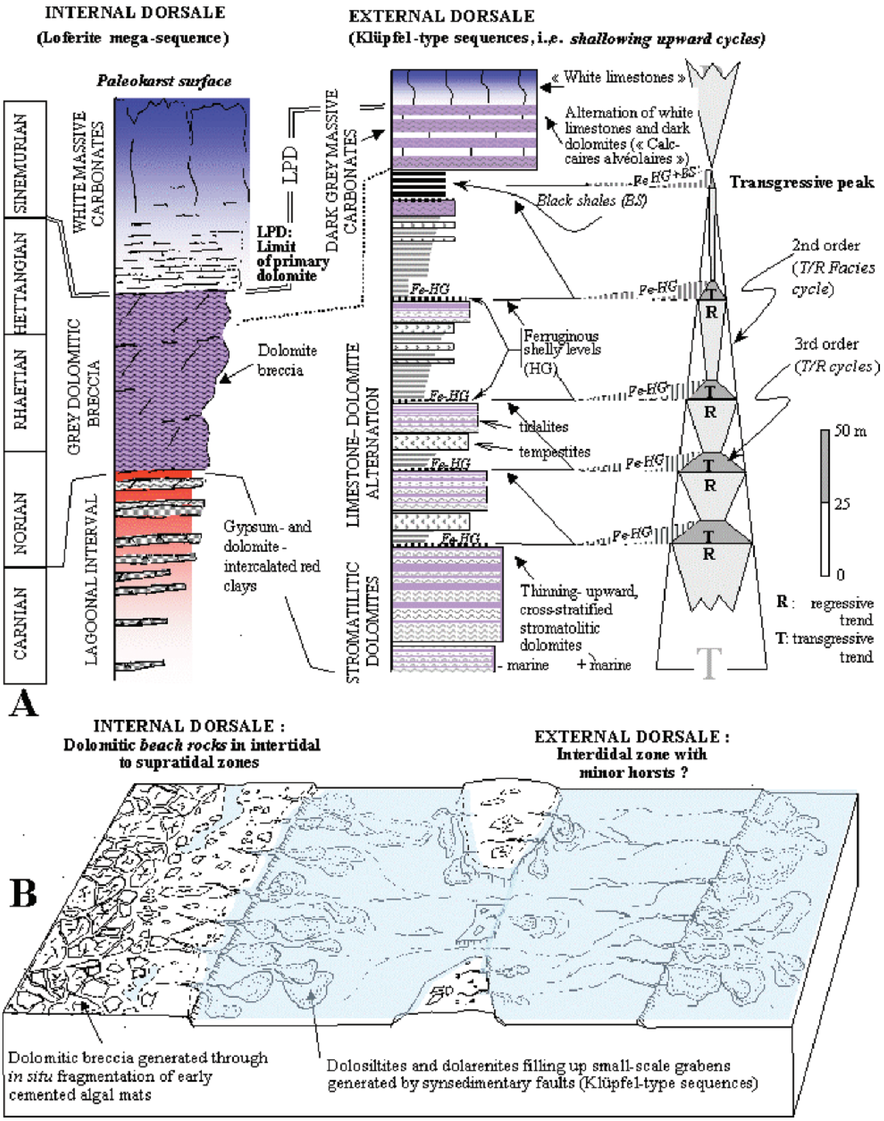


Fig. 5.19 (**A**): Comparison of the Late Triassic-Early Liassic stratigraphy of the Internal *versus* External Dorsale domains. LPD: Upper limit of primary dolomite. – (**B**): Hypothetic paleogeography, after El Kadiri & Faouzi (1996), modified. The horst within the external platform would correspond to unit D2, Fig. 5.17. A simpler paleogeographic pattern could be alternatively imagined, assuming a complex thrust tectonics (out-of-sequence D2 thrust)

played a major role in the detachment of the Dorsale units from their original (and controversial) basement.

The carbonate sequence itself begins with greyish dolomites. These are dolomitic breccias in the Internal Dorsale units (ID), and laminated, stromatolithic dolomites followed by alternating limestones-dolostones layers in the External Dorsale units (ED). They represent the Norian, Rhetian and Hettangian *pro parte* intervals. Their facies are typically Alpine, comparable with the coeval deposits of internal Briançonnais, Eastern Alps or Tuscany, and strongly contrast with the German facies of the Maghrebide and Betic External Zones.

The differences between ID and ED units increase in the Hettangian-Sinemurian massive limestone levels. ID units comprise white limestones, devoid of laminated dolomicrite facies, but still rich in stromatolitic structures and Dasycladaceae. In contrast, ED units display dark limestones, partly dolomitic (cellular limestones), but where Ammonoidae now occur. These lateral changes suggest that two neighbouring paleogeographic domains occurred at that time, i.e. a confined, shallow water, although subsiding basin (ID), and a deeper basin opened toward the oceanic domain (ED). In other words, ID units correspond to the internal carbonate shelf of the former passive margin, and ED to the external shelf, which is supported by their Jurassic-Cretaceous evolution (Sect. 5.2.3.3). This initial setting has been so deeply altered by the Oligocene-Miocene tectonics that it seems risky to infer from the present-day location of the varied units any more specific arrangement of the broad paleogeographic reconstruction such, for example, the occurrence of an internal-type horst in the middle of the external shelf (a proposal of one of us, K.E.K, which is shown in Fig. 5.19B).

5.2.3.3 Jurassic-Paleocene Pelagic Formations

During the Jurassic, sedimentation became condensed and pelagic throughout the Dorsale domain, with some significant gaps in the stratigraphic record. This suggests a submarine plateau setting. However, some differences still occur between the ID and ED.

In the *Internal Dorsale* (Fig. 5.17, columns D3, D4), following sedimentation of the Sinemurian white limestones, we observe a gap, which may attain a few millions years (D4: late Sinemurian – early Carixian), and involves an emersion with paleokarst. Then the karst is submerged and is filled and progressively covered by thin middle Carixian sediments, followed by Domerian and Toarcian *ammonitico rosso* nodular limestones. A second gap involving some erosion in part of the sections corresponds to the Middle Jurassic and the basis of Late Jurassic. It ends with the sedimentation of late Kimmeridgian-Tithonian radiolarites, followed upward by *Saccocoma* micritic limestones, then *Calpionella* limestones from the Tithonian-Berriasian. A third gap corresponds to the Early Cretaceous and part of the Late Cretaceous. It is accompanied by some erosion of the previous pelagic sediments and locally (Hafa Ferkenich) by fault scarp breccias. Cenomanian and/or Turonian pelagic sediments are locally preserved, but in most cases sedimentation resumes later with the "Couches rouges" and "Couches blanches" *Globotruncana* marls sedimentation, dated from the Campanian and Maastrichtian, respectively. The pre-orogenic sedimentation ends with Paleocene *Globigerina* black shales.

The origin of the successive gaps, and particularly of the younger ones (Toarcian-Kimmeridgian and Berriasian-Campanian) is a matter of debate. The intervention of aerial erosion and karstification has been suggested by one of us (K.E.K.) even for the two younger gaps, based on the observation of dissolution breccias and speleothems (palissadic calcite) on both sides of the pelagic infillings. However, the fact that these gaps occur between deep, pelagic episodes would suggest (A.M.) submarine gaps related to the existence of sea floor currents. It is worth noting that neptunian dykes with calcite prisms disposed radially to any interface between pelagic infilling and country rock was described in Paleozoic phyllites and granites from varied eastern Dorsale segments (Djurdjura, Peloritan Mountains, Calabria). Additional studies are needed to check these alternative interpretations.

In the *External Dorsale* (ED), there is no aerial karst during the Early Liassic, and *ammonitico rosso* deposits are observed as early as the late Sinemurian (Fig. 5.20). During this time interval, the ID belongs to the rift shoulder by contrast with the subsiding ED. Cherty limestones (which correspond to slope facies) are deposited there during Middle Liassic, then marly limestones during the Toarcian, and radiolarites during the Middle Jurassic and most of the Late Jurassic. The middle-late Tithonian and Berriasian correspond to *Aptychus* micrites as in the ID, but in the ED these micrites form the matrix of chaotic breccias (Cherafat, El Queddane). This suggests an increasing activity of normal faults related to the Tethyan rifting (Sect. 5.7). Subsequently, during the Cretaceous-Paleocene times, the DE evolution compares with that of the DI.

5.2.3.4 Eocene-Lower Miocene Unconformable Formations

A dramatic paleogeographic change took place during the Eocene, like in the Ghomaride-Malaguide domain. As early as the Early Eocene, unconformable sandy bioclastic limestones (J. Gorgues) and Nummulite rich, chaotic breccias accumulate over the varied Mesozoic formations. In places the latter breccias are overlain by Middle-Late Eocene bioclastic limestones (J. Lakraa). Other sections display conglomerates, calcareous sandstones and bioclastic limestones from the Late Eocene (J. Akroud). Hence, the Dorsale domain was strongly uplifted during the Eocene, compared to its Cretaceous position.

The Eocene sediments sometimes covered by ferrugineous crusts are overlain by Lower-Middle Oligocene coloured marls, followed upward by reddish-brown micaceous sandstones dated as Late Oligocene-Aquitanian. Conglomeratic and even chaotic formations first appear in the coloured marls, and then become abundant (Bettara, Taghzoute, Ametrasse, Tertiary sole of the Bokkoya). These deposits again evoke those from the Ghomaride-Malaguide (see Fig. 5.15, and also Fig. 5.42). They are synorogenic formations deposited just before the emplacement of the Dorsale slivers and overturned folds onto the Predorsalian domain. Likewise, the Haouz

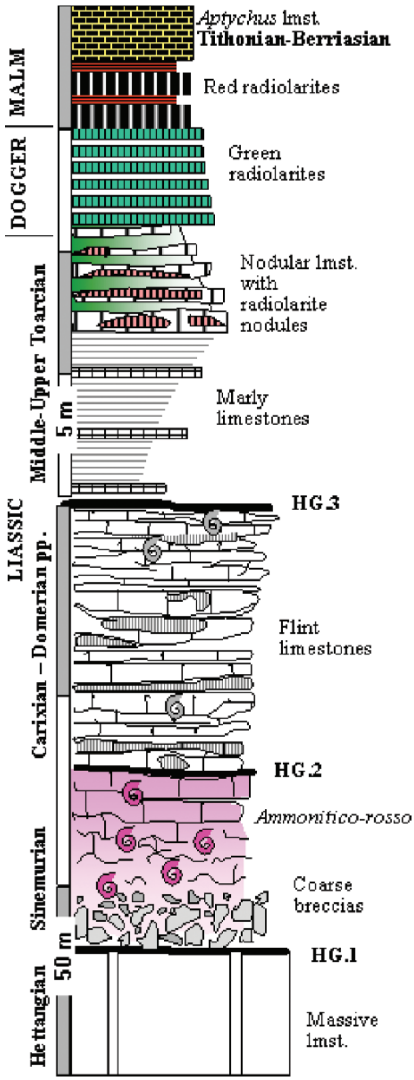


Fig. 5.20 An example of Jurassic "condensed series" from the External Dorsale, east flank of Hafat Nator, 4 km SW of Tetouan (unit D5 in Fig. 5.17), after El Kadiri (1992), modified. Note that the pelagic facies begin later in the Internal Dorsale, i.e. in the Domerian (*ammonitico-rosso*) and Tithonian (radiolarites)

backthrusting over the Ghomarides arose after the Early Burdigalian. Note that the Oligocene-Miocene deposits labelled "post-nappe" in the Ghomaride-Malaguide realm are "pre-nappe" in the Dorsale domain indicating a progressive outward migration of the deformation.

5.2.3.5 Predorsalian Domain

The narrow Predorsalian domain corresponds to relics of the transition zone between the continental margin of the Internal Zones (Dorsale domain) and the oceanic domain of the Maghrebian Flyschs. In fact, it is strongly disrupted along the suture, which separates these major domains. Two typical examples of Predorsalian sections from Northern Rif deserve illustration, namely the J. Moussa and Cherafate sections.

The *J. Moussa* (Fig. 5.21) is homologous to the Gibraltar Rock north of the Strait: they are the Ancients Pillars of Hercules. Their specific stratigraphic succession defines the "Tariquide Ridge" sub-domain (after the Arabic name of the Gibraltar Rock: Jebel Tariq). The J. Moussa succession (Fig. 5.20, right) begins with Triassic-Lower Liassic carbonates comparable with those of the Internal Dorsale, then continues from Toarcian onward in a way similar to that of the External Dorsale, except that the Aalenian-Bajocian radiolarites are substituted by nodular, ammonite-rich limestones. During the Late Jurassic, the ridge status of the sub-domain is only justified relative to the distal DE domain. Interestingly, the sequence continues upward with terms comparable with both the Dorsale and Beni Ider Flysch successions: "*Aptychus* complex" of Early Cretaceous age, Maastrichtian-Paleocene "Couches rouges", Upper Eocene-Oligocene coloured marls including upward increasing clastic-nummulitic mud flows. The sequence ends with Aquitanian holoquartzose sandstones with quartz pebbles (Numidian facies) and Lower Burdigalian brown pelites, which compare with the Ghomaride "post-nappe" formations as well as with the "pre-nappe" Dorsale equivalents.

The *Cherafate (Chrafat) klippes* occupy a smaller surface than the J. Moussa unit, and correspond to sedimentary klippes slid within the Tertiary clays of the Ametrasse unit (Fig. 5.18). The main, Beni Derkoul klippe shows an overturned

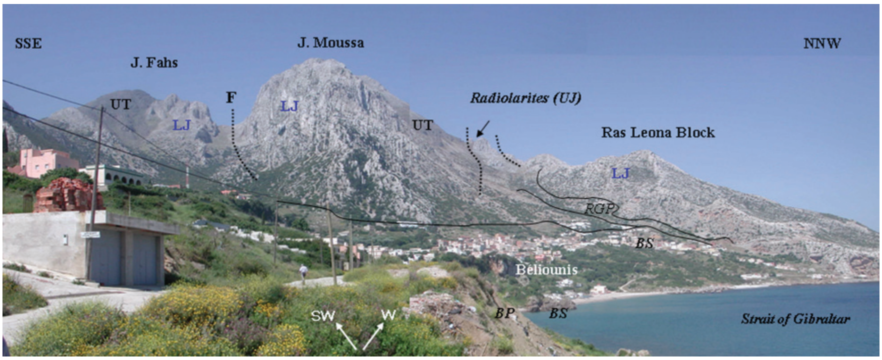


Fig. 5.21 The J. Moussa massif as seen from Beliounis (Ben Younes) village (the so-called panorama de la Mujer Muerta). For location, see Fig. 5.9. Together with the homologous Gibraltar Rock, the J. Moussa Group defines the Tariquide sub-zone of the Predorsalian distal zone (Durand-Delga et al., 2005, 2008). In contrast, the J. Fahs belongs to the proximal Internal Dorsale domain (unit D3) of the Alboran block paleomargin. The J. Moussa massif and the Ras Leona sliver overthrust the Predorsalian Cenozoic formations (BS, BP). The houses of Beliounis are built on a middle Pleistocene uplifted terrace. BP: Brown tobacco pelites (Burdigalian); BS: Beliounis sandstones (Aquitanian-lower Burdigalian); F: fault; LJ: Lower Liassic limestones; RGP: Maastrichtian-Paleocene red and grey pelites; UJ: Upper Jurassic radiolarites; UT: Upper Triassic dolomites

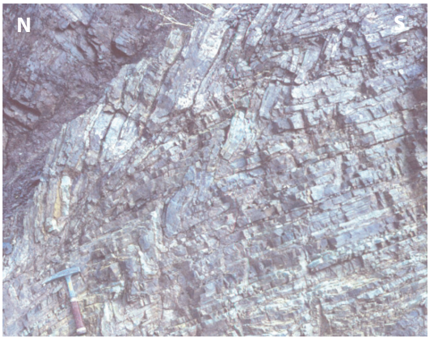


Fig. 5.22 Jurassic radiolarite/calci-radiolarite from the Predorsalian Beni Derkoul outcrops. Location: see Fig. 5.18. Note the S-vergent chevron-like folds that affect these well bedded sediments, associated with a north-dipping shear plane (*upper left*)

sequence including more distal terms than the coeval facies from the neighbouring Dorsale, such as thick Upper Jurassic radiolarites/calciradiolarites (Fig. 5.22). Therefore, they do not originate from the Dorsale, but from a specific domain, i.e. the Predorsalian domain.

The "Bokkoya Tertiary Sole" allows us to separate two periods of olistostrome emplacement, (i) the Late Oligocene, with a source area in the External Dorsale, and (ii) the Burdigalian, with a source area in the Internal Dorsale. Between both olistostrome accumulations, the sequence includes Aquitanian marls with interbedded Numidian-facies sandstones. The original substratum of this "Tertiary Sole" is unknown.

5.3 Maghrebian Flyschs

References: The main recent works on the Maghrebian Flyschs stratigraphy in the Gibraltar Arc are those by Thurow & Kuhnt (1986), Durand-Delga & Olivier (1988), Esteras et al. (1995), Olivier et al. (1996), Durand-Delga et al. (1999), Puglisi et al. (2001), Zaghloul (2002), El Kadiri et al. (2003, 2006), Zaghloul et al. (2007). The publications by Chalouan et al. (2006b) and Crespo-Blanc & Frizon de Lamotte (2006) more specifically address the Flysch nappe structure. Correlations at the Maghrebide scale and paleogeographic reconstructions are addressed by Bouillin (1986), Hoyez (1989), Durand-Delga et al. (2000), Guerrera et al. (2005), and De Capoa et al. (2007).

As defined in Sect. 5.1.2.2, the Maghrebian Flyschs form relatively thin, but extensive thrust-nappes over the External Zones and restricted back-thrust elements (e.g. J. Zemzem) over the Ghomaride-Malaguide complex (Figs. 5.5, 5.6, 5.7 5.8). Turbidite sequences ("flyschs") are dominant in these nappes, but clay-dominated sequences occur at the bottom of each nappe ("pre-flysch" sequences).

From an historical point of view, it is worth noting that the occurrence of large Flysch inliers over the Kabylian Oligocene-Miocene cover have been used as an argument for an internal origin of the Flyschs. This "ultra-kabylian" hypothesis, warmly debated in the 60s–70s, has been abandoned since.

5.3.1 Mauretanian Nappes

Above a thin Jurassic series including Upper Jurassic radiolarites, the *Tisiren nappe* series (Fig. 5.23A) begins with a pre-flysch sequence consisting of *Aptychus* and *Calpionella* marly limestones from the Berriasian-Valanginian. This sequence played the role of a décollement level at the bottom of the competent Flysch mass. The first turbidite sequence consists of graded siliciclastic layers interleaved with argillaceous-pelitic horizons where palynomorphs indicate a Hauterivian-Barremian age (Fig. 5.24). Then, a dominantly pelitic sequence occurs (Barremian-early Aptian interval), followed upward by a new turbiditic cycle (late Aptian-middle Albian). The lateral extent of these facies is considerable, i.e. from Western Betics (Los Noguales) to Algeria (Guerrouch), and to Sicily (Monte Soro).

The *Beni Ider nappe* series represents the detached ("diverticulated") upper part of the Mauretanian basin infilling. It includes a lower "pre-flysch" series, which operated as a décollement level between the Tisiren and Beni Ider successions. The "pre-flysch" series (Fig. 5.23B) begins with upper Albian-Cenomanian-Turonian spongolites and black shales. These levels are followed upward by Upper Cretaceous coloured pelites and calciturbidites, which most often include breccias with carbonate elements from the Dorsale domain. The Campanian layers also include reef fragments and Rudists of unknown origin, whereas the Maastrichtian flysch contains Permian-Triassic (Verrucano) fragments likely reworked from Ghomaride or similar sources. Calciturbidite flows, emplaced during the Paleocene, include reworked *Microcodium*. Thick sandstone layers with local nummulite accumulations correspond to the Early Eocene, and nummulitic turbidites represent the Middle-Late Eocene. The Eocene-Oligocene transition is marked by the emplacement of chaotic breccias and olistoliths within greenish-reddish pelites ("flysch coloré").

The series is topped by a thick sandy-micaceous turbidite accumulation (Fig. 5.23C), referred to as the "Flysch gréso-micacé" (Sandy-Micaceous Flysch) or "Flysch à Lépidocyclines" throughout the Maghrebides, or "Algeciras Flysch" in Andalucia, and dated by planctonic foraminiferans and nannoplankton from Late Oligocene to middle Burdigalian. One can recognize two main turbidite sequences (I, III) and a dominantly pelitic sequence (II) in between. Sequence I ends with an olistostrome where Dorsale fragments are reworked (Jurassic and Eocene limestones), as well as low grade metamorphic elements (Ghomaride?). Sequence II includes by place (Anjra unit) Numidian-like layers. Eventually, the flysch series ends with brown pelites and breccias with schist elements (sequence IV), which closely compare with the Sidi Abdeslam Fm (Sect. 5.2.2.3).

Each Mauretanian nappe displays a particular structural style in relation with its particular mechanical stratigraphy. Weak layers dominate in the Beni Ider nappe, allowing external-verging folds to form. Contrastingly, the stiff Tisiren material results in the formation of thrust sheets over the previously detached Beni Ider nappe. It is worth noting that the Tertiary cover of the Mauretanian Flyschs does not exist along the Bokkoya transect, suggesting that they have been back-thrust over the In-

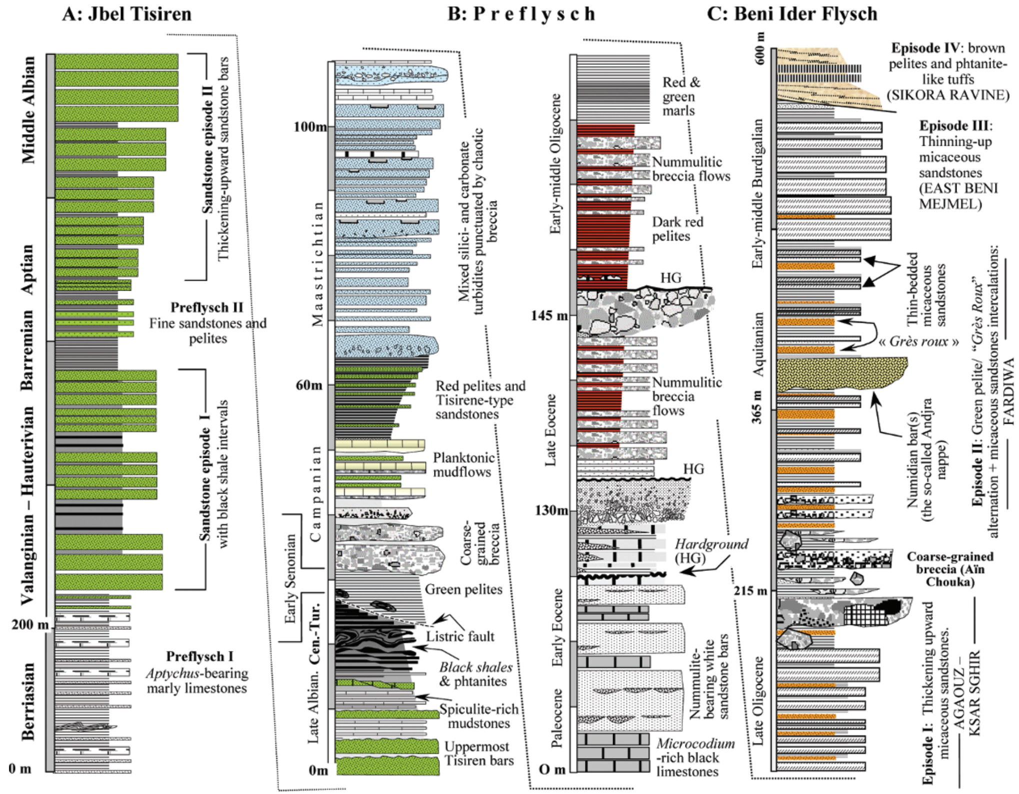


Fig. 5.23 Stratigraphy of the Mauretanian Flyschs from the Rif Belt. (**A**): J. Tisiren nappe, after Durand-Delga et al. (1999), modified. The Jurassic base of the nappe (radiolarites, basalts, locally Liassic limestones) is not shown. – (**B**) ("Préflysch") and (**C**) ("Flysch") of the Beni Ider nappe (detached from the *top* of the Tisiren series), after El Kadiri et al. (2003, 2006), Zaghloul et al. (2007)

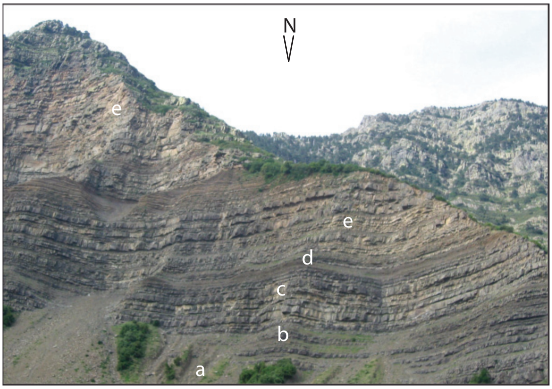


Fig. 5.24 Southern slope of the J. Tisiren, viewed from the Ketama-Bab Taza road (see Fig. 5.7 for location). The turbiditic sequence represents a 30 Ma interval, with Upper Berriasian-Valanginian (**a, b**), Upper Valanginian-Hauterivian (**c, d**), and Upper Hauterivian, Barremian, Aptian and lower Albian (**e**). Stratigraphic dates are based on nannofloras from the most pelagic episodes (Durand-Delga et al., 1999)

ternal Zones, similar to the J. Zemzem and Riffiene klippes south of Ceuta and to their widespread equivalents over the Kabylias.

5.3.2 Massylian Nappes

The name of the *Chouamat-Meloussa nappe* was based on two localities of the Central Rif and Tanger (Tangier) area, respectively. This nappe compares with the Massylian nappe *sensu stricto* of Algeria, and occurs as sheared sheets beneath the Mauretanian or Numidian nappes. This supports the idea that the Massylian basin was located externally with respect to the Mauretanian, and that the Numidian represents the detached upper part of the Massylian sedimentary pile.

The Chouamat-Meloussa series begins with an Aptian-Albian siliciclastic flysch, relatively fine grained when compared with the coeval Tisiren flysch. This 700 m-thick flysch formation is followed upward by thin (20 m) black cherts and calcareous microbreccias dated as Cenomanian-Turonian, and then by Senonian pelites and microbreccias (100 m). This specific succession can be correlated to the north with the Mauretanian one, and to the south with the Intrarif (Ketama unit; see below).

The Numidian nappe is named after the particular lithologic facies of the "numidian sandstones", defined as early as 1890 in the Kabylian coast. Such sandstones make up most of the Numidian nappe, which can be easily identified from Sicily to Andalucia (Algibe sandstones). In the Rif Belt, the Numidian nappe comprises extended, but relatively thin thrust elements or klippes. They include tilted, folded and occasionally overturned beds (J. Zinat) abruptly truncated along the nappe sole thrust (Fig. 5.25). The Numidian allochthons overlay the varied Intrarif units (either directly or through Chouamat-Melloussa slivers), except the J. Zemzem

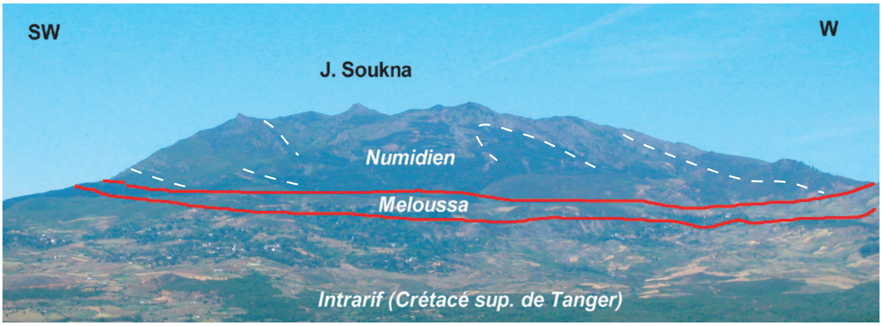


Fig. 5.25 A typical Maghrebian Flysch klippe as outcropping at J. Soukna, viewed from Chaouen (see Fig. 5.7 for location). The main part of the klippe corresponds to Aquitanian siliciclastic turbidites whose NE-dipping layers (SW-vergent folds) are deformed by a SW-vergent anticline, troncated by the sole thrust of the nappe. The Cretaceous pelites of the Meloussa nappe form a plastic cushion at the *bottom* of the competent Numidian nappe, and on *top* of the Intrarif Upper Cretaceous shales (Tanger unit)

klippe, which overlies the Internal Zones and probably originates from a relatively internal part of the Numidian basin (Anjra unit).

The stratigraphic pile (Fig. 5.26) begins with a "pre-flysch" series, namely the *Argiles sous-numidiennes* (Infra-Numidian Clays). These are vari-coloured clay deposits including scarce bioclastic layers and Fe-Mn rich concretions referred to as *Tubotomaculum* (likely epigenised crustacean burrows). They were deposited at depth during the Late Lutetian to Late Oligocene times, according to both the pelagic foraminiferans and nannoplankton associations. The weakness of this formation greatly favoured the detachement of the more than 1000 m thick Numidian pile.

The Numidian sandstones sensu stricto consist of thick yellowish, poorly cemented sandstsones, which include scattered, almond-sized quartz pebbles. Graded bedding is poorly marked, the sandstones layers are channelized, often amalgamated, and organized into upward thinning sequences interleaved with reddish pelites, suggesting a system of fluxoturbidites emplaced in deep lobate fans. The origin of the highly mature sediment (quartz sand) is to be found in the reworking of previous sandy deposits, possibly the Jurassic-Cretaceous Saharan continental sandstones, which itself has been fed by the erosion of the Cambrian-Ordovician sandstones overlying the Saharan crystalline shields. The Saharan sands would have entered the Ligurian-Maghrebian Ocean through some gates (e.g. in Tunisia, according to Hoyez, 1989), being then distributed by longitudinal turbidity currents.

The age of the Numidian sedimentation, latest Oligocene-Aquitanian, is constrained only by the age of the bounding levels. Indeed, the turbidite sequence is overlain by brownish, siliceous supra-numidian clays dated from the latest Aquitanian and early-middle Burdigalian. Flint layers of the same age are found on top of the Beni Ider series, and these siliceous levels are possibly related to an early volcanic event (Sect. 5.5).

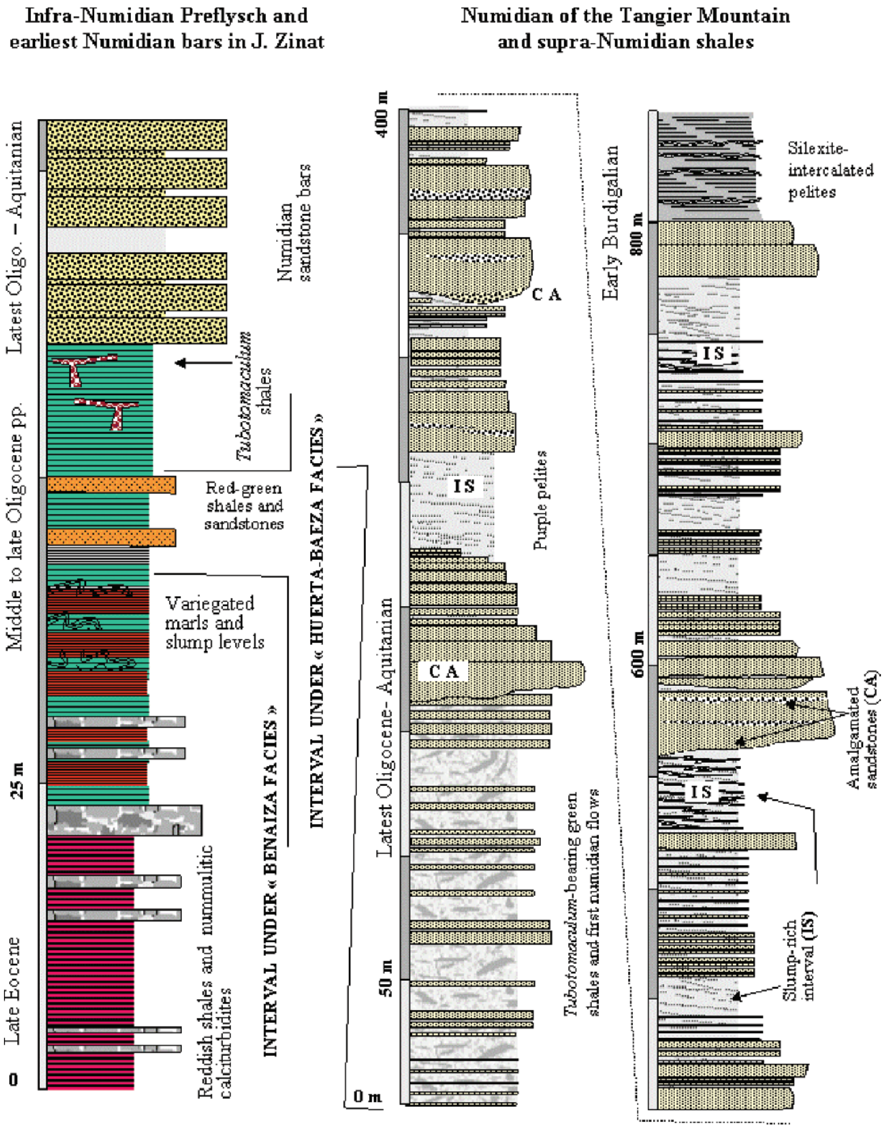


Fig. 5.26 Stratigraphy of the Numidian nappe from the J. Zinat (*left*) and Tangier (Tanger) Mountain (two columns on the *right*; note the different vertical scale used in the *left*-hand column). See Figs. 5.6 and 5.7 for location

As a whole, the Numidian flysch appears to be coeval with the Beni Ider sandy-micaceous flysch. Thus, it is not suprising to find mixed series such as the Talaa-Lakrah (Tanger) and Bolonia (Andalucia) series. Their stratigraphy compares with the Beni Ider one, except the occurrence of interbedded Numidian-type sandstones layers with almond-like quartz pebbles, sometimes located within sand-balls. This suggests that southeastern, Numidian inputs were converging with northern ones (Beni Ider).

5.3.3 Paleogeography

The Maghrebian Flyschs nappes, which display turbiditic sequences of Cretaceous-Tertiary age are detached from an oceanic or thinned continental crust domain. Ophiolite slivers occur at the bottom of the more or less recrystallized flyschs from southern Apennine Calabria, Sicily, and even beneath the Lesser Kabylia allochthon (Rekkada-Metletine serpentinites, gabbros, pillow basalts and radiolarites dated from the Jurassic). Interestingly, the Achaiche Mauretanian unit, also overthrust by the Lesser Kabylia massif, displays a continental margin-type pre-flysch series with Paleozoic metapelites, Triassic sandstones, Liassic carbonates intruded by thick sills of basalts, limestones and radiolarites of Dogger-Malm age, and Berriasian pillow basalts. Further west, Middle-Upper Jurassic pillow basalts and radiolarites associated with siliceous micrites crop out beneath the Mauretanian nappe south of the Bokkoya (Izroutene), whereas an agglomerate of Middle Jurassic limestones and variolitic pillows occurs at the bottom of the J. Chouamat Massylian nappe. Pillow basalts are also found as olistoliths within the Bokkoya Tertiary sole. In contrast, no basalt occurs in the Ouareg sheet beneath the Tisiren nappe close to Targuist, the series of which displays only Toarcian-Bajocian calciturbidites and Middle-Upper Jurassic radiolarites.

It is suggested that the Ligurian-Maghrebian basin was a true oceanic basin in its eastern, wider part, whereas it was floored mostly by thinned continental thrust in its narrower western part. However, the tomographic studies image a deep cold slab, about 600 km wide E-W and N-S below the south Balearic basin, which would correspond to a former Ligurian-Maghrebian oceanic substrate subducted down to the base of the asthenosphere (Sect. 5.7). This indicates additionally that not only most of the Ligurian-Maghrebian crust, but also a large part of the overlying sediments disappeared by subduction: the Flysch nappes and their scarce basal slivers are tiny remnants of the lost oceanic domain.

The Mauretanian sub-basin was located on the northern side of the Maghrebian basin, as indicated by the detrital elements reworked from the AlKaPeCa domain in the Beni Ider breccias and coarse turbidites. The sandy-micaceous flysch was probably fed by the erosion of the Ghomarides-Malaguides and equivalent Kabylian terranes, like the "post-nappe" cover of these mostly Paleozoic domains. Conversely, the Massylian sediments accumulated on the southern side of the Maghrebian basin, close to the African margin. This is consistent with the similarities between the Cretaceous series of the Massylian nappes and Intrarif units (see below), and also with the African source of the Numidian turbidites.

5.4 External Zones

References: The internal parts of the External Zones (Intrarif, Mesorif) have been the subject of a number of publications in the last decades: Andrieux (1971), Vidal (1977), Leblanc (1979), Leblanc & Wernli (1980), Wildi (1981, 1983), Leblanc & Feinberg (1982), Septfontaine (1983), Monié et al. (1984), Frizon de Lamotte (1985, 1987), Morley (1987, 1992), Asebriy et al. (1987), Ben Yaïch (1991), Ben Yaïch et al. (1991), Favre (1992), Michard et al. (1992), Asebriy (1994), Benzaggagh (1996), Elazzab et al. (1997), Abdelkhaliki (1997), Azdimousa et al. (1998), Toufiq et al. (2002), Zakir et al. (2004), Zaghloul et al. (2005), Crespo-Blanc & Frizon de Lamotte (2006), Negro et al. (2007), Michard et al. (2007).

As for the more external parts (Prerif and foredeep) and more recent, post-nappe deposits, the main recent references are the followings: Guillemin & Houzay (1982), Feinberg (1986), Wernli (1987), Benson et al. (1991), Kerzazi (1994), Flinch (1996), Benzaggagh (1996), Zizi (1996, 2002), Samaka et al. (1997), Lamarti-Sefian et al. (1998), Plaziat & Ahmamou (1998), Bernini et al. (1999), Krijgsman & Langereis (2000), Litto et al. (2001), Zouhri et al. (2001), Münch et al. (2001), Bargach et al. (2004), Chalouan et al. (2006a).

As reported above (Sect. 5.1.2.3), the Rif External Zones are divided into three zones, according to structural and stratigraphic criteria, i.e. from NE to SW the Intrarif, Mesorif and Prerif (Figs. 5.7, 5.8).

5.4.1 Intrarif

The Intrarif zone includes the most distal units derived from the African paleomargin. These units crop out immediately beneath the Maghrebian Flyschs and Dorsale units.

The *Ketama unit* consists mainly of Lower Cretaceous series where siliciclastic turbidites predominate. These terms are intensely folded and affected by low grade metamorphism (Sect. 5.5). The Ketama unit extends into the Central Rif range, being limited eastward by the Nekor Fault, the nature of which is discussed in Sect. 5.4.2. The Ketama unit involves, at least, two sub-units. The southern unit begins with Sinemurian massive limestones (Fig. 5.27A), suggesting a continental substrate. Then the syn-rift series involves ammonite-rich marly limestones (Middle Liassic), silty marls (Toarcian), hemipelagic “calcaires à filaments” (Aalenian), and Posidonomya marls (Dogger). The overlying post-rift series consists firstly of Upper Jurassic “ferrysch” (a rythmic marly-clastic formation), followed upward by Tithonian-Berriasian pelagic limestones. Then a pelitic-sandy sedimentation corresponds to the Valanginian, Barremian and Aptian-Albian times, being characterized by thick quartzose turbidites (Fig. 5.28). Vraconian belemnite marls and spongolites are preserved to the north.

The *Tanger unit*, partly detached from the underlying Ketama, and the *Aknoul nappe*, totally detached and thrust over the Mesorif and Prerif (and even over the Middle Atlas foreland in the easternmost Rif), expose the Upper Cretaceous-Eocene

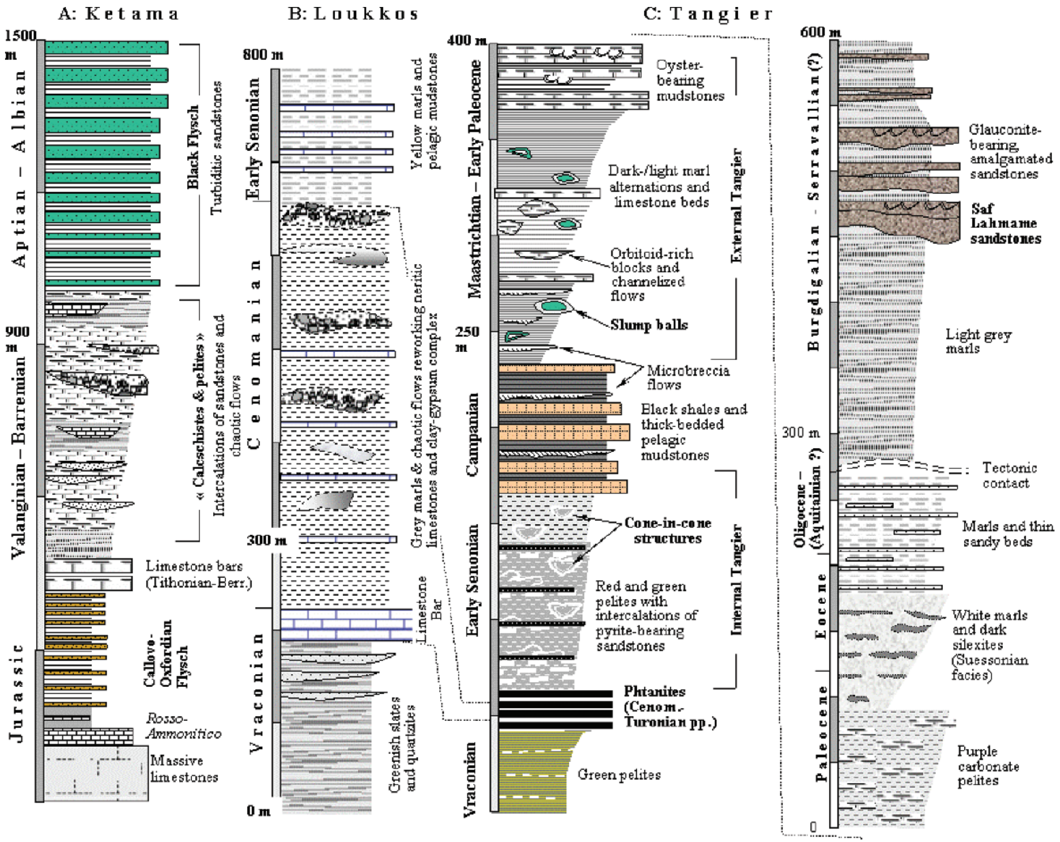


Fig. 5.27 Stratigraphy of the Intrarif "rooted units". (**A**): Ketama unit, after Frizon de Lamotte (1985). – (**B**): Loukkos unit, after Lespinasse (1975). – (**C**): Tanger unit; Saf Lahmane Neogene sequence after Zaghloul et al. (2005). Saf Lahmane is located 25 km south of Tanger (Tangier)

Fig. 5.28 Large load casted flute casts at the bottom of an overturned siliciclastic turbidite strata from the Lower Cretaceous Ketama unit, 20 km west of Ketama town. Two superimposed paleocurrent directions can be distinguished (*arrows*)

marly-pelitic formations of the Intrarif zone (Fig. 5.27C). The Tanger series spans the Cenomanian-Maastrichtian interval in Central Rif, whereas it is diverticulated in Western Rif into an Internal Tanger unit (Cenomanian-Senonian) and and External Tanger unit (Campanian-Paleocene). Some facies contrast with the dominant pelites, such as the Cenomanian-Turonian phtanites, the lower Senonian *cone-in-cone* nodules, the Campanian-Maastrichtian calcareous microbreccias, and the *Ostrea* marly limestones at about the K-T boundary.

The *Loukkos unit* conventionally belongs to the Intrarif, although it forms a transition with the western Mesorif. Compared to the Tanger unit, the Loukkos unit (Fig. 5.27B) is typified by thicker Cenomanian deposits, a higher proportion of carbonates, and frequent diapiric intrusions of the Triassic clay-gypsum complex. As for the younger formations of the former Intrarif basin, they have been detached and diverticulated, except locally (Saf Lahmane; Zaghloul et al., 2005), to form the *Habt nappe* in the west, and the *Ouezzane and Tsoul nappes* south and southeast. Indeed, Intrarif Eocene sediments consist of white siliceous marls and marly limestones, which acted as a décollement level. Sand input increased during the Middle Eocene. During the Oligocene, olistostromes occurred in part of the Habt (Rirha and Meliana units), whereas a siliciclastic flysch, namely the *Asilah-Larache Sandstone*, accumulated in the external Habt sub-basin. The latter turbidite formation is dated from the Late Oligocene-Burdigalian, and thus corresponds to a lateral facies of the Numidian. Indeed, it seems that the J. Berkane Numidian klippe (Eastern Rif) is in stratigraphic contact with the underlying Aknoul nappe, suggesting they have been transported altogether. The youngest Intrarif levels at Saf Lahmane are dated from the late Burdigalian-Middle Miocene (Serravallian?), and then resemble the younger pre-nappe levels of the Mesorif zone.

5.4.2 *Mesorif*

The Mesorif zone displays different characteristics in Western-Central Rif and Eastern Rif, east of the Nekor Fault, respectively.

5.4.2.1 Western and Central Rif

In the central part of the Rif range, the Mesorif zone is also termed *Zone des Fenêtres* ("Window Zone") as it is characterized by antiforms with Lower-Middle Miocene rocks in the core (e.g. Tamda, J. Kouine), and mainly Mesozoic thrust units above them. The allochthonous units have two possible origins, either infra- or supra-Ketama (see Figs. 5.7, 5.8 for location).

The *Tifelouest-Tafraout-Afress-Rhafsaï* group of infra-Ketama units corresponds to folded duplexes at the very front of the Ketama massif, being rooted beneath the massif. The *Senhadja nappe* is also part of the infra-Ketama units, but appears as unrooted klippes on top of the autochthonous Miocene turbidites and olistostrome. The Bou Haddoud nappe has the same infra-Ketama origin as the Senhadja nappe, but extends more to the south over the Prerif units.

The Mesozoic series typical of the Tifelouest group are found also in the Izzarene forest of Western Rif, as well as in the "Zone des Sofs", i.e. the rocky ridges that underline the Mesorif-Prerif boundary. Everywhere within this fragmented domain, rapid facies and thickness changes in the Lower and Middle Jurassic formations indicate the synsedimentary activity of normal faults, and characterize the paleomargin syn-rift evolution (Fig. 5.29). The post-rift sequence begins with the Callovian-Oxfordian "ferrysch", followed by Kimmeridgian and Tithonian-Berriasian micrites, and Neocomian pelites. The syn-orogenic, Cenozoic sedimentation begins with unconformable, blocky marls, probably Late Oligocene in age (M. Durand-Delga, written comm., 2007) as they contain both Nummulites and Lepidocyclines. These nummulitic marls are unconformably overlain by a chaotic complex (Oligocene-Aquitanian?) followed upward by the Aquitanian-Serravallian turbidites cited above. The Mesozoic formations are strongly folded and foliated, whereas the Lower-Middle Miocene formations are moderately deformed and only anchimetamorphic (Sect. 5.5). The occurrence of foliated Eocene pebbles in the Oligocene-Aquitanian chaotic complex yield evidene of a Late Eocene-Oligocene phase of synmetamorphic deformation. In the Zoumi unit of Western Rif, the Miocene formations compare with those of Central Rif, but the older formations are not metamorphic.

The Senhadja "nappe" includes hectometre- to kilometre-sized blocks (Taïneste, Merzouk, Azrou Akchar) on top of the Middle Miocene turbidites. The reworked Mesozoic layers compare with those of the Tifelouest, but they are accompanied by Triassic elements (reddish sandstones and pelites, spilitic dolerites and gabbros) and even by Paleozoic material (quartzites, phyllites). Therefore, the basement itself is clearly involved in the External Rif deformation, likely due to inversion of the paleomargin normal faults.

As for the supra-Ketama units, they correspond mainly to the already quoted *Aknoul nappe*, detached from the Ketama unit on top of the Cenomanian undercompacted clays, and to the J. Berkane *Numidian klippe* transported on top of the latter nappe. Note that the underlying Bou Haddoud unit displays a remarkable, continuous "K-T" section, dated precisely with planktonic Foraminifera (Toufiq et al., 2002).

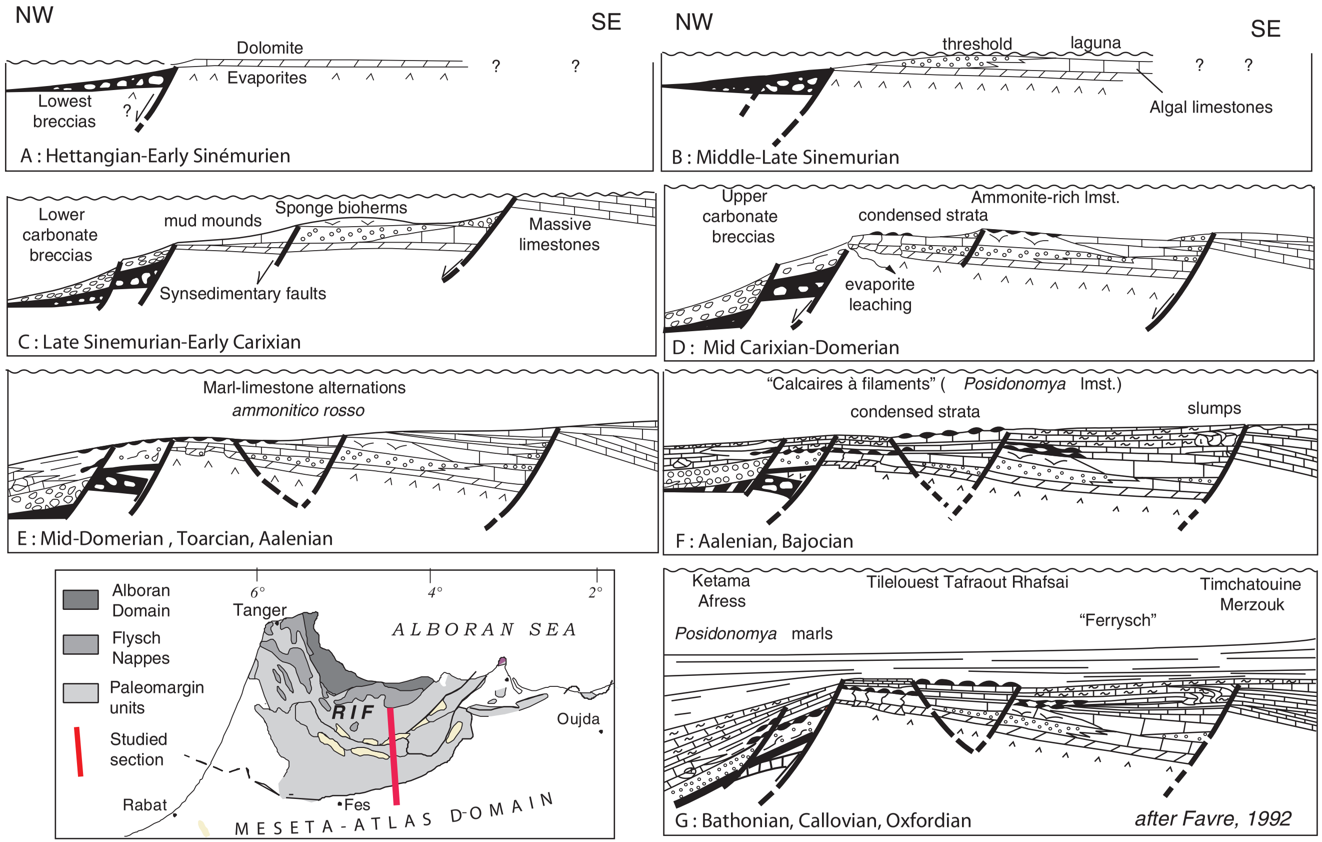


Fig. 5.29 Tectonic and sedimentary evolution of the African paleomargin during the Jurassic at the Mesorif-Intrarif border (Tifelouest and Ketama units), after Favre (1992), modified

5.4.2.2 Eastern Rif

The structural setting of the Central Rif is disturbed eastward by a large tectonic corridor, referred to as the Nekor Fault ("accident du Nekor"), which is a NE-trending left-lateral wrench fault oblique to the general trend of the Rif-Tell belt (Figs. 5.5, 5.7). The importance of this fault is well indicated by its association with a low-velocity zone at 5 km depth, coinciding with high conductivity and low-gravity structure, interpreted as a fault gouge zone and fluid-filled subsurface rock matrix (Serrano et al., 2003). East of the fault, the Mesorif can be easily recognized in the *South Temsamane* sub-zone (unit I, Fig. 5.30). The Mesorif zone can be followed northward to the Mediterranean coast in the *North Temsamane* sub-zone, through several steps of increasing deformation and metamorphic grade (Sect. 5.5.3). The Intrarif zone disappears undersea, and crops out again only in the Oran region east of the Algerian border.

The South Temsamane stratigraphy is complete and easily recognized from the Liassic to Upper Cretaceous levels, up to the unconformable Lower-Middle Miocene turbidites. In contrast, the stratigraphic formations are less continuous and less easily dated in the North Temsamane sub-zone, which consists of more or less diverticulated units (II–VII from S to N), duplicated and folded together during the pre-Miocene synmetamorphic event. Their metasediments are deformed into overturned folds stretched along their WSW-trending axes, which is consistent with a sinistral throw during the Alboran Terrane-Africa oblique collision (Sect. 5.7).

Two isolated massifs involving metamorphic units occur in Eastern Rif, i.e., (i) the Tres-Forcas (Trois-Fourches) massif (unit VIII), whose lowest unit likely continues the North Temsamane system upward; and (ii) the Khebaba unit (unit IX), which overlies the South Temsamane, being located beneath the Aknoul nappe. The Khebaba massif structural setting thus compares with that of the Senhadja klippes, but the Khebaba shows a metamorphic grade comparable with that of the northernmost Temsamane unit (Ras Afraou; Sect. 5.5.3).

In the North Temsamane domain, gabbroic sills intrude the Jurassic-Cretaceous formations, being affected also by the regional syntectonic recrystallization. These metagabbros and metadolerites testify to the importance of the paleomargin thinning in the distal Mesorif area during the Late Jurassic-Early Cretaceous.

Such crustal thinning is still better documented by the occurrence of a serpentinite massif, namely the *Beni Malek massif*, in the Nekor Fault corridor. The massif forms a kilometre scale lense at the bottom of the Ketama unit, and overlies a metasedimentary unit (Igarmaouas unit) intermediate between the Ketama and North Temsamane complexes (Fig. 5.30C). The ultrabasites (altered spinel lherzolite) are partly draped by a cover sequence consisting of limestones with ophiolitic clasts (Late Jurassique-Early Cretaceous?). Laterally, the massive serpentinites are replaced by greenschists, which correspond to metabasites and recrystallized serpentinite-gabbro sands. The Beni Malek unit is interpreted as a sliver of oceanic crust originated from an Alpine-type oceanic crust, where tectonic denudation of mantle rocks plays a major role with respect to magmatism. Modelling of the regional magnetic anomaly suggests that the serpentinite and greenschist sliver

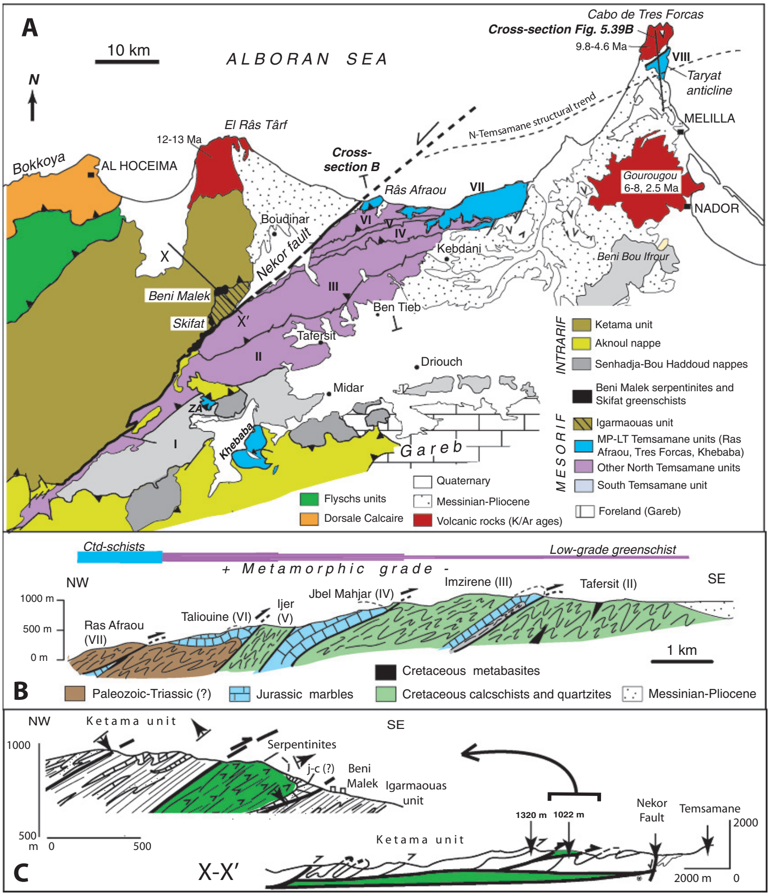


Fig. 5.30 Structure and metamorphism of the Eastern Rif. Schematic structural map (**A**) and cross-section (**B**) after Frizon de Lamotte (1985), Negro et al. (2007), and Michard et al. (2007), modified. Khebaba massif after Darraz & Leblanc (1989). K/Ar ages (Ma) of post-orogenic volcanoes after El Azzouzi et al. (1999) and Münch et al. (2001). XX': trace of lower cross-section (**C**); ZA: Zaouyet Sidi Hadj Ali. – (**C**): Geological cross-section of the Beni Malek ultrabasite massif (YY') after Michard et al. (1992), and 2D interpretation of the regional aeromagnetic anomaly (XX') suggesting the occurrence of a cryptic ultrabasic body, after Elazzab et al. (1997). j-c(?): carbonates with serpentinite clasts (Upper Jurassic-Lower Cretaceous?)

is derived from a deeper and larger serpentinite body obducted onto the Mesorif units (Fig. 5.30C). This would indicate that a minor, intracontinental (intra-margin) suture zone occurs between an Intrarif distal block and a Mesorif-Prerif proximal margin. Serpentinite outcrops are known on top of the Tres-Forcas massif. In fact, the trace of this suture can be followed eastward at least up to the Oran region, and likely up to the Chéliff Mountains south of Algiers. To the west, the suture is likely buried beneath the Intrarif thrust, whose lateral ramp corresponds to the Nekor Fault.

5.4.3 Prerif Zone and Foredeep

The main, *external Prerif Zone* comprises Upper Cretaceous-Eocene and Middle-Upper Miocene marly-argillaceous formations detached from their Jurassic-Early Cretaceous basement and slid towards the foredeep (Figs. 5.7, 5.8). The Triassic clay and salt complex formed diapirs and rock glaciers within the Cretaceous formations. The diapiric complex frequently includes ophite bodies of Late Triassic-Early Liassic age. Subsequently, the Triassic diapirs and the resedimented Triassic complex are incorporated within the Prerif nappes (Figs. 5.31, 5.32).

The Jurassic-Lower Cretaceous formations themselves are detached from their Paleozoic basement and now form an alignement of carbonate slivers in the internal Prerif Zone, also labelled the "sof line". The "sof" Mesozoic series compares with the Mesorif as they exhibit Upper Jurassic "ferrysch" and Lower Cretaceous marly limestones with turbidite intercalations. The Upper Cretaceous-Eocene marls are followed upward by Middle-Upper Eocene to Middle Miocene detrital formations including, in particular, the Eocene-Oligocene Sidi Mrayt sandstones, which were fed from the external foreland through the Meliana paleo-canyon. The latter stratigraphic levels lack in the External Prerif, suggesting a flexural uplift of the proximal margin south of the Mesorif, which played the role of an early foredeep during the Early-Middle Miocene.

The *foredeep* subsidence began during the Middle-Late Miocene at the front of the Rif-Tell tectonic prism, through flexural bending of the African plate due to tectonic overburden, and/or to slab pull from the subducting Maghrebian Ocean lithosphere (Sect. 5.7). In the central Fes-Meknes region, the *Rides prérifaines* are late anticlines formed after the synsedimentary emplacement of the Prerif nappe within the foredeep. Their varied axial trends (E-W, NE-SW and N-S) are controlled by the varied normal faults inherited from the paleomargin. The Mesozoic series of the Rides prérifaines compares with that of the Middle Atlas foreland (sandy carbonates of Dogger age, Late Jurassic-Early Cretaceous gap). It is unconformably overlain by Middle-Upper Miocene molassic sandstones, then by Upper Miocene sandy marls within which the front of the nappe is interleaved (Fig. 5.33; see also Chap. 6).

Further west in the Gharb Basin, industrial boreholes evidence the Miocene molasse onlapping onto the Caledonian-Variscan Sehoul Block barely covered by thin Cretaceous deposits. Near Rabat, the molasse directly overlies the Paleozoic basement. The lack of Jurassic formations and the reduction of Cretaceous sediments can be ascribed to the uplift of the Atlantic rift shoulder (Chap. 4). The molasse transgression onto the foreland occurred earlier in the eastern areas (Langhian) than in the western (Tortonian). Subsequently, sandy marls accumulated in the foredeep during the Tortonian. At that time, the Prerif formations, already overlain by the Intrarif nappes (Ouezzane, Tsoul, Aknoul) detached and slid on top of the foredeep sediments under submarine, synsedimentary conditions (olistostromes). The cover of the nappe consists again of terrigeneous muds of Late Tortonian-Messinian age, labelled the *Miocène post-nappe* and followed upward by similar deposits of Pliocene age. The regression occurred after the middle Pliocene (Saiss "Sables fauves"). The collapse of the orogenic prism resulted in the transgression of the post-nappe

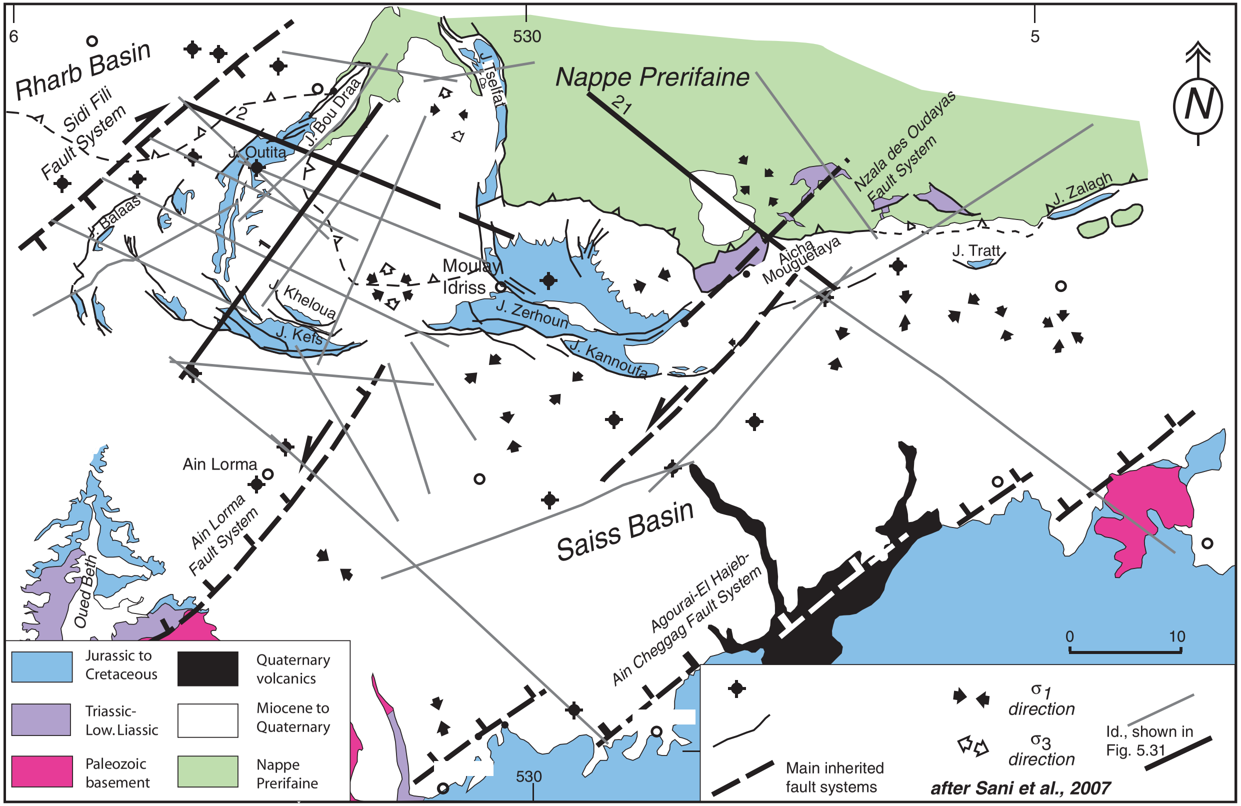


Fig. 5.31 Structural map of the Prerif front in the area of the Rides Prérifaines, with location of the ONHYM seismic profiles and industrial wells, after Sani et al. (2007), modified. Note the importance of the fault systems inherited from the Variscan evolution of the basement and active during the Triassic-Jurassic evolution. These faults heavily control the Neogene deformation

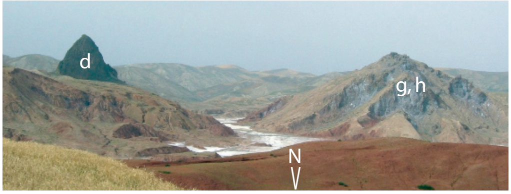


Fig. 5.32 The Late Triassic complex of the External Prerif, 25 km NW of Fes city. The complex includes red-brown clays, evaporites (*g: gypsum; h: halite*), and a neck of spilitic dolerites (*d*). The leached salt turns the bed of oued Mellah white ("mellah"=salted, in Arabic). In the background, Cretaceous and Miocene marls

deposits onto the Mesorif domain of Central-Eastern Rif. These deposits are now preserved in post-nappe synclines, which formed contemporaneously with the Rides prérifaines anticlines. The Rif foredeep connects offshore with the Betic one in the submarine accretionary prism of the Gulf of Cadiz (Fig. 5.5).

5.5 Metamorphism

In the Gibraltar Arc, metamorphism characterizes essentially the Internal Zones (Alboran Domain), and more particularly the Ghomarides-Malaguides and Sebtides-Alpujarrides. In the Dorsale units, very low-grade, post-Eocene metamorphism occurs only along the internal border of the range and along the Jebha Fault. In the two former complexes, as well as in their Kabylian equivalents, one can clearly separate, (i) Variscan metamorphism, which is the main recrystallization episode in the Ghomarides-Malaguides and the Kabylian upper units (i.e. the "upper plate" of the broad metamorphic structure), and (ii) Alpine metamorphism, which hardly affects the bottom of the upper plate, but deeply concerns the lower (Kabylian lower units, Sebtides-Alpujarrides, and Nevado-Filabrides in Central-Eastern Betics). As a whole, these upper and lower plate units define a dismembred metamorphic core complex, which records a tectonic evolution involving, initially, the subduction of the lower plate, and subsequently its exhumation (Sect. 5.7).

Metamorphic recrystallization also affects part of the External Zones in the Central and Eastern Rif, and their Tellian equivalents. Although the metamorphic grade is moderate or low in these units, it is a useful tool to delineate the intracontinental suture zone, which is also marked by the Beni Malek massif of serpentinites and greenschists.

5.5.1 Ghomaride Metamorphism

References: A limited number of works address the metamorphism of the Ghomaride, e.g. Chalouan & Michard (1990), Michard et al. (2006), Negro et al.

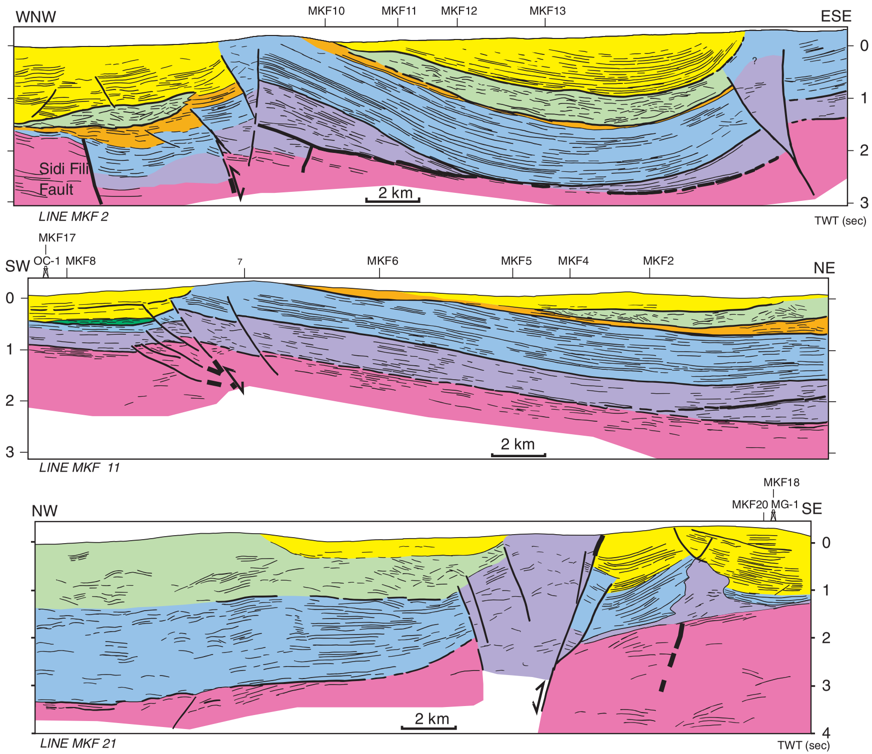


Fig. 5.33 Interpreted seismic profiles across the Rides prérifaines, after Sani et al. (2007), modified. See Fig. 5.31 for location; (**A**): Profile MKF2; (**B**): Profile MKF11; (**C**): Profile MKF21. The colours indicate the different units as follows. *Light red*: undefined Paleozoic; *violet*: Triassic units, evaporites; *light blue*: Jurassic units (Lower-Middle Liassic, Aalenian-Bajocian); *light brown*: Lower-Middle Miocene foredeep units (molasses) below the Prerif nappe; *light green*: Prerif nappe complex; *yellow*: Upper Miocene-Pliocene foredeep deposits. Note the crossed orientation of profiles (**A** and **B**), which corresponds to the curved trend of the outcropping anticlinal ridges (Fig. 5.31). Profile (**C**) illustrates a Triassic diapir first emplaced during the Cretaceous and then pinched and reactivated during the Plio-Quaternary shortening event (cf. Roca et al., 2006)

(2006). A very low grade recrystallization of the overlying Dorsale units was described locally by Olivier et al. (1992). In the Betics, the Malaguide metamorphism has been discussed by Platt et al. (2003b) and Negro et al. (2006). A review of the Kabylian upper plate metamorphism is given in Michard et al. (2006).

The Ghomaride Mesozoic-Cenozoic series are virtually devoid of metamorphic recrystallization. Contrastingly, two superimposed metamorphic histories can be distinguished in the Paleozoic terranes, Variscan and Alpine, respectively, although the latter concerns only the lower part of the lowest nappe (Aakaili).

The Variscan evolution itself is divided into two episodes (Sect. 5.2.2.1). The first affects the Lower and Middle Paleozoic series, but not the Carboniferous. This Eo-variscan episode is characterized by low grade greenschist-facies recrystallizations coeval with the formation of superimposed, NE-trending folds (P1 and P2 folds in Fig. 5.16). The second, Hercynian-Alleghanian episode affects the whole Paleozoic pile, being mainly identified in the Carboniferous formations by very low grade recrystallizations and NW-trending folds. The overlying, unfolded Triassic deposits show only a diagenetic evolution.

However, K-Ar datings of Paleozoic samples from the Ghomaride nappes fail to yield any exact Variscan date. In contrast, they reveal a progressive variation of the measured ages from 259 ± 5 Ma in the uppermost nappe to 25 Ma at the bottom of the lowest, just in contact with the Sebtides schists (Fig. 5.34). This suggests that a heating event affected the base of the Ghomaride pile, contemporaneously with the underlying Sebtides, i.e. at about 23 Ma (Sect. 5.5.2). This thermal event has been calibrated recently by Raman spectroscopy of carbonaceous material: T reached ~500 °C at the bottom of the Aakaili nappe whereas it remained below ~300 °C in the upper part of the nappe and overlying units (Fig. 5.34). Similar observations were made in the Malaguides. This Oligocene-Miocene thermal event caused biotite and andalusite growth at the very bottom of the Ghomaride-Malaguide complex, and can be ascribed to the major extension phase responsible for the opening of the Alboran Basin (Sect. 5.7).

5.5.2 Sebtide Metamorphism

References: Many recent publications concern the Sebtide-Alpujarride metamorphism. To concentrate on the Sebtide metamorphism, we must refer to the following papers, which include many Betic references: (i) for the Lower Sebtides (Beni Bousera and Filali), Saddiqi et al. (1988), Kornprobst et al. (1990), Saddiqi (1995), Kumar et al. (1996), Bouybaouene et al. (1998), Azañón et al. (1998), El Maz et Guiraud (2001), Haissen et al. (2004), Negro et al. (2006); (ii) for the Upper Sebtides (mainly Beni Mezala), Bouybaouene (1993), Zaghloul (1994), Goffé et al. (1996), Michard et al. (1997), Vidal et al. (1999), Agard et al. (1999), Negro (2005), Janots et al. (2006), Michard et al. (2006), Negro et al. (2006).

The age of the Sebtide-Alpujarride metamorphism has been repeatedly investigated. Let us particularly refer to Monié et al., 1991, 1994), Sosson et al. (1998),

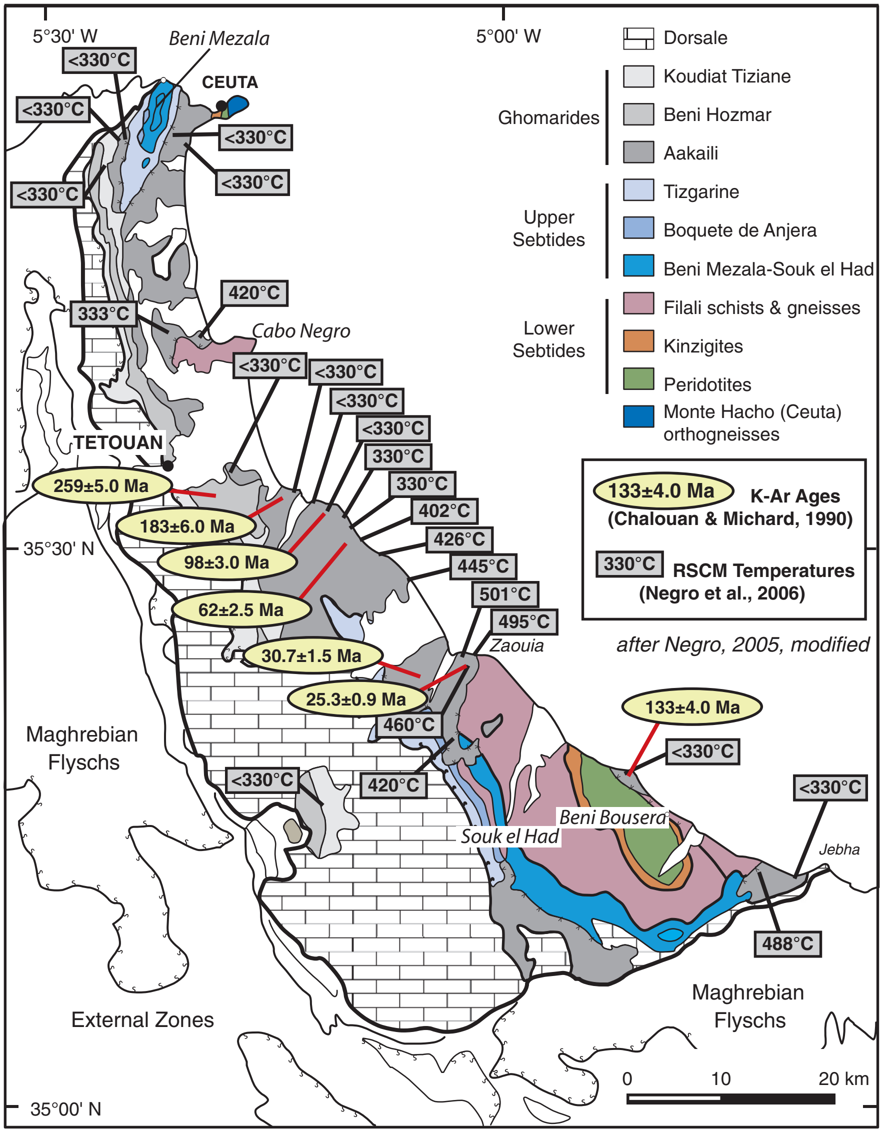


Fig. 5.34 The Alpine thermal event in the Ghomaride nappes: progressive variation of the K-Ar white mica ages (after Chalouan & Michard, 1990) and maximum T recorded in the Paleozoic rocks (RSCM method; Negro et al., 2006)

Argles et al. (1999), Platt & Whitehouse (1999), Blichert-Toft et al. (1999), Sánchez-Gómez et al. (1999), Zeck et Whitehouse (1999), Montel et al. (2000), Sánchez-Rodriguez & Gebauer (2000), Esteban et al. (2004), Platt et al. (2003b, 2005), Janots et al. (2006), Platt et al. (2006). A review of the Kabylian dates can be found in Michard et al. (2006).

In the Sebtides, Alpujarrides and equivalent Kabylian units, the most conspicuous metamorphic record results from the Alpine evolution, and the previous evolution of the corresponding crustal and mantle rocks is seldom recorded, because of the high grade of the Alpine metamorphism.

5.5.2.1 Alpine Recrystallizations in Northern Upper Sebtides

The Federico units of the Beni Mezala post-nappe antiform (Figs. 5.9, 5.14, 5.35A) offer the best opportunity to calibrate the Alpine metamorphism as most of its rock material is Permian and Triassic, and consists mostly of metapelites (Sect. 5.2.1.2). In the uppermost unit (Tizgarine), the cookeite-pyrophyllite-low Si phengite assemblages correspond to low pressure, low temperature conditions (Fig. 5.35C). In the underlying, Boquete Anjera unit, sudoite, Mg-chlorite and phengite occur in the quartz veins whereas chloritoid is abundant in the matrix; the corresponding metamorphic conditions can be estimated at ~7 kbar, 300–380 °C, i.e. intermediate pressure and temperature. Deeper in the antiform, the upper Beni Mezala unit (BM2) displays Mg-carpholite relics within chloritoid or kyanite-bearing intrafolial quartz veins. This corresponds to blueschist facies (HP-LT) conditions, between 8 kbar, 380 °C and 13 kbar, 450 °C. Eventually, in the lower Beni Mezala unit (BM1), Mg-carpholite relics associated with talc-phengite assemblages within quartz-kyanite segregations indicate that eclogite facies conditions have been reached, between 13–15 kbar, 450 °C, and 15–18 kbar, 550 °C. The underlying Benzu schists compare with the Filali recrystallized Paleozoic basement, and show garnet-chloritoid-phengite-quartz assemblages equilibrated at $P > 14$ kbar, $T \sim 550$ °C.

The earliest retrograde path is constrained in BM1 by tremolite-talc and phlogopite-chlorite associations, and appears virtually isothermal (Fig. 5.35C). Subsequently, further exhumation occurs at decreasing T, being accompanied by paragonite, muscovite, chlorite, kaolinite, cookeite and margarite growth. Microstructural observations indicate that these crystallizations were contemporaneous with a ductile, top-to-the-north extensional shearing (Fig. 5.35A).

The reported data indicate that the Sebtide units were buried by subduction (HP-LT conditions) down to 60 km at least for some of them (eclogite facies), then tectonically exhumed, forming a pile of tectonic units separated by subtractive contacts (P and T gaps). The corresponding geodynamic setting is discussed hereafter (Sect. 5.7).

5.5.2.2 Alpine Recrystallizations in the Southern Upper Sebtides and Lower Sebtides

The Federico units on top of the Beni Bousera antiform (Fig. 5.9) show Alpine mineral assemblages similar to those of their northern equivalents (Beni Mezala), except for the lowest, Souk-el-Had unit. The latter unit contains phengite-chlorite-phlogopite-kyanite assemblages, and late growth of andalusite and cordierite, which

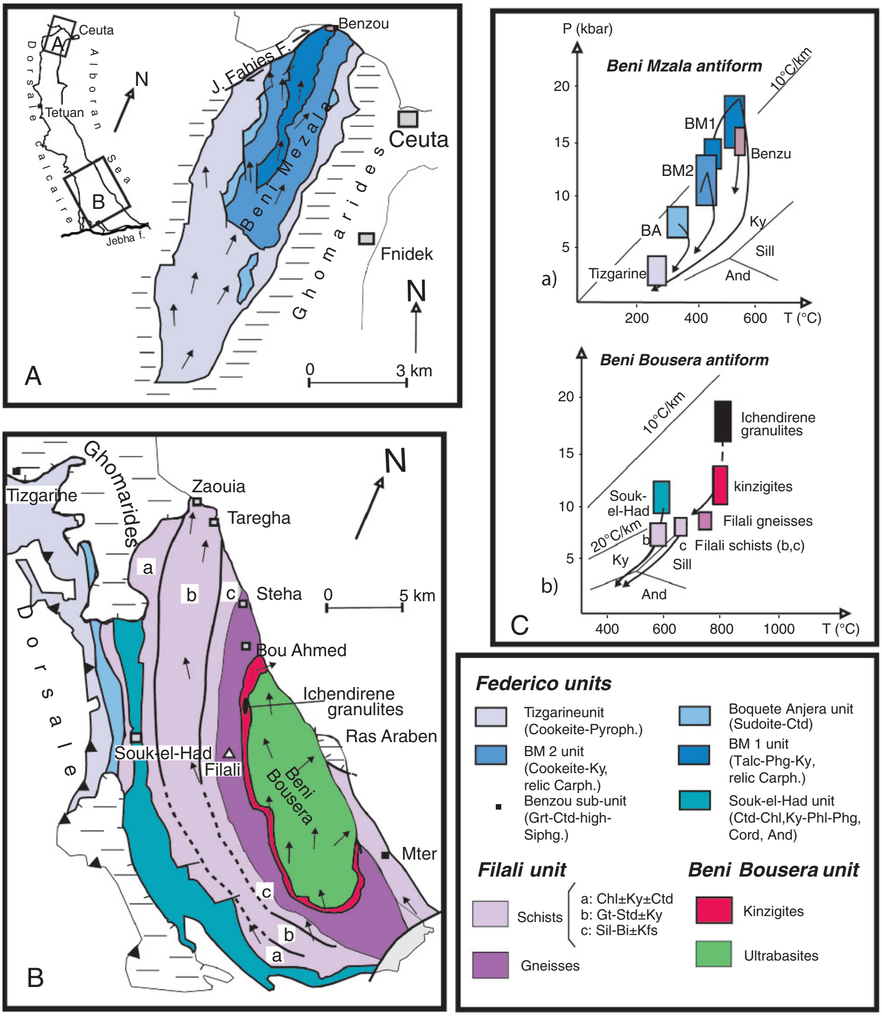


Fig. 5.35 Metamorphic structure and P-T conditions of the Sebtide units, after Bouybaouene (1993), Saddiqi (1995), Michard et al. (1997, 2006), and Negro et al. (2006). (**A**): Beni Mezala antiform. – (**B**): Beni Bousera antiform; a–c: Filali schist metamorphic zones. – (**C**): Corresponding P-T estimates. *Arrows*: sense of shear inferred in late metamorphic structures

suggests an evolution at 12 kbar, 550–600 °C (Figs. 5.35B, C), i.e. under a higher geotherm than the northern unit.

As for the underlying Filali mica-schists (Fig. 5.35B), their upper part displays chlorite-chloritoid-muscovite ± biotite ± kyanite assemblages (zone "a"), changing downward into garnet-biotite-staurolite-kyanite (zone "b"), and finally, garnet-biotite-sillimanite assemblages (zone "c"). Andalusite is almost ubiquitous, and shows syn- to post-kinematic character (Fig 5.36A). The coexistence of the three

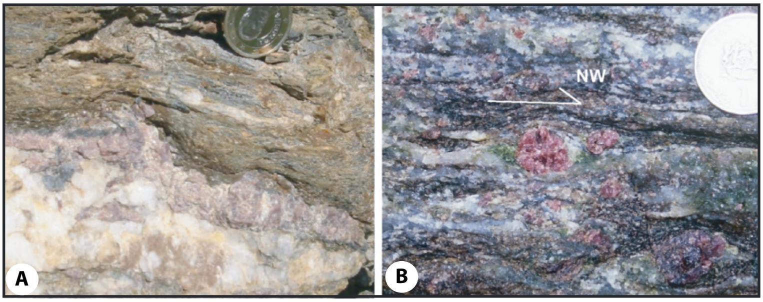


Fig. 5.36 High grade rocks from the Lower Sebtides (see Fig. 5.35 for location). (**A**): Quartz segregation with pink andalusite crystals, zone (b) of the Filali schist unit south of Taregha. – (**B**): Kinzigites from the Beni Bousera unit top slivers east of Bou Ahmed, with large garnet crystals whose asymmetric quartz-phengite-green spinel pressure shadows indicate top-to-the-NW, non-coaxial shear strain. The mylonitic matrix shows quartz-retromorphic kyanite-sillimanite ribbons and biotite-graphite foliae. Coin diameter: 15 mm. Photos by O. Saddiqi

Al-silicate polymorphs prooves the complexity of the metamorphic history, where kyanite growth seems to have preceded that of the high-temperature polymorphs. The assumed metamorphic conditions range from 7 kbar, 580 °C in zone "b" to 8 kbar, 680 °C in zone "c", and finally reach 8 kbar, 780 °C in the gneisses.

A dramatic pressure gap (which implies a tectonic omission) occurs between the Filali and Beni Bousera units. The kinzigite (or granulite) garnet-sillimanite ± kyanite-graphite assemblages characterize P-T conditions at 9–13 kbar, 800–850 °C (Figs. 5.35C, 5.36B). However, the Ichendirene metabasite lense contains a primary assemblage pyrope-jadeite rich pyroxene-kyanite-rutile-plagioclase-quartz, which corresponds to peak metamorphic conditions at 16–20 kbar, 760–820 °C (Fig. 5.35C). The peak conditions in the underlying spinel-garnet harzburgites are similar, 18–20 kbar, 850–900 °C. In contrast, within the peridotite massif itself, still higher P-T conditions are recorded by the garnet-corindon-bearing pyroxenites, $P > 20$ kbar, 1200–1350 °C.

Thus, the P-T conditions recorded in the Lower Sebtides typifie a higher geotherm than those from the Upper Sebtides. The reason for this contrast probably arises from the different location of these complexes within the subduction zone (Sect. 5.7), together with the different nature of the dominant rock material (Permian-Mesozoic sediments *versus* crustal basement and mantle rocks).

5.5.2.3 Dating the Sebtide-Alpujarride Metamorphism

The occurrence of Sebtide-Alpujarride pebbles and minerals reworked in the earliest Burdigalian detrital formations from Andalucia, and in the early-middle Burdigalian formations from the Rif (Sect. 5.2.2.3) testifies that part of the Sebtide-Alpujarride were already exhumed up to the surface at that time (ca. 20–18 Ma). Previously, during sedimentation of the earliest post-nappe formations (Fnideq, Alozaina) upon the Ghomarides-Malaguides during the latest Oligocene-Aquitanian (23–20 Ma), the

Sebtides-Alpujarrides (which belong to the lower plate) were totally hidden beneath the Ghomaride-Malaguide upper plate. In other words, the metamorphic units have been exhumed during the late Oligocene-Burdigalian interval (23–18 Ma), which corresponds to the beginning of the Alboran Sea opening (Sect. 5.7).

Recent isotopic datings are consistent with these stratigraphic constraints; they also help to precise the age of the thermal peak, but fail to attain with certainty that of the pressure peak itself. In the southern Sebtides (Fig. 5.37), most of the results concentrate in the range 30–25 Ma to 18 Ma, and more particularly between 23 and 20 Ma, whatever the isotopic method. The only exceptions are a 66 Ma Lu-Hf age, probably devoid of geologic meaning, and the ages close to 300 Ma which correspond to Variscan relic minerals. This is a good indication that the thermal peak (T > 600 °C, admittedly the closure temperature for U-Pb zircon method) occurred at about 25–23 Ma. Subsequently, a rapid exhumation down to T < 300 °C took place at ~20 Ma (K-Ar biotite dates).

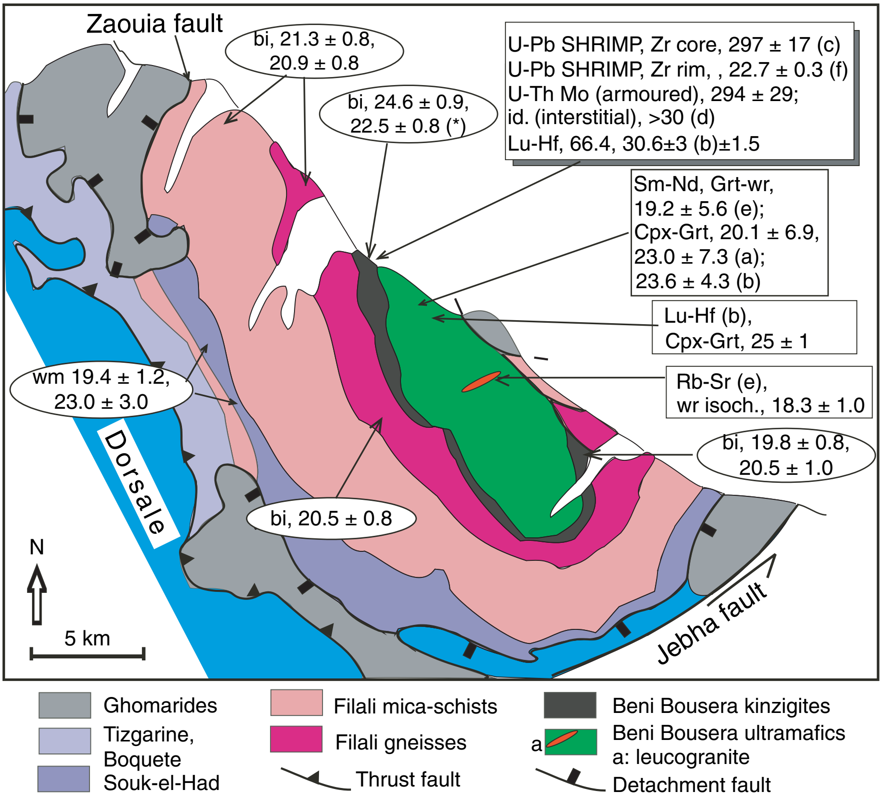


Fig. 5.37 Isotopic datings of the Sebtide units from the Beni Bousera antiform. The ellipses show the K-Ar and ^{39}Ar-^{40}Ar (*) results obtained on biotite (bi) and white micas (wm) by R. Montigny, analyst, in Michard et al. (1991). Other dates (framed in rectangles): (a) Kumar et al. (1996); (b) Blichert-Toft et al. (1999); (c): Sánchez-Rodriguez & Gebauer (2000); (d): Montel et al. (2000); (e) : Polvé (1983); (f): Platt et al. (2003a). Mo (arm)/(interst): armoured/interstitial monazite

Dates from the Alpujarrides are fairly consistent with the Sebtides ones. They show a striking concentration between 22 and 19 Ma, besides of some Variscan ages, already quoted above (Sect. 5.2.1.1). Partial melting occurred in the Ojen gneisses beneath the Ronda peridotites at about 18–20 Ma according to the age of cordierite-bearing leucogranite dykes in the peridotites.

The age of the peak of pressure was precised via ^{39}Ar-^{40}Ar dating of the phengites from the low grade units (i.e. where the measured age equal the crystallization age). A minimum age of ca. 25 Ma was obtained in Central Alpujarrides, and two minimum ages in the Beni Mezala, ca. 23 and 27 Ma. A much higher figure, 48 Ma, was ultimately obtained from Eastern Alpujarrides, together with younger dates up to 20 Ma. According to Platt et al. (2005), the Alpujarride burial would have begun during the Early Eocene. However, the 48 Ma date possibly corresponds to excess argon, as it seems likely that the pressure peak should be close to the thermal peak, i.e. at ca. 30–25 Ma (Michard et al., 2006). We recall that the Malaguides thrust are dated stratigraphically at about 28 Ma ± 1 Ma (Sect. 5.2.2.3).

5.5.3 External Zone Metamorphism

References: Metamorphism is very limited in the External Zones, and the number of related publications alike: Monié et al. (1984), Frizon de Lamotte (1985), Leikine et al. (1991), Favre (1992), Michard et al. (1992), Azdimousa et al. (1998), Negro et al. (2007), Michard et al. (2007). The equivalent zones in the Algerian Tell are described by Guardia (1975), and Kirèche (1993).

In the External Rif, metamorphism affects only parts of the central and eastern regions, namely the Ketama unit (Intrarif), the Tifelouest group of units (internal Mesorif), and the North Temsamane units on the east side of the Nekor Fault (Figs. 5.7, 5.30A). Additionally, two isolated massifs, i.e. the Tres Forcas and Khebaba massifs are related to the North Temsamane metamorphic zone.

5.5.3.1 West of the Nekor Fault

The Ketama rock materials are recrystallized under low grade greenschist facies conditions, with temperature seemingly lower in the north (~200–250 °C) than in the south (~300 °C) under pressure close to ~3 kbar. Recrystallization was coeval with S- or SE-vergent recumbent or overturned folds (Fig. 5.38A), refolded by upright folds. Tentative K-Ar datings did not yield reliable results due to the low metamorphic grade and abundance of clastic muscovite grains. In contrast, apatite fission track analysis indicates that the post-metamorphic cooling down to ca. 100 °C occurred at about 14–15 Ma.

A closely similar tectonic-metamorphic evolution can be observed, and dated stratigraphically in the Tifelouest units where syntectonic recrystallization affects the series up to the Late Oligocene blocky marls inclusively (cf. Sect. 5.4.2.1).

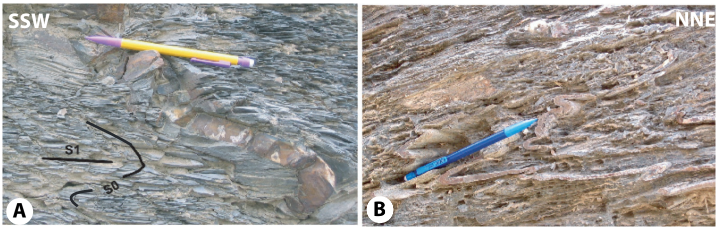


Fig. 5.38 Synmetamorphic structures from the External Rif. (**A**): Slaty cleavage S_1 and minor folds in the inverted limb of a major fold; Aptian-Albian upper part of the Ketama unit, 33 km north of Taounate (see Fig. 5.7 for location). – (**B**): Sub-horizontal foliation and associated recumbent minor folds in the eastern part of the Ras Afraou unit (north of Kebdani; see Fig. 5.30 for location). The rock material includes metapelites, quartzites and rare carbonate layers, probably Paleozoic in age

The metasedimentary duplexes are unconformably overlain by unmetamorphosed mélange with foliated Mesozoic elements, followed upward by the Lower-Middle Miocene turbidites. Therefore, the metamorphism of the Tifelouest and (probably) Ketama units probably occurred during the Late Oligocene (~28–23 Ma). Then, the tectonic prism thickened and migrated southward onto the Mesorif. As a result, upright folds with axial-plane cleavage developed in the Mesorif units (crenulation cleavage in the foliated Tifelouest material, and spaced pressure solution cleavage in the Lower-Middle Miocene deposits). This very low grade metamorphic event took place during the Serravallian-early Tortonian interval, before the transgression of the late Tortonian-Messinian post-nappe sediments, and probably resulted of the collision of the Alboran block against Africa (Sect. 5.7). In contrast, the earlier, Late Oligocene metamorphism depends on another tectonic event, which affected dominantly the regions east of the Nekor Fault.

5.5.3.2 East of the Nekor Fault

The South Temsamane units only display an anchimetamorphic evolution as in the Central Rif windows. In contrast, the North Temsamane units exhibit greenschist facies recrystallizations the grade of which increases upward in the tectonic pile, indicating a post-metamorphic stacking event. Usual mineral assemblages are chlorite-phengite-quartz-albite in metapelites, and tremolite-epidote-albite-chlorite-sphene in metabasites (Unit VI). Chloritoid appears in the highest, Ras Afraou unit (Unit VII), in association with Si-rich phengite. There, peak P-T conditions are estimated at 7–8 kbar, $350 \pm 30\,^{\circ}$C, which corresponds to medium pressure, low temperature (MP-LT) metamorphism. The coeval, ductile structures include S-vergent overturned folds and gently dipping foliation (Fig. 5.38B) associated with strong SW- to SSW-trending stretching lineation and top-to-the-WSW shear indicators.

The Tres-Forcas massif (Taryat anticline) crops out beneath the late Tortonian-Messinian deposits (Fig. 5.39B, C). The massif is cored by likely Paleozoic

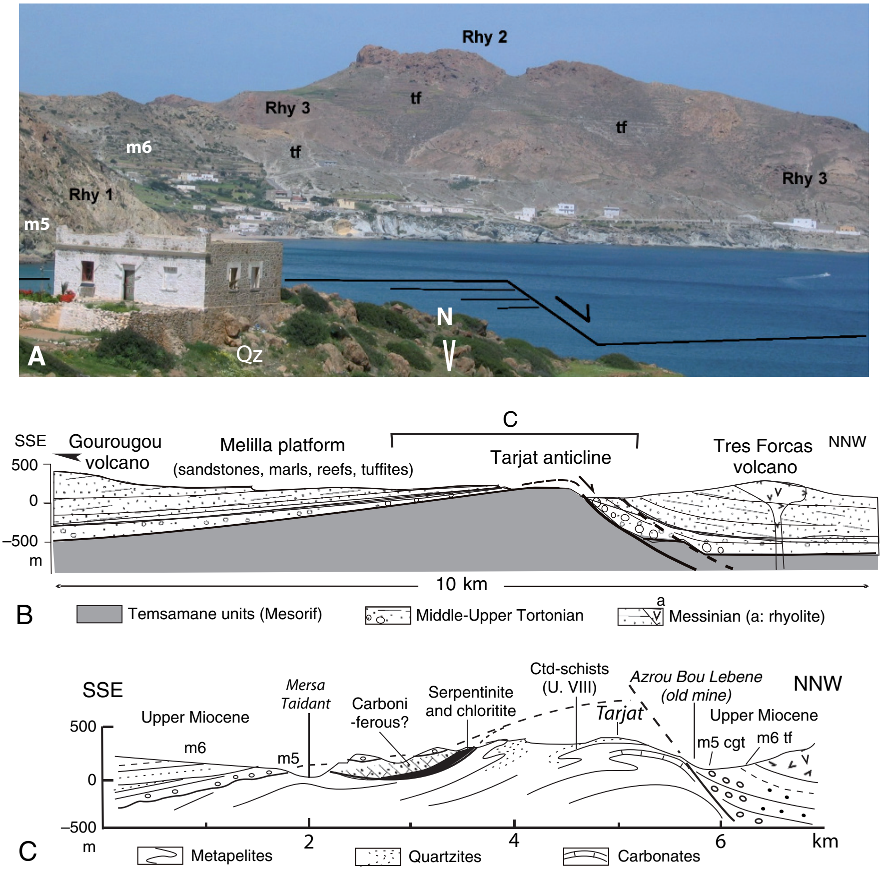


Fig. 5.39 The Cape Tres-Forcas volcano and its tectonic setting (see Fig. 5.30 for location). (**A**): The volcanic massif viewed from the ancient Azrou n'Bou Lebene mine. Qz: cataclastic quartzite layer from the top of the metamorphic "Temsamane VIII" unit; m5: Middle-upper Tortonian; m6: Messinian; tf: volcanic tufs and breccias, lahars; Rhy: rhyolites (2: with amphibole-biotite; 3: with pyroxene). – (**B**): Cross-section from the Tres-Forcas volcanic-sedimentary complex (Upper Tortonian-Messinian; age of rhyolites: 9.8–4.6 Ma) to the Melilla platform where the youngest lava flows (6.4–5.7 Ma), originated from the Gourougou strato-volcano, are interbedded. Structural data after the geologic map of Morocco, sheet Melilla (1983), and personal observations. K/Ar and stratigraphic dates after Hernandez et al. (1987), Cornée et al. (1996), and Münch et al. (2001). – (**C**): Cross-section of the Taryat anticline (Temsamane Unit VIII), after Michard et al. (2007)

quartz-phyllites, quartzites and marble recrystallized under P-T conditions hardly higher than those of the Ras Afraou unit (~8 kbar, 400 ± 30 °C). This "Unit VIII" of the Temsamane system is overlain by slivers of serpentinites, chloritites and jaspes, homologous of the Beni Malek unit, and finally topped by pelites and sandstones of probable Carboniferous age.

The Khebaba-Zaouyet Sidi Hadj Ali unit consists of dismembered terranes including Paleozoic rocks (Devonian metapelites, Early Carboniferous flysch) and their former cover series (Permian-Triassic red beds, dolomites, marbles, and gypsum). These rocks are recrystallized under MP-LT conditions similar to those of the Tres-Forcas metamorphic unit. The structural position of the Khebaba massif compares with that of the Senhadja klippes as the massif is topped by the Aknoul nappe and lies over the south Mesorif.

Preliminary ^{40}Ar-^{39}Ar phengite datings (Monié et al., 1984) yielded an age of 28.6 ± 1 Ma for the peak metamorphism of Unit V, with a low grade stage at 8 Ma. Negro (2005) obtained three groups of ^{40}Ar-^{39}Ar results from the Ras Afraou and Tres Forcas phyllites. A group of minimum ages at 23–20 Ma characterizes the high-Si phengite grains preserved in the intrafolial quartz segregates; it is referred to the peak pressure metamorphism, whose age would be close to 28–23 Ma. A second group of results at 15–10 Ma characterizes the phengite lamellae from the foliation; it is referred to the ductile deformation associated to the southwestward exhumation of the metamorphic units (Negro et al., 2007). Eventually, the dates of 10–6 Ma obtained from the illite-kaolinite-bearing retromorphic samples may represent late brittle-ductile deformation.

5.5.3.3 Interpretation: The External Maghrebide Suture Zone

As the metamorphic grade and reddish colour of some of the Ras Afraou and Khebaba metapelite outcrops evoke those of the Upper Sebtide Permian-Triassic levels in the Boquete Anjera unit, certain authors assumed that the Ras Afraou, Tres-Forcas and Khebaba units originated possibly from the Sebtide domain, having been thrust above the Dorsale and Flyschs domains (e.g. Suter, 1980a, 1980b; Negro et al., 2007). However, new examination of these units led Michard et al. (2007) to favour an external origin, as admitted by Faure-Muret & Choubert (1971a, 1971b) and Frizon de Lamotte (1985). This is strongly suggested by the continuous metamorphic gradient observed from the South Temsamane to North Temsamane units (Fig. 5.30). Moreover, the lack of Dorsale or Flysch slivers at the bottom of the Ras Afraou unit, and the fact that the Khebaba unit is overlain by the Aknoul nappe obviously contradict an origin from the Internal Zones.

Therefore, the hypothesis arises that the External Rif MP-LT metamorphism is related to a N-dipping subduction zone extending between the Intrarif and Mesorif zones of the African paleomargin (Michard et al., 2007). This is supported by the occurrence of serpentinite remnants in the Beni Malek and Tres-Forcas massifs. West of the Nekor Fault, which is a lateral ramp for the Ketama SE-verging thrust, the "Mesorif suture zone" is probably hidden beneath the Intrarif. However, a volcanogenic level with gabbro and diabase clasts occurs at the bottom of the Ketama series (Zaghloul et al., 2003), suggesting a western continuation of the former thinned crust zone. This hypothetic intra-margin (intracontinental) suture continues eastward at least up to the Oran coastal massifs where serpentinites and chloritoid-bearing metapelites occur beneath the most internal Tell units (Guardia, 1975; Fenet, 1975). Accordingly, the Mesorif suture zone can also be referred to as the "External Maghrebide Suture Zone" (Michard et al., 2007).

5.6 Syn- to Post-Orogenic Magmatism

References: The Cenozoic magmatism of the Gibraltar Arc and Maghrebide belt has been repeatedly considered in the last decades : Hernandez et al. (1987), Turner et al. (1999), Zeck et al. (1999), El Bakkali et al. (1998), El Azzouzi et al. (1999), Maury et al. (2000), Münch et al. (2001), Coulon et al. (2002), Savelli (2002), Duggen et al. (2004), Gill et al. (2004), and Pecerillo & Martinotti (2006). The earliest magmatic intrusions were described by Hernandez et al. (1976), Torres-Roldan et al. (1986), and Cuevas et al. (2006). Thermal spring geochemistry has been recently addressed by Tassi et al. (2006).

In the eastern part of the Gibraltar Arc and the Algerian-Tunisian Maghrebides, magmatism essentially developed during the Miocene. However, the magmatic climax was preceded by discrete magmatic events as early as the Paleocene, and followed by a very recent volcanic activity, which extends widely outside of the Maghrebide belt, in the Atlas and Anti-Atlas domains (see Chap. 4).

5.6.1 Early Magmatic Events

Eocene alkaline magmatism took place here and there in the African margin (e.g. Tamazert; Chap. 4). In the eastern Prerif, basanites emplaced at Sidi Maatoug, northeast of Taza (Fig. 5.7). These lava flows are dated by the occurrence of pyroxene crystals reworked from associated ashes in the neighbouring lower-middle Paleocene sediments. Moreover, they yielded a 57 ± 7 Ma Rb-Sr date, and basanite pebbles occur in the Oligocene formations close to the volcanic body (Hernandez et al., 1976). Such volcanism can be assigned to a local extensional/transtensional setting.

Another early magmatic event, probably more significant, concerns the emplacement of an andesitic dyke swarm in the western Malaguides. The dykes were first dated by K/Ar at ~23 Ma (Torres-Roldan et al., 1986). Recent datings by ^{40}Ar-^{39}Ar yielded both older and younger ages: 30 ± 0.9 Ma (Turner et al., 1999) and 33.6 ± 0.6 Ma (Duggen et al., 2004), and on the other hand several ages in the range 19.8–17.4 Ma. The older ages are consistent with the dyke emplacement in the Malaguide terrane prior to its thrust deformation (~28 Ma; see Sect. 5.2.2.3). The K/Ar system was likely disturbed by the heating event that affected the Malaguide nappe stack at about 25–23 Ma. The dominant N15E trend of the less deformed dykes suggests a dominant E-W extension of the Malaguide-Ghomaride terrane during the Early Oligocene. Moreover, the major and trace elements data and Sr-Nd isotopes data favour derivation of the Malaga dykes through the subduction process (Duggen et al., 2004).

As for the leucogranitic dykes, which intrude the Ronda and Beni Bousera peridotites and their country rocks, they are younger, 20–19 Ma (Sect. 5.5.2.2), and generally less deformed. They are assigned to partial melting of the crustal unit beneath the peridotite slab (Ojen, Monte Hacho) during the thermal peak, at about 21 Ma (see above). This early and limited magmatism is coeval with the initial opening of the most active Alboran Basin.

5.6.2 The "Orogenic", Post-Collisional Magmatism

The so-called "orogenic magmatism" of the Rif Belt is part of a large belt, which stretches from Tunisia to eastern Morocco, then forms a number of volcanic centers in the Alboran Sea (in particular the Alboran Island itself), and finally extends to eastern Betic Cordilleras ("Trans-Alboran magmatism"; Fig. 5.40). This widespread magmatism is labelled "orogenic" as it generally displays petrologic and geochemical signatures typical for supra-subduction zone (SSZ) calc-alkaline magmas. However, it differs from a genuine SSZ orogenic magmatism by its moderate

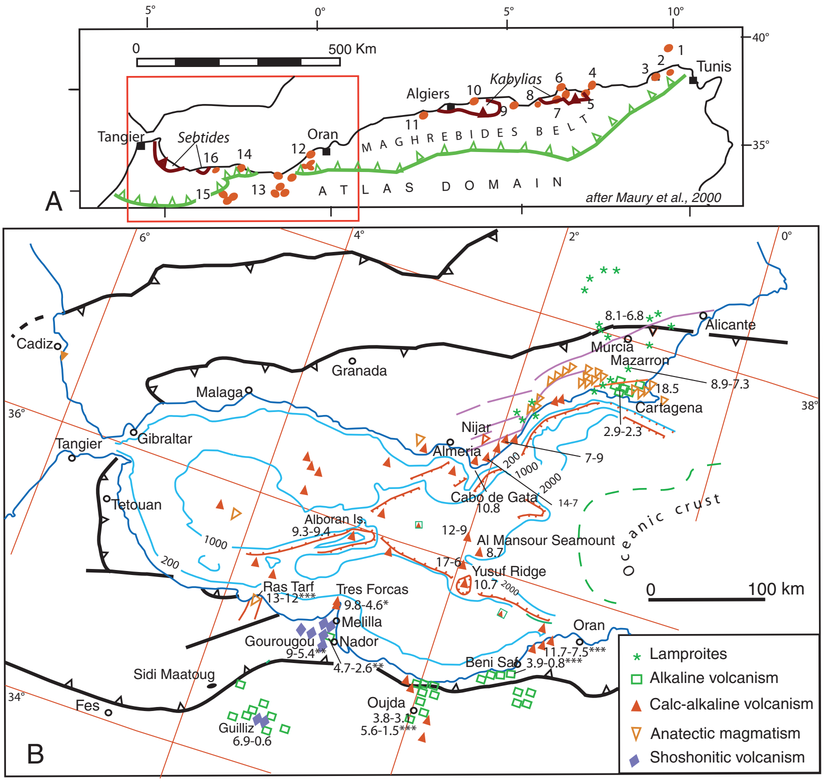


Fig. 5.40 Distribution of the late- to post-orogenic magmatism in the Maghrebides and Gibraltar Arc. (**A**): Maghrebian magmatic belt, after Maury et al. (2000), modified. G: granodiorite (with gabbro at Cap de Fer) and associated volcanics; Vo/m/po: orogenic/mixed/post-orogenic volcanos. 1 La Galite (G); 2 Mogods (Vpo); 3 Nefza (m); 4 Cap de Fer-Edough (G); 5 Filfila (G); 6 Cap Bougaroun (G); 7 Beni Touffout (G); 8 El Aouana (Vo); 9 Béjaïa-Amizour (G); 10 Algérois (G); 11 Cherchell (G); 12 Oranie (Vo, Vm, Vpo); 13 Oujda (Vpo); 14 Gourougou-Trois Fourches (Vo, Vm, Vpo); 15 Guilliz (Vm, Vpo); 16 Ras Tarf (Vo). – (**B**): Eastern Rif, Eastern Betics and Trans-Alboran domain, after Hernandez et al. (1987), El Azzouzi et al. (1999) and Duggen et al. (2004). Ages (Ma) reported mainly after Duggen et al. (2004, with reference therein), except (*), after Hernandez et al. (1987), (**), after Münch et al. (2001), and (***), after Maury et al. (2000)

volume, and because it occurs after the orogenic paroxysm. In fact, the Maghrebide and Trans-Alboran magmatism postdates the Internal Zones overthrusting on the External Zones, and straddles the limit between these zones. It begins as early as 15–16 Ma in Tunisia and eastern Algeria, then reaches western Algeria, eastern Morocco, Alboran and eastern Cordilleras around 13–10 Ma (Figs. 5.40, 5.41), being contemporaneous with the Serravallian-Tortonian sedimentation in the Alboran Basin (cf. Fig. 5.8). In other words, this "orogenic magmatism" is indeed coeval with the late orogenic extension of the Internal Zones. It is described by Lustrino

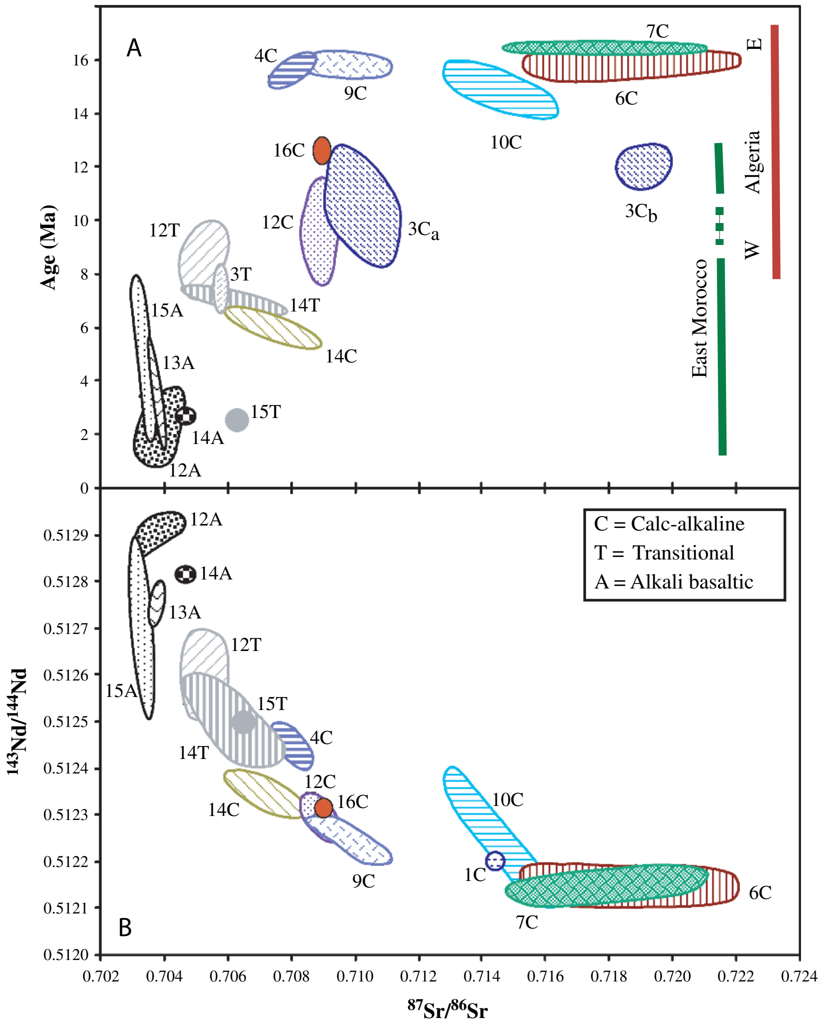


Fig. 5.41 Geochemical evolution of the Maghrebide Belt magmas through time, after Maury et al. (2000), modified. (**A**): Correlations between Sr isotopic ratios and age. – (**B**): Correlations between Sr and Nd isotopic ratios. Numbers refer to the areas shown in Fig. 5.40A. 3a/3b: cordierite-free/cordierite-bearing shoshonitic lavas (Nefza)

& Wilson (2007) as a part of the much larger circum-Mediterranean *anorogenic* Cenozoic igneous province.

The magmatic belt includes granodiorite massifs (e.g. Beni Bou Ifrour), but in most cases magmatism corresponds only to volcanic complexes of andesites, dacites, rhyodacites and rhyolites flows, dykes and sills. The lavas are generally K-enriched, up to shoshonitic compositions (Oran region, Gourougou south of Melilla). Their Sr-Nd-Pb-O isotope compositions suggest a lithospheric mantle origin with a strong crustal imprint (Fig. 5.41). The magmatic evolution ends at 10–7 Ma with the emplacement of transitional, calc-alkaline/alkaline basalts, andesitic basalts and trachy-andesites (Gourougou, Guilliz), and lamproites (Murcia).

As a whole, the detailed geochemical data now available give evidence of two distinct sources, i.e. (i) a main source in a subcontinental lithospheric mantle modified by the subduction of a lithospheric slab, and (ii) the overlying continental crust locally affected by partial melting (garnet-cordierite granites), which have contaminated the ascending calc-alkaline magmas. Many authors (e.g. Maury et al., 2000) hypothesize a direct link between this magmatic evolution and the African plate subduction, ending with the oceanic slab tear-off (Sect. 5.7). The upward flow of enriched asthenospheric mantle through the tear would have triggered melting of the lithospheric mantle already metasomatised during a previous subduction episode. Later, partial melting would have occurred at the uprising asthenosphere-lithosphere boundary, thus generating basalts having transitional character.

5.6.3 Recent Alkaline Magmatism of the Morocco Hot Line

An alkaline, intraplate-type volcanism took place at both the east and west tips of the Maghrebian magmatic belt in the most recent period, from 6 to 0.8 Ma. In contrast with the earlier magmas, the new ones also occur outside of the Maghrebide belt. The volcanic centers now occur along a NE-trending belt extending from the Trans-Alboran zone (Fig. 5.40B) to the Middle Atlas domain (Chap. 4) and to the Anti-Atlas (J. Siroua volcano). The magmatic rocks are alkaline basalts, basanites, hawaites, and nephelinite, lacking crustal contamination (Fig. 5.41). Their geochemical signature compares with that of the intra-oceanic island basalts, and suggests the role of an asthenospheric "hot line", labelled the *Morocco Hot Line* (MHL) in the Chap. 4 of the present volume. Such interpretation is consistent with the gravimetric and geodetic modelling of the lithosphere (cf. Chap. 1), and the lack of well defined age versus position trend. The MHL could extend from the Canary Islands to southeast Spain at least.

It is worth noting that CO_2-rich thermal springs with ^3He anomalies are likely related to this hot line. They are mainly distributed along a NE-SW trend from Nador to Taza, and from Fes (Moulay Yacoub) to Oulmes south of the Rif frontal thrust. The contemporary presence of ^3He anomalies and minor recent basalt outcrops indicate that CO_2 originates from mantle degassing or deep hydrothermal systems in these thermal discharges (Tassi et al., 2006).

5.7 Mountain Building

The future Rif-Betic or Gibraltar Arc orogenic domain was created by the breaking down of Pangea and opening of the Central Atlantic and western Tethys Oceans (Figs. 1.5, 1.9). The oceanic corridor between Iberia and Africa was always narrow (200–300 km). However, oceanic lithosphere occurred everywhere north of the Maghreb margin and west of the Adria plate (the "African promontory"; Fig. 1.9A), being most probably connected with the Alpine oceanic lithosphere. At about 75 Ma, the latter ocean began to close by subduction of the European plate beneath the Adria margin. Further to the southwest the scenario in the Ligurian-Maghrebide Ocean is still a matter of debate.

In this section, we discuss those geodynamic processes, which resulted in the building of the Rif mountains. This cannot be done without taking into account the entire Gibraltar Arc. After an abridged synopsis of the successive events in due chronological order (Sect. 5.7.1), and the presentation of the kinematic data and paleomagnetic rotations (Sect. 5.7.2), we first present the most recent orogenic period, which is also the best understood, i.e. the Oligocene-Neogene interval (Sect. 5.7.3). Based on this reconstruction, which is currently accepted, we then discuss the earlier and much debatable stages of the Rif-Betic orogeny (Sect. 5.7.4). The last Sect. 5.8 presents the present-day stress field in the region, which has important environmental consequences and completes the orogenic evolution up to contemporary times.

5.7.1 Abridged Orogenic Chronology and First Interpretations

References: The recent stratigraphic and radiochronologic references are indicated in the preceding Sects. (5.3–5.6), and some of them recorded in the legend of Fig. 5.42. Synthetic tables are proposed by Duggen et al. (2004), and Jolivet et al. (2006) concerning the metamorphic, magmatic and tectonic events.

Mountain building of the Betic Cordilleras and Maghrebides is basically the final product of the Africa-Eurasia plate convergence since ca. 70 Ma ago (see Chap. 1, Fig. 1.10). Africa-Europe convergence in the west, along the Gibraltar transect, is lesser than in the east, along the Sicilian transect, by approximately a factor 2. In the Gibraltar transect, the orogenic domain suffered in total 250 km of N-S shortening from Late Cretaceous to Tortonian, and 50 km of further NW shortening until present day. Convergence is directed WNW since ~3 Ma (Fig. 1.10).

Before discussing the geodynamic processes that formed the belt, it is convenient to summarize the chronology of the orogenic events (Fig. 5.42), as recorded by the stratigraphic, metamorphic and magmatic data reported above (sect. 5.2 to 5.6). At each step, the suggested geodynamic interpretation will be shortly noted hereafter in *italics*.

The earliest sedimentary events recording significant tectonic movements are observed during the ***Late Cretaceous*** in the Alboran (AlKaPeCa) Internal Domain. In the Dorsale units, Senonian hemipelagic deposits (Couches rouges) overlie, through an unconformity, the Tithonian-Berriasian limestones. Chaotic breccias interbedded within the "scaglia"-type deposits (Hafa Ferkenich in the Rif Internal Dorsale, Djurdjura in Algeria; Raoult, 1974) suggest an *increasing tectonic activity*.

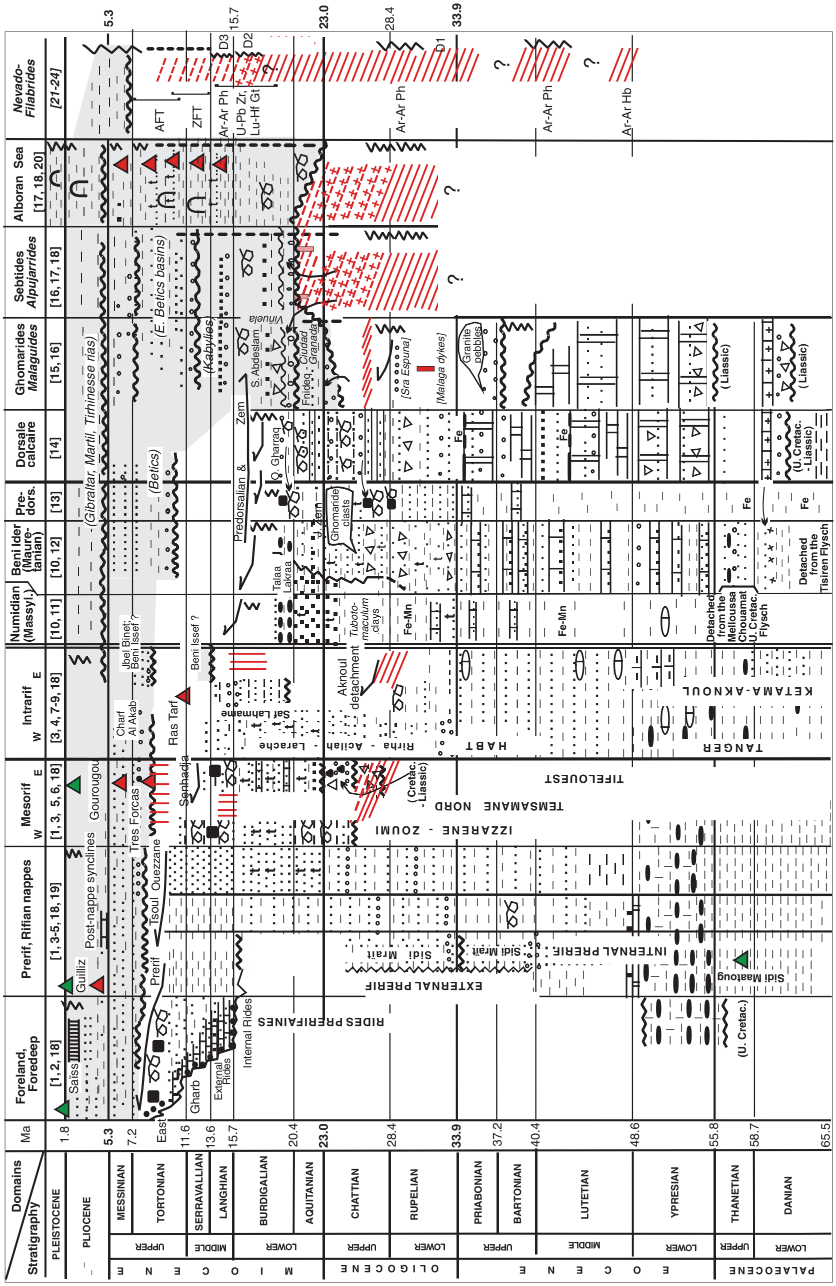
By the end of this period, during the ***Paleocene-Eocene***, the Ghomaride-Malaguide-Kabylides continental domain and its proximal margin (Internal Dorsale) first emerged, before being converted into a shallow marine platform fringing emerged lands. *The interpretation of this major event is not straightforward, but it can record the overriding of a subduction zone if the uplifted block belonged to the active margin*. At the northern (northwestern) boundary of the Maghrebian Flysch basin (Mauretanian basin), sandy turbidites and coarse olistostromes first appeared, whereas the southern part of the oceanic trough (Massylian basin) had pelagic sedimentation. *This suggests that a subduction trench was formed by the Middle-Late Eocene at the Dorsale-Maghrebian ocean transition* (Fig. 5.23).

In contrast, the African paleomargin itself remained virtually quiescent throughout Late Cretaceous to Eocene time. In the Prerif zone, Triassic evaporites and associated rocks are resedimentated in the Upper Cretaceous marls. Such phenomenon suggests the ascent of diapirs up to the Cretaceous seafloor. This was probably a result of an extensional/transtensional regime, in agreement with the Paleocene alkaline basalts erupted in the eastern Prerif (Sidi Maatoug).

Contractional events first occurred during the ***Late Eocene-Oligocene***, being mostly concentrated in the Internal (Alboran) Domain. These are: (i) stacking of the Ghomaride-Malaguide nappes, locally dated at about 28 Ma, and associated with deep erosion and coarse conglomerate deposits; (ii) turbiditic and olistostrome-rich sedimentation with internal alimentation in the Dorsale-Predorsalian-internal Flysch Trough (Beni Ider-Algeciras Flyschs); (iii) metamorphism in the Sebtide-Alpujarride units, the peak of which occurred at ~30 Ma, although some earlier isotopic ages (48 Ma) have been obtained; and (iv) emplacement of andesitic basalt dykes in the Malaguides (33–30 Ma). The latter two events are indicative of an ongoing subduction during the Oligocene. *The Dorsale and Ghomaride-Malaguide units were located in the arc domain above the subduction zone where the Sebtide-Alpujarride units were buried*.

During this Eocene-Oligocene period, coarse turbiditic influx increased in the northern part of the Flysch Trough (Fig. 5.23), which was progressively consumed, whereas its southern part was almost devoid of contemporary turbidites (Fig. 5.26). Likewise, most of the External Rif remains undisturbed, but *the Intrarif-Mesorif boundary acted as a minor suture zone* (from the Nekor-Beni Malek to the Oran massifs at least). This view is supported by the occurrence of the Tifelouest duplexes sealed by Oligocene-Miocene chaotic breccias and turbidites, and by the age of the greenschist to MP-LT metamorphism of the Ketama–Temsamane massifs, dated at ca. 28–23 Ma.

At the transition from ***Oligocene to Miocene*** (latest Oligocene-Early Burdigalian, 25–18 Ma), the upper plate, i.e. the Ghomaride-Malaguide-Kabylian range, was eroded, faulted, and progressively submerged. Contemporaneously, the buried Sebtide-Alpujarride units were exhumed under increasing geothermal gradients.


Stratigraphy
Domains
Ma
Foreland, Foredeep
[1, 2, 18]
Prerif, Rifian nappes
[1, 3-5, 18, 19]
Mesorif
[1, 3, 5, 6, 18]
Intrarif
[3, 4, 7-9, 18]
Numidian (Massyl.)
[10, 11]
Beni Ider (Mauretanian)
[10, 12]
Pre-dors.
[13]
Dorsale calcaire
[14]
Ghomarides Malaguides
[15, 16]
Sebtides Alpujarrides
[16, 17, 18]
Alboran Sea
[17, 18, 20]
Nevado-Filabrides
[21-24]
PLEISTOCENE
PLIOCENE
MESSINIAN
TORTONIAN
SERRAVALLIAN
LANGHIAN
BURDIGALIAN
AQUITANIAN
CHATTIAN
RUPELIAN
PRIABONIAN
BARTONIAN
LUTETIAN
YPRESIAN
THANETIAN
DANIAN
MIOCENE
OLIGOCENE
EOCENE
PALAEOCENE
1.8
5.3
7.2
11.6
13.6
15.7
20.4
23.0
28.4
33.9
37.2
40.4
48.6
55.8
58.7
65.5
(Gibraltar, Martil, Tirhinesse rias)
(Betics)
(E. Betics basins)
(Kabylies)
Post-nappe synclines
Predorsalian & Zem
EXTERNAL PRERIF
INTERNAL PRERIF
RIDES PRERIFAINES
IZZARENE - ZOUMI
TEMSAMANE NORD
TIFELOUEST
KETAMA-AKNOUL
TANGER
HABT
Rirha - Aciiah - Larache
Ghomaride clasts
Aknoul detachment
Tuboto-maculum clays
Detached from the Tisiren Flysch
Detached from the Melloussa Chouamat U. Cretac. Flysch
(Malaga dykes)
(Sra Espuna)
Granite pebbles
(Liassic)
(U. Cretac. - Liassic)
Fnideq - Ciudad Granada
S. Abdeslam
Viñuela
AFT
ZFT
Ar-Ar Ph
U-Pb Zr, Lu-Hf Gt
Ar-Ar Hb
D1
D2
D3

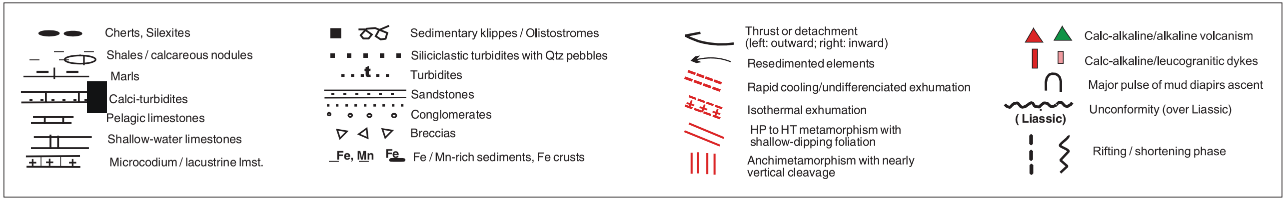


Fig. 5.42 Chronology of the stratigraphic, metamorphic and magmatic events recorded in the Rif Belt and Betic Cordilleras (*names in italics*) during the Cenozoic, after Chalouan et al. (2001), substantially modified. Time scale from the International Commission on Stratigraphy (2004). Main data sources, in addition to Suter (1980a, 1980b): 1: Feinberg (1986), Wernli (1987); Kerzazi (1994); 2: Faugères (1978), Plaziat & Ahmamou (1998), Zizi (1996), Zouhri et al. (2001), Litto et al. (2001); 3: Ben Yaïch (1991), Toufiq et al. (2002); 4: Morley (1992), Leblanc (1979); 5: Cornée et al. (1996), Samaka et al. (1997), Münch et al. (2001); 6: Frizon de Lamotte (1985), Ben Yaïch et al. (1989), Favre (1992), Negro et al. (2007); 7: Zaghloul et al. (2005); 8: Abdelkhaliki (1997), Zakir et al. (2004); 9: Didon & Feinberg (1979), Septfontaine (1983), Lamarti-Sefian et al. (1998); 10: Hoyez (1989), Guerrera et al. (2005); 11: Esteras et al. (1995), El Kadiri et al. (2006); 12: Didon & Hoyez (1978), Zaghloul (2002), Puglisi et al. (2001), Zaghloul et al. (2007); 13: Mourier et al. (1982), Olivier (1984), Durand-Delga & Maaté (2003); 14: Wildi et al. (1977), Olivier et al. (1979), Durand-Delga (1980), Nold et al. (1981), Olivier (1981–1982), Ben Yaïch et al. (1986), El Kadiri et al. (1992), Hlila et al. (1994), El Kadiri (2002a, 2002b), El Kadiri et al. (2005); 15: El Kadiri et al. (1992), Martín-Martín et al. (1997), Martín-Algarra et al. (2000), Negro et al. (2006); 16: Chalouan & Michard (1990), Feinberg et al. (1990), Durand-Delga et al. (1993), Lonergan & Mange-Rajetsky (1994), Serrano et al. (2006); 17: Michard et al. (1991, 1997), Sánchez-Rodriguez & Gebauer (2000), Platt et al. (2003b), Negro (2005); 18: Hernandez et al. (1987), El Bakkali et al. (1998), El Azzouzi et al. (1999), Maury et al. (2000), Duggen et al. (2004); 19: Hernandez et al. (1976); 20: Platt et al. (1988), Comas et al. (1992, 1999), Chalouan et al. (1997), Soto & Platt (1999), Soto et al. (2003), Sautkin et al. (2003), Talukder et al. (2003); 21: Johnson et al. (1997); 22: Martínez-Martínez et al. (2002); 23: Augier et al. (2005a, 2005b); 24: Platt et al. (2006)

Turbiditic sedimentation then invaded the entire, residual Flysch Trough and the Intrarif domain. By the end of this period, during the Middle Miocene (16–11 Ma), shortening encroached the Flysch Trough, Intrarif, and Subbetic domains.

Nevertheless, extension in the central part of the Alboran Domain continued during the whole ***Miocene*** (Late Burdigalian-Early Tortonian, 18–9 Ma), resulting in the continued subsidence and the development of the Alboran Sea in the west. This protracted extension at the core of the Alboran Domain was accompanied by conspicuous calc-alkaline volcanism. It was also coeval with the outward displacement of the turbiditic depocenters and thrust contacts into the Mesorif domain, and then into the Prerif domain. Obviously, plate convergence is not the only process at work, as shortening is combined with extension in the Alboran Domain. *This is interpreted through the retreat of the Maghrebian subduction zone with tearing and break-off of the plunging slab* (see below).

Finally, during the ***Late Tortonian-Pleistocene times*** (9 Ma to Present), the Mediterranean Sea overlay large parts of the orogen, due to *late orogenic collapse of the tectonic prism*. However, *contractional processes mostly related to plate convergence* also operated at some places (e.g. Alboran Ridge, post-nappe synclines of the Mesorif), being still active in the Rides prérifaines. Alkaline basalts emplaced in the eastern Rif, in relation with the Morocco Hot Line (Sect. 5.6.3) superimposed onto the Maghrebide-Betic structures.

5.7.2 Kinematic Data and Paleomagnetic Rotations

References: Kinematic data (transport direction and sense of shear) have been collected throughout the Gibraltar Arc by many authors and for different time intervals. They are presented synthetically in the following works (with references therein): (i) for the Sebtide-Alpujarride units (late Oligocene-Miocene deformations), by García-Dueñas et al., 1992, 1995), Michard et al. (1997), Chalouan et al. (1995, 1997), Balanyá et al. (1997), Martínez-Martínez & Azañón (1997), Azañón & Crespo-Blanc (2000), and Booth-Rea et al. (2004); (ii) for the Nevado-Filabride Complex (Middle-Late Miocene deformation) by Martínez-Martínez et al. (2002) and Augier et al. (2005a); (iii) for the External Zones of the entire orogenic arc (Early-Late Miocene to Pleistocene deformation) by Frizon de Lamotte et al. (1991), Crespo-Blanc & Campos (2001), Aït Brahim et al. (2002), Platt et al. (2003a) – a paper discussed by Michard et al. (2005), Zakir et al. (2004), Bargach et al. (2004), and Crespo-Blanc & Frizon de Lamotte (2006). Concerning paleomagnetic investigations, a number of references are given in the caption to Fig. 5.43. Other pertinent works are those by Villalain et al. (1994), Platt et al. (2003a), Villasante-Marcos et al. (2003), Osete et al. (2004), Krijgsman & Garcès (2004), and Cifelli et al. (2008).

Kinematic indicators are widespread in the Sebtides (Fig. 5.35), and come from the top of the Beni-Bousera peridotites and the Federico units (Upper Sebtides) in the Beni Mezala area. They are associated with retrogressive mineral phases, and then related to the exhumation processes. They show a remarkably constant top-to-NW

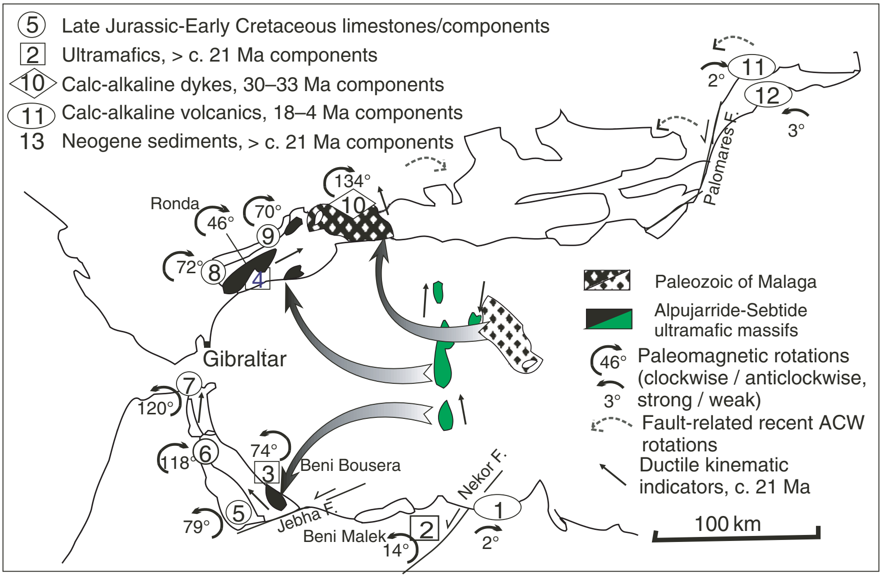


Fig. 5.43 Paleomagnetic rotations (mean site values) in the Betic-Rif Belt, after Feinberg et al. (1996) and Chalouan & Michard (2004), modified. The inferred approximate N–S strike of the pre-Early Miocene orogen is shown schematically by the alignement of the three ultrabasic bodies in the mid-Alboran area. This also restores the main ductile shear directions of the west Gibraltar Arc, as reported by Michard et al. (1997), Balanyá et al. (1997), Martínez-Martínez et al. (2002), into an broadly N-S trend. 1: Najid et al. (1981); 2: Elazzab & Feinberg (1994); 3: Saddiqi et al. (1995); 4: Feinberg et al. (1996); 5–9: Platzmann (1992), Platzmann et al. (1993), Allerton et al. (1994); 10: Platzmann et al. (2000), Calvo et al. (2001); 11, 12: Calvo et al. (1997); 13: Mattei et al. (2006)

(Beni Bousera) and top-to-N (Beni Mezala) direction of shear. In the northern branch of the Gibraltar Arc, i.e. in the western Alpujarrides, coeval kinematic indicators point to top-to-N to top-to-NE shear. This strongly suggests that the corresponding exhumation tectonics originally occurred with a top-to-N sense of shear, and that the metamorphic units carrying the stretching lineations were bended during a further stage. Assuming that the recorded exhumation phase occurred at ca. 23–20 Ma, the curvature of the arc would have developed after the lowermost Miocene.

Paleomagnetic data permit to precise the latter conclusion (Fig. 5.43). Rotations of the Late Jurassic and Late Cretaceous limestones are mostly anticlockwise in the Rif Dorsale units, and clockwise in the Betic Dorsale and Penibetic (Internal Sub-Betic) zones. Similar opposite rotations are observed both in the Beni Bousera and Ronda peridotites, and within their leucogranite dykes. This observation enables us to demonstrate that rotations occurred after the cooling of these rocks (ca. 20 Ma). The moderate anticlockwise rotation measured in the Beni Malek ultramafics and overlying metasediments can be assigned to the sinistral deformation along the Nekor fault zone. At first sight, opposite and low rotations inferred in calc-alkaline volcanic rocks (cf. sites 1, 11, and 12; Fig. 5.43) suggest that rotation within the arc was completed at ca. 13–7 Ma. However, paleomagnetic results from

Fig. 5.44 An example of Miocene normal fault from the southern Alboran Sea shore: the Cape of Tres Forcas NW-dipping fault, cutting across the Late Tortonian-Messinian basal conclomerates at the north boundary of the Tarjat anticline (see Fig. 5.39 for location). The fault operated during the Messinian subsidence of the Cape Tres-Forcas block, with alternating normal and sinistral movements

Neogene sedimentary sequences from the Betic Chain show also that vertical axis rotation continued after the Late Miocene (Mattei et al., 2006; Cifelli et al., 2008). In summary, bending of the Gibraltar Arc occurred mostly during the Early-Middle Miocene, i.e. during the climax of extension, but continued afterwards.

Transport direction along Miocene thrusts display a broadly radiating pattern in the External Zones of the Arc (Fig. 5.5). They show a dominant westward component, thus suggesting a westward migration of the Gibraltar Arc. Such sense of displacement is clearly recorded in the N-Temsamane domain (Fig. 5.30) and results congruent with the one observed in the low-angle detachment that separates the Alpujarride Complex from the underlying Nevado-Filabride Complex. There, top-to- west shearing evolved from ductile to brittle conditions between ca. 12 and 8 Ma, contemporaneously with subsidence in the nearby Serravallian-Tortonian basins of the Betic Cordillera. The coeval, extensional directions associated with brittle normal faults all around the Alboran basin itself are roughly centripetal (Figs. 5.5, 5.44). *These observations are consistent with the formation of an orogenic arc, by simultaneous frontal thrusting and back, centripetal extension, in the context of a west-directed slab retreating process*.

5.7.3 Oligocene-Neogene: The Slab Retreat Process

References: The role of the slab retreat process in the opening of the Mediterranean basins and dispersal of the AlKaPeCa units was advocated by Rehaut et al. (1984), Frizon de Lamotte (1985), Malinverno & Ryan (1986), Royden (1993), Lonergan & White (1997), Doglioni et al. (1998), Frizon de Lamotte et al. (1991, 2000), and Jolivet & Faccenna (2000), among others. Recent papers describing the Gibraltar E-dipping slab and associated accretionary prism, based on marine geophysics, seismology and/or tomography are those by Torelli et al. (1997), Calvert et al. (2000), Gutscher et al. (2002), Faccenna et al. (2004), and Spakman & Wortel (2004). The occurrence of edge delamination is particularly advocated by Seber et al. (1996), Calvert et al. (2000), and Fadil et al. (2006). A detailed kinematic reconstruction of the movements of the Mediterranean microblocks (except Alboran) is proposed by Schettino & Turco (2006). Other seismological and geodetical references are reported in Chap. 1, Sect. 1.4.

Recently acquired seismological data offer convincing evidence for active east-dipping oceanic subduction below the western Aboran Sea. An east-dipping slab of subducted lithosphere is clearly imaged by tomography in the Western Mediterranean mantle (Fig. 5.45). Beneath the Betic-Rif-Alboran region, a positive (fast) P-wave velocity anomaly (i.e. a cold, dense body respective to the warmer ambient mantle), interpreted as a subducting slab, is found from the base of the crust across the entire upper mantle, down to the 660 km discontinuity. The deeper part of the anomaly extends beneath SE Spain, north of the Alboran basin. The upper part of the slab connects with the Atlantic oceanic lithosphere west of the Strait of Gibraltar. Evidence for current activity of this subducting slab is offered by seismicity distribution and seismic-reflection profiling (Fig. 5.46). Intermediate depth earthquake hypocentres are concentrated in the Alboran Sea, where plate curvature increases abruptly, probably due to P and T dependant dehydration reactions in the plunging slab. The deepest part of the slab coincides with the locus of deep earthquakes beneath southern Spain. On the Atlantic side, multichannel seismic profiling has imaged the "olistostrome" of the Gulf of Cadiz as an eastward-thickening accretionary

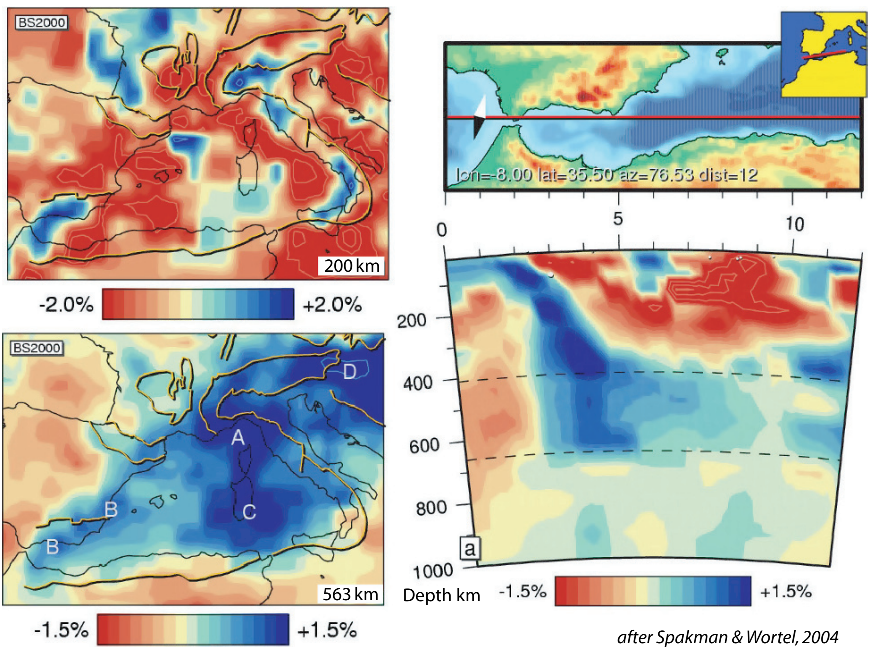


Fig. 5.45 V_P tomography of the Western Mediterranean area, after Spakman & Wortel (2004). *Left*: horizontal sections at 200 km and 563 km depth. *Right*: E-W vertical section across the Alboran-southern Algerian basin down to 1000 km depth, with location map. *Dashed lines* represent mantle discontinuities at 410 and 660 km depth

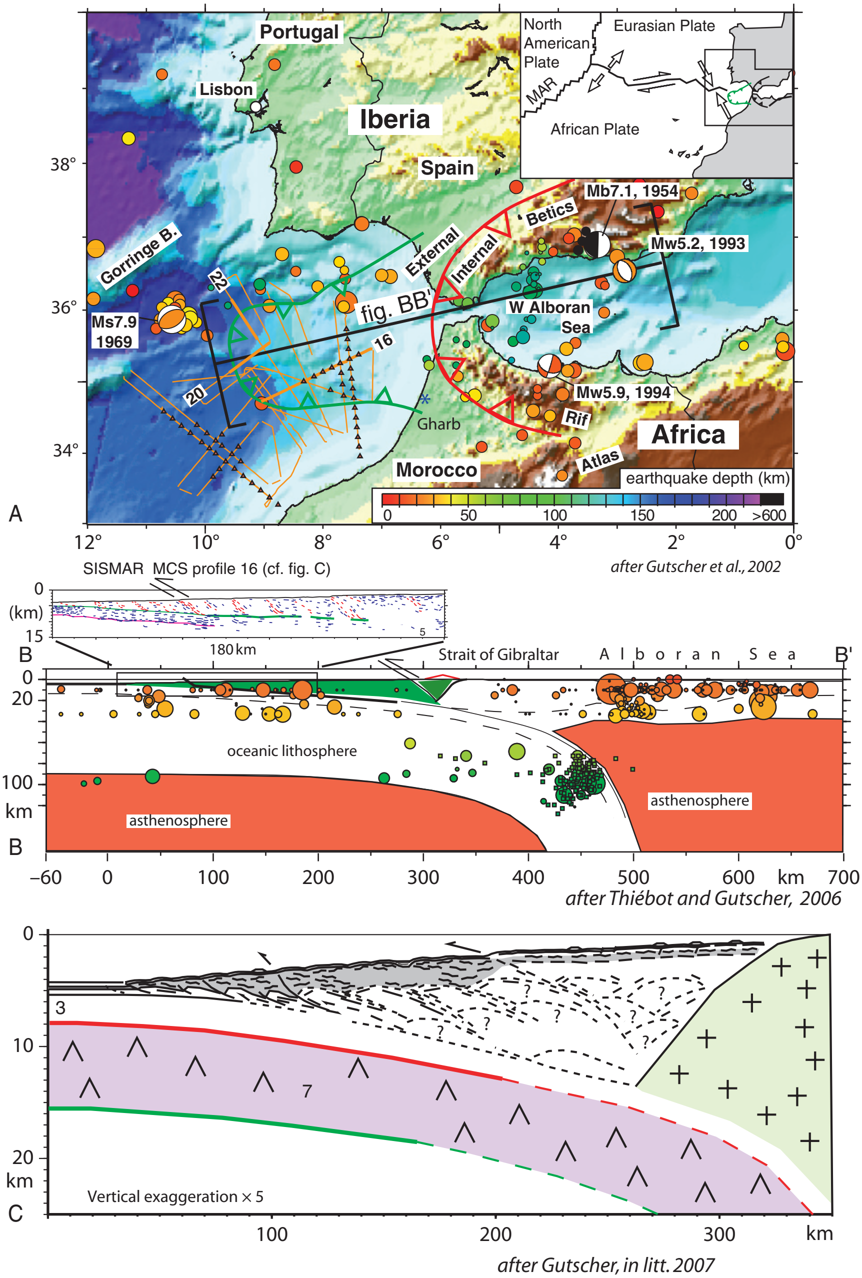


Fig. 5.46 (continued)

wedge ("Atlantis wedge"), overlying eastward dipping undeformed sediments and basement. Although some authors suggest that subduction is not active at present (e.g. Mauffret et al., 2007), the east-dipping reflectors deforming the seafloor indicate active ramp thrusts, thus suggesting that subduction is still active.

The shape of the Betic-Alboran subducting slab at a depth of 200 km correlates with the arcuate shape of the Gibraltar Arc and is also consistent with the spatial distribution of calc-alkaline volcanism in the back-arc domain. These observations offer a coherent timing for the kinematic evolution of the slab roll-back during the Miocene (Fig. 5.47). The subduction trench progressively turned from E-W to roughly N-S trend, through tearing and detachment along both the Iberia and the Maghreb margins. Indeed, no north-dipping slab is observed by tomography along the Algerian-Moroccan coast. The influx of asthenospheric mantle in the lithosphere tear-zones resulted in calc-alkaline magmatism, which tracks the westward mantle tearing (16–7 Ma in Algeria *versus* 12–6 Ma in Morocco and Alboran).

Fig. 5.46 (continued) The active subduction beneath Gibraltar. (**A**) Geographic map with shaded relief and location of epicentres (1973–Present; M > 3) and some focal mechanisms, after Gutscher et al. (2002). Red thrust teeth symbols indicate Gibraltar Arc; green thrust teeth symbols indicate active "Atlantis" accretionary wedge. SISMAR seismic reflection profiles in orange; position of bottom seismometers as small, lined up red triangles. Seismicity sampling box for B is also indicated. – (**B**): Simplified lithospheric cross-section showing the distribution of earthquake hypocenters (sampling box in **A**), and the geometry of the upper plate (Gibraltar block), lower plate and accretionary prism, after Thiébot & Gutscher (2006). – (**C**): Detailed cross-section of the accretionary prism along the SISMAR MCS Profile 16 (for location, see **A** and **B**), after M.-A. Gutscher (pers. comm., 2007)

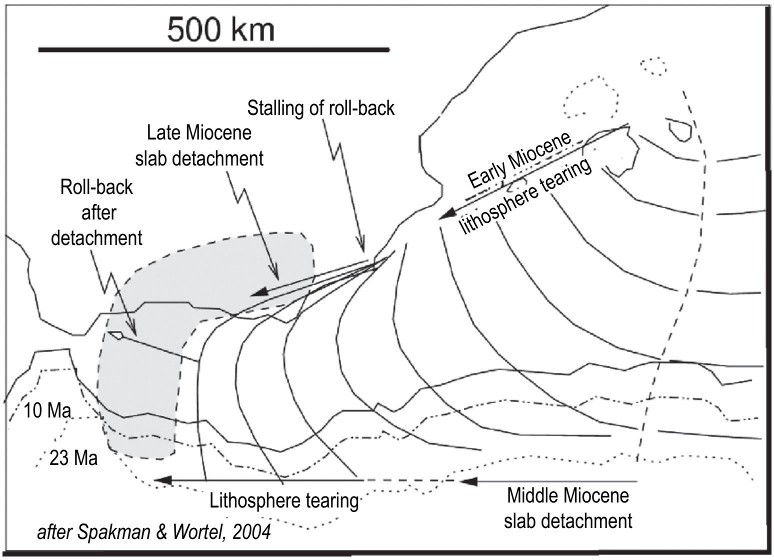


Fig. 5.47 Cartoon of the Miocene slab roll-back and lateral detachment and tearing of the Maghrebian-Ligurian oceanic slab in the Alboran area, after Spakman & Wortel (2004). The grey pattern shows the present-day position of the slab at 200 km depth (see Fig. 5.45). Relative position of Africa with respect to fixed Iberia is shown at 23 Ma, 10 Ma and Present

In this generally accepted scenario, the Alboran Basin spread in a back-arc position, similar to the Provençal and Valencia Basin (Fig. 5.48D, E). Mauffret et al. (2007) proposed that the western part of the Alboran Basin could have developed in a fore-arc position, but this is just open to discussion. It must be emphasized that

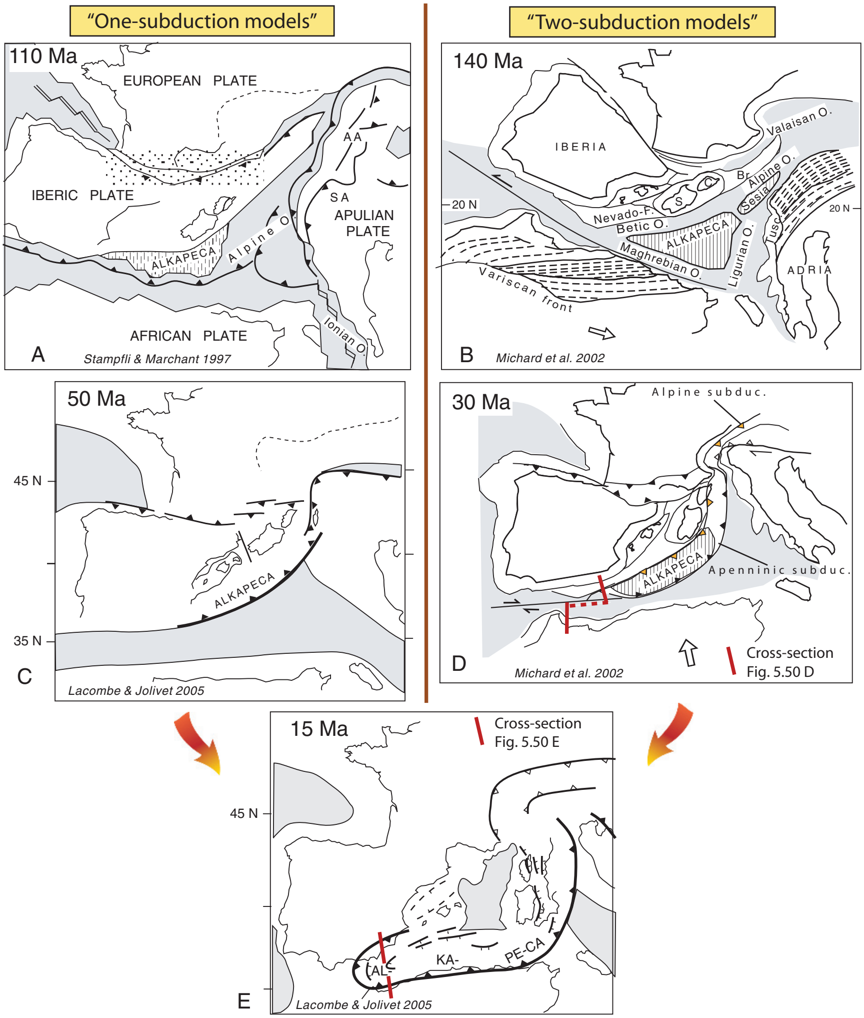


Fig. 5.48 Alternative scenarios for the Mesozoic setting of AlKaPeCa continental blocks and the successive positions of the subduction zone(s), after Michard et al. (2006), modified. *Left*: single subduction hypothesis; AlKaPeCa blocks were parts of SE Iberia during Early Cretaceous (**A**); during Tertiary convergence (**C**), the SE dipping Alpine subduction coexists with a NW-dipping Ligurian-Maghrebian subduction south of Corsica. – *Right*: two-subductions hypothesis; during the Mesozoic (**B**), AlKaPeCa formed a microcontinent separated from Iberia by a Betic oceanic arm; during the Eocene (**D**), a hypothetic SW extension of the Alpine subduction closes the Betic Ocean, being followed by the Ligurian-Maghrebian subduction at *ca*. 30 Ma. The Oligocene-Miocene evolution by back-arc extension and slab roll-back (**E**) is identical in both scenarios

the slab subduction does not result from E-W plate convergence but from passive sinking of unstable lithosphere into the mantle, within the narrow oceanic corridor between Iberia and Africa. At the scale of the Western Mediterranean, the subducted Ligurian lithosphere is now found at the base of the upper mantle, and as narrow, steeply dipping slabs in the Gibraltar Arc and its mirror image, i.e. the Calabrian Arc.

Slab roll-back was able to transport the fragments of the Betic-Rif Internal Zones (which were probably concentrated along the Balearic margin by the Eocene-Early Oligocene; see below) towards their present-day position with a predicted, dominant ENE-WSW trending extension. Slab roll-back also accounts for the rotations of the Alpujarride-Sebtide structures and paleomagnetic components during the Early Miocene, as described above (Fig. 5.43).

5.7.4 Late Cretaceous-Eocene: The Debatable Issues of the Early Subduction-Collision Tectonics

References: Tectonic scenarios for this period are still warmly debated. Correlations with the Alps in terms of plate tectonics have been repeatedly addressed since the late 70s: see reviews and references in Bouillin (1984) and Michard et al. (2002). Certain authors emphasized the role played by collisional processes and late-orogenic extension in the origin and evolution of the Betic-Rif orogen (e.g. Platt & Vissers, 1989; Turner et al., 1999; Houseman & Molnar, 2001). The occurrence of subduction is now widely accepted, although two competing models are proposed: (i) a single, NW-dipping subduction (e.g. Jolivet & Faccenna, 2000; Stampfli & Marchant, 1997; Stampfli et al., 2002; Lacombe & Jolivet, 2005; Jolivet et al., 2006), and (ii) two opposite subductions operating successively (e.g. Andrieux et al., 1989; Doglioni et al., 1999; Frizon de Lamotte et al., 2000; López Casado et al., 2001, Michard et al., 2002; Chalouan & Michard, 2004; Guerrera et al., 2005; Pecerillo & Martinotti, 2006). A discussion of these alternative models is proposed in Michard et al. (2006), and summarized hereafter.

5.7.4.1 Plate Tectonic Setting

During the latest Cretaceous-Paleogene times, NW-Africa moves northward relative to Eurasia by 200–250 km in the Morocco-Iberia transect (cf. Sect. 1.1, Fig. 1.10). Taking into account the shortening between Iberia and stable Europe (ca. 100 km across the Pyrenean belt), 100–150 km must have been consumed south of Iberia. As shortening across the Atlas is negligible up to the Neogene (Chap. 4), most of this shortening must have been accommodated by subduction of the Ligurian-Maghrebian oceanic lithosphere. During the Early Cretaceous, the Ligurian-Maghrebian (or, shortly, Ligurian) ocean was a triangular area connecting Central Atlantic, Alpine and Ionian oceans (Chap. 1, Fig. 1.9). When the Alpine ocean closed during the Eocene by subduction of the European plate below Adria, subduction affected most likely the Ligurian lithosphere, and thus may have dragged down some parts of the nearby continental blocks, thus generating HP-LT metamorphism in some of the AlKaPeCa units.

However, the location and number of subduction zones in the Ligurian area during the Late Cretaceous-Paleogene are questionable, as well as the location of the AlKaPeCa units (and particularly the Alboran Domain) at the onset of convergence. Several authors proposed that AlKaPeCa was part of the southeastern Iberian margin, close to Sardinia and the Balearic Islands (Fig. 5.48A). In contrast, others (included the authors of the present chapter) suggested that AlKaPeCa formed a microcontinent within the Ligurian oceanic area (Fig. 5.48B). In the latter hypothesis, a southwestward projection of the SE-dipping Alpine subduction could have been responsible for the consumption of the oceanic lithosphere between AlKaPeCa and Iberia (Fig. 5.48D). Metabasites and meta-serpentinites located toward the top of the Nevado-Filabride Complex can be taken as evidence for this interpretation. In consequence the Nevado-Filabrides could correspond to the distal part of the Iberian margin (as suggested recently by Platt et al., 2006). In contrast, in the "single-subduction hypothesis", the Ligurian subduction zone could have been located at the southeastern boundary of the AlKaPeCa units as early as the Late Cretaceous. As shown in Fig. 5.48C, this implies a flip-like reversal of the Alpine subduction from a SE dip along the Corsica-Northern Apennine transect to a NW dip along the AlKaPeCa-Southern Apennine/Maghreb transects. In both hypotheses, the future Alpine terranes of the western Mediterranean were located next to the Iberian margin, immediately before the slab retreat process responsible for their migration and opening of the Mediterranean Sea (Fig. 5.49).

5.7.4.2 The Nevado-Filabrides Issue

References: A new scenario was proposed by Platt et al. (2006) based on the young dating (ca. 18–14 Ma) of the Nevado-Filabride high-pressure (HP) metamorphism (under eclogite facies conditions). However, and due to the nature of this metamorphism, other scientists inferred older ages, ranging from Middle Eocene to Early Miocene, as for example Monié et al. (1991), López Sánchez-Vizcaíno et al. (2001), Puga et al. (1999, 2002a, 2002b), De Jong (2003), and Augier et al. (2005b).

None of the above tectonic scenarios attain a consensus, partly due to the lack of unequivocal information on the Nevado-Filabride Complex, its stratigraphy, the age of the high pressure (HP) metamorphism, the initial relationships with respect to the Alpujarride-Malaguide complexes in the Betic Cordillera, and its former position in the western Mediterranean. Did the Nevado-Filabride separate from the Iberian margin (e.g. Fig. 5.48B) or from the African one (Bouillin, 1984)? Or did it form an independent terrane located either north or south of the Alpujarride-Malaguide complex? Moreover, it was assumed that the Nevado-Filabride HP metamorphism (with eclogite facies rocks) was older or simultaneous with the Alpujarride one, but most recent datings at ca. 18–14 Ma (U-Pb in zircon, López Sánchez-Vizcaíno et al., 2001; Lu-Hf in garnet, Platt et al., 2006) now conflict with others radiometric ages at ca. 40–30 Ma (*in situ* laser $^{40}Ar/^{39}Ar$ on phengite, Augier et al., 2005b). This, of

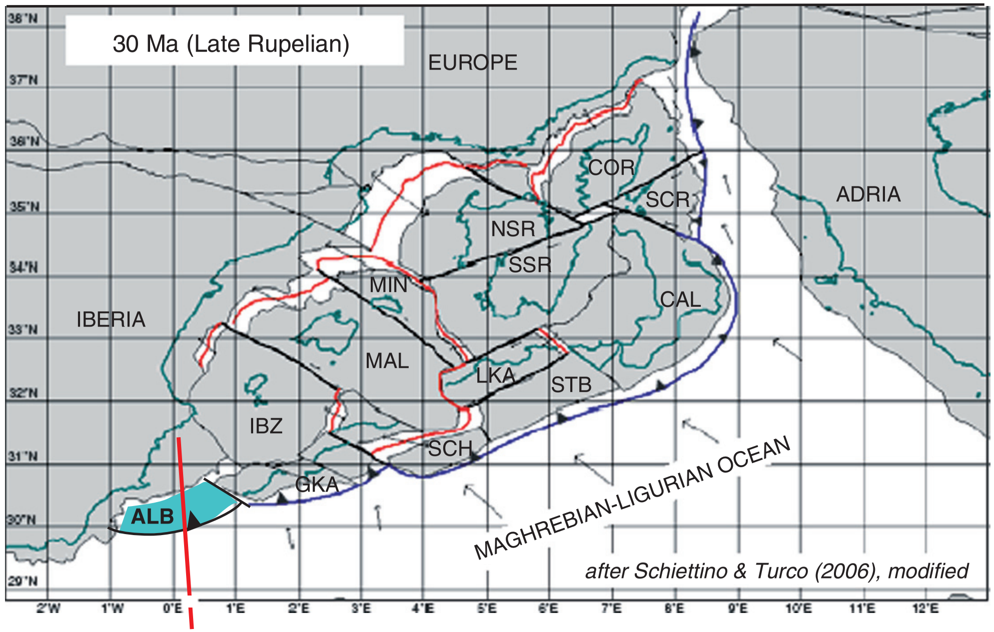


Fig. 5.49 Plate tectonic reconstruction of the Western Mediterranean microplates at 30 Ma, i.e. by the beginning of their disruption, after Schettino & Turco (2006), modified. Red lines are extension centres. *Straight black lines* are strike-slip faults. *Curved black lines* with teeth are subduction zones (note the hypothetized flip in front of southern Corsica). *Arrows* represent direction and magnitude of motion relative to Eurasia. *Thick red line* across Alboran corresponds to cross-section in Fig. 5.50. ALB: Alboran; CAL: Calabria; COR: Corsica; GKA: Greater Kabylia; IBZ: Ibiza; LKA: Lesser Kabylia; MAL: Mallorca; MIN: Menorca; NSR: Northern Sardinia; SCH: Sardinian Channel; SCR: Southern Corsica; SSR: Southern Sardinia; STB: South Tyrrhenian Block

course, results in very distinct reconstructions of the pre-Oligocene evolution of the Alboran Domain.

In particular, Platt et al. (2006) suggest that two phases of continental subduction operated successively; with (i) a Paleogene, north-dipping Alpujarride subduction beneath the Malaguides, then (ii) an Early Miocene, south-dipping Nevado-Filabride subduction underneath the Malaguide-Alpujarride stack. Assuming this interpretation, Early Miocene subduction of the Nevado-Filabrides is coeval with the pervasive extension of the upper terranes of the Alboran Domain (Alpujarrides and Malaguides) and with the slab retreating described above. This scenario corresponds to the Burdigalian-Langhian interval, very close to the onset of continental to shallow-marine sedimentation observed in some of the sedimentary basins placed close to the Nevado-Filabrides. Therefore, it probably indicates that subduction was followed immediately by ultra-rapid exhumation of this terrane and concomitant subsidence during the Middle Miocene. However, one cannot rule out confidently that some of these ages could have been rejuvenated during the isothermal exhumation episode.

5.7.4.3 Internal Paleogeography of the Alboran Domain

The respective location of the Sebtide-Alpujarride, Ghomaride-Malaguide and Dorsale units in the initial paleogeography are seldom addressed in the tectonic scenarios for Betic-Rif mountain building. However, this paleogeographic problem is quite important because its solution puts strong constraints on the interpretation of the Sebtide-Alpujarride metamorphism. The Dorsale domain was certainly located at the south border of the continental domain as it represents its passive margin north of the Maghrebian Flyschs oceanic arm. If we assume with Durand-Delga (1980, 2006) that the Sebtide-Alpujarride domain was located north of the Ghomaride-Malaguide and formed an uplifted, deeply eroded part of the continental domain, then a south-dipping subduction must be hypothetized to explain the present-day structure (Fig. 5.50A, B), and the Sebtide-Alpujarride metamorphism could then be nearly coeval with that of the Nevado-Filabrides. In contrast, we may assume with Wildi et al. (1977) that the Sebtide-Alpujarride units represent the former Paleozoic-Middle Triassic basement of the Dorsale units, as the latter are detached on the Carnian evaporites. In that case, the Sebtide-Alpujarride units were located south of the Ghomaride-Malaguide domain (Fig. 5.50C), and the corresponding subduction would dip northward, being distinct from the Nevado-Filabride (Fig. 5.50D). The present-day structural setting (Fig. 5.50E) seems more easily obtained (after the slab roll-back evolution) in the frame of the latter hypothesis than of the former. Discussing more deeply the above scenarios, either in map view or in cross-section, would clearly be beyond the scope of this chapter. They must be regarded as working hypotheses, not as the only possible answers to the Rif-Betic conundrum.

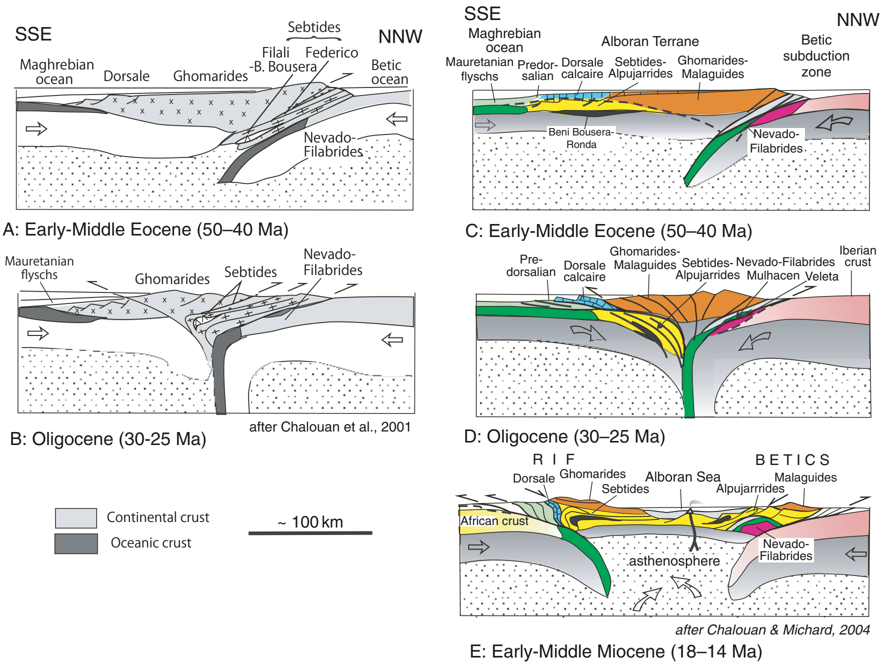


Fig. 5.50 Alternative hypotheses for the Betic-Rif mountain building in cross-section, after Chalouan & Michard (2004). (**A, B**): In this scenario (Chalouan et al., 2001), the Sebtide-Alpujarride domain (future *lower* plate) is initially located north of the Ghomaride-Malaguide domain (future *upper* plate), and then enters in a south-dipping subduction zone. – (**C, D**): In this scenario, the Sebtide-Alpujarride complex forms the basement of the Dorsale units which detach on the Carnian evaporites and form the accretionary prism together with the Flysch units during the north-dipping Oligocene-Miocene subduction

5.7.4.4 The Peridotite Emplacement

References: Literature concerning the Gibraltar Arc peridotites abounds. The most significant and essentially recent references are given directly in the following text.

The Gibraltar Arc peridotites are among the largest infracontinental mantle rock outcrops worldwide. Their emplacement mechanisms have been certainly more debated than if they were part of an ophiolite. Ophiolititic peridotites would have been regarded as dismembred thrust unit obducted during the early collisional stages of the Betic-Rif orogeny, comparable to the Alps and Apennine ophiolites. This manner of thinking was first adopted by Kornprobst (1974), and by Reuber et al. (1982) who interpreted the Beni Bousera peridotites as “cold” slivers of Jurassic infracontinental mantle included in the Cenozoic nappe stack. However, this “cold” tectonic interpretation was challenged as early as the eve of the 70s by a “hot” diapiric interpretation suggesting that the Ronda peridotites originate from a Neogene asthenospheric mantle diapir (Loomis, 1972; Obata, 1980). This “hot” emplacement theory was based, at that time, on poor geochronologic, petrologic and structural data, but still inspires a trend of thinking today.

The diapiric emplacement theory essentially rests on the late Oligocene-Early Miocene multimethod isotopic ages obtained from the ultrabasites and (mostly) from their country rocks, whose recrystallization would be allegedly caused by the peridotite emplacement. Moreover, the theory takes advantage of the occurrence of coeval mantle uplift recorded in the Alboran Basin area. In recent years, evidence was derived from the occurrence of a high temperature, low-pressure plagioclase peridotites associated with a recrystallization front toward the bottom of the Betic peridotite massifs (Van der Wal & Vissers, 1993; Lenoir et al., 2001; Tubía et al., 2004). According to Tubía et al. (2004), the Ronda peridotites would have a dual origin, including a cold sub-continental lithosphere (garnet and spinel domains), uplifted during the Mesozoic (cf. Reuber et al., 1982), and a hot (virtually intrusive) Miocene asthenosperic diapir.

However, Vissers et al. (1995) recognized that "there is no immediate causal relationship between the emplacement of the peridotites and the thermal metamorphic event [in the crustal rocks]: both rock bodies were affected by a thermal pulse at different levels". On the other hand, the diapiric emplacement theory has to consider the fact that the peridotites are included as relatively thin thrust sheets (less than 3 km thick) within the Alpujarrides crystalline nappe stack (Lundeen, 1978). Montel et al. (2000) suggested that a compressional event would have brought the diapir head on top of the adjoining continental crust immediately after the alleged diapir ascent (dated at 20–30 Ma). Platt et al. (2003b) and Tubía et al. (2004) recognized that the 25–20 Ma interval corresponds to a well documented regime of extensional tectonics in the Alboran domain, and then proposed that interleaving of the peridotite sliver within the crustal nappe stack would result from a complex sequence of extensional detachements. However, others authors emphasized that extensional tectonics alone cannot account for the early tectonic evolution of the Alpujarride-Sebtide nappe stack, particularly the occurrence of HP-LT recrystallization below and above the peridotites (Michard et al., 1991, 1997; Torné et al., 1992; Sánchez-Gómez et al., 2002; Chalouan & Michard, 2004). The emplacement model proposed by Sánchez-Gómez et al. (2002) includes the following steps during the Betic-Rif orogeny (i.e. after the Paleozoic-Mesozoic evolution of the Tethyan margin lithosphere): (i) pre-Miocene subduction-collision and HP-LT metamorphism; (ii) early exhumation of the Alpujarride crust, which produced its thinning and the rise of the peridotites up to c. 18 km depth; (iii) contractive emplacement of a peridotite slab onto the crust, recorded in the footwall of the thrust by a HT melange, overturned folds with HT crenulation cleavage, and a complete inversion of the Ojen-Blanca footwall unit in the HT-LP conditions of the plagioclase peridotites; and (iv) Miocene collapse of the Alboran Basin, with dismembering of the former peridotite slab, granite generation at 22–18 Ma, and plastic flow of serpentinites between the peridotite bodies. This scenario is compatible with the tectonic scheme of Fig. 5.50. Moreover, a close parallelism with the emplacement history of the Lower Penninic infracontinental peridotites of Western Alps can be remarked (e.g. Geisspfad Complex; Pastorelli et al., 1995; Bianchi et al., 1998).

5.8 Neotectonics, Seismicity and Present-Day Stress Field

References: The references concerning the Gibraltar Arc active tectonics are indicated within the following text. They are implemented by those associated with Chap. 1, Sect. 1.4.

The active deformation of the Gibraltar Arc has been evidenced years ago, based on the differential uplift of the Quaternary terraces (Cadet et al., 1977; Brückner & Radtke, 1986; Hillaire-Marcel et al., 1986; Zazo et al., 1999). Such very recent deformations and the present-day stress field itself result mainly of the ongoing Africa-Eurasia plate convergence (see Chap. 1, Sect. 1.4), with little (if any) contribution of the subduction process described above (Sect. 5.7.4). The stress field evolution from the late Miocene-Pliocene to the present-day, and the associated active fault structure have been discussed repeatedly in the Maghrebian region (e.g. Morel, 1989; Morel & Meghraoui, 1996; Aït Brahim et al., 2002; Bargach et al., 2004; Meghraoui et al., 2004).

Detailed structural observations demonstrate that very recent deformation occurred at the front of the Rif Belt. Recent shortening is clearly visible in the Rides Prérifaines (Fig. 5.31), where Plio-Quaternary conglomerates are locally verticalized (e.g. J. Tratt next to Fes city) and display pressure solution imprints recording the entire progression of the folding process (Bargach et al., 2004; Chalouan et al., 2006a). Further to the west, in the northern Gharb Basin near the Moulay Bouselham lagoon (Figs. 5.7, 5.46), high-rate (up to 14 mm/yr) uplift has affected the lagunal deposits since 2400 BP (Benmohammadi et al., 2007). This local deformation is likely related to argilokinetic deformation of the Prerif front, also evidenced offshore by mud volcanoes. Around the Strait of Gibraltar region in southern Iberia, uplift rates have been calculated for the Late Interglacial period, using marine terraces by Zazo et al. (1999). The deformation rates deduced from these studies must be regarded with caution, due to possible chronological bias (see Plaziat et al., Chap. 8, this vol.). Nevertheless, these authors showed that to the west of the Strait of Gibraltar, the terraces suffered differential uplift, whereas to the east (along the northern margin of the Alboran Sea) they were affected by subsidence. Coastal uplift would result from the Africa-Iberia convergence accommodated by conjugate NE-SW sinistral and NW-SE dextral strike-slip faults. These active faults connect in depth with scattered seismic swarms and merge into a shallow (12–9 km depth) brittle-ductile transition (Fernández-Ibáñez & Soto, 2008).

Available GPS measurements yielded further evidence for active deformation related to the ongoing plate convergence in the Alboran region (cf. Chap. 1, Fig. 1.17). Recent geodetical observations in permanent stations (Reilly et al., 1992; Fernandes et al., 2003, 2004; Fadil et al., 2006; Stich et al., 2006; Serpelloni et al., 2007) depict a broad view of the present-day velocity field of the region. Although its precise reconstruction deserves further studies, preliminary data suggest a W-to-SW motion of the front of the Gibraltar Arc in the Rif region. Most of the stations surrounding the Alboran Sea region show a distinctive motion with respect to the overall pattern of Africa-Eurasia convergence inferred from global geodetic models. These motions reflect independent motions of crustal blocks, bounded by active faults, which suggest active delamination processes (see also Chalouan et al., 2006a).

However, the dense seismic activity of the Alboran area (cf. Fig. 1.16) yields probably the most robust evidence for the ongoing deformation of the Gibraltar Arc (e.g., Grimison & Chen, 1986; Udías & Buforn, 1991; Rebai et al., 1992; Buforn et al., 2004; Stich et al., 2006; Serpelloni et al., 2007). Fernández-Ibáñez et al. (2007) have recently compiled four types of stress indicators (wellbore breakouts, earthquake focal plane mechanisms, young geologic fault slip data, and hydraulic fracture orientations) to reconstruct the present-day stress field of the Gibraltar Arc. They indicate a regional NW-SE compressive stress field resulting from Africa-Eurasia plate convergence (Fig. 5.51A). In some particular re-

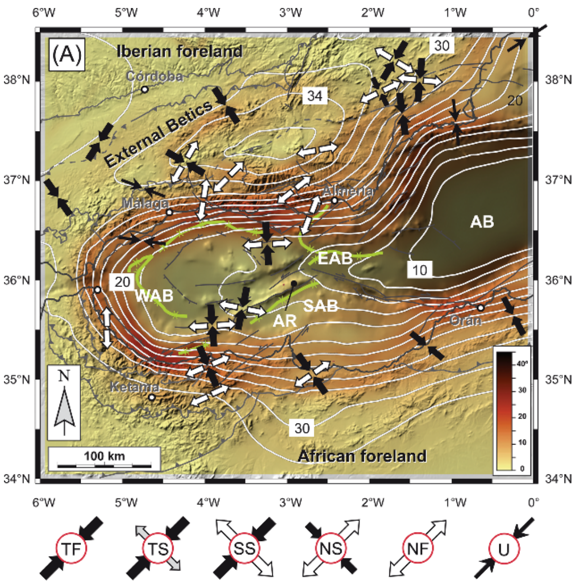


Fig. 5.51 The Present-day stress field of the Gibraltar Arc, after Fernández-Ibáñez et al. (2007). (**A**): Gradients of crustal thickness variation in the Gibraltar Arc and synthetic stress regime map. Moho contour lines (in km) are taken from Torné et al. (2000). AB, Algerian Basin; AR, Alboran Ridge; EAB, East Alboran Basin; SAB, South Alboran Basin; WAB, West Alboran Basin. Major sedimentary depocenters (*in green*). NF: normal faulting; NS: predominantly normal faulting with strike-slip component; SS: strike-slip faulting; TS: predominantly thrust faulting with strike-slip component; TF: thrust faulting; U: unknown stress regime. – (**B**): Tectonic sketch of the Gibraltar Arc showing the active fault structure, the associated stress rotations, and suggested mode of deformation partitioning within the Africa-Eurasia plate boundary. S_{Hmax} orientation and stress rotation with respect to the regional stress field are taken from Fig. 5.51A (*blue circles*, clockwise rotation; *red circles*, anticlockwise rotation; *white*, no rotation). Large arrows correspond to the Africa-Eurasia relative motion according to NUVEL-1A (DeMets et al., 1994). AD, Alboran Domain; ALF, Alpujarras fault zone; AF, Alhoceima fault zone; AMF, Alhama de Murcia fault; ARF, Alboran Ridge fault; CF, Carboneras fault; JF, El-Jebha fault; MF, Maro-Nerja fault zone; NF, Nekor fault; PF, Palomares fault; YF, Yusuf fault

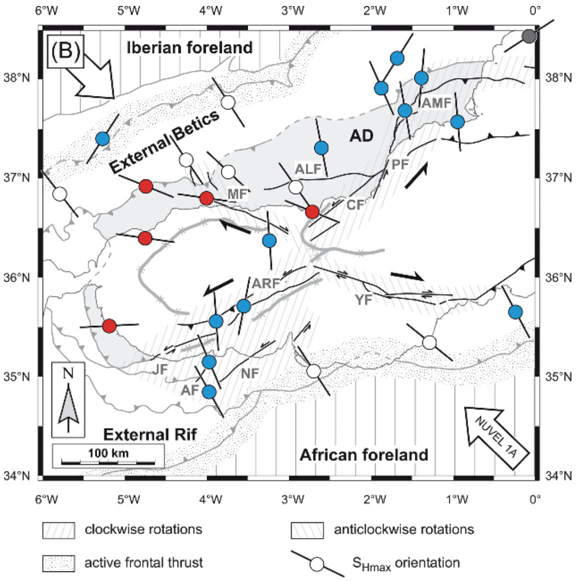


Fig. 5.51 (continued)

gions, deviations of S_{Hmax} are observed with respect to the regional stress field. They are gentle-to-moderate (22–36°) anticlockwise rotations located along the North Alboran margin and moderate-to-significant (36–78°) clockwise rotations around the Trans-Alboran Shear Zone (TASZ) (Fig. 5.51B). This is a broad fault zone, with a probable weak strength, and composed of different left-lateral strike-slip fault segments running from the eastern Betics to the Alhoceima region in the Rif and resulting in a major bathymetric high in the Alboran Sea (the Alboran Ridge fault zone). Some of these stress rotations appear to be controlled by steep gradients of crustal thickness variation across the North Alboran margin (Fig. 5.51A) and/or differential loading imposed by thick sedimentary accumulations in basin depocenters parallel to the shoreline. Other stress perturbations may be related to active left-lateral, strike-slip deformation within the TASZ that crosscuts the entire orogenic arc on a NE–SW trend and represents a key element to understand present-day deformation partitioning in the Western Mediterranean (Fig. 5.51B).

Acknowledgments The stimulating reviews of an early draft by Pr. Jean-Pierre Bouillin (Univ. Joseph-Fourier, Grenoble) and Pr. Michel Durand-Delga are gratefully acknowledged. Pr. R. Maury (Brest University) reviewed the section dedicated to the magmatism, and B. Purser the entire text for English. Thanks are also due to the colleagues who kindly provided the original files of a number of figures. This work results for a long collaboration between French, Spanish (Granada University) and Moroccan teams involved in the Betic-Rif geology. The authors thank their respective Universities for their constant support. AC and AM thank the “Office National des

Hydrocarbures et des Mines" (ONHYM) for supporting their 2006 field trip in the Rif together with Saïd Aït Brahim. AM also acknowledges the "Service des Publications" of the Ministry of Mines and Geology, Rabat, for kindly providing maps. For recent years, DFL and FN acknowledge funding by CNRS-INSU "Relief de la Terre" program, by the French-Moroccan "Action intégrée" Volubilis, Project MA/05/125, by the Junta de Andalucia (KEK), and (FN) by the French-Spanish "Action Intégrée" Picasso. JIS acknowledges support given by the Spanish project CSD2006-00041.

References

Abdelkhaliki L., Evolution tectono-sédimentaire des dépôts gravitaires dans le Prérif interne et l'unité du Habt (Rif externe occidental, Maroc): mise en place dans les bassins néogènes d'avant-fosse. Thèse Doct. Univ. Mohammed V, Rabat, 1997, 176p.

Agard P., Jullien M., Goffé B., Baronnet A., Bouybaouene M., The evidence for high-temperature (300 °C) smectite in multistage clay-mineral pseudomorphs in pelitic rocks (Rif, Morocco), *Eur. J. Mineral*. 11 (1999) 655–668.

Aït Brahim L., Chotin P., Hinaj S., Abdelouafi A., El Adraoui A., Nakcha C., Dhont D., Charroud M., Sossey Alaoui F., Amrhar M., Bouaza A., Tabyaoui H., Chaouni A., Paleostress evolution in the Moroccan African margin from Triassic to Present, *Tectonophysics* 357 (2002) 187–205.

Allerton S., Reicherter K., Platt J.P., A structural and paleomagnetic study of a section through the eastern Subbetic, southern Spain, *J. Geol. Soc. London* 151 (1994) 659–668.

Andrieux J., La structure du Rif central, *Notes Serv. Géol. Maroc* 235 (1971) 1–155.

Andrieux J., Fontboté J.M., Mattauer M., Sur un modèle explicatif de l'arc de Gibraltar, *Earth Planet. Sci. Lett*. 12 (1971) 191–198.

Andrieux J., Frizon de Lamotte D., Braud J., A structural scheme for the Western Mediterranean area in Jurassic and Early Cretaceous times, *Geodin. Acta* 3 (1989) 5–15.

Argles T.W., Prince C.I., Foster G.L., Vance D., New garnets for olds? Cautionary tales from young mountain belts, *Earth Planet. Sci. Lett*. 172 (1999) 301–309.

Asebriy L., Evolution tectonique et métamorphique du Rif central (Maroc): Définition du domaine subrifain, Thèse Doct. Etat, Univ. Mohammed V, Rabat, 1994, 283p.

Asebriy L., De Luca P., Bourgois J., Chotin P., Resédimentation d'âge sénonien dans le Rif central (Maroc): conséquences sur les division paléogéographiques et structurales de la chaîne, *J. Afr. Earth Sci*. 6 (1987) 9–17.

Augier R., Agard P., Monié P., Jolivet L., Robin C., Booth-Rea G., Exhumation, doming and slab retreat in the Betic Cordillera (SE Spain): in situ ^{40}Ar/^{39}Ar and P-T-d-t paths for the Nevado-Filbrides Complex, *J. Metamorphic Geol*. 23 (2005a) 357–381.

Augier R., Jolivet L., Robin C., Late orogenic doming in the eastern Betic Cordilleras: final exhumation of the Nevado-Filabride complex and its relation to basin genesis, *Tectonics* 24 (2005b) TC 4003, doi:10.1029/2004TC001687.

Azañón J.M., García-Dueñas V., Goffé B., Continental collision, crustal thinning and nappe forming during the pre-Miocene evolution of the Alpujarride complex (Alboran Domain, Betics), *J. Struct. Geol*. 19 (1998) 1055–1071.

Azañón J.M., Crespo-Blanc A., Exhumation during a continental collision inferred from the tectonometamorphic evolution of the Alpujarride Complex in the central Betics (Alboran Domain, SE Spain), *Tectonics* 19 (2000) 549–565.

Azdimousa A., Bourgois J., Poupeau G., Montigny R. Histoire thermique du massif de Ketama (Maroc): sa place en Afrique du Nord et dans les Cordillères bétiques, *C. R. Acad. Sci*. 326 (1998) 847–853.

Balanyá J.C., García-Dueñas V., Azañón J.M., Sánchez-Gómez M., Alternating contractional and extensional events in the Alpujarride nappes of the Alboran Domain (Betics, Gibraltar Arc), *Tectonics* 16 (1997) 226–238.

Bargach K., Ruano P., Chabli A., Galindo-Zaldivar J., Chalouan A., Jabaloy A., Akil M., Ahmamou M., Sanz de Galdeano C., Benmakhlouf M., Recent tectonic deformations and stresses in the frontal part of the Rif Cordillera and the Saïss Basin (Fes and Rabat regions, Morocco), *Pure Appl. Geophys*. 161 (2004) 521–540.

Baudelot S., Bouhdadi S,. Durand-Delga M., Datation palynologique du Trias moyen au sein des grès rouges “permo-triasiques” des environs de Tétouan (Rif septentrional, Maroc), *C.R. Acad. Sci. Paris* 299 (1984) 1061–1068.

Ben Yaïch A., Evolution tectono-sédimentaire du Rif externe centre-occidental (régions de M’Sila et Ouezzane, Maroc): la marge africaine du Jurassique au Crétacé; les bassins néogènes d’avant-fose Thèse Doct. Etat, Univ. Pau et Pays de l’Adour, 1991, 308p.

Ben Yaïch A., Durand-Delga M., Feinberg H., Maaté A., Magné J., Implications de niveaux du Miocène inférieur dans les rétrocharriages de la Dorsale rifaine (Maroc): signification à l’échelle de l’arc de Gibraltar, C. *R. Acad. Sci*. 302 (1986) 587–592.

Ben Yaïch A., Duée G., El Hatimi N., El Kadiri Kh., La formation à klippes sédimentaires d’âge oligo-burdigalien du Rif septentrional (Maroc): signification géodynamique, *Notes Serv. Géol. Maroc* 334 (1988) 99–126.

Ben Yaïch A., Duée G., Souquet P., Fondecave-Wallez M.J., Les grès de Zoumi: Dépôts turbiditiques d’une avant-fosse miocène (Burdigalien-Serravallien) dans le Rif occidental (Maroc), *C. R. Acad. Sci. Paris* 309 (1989) 1819–1825.

Ben Yaïch A., Hervouët Y, Duée G., Les turbidites calcaires du passage Jurassique-Crétacé du Rif externe occidental (Maroc): processus et contrôle de dépôt, *Bull. Soc. Géol. Fr*. 162 (1991) 841–850.

Benmohammadi A., Griboulard R., Zourarah B., Carruesco C., Mehdi K., Mridekh A., El Moussaoui A., Mhamdi Alaoui A., Carbonel P., Loudeix L., Hyperactive neotectonic near the South Rifian front lifted Late Quaternary lagunal deposits (Atlantic Morocco), *C. R. Geosci*. 339 (2007) 831–839.

Benson R.H., Rakic-El Bied K., Bonaduce G., An important current reversal (influx) in the Rifian corridor (Morocco) at the Tortonian-Messinian boundary: the end of Tethys Ocean, *Paleoceanography* 6 (1991) 164–192.

Benzaggagh M., Le Malm supérieur et le Berriasien dans le Prérif interne et le Mésorif (Rif, Maroc): stratigraphie, sédimentologie, paléogéographie et évolution tectono-sédimentaire, Thèse Doct. Univ. Mohammed V, Rabat, 1996, 403p.

Bernini M., Boccaletti M., Gelati R., Moratti G., Papani G., El Mokhtari J., Tectonics and sedimentation in the Taza-Guercif basin, northern Morocco: implications for the Neogene evolution of the Rif-Middle Atlas orogenic system, *J. Petrol. Geol*. 22 (1999) 115–128.

Bianchi G., Martinotti G., Oberhänsli R., Metasedimentary cover sequences and associated metabasites in he Sabbione Lale zone, Formazza Valley, Italy, NW Alps, *Schweiz. Mineral. Petrol. Mitt*. 78 (1998) 133–146.

Blichert-Toft J., Albarède F., Kornprobst J., Lu-Hf isotope systematics of garnet pyroxenites from Beni Bousera, Morocco: implications for basalt origin, *Science* 283 (1999) 1303–1306.

Bokelman G., Maufroy E., Mantle structure under Gibraltar constrained by dispersion of body waves, *Geoph. Res. Lett*. 34 (2007) L22305.

Booth-Rea G., Azañón J.M., García-Dueñas V., Extensional tectonics in the northeastern Betics (SE Spain): case study of extension in a multi layered upper crust with contrasting rheologies, *J. Struct. Geol*. 26 (2004) 2039–2058.

Bouillin J.P., Nouvelle interprétation de la liaison Apennin-Maghrébides en Calabre; conséquences sur la paléogéographie téthysienne entre Gibraltar et les Alpes, *Rev. Géol. Dyn. Géogr. Phys*. 25 (1984) 321–338.

Bouillin J.P., Le “bassin maghrébin”: une ancienne limite entre l’Europe et l’Afrique à l’ouest des Alpes, *Bull. Soc. Géol. Fr. (8)* 2 (1986) 547–558.

Bouillin J.P., Bellomo D., Les filons sédimentaires jurassiques de Longobuco-Caloveto (Calabre, Italie); application à l’étude des paléostructures d’une arge téthysienne, *Geodin. Acta* 4 (1990) 111–120.

Bouillin J.P., Dumont T., Mouterde R., Somma R., Hippolyte J.C., Un escarpement sous-marin permanent du Lias à l'Eocène, dans la dorsale Péloritaine (Sicile, Italie), *C. R. Acad. Sci. Paris* 328 (1999) 347–352.

Bouybaouene M.L., Etude pétrologique des métapélites des Sebtides supérieures, Rif interne, Maroc, Thèse Doct. Etat, Univ. Mohamed V, Rabat, 1993, 160p.

Bouybaouene M.L., Goffé B., Michard A., High-pressure granulites on top of the Beni Bousera peridotites, Rif Belt, Morocco: a record of an ancient thickened crust in the Alboran domain, *Bull. Soc. Géol. Fr.* 169 (1998) 153–162.

Brückner H., Radtke H., Paleoclimatic implications derived from profiles along the Spanish Mediterranean coast, in López-Vera, F. (Ed.), *Quaternary Climate in Western Mediterranean*, Univ. Complutense Madrid (1986) 467–486.

Buforn E., Bezzeghoud M., Udías A., Pro C., Seismic sources on the Iberia-African plate boundary and their tectonic implications, *Pure Appl. Geophys.* 161 (2004) 623–646.

Cadet J.P., Fourniguet J., Gigout M., Guillemin M., Pierre G., L'histoire tectonique récente (Tortonien à Quaternaire) de l'Arc de Gibraltar et des bordures de la mer d'Alboran. III: Néotectonique des littoraux,. *Bull. Soc. Géol. Fr.* 19 (1977) 600–605.

Calvert A., Sandvol E., Seber D., Barazangi M., Roecker S., Mourabit T., Vidal F., Alguacil G., Jabour N., Geodynamic evolution of the lithosphere and upper mantle beneath the Alboran region of the western Mediterranean: constraints from travel time tomography, *J. Geophys. Res.* 105 (2000) B5 10871–10898.

Calvo M., Vegas R., Osete M.-L., Paleomagnetic results from Upper Miocene and Pliocene rocks from the Internal Zone of the eastern Betic Cordilleras (southern Spain), *Tectonophysics* 277 (1997) 271–283.

Calvo M., Cuevas J., Tuba J.M., Preliminary paleomagnetic results on Oligocene-early Miocene mafic dykes from southern Spain, *Tectonophysics* 332 (2001) 333–345.

Chalouan A., Les dépôts du Trias du Rif interne: témoins de deux paléomarges téthysiennes en voie d'individualisation, in Medina F. (Ed.), *Le Permien et le Trias du Maroc: état des connaissances*, Pumag Edit., Marrakech (1996) 155–179.

Chalouan A., Michard A, The Ghomarides nappes, Rif coastal Range, Morocco: a Variscan chip in the Alpine belt, *Tectonics* 9 (1990) 1565–1583.

Chalouan A., Ouazani-Touhami A., Mouhir L., Saji R., Benmakhlouf M., Les failles normales à faible pendage du Rif interne (Maroc) et leur effet sur l'amincissement crustal du domaine d'Alboran, *Geogaceta* 17 (1995) 107–109.

Chalouan A., Saji R., Michard A., Bally A.W., Neogene tectonic evolution of the southwestern Alboran basin as inferred from seismic data off Morocco, *AAPG Bull.* 81 (1997) 1161–1184.

Chalouan A., Michard A., Feinberg H., Montigny R., Saddiqi O., The Rif mountain building (Morocco): a new tectonic scenario, *Bull. Soc. Géol. Fr.* 172 (2001) 603–616.

Chalouan A., Michard A., The Alpine Rif Belt (Morocco): a case of mountain building in a subduction-subduction-transform fault triple junction, *Pure appl. Geophys.* 161 (2004) 489–519.

Chalouan A., Galindo-Zaldívar J., Akil M., Marín C., Chabli A., Ruano P., Bargach K., Sanz de Galdeano C., Benmakhlouf M., Ahmamou M., Gourari L., Tectonic wedge expulsion in the southwestern front of the Rif Cordillera (Morocco), in Moratti, G., Chalouan, A. (Eds), Tectonics of the Western Mediterranean and North Africa, *Geol. Soc. London, Spec. Publ.* 262 (2006a) 101–118.

Chalouan A., El Mrihi A., El Kadiri Kh., Bahmad A., Salhi F., Hlila R., Mauretanian flysch nappe in the northwestern Rif Cordillera (Morocco): deformation chronology and evidence for a complex nappe emplacement, in Moratti, G., Chalouan, A. (Eds.), Tectonics of the Western Mediterranean and North Africa, *Geol. Soc. London, Spec. Publ.* 262 (2006b) 161–175.

Cifelli F., Mattei M., Porreca M., New paleomagnetic data from Oligocene-Upper Miocene sedimentsin the Rif Chain (Northern Morocco): insights on the Neogene tectonic evolution of the Gibraltar Arc, *J. Geophys. Res.* 113, B02104 (2008) doi:10.1029/2007JB005271.

Comas M.C., García-Dueñas V., Jurado M.J., Neogene tectonic evolution of the Alboran Sea from MCS data, *Geo-Mar. Lett.*, 12 (1992) 157–164.

Comas M.C., Platt J.P., Soto J.I., Watts A.B., The origin and tectonic history of the Alboran basin: insights from ODP leg 161 results, in Zahn R., Comas M.C., Klaus A. (Eds.), *Proc. Ocean Drill. Program, Sci. Res.*, 161 (1999) 555–580.

Cornée J.J., Saint-Martin J.P., Conesa G., André J.P., Muller J., Benmoussa A., Anatomie de quelques plates-formes carbonatées progradantes messiniennes de Méditerranée occidentale, *Bull. Soc. Géol. Fr.* 167 (1996) 495–507.

Coulon C., Megartsi M., Fourcade S., Maury M., Bellon H., Louni-Hacini L.A., Cotten J., Coutelle A., Hermitte D., Post-collisional transition from calc-alkaline to alkaline volcanism during the Neogene in Oranie (Algeria): magmatic expression of a slab breakoff, *Lithos* 62 (2002) 87–110.

Crespo-Blanc A., Campos J., Structure and kinematics of the South Iberian paleomargin and its relationship with the Flysch Trough units: extensional tectonics within the Gibraltar Arc fold-and-thrust belt (western Betics), *J. Struct. Geol.* 23 (2001) 1615–1630.

Crespo-Blanc A., Frizon de Lamotte D., Structural evolution of the External Zones derived from the Flysch Trough and the South Iberian and Maghrebian paleomargins around the Gibraltar Arc: a comparative study, *Bull. Soc. Géol. Fr.* 177 (2006) 267–282.

Cuevas J., Esteban J.J, Tubía J.M., Tectonic implications of the granite dyke swarm in the Ronda peridotites (Betic Cordilleras, southern Spain), *J. Geol. Soc. London* 163 (2006) 631–640.

Darraz C., Leblanc D., Interprétation du massif paléozoïque du Khebaba (Rif oriental, Maroc) comme extrusion d'un lambeau de la nappe externe des Senhadja, *C. R. Acad. Sci. Paris* 308 (1989) 71–74.

De Capoa P., Di Staso A., Perrone V., Zaghloul M.N., The age of the fordeep sedimentation in the Betic-Rifian Mauretanian units: a major constraints for the reconstruction of the evolution of the Gibraltar Arc, *C. R. Geosci.* (2007) 161–170.

De Jong K., Very fast exhumation of high-pressure metamorphic rocks with excess ^{40}Ar and inherited ^{87}Sr, Betic Cordilleras, southern Spain, *Lithos* 70 (2003) 91–110.

De Wever P., Duée G., El Kadiri Kh., Les séries stratigraphiques des klippes de Chrafate (Rif septentrional, Maroc): Témoins d'une marge continentale subsidente au cours du Jurassique-Crétacé, *Bull. Soc. Géol. Fr. (8)* 1 (1985) 363–379.

DeMets C., Gordon R.G., Argus D.F., Stein S., Effects of recent revisions to the geomagnetic reversal time scale on estimate of current plate motions, *Geophys. Res. Lett.* 21 (1994) 2191–2194.

Didon J., Hoyez B., Les séries à faciès mixte, numidien et gréso-micacé, dans le Rif occidental (Maroc), *C. R. Somm. Soc. Géol. Fr.* 6 (1978) 304–307.

Didon J., Feinberg H., Données nouvelles sur l'âge et la signification géodynamique du Miocène des Beni-Issef: importance de la tectonique burdigalienne dans le Rif septentrional (Maroc), *C. R. Somm. Soc. Géol. Fr.* 7 (1979) 183–187.

Diez J.B., Geología y Paleobotánica de la Facies Buntsandstein en la Rama Aragonesa de la Cordillera Ibérica. Implicaciones bioestratigráficas en el Peritethys Occidental. Unpubl. Tesis doctoral Univ. Zaragoza-Univ. Paris-6, 2000, 424p.

Doglioni C., Mongelli F., Pialli G., Boudinage of the Alpine belt in the Apenninic back-arc, *Mem. Soc. Geol. It.* 52 (1998) 457–468.

Doglioni C., Fernandez M., Gueguen E., Sabat F., On the interference between the early Apennines-Maghrebides back-arc extension and the Alps-Betics orogen in the Neogene geodynamics of the Western Mediterranean, *Bull. Soc. Geol. It.* 118 (1999) 75–89.

Domzig A., Yelles K., Le Roy C., Deverchère J., Bouillin J.-P., Bracène B., Mercier de Lépinay B., Le Roy P., Calais E., Kherroubi A., Gaullier V., Savoye B., Pauc H., Searching for the Africa-Eurasia Miocene boundary offshore western Algeria (MARADJA'03 cruise), *C.R. Geosci.* 338 (2006) 80–91.

Downes H., Origin and significance of spinel and garnet pyroxenites in the shallow lithospheric mantle: ultramafic massifs in orogenic belts in Western Europe and NW Africa, *Lithos* 99 (2007) 1–24.

Duggen S., Hoernle K., Van den Bogaard P., Harris C., Magmatic evolution of the Alboran region: the role of subduction in forming the Western Mediterranean and causing the Messinian Salinity Crisis, *Earth Planet. Sci. Lett*. 218 (2004) 91–108.

Durand-Delga M., La Méditerranée occidentale, étapes de sa genèse et problèmes structuraux liés à celle-ci, *Mém. Soc. Géol. Fr*. 10 (1980) 203–224.

Durand-Delga M., Geological adventures and misadventures of the Gibraltar Arc, *Z. deuts. Gesel. Geowiss*. 157 (2006), 687–716.

Durand-Delga M., Olivier Ph., Evolution of the Alboran block margin from Early Mesozoic to Early Miocene time, in Jacobshagen, V.H. (Ed.), The Atlas system of Morocco, *Lect. Notes Earth Sci*. 15 (1988) 465–480.

Durand-Delga M., Feinberg H., Magné J., Olivier Ph., Anglada R., Les formation oligo-miocènes discordantes sur les Malaguides et les Alpujarrides et leurs implications dans l'évolution géodynamique des Cordillères bétiques (Espagne) et de la Méditerranée d'Alboran, *C. R. Acad. Sci. Paris* 317 (1993) 679–687.

Durand-Delga M., Gardin S., Olivier Ph., Datation des Flyschs éocrétacés maurétaniens des Maghrébides: la formation du Jbel Tisirène, *C. R. Acad. Sci. Paris* 328 (1999) 701–709.

Durand-Delga M, Rossi P., Olivier Ph., Puglisi D., Situation structurale et nature ophiolitique de roches basiques jurassiques associées aux flyschs maghrébins du Rif (Maroc) et de Sicile (Italie), *C. R. Acad. Sci*. 331 (2000) 29–38.

Durand-Delga M., Maaté A., Illustration de la zone Tariquide au Jurassique: le rocher de Lechkrach, dans le Rif septentrional (Province de Tétouan, Maroc), *Trav. Inst. Sci. Rabat, Sér. Géol. Géogr. Phys*., 21 (2003) 127–134.

Durand-Delga M., Gardin M., Esteras M., Paquet H., Le domaine Tariquide (arc de Gibraltar, Espagne et Maroc): successions sédimentaires et événements structuraux au Lias et au Dogger, *C. R. Geosci*. 337 (2005) 787–789.

Durand-Delga M., Esteras M., Olivier Ph., The Tariquides (Gibraltar Arc): structural and paleogeographic issues, *Rev. Soc. Geol. España* 20 (2007) 119–134.

Elazzab D., Feinberg H., Paléomagnétisme des roches ultrabasiques du Rif externe (Maroc), *C. R. Acad. Sci. Paris* 318 (1994) 351–357.

Elazzab D., Galdeano A., Feinberg H., Michard A., Prolongement en profondeur d'une écaille ultrabasique allochtone: traitement des données aéromagnétiques et modélisation 3D des péridotites des Beni Malek (Rif, Maroc), *Bull. Soc. Géol. Fr*. 168 (1997) 667–683.

El Azzouzi M., Bernard-Griffiths B., Bellon H., Maury R.C., Piqué A., Fourcade S., Cotten J., Hernandez H., Evolution des sources du volcanisme marocain au cours du Néogène, *C. R. Acad. Sci. Paris* 329 (1999) 95–102.

El Bakkali S., Gourgaud A., Bourdier J.L., Bellon H., Gundogdu N., Post-collision neogene volcanism of the Eastern Rif (Morocco): magmatic evolution through time, *Lithos* 45 (1998) 523–543.

El Hatimi N., Ben Yaich A., El Kadiri K., Evolution méso-cénozoïque à la limite zones internes-zones externes dans la chaîne rifaine, *Bull. Inst. Sci. Rabat* 12 (1988) 9–18.

El Hatimi N., Duée G., Hervouet Y., La Dorsale calcaire du Haouz: ancienne marge continentale passive téthysienne (Rif, Maroc), *Bull. Soc. Géol. Fr*. 162 (1991) 79–90.

El Kadiri Kh., Description de nouvelles espèces de radiolaires jurassiques de la Dorsale calcaire externe (Rif, Maroc), *Rev. Esp. Paleont., num. extra*. (1992) 37–48.

El Kadiri Kh., Jurassic ferruginous hardgrounds from the "Dorsale Calcaire" and the Jbel Moussa Group (internal Rif, Morocco) stratigraphical context and paleoceanographic consequences of mineralization processes, *Geol Romana* 36 (2002a) 33–70.

El Kadiri Kh., "Tectono–eustatic sequences" of the Jurassic successions from the Dorsale Calcaire (Internal Rif Morocco) evidence from a eustatic and tectonic scenario, *Geol. Romana* 36 (2002b) 71–104

El Kadiri Kh., Linares A., Olóriz F., Les éléments du Groupe du Jbel Moussa (Chaîne Calcaire Rif Maroc) évolutions stratigraphique et géodynamique au cours du Jurassique–Crétacé, *Comm. Serv. Geol. Portugal* 76 (1990) 141–161.

El Kadiri Kh., Linares A., Oloriz F., La Dorsale calcaire rifaine (Maroc septentrional): evolution stratigraphique et géodynamique durant le Jurassique-Crétacé, *Notes Mém. Serv. Géol. Maroc* 336 (1992) 217–265.

El Kadiri Kh., Faouzi M., Les formations carbonatées massives de la Dorsale calcaire externe (Rif interne, Maroc), un exemple de plate-forme tidale sous contrôle géodynamique durant le Trias moyen-Lias inférieur. *Mines Géol., Rabat*, 55 (1996) 79–92.

El Kadiri K., Chalouan A., El Mrihi A., Hlila R., López-Garrido A., Sanz de Galdeano C., Serrano F., Kerzazi K., Les formations sédimentaires de l'Oligocène supérieur-Miocène inférieur dans l'unité ghomaride des Beni-Hozmar (secteur de Talembote, Rif septentrional, Maroc), *Eclogae Geol. Helv*. 94 (2001) 313–320.

El Kadiri K.h., El Kadiri K.E., Raouti A., Sédimentologie et ichnologie des calciturbidites du Crétacé supérieur – Oligocène inférieur de la série maurétanienne (nappe des Béni Ider, Rif septentrional, Maroc): implications paléogéographiques, *Bull. Inst. Sc. Rabat, 25* (2003) 73–91.

El Kadiri K.h., Serrano F., Hlila R., Liemlahi H., Chalouan A., López-Garrido A.C., Guerra-Merchán A., Sanz-de-Galdeano C., Kerzazi K., El Mrihi A., Lithostratigraphy and sedimentology of the latest Cretaceous-early Burdigalian Tamezzakht Succession (Northern Rif, Morocco): consequences for its sequence stratigraphic interpretation, *Facies* 50 (2005) 477–503.

El Kadiri Kh., El Kadiri K., Chalouan A., Bahmad A., Salhi F., Liemlahi H., Hlila H., Transgressive-Regressive Facies cycles in late Cretaceous calciturbidites from the Mauretanian Series (Beni Ider thrust sheet, Northwestern external Rif, Morocco): application of the "Facies Tract/Facies Sequence" concepts, in Moratti G., Chalouan A. (Eds.), Tectonics of the Western Mediterranean and North Africa, *Geol. Soc. London, Spec. Publ*. 262 (2006) 177–192.

El Maz A., Guiraud M., Paragenèse à faible variance dans les métapélites de la série de Filali (Rif interne marocain): description, interprétation et conséquence géodynamique, *Bull. Soc. Géol. Fr*. 172 (2001) 469–485.

Esteban J.J., Sánchez-Rodríguez L., Seward D., Cuevas J., Tubía J.M., The late thermal history of the Ronda area, southern Spain, *Tectonophysics* 389 (2004) 81–92.

Esteras M., Feinberg H., Durand-Delga M., Nouveaux éléments sur l'âge des grès numidiens de la nappe d'Aljibe (Sud-Ouest de l'Andalousie, Espagne), in 4th Coloquio Internacional sobre el Enlace fijo del Estrecho de Gibraltar, SCEG, Madrid, 1995, 103–118.

Faccenna C., Piromallo A., Crespo-Blanc A., Jolivet L., Rossetti F., Lateral slab deformation and the origin of the Mediterranean arcs, *Tectonics* 23 (2004), 23, TC1012, doi:10.1029/2002 TC001488.

Fadil A., Vernant P., McClusky S., Reilinger R., Gomez F., Ben Sari D., Mourabit T., Feigl K., Barazangi M., Active tectonics of the western Mediterranean: geodetic evidence for rollback of a delaminated subcontinental lithosphere slab beneath the Rif Mountains, *Geology* 34 (2006) 529–532.

Faugères J.C., Les Rides sud-rifaines: evolution sédimentaire et structurale d'un bassin atlantico-mésogéen de la marge africaine, Thèse Doct. Etat, Univ. Bordeaux I, 1978, 480p.

Faure-Muret A., Choubert G., Note au sujet des nappes de charriage des Temsamane (Rif oriental, Maroc), *C. R. Acad. Sci. Paris* 272 (1971a) 2657–2660.

Faure-Muret A., Choubert G., Le Maroc. Domaine rifain et atlasique, in *Tectonique de l'Afrique*, UNESCO, 1971b, pp. 17–46, 2 pl.

Favre P., Géologie des massifs calcaires situés au front S de l'unité de Kétama (Rif, Maroc), *Publ. Dépt. Géol. Paléonto. Univ. Genève (11)* 1 (1992) 138p.

Favre P., Analyse quantitative du rifting et de la relaxation thermique de la partie occidentale de la marge transformante nord-africaine: le Rif externe (Maroc). Comparaison avec la structure actuelle de la chaîne, *Geodin. Acta* 8 (1995) 59–81.

Feinberg H., Les séries tertiaires des zones externes du Rif (Maroc); biostratigraphie, paléogéographie et aperçu tectonique, *Notes Mém. Serv. Géol. Maroc* 315 (1986) 1–192.

Feinberg H., Maaté A., Bouhdadi S., Durand-Delga M., Maaté M., Magné J., Olivier Ph., Significations des dépôts de l'Oligocène supérieur-Miocène inférieur du Rif interne (Maroc) dans l'évolution géodynamique de l'arc de Gibraltar, *C. R. Acad. Sci. Paris* 310 (1990) 1487–1495.

Feinberg H., Saddiqi O., Michard A., New constraints on the bending of the Gibraltar Arc from paleomagnetism of the Ronda peridotite (Betic Cordilleras, Spain), in Morris A., Tarling D.H. (Eds.), Paleomagnetism and Tectonics of the Mediterranean Region, *Geol. Soc. London, Spec. Publ*. 105 (1996) 43–52.

Fenet B., Recherche sur l'alpinisation de la bordure septentrionale du Bouclier africain à partir d'un élément de l'Orogène nord-maghrébin: les Monts du Djebel Tessala et les Massifs du littoral oranais, Thèse Doct. Etat, Univ. Nice, 1975, 301p.

Fernandes R., Ambrosius B.A.C., Noomen R., Bastos L., Wortel M.J.R., Spakman W., Govers R., The relative motion between Africa and Eurasia as derived from ITRF2000 and GPS data, *Geophys. Res. Lett*. 30 (2003) 1828, doi:1810.1029/2003GL017089.

Fernandes R.M.S., Bastos L., Ambrosius B.A.C., Noomen R., Matheussen S., Baptista P., Recent geodetic results in the Azores Triple Junction region, *Pure Appl. Geophys*. 161 (2004) 683–699.

Fernández-Ibáñez F., Soto J.I., Zoback M.D., Morales J., Present-day stress field in the Gibraltar Arc (western Mediterranean), *J. Geophys. Res*. 112 (2007) B08404, doi:10.1029/2006JB004683.

Fernández-Ibáñez F., Soto, J.I., Crustal rheology and seismicity in the Gibraltar Arc (western Mediterranean), *Tectonics* 27, TC 2007 (2008) doi: 10.1029/2007TC002192.

Flinch F.J., Accretion and extensional collapse of the external Western Rif (Northern Morocco), in Ziegler P.A., Horvath F. (Eds.), Peri-Tethys Memoir 2: structure and prospects of Alpine basins and forelands, *Mém. Mus. Nation. Hist. Natur. Paris* 170 (1996) 61–85.

Frizon de Lamotte D., La structure du Rif oriental (Maroc), rôle de la tectonique longitudinale et importance des fluides. Thèse Doct. Etat, Univ. P. et M. Curie, Paris, 85-03, 1985, 436p.

Frizon de Lamotte D., Un exemple de collage synmétamorphe: la déformation miocène des Temsamane (Rif externe, maroc), *Bull. Soc. Géol. Fr. (8)* 3 (1987) 337–344.

Frizon de Lamotte D., Andrieux J., Guezou J.-C., Cinématique des chevauchements néogènes dans l'Arc bético-rifain: discussion sur les modèles géodynamiques, *Bull. Soc. Géol. Fr*. 169 (1991) 611–626.

Frizon de Lamotte D., Saint Bezar B., Bracène R., Mercier E., The two main steps of the Atlas building and geodynamics of the western Mediterranean, *Tectonics* 19 (2000) 740–761.

Frizon de Lamotte D., Crespo-Blanc A., Saint-Bézar B., Comas M., Fernandez M., Zeyen H., Ayarza H., Robert-Charrue C., Chalouan A., Zizi M., Teixell A., Arboleya M.L., Alvarez-Lobato F., Julivert M., Michard A., TRASNSMED-transect I [Betics, Alboran Sea, Rif, Moroccan Meseta, High Atlas, Jbel Saghro, Tindouf basin], in: Cavazza W., Roure F.M., Spakman W., Stampfli G.M., Ziegler P.A. (Eds.), *The TRANSMED Atlas – the Mediterranean region from crust to mantle, Springer, Berlin* (2004) ISBN 3-540-22181-6, CD Rom.

Fullea Urchulutegui J., Fernàndez M., Zeyen H., Lithospheric structure in the Atlantic-Mediterranean transition zone (southern Spain, norther Morocco): a simple approach from regional elevation and geoid data, *C. R. Geosci*. 338 (2006) 140–151.

García-Dueñas V., Balanyá J.C., Martínez-Martínez J.M., Miocene extensional detachment in the outcropping basement of the northern Alboran Basin (Betics) and their tectonic implications, *Geo-Mar. Lett*. 12 (1992) 88–95.

García-Dueñas V., Balanyá J.C., Sánchez-Gómez M., El despegue extensional de Lahsene y los jirones de serpentinitas del anticlinal de Taryat (Melilla, Rif), *Geogaceta* 17 (1995) 138–139.

Gill R.C.O., Aparicio A., El Azzouzi M., Hernandez J., Thirlwall M.F., Bourgois J., Marriner G.F., Depleted arc volcanism in the Alboran Sea and shoshonitic volcanism in Morocco: geochemical and isotopic constraints on Neogene tectonic processes, *Lithos* 78 (2004) 363–388.

Goffé B, Azañón J.M., Bouybaouene M.L., Jullien M., Metamorphic cookeite in Alpine metapelites from Rif (northern Morocco) and Betic chains (southern Spain), *Eur. J. Mineral*. 6 (1996) 897–911.

Grimison N.L., Chen W.-P., The Azores-Gibraltar plate boundary: focal mechanisms, depth of earthquakes, and their tectonic implications, *J. Geophys. Res*. 91 (1986) 2029–2047.

Guardia P., Géodynamique de la marge alpine du continent africain d'après l'étude de l'Oranie nord-occidentale, Thèse Doct. Etat, Univ. Nice, 1975, 286p.

Guerrera F., Martín-Martín M., Perrone V., Tramontana M., Tectono-sedimentary evolution of the southern branch of the Western Tethys (Maghrebian Flysch basin and Lucanian ocean): consequences for Western Mediterranean geodynamics, *Terra Nova* 17 (2005) 358–367.
Guillemin M., Houzay J.P., Le Néogène post-nappes et le Quaternaire du Rif nord-oriental (Maroc). Stratigraphie et tectonique des bassins de Melilla, du Kert, de Boudinar et du piedmont des Kebdana, *Notes Mém. Serv. Géol. Maroc* 314 (1982) 7–238.
Gurría E, Mezcua J., Seismic tomography of the crust and lithospheric mantle in the Betic Cordillera and Alboran Sea, *Tectonophysics* 329 (2000) 99–119.
Gutscher M.A., Malod J., Rehault J.P., Contrucci I., Klingelhoefer F., Mendes-Victor L., Spakman W., Evidence for active subduction beneath Gibraltar, *Geology* 30 (2002) 1071–1074.
Haissen F., Garcia-Casco A., Torres-Roldan R., Aghzer A., Decompression reactions in high-pressure granulites from Casares-Los Reales units of the Betic-Rif Belt (S Spain and N Morocco), *J. Afr. Earth Sci*. 39 (2004) 375–383.
Helbing H., Frisch W., Pons P.D., South Variscan accretion: sardinian constraints on the intra-Alpine Variscides, *J. Struct. Geol*. 28 (2006) 1277–1291.
Herbig H-G., Carboniferous paleogeography of the West-Mediterranean Paleotethys, *C. R. 11th Int. Congr. Strat. Geol. Carboniferous*, Beijing 1987, 4 (1989) 186–196.
Herbig H.-G., Mamet B., Stratigraphy of the limestone boulders, Marbella Formation (Betic Cordillera, Southern Spain), *C.R. 10ème Congr. Intern. Strat. Géol. Carbonifère*, Madrid 1983, 1 (1985) 199–212.
Hernandez J., Leblanc D., Marçais J., Une manifestation volcanique d'âge paléocène dans le Rif (Maroc): les laves basaltiques de Sidi Maatoug, *Bull. Soc. Géol. Fr. (7)* 18 (1976) 697–705.
Hernandez J., de Larouzière F.D., Bolze J., Bordet P., Le magmatisme néogène bético-rifain et le couloir de décrochement trans-Alboran, *Bull. Soc. Géol. Fr. (8)* 3 (1987) 257–267.
Hillaire-Marcel C., Carro O., Causse C., Goy J. L., Zazo C., Th/U dating of *Strombus bubonius*-bearing marine terraces in southeastern Spain, *Geology* 14 (1986) 613–616.
Hlila R., Sanz de Galdeano C., Structure de la chaîne du Haouz (Rif interne, Maroc). Interprétation et aspects chronologiques, *C. R. Acad. Sci. Paris* 318 (1994) 1261–1266.
Houseman G. A., Molnar P., Mechanisms of lithospheric rejuvenation associated with continental orogeny, in Miller J.A., Holdsworth R.E., Buick I.S., Hand M. (Eds.), Continental reactivation and reworking, *Geol. Soc. London, Spec. Publ*. (2001) 13–38.
Hoyez B., Le Numidien et les flyschs oligo-miocènes de la bordure sud de la Méditerranée occidentale, Thèse Doct. Etat, Univ. Lille, 1989, 464p.
Janots E., Negro F., Brunet F., Goffé B., Engi M., Bouybaouene M.L., Evolution of the REE mineralogy in HP-LT metapelites of the Sebtides complex, Rif, Morocco: monazite stability and geochronology, *Lithos* 87 (2006) 214–234.
Johnson C., Harbury N., Hurford A.J., The role of extension in the Miocene denudation of the Nevado-Filabride Complex, Betic Cordillera (SE Spain), *Tectonics* 16 (1997) 189–204.
Jolivet L., Faccenna C., Mediterranean extension and the Africa-Eurasia collision, *Tectonics* 19 (2000) 1095–1106.
Jolivet L., Augier R., Robin C., Suc J.P., Rouchy J.M., Lithospheric-scale geodynamic context of the Messinian salinity crisis, *Sedim. Geol*. 188–189 (2006) 9–33.
Kerzazi K., Etudes biostratigraphique du Miocène sur la base des foraminifères planctoniques et nannofossiles calcaires dans le Prérif et la marge atlantique du Maroc (site 547A du DSDP Leg 79); aperçu sur leur paléoenvironnement. Thèse Univ. P. et M. Curie, Paris, 1994, 230p.
Kirèche O., Evolution géodynamique de la marge tellienne des Maghrébides d'après l'étude du domaine parautochtone schisteux (Massifs du Chéliff et d'Oranie, de Blida-Bou Maad, des Babors et Bibans), Thèse Doct. Etat, Univ. Nice, 1993, 328p.
Kornprobst J., Contribution à l'étude pétrographique et structuralede la Zone interne du Rif (Maroc septentrional), *Notes Mém. Serv. Géol. Maroc*, 251 (1974) 1–256.
Kornprobst J., Piboule M., Roden M., Tabit A., Corundum-bearing garnet clinopyroxenites at Beni Bousera (Morocco): original plagioclase-rich gabbros recrystallized at depth within the mantle, *J. Petrol*. 31 (1990) 717–745.

Krijgsman W., Langereis C.G., Magnetostratigraphy of the Zobzit and Koudiat Zarga sections (Taza-Guercif basin, Morocco): implications for the evolution of the Rifian Corridor, *Marine Petrol. Geol*. 17 (2000) 359–371.

Krijgsman W., Garcès M., Paleomagnetic constraints on the geodynamic evolution of the Gibraltar Arc, *Terra Nova* 16 (2004) 281–287.

Kumar N., Reisberg L., Zindler A., A major and trace elements and strontium, neodymium, and osmium isotopic study of a thick pyroxenite layer from the Beni Bousera ultramafic complex of northern Morocco, *Geochim. Cosmochim. Acta* 60 (1996) 1429–1444.

Lacombe O., Jolivet L., Structural and kinematic relationships between Corsica and the Pyrenees-Provence domain at the time of the Pyrenean orogeny, Tectonics 24 (2005) TC1003 doi:10.1029/2004TC001673.

Lamarti-Sefian N., André J.-P., El Hajjaji Kh., Pouyet S., Ben Moussa A. Une plate-forme ouverte à faciès bryomol: le bassin Miocène supérieur de Charf El Akab (Maroc atlantique), *C. R. Acad. Sci. Paris* 327 (1998) 377–383.

Leblanc D., Etude géologique du Rif externe oriental au nord de Taza (Maroc), *Notes Mém. Serv. Géol. Maroc* 281 (1979) 1–159.

Leblanc D., Wernli R., Existence probable d'un important charriage dans l'unité de Kétama (Rif, Maroc), *C. R. Soc. Phys. Hist. Nat. Genève* 15 (1980) 154–156.

Leblanc D., Feinberg H., Nouvelles données stratigraphiques et structurales sur le Numidien du Rif oriental (Maroc). Implications géodynamiques, *Bull. Soc. Géol. Fr. (7)* 24 (1982) 861–865.

Leblanc D., Olivier P., Role of strike-slip faults in the Betic-Rifian orogeny, *Tectonophysics* 101 (1984) 345–355.

Leikine M., Asebriy L., Bourgois J., Sur l'âge du métamorphisme anchi-épizonal de l'unité de Ketama, Rif central (Maroc), *C. R. Acad. Sci. Paris* 313 (1991) 787–793.

Lenoir X., Garrido C.J., Bodinier J.L., Dautria J.M., Gervilla F., The recrystallization front of the Ronda peridotite: evidence for melting and thermal erosion of subcontinental lithospheric mantle beneath the Alboran bBasin, *J. Petrol*. 42 (2001) 141–158.

Lespinasse P., Géologie des zones externes et des flyschs entre Chaouen et Zoumi (Centre de la Chaîne rifaine, Maroc), Thèse Doct. Etat, Univ. P. & M. Curie, Paris, 1975, 247p.

Litto W., Jaaidi E., Dakki M., Medina F., Etude sismo-structurale de la marge nord du bassin du Gharb (avant-pays rifain, Maroc): mise en évidence d'une distension d'âge miocène supérieur, *Eclogae Geol. Helv*. 94 (2001) 63–73.

Loget N., Van Den Driessche J., On the origin of the Strait of Gibraltar, *Sedim. Geol*. 188–189 (2006) 341–356.

Lonergan L., Mange-Rajetsky M., Evidence for Internal Zone unroofing from foreland basin sediments, Betic Cordillera, SE Spain, *J. Geol. Soc. London* 151 (1994) 515–529.

Lonergan L., White N., Origin of the Betic-Rif mountain belt, *Tectonics* 16 (1997) 504–522.

Loomis T.H., Diapiric emplacement of the Ronda high-temperature ultramafic intrusion, southern Spain, *Geol. Soc. Am. Bull*. 83 (1972) 2475–2496.

López Casado C., Sanz de Galdeano C., Molina Palacios S., Henares Romero J., The structure of the Alboran Sea: an interpretation from seismological and geological data, *Tectonophysics* 338 (2001) 79–95.

López Sánchez-Vizcaíno V., Rubatto D., Gómez-Pugnaire M.T., Trommsdorff V., Müntener O., Middle Miocene high-pressure metamorphism and fast exhumation of the Nevado-Filabride Complex, SE Spain, *Terra Nova* 13 (2001) 327–332.

Lundeen M.T., Emplacement of the Ronda peridotite, Sierra Bermeja, Spain, *Geol. Soc. Am. Bull*. 89 (1978) 172–180.

Lustrino M., Wilson M., The circum-Mediterranean anorogenic Cenozoic igneous province, *Earth Sci. Rev*. 81 (2007) 1–65.

Maaté A., Estratigrafia y evolucion paleogeografica alpina del dominio gomaride (Rif interno, Marruecos), Tesis doct. Univ. Granada, 1996, 397p.

Maaté A., Solé De Porta N., Martin-Algarra A., Données paléontologiques nouvelles sur le Carnien des séries rouges des Maghrébides (Ghomarides et Dorsale calcaire du Rif septentrional, Maroc), *C. R. Acad. Sci. Paris* (1993) 316 II 137–143.

Maillard A., Gorini C., Mauffret A., Sage F., Lofi J., Gaullier V., Offshore evidence of polyphase erosion in the Valencia basin (NW Mediterranean): scenario for the Messinian salinity crisis, *Sedim. Geol*. 188–189 (2006) 69–91.

Maldonado A., Somoza L., Pallarés L., The Betic orogen and the Iberian-African boundary in the Gulf of Cadiz: geological evolution (central North Atlantic), *Marine Geol*. 155 (1999) 9–43.

Malinverno A, Ryan B.F., Extension in the Tyrrhenian Sea and shortening in the Appenines as result of arc migration driven by sinking of the lithosphere, *Tectonics* 5 (1986) 227–245.

Martín-Algarra A., Messina A., Perrone V., Russo S., Maate A., Martín-Martín M., A lost realm in the Internal domains of the Betic-Rif orogen (Spain and Morocco): evidence from conglomerates and consequences for Alpine geodynamic evolution, *J. Geol*. 108 (2000) 447–467.

Martín-Martín M., El Mamoune B., Martín-Algarra A., Serra-Kiel J., La formation As, datée de l'Oligocène, est impliquée dans les charriages des unités Malaguides supérieures de la Sierra Espuña (zones internes bétiques, province de Murcie, Espagne), *C. R. Acad. Sci. Paris* 325 (1997) 861–868.

Martín-Martín M., Martín-Rojas I., Caracuel J.E., Estévez-Rubio A., Martín-Algarra A., Sandoval J., Tectonic framework and extensional pattern of the Malaguide complex from Sierra Espuña (Internal Betic Zone) during Jurassic-Cretaceous: implications for the Westernmost Tethys geodynamic evolution, *Int. J. Earth Sci*. (2006) doi:10.1007/s00531-005-0061-7.

Martínez-Martínez J.M., Azañón J.M., Mode of extensional tectonics in the southeastern Betics (SE Spain): implications for the tectonic evolution of the peri-Alboran orogenic system, *Tectonics* 16 (1997) 205–225.

Martínez-Martínez J.M., Soto J.I., Balanyá J.C., Orthogonal folding of extentional detachments: structure and origin of the Sierra Nevada elongated domes (Betics, SE Spain), *Tectonics* 21/3 (2002) 1012, doi:10.1029/2001TC001283.

Mattei M., Cifelli F., Martín Rojas I., Crespo Blanc A., Comas M., Faccenna C., Porreca M., Neogene tectonic evolution of the Gibraltar Arc: new paleomagnetic constrains from the Betic chain, *Earth Planet. Sci. Lett*. 250 (2006) 522–540.

Mauffret A., Frizon de Lamotte D., Lallemant S., Gorini C., Maillard A., E-W opening of the Algerian basin (Western Mediterranean), *Terra Nova* 16 (2004) 257–264.

Mauffret A., Ammar A., Gorini C., Jabour H., The Alboran Sea (Western Mediterranean) revisited with a view from the Moroccan margin, *Terra Nova* 19 (2007) 195–203.

Maury R.C., Fourcade S., Coulon C., El Azzouzi M., Bellon H., Coutelle A., Ouabadi A., Semroud B., Megartsi M., Cotten J., Belanteur O., Louni-Hacini A., Piqué A., Capdevila R., Hernandez J., Rehault J.-P., Post-collisional Neogene magmatism of the Mediterranean Maghreb margin: a consequence of slab breakoff, *C. R. Acad. Sci*. 331 (2000) 159–173.

Meghraoui M., Maouche S., Chemaa B., Cakir Z., Aoudia A., Harbi A., Alasset P.J., Ayadi A., Bouhadad Y., Benhamouda F., Coastal uplift and thrust faulting associated with the Mw = 6.8 Zemmouri (Algeria) earthquake of 21 May, 2003, *Geophys. Res. Lett*. 31 (2004) L19606, doi:19610.11029/12004GL020466.

Michard A., Goffé B., Chalouan A., Saddiqi O., Les corrélations entre les Chaînes bético-rifaines et les Alpes et leurs conséquences, *Bull. Soc. Géol. Fr*. 162 (1991) 1151–1160.

Michard A., Feinberg H., Elazzab D., Bouybaouene M.L., Saddiqi O., A serpentinite ridge in a collisional paleomargin setting: the Beni Malek massif, External Rif, Morocco, *Earth Planet. Sci. Lett*. 113 (1992) 435–442.

Michard A., Goffé B., Bouybaouene M., Saddiqi O., Late Hercynian-Mesozoic thinning in the Alboran domain: metamorphic data from the northern Rif, Morocco, *Terra Nova* 9 (1997) 1–8.

Michard A., Chalouan A., Feinberg H., Goffé B., Montigny R., How does the Alpine belt end between Spain and Morocco? *Bull. Soc. Géol. Fr*. 173 (2002) 3–15.

Michard A., Frizon de Lamotte D., Chalouan A., Comment on "The ultimate Arc: differential displacement, oroclinal bending, and vertical axis rotation in the External Betic-Rif arc" by J.P. Platt et al. *Tectonics* 24 (2005) TC 1005, 1–3.

Michard A. Negro F., Saddiqi O., Bouybaouene M.L., Chalouan A., Montigny R., Goffé B., Pressure-temperature-time constraints on the Maghrebide mountain building: evidence from the Rif-Betic transect (Morocco, Spain), Algerian correlations, and geodynamic implications, *C. R. Geosci*. 338 (2006) 92–114.

Michard A., Frizon de Lamotte D., Negro F., Saddiqi O., Serpentinite slivers and metamorphism in the External Maghrebides: arguments for an intracontinental suture in the African paleomargin (Morocco, Algeria), *Rev. Soc. Geol. España* 20 (2007) 173–185.

Micheletti F., Barbey P., Fornelli A., Piccarreta G., Deloule E., Latest Precambrian to Early Cambrian U-Pb zircon ages of augen gneisses from Calabria, with reference to the Alboran microplate in the evolution of the peri-Gondwana terranes, *Int. J. Earth Sci*. (2006) doi:10.1007/s00531-006-0136-0.

Monié P., Frizon de Lamotte D., Leikine M., Etude géologique préliminaire par la méthode $^{39}Ar/^{40}Ar$ du métamorphisme alpin dans le Rif externe (Maroc). Précisions sur le calendrier tectonique tertiaire, *Rev. Géol. Dynam. Géogr. Phys*. 25 (1984) 307–317.

Monié P., Galindo Zaldivar J., Gonzalez Lodeiro F., Goffé B., Jabaloy A., $^{40}Ar/^{39}Ar$ geochronology of Alpine tectonism in the Betic Cordilleras (southern Spain), *J. Geol. Soc. London* 148 (1991) 288–297.

Monié P., Torres-Roldan R.L., García-Casco A., Cooling and exhumation of the Western Betic Cordilleras, $^{40}Ar/^{39}Ar$ thermochronological constraints on a collapsed terrane, *Tectonophysics* 238 (1994) 353–379.

Montel J.-M., Kornprobst J., Vielzeuf D., Preservation of old U-Th-Pb ages in shielded monazites: example from the Beni-Bousera Hercynian kinzigites (Morocco), *J. Metam. Geol*. 18 (2000) 335–342.

Montenat C., Ott d'Estevou P., Masse P., Tectonic-sedimentary charcter of the Neogene basins evolving in a crustal transcurrent shear zone (SE Spain), *Bull. Cent. Res. Explor.-Prod. Elf-Aquitaine* 11 (1987) 1–22.

Morel J.C., Etats de contrainte et cinématique de la chaîne rifaine (Maroc) du Tortonien à l'actuel, *Geodin. Acta* 3 (1989) 283–294.

Morel J.C., Meghraoui M., Goringe-Alboran-Tell tectonic zone: a transpression system along the Africa-Eurasia plate boundary, *Geology* 24 (1996) 755–758.

Morley C.K., Origin of a major cross-element zone: Moroccan Rif, *Geology* 15 (1987) 761–764.

Morley C.K., Notes on Neogene basin history of the western Alboran Sea and its implications for the tectonic evolution of the Rif-Betic orogenic belt, *J. Afr. Earth Sci*. 14 (1992) 57–65.

Mourier T., Frizon de Lamotte D., Feinberg H., Etapes de la structuration tertiaire dans le chaînon des Bokoyas, *C. R. Acad. Sci. Paris* 294 (1982) 1147–1150.

Münch P., Stephan R., Cornée J.J., Saint-Martin J.P., Féraud G., Ben Moussa A., Restriction des communications entre l'Atlantique et la Méditerranée au Messinien: apport de la téphrochronologie dans la plate-forme carbonate et le basin de Mellila-Nador (Rif oriental, Maroc), *C. R. Acad. Sci. Paris* 332 (2001) 569–576.

Najid D., Westphal M., Hernandez J., Paleomagnetism of Quaternary and Miocene lavas from North-East and Central Morocco, *J. Geophys*. 49 (1981) 149–152.

Negro, F., Exhumation des roches métamorphiques du Domaine d'Alboran: étude de la chaîne rifaine (Maroc) et corrélation avec les Cordillères bétiques (Espagne), Thèse Doct. Univ. Paris-XI Orsay, 2005, 250p.

Negro F., Beyssac O., Goffé B., Saddiqi O., Bouybaouene M.L., Thermal structure of the Alboran Domain in the Rif (northern Morocco) and the Western Betics (southern Spain). Constraints from Raman spectroscopy of carbonaceous material, *J. Metamorph. Geol*. (2006) doi:1111/j.1525-1314.2006.00639.

Negro F., Agard P., Goffé B., Saddiqi O., Tectonic and metamorphic evolution of the Temsamane units, External Rif (northern Morocco). Implications for the evolution of the Rif and the Betic-Rif arc, *J. Geol. Soc. London* 164 (2007) 824–842.

Nold M., Uttinger J., Wildi W., Géologie de la Dorsale calcaire entre Tétouan et Assifane (Rif interne, Maroc), *Notes Mém. Serv. Géol. Maroc* 300 (1981) 1–233.

Obata M., The Ronda peridotite: Garnet-, spinel-, and plagioclase-lherzolite facies and the P-T trajectories of a high-temperature mantle intrusion, *J. Petrol*. 21 (1980) 533–572.

Olivier Ph., L'accident de Jebha-Chrafate (Rif, Maroc), *Rev. Géol. Dyn. Géogr. Phys*. 22 (1981–1982) 201–212.

Olivier Ph., Evolution de la limite entre zones internes et zones externs dans l'arc de Gibraltar (Maroc, Espagne), Thèse Doct. Etat, Univ. Toulouse, 1984, 229p.

Olivier Ph., Les unités de Beni-Derkoul (Rif, Maroc). Place et signification dans l'évolution alpine de la marge nord de la Téthys maghrébine, *Bull. Soc. Géol. Fr. (8)* 6 (1990) 145–154.

Olivier Ph., Leikine M., Decrouez D., Caractérisation et interprétation d'Eocène moyen-supérieur épimétamorphique dans les zones internes rifaines (Maroc septentrional), *C. R. Acad. Sci. Paris* 314 (1992) 499–506.

Olivier Ph., Durand-Delga M., Manivit H., Feinberg H., Peybernes B., Le substratum jurassique des flyschs maurétaniens de l'ouest des Maghrébides: l'unité de Ouareg (région de Targuist, Rif, Maroc), *Bull. Soc. Géol. Fr*. 167 (1996) 609–616.

Orozco M., Molina J.M., Crespo-Blanc A., Alonso-Chaves F.M., Palaeokarst and rauhwacke development, mountain uplift and subaerial sliding of tectonic sheets (northern Sierra de los Filabres, Betic Cordilleras, Spain), *Geol. Mijnb*. 78 (1999) 103–117.

Osete M.L., Villalain J.J., Palencia A., Osete C., Sandoval J., García-Dueñas V., New palaeomagnetic data from the Betic Cordillera: constraints on the timing and the geographical distribution of tectonic rotations in southern Spain, *Pure Appl. Geophys*. 161 (2004) 1–22.

Pastorelli S., Martinotti G., Piccardo G.B., Rampone E., Scambelluri M., The Geisspfad Complex and its relationships with the Monte Leone Nappe (Lower Pennine, Western Alps), *Rend. Acc. Naz. Lincei* 14 (1995) 349–358.

Pearson D.G., Davies G.R., Nixon P.H., Milledge H.J., Graphitized diamonds from a peridotite massif in Morocco and implications for anomalous diamond occurrences, *Nature* 335 (1989) 60–66.

Pearson D.G., Nowell G.M., Re-Os and Lu-Hf isotope constraints on the origin and age of pyroxenites from the Beni Bousera peridotites massif: implications for mixed peridotites-pyroxenite mantle sources, *J. Petrol*. 45 (2004) 439–455.

Pecerillo A., Martinotti G., The Western Mediterranean lamproitic magmatism: origin and geodynamic significance, *Terra Nova* 18 (2006) 105–117.

Platt J.P., Soto J.I., Whitehouse M.J., Hurford A.J., Kelley S.P., Thermal evolution, rate of exhumation, and tectonic significance of metamorphic rocks from the floor of the Alboran extensional Basin, Western Mediterranean, *Tectonics*, 17 (1988) 671–689.

Platt J.P., Vissers R.L.M., Extensional collapse of thickened continental lithosphere: a working hypothesis for the Alboran Sea and Gibraltar Arc, *Geology* 17 (1989) 540–543.

Platt J.P., Whitehouse M.J., Early Miocene high-temperature metamorphism and rapid exhumation in the Betic Cordillera (Spain): evidence from U-Pb zircon ages, *Earth Planet. Sci. Lett*. 171 (1999) 591–605.

Platt J.P., Allerton S., Kirker A., Mandevill C., Mayfield A., Platzmann E.S., Rimi A., The ultimate Arc: differential displacement, oroclinal bending, and vertical axis rotation in the External Betic-Rif arc, *Tectonics* 22 (2003a) 1017, 1–29.

Platt J.P., Argles T.W., Carter A., Kelley S.P., Whitehouse M.J., Lonergan N., Exhumation of the Ronda peridotite and its crustal envelope: constraints from thermal modelling of a P-T-time array, *J. Geol. Soc. London* 160 (2003b) 655–676.

Platt J.P., Kelley S.P., Carter A., Orozco M., Timing of tectonic events in the Alpujarride Complex, Betic Cordillera, S. Spain, *J. Geol. Soc. London* 162 (2005) 451–462.

Platt J., Anczkiewicz R., Soto J.-I., Kelley S.P., Thirwall M., Early Miocene subduction and rapid exhumation in the west Mediterranean, *Geology* 34 (2006) 981–984.

Platzmann E.S., Paleomagnetic rotations and kinematics of the Gibraltar Arc, *Geology* 20 (1992) 311–314.

Platzmann E.S., Platt J.P., Olivier P., Paleomagnetic rotations and fault kinematics in the Rif Arc of Morocco, *J. Geol. Soc. London* 150 (1993) 707–718.

Platzmann E.S., Platt J.P., Kelley S.P., Large clockwise rotations in an extensional allochthon, Alboran Domain (Southern Spain), *J. Geol. Soc. London* 17 (2000) 1187–1197.

Plaziat J.-C., Ahmamou M., Les différents mécanismes à l'origine de la diversité des séismites, leur identification dans le Pliocène du Saïss de Fès et de Meknès (Maroc) et leur signification tectonique, *Geodin. Acta* 11 (1998) 182–203.

Polvé M.., Les isotopes du Nd et du Sr dans les lherzolites orogéniques: contribution à la détermination de la structure et de la dynamique du manteau supérieur, Thèse Univ. Paris-VII, 1983, 361p.

Polyak B.G., Fernàndez M., Khutorskoy M.D., Soto J.I., Basov I.A., Comas M.C., Khain V.Y., Agapova G.V., Mazurova I.S., Negredo A., Tochitsky V.O., de la Linde J., Bogdanov N.A., Banda E., Heat flow in the Alboran Sea, western Mediterranean, *Tectonophysics* 263 (1996) 191–218.

Puga E., Nieto J.M., Díaz de Federico A., Bodinier J.L., Morten L., Petrology and metamorphic evolution of ultramafic rocks and dolerite dykes of the Betic Ophiolitic Association (Mulhacén Complex, SE Spain): evidence of eo-Alpine subduction following an ocean-floor metasomatic process, *Lithos* 49 (1999) 23–56.

Puga E., Díaz de Federico A., Nieto J.M., Tectonostratigraphic subdivision and petrological characterisation of the deepest complexes of the Betic zone: a review, *Geodin. Acta* 15 (2002a) 23–43.

Puga E., Ruiz Cruz M.D., Díaz de Federico A., Polymetamorphic amphibole veins in metabasalts from the Betic ophiolitic association at Cóbdar, southern Spain: relics of ocean-floor metamorphism preserved through the Alpine orogeny, *Canad. Mineral*. 40 (2002b) 67–83.

Puglisi D., Zaghloul M.N., Maaté A., Evidence of sedimentary supply from plutonic sources in the Oligocene-Miocene flyschs of the Rifian Chain (Morocco): provenance and paleogeographic implications, *Bull. Soc. Geol. It*. 120 (2001) 55–68.

Raoult J.F., Géologie du centre de la Chaîne numidique (Nord du Constantinois, Algérie), *Mém. Soc. Géol. Fr*. 53–121 (1974), 163p.

Raumer J.F. von, Stampfli G.M., Bussy F., Gondwana derived microcontinents – the constituents of the Variscan and Alpine collisional orogens, *Tectonophysics* 365 (2003) 7–22.

Rebai S., Phillip H., Taboada A., Modern tectonic stress field in the Mediterranean Region-Evidence for variation in stress directions at different scales, *Geophys. J. Intern*. 110 (1992) 106–140.

Rehaut J.P., Boillot G., Mauffret A., The western Mediterranean Basin geological evolution, *Marine Geol*. 55 (1984) 447–477.

Reilly W.I., Frederich G., Hein G.W., Landau H., Almazán J.L., Caturla J.L., Geodetic determination of crustal deformation across the Strait of Gibraltar, *Geophys. J. Intern* 111 (1992) 391–398.

Reuber I., Michard A., Chalouan A., Juteau T., Jermoumi B., Structure end emplacement of the alpine-type peridotite from Beni Bousera, Rif, Morocco: a polyphase tectonic interpretation, *Tectonophysics* 82 (1982) 231–251.

Rimi A., Chalouan A., Bahi L., Heat flow in the westernmost part of the Alpine Mediterranean system (the Rif, Morocco), *Tectonophysics* 285 (1998) 135–146.

Roca E., Sans M., Koyi H.A., Polyphase deformation of diapiric areas in models and in the eastern Prebetics (Spain), *AAPG Bull*. 90 (2006) 115–136.

Royden L.H., Evolution of retreating subduction boundaries formed during continental collision, *Tectonics* 12 (1993) 629–638.

Saddiqi O., Exhumation des roches profondes, péridotites et roches métamorphiques HP-BT dans deux transects de la chaîne alpine: Arc de Gibraltar et Montagnes d'Oman, Thèse Doct. Etat, Univ. Casablanca Aïn Chock, 1995, 245p.

Saddiqi O., Reuber I., Michard A., Sur la tectonique de dénudation du manteau infracrustal dans les Beni Bousera, Rif septentrional, Maroc, *C. R. Acad. Sci*. 307 (1988) 657–662.

Saddiqi O., Feinberg H., Elazzab D., Michard A., Paléomagnétisme des péridotites des Beni Bousera (Rif interne, Maroc): conséquences pour l 'évolution miocène de l'Arc de Gibraltar, *C. R. Acad. Sci*. 321 (1995) 361–368.

Samaka F., Ben Yaïch A., Dakki M., Hçaine M., Bally A.W., Origine et inversion des bassins miocènes supra-nappes du Rif Central (Maroc). Etude de surface et de subsurface. Exemple des bassins de Taounate et de Tafrannt, *Geodin. Acta* 10 (1997) 30–40.

Sánchez-Gómez M., Azañon J.M., García-Dueñas V., Soto J.I., Correlation between metamorphic rocks recovered from site 976 and the Alpujarride rocks of the Western Betics, in Zahn R., Comas M.C., Klaus A. (Eds.), *Proc. Ocean Drilling Program, Sci. Results* 161 (1999) 307–317.

Sánchez-Gómez M., Balanyá J.C., García-Dueñas V., Azañon J.M., Intracrustal tectonic evolution of large lithosphere mantle slabs in the western end of the Mediterranean orogen (Gibraltar Arc), in Rosenbaum G., Lister G.S. (Eds.), Reconstruction of the Alpine-Himalayan Orogent, *J. Virt. Explorer* 8 (2002) 23–34.

Sánchez-Rodriguez L., Gebauer D., Mesozoic formation of pyroxenites and gabbros in the Ronda area (southern Spain), followed by early Miocene subduction metamorphism and emplacement into the middle crust: U-Pb sensitive high-resolution ion microprobe dating of zircon, *Tectonophysics* 316 (2000) 19–44.

Sani F., Del Ventisette C., Montanari D., Bendkik A., Chenakeb M., Structural evolution of the Rides Prerifaines (Morocco): structural and seismic interpretation and analogue modelling, *Int. J. Earth Sci*. 96 (2007) 685–706.

Sanz de Galdeano C., El Kadiri K., Simancas J.F., Hlila R., López-Garrido A.C., El Mrihi A., Chalouan A., Palaeogeographical reconstruction of the Malaguide-Ghomaride Complex (Internal Betic-Rifian Zone) based on Carboniferous granitoid pebble provenance, *Geol. Carpath*. 57 (2006) 327–336.

Sautkin A., Talukder A.R., Comas M.C., Soto J.I., Alekseev A., Mud volcanoes in the Alboran Sea: evidence from micropaleontological and geophysical data, *Mar. Geol*., 195 (2003) 237–261.

Savelli C., Time-space distribution of magmatic activity in the western Mediterranean and peripheral orogens during the past 30 Ma (a stimulus to geodynamic considerations), *J. Geodyn*. 34 (2002) 99–126.

Schettino A., Turco E., Plate kinematics of the Western Mediterranean region during the Oligocene and Early Miocene, *Geophys. J. Int*. 166 (2006) 1398–1423.

Seber D., Barazangi M., Ibenbrahim A., Demnati A., Geophysical evidence for lithospheric delamination beneath the Alboran sea and the Rif-Betic mountains, *Nature* 379 (1996) 785–790.

Septfontaine M, La formation du Jbel Binet (Rif externe oriental, Maroc), un dépôt “anté-nappes” d’âge miocène supérieur. Implications paléotectoniques, *Eclogae Geol. Helv*. 76 (1983) 581–609.

Serpelloni E., Vannucci G., Pondrelli S., Argnani A., Casula G., Anzidei M., Balde P., Gasperini P., Kinematics of the Western Africa-Eurasia plate boundary from focal mechanisms and GPS data, *Geophys. J. Intern* 169 (2007) 1180–1200.

Serrano F., Sanz de Galdeano C., El Kadiri Kh., Guerra-Merchán A., López-Garrido A.C., Martín-Martín M., Hlila R., Oligocene-early Miocene cover of the Betic-Rifian Internal Zone. Revision of its geologic significance, *Eclogae Geol. Helv*., 2006, doi:10.1007/s00015-006-1186-9.

Serrano I., Zhao D., Morales J., Torcal F., Seismic tomography from local crustal earthquakes beneath eastern Rif Mountains of Morocco, *Tectonophysics* 367 (2003) 187–201.

Sosson M., Morillon A.C., Bourgois J., Feraud G., Poupeau G., Saint-Marc P., Late exhumation stages of the Alpujarride complex (Western Betic Cordilleras, Spain): new thermochronological and structural data on Los Realaes and Ojen nappes, *Tectonophysics* 285 (1998) 255–273.

Soto J.I., Platt J.P., Petrological and structural evolution of high-grade metamorphic rocks from the floor of the Alboran Sea basin, Western Mediterranean, *J. Petrol*. 40 (1999) 21–60.

Soto J.I., Comas M.C., Talukder A.R., Evolution of the mud diapirism in the Alboran Sea (Western Mediterranean), *AAPG Intern. Conv. Barcelona, Extend. Abst*. (2003) 1–6.

Spakman W., Wortel M.J.R., A tomographic view on western Mediterranean geodynamics, in Cavazza W, Roure F., Spakman W., Stampfli G.M., Ziegler P. (Eds.), *The TRANSMED Atlas-The Mediterranean region from crust to mantle*, Springer V., Berlin, Heidelberg (2004) 31–52.

Stampfli G.M., Marchant R., Geodynamic evolution of the Tethyan margins of the Western Alps, in Pfiffner O.A., Lehner P., Heitzman P.Z., Mueller S., Steck A. (Eds.), *Deep structure of the Swiss Alps- Results from NRP 20*, Birkhauser, Basel (1997) 139–153.

Stampfli G.M., Borel G.D., Marchant R., Mosar J., Western Alps geological constraints on western Tethyan reconstructions, in Rosenbaum G., Lister, G.S. (Eds.), Reconstruction of the Evolution of the Alpine-Himalayan Orogen, *J. Virt. Explorer* 8 (2002) 77–106.

Stich D., Serpelloni E., Mancilla F., Morales J., Kinematics of the Iberia-Maghreb plate contact from seismic moment tensors and GPS observations, *Tectonophysics* 426 (2006) 293–317.

Suter G., Carte géologique du Rif, 1/500.000, *Notes Mém Serv. Géol. Maroc* (1980a) 245a.

Suter G., Carte structurale du Rif, 1/500.000, *Notes Mém Serv. Géol. Maroc* (1980b) 245b.

Tabit A., Kornprobst J., Wooland A.B., Les péridotites à grenat du massif des Beni Bousera (Maroc): mélanges tectoniques et interdiffusion du fer et du magnésium, *C. Acad. Sci. Paris* 325 (1997) 665–670.

Talukder A.R., Comas M.C., Soto J.I. Pliocene to recent mud diapirism and related mud volcanoes in the Alboran Sea (Western Mediterranean), in Van Rensbergen P., Hills R.R., Maltman A., Morley C. (Eds.), Subsurface Sediment Mobilisation, *Geol. Soc. London, Spec. Publ*. 216 (2003) 443–459.

Tassi F., Vaselli O., Moratti G., Piccardi L., Minissale A., Poreda R., Delgado Huertas A., Bendkik A., Chenakeb M., Tedesco D., Fluid geochemistry versus tectonic setting: the case study of Morocco, in Moratti G., Chalouan A. (Eds.), Tectonics of the western Mediterranean and north Africa, *Geol. Soc. London, Spec. Publ*. 262 (2006) 131–145.

Thiébot E., Gutscher M.-A., The Gibraltar Arc seismogenic zone (part 1): constraints on a shallow east dipping fault plane source for the 1755 Lisbon earthquake provided by seismic data, gravity and thermal modeling, *Tectonophysics* 426 (2006) 135–152.

Thurow J., Kuhnt W., Mid-Cretaceous of the Gibraltar Arch Area., in Summerhayes C.P., Shackleton N.J. (Eds.), North Atlantic Palaeoceanography, *Geol. Soc. London Spec. Publ*. 22 (1986) 423–445.

Torelli L., Sartori R., Zitellini N., The giant chaotic body in the Atlantic Ocean off Gibraltar: new results from a deep seismic reflection survey, *Marine Petrol. Geol*. 14 (1997) 125–138.

Torné M., Banda E., García-Dueñas V., Balanyá J.C., Mantle-lithosphere bodies in the Alboran crustal domain (Ronda peridotites, Betic-Rif orogenic belt), *Earth Planet. Sci. Lett*. 110 (1992) 163–171.

Torné M., Fernàndez M., Comas M.C., Soto J.I., Lithospheric structure beneath the Alboran basin: results from 3D gravity modeling and tectonic relevance, *J. Geophys. Res*. 105 B2 (2000), 3209–3228.

Torres-Roldan R.L., Poli G., Pesserillo A., An early Miocene arc-tholeitic magmatic dike event from the Alboran Sea: evidence for precollisional subduction and back-arc crustal extension in the westernmost Mediterranean, *Geol. Rundsch*. 75 (1986) 219–234.

Toufiq A., Bellier J.-P., Boutakiout M., Feinberg H., La coupe d'Oulad Haddou (Rif externe oriental): un affleurement continu de la transition Crétacé-Paléogène au Maroc, révélé par les Foraminifères planctoniques, *C. R. Geosci*. 334 (2002) 995–1001.

Trombetta A., Cirrincione R., Corfu F., Mazzoleni P., Pezzino A., Mid-Ordovician U-Pb ages of porphyroids in the Peloritan Mountains (NE Sicily): palaeogeographical implications for the evolution of the Alboran microplate, *J. Virt. Explorer* 161 (2004) 265–276.

Tubía J.M., Cuevas J., Esteban J.J., Tectonic evidence in the Ronda peridotites, Spain, for mantle diapirisme related to delamination, *Geology* 32 (2004) 941–944.

Turner S.P., Platt J.P., George R.M.M., Kelley S.P., Pearson D.G., Nowell G.M., Magmatism associated with orogenic collapse of the Betic-Alboran Domain, SE Spain, *J. Petrol*. 40 (1999) 1011–1036.

Udías A., Buforn E., Regional stresses along the Eurasia-Africa plate boundary derived from focal mechanisms of large earthquakes, *Pure Appl. Geophys*. 136 (1991) 433–448.

Van der Wal D., Vissers R.L.M., Uplift and emplacement of upper mantle rocks in the Western Mediterranean, *Geology* 21 (1993) 1119–1122.

Vidal J.-C., Structure actuelle et évolution depuis le Miocène de la chaîne rifaine (partie sud de l'Arc de Gibraltar), *Bull. Soc. Géol. Fr*. 19 (1977) 789–796.

Vidal O., Goffé B., Bousquet R., Parra T., Calibration and testing of an empirical chloritoid-chlorite Mg-Fe exchange thermometer and thermodynamic data for daphnite, *J. Metamorph. Geol*. 17 (1999) 25–39.

Villalain J.J., Osete M.L., Vegas R., García-Dueñas V., Heller F., Widespread Neogene remagnetization in Jurassic limestones of the South-Iberian paleomargin (Western Betics, Gibraltar Arc), *Phys. Earth Planet. Int*. 85 (1994) 15–33.

Villasante-Marcos V., Osete M.L., Gervilla F., García-Dueñas V., Paleomagnetic study of the Ronda peridotites (Betic Cordillera, southern Spain), *Tectonophysics* 377 (2003) 119–141.

Vissers R.L.M., Platt J.P., Van der Wal D., Late orogenic extension of the Betic Cordillera and the Alboran Domain: a lithospheric view, *Tectonics* 14 (1995) 786–803.

Weijermars R., Geology and tectonics of the Betic Zone, SE Spain, *Earth Sci. Rev*. 31 (1991) 153–236.

Weijermars R., Roep Th.B., Van den Eeckhout B., Postma G., Klverlaan K., Uplift history of a Betic fold nappe inferred from Neogene-Quaternary sedimentation and tectonics(in the Sierra Alhamilla and Almería, Sorbas and Tabernas Basins of the Betic Cordilleras, SE Spain), *Geol. Mijnb*. 64 (1985) 397–411.

Wernli R., Micropaléontologie du Néogène post-nappes du Maroc septentrional et description systématique des foraminifères planctoniques, *Notes Mém. Serv. Géol. Maroc* 331 (1987) 1–266.

Wildi W., Evolution de la plat-forme carbonatée de type austro-alpin de la Dorsale calcaire (Rif interne, Maroc septentrional) au Mésozoïque, *Bull. Soc. Géol. Fr. (7)* 21 (1979) 49–56.

Wildi W., Le Ferrysch: cône de sédimentation détritique en eau profonde à la bordure nord-ouest de l'Afrique au Jurasique moyen à supérieur (Rif externe, Maroc), *Eclog. Geol. Helv*. 74 (1981) 481–527.

Wildi W., La chaîne tello-rifaine (Algérie, Maroc, Tunisie): structure, stratigraphie et évolution du Trias au Miocène, *Rev. Géol. Dyn. Géogr. Phys*. 24 (1983) 201–297.

Wildi W., Nold M., Uttinger J., La Dorsale Calcaire entre Tetouan et Assifane (Rif interne, Maroc), *Eclogae Geol. Helv*. 70 (1977) 371–415.

Zaghloul M.N., Les unités Federico septentrionales (Rif interne, Maroc): inventaire des déformations et contexte géodynamique, Thèse Doct. Univ. Mohammed V Rabat, 1994, 218p.

Zaghloul M.N., La sédimentation silico-clastique oligo-miocène de type "flysch" dans le Rif, Maroc: évolution et corrélations à l'échelle de la chaîne maghrébide, Thèse Doct. Etat, Univ. Tétouan, 2002, 329p.

Zaghloul M.N., Amri I., El Moutchou B., Mazzoli S., Ouazani-Touhami A., Perrone V., First evidence of Upper Jurassic-Lower Cretaceous oceanic-derived rocks in the Ketama unit (External Rif Zones, Morocco), in Intern. Congr. 3Ma, Casablanca, Abstr. Vol., 2003, 70.

Zaghloul M.N., Di Staso A., Gigliuto L.G., Maniscalco R., Puglisi D., Stratigraphy and provenance of Lower and Middle Miocene strata within the External Tanger Unit (Intrarif sub-domain, External domain, Rif, Morocco): first evidence, *Geol. Carpath*. 56 (2005) 517–530.

Zaghloul M.N., Di Staso A., De Capoa P., Perrone V., Occurrence of upper Burdigalian silexite beds within the Beni Ider Flysch Fm. In the Ksar-es-Sghir area (Maghrebian Flysch Basin, Northern Rif, Morocco): stratigraphic correlations and geodynamic implications, *Ital. J. Geosci*. 2 (2007) 223–239.

Zakir A., Chalouan A., Feinberg H., Evolution tectono-sédimentaire d'un domaine d'avant-chaîne: exemple des bassin d'El-Habt et de Sidi Mrayt, Rif externe nord-occidental (Maroc); précisions stratigraphiques et modélisation tectonique, *Bull. Soc. Géol. Fr*. 175 (2004) 383–397.

Zazo C., Silva P.G., Goy J.L., Hillaire-Marcel C., Ghaleb B., Lario J., Bardají T., González A., Coastal uplift in continental collision plate boudaries: data from the Last Interglacial marine terraces of the Gibraltar Strait area (south Spain), *Tectonophysics* 301 (1999) 95–109.

Zeck H.P., Kristensen A.B., Nakamura E., Inherited Paleozoic and Mesozoic Rb-Sr isotopic signatures in Neogene calc-alkaline volcanics, Alboran volcanic province, SE Spain, *J. Petrol*. 40 (1999) 511–524.

Zeck H.P., Whitehouse M.J., Hercynian, Pan-African, Proterozoic and Archean ion-microprobe zircon ages from a Betic core complex, Alpine belt, W Mediterranean – consequences for its P-T-t path, *Contrib. Mineral. Petrol*. 134 (1999) 134–149.

Zizi M., Triassic-Jurassic extension and Alpine inversion in Northern Morocco, inZiegler P., Horvath F. (Eds.), Peri-Tethys Memoir 2: structure and prospects of Alpine basins and forelands, *Mém. Mus. Nation. Hist. Natur. Paris* 170 (1996) 87–101.

Zizi M., Triassic-Jurassic extensional systems and their Neogene reactivation in northern Morocco (the Rides prérifaines and Guercif basin), *Notes Mém. Serv. Géol. Maroc* 416 (2002) 1–138.

Zouhri L., Lamouroux C., Buret C., La Mamora, charnière entre la Meseta et le Rif: son importance dans l'évolution géodynamique post-paléozoïque du Maroc, *Geodin. Acta* 14 (2001) 361–372.