C H A P T E R 12

MIOCENE EXTENSION IN THE ALBORÁN DOMAIN

Summits of Sierra Nevada and lakes developed in old glacier cirques.

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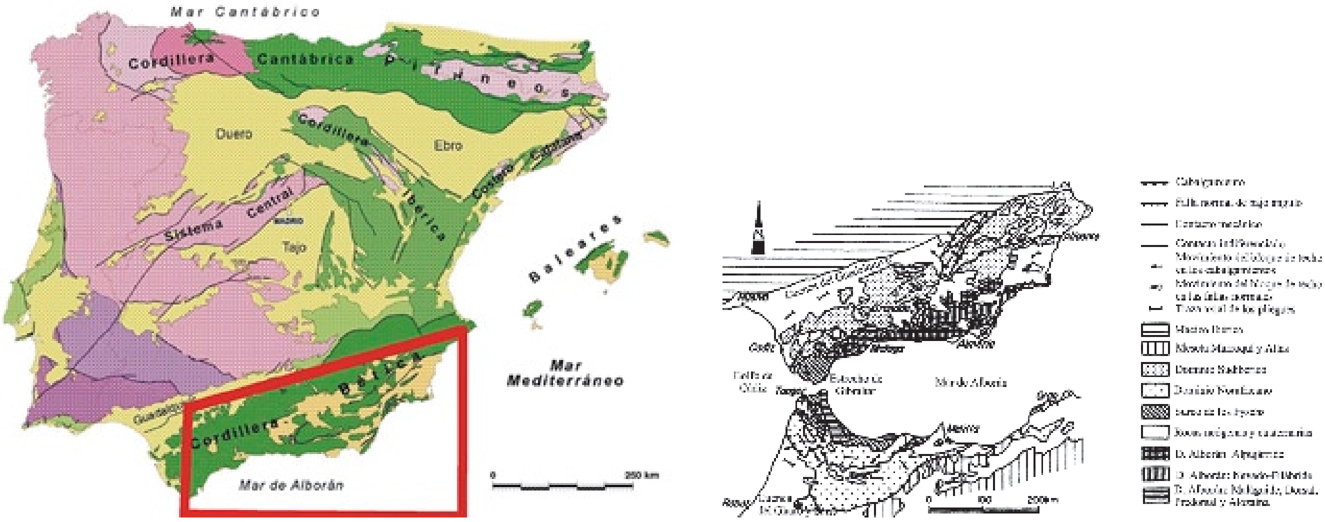


Figure 1, left*. Regional extensión of the geological framework.* Right, *Simplified geological scheme of the Betic-Rif Mountain Ranges (González-Lodeiro* et al.*, 2006, modified from Galindo-Zaldívar* et al.*, 1993).*

The Alborán Domain, together with the South Iberian, North African and Flysch domains make up the Betic and Rif Mountain Ranges, which represent the western end of Mediterranean Alpine mountain ranges. As explained in the previous chapter, these ranges are located to the north and south of the Alborán sea, creating an arch when they are joined together through the Strait of Gibraltar (Figure 1). This arch formed during the Messozoic and Cenozoic as a consequence of convergence between the Eurasian and African plates. The Alborán Domain is formed by three complexes, which from base to top are the following: Nevado-Filábride, Alpujárride and Maláguide. Besides these, there is a set of sedimentary rocks of Triassic through early Neogene age, known as Dorsal and Pre-Dorsal units, which are structurally located between the units of the Flysch Trough and the Maláguide Complex (Figure 2).

The tectonic structures formed in the Alborán Domain during the early and middle Miocene are wide extensional detachments, with thick shear zones in the lower blocks, and high and low angle faults in the upper blocks. The two most important detachment levels are that separating the Nevado-Filábride and Alpujárride complexes, and that separating the latter from the Maláguide Complex. The structures created from the late Miocene to present times are also compressive (folds, reverse and shear faults) as a result of convergence between the European and African plates in a NW-SE direction, and normal faults with different orientations indicating the existence of an extension which varies between a radial disposition and the WSW-ENE direction.

The biggest interest of this domain lies on the **co-existence of extensive and compressive deformations** which gave place to crustal thinning and thickening structures, within a convergence regime between the European and African plates. This tectonic regime was active from the Miocene to present day, and resulted in a strong relief, faults and active folds, an important seismic activity, significant variations in crustal thickness, and the formation of sedimentary basins with active depocentres within an uplifted chain.

The concept of orogeny implies **compression** located in an area of the Earth surface. This compression creates a set of structures such as folds and reverse faults in the upper levels, and fold-related foliations and contraction shear zones in the lower levels. These structures cause a horizontal shortening and an increase in crustal thickness. At the same time, the higher crustal thickness forms a root of less dense materials responsible for the formation of the relief as the rocks located over the thickened zone are lifted by isostasis.

Within this context of general compression, it is difficult to understand the presence of extensional processes which cause the opposite effects: extension and crust thinning. As a matter of fact, it was not until the early eighties when the **presence of extensional structures developed in a chain at the same time as compression** began to be documented. It was soon discovered that extension could represent another way of denudation, apart from erosion, allowing the dismantling of a mountain range and the exposition in surface of deeper crustal levels.

This paradox can be explained by two models (Brun and Van Den Driessche, 1993). In the first model, the structures accommodating the extension are created in a **late stage** of mountain chain formation or even immediately after it is over. This model of extension after thickening is caused by a gravitational collapse of the chain, since the rocks piled during the thickening are not able to withstand the weight of the materials on top of them, and the chain therefore collapses.

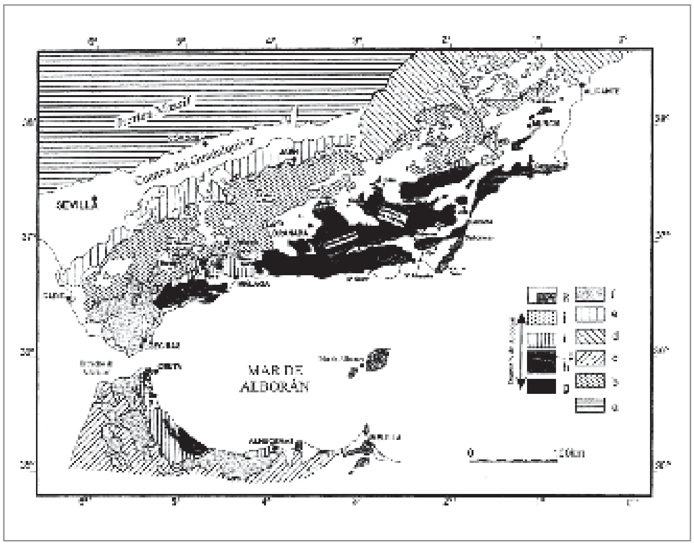


Figure 2. *Geological map of the Betic Mountain Ranges (González-Lodeiro* et al.*, 2006, modified from Azañón* et al.*, 2003). Legend:*
a) Iberian Massif;
b) South Iberian Domain (Sub-Betic);
c) North African Domain;
d) *South Iberian Domain (Pre-Betic);*
e) South Iberian Domain (Olistostromes of the Guadalquivir);
f) Units of the Flysch Trough;
g) Alborán Domain (Nevado-Filábride Complex);
h) Alborán Domain (Alpujárride Complex, including peridotites of Ronda);
i) Alborán Domain (Maláguide Complex);
j) Alborán Domain (Dorsal, Pre-Dorsal, Alozaina Complex);
k) Neogene and Quaternary rocks (dotted, volcanic rocks).

The second model consists on stretching contemporary to compression, and is usually explained by a lateral extrusion of the mountain range rocks of the orogen by pure horizontal shear. In this case, extension and thickening happen at the same time. The stretch direction is subparallel to the chain and perpendicular to the shortening direction. The most interesting feature in the Alborán Domain is that, unlike the Alps and the Tibetan high plateau (with similar anomalies) also with over-thickened continental crusts, the Alborán Domain crust underwent an intense thinning, reaching a thickness of approximately 23 km in the eastern sector (Band *et al.*, 1993), which is obviously lower than the 30-40 km thickness in a regular continental crust.

Both extension models create similar structures, generating huge extensional detachments as well as associated extensional shear zones allowing the exhumation at surface of deep crustal units. High and low angle normal faults, and folds adapted to the ramp and flat geometry of these faults, are also linked to these extensional systems. All these structures have been identified in the Alborán Domain.

The most striking structures are the big detachments linked to extensional ductile shear zones. The biggest detachments found in the Alborán Domain are the Alpujárride/Maláguide contact in the region of the Corredor de Vélez Rubio and west of Málaga, and the Alpujárride/Nevado-Filábride contact in Sierra Alhamilla, Sierra de los Filabres and Sierra Nevada (Figure 2), which has been called "Mecina fault" (González-Lodeiro *et al.*, 1984; Galindo-Zaldívar *et al.*, 1989).

In the Corredor de Vélez Rubio, the contact between the Alborán and South Iberian domains crops out with an ENE-WSW trend. To the south of this exposure, and with a trend parallel to the previous one, crops out the contact between the Alpujárride and Maláguide complexes (Figure 3). This contact is a fault with an associated one-metre thick breccioid fault gauge.

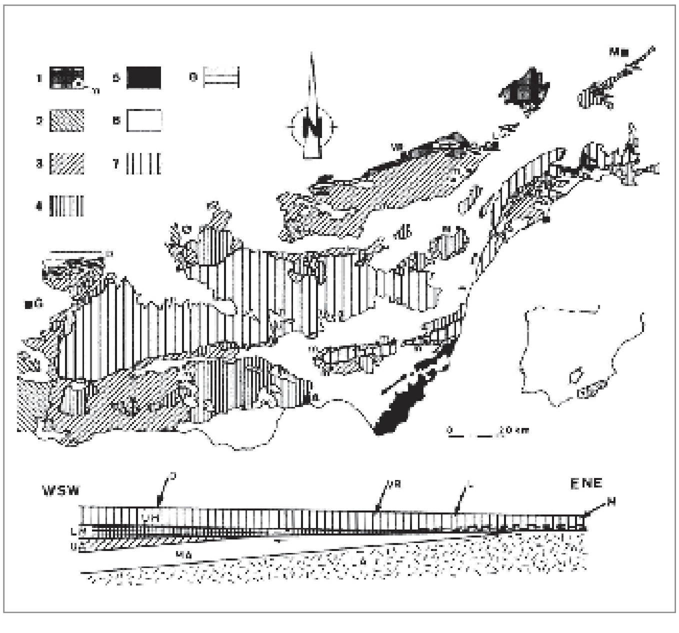


Figure 3. *Direction and sense of movement of the Maláguide and Alpujárride detachment between Granada (G) and Murcia (M) (González-Lodeiro* et al.*, 2006, modified from Aldaya* et al.*, 1991). Legend:*
1) *Maláguide Complex (m= small tectonic islets from this complex);*
2) *Upper Alpujárride units;*
3) *Mid Alpujárride units;*
4) *Lower Alpujárride units;*
5) *Volcanic rocks;*
6) *Neogene and Quaternary sedimentary rocks;*
7) *Nevado-Filábride Complex;*
8) *Sub-Betic.*

The lower part of the figure shows a scheme of the structural relationships in this detachment; D, VR, L and M refer to different localities Diezma, Vélez Rubio, Lorca and Murcia; UM, upper Maláguide, LM, lower Maláguide, UA, upper Alpujárride, MA, mid Alpujárride, and LA, Lower Alpujárride..

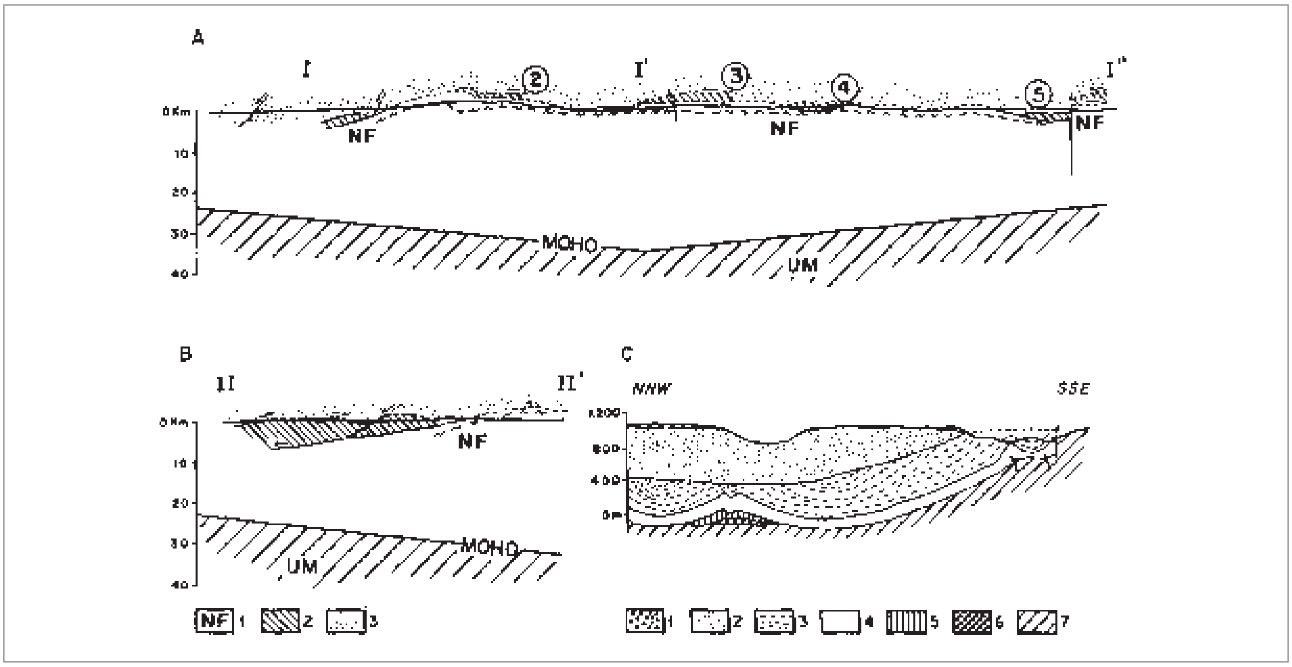


Figure 5, above. *Geological cross-section through the Mecina Fault detachment.*

Legend for section A and B:

1. *Nevado-Filábride Complex;*
2. *Lower units of the Alpujárride Complex;*
3. *Middle and upper units of the Alpujárride Complex. UM: upper mantle. Discontinuous wave lines: lower limit of the planar-linear fabric in the Nevado-Filábride Complex;*

Legend for section C:

1. *Guadix Formation;*
2. *Molicias and Morollón Formations;*
3. *La Peza Formation, upper member;*
4. *La Peza Formation, lower member;*
5. *Mesozoic-Tertiary allochthonous units;*
6. *Viñuela Group;*
7. *Alpujárride and Maláguide Complexes (González-lodeiro* et al.*, 2006, taken from Jabaloy* et al.*, 1992).*

Figure 4. *Panoramic view of the Mecina fault along the eastern margin of Sierra Nevada, as seen from the Ermita del Padre Eterno (González-Lodeiro* et al.*, 2006).*

This fault is subvertical and is located in the northern flank of an antiform verging to the north. The hinge and southern flank of this fold are seen in the region of Lorca, where the fault becomes subhorizontal. Towards the east, the contact crops out in the south-east end of Sierra Espuña, and to the east of Murcia, showing similar features.

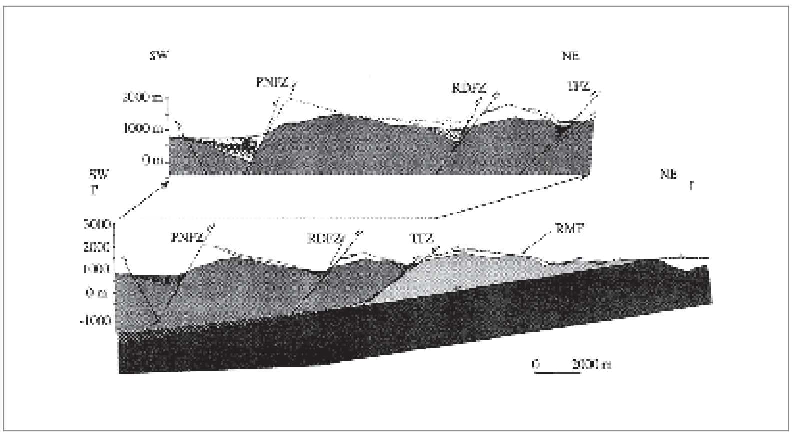
The Alpujárride/Maláguide contact is located between two complexes with very different histories and metamorphic conditions. In the Maláguide Complex, rocks were submitted to low pressure and temperature between 0 and 300 °C, whereas the Alpujárrides phyllites underwent temperatures near 400 °C and pressures of 10 kb (Azañón *et al.*, 1994). On the other hand, the contact surface between both complexes deepens to the east for the lower block (Figure 3). All together, the evidence allows to interpret this contact as an extensional process which enabled the exhumation of the Alpujárride Complex.

The contact separating the **Nevado-Filábride and Alpujárride complexes** is the deepest detachment cropping out in the Alborán Domain, and was active all along its surface during the Lower Miocene. This detachment has been called Mecina Fault (Figure 4) and was affected by long late radial folds with an E-W direction. Associated to this detachment, there are fragile deformations in the upper block, as well as ductile deformations evolving to fragile ones in the lower block. The ductile, ductile-fragile and fragile deformations in the lower block point to a prevailing displacement of the Alpujárride over the Nevado-Filábride to the west (Figure 5).

Figure 6, above. *Folds formed after the main fabric in the Sierra de los Filabres.*

Figure 7, below. *Schematic geological cross-section of the normal fault system in the western edge of Sierra Nevada.*

PNFZ, Padul-Nigüelas fault.
RDFZ, Dilar River fault.
TZF, Trevenque fault.
RMF, Monachil River fault
(González-Lodeiro et al.*, 2006, after Galindo-Zaldívar* et al.*,1996)*



The Mecina Fault can be considered a low-angle normal fault. It displays a typical fault breccia made up by schist fragments, phyllites and tectonic breccias with carbonate fragments, from the crushing of the Alpujárride phyllites, and in some cases of Nevado-Filábrides schists. Tortonian sediments cover this fault.

The sense of movement can be inferred from the micro-structures developed on the fault gauge. The micro-fault planes present grooves showing movement directions changing from E-W to NE-SW, and the fault jump is difficult to define.

In the Alpujárride and Nevado-Filábride complexes it is common to find deformation microstructures (Figure 6). This fault activity caused the exhumation of the Nevado-Filábride rocks which initially were in the eastern part of the Alborán Domain during the Serravallian, and later in the central regions during the Tortonian (Johnson *et al.*, 1997). The Tortonian sediments cover (fossilize) this fault, although in some specific sectors it is possible to observe late reactivations of the contact, such as in western Sierra Nevada (Galindo-Zaldívar *et al.*, 1996).

The big low-angle normal faults observed in the surface separating Nevado-Filábride, Alpujárride and Maláguide complexes stopped their activity in the Alborán Domain during the Tortonian, since rocks of such an age cover all them. Nonetheless, **from the late Miocene-Pliocene and to the present day, extensional deformation continued in the Alborán Domain**. This deformation is shown as **high-angle normal faults** and in the local reactivation of the extensional detachments. Among the high-angle faults, two of the most representative are the Padul Fault and the Zafarraya Fault.

The **Padul Fault**, also called Padul-Nigüelas Fault, is located in the western edge of Sierra Nevada. It is part of a normal fault system dipping to the SW, active from the Tortonian to the present, and with a basal detachment located in the contact between the Alpujárride and Nevado-Filábride complexes (Figure 7). The fault displays a prevailing NW-SE orientation, the dip has a SW component and varies between 25º and 50º, with extreme values between 20º and 80º, depending on the sectors considered. This fault forms a mountain front (Figure 8) made up by rocks of the Alpujárride Complex, mostly dolomitic marbles of the Triassic. Upper Miocene calcarenites and marls crop out in the collapsed block. The displacement of the calcarenite levels shows a jump close to 1.5 km from the Tortonian to the present (Sanz de Galdeano, 1976).

An asymmetrical basin filled with a fan-like distribution of layers developed in the down-dropped block. The basin has Tortonian to Quaternary sediments, indicating a continuous activity of the fault during all this time interval. Two types of

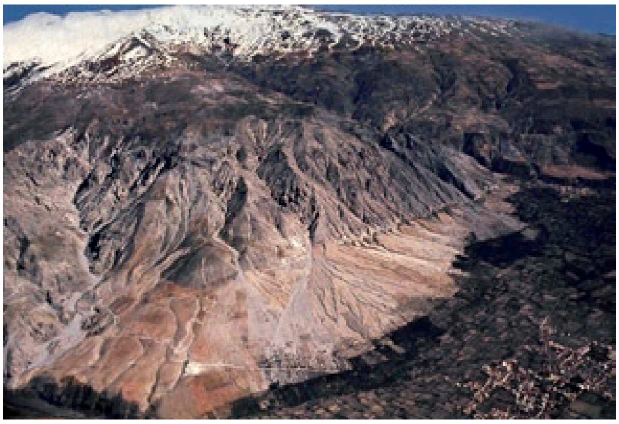


Figure 8. *Aerial view of the Padul-Nigüelas Fault. The triangular facets along the fault trace, as well as ravine incision, indicate it is an active fault (Photo by F. Aldaya).*

Figure 9. *Padul peat bog (Cenefa de Marchena).*

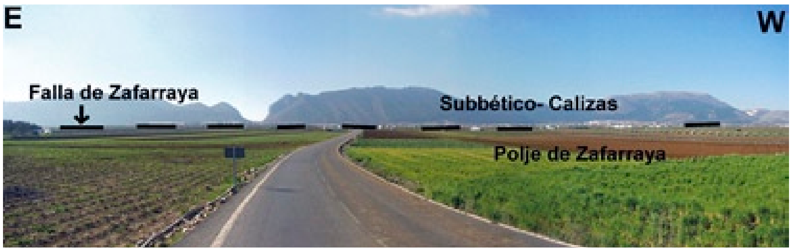


Figure 10. *Panoramic view and geological scheme of the Zafarraya Fault.*

Quaternary formations must be highlighted: the peat (Figure 9) found in the sector previously occupied by the Padul lake, and the alluvial fans coming out from the ravines in the eastern margin of Sierra Nevada. From the geological point of view, the Padul fault can be considered an **active fault**.

The **Zafarraya Fault** is one of the most active structures in the area. It was involved in the strong earthquake (Muñoz and Udías, 1980) of Christmas Day 1884. The total length of the fault exceeds 15 km. Its orientation varies through all its course, from E-W to NW-SE, the fault plain dips 60º to the north, and its striations indicate it is a normal fault.

The Zafarraya Depression is an endorheic basin found in the fault's upper block and it is filled by sediments spanning from the Tortonian to present. The fault plane cuts several recent soils. ^{14}C dating of the soils confirms the repeated fault activity, with at least three likely events in the last 9000 years. The best exposure of this fault is seen at Ventas de Zafarraya, near the road C-335, where displacements of around one meter occurred during the earthquake of 1884, together with the formation of some cracks (Figure 10).

Finally, **strike-slip faults** stand out within the compressive structures contemporary with extension in the Alborán Domain. These are sub-vertical faults with a NE-SW to NNE-SSW strike. Active faults such as Alhama de Murcia, and the faults of Carboneras and Palomeras, stand out among them.

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