Crustal decoupling and intracrustal flow beneath domal exhumed core complexes, Betics (SE Spain)

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ABSTRACT

The Sierra Nevada core, located in the Betic hinterland, features a N–S large-scale open antiform with a central relatively uplifted highly extended domain placed between two less extended domains (in the east and in the west) dipping eastwards and westwards, respectively. The core-bounding detachment system formed during the Serravallian (15–11 Ma) in an episode of ENE–WSW extension. The ESCI-Béticas 2 deep seismic reflection profile, a transect through the core, shows a highly reflective deep crust overlying a subhorizontal Moho, and a fairly transparent upper crust and upper mantle. The lack of Moho relief beneath this area, with differential values for supracrustal thinning, suggests a mechanism of intracrustal isostatic compensation. Surface geology data together with seismic imaging indicate intracrustal flow and upward doming as a response to footwall unloading accompanying the middle Miocene supracrustal extension. A prominent mid-crustal reflector (MCR) is deemed to represent a decoupling zone between the upper and the deep crust. Subsequent N–S shortening and associated folding occurred in the late Miocene. The interference pattern of this folding over the middle Miocene core produced the current E–W dome-shaped tectonic windows where the deepest complex of the Betic hinterland crops out.

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Introduction

Seismic reflection profiling supported by detailed field studies has proven to be a key to understanding continental crustal structures. Reflection transects obtained by COCORP in the western United States (Klemperer *et al.*, 1986; Allmendinger *et al.*, 1987) and studies of other regions around the world (e.g. Matthews, 1986) show the existence of a common pattern. There is frequently a highly reflective deep crust sandwiched between a transparent or scarcely reflective upper crust and upper mantle, situated over a sub horizontal Moho. The seismic fabric provides clues as to the mode of extension in a given region. In addition, the lack of Moho relief below terrains with different supracrustal extension values suggests the involvement of a mechanism capable of thickening the crust beneath the area of greatest upper crustal thinning. Several mechanisms have been proposed: (i) intrusion of crustal melts from the mantle (e.g. Gans, 1987); (ii) ductile flow of lower crust accompanied by injection and underplating of mantle-derived magmas with crustal densities (e.g. McCarthy and Thompson, 1988); (iii) lower crustal flow driven by lateral pressure gradients caused by differential thinning of the overlying crust (e.g. Block and Royden, 1990); and (iv) a variant of the latter proposed by Wernicke (1990), advocating as the compensating medium a largely quartzose fluid crustal layer (fluid in the sense of the asthenosphere) situated upon a generally mafic, solid lower crust.

In the Betics, which represent the westernmost section of the peri-Mediterranean Alpine orogen (Fig. 1), Miocene extension of the upper crust has been well documented (Galindo-Zaldívar *et al.*, 1989; Platt and Vissers, 1989; García-Dueñas *et al.*, 1992; Martínez-Martínez and Azañón, 1997). In the present study, previous and new geological surface data are combined with a deep seismic reflection profile, the ESCI-Béticas 2 profile, through the highly extended Alborán domain. We address the question of crustal response to Miocene extension and the subsequent late Miocene tectonic inversion. This tectonic inversion strongly controls the present-day features of the Betics, where a series of E–W orientated basins and ranges run subparallel to the main trend of extension (Fig. 1).

Tectonic evolution of the Alborán domain

The Alborán domain is a continental crustal terrain made up of three main metamorphic nappe complexes, from bottom to top: the Nevado-Filabride, the Alpujarride, and the Malaguide. Most of the stacking process occurred during the Palaeogene, E of zero meridian, in a probable poly-collisional orogen (García-Dueñas *et al.*, 1992; Balanyá *et al.*, 1997). During the Miocene, the Alborán domain became the hanging wall of the W-directed Gibraltar thrust, superimposing itself on the South-Iberian and Maghrebian domains after the obliteration of the Flysch Trough (Balanyá and García-Dueñas, 1988). Coeval with thrusting, the Alborán domain underwent significant extensional thinning, giving rise to the Alborán basin (Comas *et al.*, 1992; Martínez-Martínez and Azañón, 1997). Continued extension finally affected the contractional areas, thus producing the negative tectonic inversion of the Gibraltar thrust during the middle Miocene, while the mountain front advanced into the footwall, and moved towards the outermost zones (Balanyá and García-Dueñas, 1988). Extensional tectonics took place in successive rifting episodes with changing directions of extension. In these episodes, different brittle-ductile to brittle extensional systems progressively attenuated deeper complexes (García-Dueñas *et al.*, 1992). Thus, low-angle normal faults and extensional detachments with variable extension directions thinned the Malaguide complex and some Alpujarride units during the early Miocene (Aldaya *et al.*, 1991; Lonergan and Platt, 1995; Sánchez-Gómez *et al.*, 1995). The thinning of the Alpujarride took place in the upper Burdigalian-lower Langhian (19–16 Ma) through low-angle normal faulting with a NNW-SSE extension direction (Crespo-Blanc *et al.*, 1994). During the Serravallian (15–11 Ma), WSW-directed, low-angle normal faults associated to a

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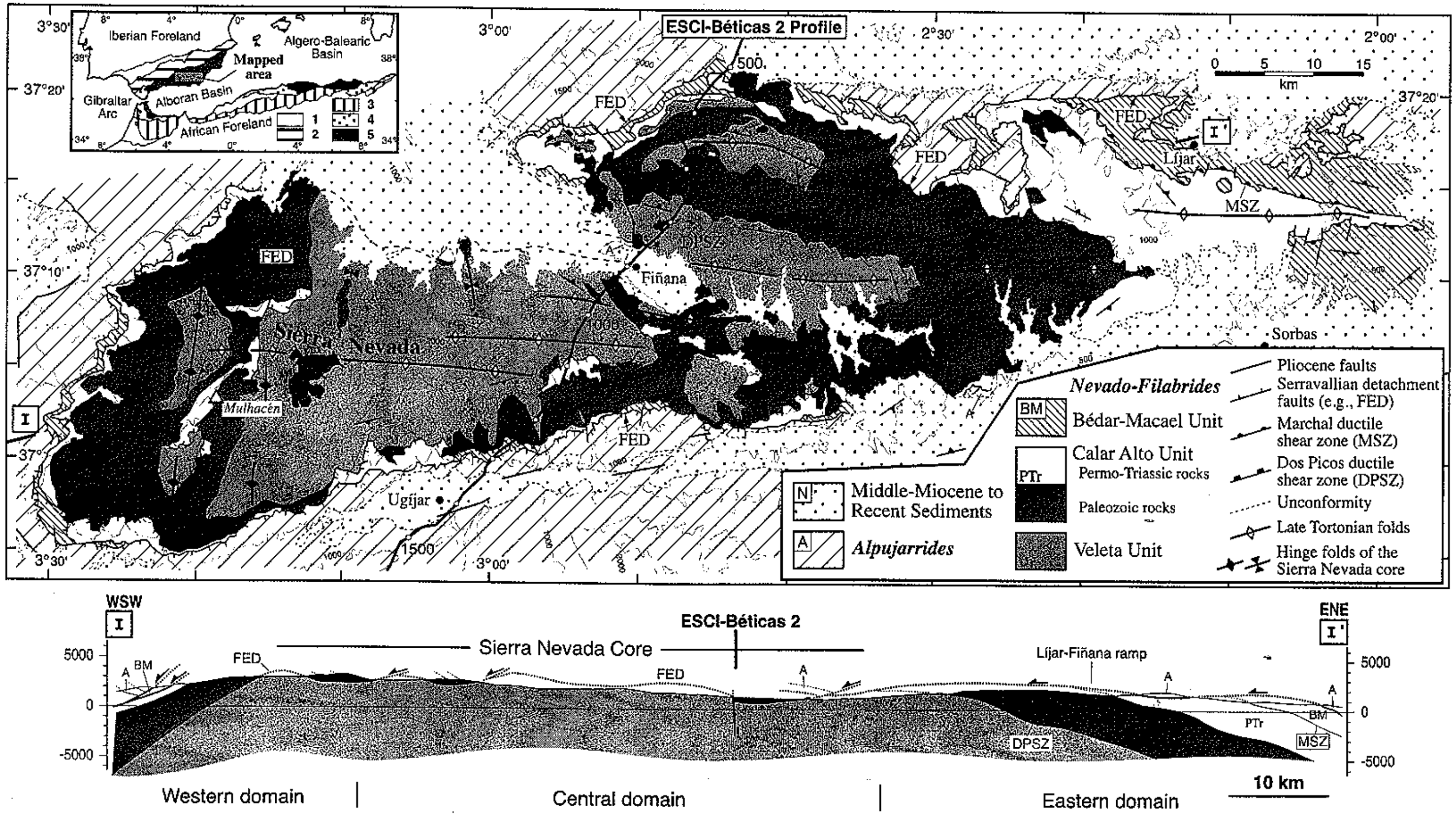

Fig. 1 Tectonic map and structural cross-section of the Sierra Nevada and Sierra de Filabres culminations, showing the Serravallian extensional detachment system and folds in the Sierra Nevada core. The attitude of the main foliation and bedding are also shown. Upper left inset: 1, Neogene basins; 2, South-Iberian domain; 3, Maghrebian domain; 4, Flysch Trough units; 5, Alborán domain. Numbers along the profile mark station locations.

major extensional detachment (Filabres extensional detachment) attenuated the Alpujarride and the Nevado-Filabride, and contributed to the exhumation of the latter complex. The extensional systems are deformed by large-scale, open N-vergent folds that developed during the late Tortonian (7–6 Ma) in a contractional episode (Platt *et al.*, 1983; Martínez-Martínez *et al.*, 1995) (Fig. 1).

The Sierra Nevada core and late Miocene folding interference

The Nevado-Filabride outcrops are restricted to the central and eastern Betics and correspond to antiform-shaped tectonic windows where this complex, which was buried below the Alpujarride during the Palaeogene and early Miocene, is exposed in the footwall of a middle Miocene low-angle detachment system (Filabres extensional system). The most extensive outcrop is the Sierra Nevada–Sierra de los Filabres window. In general, this is an elongated E–W tectonic window that in detail shows a complicated pattern resulting from the interference of two sub-orthogonal fold systems, trending N–S and E–W, respectively (Fig. 1). The E–W folds are late Tortonian contractional folds. The N–S folds are described below.

The Nevado-Filabride complex consists of three main stacked units (Fig. 1); (in ascending order) the Veleta, the Calar Alto, and the Bédar-Macael units. The lithostratigraphic sequences of the units are composed of Palaeozoic graphitic-schists and quartzites; a sequence of Permo-Triassic light-coloured metapelites and metapsammites; and a Triassic calcite and dolomite marble formation. The units show significant differences in their metamorphic record, from low-grade conditions in the lowest unit up to medium-grade conditions in the highest one (García-Dueñas *et al.*, 1988).

The Filabres extensional system is formed by listric fans coalescing in a major fault zone (Filabres extensional detachment, FED). The transport sense was top-to-WSW (García-Dueñas and Martínez-Martínez, 1988; Galindo-Zaldívar *et al.*, 1989; Martínez-Martínez and Azañón, 1997). The detachment has a footwall ramp-and-flat geometry. A low-angle (< 10°), large-scale ramp can be observed between the villages of Líjar and Fiñana (Fig. 1), where the detachment cuts the Nevado-Filabride stack down-section. Towards the west the detachment is a footwall flat following the Calar Alto/Veleta boundary, finally sinking westwards in the western area of the Mulhacén peak.

A cross-section trending close to the extension direction shows the large-scale geometry of the Filabres extensional system (Fig. 1). We define three structural domains E–W. In the eastern domain (40 km-long) large-scale wedges thinning westwards are defined in the footwall between the detachment (Líjar-Fiñana ramp) and the eastwards-dipping regional reference surfaces, including two large-scale ductile shear zones subparallel to both the main foliation and the lithological contacts (Fig. 1). In this domain, C planes in the extensional crenulation cleavage are subhorizontal or dip with an eastwards component. The central domain (50 km long), passing through the ESCI-Béticas 2 profile, is characterized by high-extension riders in the hanging wall. The FED here has a footwall flat geometry and a gently variable dip with a subhorizontal envelope. In the riders, mainly composed of rocks belonging to the Calar Alto unit, the foliation is consistently tilted towards the east. The western domain is located close to the western end of Sierra Nevada, where the highest mountain peaks are found. In this area the FED also has a footwall flat geometry but it dips, together with the extensional crenulation cleavage, towards the west. There are no isolated riders. Here the Bédar-Macael unit is as thick as in the eastern domain, and the Calar-Alto unit is relatively less extended and thickens westwards. In short, the section shows a N–S upwards arched structure with a relatively uplifted highly extended domain (central) between two flexured, less extended margins (eastern and western domains), where major rock wedges thicken in opposite senses. These marginal domains must correspond to the proximal and distal blocks of the Filabres extensional detachment, respectively.

A level of Tortonian shallow marine conglomerates overlies the different Nevado-Filabride units along the FED ramp, indicating the ramp was readjusted into a subhorizontal attitude at that time (García-Dueñas *et al.*, 1992; Martínez-Martínez and Azañón, 1997). In contrast, in the western part of Sierra Nevada, unconformable Tortonian sediments lie on the higher Alpujarride units belonging to the distal block of the Filabres system.

These observations indicate that the upwards arched structure shown in the cross-section in Fig. 1 is tied to the Serravallian extensional process. In terrains with differential values of extension, highly extended domains are characterized by uplift and flexure on their margins, driven by the isostatic forces that accompany footwall unloading (Wernicke, 1992). This N–S large-scale open antiform that developed during the Serravallian will henceforth be referred to as the 'Sierra Nevada core'.

Crustal seismic imaging beneath the core complex

The ESCI-Béticas 2 profile cuts N30°E across the Alborán domain and reaches as far as the Mediterranean coast of southern Spain. A major part of its path goes through the Nevado-Filabride. Our analysis centres on a window of the stacked section between stations 400 and 1750 (Fig. 2).

The seismic profile shows a gently undulated, nearly flat reflection Moho (M in Fig. 2), distinguished both by discontinuous high-amplitude reflective bands and by single reflections located between 10.5 s and 11 s twt to, respectively, the SSW and the NNE at the base of the crust. The upper mantle is generally transparent, although there are several instances of both SSW-dipping and flat-lying bright reflections (Fig. 2). The crust comprises two layers with very different reflectivity patterns. The deep one is highly reflective, having broad areas of laminated crust with densely packed reflections. The pervasive laminated fabric of the deep crust is defined by strong, subparallel, multicyclic events, lacking observable diffractions, that bound relatively transparent lenses of deep crust. Towards the NNE the reflectivity of the deep crust diminishes, and only local events of laminated crust gently dipping to the NNE and to the SSW are observed. This sector also presents noteworthy discontinuous, low-amplitude reflectors or reflector bands that can nevertheless be traced throughout the crust. In general, they dip towards the SSW and merge with the lower crust. Downwards, some of these reflector bands appear to merge with the Moho, while reflections in the mantle show similar dipping (Fig. 2). The upper crustal layer

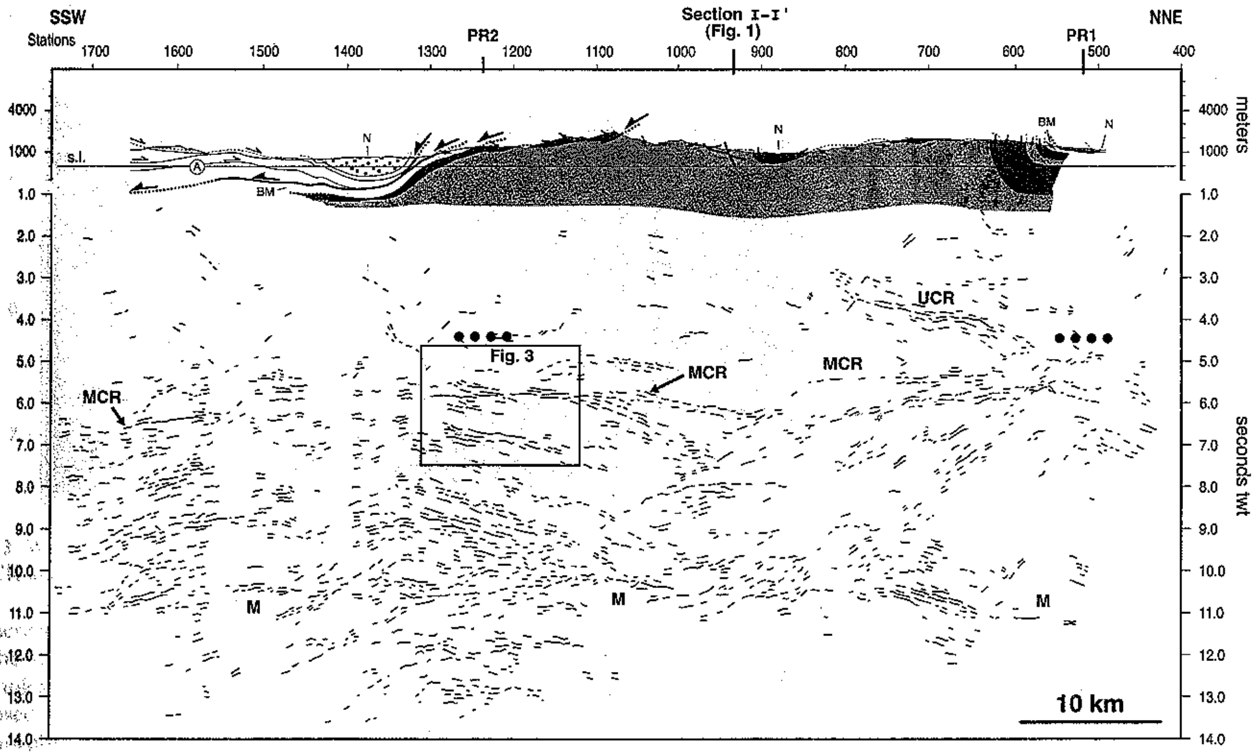

Fig. 2 Crustal cross-section combining a line drawing of the ESCI-Béticas 2 profile and a structural section based on field data. Arrows represent projection of the kinematic vectors of extensional systems on the profile plane: thin arrowheads, upper Burdigalian-lower Langhian system; thick arrowheads, Serravallian system. Black circles indicate the position of the V_p change boundary reported by Banda *et al.* (1993) from two refraction profiles (PR1 and PR2) intersecting the ESCI-Béticas 2 profile. Legend of the geological cross-section as in Fig. 1. For other abbreviations see text.

is fairly transparent, with scattered, variably dipping reflective bands. The most prominent reflector is a NNE-dipping, highly reflective coherent band, the so-called UCR (Upper Crustal Reflector). It can be interpreted as a mylonitic band similar to the Nevado-Filabride shear zones that crop out on the surface (Fig. 1) (García-Dueñas *et al.*, 1994). This band does not reproduce the folds observed in the northern part of the section in Fig. 2.

The boundary between the two crustal layers is sharp. It is marked by a prominent reflector labelled MCR (Mid-Crustal Reflector), defined by discontinuous large-amplitude reflectors aligned at a depth of 5.5–7 s twt (16.5–21 km, using an average V_p value of 6.0 km s^{-1}) from stations 600 to 1750 (Fig. 2). This reflector is clearly oblique to the reflection bands above and below it (e.g. between stations 1020–1310, Fig. 3). The MCR is quite flat, dipping very gently SSW. Between stations 850 and 900, the MCR is displaced by low-amplitude reflector bands dipping SSW, which tilt the MCR towards the NNE and make it deeper in the southern part of the profile.

Discussion and conclusions

In the Alborán domain surface geology data show upwards doming in response to different supracrustal extension rates. In the case studied, this suggests the existence of flow beneath the readjusted Filabres detachment.

The lack of Moho relief beneath areas with differential values for supracrustal thinning indicates the involvement of a mechanism of intracrustal isostatic compensation. The significance of the MCR is crucial to understanding what types of mechanisms may be operating. Likewise, certain possible interpretations of the nature of this reflector can be discarded. For instance, the MCR does not coincide with the V_p boundary, from 6.0 to 6.5 km s^{-1}, placed at a depth of 12 km by refraction data (Banda *et al.*, 1993) (Fig. 2). Nor can the MCR be considered the basal detachment of the late Tortonian folds, which attenuate at shallower levels (see also Martínez-Martínez *et al.*, 1995).

The seismic imaging suggests that the domal shape of the core is flatter at greater depths and disappears in the MCR. The UCR, above the MCR, would therefore constitute a geometric element of the dome, corresponding to a ductile shear zone beneath the two that crop out on the surface, similarly and congruently tilted by the isostatic readjustment of the FED ramp. The compensation layer would have the characteristics of a mid-crustal fluid layer, as proposed by Wernicke (1990) in the Basin and Range province. This interpretation could accomodate the existence of an upper crustal low-velocity layer detected by Banda and Ansorge (1980) in refraction profiles near the ESCI-Béticas 2 profile, and the presence of seismicity restricted to upper crustal levels around the area (Galindo-Zaldívar *et al.*, 1993). In short, the MCR could represent the basal boundary of a layer of intracrustal isostatic compensation.

Two significant differences between the Sierra Nevada core and the classic

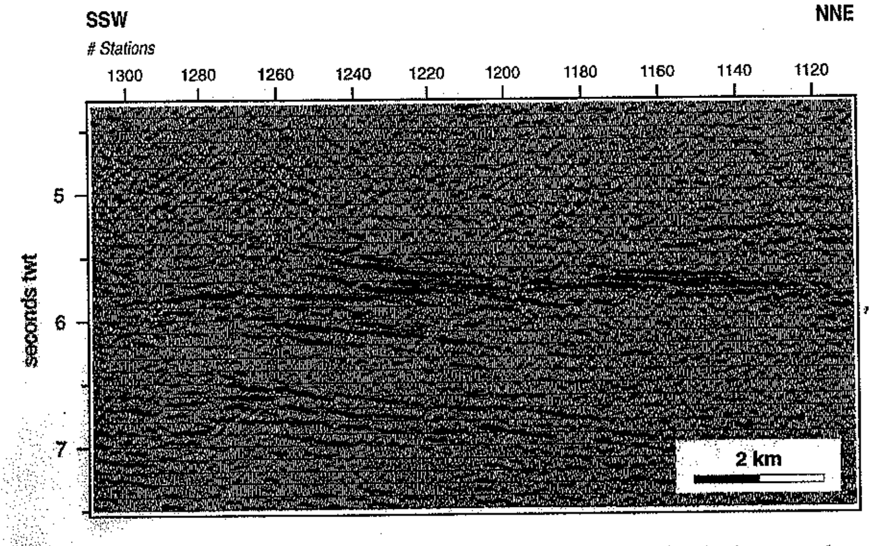

Fig. 3 Window of the ESCI-Béticas 2 stacked section showing the obliquity between the MCR and reflection bands above and below it.

American core complexes can be noted. 1 The fundamental relationship in a core complex of low-grade or unmetamorphosed rocks overlying high-grade metamorphic core rocks (Davis, 1983) shows some variance. While throughout the FED low-grade Alpujarride rocks are frequently disposed upon medium-grade Nevado-Filabride rocks, many of the Alpujarride units have a higher metamorphic grade than the Nevado-Filabrides. The tectonic units of both complexes show metamorphic inversion, the units with lesser metamorphic grade occupying deeper levels (Azañón *et al.*, 1994). 2 The current E–W antiform-shaped tectonic windows, where the Nevado-Filabride rocks of the lower plate of the detachment crop out, do not result from a simple, isostatic rebound-related structure; this shape derives from the superposition of the late Tortonian contractional folds over the Serravallian Sierra Nevada core.

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