Evidence for an active sinistral shear zone in the western Alboran region

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ABSTRACT

A compilation of gravity, seismicity, neotectonics, geology, tomography and topography data from the Alboran region reveals distinctive differences between the eastern and western part of the Alboran region and Betic Cordillera. Calculated profiles of integrated crustal strength reveal that lateral differences in mechanical behaviour are caused by marked inherited differences in crustal make-up. The two domains with different tectonic behaviour are separated by a N025°-trending lineament in the western Alboran and central Betic Cordillera. This lineament can be interpreted as an upper mantle – lower crustal sinistral shear zone accommodating a large part of the convergence between Africa and Iberia.

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Introduction

The Alboran Basin and the surrounding Betic-Rif Cordilleras (see Fig. 1) constitute an arc-shaped thrust-belt that exemplifies contemporaneous internal extension and frontal thrusting in an overall compressional setting. The complex tectonic evolution of the region is the result of ongoing convergence between Africa and Eurasia since late Mesozoic. Until the amalgamation of Iberia with Europe, forming the Pyrenees, the relative motion between Africa and Iberia was minor. From late Eocene to the present, the active plate boundary between Eurasia and Africa was located near to or in the study region. Crustal thickening in the Internal Zones, subsequent nearly radial frontal continental thrusting and contemporaneous internal extension (Watts *et al.*, 1993) have been the main processes in the tectonic evolution. The relationship between these processes is a matter of ongoing debate – see, e.g., Vissers *et al.* (1995) and Lonergan and White (1997) – and beyond the scope of this paper. As in other arc-shaped belts, e.g. the Carpathians (Matenco *et al.*, 1997), space problems are accommodated by strike-slip zones enabling large block rotations (Lonergan and White, 1997). The importance of strike-slip tectonics in at least the late stage tectonic evolution of the Alboran/Betic region has been put forward by several authors (e.g. Biermann, 1995, and Sanz de Galdeano, 1996). The present paper focuses on recent to present-day deformation of the region, from discussion of datasets to their implications for the location of a previously unrecognized tectonic feature. This compilation and new constraints on the thermo-mechanical structure support a scenario in which late Miocene to present-day tectonic evolution of the region is accommodated by (predominantly) strike-slip reactivation of inherited crustal structures.

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Observations

Surface geology and neotectonics

Marked differences in surface geology and neotectonics occur between the Eastern and Western Betics (Fig. 2A). The Sierra Nevada forms the westernmost outcrop of a high P/T series (Nevado–Filabride Complex), nearly coincident with the eastern limit of the flysch nappes (Dorsalian of the Sierra Arana between Granada and Guadix basins). The Sierra Nevada has developed by folding since the end of the Miocene epoch, leading to rapid erosional denudation, as documented by fission track data (Johnson, 1997). This folding has redistributed the kinematic indicators along the middle Miocene Betic Movement Zone (Fig. 3), which shows an anticlockwise rotation from east to west (Vissers *et al.*, 1995). This development of the Sierra Nevada is similar to that of the Sierra Carrascoy along the northern continuation of the Palomares N020°-trending major sinistral strike-slip zone (Sanz de Galdeano *et al.*, 1998) and the Sierra Alhamilla (Weijermars *et al.*, 1985). The development of these anticlinal ranges is related to development of a new suite of strike-slip basins (Geel and Roep, 1998) in which the erosional products of the rapidly rising anticlinal structures have been deposited. Their uplift has been dated by analysis of sediments derived from the ranges and elevation of late Tortonian reef sediments (Weijermars *et al.*, 1985). Pleistocene and later uplift has led to considerable deepening of the fluvial network surrounding the Sierra Nevada (Sanz de Galdeano and López-Garrido, 1999). The Granada–Guadix-Baza basins in front of the Sierra Nevada formed as a single basin prior to discretization since the late Tortonian (Fernandez *et al.*, 1996). The Upper Tortonian marine sediments in both the Guadix-Baza and the Granada basins have been elevated up to an average of 1000–1200 m in the first (Galindo-Zaldívar *et al.*, 1997) and ~700 m in the latter basin, which indicates the independent behaviour of the basins since the Lower Tortonian. The late Miocene to present-day folding, the redistribution of the movement indicators on the Betic Movement Zone and the general shape of the Sierra Nevada, are interpreted herein to have resulted from a restraining bend of a sinistral shear zone. Faulting in the Granada Basin (Sanz de Galdeano and López-Garrido, 1999), recent seismic activity and related normal faulting (Galindo-Zaldívar *et al.*, 1999) and the discretization of the Granada/Guadix basins support this interpretation.

The Guadalquivir basin (see Fig. 2A) shows a homogeneous

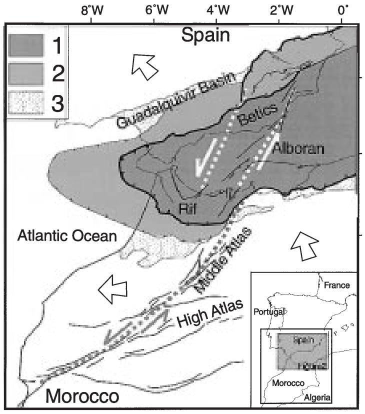


Fig. 1 Location and structural outline of the Alboran region and surroundings. 1, 'Alboran Block'/Internal Zones; 2, External Zones; 3, related foreland basins. Dashed light lines denote the major shear zones. The right one is the Transalboran Shearzone (Jacobshagen, 1992), running from southern Morocco to the eastern Betics. To the left is the Almuñecar shear zone, described in this present paper. Arrows indicate inferred motion of different crustal segments.

basement deflection from west to east (Fernàndez *et al.*, 1998a), but a sharp change in deformation style occurs at the eastern culmination of the basin: the basin basement (upper Mesozoic) is deformed into a duplex thrust system in the western Prebetic zone (Sierra Segura). To the south, along the same lineament, the northward-dipping contact between the External and Internal zones of the Betics shows a horizontal sinistral offset of about 30 km.

The main depocentres of the Miocene and Plio-Quaternary sediments in the Alboran Basin are located in its western part (Docherty and Banda, 1995), where major late Cenozoic inversion structures are lacking. In contrast, seismic reflection profiles in the central Alboran (e.g. Chalouan *et al.*,1997; Watts *et al.*, 1993) indicate recent compressional features in this area, related to the development of the Alboran Ridge and the Yussuf Ridge.

As in the entire Western Mediterranean realm, late Miocene to recent volcanism is widespread in the Alboran region. In the eastern Alboran Basin and both the Betic and the African margins, several pulses of volcanic activity have been observed, from calc-alkaline to K-enriched and basaltic outflows (Lonergan and White, 1997). The calc-alkaline suite is related to either northwestward oceanic subduction under Iberia or to delamination. Remarkably, in the western Alboran, the Rif of Morocco and the Western Betics with its foreland, this volcanic activity has not been detected. In contrast, several peridotitic bodies (Ronda, Alpujata, Carratraca and Beni Nouchera) are restricted to this part of the system.

Seismicity

Seismicity distribution displays a pattern (Fig. 2B) in which deep seismic events (> 30 km) are restricted to the western Alboran basin. These events have been related to continental subduction (Morales *et al.*, 1999), to a detached oceanic slab (Blanco and Spakman, 1993), or to delamination (Docherty and Banda, 1995; Seber *et al.*, 1996). Shallow seismicity in the western Betics seems related to the frontal superficial over-thrusting of the Betics over the Guadalquivir basin. In the central Alboran, seismic activity is limited while further to the east a N025°-trending zone of pronounced shallow seismicity can be observed. Focal mechanism solutions by Morales *et al.* (1999) show a NW–SE compressional direction in the Iberian foreland. In contrast, the Alboran plate is characterized by a SW–NE-orientated maximum compression.

Gravity

In Fig. 2(C) offshore Free-Air gravity data (Sandwell and Smith, 1997) are presented. The coastline of Malaga to Gibraltar and the Rifian coast are characterized by a ridge of positive anomalies. These positive anomalies can be correlated with the presence of the peridotitic bodies in this part of the system. In the inner western Alboran basin a large negative anomaly is observed. This pattern changes to the east in a diffuse pattern without clear highs and lows.

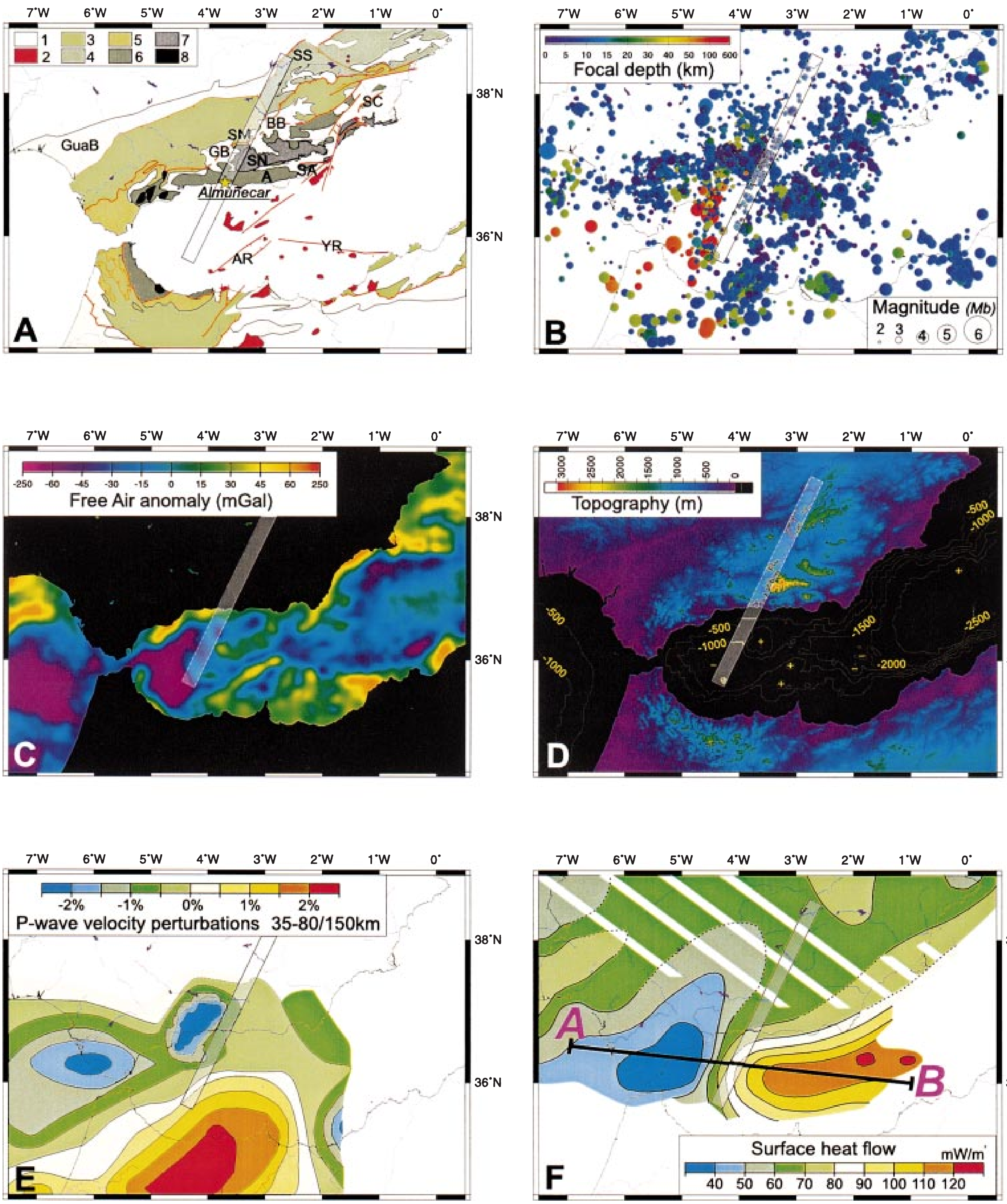
Topography

The present-day topography (Fig. 2D) of the area is closely linked to surface geology, showing an E–W-trending grain of basins and anticlinal structures. The mean elevation of the ranges and basins in east and west shows a marked difference. The elevation of the Sierras in the eastern Betics is over 2000 m (Sr. Baza 2271 m, Sr. de Segura 2381 m, Sr. de los Filabres 2168 m, Sr. de Gador 2236 m) and the Sierra Nevada reaches well over 3000 m (Mulhacén, 3482 m). In the western Betics elevations over 2000 m are rare (Sr. Mágina 2163 m, Sr. Alhama 1832 m, Sr. Gorda 1669 m, Serrania de Ronda 1919 m). Generally the basins and ranges are far from continuous owing to dipping axes of the anticlinal mountain ranges. Therefore, lateral discontinuities occur in the E–W structure. Normally, these laterally limited features generate an alternating pattern of basins and ranges; however, just west of the Sierra Nevada an obvious line-up of main discontinuities can be observed. From north to south: the eastern culmination of the Guadalquivir basin next to the Sierra Segura, the Sierra Mágina and the Guadix-Baza basin, the Granada Basin is next to the Sierra Nevada and the Sierra Alhama next to the depression between the Sierra Nevada and the Alpujarras.

Tomography

Recently, Morales *et al.* (1999) observed a low-velocity anomaly in the upper mantle beneath the Betic Cordillera and the Alboran Sea. They interpreted this feature as an active continental subduction of the Iberian plate under the overriding Alboran/Betic realms. The implications of the limited lateral extent of the low-velocity anomaly have not been addressed. The subducting continental slab detected by Morales *et al.* (1999) shows deepening towards the SE and is limited to the SE by a straight line trending N025°.

Seber *et al.* (1996) showed the presence of high-velocity material in the upper mantle under the Rif region and the Alboran, extending north-east under southern Spain, which they interpret as delaminated lithosphere. They do note the existence of a low-velocity body in the upper mantle under the western Rif/Gibraltar area and a sharp vertical transition boundary near the Strait of Gibraltar separating both anomalies. Blanco and Spakman (1993) observed a similar



positive anomaly of limited lateral extent under the eastern Betics and the Alboran region trending SW–NE and interpret this feature as a detached subducted slab. Figure 2E shows a compilation of the data from Seber *et al.* (1996) and Morales *et al.* (1999) for lower crustal to upper mantle levels. The boundary between the above mentioned anomalous bodies is located in the western Alboran region. The SW-dipping 'continental subduction' of Morales *et al.* (1999) can be interpreted as the oblique overriding of the Iberian continental lithosphere by the Alboran basement.

Heat flow, crustal structure and integrated strength

The heat flow in Iberia (Fernàndez *et al.*, 1998b) shows a smooth pattern except around the Alboran region. Generally, heat flow in the eastern Betics is 60–70 mW m^{-2} while the

Fig. 2 Integration of different data sets for the Alboran. Lens-box denotes the Almuñecar sinistral shear zone. (A) Simplified geological map. 1, Neogene onshore basins; 2, Neogene volcanics; 3, External zones; 4, Prebetics; 5, Flysch nappes; 6, Malaguide/Alpujarride domain; 7, Nevado Filabride domain; 8, peridotites; SN, Sierra Nevada; SC, Sierra Carrascoy; SA, Sierra Alhamilla; SS, Sierra Segura; SM, Sierra Magina; A, Alpujarras; GB, Granada Basin; BB, Guadix/Baza Basin; GuaB, Guadalquivir Basin; AR, Alboran Ridge; YR, Yussuf Ridge. Yellow star: location of the city Almuñecar. (B) Seismicity distribution. Deep earthquakes (> 50 km) are restricted to the westernmost Alboran basins. Note a NE–SW-trending zone of limited seismicity next to a zone trending in the same direction with increased seismicity in the central/eastern Alboran basin. Data from interactive Council of the National Seismic System (CNSS) database (http://quake. geo.berkeley.edu/cnss/catalog-search. html). (C) Free Air anomaly (Sandwell and Smith, 1997). (D) Topography and bathymetry (gtopo30 and etopo5 databases). (E) P-wave velocity perturbations at lithospheric to lower crustal levels. Compilation of data from Seber *et al.* (1996) and Morales *et al.* (1999). (F) Heat flow (after Fernàndez *et al.*, 1998b). Note strong gradient from Gibraltar eastward. A–B indicates profile line along which strength profile calculations have been performed (Fig. 4).

western Betics show extremely low values of 40–50 mW m^{-2} (Fig. 2F). The strongest gradient is situated in the western Alboran basin, from as much as 110 mW m^{-2} at the Alboran Ridge in the central part of the Alboran Basin to only 40 mW m^{-2} east of Gibraltar. The latter value is equivalent to or even below values for thermally stable cratonic areas, which is remarkable since southern Iberia has experienced several thermal events related to the opening of the Atlantic. Fernàndez *et al.* (1998b) recognize some areas with local perturbations of the thermal regime, probably related to groundwater circulation, but consider the 40–50 mW m^{-2} values not to have been caused by this. Most likely the low values are a dynamic effect of the active underthrusting of the Iberian crust under the Alboran crust (Morales *et al.*, 1999) temporarily blocking the mantle heat flow component. Based on now outdated heat flow data and flexural modelling of the deflection of the Iberian lithosphere under the Guadalquivir Basin and Betics, Van der Beek and Cloetingh (1992) inferred a large lateral variation in lithospheric strength between the eastern and western part of the Iberian foreland. Following the approach of Lankreijer *et al.* (1999) using the new compilation of heat flow data and Moho depth by Fernàndez *et al.* (1998a), an integrated strength profile was constructed through the Alboran, parallel to the abovementioned gradient (see Fig. 2F for location). Crustal thickness does not change considerably over the region. Owing to the strong gradient in heat-flow, the calculated integrated crustal strength increases dramatically

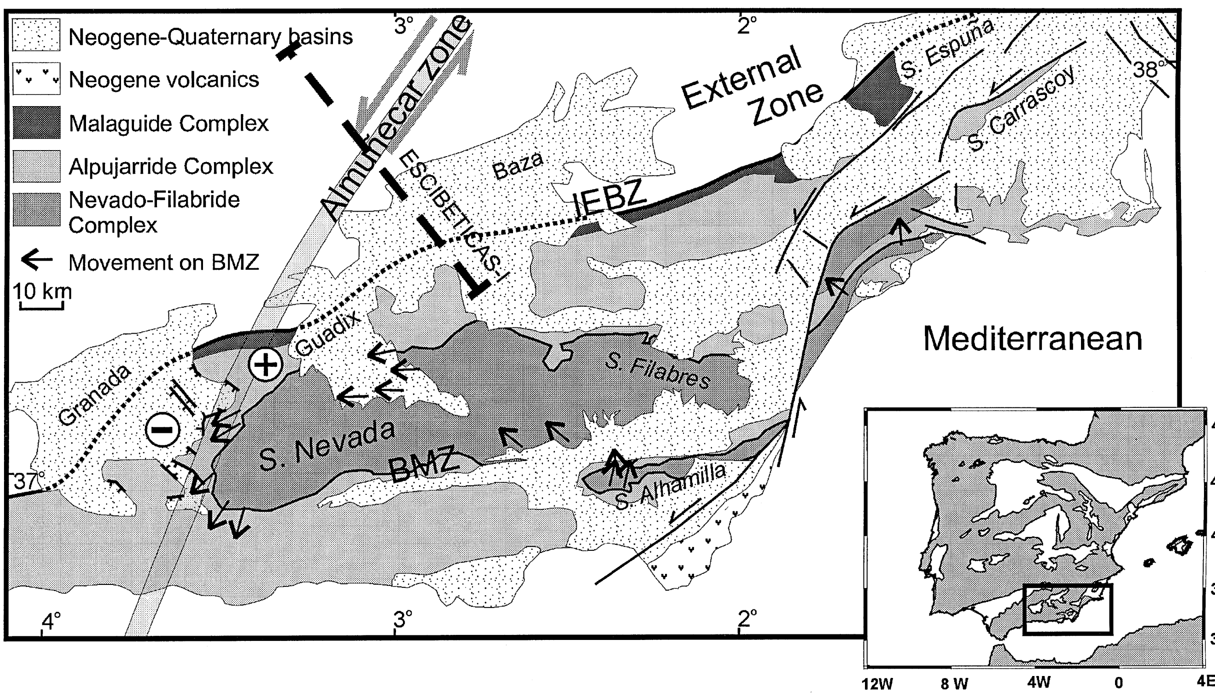


Fig. 3 The Sierra Nevada indenting the Iberian foreland in the restraining bend of the sinistral shear zone (denoted by lens-box). The late Miocene to present-day folding, the redistribution of the movement indicators on the Betic Movement Zone (BMZ), general shape of the Sierra Nevada, recent seismic activity, related normal faulting in the Granada Basin and the individualization of the Granada/Guadix basins support this interpretation. Dashed line locates the ESCIBETICAS-I seismic reflection profile presented in Fig. 5. IEBZ, Internal–External Boundary Zone. Inset shows location.

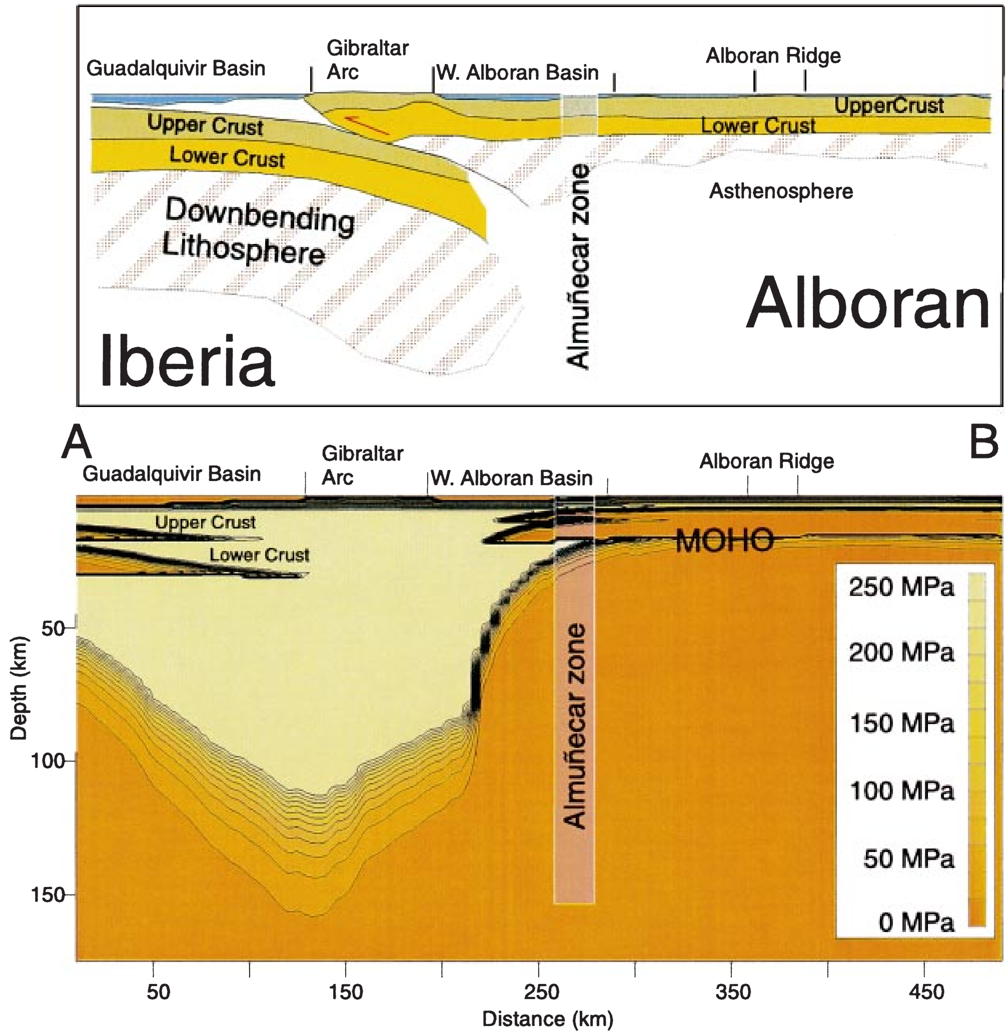


Fig. 4 Bottom: integrated compressional strength along profile A–B (Fig. 2F) showing dramatic increase of crustal strength over the Almuñecar zone. Top: schematic interpretation. See Tables 1 and 2 for the input parameters used in the calculations. Crustal thickness is constrained by seismic reflection and refraction data.

from east to west (Fig. 4, see Table 1 and Table 2 for input parameters for the calculations).

Similarly, Banda and Ansorge (1980) inferred from seismic refraction profiles that the crustal blocks on both sides of the Palomares–Alhama de Murcia fault system are different in structure, as well as in thickness.

Table 1 Input parameters for the calculation of integrated crustal strength following the approach of Lankreijer *et al.* (1999)

Strain-rate	1×10^{-15} s^{-1}
Slope pressure branch (compression)	1.67
Cut-off yield strength (compression)	250 MPa
Thermal base (km)	250
Temperature at base (°C)	1300
Surface temperature (°C)	0

Crustal structure in the region can further be derived from deep seismic reflection profile ESCIBETICAS-I running NNW from the Sierra Nevada to the culmination of the Guadalquivir basin (see Fig. 5). Galindo-Zaldívar *et al.* (1997) published and interpreted the profile to display a continuous Moho at around 10 s TWT, but put question marks on their interpretation. A zone of gently dipping reflectors can be observed in the left central part of the profile, the base of which deepens from around 13 s TWT to around 15 s TWT towards the south-east. At around halfway along the line, the deepest reflectors are near horizontal and again located at around 13 s TWT. This break coincides with the inferred position of the shear zone. Another break in the reflective zone is present to the south-eastern part of the line, which has been correlated with the External/Internal Boundary Zone (e.g. Banda and Ansorge, 1980). Reinterpretation of the profile supports the idea of oblique overthrusting of the Alboran crust over the downwarped Iberian crust.

A N025°-trending sinistral shear zone

In all the datasets presented, a marked difference can be observed between

Table 2 Rheological input parameters for the calculation of integrated crustal strength following the approach of Lankreijer *et al.* (1999)

	Upper crust	Lower crust	Mantle
Petrology	Granite (dry)	Diorite	Olivine
Density (kg m^{-3})	2700	2900	3300
Heat production (W m^{-3})	2.00×10^{-6}	0.50×10^{-6}	0
Thermal conductivity (W mK^{-1})	2.5	2.0	3.5
Heat capacity (J kgK^{-1})	1136	1029	1212
Yield function	Powerlaw	Powerlaw	powerlaw + Dornlaw
Skin depth (m)	10×10^3	0	0

Parameters used in the calculation of the integrated strength profile (Fig. 4).

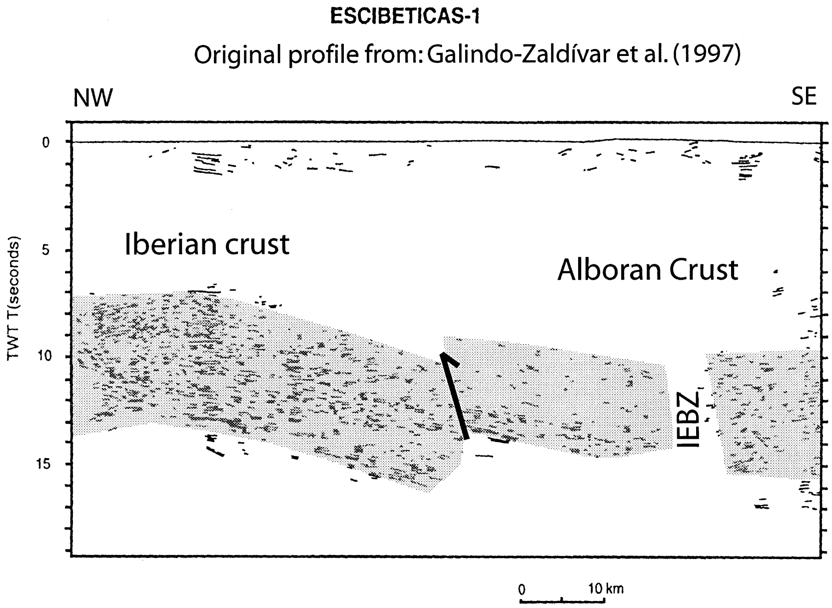


Fig. 5 New interpretation of the ESCIBETICAS-I seismic reflection profile through SE Spain (original profile after Galindo-Zaldívar *et al.*, 1997). IEBZ, Internal–External Boundary Zone. See Fig. 3 for location and text for discussion.

the eastern/central and western Alboran regions. In several datasets, the limit between the two areas with different features or behaviour cannot be determined precisely. In most sets, however, the existence of a N025°-trending zone (elongated box in Fig. 2) can be observed that enters mainland Iberia near Almuñecar. The absence of a discrete fault plane at the surface suggests diffuse upper crustal deformation over a deeper crustal–upper mantle shear zone. Within the diffuse plate boundary region between Africa and Iberia (recently) active large NE/SW-trending sinistral zones have been documented; for example, the Palomares fault zone in the eastern Betics (Biermann, 1995) and the Moroccan Middle Atlas Northern Border Fault, running down south-west to Agadir (Jacobshagen, 1992; Bernini *et al.*, 2000). Because the Almuñecar zone shows a similar trend to the other crustal shear zones, the sinistral motion along the zone fits into the regional picture. The trend and crustal nature of the lineaments and the pronounced difference in thermo-mechanical structure and crustal strength on both sides of these zones might point to transform faults related to the opening of the Tethys ocean. This would explain most of the observed differences between the eastern and central/western part of the Alboran Basin and circum-surrounding Rif–Betic belt.

The presented zone is consistent with a model that explains the accommodation of a large part of the convergence between Africa and Eurasia from latest Miocene to present day by sinistral wrenching along major N020–045°-trending strike-slip zones. This suggests decoupling of Morocco from mainland Africa that is pushing Iberia westward on its northward movement.

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