

The Baza Fault: a major active extensional fault in the central Betic Cordillera (south Spain)

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Abstract In the Guadix-Baza Basin (Betic Cordillera) lies the Baza Fault, a structure that will be described for the first time in this paper. Eight gravity profiles and a seismic reflection profile, coupled with surface studies, indicate the existence of a NE-dipping normal fault with a variable strike with N-S and NW-SE segments. This 37-km long

fault divides the basin into two sectors: Guadix to the West and Baza to the East. Since the Late Miocene, the activity of this fault has created a half-graben in its hanging wall. The seismic reflection profile shows that the fill of this 2,000–3,000 m thick asymmetric basin is syntectonic. The fault has associated seismicity, the most important of which is the 1531 Baza earthquake. Since the Late Tortonian to the present, i.e. over approximately the last 8 million years, extension rates obtained vary between 0.12 and 0.33 mm/year for the Baza Fault, being one of the major active normal faults to accommodate the current ENE–WSW extension produced in the central Betic Cordillera. The existence of this fault and other normal faults in the central Betic Cordillera enhanced the extension in the upper crust from the Late Miocene to the present in this regional compressive setting.

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Introduction

The development of the Betic and Rif Cordillera in the Western Mediterranean is a consequence of deformations associated with the Eurasian and African plate boundaries. Since the Miocene, the geodynamic setting of NW–SE oblique convergence (4–5 mm/year sensu DeMets et al. 1994) has determined a regional NW–SE compression (Montenat and Ott d'Estevou 1990; Sanz de Galdeano 1990; Galindo-Zaldívar et al. 1993; Herraiz et al. 2000). Within this geodynamic setting, an arched orogen has formed, namely the Arc of Gibraltar. The Alboran Sea, a basin formed by the crustal thinning of the Internal Zones precisely where one might expect to find the greatest

thicknesses and relief, is one of the most important structural features of this orogen.

Although the Betic Cordillera is located at a convergent plate boundary, Neogene and Quaternary evolution in the Internal Zone is characterized by the development of low-angle normal faults that cause the extension of the upper part of the crust (Platt and Vissers 1989; Galindo-Zaldívar et al. 1989). High-angle normal faults and strike-slip fault systems have also been identified. These extensional structures have been active since the Miocene (Galindo-Zaldívar et al. 1989, 1999). Therefore, the compression has been accompanied by ENE–WSW extension (Galindo-Zaldívar et al. 1999; Sanz de Galdeano and López-Garrido 2000; Marín-Lechado et al. 2005).

Most of the better known normal faults are situated in the Granada Basin, located slightly over 100 km to the SW of the study area. Microtectonic studies and analysis of the focal mechanisms in this basin reveal the existence of NE–SW extension from the late Miocene until today (Galindo-Zaldívar et al. 1999). Sanz de Galdeano and López-Garrido (1999, 2000) studied the uplift of the western Sierra Nevada, the largest relief in the Betic Cordillera, which borders the Granada Basin. These authors describe NW–SE, N–S and NNE–SSW conjugate normal faults that accommodate the Sierra Nevada uplift and the E–W extension, in a N–S compressive setting. Gil et al. (2002) selected a 15-km long segment of the eastern area of the Granada Basin where several active normal faults crop out. Using the marine Tortonian rocks as a reference, they calculate a minimum extensional rate of 0.15–0.30 mm/year for approximately the last 8 million years.

In the Guadix-Baza Basin, located in the central area of the Betic Cordillera (Fig. 1), many geological studies have been carried out, focusing mostly on biostratigraphic and sedimentological aspects of its late Neogene and Quaternary deposits. Neotectonic studies are scarce and have only been undertaken at a regional scale. For this reason, no information has previously been provided about the existence of a large NW–SE normal fault that divides the basin into two areas: Guadix to the West and Baza to the East. This fault, referred to in this paper as the Baza Fault, is highly significant in the geodynamic evolution of this part of the Betic Cordillera. Some previous studies do mention segments or splays of this fault, although none define or characterise it as a fracture of regional importance.

The main aim of this study is to define the geometry of the Baza Fault from surface geology and geophysical data. Eight gravity profiles have been performed in order to estimate the depth of the basement in the hanging wall of the Baza Fault. In addition, we interpreted a seismic reflection profile carried out by the Compañía General de Geofísica, S.A. for ENIEPSA in January, 1984 (ITGE 1999). The results obtained have been compared with the

results of studies carried out by the ITGE (1999) using vertical electrical soundings. Finally, the calculated extensional rates indicate the regional importance of the Baza Fault in the recent evolution of the Betic Cordillera.

Geological context

The Guadix-Baza Basin where the Baza Fault is located is an intramontane basin in the central area of the Betic Cordillera (Fig. 1). The basement of the southern part of the basin is essentially formed by metamorphic complexes that are, from bottom to top: the Nevado-Filábride, Alpujarride and Maláguide, as well as the Dorsal Complex.

In the Sierra de Baza located in the Southwest of the studied area, Middle-Upper Triassic limestones and dolostones of the Alpujarride complex crop out, which have been subjected to low-grade metamorphism. To a lesser extent, there are also mica schists, quartzite and gypsum from the Early Triassic. Northwards, in the Sierra del Jabalcón (Fig. 2), Jurassic limestone and dolostones predominate in the so-called Dorsal Complex (Internal Zone). Finally, to the North of Jabalcón, materials belonging to the Subbetic domain (External Zone) crop out in valleys near the northern end of the Baza Fault.

This varied basement, which includes the contact between the Internal and External Zones of the Betic Cordillera in the area studied, is covered with a sedimentary fill that begins with Upper Miocene marine rocks and ends with Quaternary continental rocks. The sedimentary fill of the Guadix-Baza Basin has been the focus of many stratigraphic and biostratigraphic studies (Vera 1970a, b; Peña 1979, 1985; Viseras 1991; Guerra-Merchán 1992; Agustí 1986; Agustí et al. 1997; Vera et al. 1994; Soria et al. 1998).

In the area studied, Upper Miocene marine sediments mainly crop out in the Bodurria sector (Fig. 2). Marine sedimentation is essentially represented by Tortonian calcarenites and Tortonian and Messinian marls, interpreted as fan delta deposits. These rocks form part of the first tectonosedimentary unit of the basin (Guerra-Merchán 1992), which ends with its continentalisation. García-García et al. (2000) and García-García (2003) have recently narrowed down the age of these marine materials to the end of the late Tortonian.

Overlying the marine rocks are Plio–Quaternary fluvial and lacustrine rocks. Like those mentioned previously, these represent an important sedimentary cycle with internal unconformities, some of which may also be attributed to tectonic events (*sensu* Viseras 1991; Guerra-Merchán 1992). The fluvial sediments mainly consist of limestones, sandstones and conglomerates from the so-called Guadix Formation (Von Drasche 1879; Vera 1970a, b),

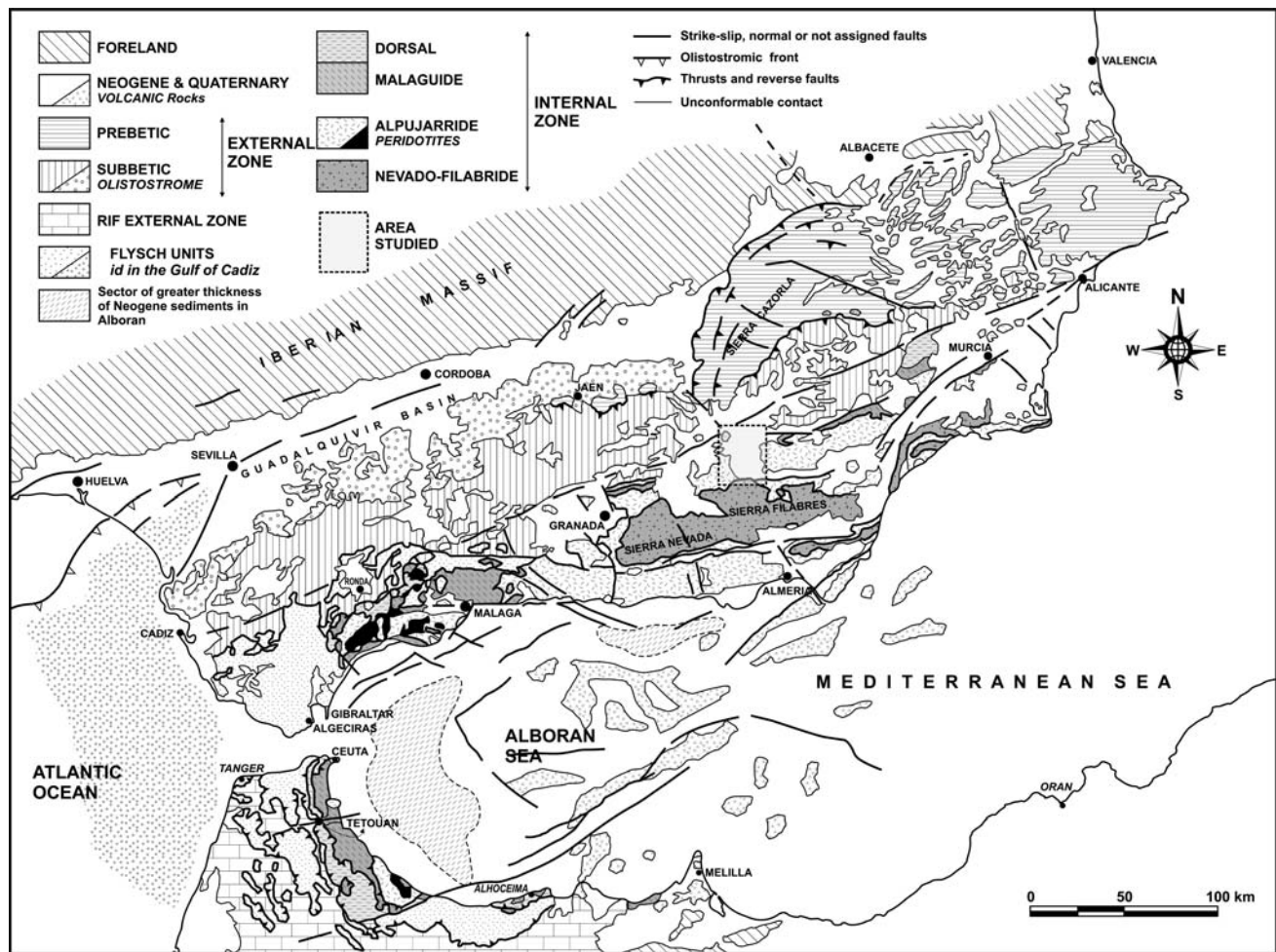


Fig. 1 Simplified geological map of the Betic Cordillera and location of the studied area

which are exposed mostly to the West of the Baza Fault. On the other hand, the lacustrine deposits, formed mainly of limestone, marls and gypsum from the so-called Baza Formation (Vera 1970a), essentially crop out to the East of the fault. Lacustrine and fluvial sedimentation ended during the Late Pleistocene (Calvache and Viseras 1997) when the basin drainage changed from endorheic to exorheic. As of this point in time, erosion predominates in the area.

We should point out the lack of a detailed study, to date, of the basin tectonics. Only in a few regional studies or basin analyses have certain tectonic aspects been taken into account in order to determine the geodynamic evolution of the basin. As regards the paleostress history of the basin, Estévez et al. (1976) studied the anticlines of the Negratín related to recent diapirism (López-Garrido and Vera 1974). In this area, located 12 km to the West of the Jabalcón, these authors have determined a compressive stress field from the Pliocene to the Quaternary.

Several previous studies document the presence of normal NW–SE to N–S faults, some of which correspond to one or more segments or splays of the Baza Fault.

However, none of these studies mentions the regional relevance of this fracture.

Vera (1970a) is the first author to underline the presence of this fault in the southern-most area studied here, specifically near Bodurria (Fig. 2). He draws normal faults in some geological cross-sections and maps, which generally coincide with some of the splays located SE of the area studied. Similar to Vera (1970a), Delgado et al. (1980) characterise two NW–SE splays in the Bodurria area on the geological map of Spain at a scale of 1:50,000 (number 994 of Baza). Neither study identifies the northerly segments nor represents the eastern splays in this sector.

Goy et al. (1989) provide an interesting and detailed geological and geomorphological map of the area between Baza and Caniles. Several NW–SE splays—some of them as supposed faults—and morphological scarps are mapped. Yet, the main splays located to the West and North are not described.

Viseras (1991), in a stratigraphic-sedimentological study of the Guadix-Baza Basin, suggests it is divided into several sectors by NW–SE fractures. In this way, the Tíscar

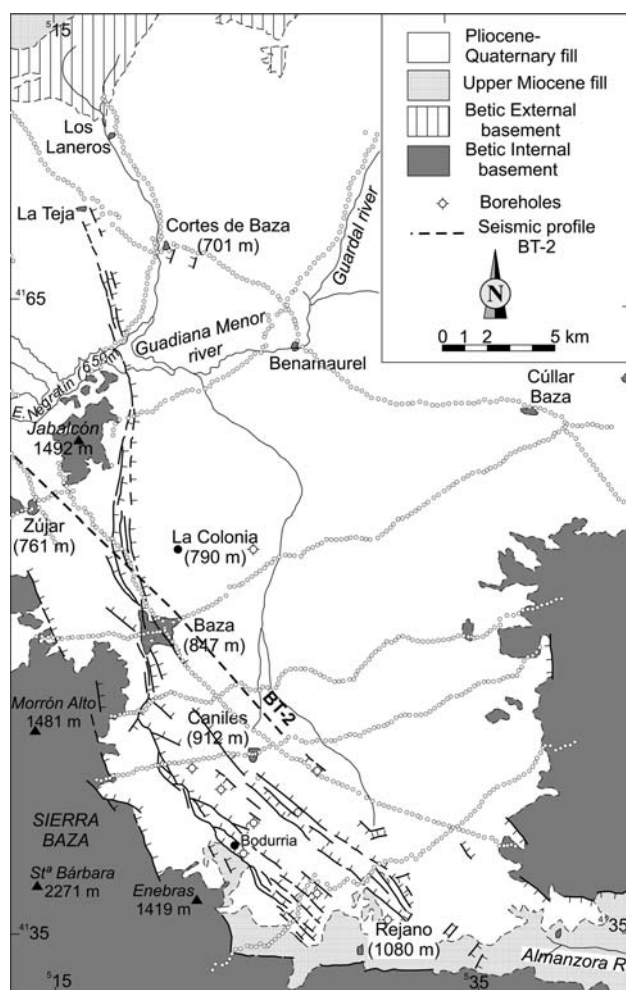


Fig. 2 Geological map of the studied area showing the main Baza Fault splays and location of the gravity profiles (the dotted line indicates location of gravity measurements)

Fault (located a few kilometres to the NW of the area studied) would be the main structure responsible for the division between the western and eastern areas of the basin. This author provides no more details, nor does he define the Baza Fault.

Guerra-Merchán et al. (1991) and Guerra-Merchán and Ruiz Bustos (1991) date a microvertebrate site and indicate the existence of normal faults to the West of Baza. According to these authors, some of these faults have a throw of over 100 m, produced after the Pliocene. They indicate that the fault must have been active recently as it affects the glacia associated with the top sediment bed, dated as Late Pleistocene (~100 ka) (Botella et al. 1985, 1986). Recently, Azañón et al. (2006) date the calcrete that caps the recent fill of the basin as 42.6 ka.

Guerra-Merchán and Ruiz Bustos (1992) study other microvertebrate sites located a few kilometres to the South of Baza in the Caniles sector; and, they also indicate the

existence of normal faults to the South and West of Caniles, pointing out that the most recent sediments cut by these fractures date back to the Middle Pleistocene. Guerra-Merchán (1992) describes several topographic steps related to these NW–SE normal faults, which cut the glacia.

Heddi et al. (1999) have recently mapped the main fractures of the basin using Landsat Satellite orthoimage lineaments. They identify three main lineaments related to three sets of fractures running NE–SW, NW–SE and ENE–WSW. Although these supposed fractures are not identified in surface geological studies, one of them reveals an approximate fit with the Baza Fault trace.

García-García et al. (2000) and García-García (2003) carried out a sedimentological study of the marine materials located in the Bodurria area (southern-most end of the study area). These authors link marine sedimentation to listric normal faults which correspond to some parts of the Baza Fault. From roll-over folds, they propose the supposed existence of a main fault trace at the contact between the basement and the sedimentary fill. According to the authors, these marine deposits date back to the end of the late Tortonian.

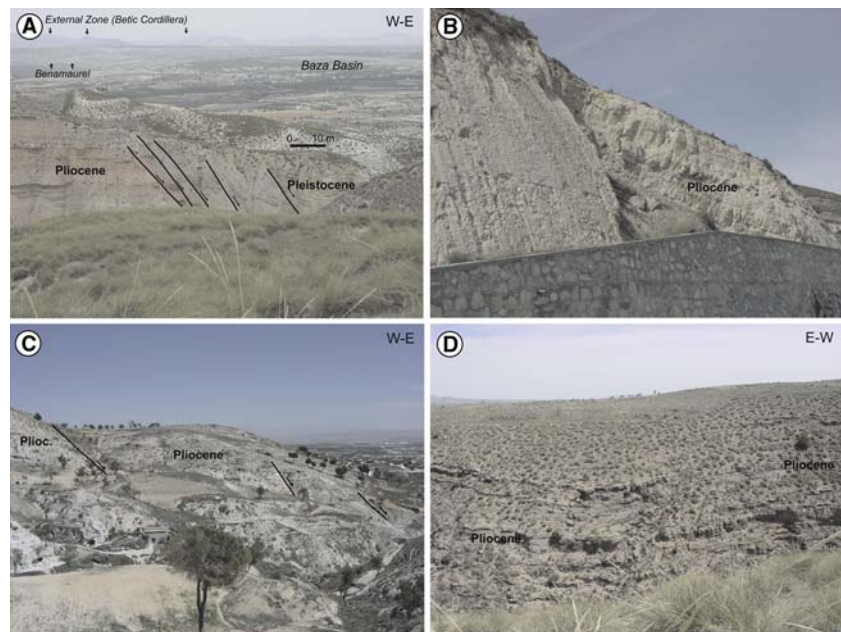
Surface geology of the Baza Fault

From the geological mapping carried out in this study, it can be concluded that the Baza Fault is an active normal fault measuring ~37 km in length and extending from the South of Caniles to La Teja (Fig. 2). This fault has a southern segment that runs on average NW–SE, a central segment running N–S and a northern segment with a NNW–SSE strike. These strike variations correspond to the heterogeneity of the basement in this area of the Cordillera. The carbonated Jabalcón Mount (Internal Zone) appears to act as an obstacle that refracts the regional NW–SE trend of the fault, producing the N–S strike in its central segment.

At the surface, the fault cuts through Upper Miocene, Pliocene and Pleistocene rocks (Fig. 3). There are abundant cross-sections where Pliocene soft rocks crop out in the foot wall and Pleistocene soft rocks in the hanging wall. Although we have no precise dates for the Holocene materials deformed by the fault, it cuts through and displaces the Late Pleistocene glacia (100 ka sensu, Botella et al. (1985, 1986) 45 ka sensu Azañón et al. (2006)).

The fault trace has several splays, roughly parallel to each other, which are more abundant in the southern segment and scarce to the NE of the Jabalcón (Figs. 2, 3a). The southern branches converge northwards until merging into one near Jabalcón. Therefore, the Baza fault zone narrows gradually to the North. At the surface, most of the fault plane dips vary between 40° and 55° ENE. In most of the outcrops, dip slip is observed in Pliocene–Pleistocene

Fig. 3 **a** General view of the Baza fault zone in the Jabalcón area. **b** Detailed view of the fault plane. **c** Parallel fault scarps developed in Pleistocene rocks near Baza. **d** Morphological scarp developed by a splay near Bodurria



soft rocks (Fig. 3b). Abundant gypsum slickenfibers indicate the normal kinematics of the different splays.

In the southern zone, the splays produce a number of more highly developed morphological scarps that are positioned far apart from each other (Fig. 3c, d). They thin out into just a few closely spaced scarps in the central segment of the fault, and finally one scarp remains in the northern zone. These scarps are formed in Pliocene and Pleistocene soft rocks (Fig. 3c, d).

The fault termination varies at either end. At the northern end, a gradual decrease of the throw is produced, practically on one single superficial fracture, with a progressively steeper dip. On the other hand, the southern end of the fault branches off, dividing its total throw into a number of splays, and several NE–SW faults are also present.

Geophysical research

Previous geophysical data are scarce for the studied area. The FAO carried out a series of vertical electric soundings (VES) in the Zújar area, in the sector surrounding the Jabalcón, in 1968 and 1969, which were complemented by the ITGE with a new campaign in 1999. These soundings were carried out to the East and West of the fault trace.

Interestingly, they identify a sudden depression of the basement surface and a significant increase in Plio–Quaternary fill to the East of the Zújar area, in the hanging wall of the fault. Furthermore, the analysis of the seismic reflection profile BT-2 (ITGE 1999) shows that the reflector marking the contact between the Triassic basement and the

sedimentary fill is situated at a depth of between 1,300 and 1,500 m, and that the increase in thickness towards the SE coincides with the information provided by the VES.

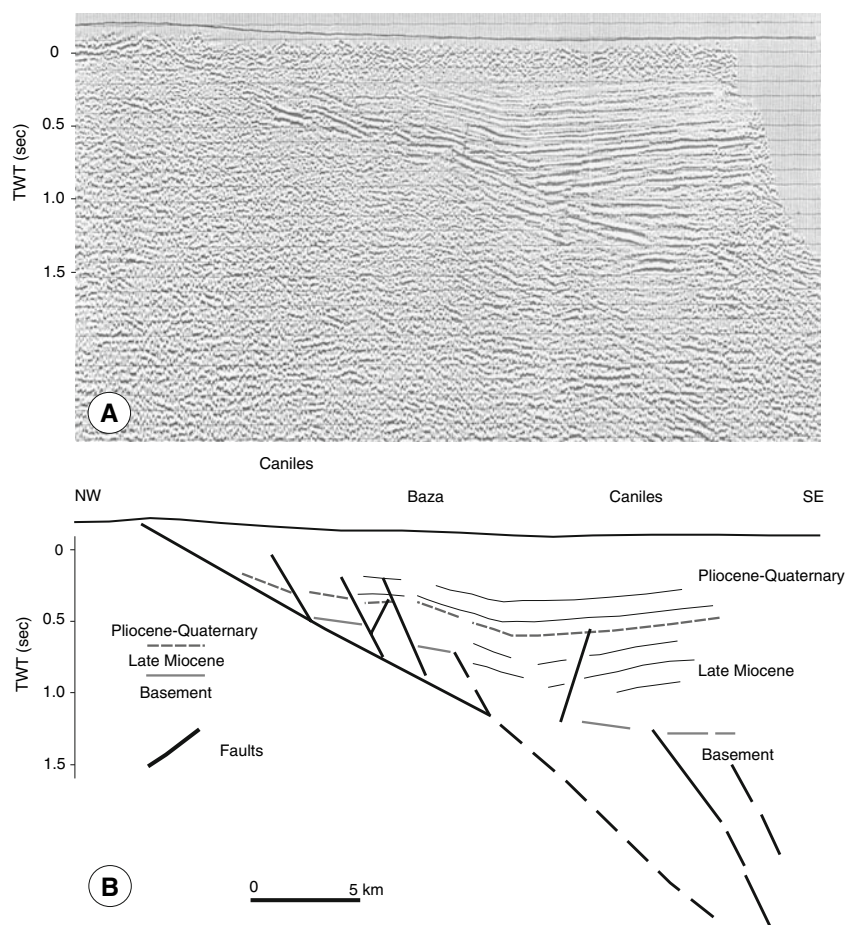
In addition to this geophysical information, data was obtained from ten boreholes drilled in the area between Baza and Caniles (Urbano et al. 1991), where depths range from 81 to 310 m. The Triassic basement is cut in only two of these, both located in the foot wall of the Baza Fault. The rest of the boreholes, located in the hanging wall, cut the fill of the basin without reaching the basement. The deepest, at 310 m, lies between Caniles and Baza.

Seismic reflection

The seismic profile BT-2 (ITGE 1999) is the only one available for the studied area. This profile cuts through the fault in the area located between Jabalcón and Caniles and runs along the hanging wall in a NW–SE direction, oblique to the main strike of the fault. This obliquity determines the registration of lateral reflections from the main line of the fault, resulting in overprinted reflectors and an apparent low dip of this fault.

In the seismic profile (Fig. 4), the fault dips towards the SE, separating the Triassic basement from the Neogene fill of the basin. In our interpretation, the fault, with the Neogene sediments in the hanging wall, is located at 1.3 s (two-way travel time) at the central part of the profile. From the RMS velocities (3,300 m/s), we calculated a basement depth of 2,150 m, which is greater than that determined by ITGE (1999). The greater basement depth in our interpretation is coherent with the high gravity anomalies in most of the profiles.

Fig. 4 **a** Seismic section BT-2, oblique to the main strike of the fault. **b** Geological interpretation of the seismic reflection profile (BT2)



The basin in the hanging wall of the Baza Fault has been filled syntectonically from the Late Miocene to the present. Several normal basement faults propagate upwards through the basin fill sediments to the surface (NW of the seismic profile), whilst others are sealed by the Plio–Quaternary fill (SE of the profile). The fault zone mostly contains synthetic faults with a few antithetic faults.

Gravity

Data collection

The gravity data presented in this study are part of a broader research project carried out over the whole of the Guadix-Baza Basin, whereby several profiles and isolated measurements have been made in order to accurately determine the Bouguer anomaly in this basin. The gravity data corresponding to the area described here refer to eight profiles whose lengths range from 15 to 38 km (Fig. 2). With respect to the fault, most of these profiles are perpendicular, particularly profiles 1, 2, 3 and 4 which run ENE–WSW. Profiles 5 and 6, with a NE–SW orientation and profile 8, with a NW–SE orientation, are oblique to the fault trace. Finally, gravity profile 7, which cuts through

the first four, is oblique to the fault and in some areas almost parallel, so that it coincides approximately with seismic profile BT-2.

Approximately 900 measurements were carried out using a Sodin 200T gravimeter, with temperature compensation and an accuracy of 0.1 mGal. Stations were located using GPS and a barometric altimeter with a precision of 0.5 m. Spacing between measurements varies approximately between 200 and 250 m. Measurements were made over cycles of less than three hours in order to correct for gravimeter drift. Altimetric drift was corrected making base-points for each profile whose orthometric heights with respect to the Spanish Vertical Datum were derived from relative GPS measurements and the AndalusGeoid 2002: the new gravity geoid model of Andalusia (Blázquez et al. 2003). The accuracy of this relative GPS/Geoid levelling is within a few centimetres.

Gravity anomalies

Gravity data were calibrated from absolute gravity measurements taken at the station of the Instituto Geográfico Nacional in Baza. Based on these data, the Bouguer anomaly was calculated, taking into account a standard

density of $2,670 \text{ kg/m}^3$. In addition, the terrain correction was calculated up to 10 km. A map of the Bouguer anomaly was obtained by gridding these data.

Measurements on basement rocks were taken at both ends of each profile to calculate the regional anomaly. They were interpolated to create a map showing the regional trend of the gravity anomaly. This map shows a gentle regional trend decreasing towards the Northwest of the study area, reaching a minimum value of -130 mGals North of Negratín dam.

Both maps were used to calculate the residual anomaly by subtracting the regional anomaly from that of the Bouguer. The resulting residual anomaly map shows a large area of negative anomaly (Fig. 5) whose western border runs parallel to the fault. The maximum negative values of this anomaly are located very close to this border. The first is located ENE of the Jabalcón Mount and shows maximum negative values of more than -30 mGals . The other is located between Baza and Caniles and shows

maximum negative values of about -25 mGals . These two zones may correspond to two different depocentres within the basin, produced by the activity of the fault.

This map was then used to obtain the residual anomaly for each station in the profiles made. The largest anomaly was found in profile 8, with a maximum negative value of -32 mGals . In the remaining profiles, the anomalies range from -24 to -27 mGals , with the exception of profiles 1 and 6, located at the southern and northern terminations of the fault, respectively. The maximum negative value of the anomaly is -8 mGals in profile 1 and -18 mGals in profile 6. These profiles show how the fault throw decreases towards the ends.

Gravity models and geological interpretation

Two-dimensional models of the residual anomaly were made for the eight profiles with the Gravmag v.1.7 programme (Pedley et al. 1993) (Fig. 6) using the contrast in the density of the lithological contact between the Triassic basement and sedimentary fill observed from the field data. No data are available regarding rock density or depth to the basin basement in the hanging wall. To avoid, or at least to minimize any subjective interpretation as regards these points, the seismic profile BT-2 was used as a reference. As previously indicated, the depth to the basement is estimated to be of the order of $2,150 \text{ m}$. Taking into account that gravity profile 7 coincides approximately with the seismic profile trace, the sedimentary fill density was adjusted until a similar basement depth was achieved. The optimum adjustment obtained was with a sedimentary fill density of $2,320 \text{ kg/m}^3$. Therefore, a density contrast of 350 kg/m^3 between the fill and the basement was used.

In the eight gravity profiles, small variations in the supposed sedimentary fill density notably affect the calculation of the basement depth. For example, in gravity profile 7, parallel to the seismic profile, a sedimentary fill density of $2,320 \text{ kg/m}^3$ was used in order to obtain a Triassic basement of $2,150 \text{ m}$ in depth (identical to the one obtained in the seismic profile). However, the depth obtained is $2,900 \text{ m}$ at a density of $2,400 \text{ kg/m}^3$, $2,400 \text{ m}$ at $2,350 \text{ kg/m}^3$ and only $1,900 \text{ m}$ when the density is less than $2,270 \text{ kg/m}^3$. Such uncertainty also arises when calculating fill thickness at the Guadix-Baza Basin depocentre, to the ENE of Jabalcón Mount, where the maximum gravity anomaly (32 mGal) is located. In profile 8, which passes through this depocentre, sedimentary fill thickness reaches a maximum of $3,000 \text{ m}$. However, this value may be exaggerated given the abundance of less dense evaporitic rocks in this area of the basin than at the margins. This could cause the depocentre to appear deeper than it really is.

Profile 1 (Fig. 7) shows the termination of the Baza Fault at its southern end. In this area, the fault throw is

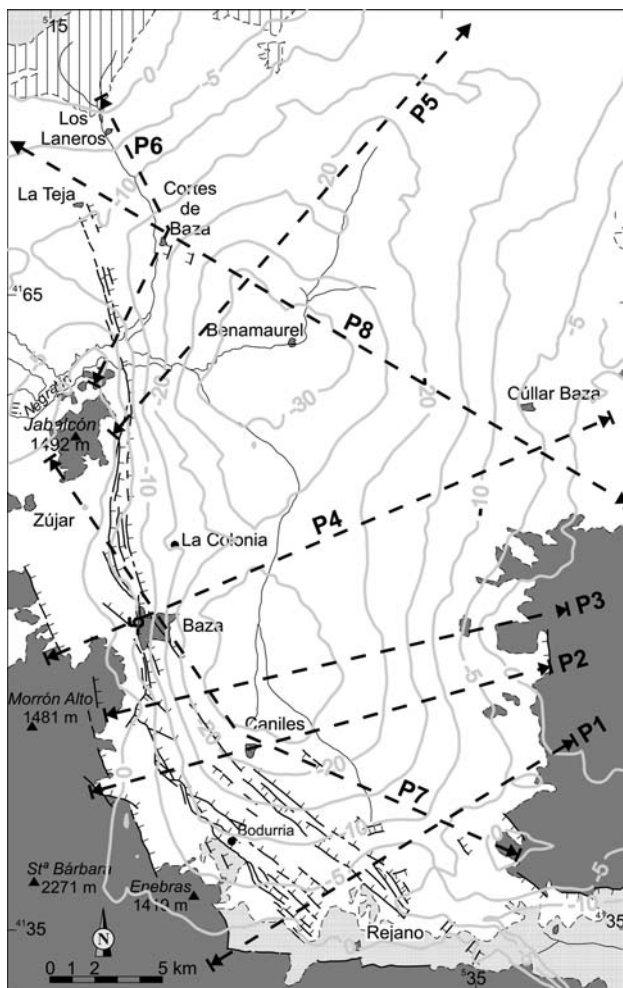


Fig. 5 Residual gravity map (contour interval 5 mGal), showing location of two-dimensional models. Geological legend as in Fig. 2

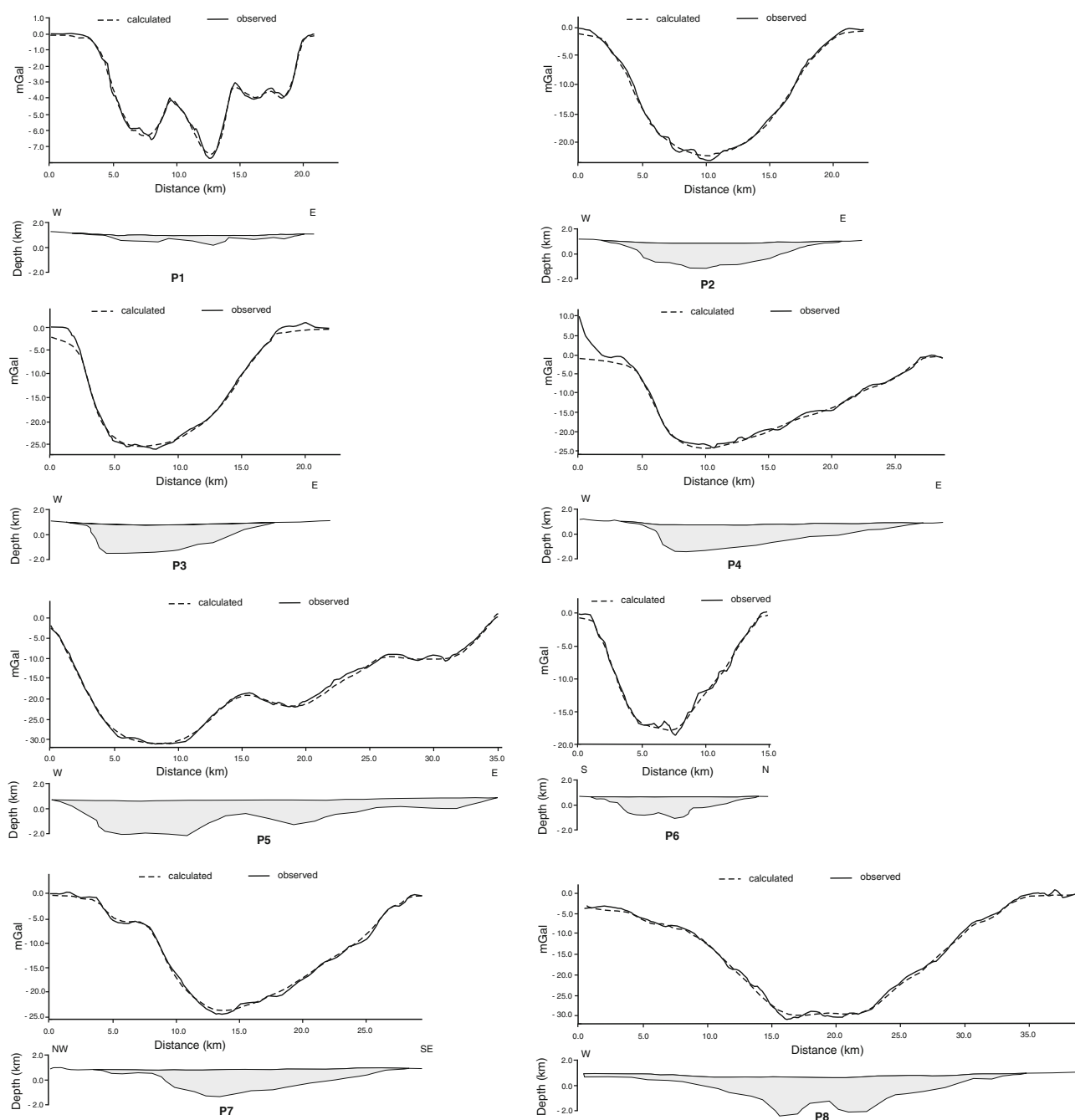


Fig. 6 Gravity anomalies and 2D modelling of the eight profiles, shown in Fig. 5

barely 400 m, whilst just a few kilometres to the NW it exceeds 2,000 m. Towards the East, the basement has an irregular geometry linked probably to several normal faults that organise the basement into small grabens and horsts.

In profiles 2, 3 and 4 (Fig. 7), all with an ENE–WSW orientation, the Baza Fault is located several kilometres to the East of the topographic range front boundary. The half-graben geometry of the hanging wall is clearly evident in all the profiles, with an elongated trough bounded by a

normal fault. In these three profiles, the sedimentary fill thickness reaches maximum values of 2,000 (Profile 2), 2,400 (Profile 3) and 2,200 m (Profile 4).

Profile 5 (Fig. 7), with a NE–SW orientation, is located in the North of the study area. The step morphology of the basement, close to the trace of the fault, is probably linked to the branching off of the fault near the surface. The rest of this profile reveals a more complex basement geometry, linked to the contact between the Internal and External

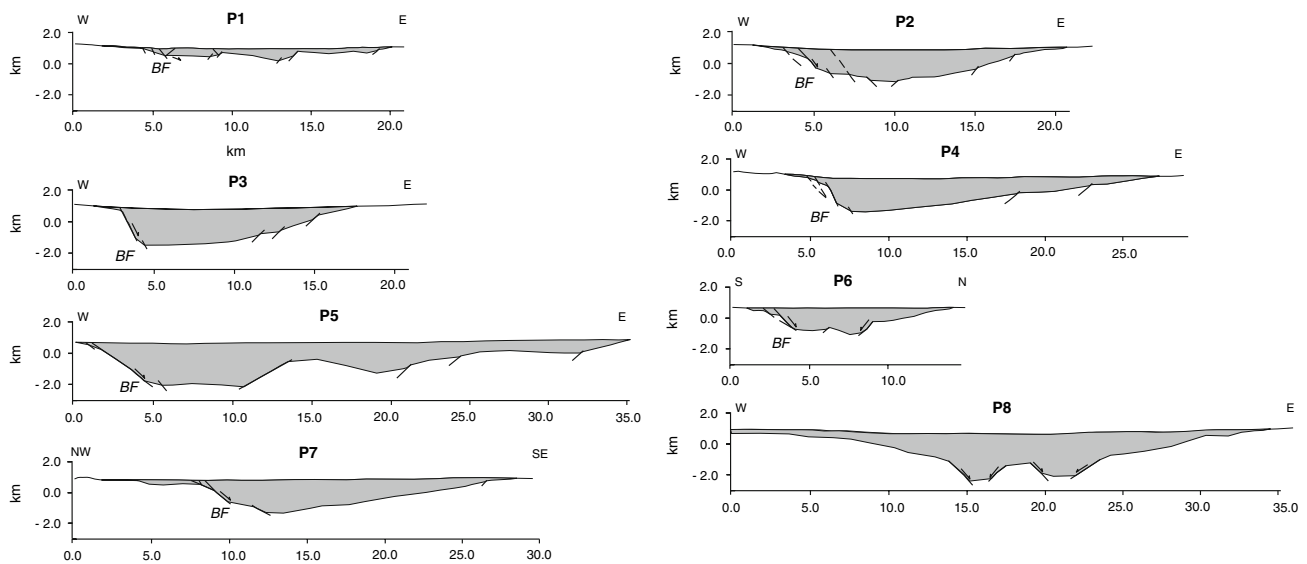


Fig. 7 Geological cross-sections elaborated by integration of gravity results and surface geology. *BF* Baza Fault, *grey colour* sedimentary fill, *white colour* basement

Zones of the Betic Cordillera. In this profile, the basement reaches a greater depth than in those mentioned previously, with a maximum sedimentary fill thickness of 2,400 m.

Profile 6 (Fig. 7) has a NE–SW direction in its first segment and a NW–SE direction in the second. The basement depth reaches ~1,200 m in this profile. A branching off of the fault is also observed near the surface, as in Profile 5.

Profile 7 (Fig. 7), with a NW–SE direction, runs almost parallel to the southern end of seismic profile BT-2. In this profile, the asymmetric geometry of the basin is observed, as in profiles 2, 3 and 4, with a maximum sedimentary fill thickness of 2,150 m. To the NW, step morphology is observed in the basement, which is linked to the branching off of the fault.

Profile 8 (Fig. 7), with a NW–SE direction, is located at the northern end of the Baza Fault (near La Teja, see Fig. 5). The gravity model indicates that this profile is near the termination of the fault. Towards the East, a complex geometry is observed with various grabens and horsts in the basement, which are related to the greater structural complexity of this area. In the same way as in Profile 5, this profile cuts through the contact area between the Internal and External Zones. Furthermore, this profile is located in the area which contains the thickest sedimentary fill (3,000 m) in the basin.

Seismicity

As regards seismic activity in the Guadix-Baza Basin, Alfaro et al. (1997) describe seismites in the Pliocene–

Quaternary fill. Some of the outcrops are to be found very close to the fault whilst others are located at a distance of 20 km in the Cúllar sector. Scott and Price (1988) indicate that an earthquake with a magnitude of 7.0 does not significantly affect sediment located over 20 km from the epicentre. Given that faults in the Guadix-Baza Basin are short in length, the longest being the Baza Fault, earthquakes must be of a magnitude lower than 7.0 (there is no evidence of historical or instrumental earthquakes with a greater magnitude in the Betic Cordillera). It is not possible to confirm with total certainty that these seismites were formed by Baza Fault activity, as seismic liquefaction may occur at up to 100 km from the epicentre (Ambraseys, 1988). Nevertheless, the Baza Fault, which is the longest and most active one in the basin and the seismogenic structure closest to the main seismite outcrops, is the most likely trigger fault of these soft-sediment deformation structures.

Figure 8 shows the spatial distribution of recent seismicity in the studied area for the period 1500–2004, characterized by low-magnitude earthquakes. The 1531 Baza earthquake stands out in the historical seismicity. Martínez-Solares and Mezcua (2003) assigned it a VIII–IX maximum intensity; and, according to López-Casado et al. (2000), this earthquake corresponds to a macroseismic magnitude *mb* of 5.1. This historical earthquake destroyed part of the cities of Baza and Benamaurel and also caused some structural damage to Bátor Castle to the SW of Baza. As for Caniles and Cúllar Baza, towns neighbouring Baza and Benamaurel, there is no information as to whether they suffered damage (Espinosa et al. 1994). This could be indicative of a highly superficial focus or, probably, of site effects in Baza and Benamaurel.

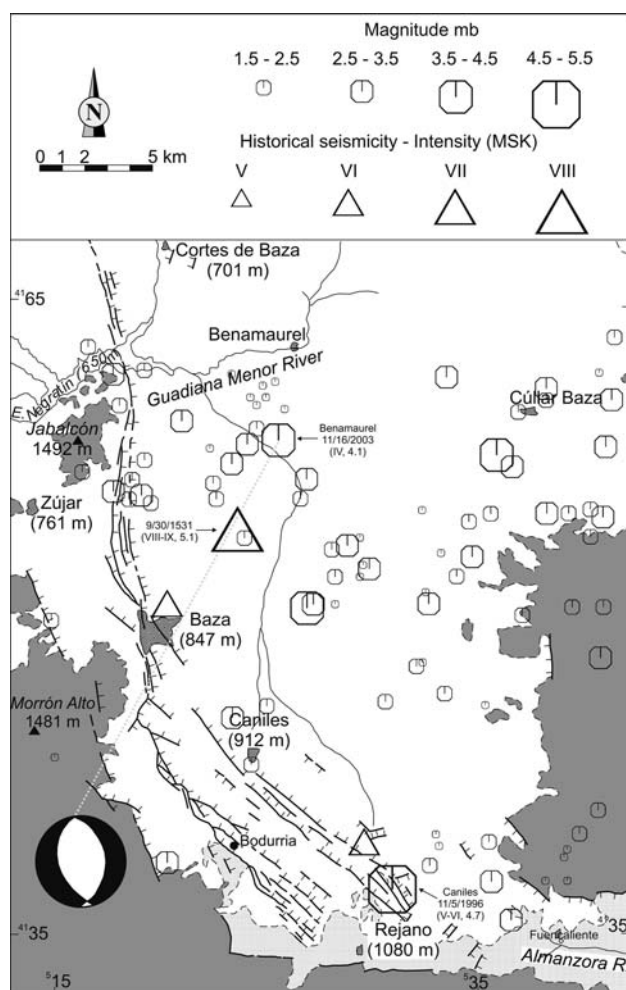


Fig. 8 Seismicity in the studied area for the period 1500–2004 showing the location of the 1531 Baza earthquake. The focal mechanisms of the 4.1 earthquake located between Benamaurel and Baza (Instituto Andaluz de Geofísica) is also included. Geological legend in Fig. 2

According to the data from the Seismological Network of the Instituto Geográfico Nacional of Spain, the maximum magnitude that can be related to the instrumental seismicity in the studied area is 4.7 for a localized earthquake southeast of Caniles in 1996. In 2003, an earthquake of magnitude 4.1 was located in Benamaurel. The Instituto Andaluz de Geofísica has calculated the only focal mechanisms of the studied area. As can be seen in Fig. 8, the normal solution of this focal mechanism is coherent with the surface expression of the Baza Fault. It is in the surrounding areas of Baza, Caniles and Benamaurel that the greatest instrumental seismicity was registered. It is interesting to note that the northern part of the fault registers no seismicity. Another important feature is earthquake swarms, which occurred on 16 February 2004 in Benamaurel when six earthquakes were registered at magnitudes varying from 1.0 to 1.3.

Extension in the Baza Basin

All previous studies about the recent extension in the central part of the Betic Cordillera focus on the Granada Basin. However, in the Guadix-Baza Basin—which, together with the Granada Basin, has the lowest minimum Bouguer anomaly values in the whole of the Betic Cordillera and a crustal thickness between 34 and 38 km (sensu Banda et al. 1993)—no indication has been given of the existence of regionally important structures that accommodate extension on the whole.

This study reflects the existence of several normal faults in the Guadix-Baza basin accommodating the regional ENE–WSW extension, among which the Baza Fault may be highlighted. On the one hand, these faults have uplifted the Sierra de Baza and Jabalcón relief, and on the other, they have created areas of subsidence amongst which the most relevant is the Guadix-Baza basin depocentre located ENE of Jabalcón. This is a relative subsidence, however, as the whole central Betic Cordillera where the Guadix-Baza Basin is located is currently undergoing a regional uplift. Therefore, this fault divides the basin into two sectors: Guadix to the West and Baza to the East. The Tiscar fault, with different kinematics, is located to the NW.

Below, we give calculations for the throw of this fault and the extension rates that are being accommodated in this part of the Cordillera. In order to estimate the throw produced by the Baza Fault and other normal faults of the area studied, Upper Miocene marine rocks were used as a marker, which, according to Guerra-Merchán (1992), were the first to fill the basin. According to the sedimentological study carried out by this author, a sudden subsidence linked to a tectonic event occurred here during the Late Miocene. The stratigraphic data obtained by García-García et al. (2000) and García-García (2003), who carried out a study on a segment of this fault in the Bodurria area (in the extreme South of the Baza Fault), show that a tectonic event producing an important change in the sedimentation of the Baza Basin occurs during the late Tortonian. Therefore, we deduce that the Baza Fault began its activity during the late Tortonian.

This fact coincides with the results of Sanz de Galdeano and Alfaro (2004), which indicate that the current relief of the Betic Cordillera has almost entirely formed since the Tortonian. Previously, Johnson et al. (1997) on the basis of apatite and zircon fission track analyses of the Nevado-Filabride rocks indicated that the uplift of the Sierra Nevada (located to the West of the study area) began about 9–8 Ma ago, during the Tortonian.

Taking into account: (a) the important transgression in the Betic Cordillera during the Late Miocene, in the Tortonian, between ~8.5 and 7.2 Ma (Rodríguez-Fernández 1982), which almost completely covered the Cordillera except for a few areas which became islands, and (b) that

the sedimentation of these Tortonian deposits coincides with the beginning of activity at the fault, in this study, we estimate a value of 8 Ma as the beginning of activity of the Baza Fault. According to the seismic and gravity profiles, these Tortonian marine rocks, which crop out in the area surrounding Bodurria (at over 1,000 m above sea level), should be found over the basement at ~1,000–2,000 m below sea level on the hanging wall of the fault (Figs. 4, 6, 7).

In order to make an approximate calculation of the extension accommodated in the Baza Basin, we assume that: (1) the average dip of these faults ranges between 45° and 60°, (2) activity at the faults began 8 Ma ago, including the Baza Fault and (3) the average throw produced by the Baza Fault (and probably by other secondary normal faults which are inferred by the stepped basement morphology of several 2D-gravity models) varies between 2,000 and 3,000 m, as determined from the thickness of sedimentary fill.

From these assumptions, the extension values obtained vary between 0.12 (2,000 m and 60° dip) and 0.33 mm/year (3,000 m and 45° dip). These values are very similar to those obtained by Gil et al. (2002) in the western Sierra Nevada and the eastern part of the Granada Basin. The uplift rates of these faults are also similar to those calculated by Sanz de Galdeano (1996) and Keller et al. (1996) in the western Sierra Nevada. They report uplift rates of over 0.6 mm/year, occasionally reaching 0.84 mm/year. However, the average rate obtained is ~0.4 mm/year since the beginning of the Tortonian.

In the study area, unlike in the Granada Basin-Sierra Nevada, where the extension is accommodated by several normal faults, the extension here is produced for the most part by the Baza Fault. Therefore, this study underlines the regional importance of the Baza Fault which, at 37 km in length and with an average throw varying between 2,000 and 3,000 m, is one of the main active normal faults in the Betic Cordillera.

The NE–SW to E–W extension in the central part of the Betic Cordillera is not exclusive to the Granada Basin and neighbouring areas but extends towards the East until, at least, the Guadix-Baza Basin. In this area, the average trend is ENE–WSW.

Therefore, the current NW–SE compression in the Betic Cordillera due to convergence between the African and Eurasian plates, which is responsible for the regional uplift, coexists with a NE–SW extension in the highest structural domain (Galindo-Zaldívar et al. 2003; Ruano et al. 2004; Marín-Lechado et al. 2005).

Conclusions

The Baza Fault is an active normal fault with a surface trace of ~37 km in length that divides the Guadix-Baza

Basin in the central Betic Cordilleras. This NE-dipping fault has a southern segment with an average NW–SE strike, a central segment running N–S and a northern segment with a NNW–SSE strike. The fault has several splays, which are much more predominant in the southern area.

In some of the gravity profiles throughout the hanging wall of the Baza Fault, we found anomalies that range between –25 and –32 mGal (Fig. 5) and constitute the maximum negative values in the Betic Cordillera. These anomalies are mainly related to the Baza Fault activity which, according to our interpretation, has caused a 2,000–3,000 m throw in the basement, creating a sedimentary basin in its hanging wall that was filled with Upper Miocene, Pliocene and Quaternary rocks. In this half-graben erosion currently predominates over the sedimentation.

In some previous studies, the main trace of the Baza Fault has been mapped between the Triassic basement and the sedimentary fill. However, the gravity profiles and the geological mapping carried out in this study show that the main splays are located a few kilometres to the East, cutting through the Pliocene and Quaternary fill.

The termination of the fault is visible in gravity profiles 1 and 8. From the superficial geological data, it can be seen that the fault dies out at the southern end in a set of splays that branch off from the main fault. At its northern end, a gradual decrease is produced in the throw. Some profiles reveal several basement steps that are related to main fault splays.

The southern part of the basin is structurally simple (a half-graben) (profiles 2, 3, 4 and 7), whereas the northern area is more complex, with various fractures that divide the basement.

The Baza Fault is a seismogenic structure producing low to moderate magnitude earthquakes. This fault generated the 1531 Baza earthquake which caused damage in Baza and Benamaurel. The 2003 Benamaurel earthquake (mb 4.1) shows a clear normal fault mechanism, coherent with surface geology.

In the Guadix-Baza Basin, several NW–SE to N–S normal faults accommodate the ENE–WSW extension that is currently being active in the upper crust of the Central Betic Cordillera, simultaneous with the uplift of the mountain range. We calculate extension rates between 0.12 and 0.33 mm/year for the Baza Fault. Therefore, it is one of the most important active normal faults of the Betic Cordillera. The extension is probably also accommodated by a set of secondary normal faults located in the hanging wall of the Baza Fault.

Finally, the integration of the extensional tectonics evidenced by the Baza Fault, those of the Granada Basin and others from the rest of the central Betic Cordillera indicate the great importance of the ENE–WSW extension at shallow crustal levels of the cordillera from the Late

Miocene to the present, developing simultaneously with a NW–SE compressive setting determined by the Eurasian and African plate convergence.

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