

Geomorphologic evidence of the active Baza Fault (Betic Cordillera, South Spain)

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Received 15 February 2006; received in revised form 20 August 2007; accepted 21 August 2007

Available online 27 August 2007

Abstract

The present work investigates a mountain front within the Plio-Quaternary deposits belonging to the sedimentary fill of the Guadix-Baza Basin (Betic Cordillera, Southern Spain). This 30 km-long front, developed in soft sediments and within a context of high erosion, is generated by the recent activity of the Baza Normal Fault. The mountain front is the natural limit between the western and eastern sectors, corresponding to the two sub-basins of Guadix and Baza. The two main glacis described in previous works in the area of the Baza Fault – the Old Glacis in the Guadix Sub-basin and the Recent Glacis in the Baza Sub-basin – are interpreted here as a single one, displaced by the fault. Using this Glacis as a marker we deduced that its age and the transition of the basin from endorheic to exorheic must be much older than previous estimations. The Baza Fault may be considered as one of the most active faults of the central part of the Betic Cordillera, according to the results of the general quantitative analysis of the mountain front relief using the S_{mf}/V_f ratio and the SL index.

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Keywords: Mountain front; Geomorphic indices; Active normal fault; Baza fault; Betic Cordillera

1. Introduction

The Guadix-Baza Basin (GBB), inside the Betic Cordillera (Fig. 1), is traditionally divided into two sub-basins: Guadix to the west; and Baza to the east. A

mountain front is situated between these two parts (Fig. 2). Generally, most mountain fronts generated by active normal faults separate on the surface, with footwall basement rocks moving away from hanging wall sedimentary rocks, constituting the border of the basin (Keller, 1986; Silva, 1994; Ramírez, 1999). The peculiarity of the mountain front described here is that it developed entirely from soft rocks belonging to the Plio-Quaternary continental deposits of the GBB. This mountain front, nearly 30 km long, has been considered

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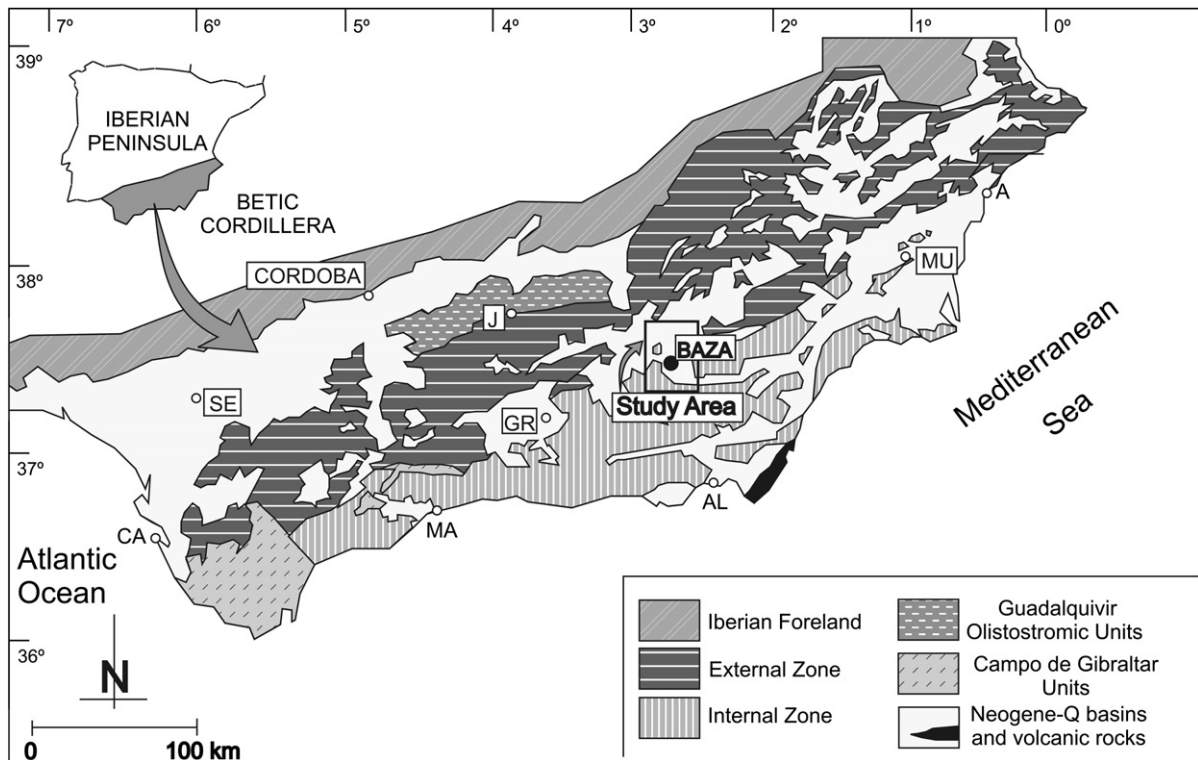


Fig. 1. Geological context. The squared area shows the location of the study sector within the Betic Cordillera.

until now as an erosive feature separating two generations of subhorizontal erosive surfaces: the Old Glacis and the Recent Glacis (Vera, 1970; Calvache and Viseras, 1997; Díaz-Hernández and Juliá, 2006). Recently, Alfaro et al. (in press) described an active normal fault 37 km in length, whose cartographic trace coincides with the mountain front. In the present work, we propose that the two glacis constitute a single one that was fractured and displaced by this fault.

The Baza Fault is associated with seismicity. The most important event was the 1531 Baza earthquake, of a magnitude of 5.1 mb. The earthquake near Caniles in 1962, magnitude 4.7 mb, might also be related to the Baza fault. More recently, in 2003, in Benamaurel an earthquake of magnitude 4.1 mb occurred in the proximity of the studied fault. The focal mechanism of this earthquake, as calculated by the Geophysical Institute of Andalusia, would correspond to a normal fault of NW–SE direction, in accordance with surface geological observations (Alfaro et al., in press).

The aim of the present work is to discuss the origin of this mountain front, linked to the active Baza Fault, and to provide new insights regarding the development of mountain fronts in soft rocks. The application of geomorphic indices for the study of geomorphological anomalies allows the detection of active tectonics and, in

some cases, an evaluation of the age of deformation (Hack, 1973; Keller, 1986; Masana, 1995; Keller and Pinter, 1996; among others). These indices have provided good results in semiarid zones similar to the GBB (Silva, 1994; Silva et al., 2003), hence we have applied the mountain front sinuosity index, the valley width/height ratio index and the stream length-gradient index.

2. Geological context

The GBB, located in the central Betic Cordillera (Fig. 1) is an intramontane depression covering an area of about 4000 km². Altitude ranges from 1200 m in marginal zones to 600 m in some valley bottoms, with an average of 800 m. The bounding relief, belonging to the basement, can be as high as 2000 m with a mean altitude of 1500 m. The northern edge of the GBB consists mainly of Mesozoic carbonate rocks belonging to the External Zone of the Betic Cordillera. The southern edge generally consists of Triassic metamorphic rocks of the Internal Zone. These significant lithological differences between the two domains permit easy recognition of the source areas of sedimentary fill in different parts of the basin. Deposition has had a continental character since the end of the Miocene, the period in which the basin ceased to have marine influence and became endorheic.

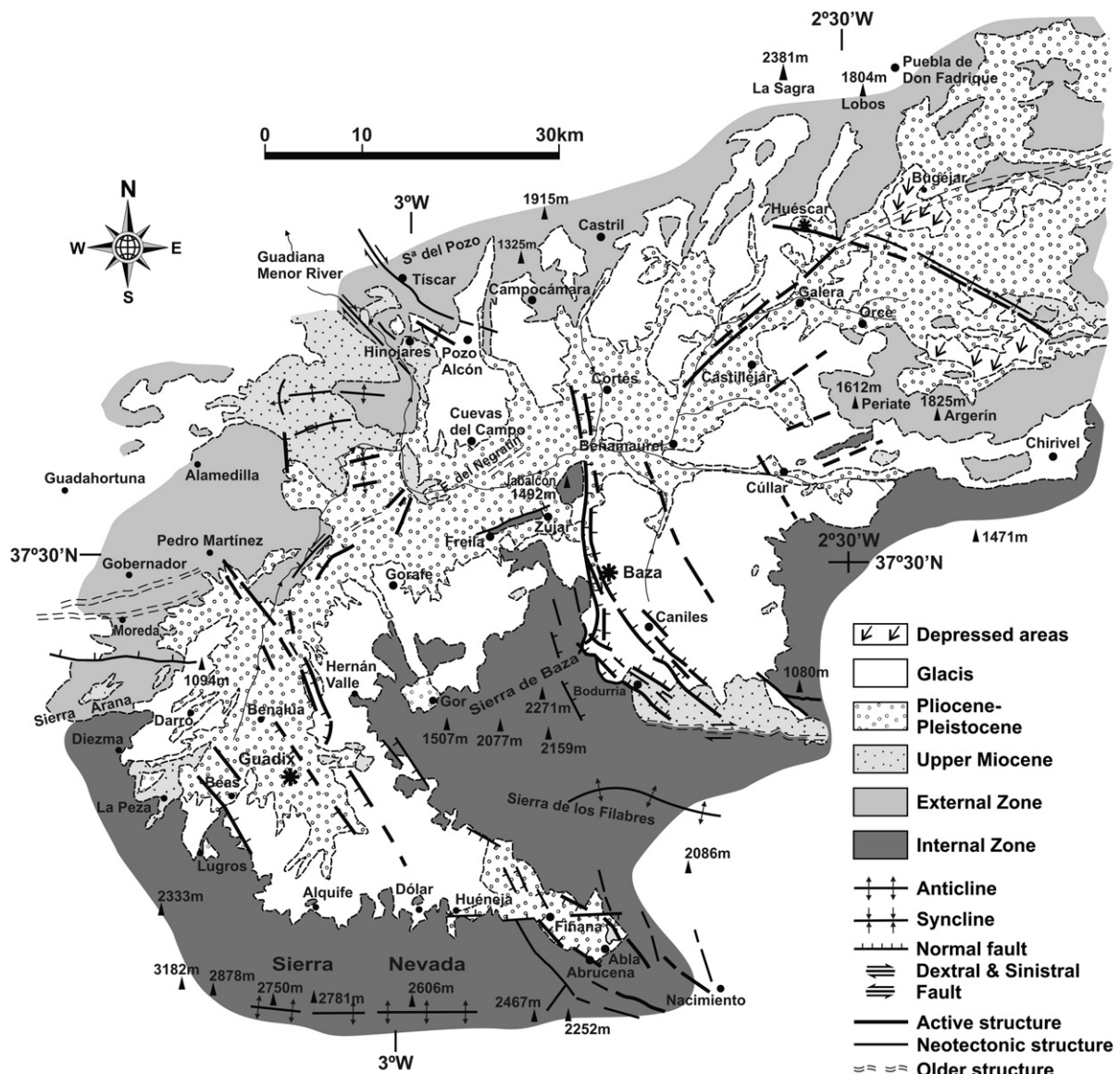


Fig. 2. General geological–geomorphological map of the GBB. Note location of the Baza Fault which separates the Guadix Sub-basin to the west, and the Baza Sub-basin to the east.

The Plio–Quaternary continental sediments have been the subject of numerous stratigraphic and biostratigraphic studies (Vera, 1970; Peña, 1979, 1985; Viseras, 1991; Guerra-Merchán and Ruiz-Bustos, 1992; Agustí, 1996; Gibert, 2006; among others). The fluvial sediments are composed mainly of silts, sands and conglomerates of the so-called Guadix Formation (Vera, 1970; Von Drasche, 1879); lacustrine deposits, fundamentally made up of limestones, marly limestones and gypsums, appear mainly in the Baza Sub-basin. During the Pliocene and Pleistocene there developed a Ca-sulphate,

shallow, saline lake system. Three facies belts can be distinguished from the centre (more evaporitic) to the margin of the sub-basin. Together, the inner and the intermediate zones constitute the Benamaurel Gypsum unit. The marginal zone consists of detrital and palustrine sedimentary rocks (Gibert 2006; Gibert et al., 2007). Ortiz et al. (2006) studied the stratigraphy of the Baza Sub-basin, and presented a chronostratigraphy using amino acid racemization and paleomagnetism. Sedimentation rates deduced from these results are approximately 0.2 mm/year.

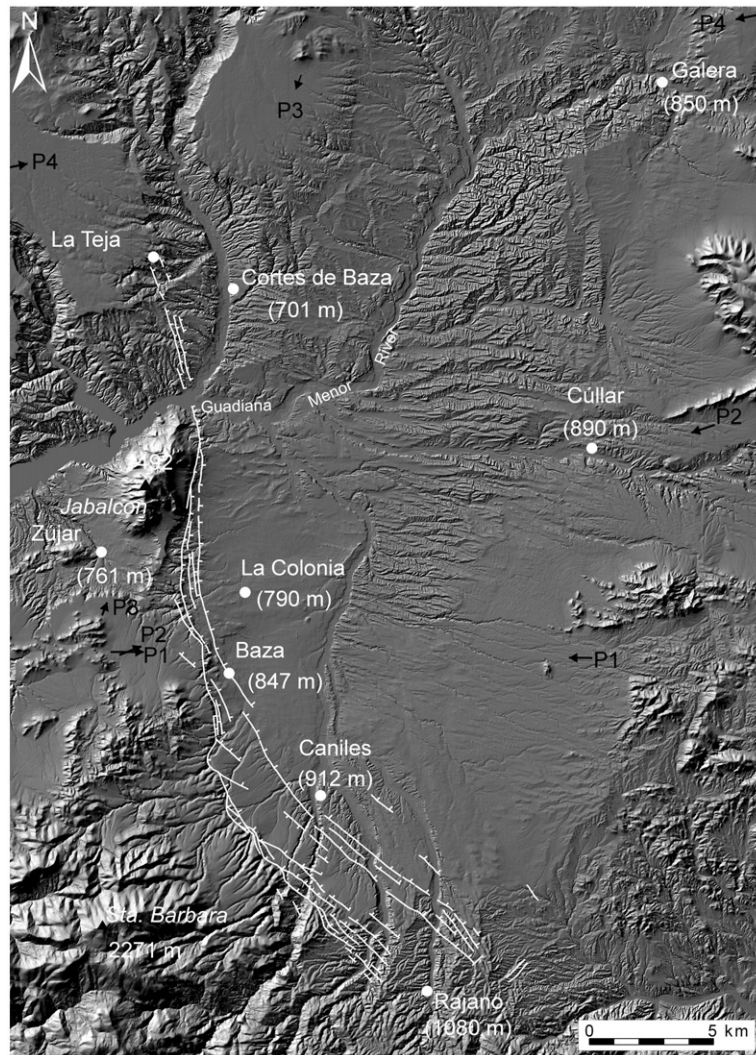


Fig. 3. Digital terrain model of the GBB showing the mapping of the Baza Fault zone (continuous white lines). Inside is the location of the profiles of the Fig. 7.

The endorheic character of the GBB was achieved when it was “captured” by the drainage network of the Guadalquivir River (Vera, 1970; Calvache and Viseras, 1997). After transformation to an exorheic basin, sedimentation was restricted to alluvial fans and piedmont deposits on the basin margin and on fluvial terraces, and valley-bottom deposits towards the centre.

3. Structural features of the Baza Fault

The Baza Fault is a normal active fault that is approximately 37 km long and extends from the south of Caniles to the village of La Teja (Fig. 3). As opposed to other major active normal faults (Masana, 1995; Keller

and Pinter, 1996; among others), its trace is situated a few km east of the cartographic contact between the basement and the sedimentary fill, within soft materials (Fig. 4). The surface of the fault, which dips eastward, presents a southern segment with a NW–SE mean direction, a central segment of N–S direction, and a northern segment of NNW–SSE direction (Figs. 3 and 4). The Jabalcón mountain, formed essentially by the basement of hard limestones of the Internal Zone, could be the obstacle that most influenced the orientation of the fault, forcing the N–S direction of its central segment.

At the surface, several roughly parallel splays are visible along the fault zone, producing various stepped



Fig. 4. Geological–geomorphological map with the main geomorphological elements of the sector studied: glacis and mountain front of the Baza Fault.

escarpments. These splays are more numerous in the southern segment, whereas towards the north they converge (Figs. 3 and 4). The vertical height of the escarpments gradually decreases toward the ends of the Baza Fault.

On the basis of their gravimetric study, Alfaro et al. (*in press*) estimated that the maximum fault throw ranges from 2000 to 3000 m. These authors calculate vertical movement rates in the hanging wall varying between 0.12 and 0.33 mm/year for the Baza Fault.

Micropaleontological sites within the Baza fault zone (Guerra-Merchán et al., 1991; Guerra-Merchán and Ruiz-Bustos, 1991, 1992) provide data on the vertical-displacement values. Thus, in the footwall, just 1 km SW of Baza and at an altitude of 1000 m, the outcrops are late Miocene–early Pliocene in age (Guerra-Merchán et al., 1991), while to the east of Caniles, in one of the faulted blocks of the hanging wall and at some 900 m altitude, the deposits are from the boundary of the early/middle Pleistocene (Guerra-Merchán and

Ruiz-Bustos, 1992). Therefore, at 100 m lower the sediments are about 4 My younger. Based on these age data, Guerra-Merchán and Ruiz-Bustos (1991) described the existence of normal faulting that moved the easternmost blocks downward.

4. Geomorphology of the GBB

The general geomorphological features of the basin have been studied by Goy et al. (1989), Romero-Díaz (1989), Calvache and Viseras (1997), Azañón et al. (2007) and Díaz-Hernández and Juliá (2006). At present, the GBB is crossed by an exorheic fluvial network draining towards the Guadalquivir River via the Guadiana Menor River. The intensive downcutting of the fluvial network (in some valleys reaching 200 m; Azañón et al., 2005) is due to three main factors: the high mean altitude of the basin, the semiarid climate and the high erodability of the infilling sediments. One of the main geomorphological features of the basin is the badland relief, typical of semiarid regions (Gutiérrez-Elorza, 2001). The area occupied by badlands, together with floodplains of the main river draining this region, represents approximately half of the total area of the basin. The badlands develop upon the extended glaciais surface. The glaciais appears intensively eroded in the central part of both sub-basins, yet is well-preserved in the marginal zones where it passes to piedmont and alluvial fan deposits. The alluvial fans coalesce forming typical ‘bajadas’.

4.1. The endorheic–exorheic transition

For Vera (1970) and Calvache and Viseras (1997), among other authors, the final filling level of the basin before it became exorheic, extending across the whole GBB, is a lithostratigraphic unit of fluvial origin. According to Calvache and Viseras (1997) the top of this unit is approximately at the middle–late Pleistocene boundary. They support their interpretation with previous dating of the archaeological–paleontological site of Solana del Zamborino (100 ky) (Botella et al., 1986; Martín-Penela, 1988). This site is situated in the distal alluvial fan facies of the Guadix Sub-basin.

Calvache and Viseras (1997) placed the age of the capture of the GBB by a tributary of the Guadalquivir River between 100 ky and 17 ky (age of some deposits dated in the present-day drainage network, sensu Jiménez de Cisneros, 1994).

In recent work, Azañón et al. (2007) radiometrically dated a calcareous crust (calcrete) of edaphic origin developed on fine-to coarse-grained fluvial and lacustrine deposits, on the final filling level of the endorheic

basin. According to these authors, the age of this calcrete is 42 ky, which indicates the minimum age for the cessation of active sedimentation in the Guadix-Baza Basin. Nevertheless, Gibert (2006) and Gibert et al. (in press), based on magnetostratigraphic and paleontological studies, attribute an age of 450 ky to materials previously considered as the final filling level of the Baza Sub-basin (Vera, 1970). Therefore, the data of Gibert et al. (in press) suggest an older age for the endorheic to exorheic transition of the basin drainage.

Díaz-Hernández and Juliá (2006) carried out radiometric dating of travertines found in the Guadix Sub-basin. The travertines are incised within the present-day drainage network. These authors obtained ages ranging from 205 to 115 ky for the oldest terrace. The formation of this terrace required the earlier encroachment of the exorheic drainage network. Therefore, the transition would have taken place before 205 ky, the age of the oldest incised terrace. They also suggest that the major encroachment of the drainage network would have occurred between 115 and 48 ky.

4.2. The glaciais

The glaciais of the GBB was previously divided in Old or Upper Glaciais and Modern or Recent Glaciais (Vera, 1970; Peña 1979; Romero-Díaz, 1989; Viseras, 1991; Guerra-Merchán, 1992).

The glaciais of the GBB is a concave surface, with a smooth inclination from the margins towards the centre. It slopes toward the edges, where it reaches an average altitude of 1050 m and exhibits values between 6° and 3°, decreasing toward the central zones of the basin where the surface has been extensively eroded. In the most central sectors preserved, it shows an average altitude of 925 m, while the observed slope exhibits values as low as 2°. The formation of this glaciais has a mixed character; generally speaking, erosion was more important, although deposition dominated at the basin margins. It is very well-preserved in the areas situated not far from the mountains, especially south of the GBB.

5. Geomorphology of the Baza Fault

5.1. The mountain front of the Baza Fault

The mountain front of the Baza Fault, some 30 km long, is associated with the main escarpment produced by this active fault, though there are smaller escarpments related to the different splays (Figs. 5 and 6). This stepped zone of variable width has a mean height of

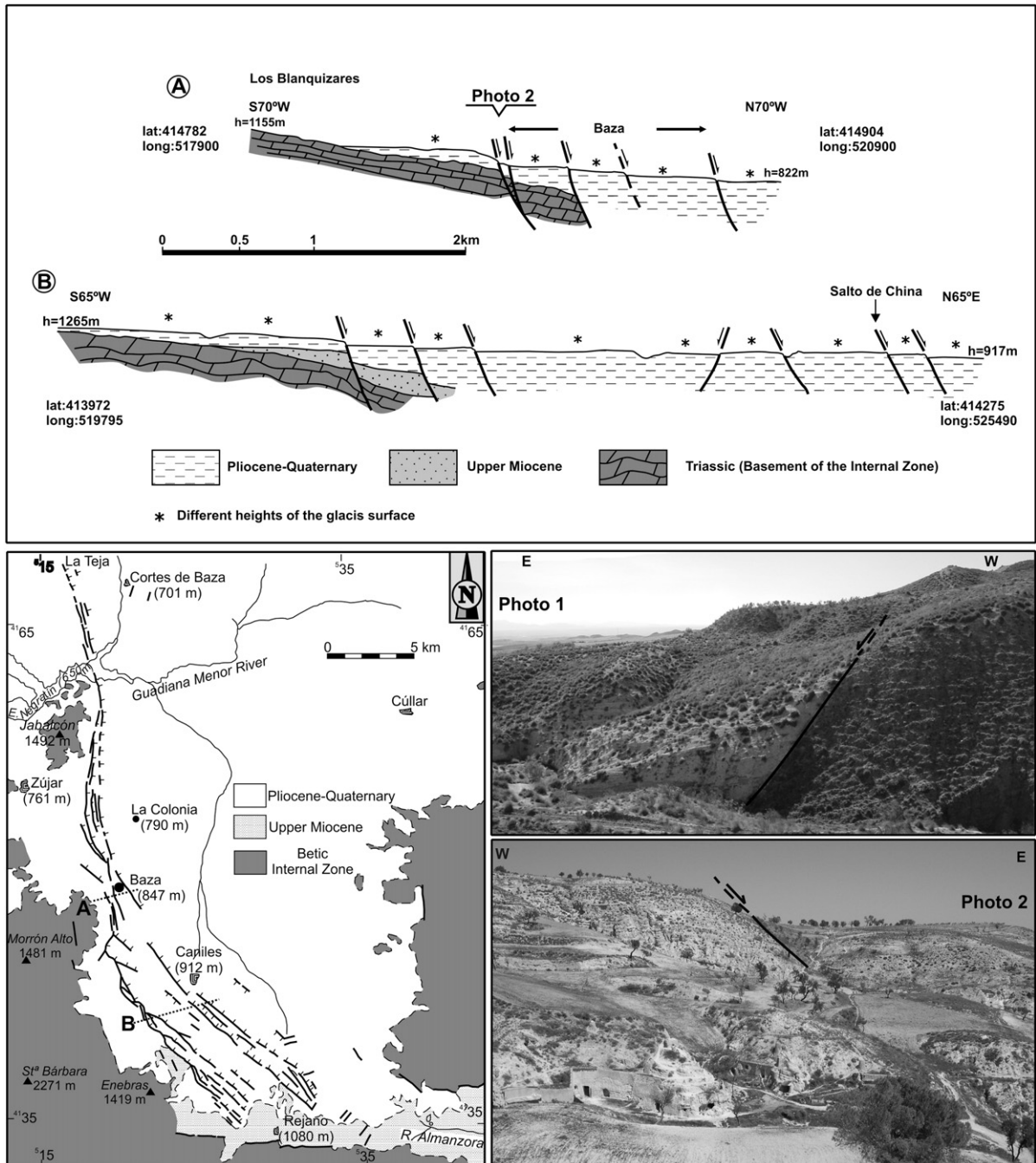


Fig. 5. Geological cross-sections in which the glacia surface offset is shown. The map below indicates the location of both geological cross-sections. Two pictures show outcrops of the Baza Fault zone.

more than 60 m, reaching a maximum value of about 200 m, representing an important geomorphic feature at the regional scale.

Mountain fronts in normal faults are usually formed in the basement, constituting the border of the basin (Keller and Pinter, 1996; Silva, 1994; Ramírez, 1999). This is not the case of the Baza Fault, which developed

within the Plio-Quaternary fill deposits of the basin (Figs. 5 and 6).

The mountain front is dissected by the present-day fluvial network, which has a dendritic drainage pattern. Although this erosion confers the front some of its sinuosity, it is also due to the original morphology of the fault zone (Figs. 3 and 5).

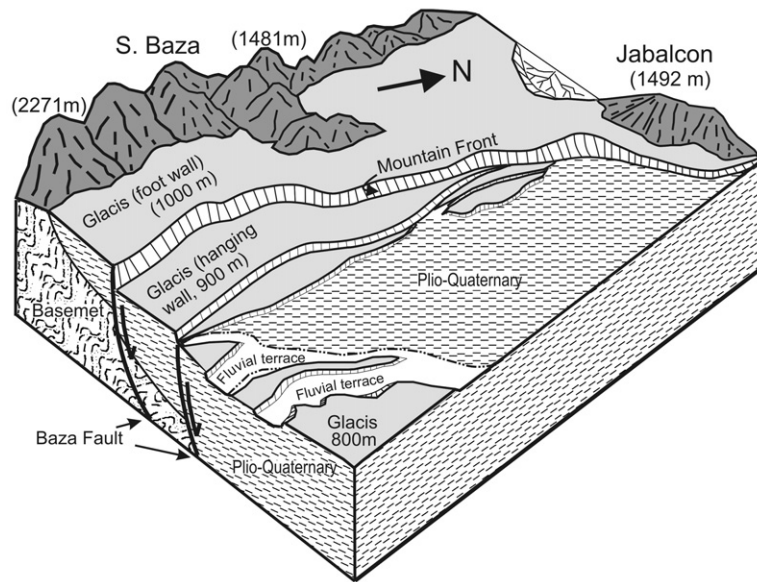


Fig. 6. 3D tectonic–geomorphological sketch of the deformed glacia surface.

5.2. Vertical displacements of the glacia

The glacia reaches the highest altitudes, around 1100 m, in the western block of the Baza Fault, near the border of Sierra de Baza, where it gives rise to a piedmont and alluvial fan deposits. Its height diminished to 960 m and even to 830 m in the eastern side of the fault, where it was identified as the “Recent Glacia” (e.g. Vera, 1970; Peña, 1979; Viseras 1991). According to these authors, this surface was linked to erosion of the “Old Glacia” (e.g. Vera, 1970; Peña 1979; Romero-Díaz, 1989; Viseras, 1991; Guerra-Merchán, 1992), and generated by the transition of the basin from endorheic to exorheic. The limit between the supposed “Old Glacia” and “Recent Glacia” in the Baza Sub-basin coincides exactly with the mountain front of the Baza fault, unacknowledged at that time.

The maximum difference in altitude between these two supposedly different surfaces, reaching 100 to 200 m, is located in the central segment of the fault, coinciding with its maximum throw. Towards the ends of the fault, the difference between the two surfaces decreases progressively until disappearing, and glacia surfaces are joined as a single one (Fig. 7). At the north end of the fault, the glacia, with a maximum altitude of 1000 m, passes from the Guadix to the Baza Sub-basins without any vertical displacement. Therefore, the only difference between the two – in altitude – is strictly limited to the fault zone.

Fig. 7 represents the glacia envelope in both sides of the fault. The dashed line in this figure indicates the prolongation of the glacia surface, in absence of erosion and deformation. This surface is reconstructed using a low degree polynomial function in order to extract the trends of the glacia; then, this envelope was translated to the maximum height of the glacia surface.

West of the fault, in the footwall, the glacia surface appears not to be tilted, while in the hanging wall the surface is indeed tilted towards the fault. Minimum and maximum high envelopes were calculated in the hanging wall, the latter taking into account the possible effect of erosion on the original glacia surface, before the development of the badland relief, and the limitation of the reconstruction process. The vertical displacement accumulated between the different splays of the fault is some 100–200 m, if the glacia surface is considered as a corresponding marker (Figs. 5 and 6). It should be underlined that the fault throw is variable along its trace, with maximum values in its central part.

According to field data and to the tectonic–geomorphological approach illustrated in Fig. 7, we support the interpretation that these two glacia surfaces in the sector of transition between the Guadix and Baza Sub-basins are, in fact, a single geomorphological surface displaced by the Baza Fault. As a consequence, a major part of the surface mapped as “Recent Glacia” in previous research in the Baza fault sector, would actually correspond to the “Old Glacia” moved 100–200 m downward by the Baza

Fault (Figs. 5 and 6). This is in agreement with Guerra-Merchán (1992), who described the presence of several NW–SE splays of the Baza Fault in the Caniles and Baza sectors (Fig. 8), where they produce several topographical steps. This author therefore correlates, for the first time, some surfaces that were previously defined as different. The topographic escarpments (Figs. 9 and 10) in the glacis are more numerous where the fault has more splays.

6. Methodology of morphometric analysis

The morphometric analysis of landforms related to a fault, using geomorphic indices, allows evaluation of their tectonic activity and permits us to assign the fault to a tectonic activity class. We selected the following three

indices, which have been successfully calculated in several tectonic contexts: the mountain front sinuosity index or “Smf” (Bull and McFadden, 1977; Keller and Pinter, 1996), the valley width/height ratio or “Vf” (Bull and McFadden, 1977) and the stream length-gradient index or “SL” (Hack, 1973; Keller and Pinter, 1996). Several studies have used a combination of Smf and Vf values in order to evaluate the relative degree of tectonic activity of the related mountain fronts (e.g. Bull and McFadden, 1977; Rockwell et al., 1984; Silva et al., 2003). In general, tectonically active fronts (Class 1) are characterised by low values of both indexes, whilst inactive fronts (Class 3) normally show high values (Rockwell et al., 1984). Silva et al. (2003) proposed a statistical method based on analysis of Smf and Vf values in order to classify 17 mountain fronts in SE Spain.

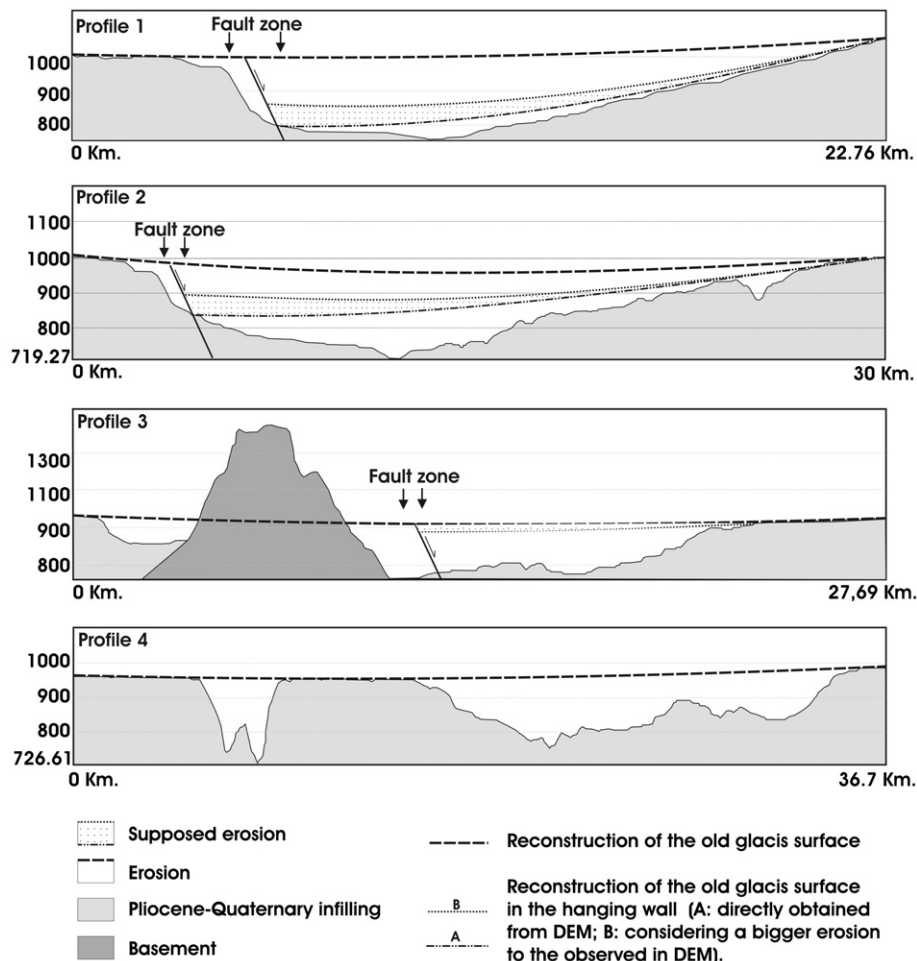


Fig. 7. Topographic profiles including the reconstruction of the glacia surface (envelope with strong dashed line). Dashed–dotted line in the hanging wall represents the lowered glacia surface obtained by DEM. The dotted line is drawn for the hanging wall, taking into account the possible erosion of the original glacia surface (dotted zone). The position of the profiles is indicated in Fig. 3.

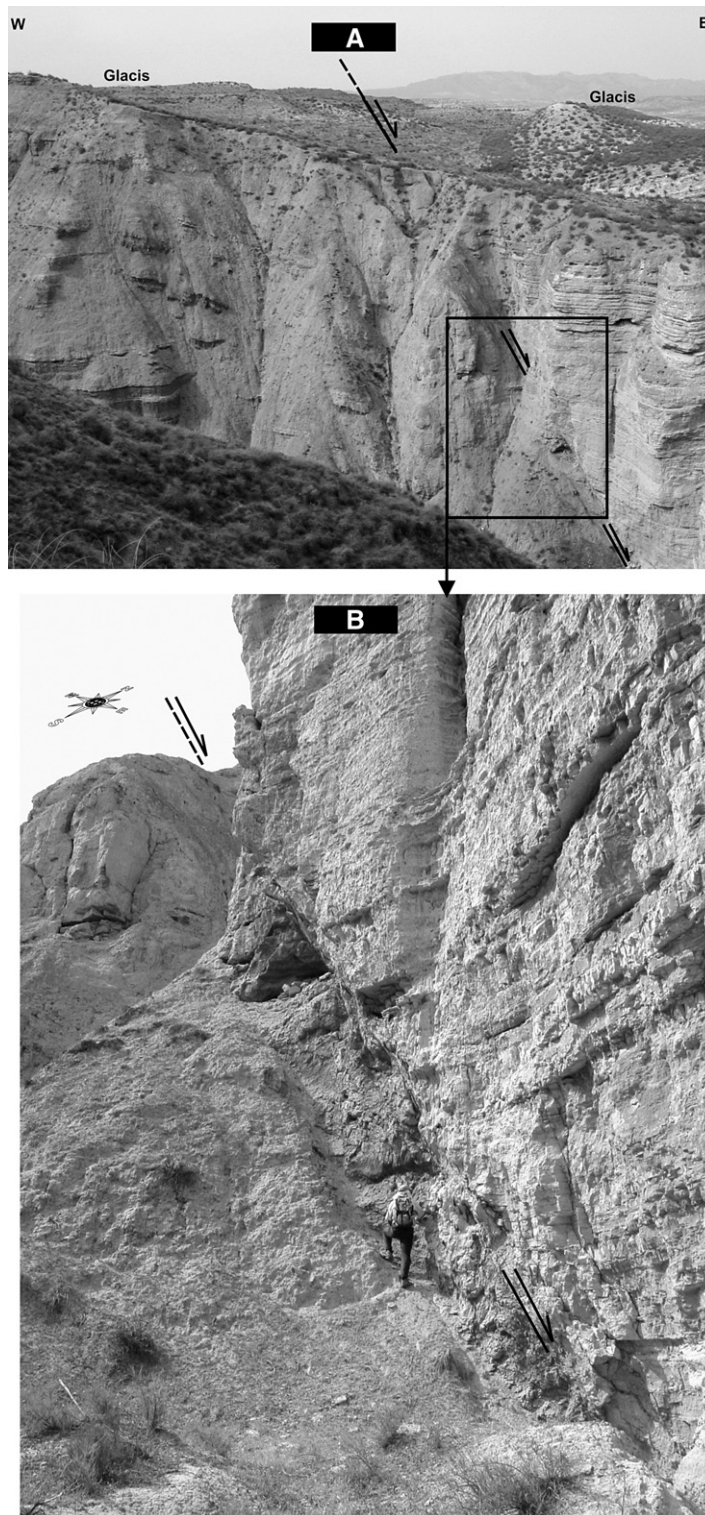


Fig. 8. A. Panoramic view of the fault zone taken in NNW direction on the east of Jabalcón Mountain. B. Detailed view of the fault zone.

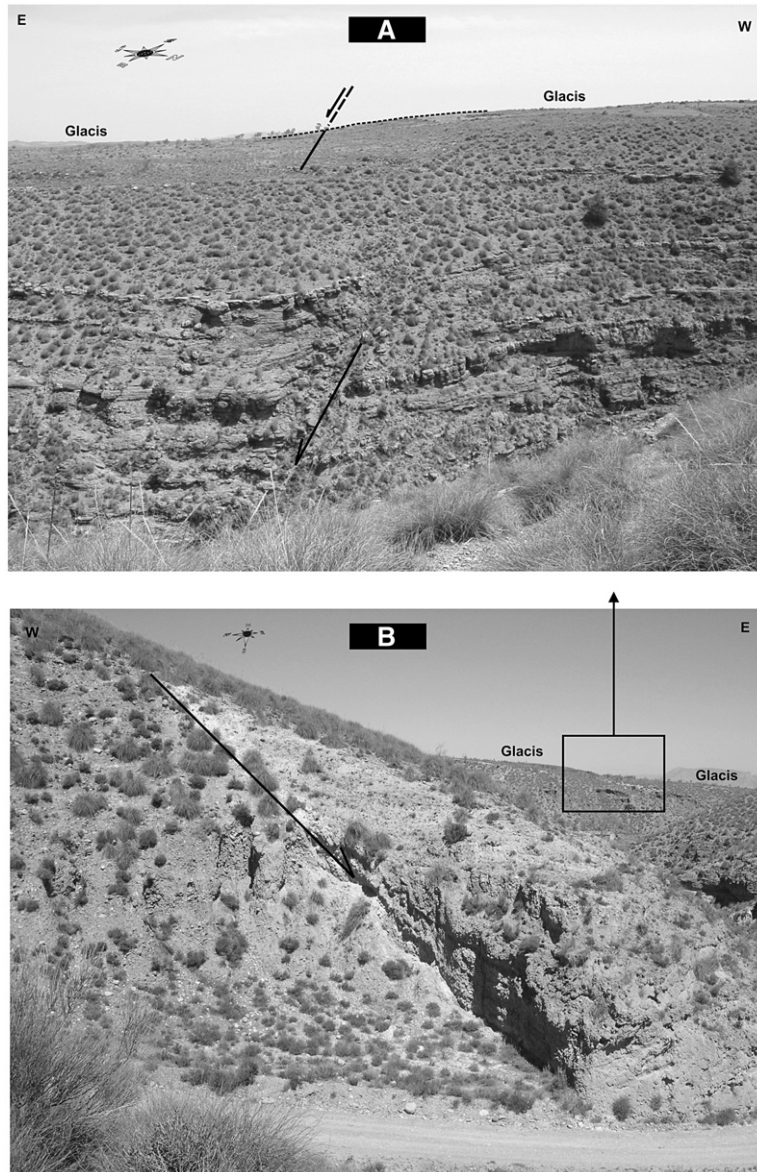


Fig. 9. A. Panoramic view of a morphologic escarpment in the glacia related to a splay. B. Fault surface and a panoramic view to the north showing the site illustrated in panel A.

These mountain fronts have the same geological context as that of the Baza Fault. For this reason we have used the same methodology in classifying the tectonic activity of Baza Fault. Moreover, the stream length-gradient index, SL, was calculated to analyse the anomalies of the drainage net.

In order to determine the geomorphic indices we used the ArcGIS 9.0 Geographical Information System and Map Objects API Extension with three digital datasets: the Digital Elevation Model (DEM) of the study zone; the distribution of the fluvial network; and geomorphologic maps.

The precision of these indices, calculated using GIS techniques, are constrained by the resolution of the raster grid and the precision in the Z values of this grid or the precision achieved using an interpolation inside a Triangular Irregular Network.

The DEM used was obtained from Digital Vector Maps of Andalusia (scale 1/10,000), with contour curves of 10 m equidistance. The model was developed using ArcINFO command TOPOGRID determining a grid of the zone with 5 m precision and 5 m of resolution in both the X and Y axes. We were able to enhance the original precision of 10 m of the contour curves because the

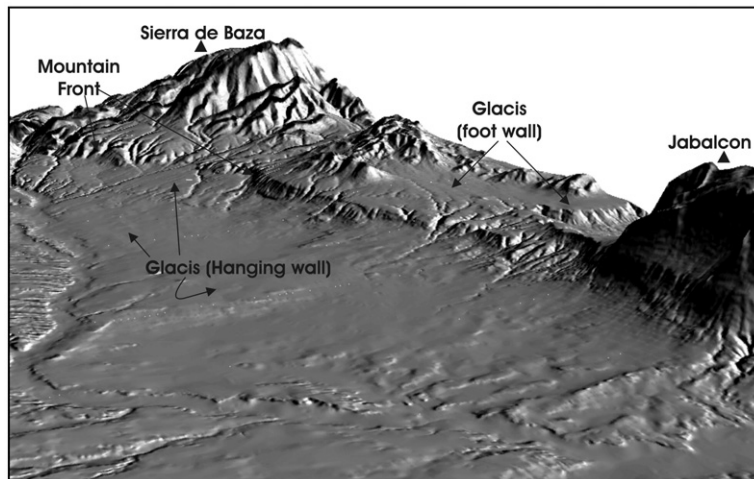


Fig. 10. Panoramic view of the central part of the mountain front showing the offset of the glacis.

original data were defined with an accuracy of just a quarter that of the original contour separation.

6.1. Mountain front sinuosity index (*Smf*)

The mountain front sinuosity index is the ratio between the total length of the front (*L_{mf}*) and the mean length along the straight line parallel to the front (*L_s*) (Bull and McFadden, 1977): $Smf = L_{mf}/L_s$.

The mountain front has an originally curved line, a characteristic that we took into account to calculate its present-day sinuosity. It can be divided into three segments of slightly different orientations and characteristics. The southernmost has a length of 11.5 km with SE–NW direction; the central segment has a SSE–NNW direction and is 9.4 km in length; and finally, the northern segment is 9.4 km long in an almost N–S direction. In total, then, the length spans 29.3 km, less than the Baza Fault, as in its northern part the throw of the fault diminishes.

Mapping of the mountain front (Figs. 4 and 11) shows that sinuosity is greater in the northern segment than in the central and southern ones, where they coincide with the escarpment of the main fault.

The *Smf* index we calculated – from the ratio between the distance of the front (29.3 km), and the distance in a straight line between the two ends of this front (26.2 km) – is 1.11. This value is lower than the sinuosity indices of several different mountain fronts of active faults in the SE Iberian Peninsula (Silva, 1994; Silva et al., 2003).

If we consider that this front was originally curved, the *Smf* value is even lower. Thus, with a curved line, as represented in Fig. 11 (*L_{sc}*), the length of which is 26.74 km, the resulting *Smf* index is 1.09. Additionally,

the *Smf* index was calculated for the three segments, all considered rectilinear. The separate results of the *Smf* are 1.055 for segment A, 1.047 for B, and 1.119 for C.

6.2. The valley width/height ratio (*Vf*)

The valley width/height ratio (Bull and McFadden, 1977) is:

$$Vf = \frac{2V_{fw}}{(E_{ld} - E_{sc}) + (E_{rd} - E_{sc})},$$

where V_{fw} is the width of the valley, E_{ld} and E_{rd} are the heights of both sides of the valleys and E_{sc} is the height of the valley floor or stream channel. The *Vf* index reflects the difference between V-shaped valleys actively down-cutting in response to active uplift (*Vf* values lower than 1.0) and broad valleys (U-shaped) with important lateral erosion in response to relative base-level stability (*Vf* values higher than 1.0) (Silva et al., 2003).

The position of the transverse profile of the river is situated 250 m upstream from the mountain front, using the distance indicated by Silva et al. (2003). From the transverse profile we obtain the upper and lower height on the right part of the watershed and the same parameters on the left side. In this way, we can calculate the *Vf* shown in Table 1.

The *Vf* values range between 0.28 and 0.86, with a mean value of 0.57 and a standard deviation of 0.25. These *Vf* values, along with the *Smf* determined previously, lead us to include the mountain front of the Baza Fault in class 1 (active tectonics), which has uplift rates greater than 0.08 m/ky (Silva et al., 2003).

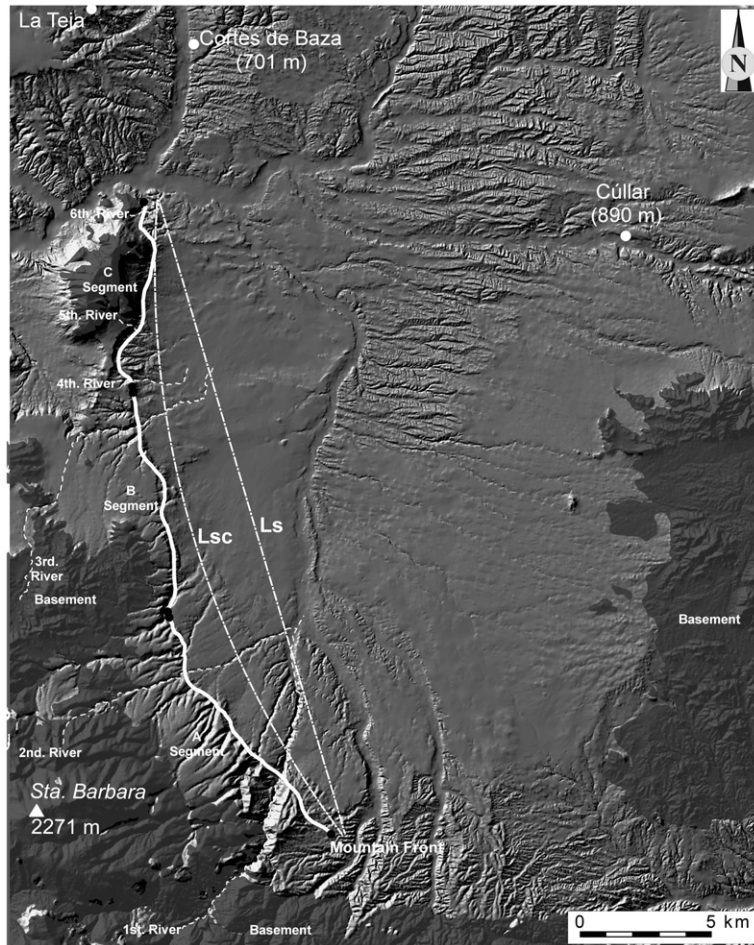


Fig. 11. Analytical hill shading of the calculated DEM. The strong white lines represent the position of the mountain front of the Baza Fault divided into three segments by the black points. The white dashed lines are the fluvial courses selected for analysis of SL index.

6.3. Stream length-gradient index (SL)

The stream length-gradient index expresses the relationship between $(\Delta h / \Delta l) \bullet L$, where Δh is the height increase, Δl the horizontal distance corresponding in each case to Δh , and L the accumulated length from the starting point to the middle point of the interval (Hack, 1973). This index, based on the longitudinal profile of the rivers crossing the front, shows irregularities related to escarpments of the fault induced by recent tectonic activity or lithological contrast.

The calculation of the SL index provides criteria for evaluating and comparing the tectonic activity between the different splays of the Baza Fault. Taking into account that the study area is characterized by a very homogeneous and soft lithological succession, these anomalies are probably produced by the fault activity and would reveal the existence of some escarpments connected to the fault not observed previously (Fig. 12).

The calculated DEM allows us to determine the SL index with a constant Δh , a constant Δl or using a constant displacement equal to grid resolution. We used the Δh constant method because it marks the position of the fault splays better. Thus, this methodology is similar to the manually obtained SL but lends greater precision.

The selection of the hydrological elements used can be seen in Fig. 11. The marginal elements of each river were eliminated, seeking in all cases to leave only its main channel and to keep its continuity.

We determined the SL index using an accumulator of distance from the origin of the stream and the present position. This position was defined by an iteration of Δl until we can obtain a constant Δh . We have tested various Δh : 20 m, 10 m, 8 m, 6 m, 5 m and 2 m. However, Δh less than 6 m gives too many data points, and does not allow us to differentiate between the fault and other noise from nearby objects. Consequently we used a Δh of 6 m.

Table 1
Vf values for each river

River	Smf	Origin distance to M.F. [m]	Distance from Vf to M.F. [m]	V_{fw}	E_{sc}	E_{rd}	E_{ld}	Vf
1	1.11	8796.51	250	30	983.6	1136.0	1047.1	0.28
2	1.11	6444.20	250	20	1054.7	1090.2	1083.3	0.62
3	1.11	11128.46	250	20	865.2	886.5	925.5	0.49
4	1.11	565.90	250	20	867.0	877.0	903.3	0.86
5	1.11	914.00	250	20	876.2	909.4	891.5	0.82
6	1.11	666.20	250	20	756.8	767.4	873.1	0.32
Mean								0.57
σ_{n-1}								0.25

The mean and σ_{n-1} values of Vf.

The height values of the river used to determine the profile of streams were determined using the Inverse Distance Weighted (IDW) method of [Watson and Philip \(1995\)](#):

$$\text{Height}(X, Y) = \frac{\sum_i \text{DEM}(X_i, Y_i) \left((X_i - X)^2 + (Y_i - Y)^2 \right)^{-p}}{\sum_i \left((X_i - X)^2 + (Y_i - Y)^2 \right)^{-p}}.$$

The height is determined, for each position (X, Y) of the stream, by a weighted mean of some near altitude values $(\text{DEM}(X_i, Y_i))$ by its distance to the original point. The p value refers to the influence of the altitude from the position (X, Y) to the near altitudes. Generally a value of 2 is used.

Some of the local maxima in SL index ([Fig. 12](#)) are concentrated within the fault zone and are largely associated with its westernmost splay. These local maxima coincide with the main escarpment of the fault. Despite the softness of these materials, their homogeneity, and the high erosion rates throughout the basin ([Calvache and Viseras, 1997](#); [Azañón et al., 2007](#)), the irregularities in the river profiles indicate recent activity of the Baza Fault.

As a general result, the SL index shows higher values for the segments of the Baza Fault where the lowest Smf values were found.

7. Discussion

The active Baza Fault, with over 2000 m throw from the late Miocene up to the present ([Alfaro et al., in press](#)), has a great influence on the geomorphological evolution of the GBB.

Its activity, at a rate between 0.12 and 0.33 mm/year ([Alfaro et al., in press](#)), displaced the geomorphological

surfaces formed during the Pleistocene, generating a major mountain front.

The morphometric analysis of the Baza mountain front (with 0.57 Vf and 1.11 Smf values) allows its assignment to class 1 of tectonic activity and indicates that the Baza Fault is one of the most active faults within the Betic Cordillera.

The Vf and Smf values calculated are even more important if we take into account the original non-rectilinear form of the Baza Fault and the fact that the mountain front is developed in soft materials which are more easily eroded.

These quantitative measurements may indicate different activity along segments or splays of the Baza Fault. Thus, the Smf index values calculated for the three segments of the mountain front (1.055 for segment A, 1.047 for B, and 1.118 for C) indicate less tectonic activity in the northern part of the fault, where indeed the mountain front presents less difference in levels.

The highest values of the SL indices calculated correspond to different mapped splays of the fault. In addition, they reveal the existence of some escarpments linked to faults that were not recognized in the field or in aerial photographs used for the earliest mapping.

Previous research indicates the presence of two main glacis surfaces (the Old and Recent Glacis) and locate their boundary just along the Baza Fault zone. However, we interpret that both glacis actually correspond to a single one, displaced by the Baza Fault. The maximum throw that affects the glacis surface is located in the central segment of the fault and progressively decreases towards the fault ends.

Maximum glacis displacement varies between 100 and 200 m, taking into account different envelopes of the glacis surface. If we consider a 100 m throw and a vertical slip rate of 0.25 mm/year (mean value supported by [Alfaro et al., in press](#)), the fault would require 400 ky to reach the present-day glacis displacement. These data are compatible with the oldest ages evoked for the glacis

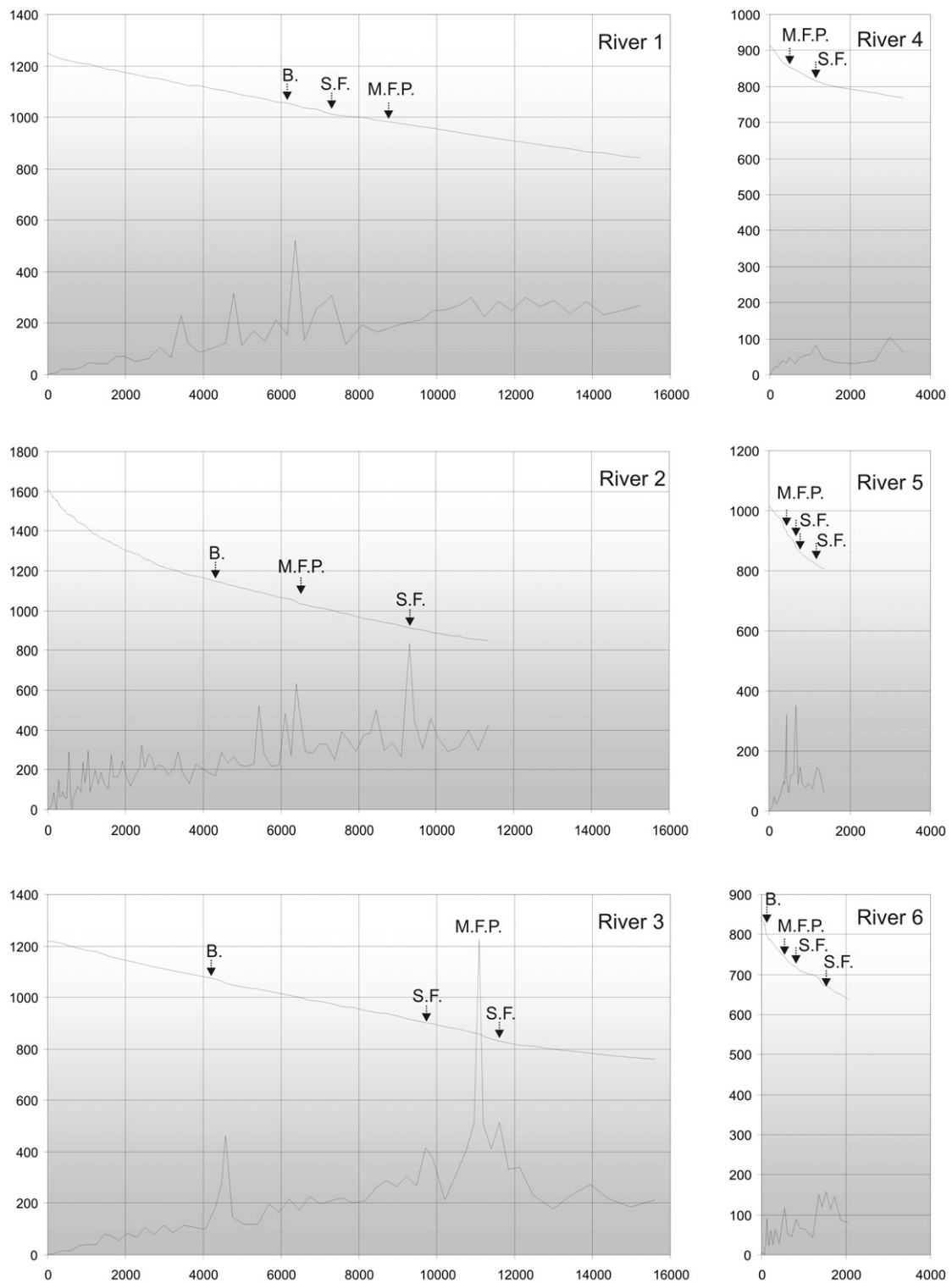


Fig. 12. Graphs with the SL index obtained from the six fluvial courses represented in Fig. 11. The upper lines represent the longitudinal profile of the fluvial course. The bottom lines in each graph represent the value of SL index. (M.F.P.: Mountain Front; S.F.: Splay Fault; B: Basement).

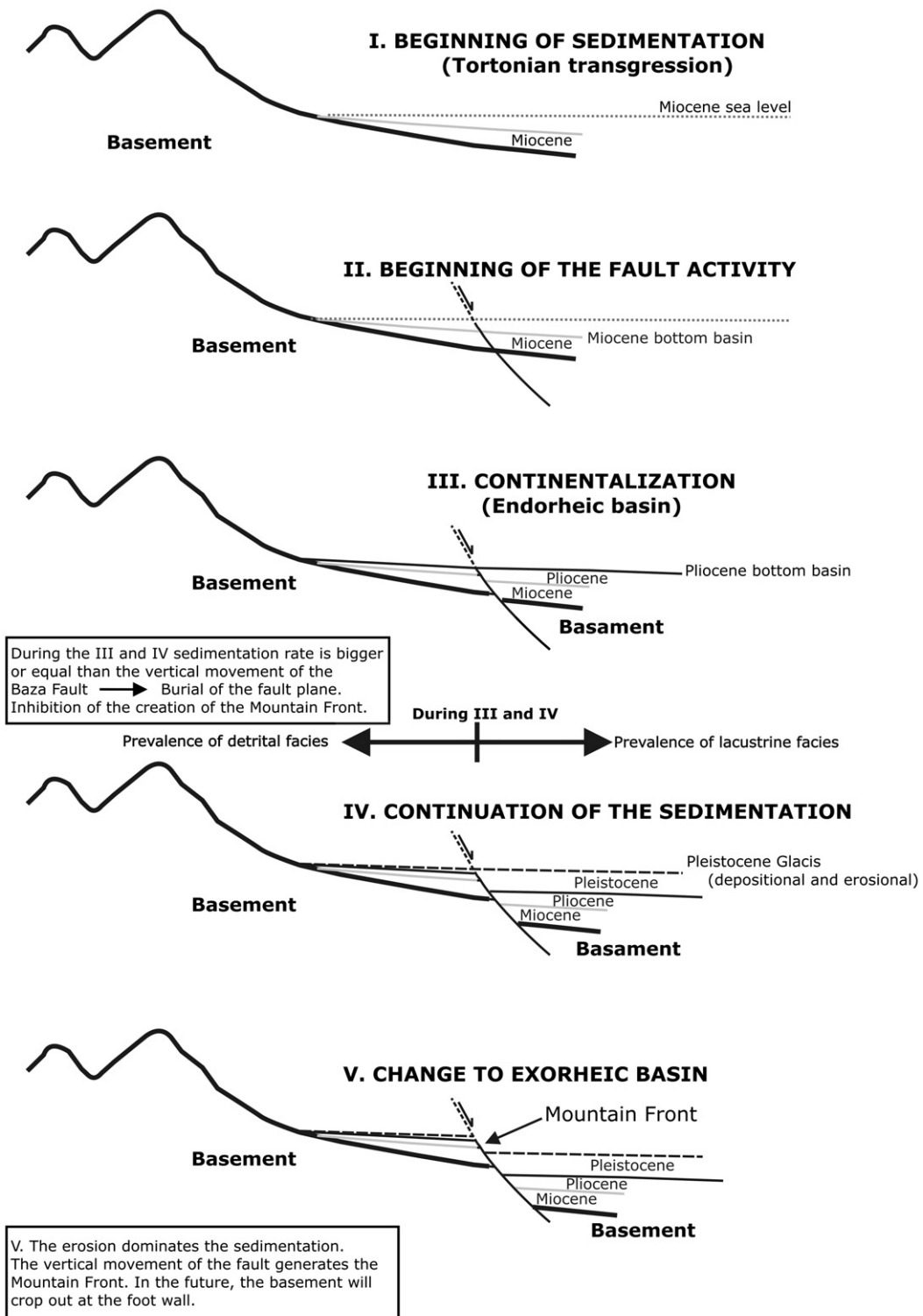


Fig. 13. Proposed model for the formation of the mountain front in the context of the Plio-Quaternary sedimentary infilling.

development, as by Díaz-Hernández and Juliá (2006) of over 350 ky. However, this is in disagreement with younger ages, such as the 100 ky proposed by Calvache and Viseras (1997) based on the paleontological ages of the Solana del Zamborino (uppermost middle Pleistocene). In any case, one possible explanation is that the alluvial sediments of the Solana del Zamborino may have been deposited after capture of the basin by the drainage system of the Guadalquivir River, that is when the basin was already exorheic. The same may be true of the radiometric age determined by Azañón et al. (2007). This possibility agrees with the results obtained by Gibert (2006) and Gibert et al. (in press) in the Baza Sub-basin, where an age of 450 ky was obtained for the final endorheic sediments.

The Baza Fault constituted a major tectonic structure that influenced the evolution of the GBB. Taking into account previous data, we propose the following Quaternary evolution (Fig. 13):

1. While the basin was endorheic: The subsidence rate (generation of accommodation space) was similar to the sedimentation rate in the hanging wall. From paleomagnetism and the amino acid racemization method of Ortiz et al. (2006), we deduce an average sedimentation rate during the Pleistocene of 0.2 mm/year. These similar values of sedimentation and fault activity (from Alfaro et al., in press, we deduce a vertical slip rate of 0.25 mm/year) do not favour the development of a mountain front during the Pleistocene.
2. Transition of the basin from endorheic to exorheic: The endorheic character of the basin continues up to the latest middle Pleistocene (approximately 400 ky), when the GBB was captured by the Guadalquivir Basin. At this time, lacustrine sedimentation ends in the Baza Sub-basin and erosion predominates in the study area.
3. When the basin was exorheic: The end of sedimentation in the hanging wall and of the activity of the Baza Fault progressively gave rise to several topographic escarpments along the fault trace. During the last 400 ky, the mountain front of the Baza Fault was developed. If fault activity continues, the basement will crop out again in the footwall.

Taking into account the softness of the Pliocene and Pleistocene sediments and the high erosion rates in the basin, the mountain front of the Baza Fault is very unstable. This mountain front indicates high activity of the Baza Fault, which agrees with the values of the geomorphic indices calculated and the overall seismic activity of the area.

8. Conclusions

The Baza Fault generates a major mountain front nearly 30 km long, located entirely within Plio-Quaternary sediments of the basin infill and not at the contact between the basement rocks and the sediments. The present preservation of this front, which developed over very soft sediments and thus eroded easily, indicates the active nature of the Baza Fault. When the Basin was endorheic, similar values of sedimentation and subsidence in the hanging wall did not favour the mountain front development; yet after the transition of the basin to exorheic drainage, erosion predominated over sedimentation and the mountain front was formed.

This tectonic boundary has largely controlled the geomorphological and sedimentological evolution of the GBB. The Baza Fault cuts the main geomorphological surface of the basin, the glacia, which is down-thrown approximately 100 m into the Baza Sub-basin. Considering the proposed rates for the Baza Fault, the glacia should be older than 100 ky, the maximum age considered by most previous researchers. Younger Glacia ages imply an extremely high fault activity (around 1 mm/year) that is not very likely to occur in this region. Notwithstanding, the Baza Fault is one of the most active faults in the central part of the Betic Cordillera. This active character is supported by the calculated geomorphic indices.

Acknowledgements

This study was financed by Projects BTE2001-5230-E, CGL2004-01636, CGL2004-03333/BTE, CGL2006-06001 and CSD00041 and Groups 217, 325 and 327 of the Junta de Andalucía.

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