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Quaternary deformation of the Bajo Segura blind fault (eastern Betic Cordillera, Spain) revealed by high-resolution reflection profiling

P. ALFARO*‡, J. M. ANDREU*, J. DELGADO*, A. ESTÉVEZ*, J. M. SORIA* & T. TEIXIDÓ†

*Dpto. Ciencias de la Tierra y del Medio Ambiente, Universidad Alicante, Apdo. 99, E-03080 Alicante, Spain
†Institut Cartogràfic de Catalunya, Parc de Montjuïc, E-08038 Barcelona, Spain

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Abstract – The blind reverse Bajo Segura Fault is located at the eastern extreme of the Trans-Alboran shear zone (Betic Cordillera, southeast Iberian Peninsula). The surface expression of recent activity of this blind ENE–WSW fault is represented by coseismic surface anticlines and growth synclines on both sides of the anticlines. In the synclines, the deformation of the most recent Quaternary materials is obscured by a sedimentary unit more than 30 m thick which was deposited during the later part of the Late Pleistocene and the Holocene. The present study reports three high-resolution seismic profiles made in the northern growth syncline, which was the one developed most by the Bajo Segura Fault. In these seismic profiles we recognize the boundary between pre-growth strata and growth strata. This marker, Early Pliocene in age, dates the start of the activity of this blind reverse fault. The geometry observed in the seismic profiles of the syntectonic strata, dating from the Late Pliocene and Quaternary, indicates a limb rotation folding mechanism. On seismic profile 2, the complex geometry of the Benejúzar anticline forelimb can be attributed to several splay faults close to the surface of Bajo Segura Fault.

Keywords: active tectonics, blind faults, Betic Cordillera, seismic profiles.

1. Introduction

The eastern Betic Cordillera (southeastern Spain) is a seismically active zone (López Casado *et al.* 1987) characterized mainly by the occurrence of low-magnitude earthquakes, though there have been occasional moderate to high-magnitude earthquakes, among which the 1829 Torrevieja earthquake stands out. Based on the damage caused by this earthquake, the intensity reached at the epicentre has been estimated as X on the MSK scale (Muñoz, Udías & Moreno, 1984). Other authors, on the basis of the spatial distribution of the damage, have estimated its magnitude (Ms) as between 6.3 and 6.9 (Muñoz & Udías, 1991; Delgado *et al.* 1993). Other earthquakes with intensity of about VIII occurred in Guardamar del Segura (1523) and Jacarilla-Benejúzar (1919).

All these earthquakes were located along the trace of the Bajo Segura Fault, which is one of the most active faults in this eastern sector of the Iberian Peninsula. It is a blind reverse fault (Montenat, 1977), similar to that of El Asnam (Algeria), which in 1980 produced an earthquake of magnitude 7.3 (Philip & Meghraoui, 1983). The geodynamic context of these two blind reverse faults is similar; they are located in the wide collision zone of the African and Eurasian plates, with a maximum compressive regional stress trending NNW–SSE (Buforn, Udías & Mezcua, 1988).

The only surface expression of activity of this blind fault is coseismic folding (Taboada, Bousquet & Philip, 1993). The fault has developed various asymmetric anticlines running ENE–WSW (Guardamar, Lomas de la Juliana, Benejúzar and Hurchillo). On either side of the anticlines two synclines have developed forming subsiding sectors. The more strongly developed syncline is situated to the north, where the river Segura flows. This river flows parallel to the fold axes and the Bajo Segura Fault. During the folding, this growth syncline was filled by syntectonic sediments, Late Pliocene–Quaternary in age. The last sedimentary unit that fills the basin is Late Pleistocene–Holocene in age, on the basis of 30 absolute ^{14}C datings (Soria *et al.* 1999). These recent deposits, more than 30 m thick, hide the trace of the Bajo Segura Fault, and consequently the possibility of obtaining information about deformation of sediments which fill this growth syncline is reduced to subsurface studies.

For this purpose we collected three high-resolution seismic reflection profiles in the northern growth synclines linked to the Bajo Segura Fault. The data supplied by these seismic profiles were complemented

‡ Author for correspondence: pedro.alfaro@ua.es

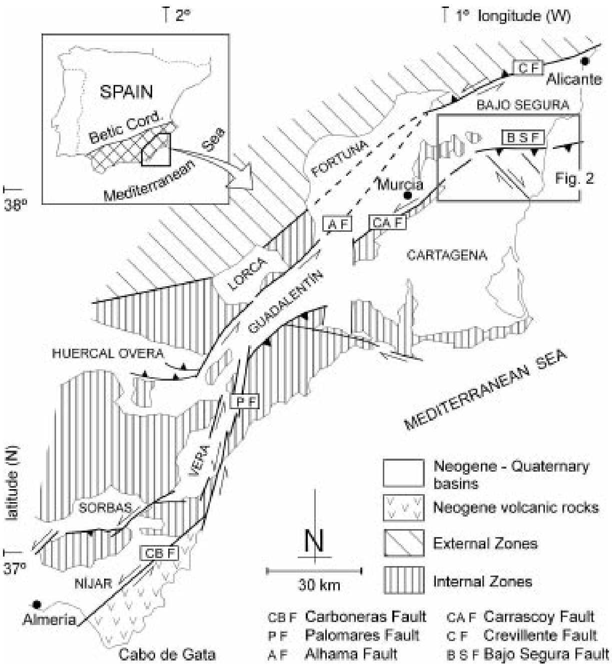

Figure 1. Regional map of the Betic segment of the Trans-Alboran shear zone showing the location of the Bajo Segura Fault.

by surface geological data with the aim of understanding better the recent activity of this blind thrust fault.

2. Geological context

The Bajo Segura Fault is located in the eastern Betic Cordillera (southeast Spain), which is subject to a present-day compressive stress field, with a maximum horizontal axis in a NNW–SSE direction (Herraiz *et al.* 2000). This compressive geodynamic situation is related to the convergence of the African and Eurasian plates at a rate of 4–6 mm yr^{-1} (Argus *et al.* 1989).

The Bajo Segura Fault is located in the northern sector of the Betic segment of the Trans-Alboran Shear Zone (De Larouzière *et al.* 1988), also known as the Eastern Betic shear zone (Silva *et al.* 1993). In this compressive geodynamic context, the left-lateral shear zone has operated from at least Late Miocene time to the present. This sigmoidal shear zone (Silva *et al.* 1993), more than 250 km long, extends from Almería to Alicante (Fig. 1). Along this fault zone several outstanding faults deserve special mention. One of these, the Carboneras sinistral strike-slip fault, which runs in a NE–SW direction, characterizes its southernmost end (Bousquet, 1979). To the north is the Palomares Fault, running NNE–SSW (N 10° E to N 20° E) (Bousquet, Dumas & Montenat, 1975). In its central sector, running NE–SW, are the Alhama de Murcia sinistral strike-slip fault and the Carrascoy Fault (Bousquet & Montenat, 1974; J. J. Martínez-Díaz, unpub. Ph.D. thesis, Univ. Complutense Madrid, 1998). Finally, in its northern sector are found the Crevillente Fault (Foucault, 1974) and the Bajo Segura Fault (Montenat, 1977), both running ENE–WSW.

Both the Crevillente and the Bajo Segura faults form the limit, to the north and south respectively, of the Plio-Quaternary basin of the Bajo Segura (Fig. 1). Based on an analysis of focal mechanisms, Alfaro *et al.* (1999) deduced that this basin is subject to a NNW–SSE compressive stress field. In this geodynamic setting, the Crevillente and Bajo Segura faults, oriented perpendicular to the maximum compressive stress, basically operate as reverse faults.

The various authors who have studied the active tectonics of the Bajo Segura Basin (Montenat, 1977; Bousquet, 1979; López Casado *et al.* 1987; Somoza, 1993; Taboada, Bousquet & Philip, 1993; P. Alfaro, unpub. Ph.D. thesis, Univ. Alicante, 1995) have highlighted as the most active faults, the aforementioned Crevillente and Bajo Segura faults, and several other NW–SE right-lateral faults (Guardamar del Segura, Torrevieja and San Miguel de Salinas) (Fig. 2a).

In contrast to what occurs in the central sector of the Eastern Betic shear zone, where the active left-lateral Alhama Fault has a surface trace which is visible for more than 100 km (Bousquet & Montenat, 1974; Silva *et al.* 1993; J. J. Martínez-Díaz, unpub. Ph.D. thesis, Univ. Complutense Madrid, 1998), the faults in the northern sector of the shear zone do not rupture at the surface. Their main superficial expression is the folding of the most recent materials dating from the Late Miocene, Pliocene and Quaternary, which is particularly developed along the Bajo Segura Fault.

3. Activity of the Bajo Segura Fault

The Bajo Segura Fault extends for a distance of almost 30 km from the southwest of Orihuela as far as Guardamar del Segura, in a ENE–WSW direction. The seismicity and the high-resolution seismic profiles of the adjacent continental shelf show its continuation towards the east in the Mediterranean Sea (P. Alfaro, unpub. Ph.D. thesis, Univ. Alicante, 1995) (Fig. 2b).

At depth this fault offsets Triassic basement rocks, whilst in the more superficial part there is a folded sedimentary cover dating from Late Miocene–Quaternary times (Montenat, 1977; Taboada, Bousquet & Philip, 1993). The boreholes made for oil exploration within the study area cut through the basement, composed of Triassic carbonate rocks from the Alpujarride Complex (Internal Zone of the Betic Cordillera), at a depth of 1300 m in the Guardamar sector and at a depth of 1550 m just to the south of Benejúzar.

The folds that developed as a result of the activity of this fault are asymmetric anticlines running ENE–WSW, with steep forelimbs in the north and gentle back limbs in the south. The anticlinal folds running from east to west are those of Guardamar, Lomas de

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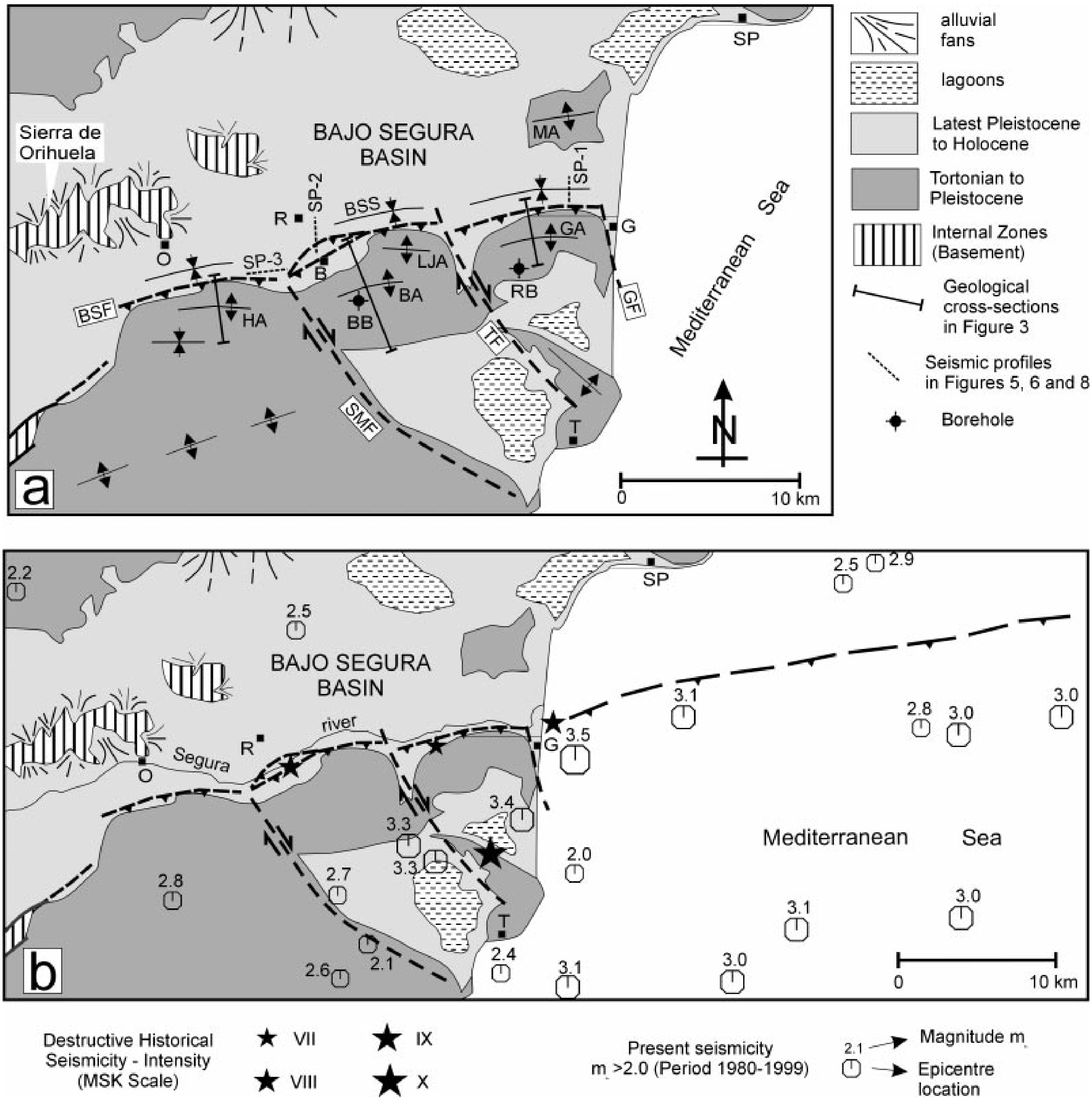

Figure 2. Geological map of the Plio-Quaternary basin of the Bajo Segura (upper sketch) and main historical and instrumental seismicity (lower sketch). BSF: Bajo Segura Fault, SMF: San Miguel de Salinas Fault, TF: Torrevieja Fault, GF: Guardamar Fault, HA: Hurchillo anticline, BA: Benejúzar anticline, LJA: Lomas de la Juliana anticline, GA: Guardamar anticline, MA: La Marina anticline, BSS: Bajo Segura syncline. Towns: Santa Pola (SP), Guardamar del Segura (G), Torrevieja (T), Rafal (R), Benejúzar (B), Orihuela (O). Boreholes: BB (Benejúzar), RB (Rojales). Seismic profiles: SP-1, SP-2 and SP-3.

la Juliana, Benejúzar and Hurchillo. These anticlines are separated by NW–SE dextral strike-slip faults (Montenat, 1977; Taboada, Bousquet & Philip, 1993), notable amongst which are the faults of Guardamar del Segura, Torrevieja and San Miguel de Salinas (Fig. 2a). On either side of the anticlines, two synclines have formed which, since the beginning of folding, were axes of subsidence. Along the northern syncline, which is much more developed, the Segura river flows from Benejúzar to the sea, running parallel and very close to the northern limb (forelimb) of the anticlines (Fig. 2).

In order to date the recent tectonics of the Bajo Segura Fault it is important to consider the chronology of the Pliocene formations which fill the northern trough. The Variegated Lutite Formation, in its vertical transition zone with the Segura Conglomerate Formation, has been dated as Early Pliocene (zone MN15: Soria *et al.* 1996), using micromammals. This would suggest that the base of the Segura

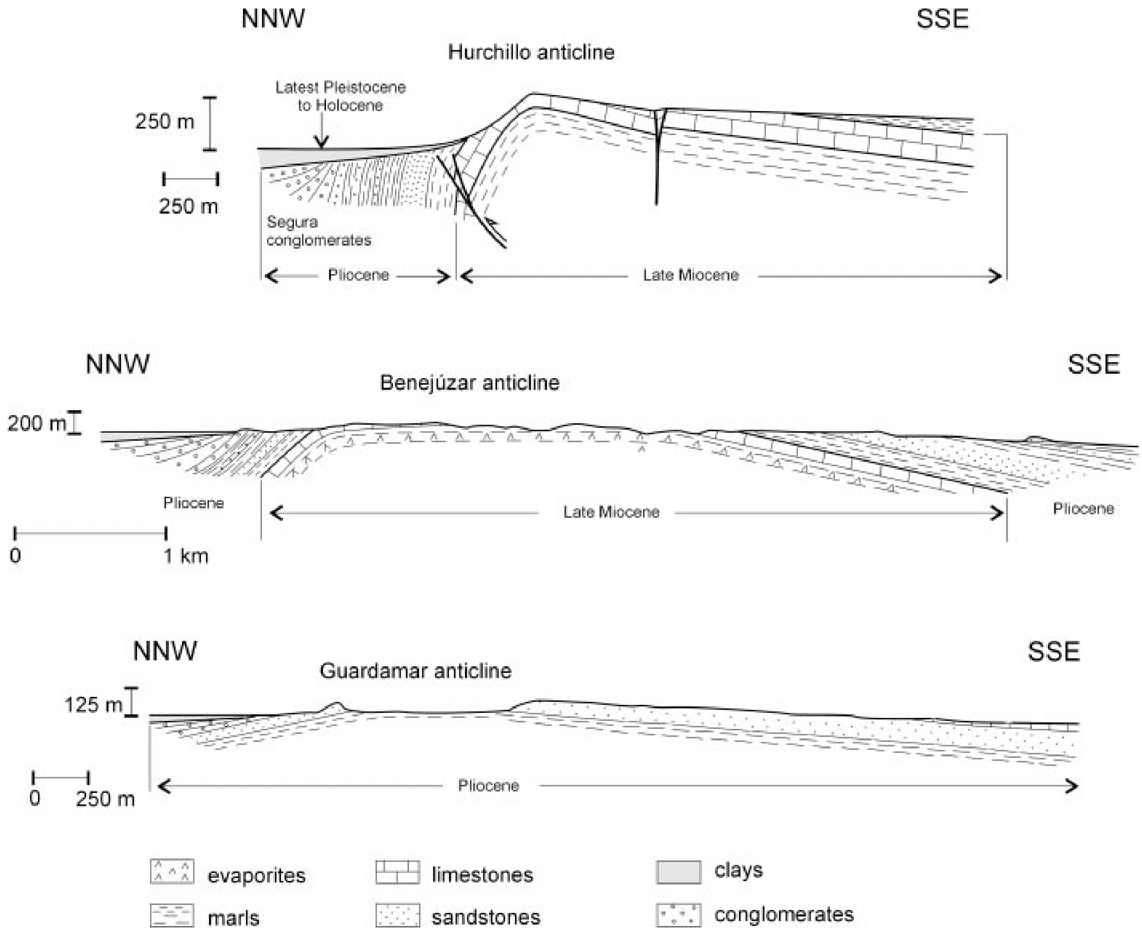

Figure 3. Geological cross-sections of the anticlines related to the Bajo Segura Fault.

Conglomerate Formation also corresponds to the Early Pliocene. Interestingly, the uppermost part of the Segura Conglomerate Formation does not crop out at any point within the northern trough, since this formation is covered unconformably by the Quaternary unit. This upper part has been recognized by means of boreholes in the axial zone of the basin (Soria *et al.* 1999), grading vertically with the Variegated Lutite Formation. Unfortunately, however, there are no criteria for dating it. For this reason, we cannot reject the possibility that the uppermost part of the Segura Conglomerates Formation may be Late Pliocene or Pleistocene, as indicated by Montenat *et al.* (1990) and Bardají *et al.* (1995).

The theoretical models of blind reverse faults (for example, Ward & Valensise, 1996) indicate that the morphology of the surface folds is highly dependent upon the fault geometry at depth. The resulting geometry of the Bajo Segura folds consists of northward-verging anticlines and synclines, the latter being more developed in the north limbs of the anticlines than in the south. Based on the morphology of the folds, modelling of blind reverse faults (Ward & Valensise, 1996) suggests that the Bajo Segura Fault dips rather steeply towards the south, as was previously suggested by Montenat (1977) and Taboada, Bousquet & Philip (1993). One more superficial expression of this steep dip of the fault is the location of the Segura river, which flows along the depocentre of the growth synclines, very close to the northern forelimb of the aforementioned anticlines (Fig. 2).

Structural analysis of these anticlinal folds indicates that deformation becomes more intense towards the west (Fig. 3). Using as a reference the Segura Conglomerate Formation, which dates at its base from the Early Pliocene (Montenat, 1977; Soria *et al.* 1996), it can be seen how its strata dip towards the north by approximately 20° in the Guardamar anticline (Fig. 4a), 50° in the Benejúzar anticline and 90° in the Hurchillo anticline (Fig. 4c). In the western sector of the fault, the shortening is mainly concentrated in a unique folding structure, the Hurchillo anticline, where the Segura Conglomerate Formation dips more steeply. In contrast, in the eastern part of the study area the shortening is distributed through several folds, such as the Guardamar anticline and also the La Marina and Santa Pola anticlines, situated further north of the Bajo Segura Fault.

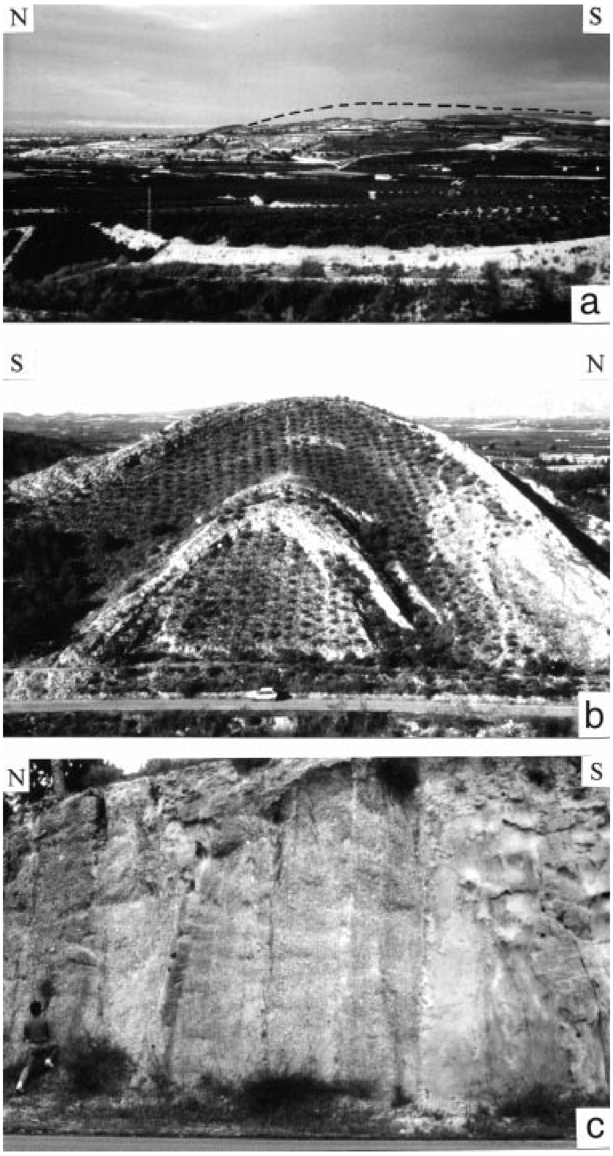

Figure 4. (a) Panoramic view of the Guardamar anticline. The width of the panoramic view is 3 km. (b) Hectometric fold located in the forelimb of the Benejúzar anticline. See the car at the bottom for scale. (c) Conglomerates of the Bajo Segura with a vertical dip on the northern limb of the Hurchillo anticline.

3.a. Associated seismicity

The seismic activity associated with the Bajo Segura Fault is among the most remarkable of the Iberian Peninsula. Within the study area, the instrumental record of seismicity dates back to the beginning of the twentieth century, however, it was not until 1980, when the number of stations in the region increased and localization became more reliable, that the error of localization was reduced. In the majority of cases, therefore, it is difficult to assign the earthquakes which occurred before 1980 to the Bajo Segura Fault or to another of the NW–SE faults present in the area of study.

The seismicity registered during the twentieth century is characterized by low-magnitude earthquakes, and only a few exceeded magnitude 3.5. Notable amongst these was the Jacarilla-Benejúzar earthquake of 1919, with a m_b magnitude of 5.2, which was followed by significant aftershocks, one of which reached a magnitude of 5.1 (Mezcua & Martínez Solares, 1983). With respect to the most recent instrumental period (1980–1999), when localizations have been more reliable, the seismicity registered along the Bajo Segura Fault was superficial, with most foci located between a depth of 4 and 10 km. Several earthquakes have been located in the offshore continuation of the Bajo Segura Fault (Fig. 2b).

In spite of this low-magnitude seismicity, several destructive earthquakes (Io ≥ VIII) have occurred in the past. The 1829 Torrevieja earthquake destroyed the town of Torrevieja and caused serious damage and loss of life in the valley of the river Segura (Io = X MSK; Ms = 6.3–6.9) (Muñoz & Udías, 1991; Delgado *et al.* 1993). According to Larramendi (1829) there were 389 deaths, a total of 2965 houses totally destroyed and 2396 houses partially damaged. Considering the isoseismal maps for this earthquake and the southward dip of the Bajo Segura Fault, it is highly probable that this reverse fault is the seismogenic structure responsible for this catastrophic earthquake. In addition to this earthquake, there have been others with an epicentre intensity of VII and VIII (MSK) also located over the trace of the Bajo Segura Fault. One of these occurred in 1523 at Guardamar and another in 1746 at Rojales (Fig. 2b). In spite of the localization error, it is probable that these historical earthquakes were related to the activity of the Bajo Segura Fault.

Taboada, Bousquet & Philip (1993) established recurrence periods for two possible earthquakes of magnitude 6.7 Ms and 7 Ms, ranging from 1000 to 2000 yr, respectively. These results were obtained assuming that the folding started at the end of the Pliocene (2 Ma) or at the beginning of Early Quaternary times (1.5 Ma).

4. Seismic profiles

We acquired three seismic reflection profiles (SP) over a total length of 7600 m (Fig. 2a). Profiles SP-1 and SP-2 were directed approximately transverse to the Bajo Segura Fault, with the aim of determining the geometry of the sediments that fill the northern growth syncline (Fig. 2a). SP-1 was 1500 m long and directed N–S; it was located at the north of the anticlinal fold of Guardamar. SP-2, 2500 m long and running NW–SE, was located in the north of the Benejúzar anticline. SP-3, 3500 m long and running ENE–WSW, was positioned perpendicular to the NW–SE San Miguel de Salinas fault zone, in order to check whether this fault stretches towards the northwest through the whole of the Bajo Segura Basin.

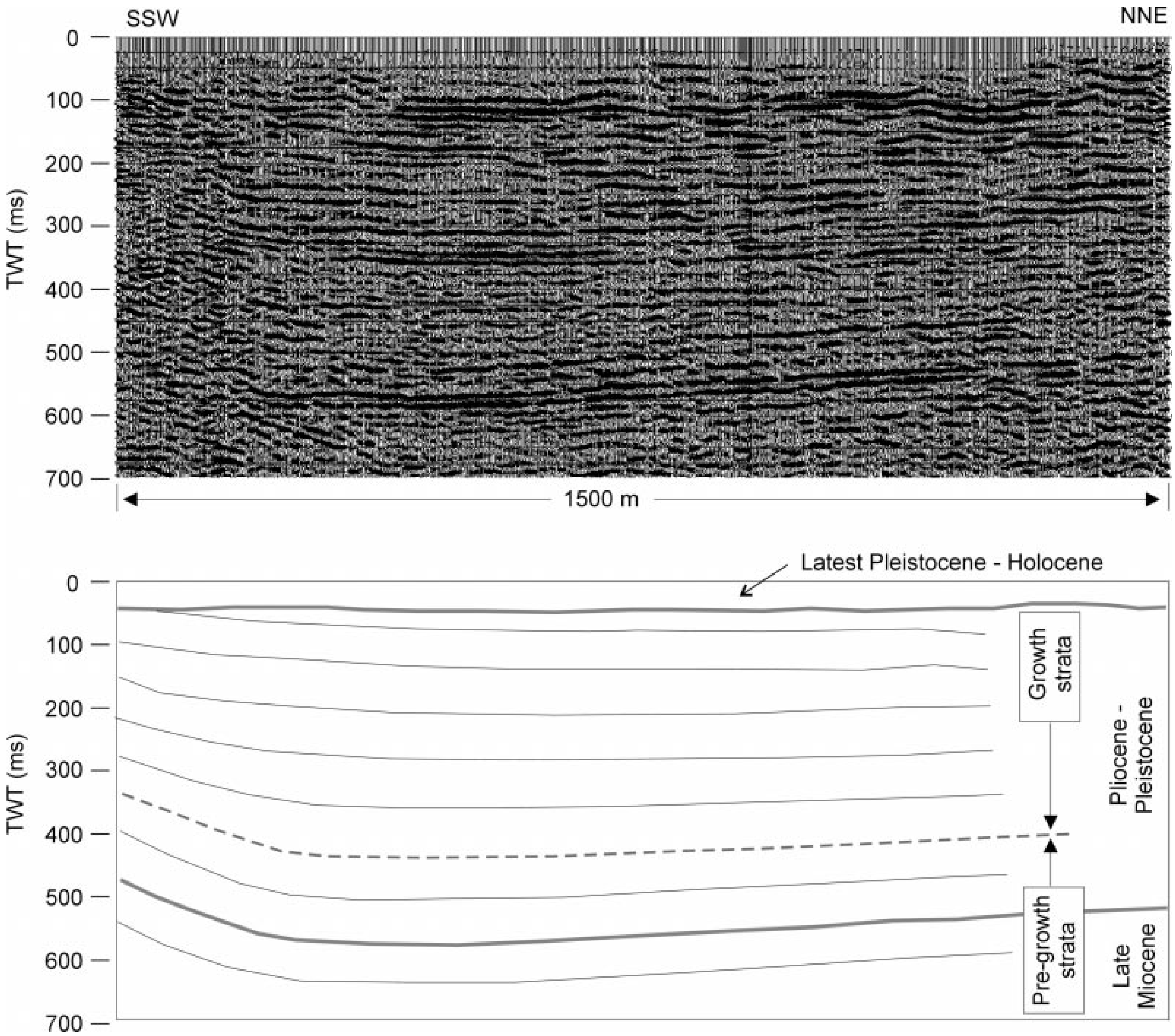

Figure 5. High-resolution seismic profile and interpretative scheme of SP-1. For location, see Figure 2.

4.a. Data acquisition and processing

Single vertical 40 Hz geophone stations were deployed and a 48-channel digital Seismograph (BISON 4098) was used for acquiring the seismic data. The acquisition parameters were as follows: a sample rate of 0.1 ms, 8 Hz low-cut and 1000 Hz high-cut filters. The record length was 1000 ms. Geophones were placed with a spacing of 5 m and the selected shot interval was 10 m. The shots were located in front of the seismic line with a nearest offset of 7.5 m. This offset was determined by taking into account the time window between the first arrivals and ground-roll. The seismic source utilized was a special type of low energy explosive (fireworks) composed of perchlorite (Benjumea & Teixidó, 2001).

The data were processed on a workstation using Landmark's ProMAX seismic processing package. The seismic reflection data processing consisted of a standard flow to reveal the prominent reflections along the profiles (lines 1, 2 and 3). In the pre-stacking step the common-shot gathers were processed to optimize the signal quality and remove random and coherent noise (waveguide reverberations, surface waves and the aerial wave). Muting was applied to eliminate critical refractions. The main objective was to eliminate the high-amplitude surface waves, which interfere with the reflected ones. These surface waves are spatially aliased, which makes 2-D pre-stack filtering useless. Therefore, two-step processing was conducted: first, a pre-stack band-pass filter that attenuates the low frequency content was used, and second, a post-stack F-K filter eliminated noise from surface waves having a high frequency content of around 90 Hz. A control test was carried out to check possible artifacts in seismic sections due to residual surface waves energy

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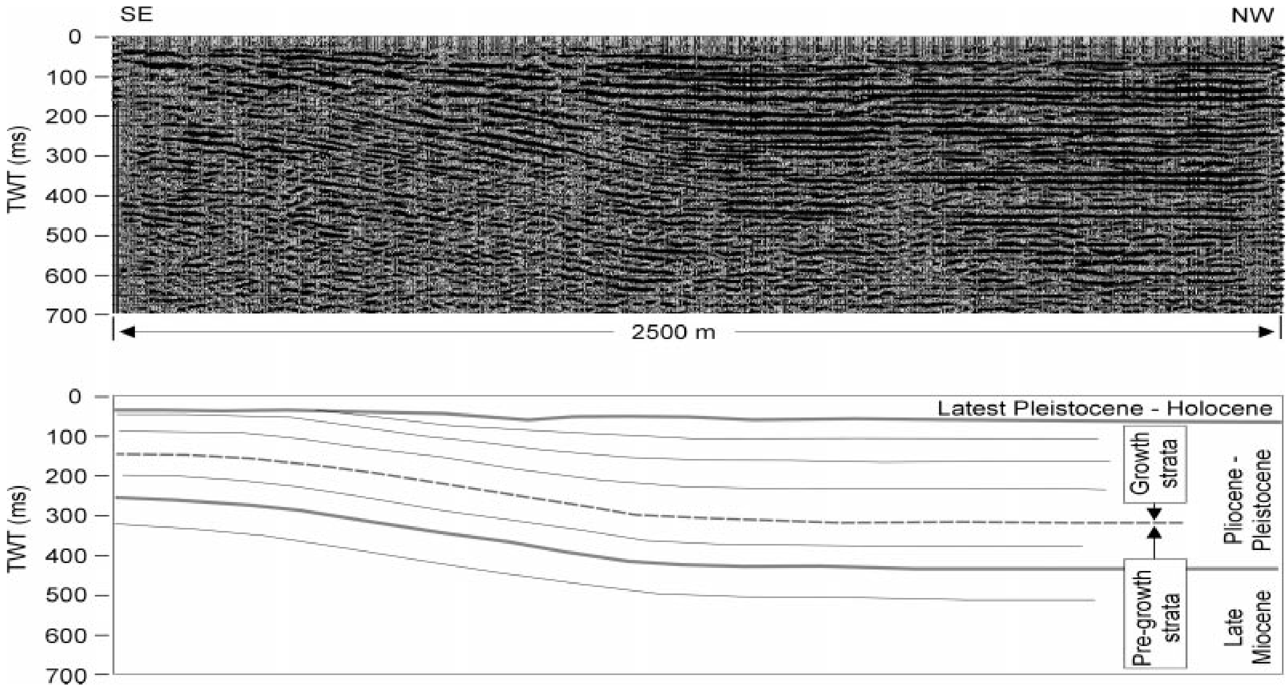

Figure 6. High-resolution seismic profile and interpretative scheme of SP-2. For location, see Figure 2.

(between 500 and 700 ms). This control was performed comparing the seismic sections with and without surgical muting of this event. Migration of the stacked seismic data was successful in line 3 and was compared with the unmigrated section in order to verify the possible rupture zones of the seismic images.

4.b. Interpretation

In the three seismic profiles, folding of the upper Miocene–Quaternary materials that fill the basin was observed. In profiles SP-1 and SP-2 (Figs 5, 6), which were transverse to the Bajo Segura Fault, a structure of divergent beds northward, similar to a layered fan, was identified; the geometry of the seismic reflectors is especially visible in SP-2. It may be observed in this profile how, before the middle of the Pliocene, the sedimentary units filling the basin have more or less conserved their thickness (pre-growth strata, *sensu* Burbank & Vergès, 1994; Suppe *et al.* 1997). The marker which is located at the base of the Segura Conglomerate Formation has been dated as Early Pliocene. However, from the Late Pliocene, significant lateral variations in thickness are observed, apparently coeval with the development of growth folds. Thus, these seismic profiles indicate that the folding of these materials began during the Early Pliocene and continued to the present day.

The geometry of the fill observed in seismic profile 2 is in keeping with a model of limb rotation (*sensu* Suppe *et al.* 1997), in which the change in thickness of each growth bed is spread out over the fold limb, causing a progressive dip change of the fold limb.

Combining the surface geological data with those from SP-2, we have constructed a geological cross-section of the Bajo Segura Fault in the sector of the Benejúzar anticline (Fig. 7a). It shows an asymmetrical anticline with a southern limb in which the Pliocene rocks dip gently, approximately 15° southwards, whilst the materials of the same age on the northern limb dip more than 50° northwards. The northern limb has a more complex geometry than the southern one; there is a small hectometric-scale fold (Fig. 4b). Also, two kilometres north of the sector where the materials of this northern limb crop out, SP-2 highlights the existence of a new monocline fold (Fig. 7a). We interpret that several imbricate thrusts are responsible for the complex geometry of this fold forelimb. The main Bajo Segura Fault plane probably has several secondary splay faults close to the surface (Fig. 7b).

In the geological section in Figure 7a the most recent materials that fill the Bajo Segura basin show an offlap stratigraphic relationship in the sector situated to the south of Benejúzar (sector A in Fig. 7a) since the uplift in this zone has been greater than the accumulation of sediments. However, in the Rafal sector (sector B in Fig. 7a) there is an overlap geometry, because the accumulation of sediments here has exceeded the uplift produced by the monocline fold.

Amongst the stratigraphic units that overlap the monocline fold (sector B), mention should be made of the most recent one, which dates from the Late Pleistocene to the Holocene and whose thickness may exceed 30 m in certain sectors of the basin. This relatively great thickness of recent sediments is mainly due

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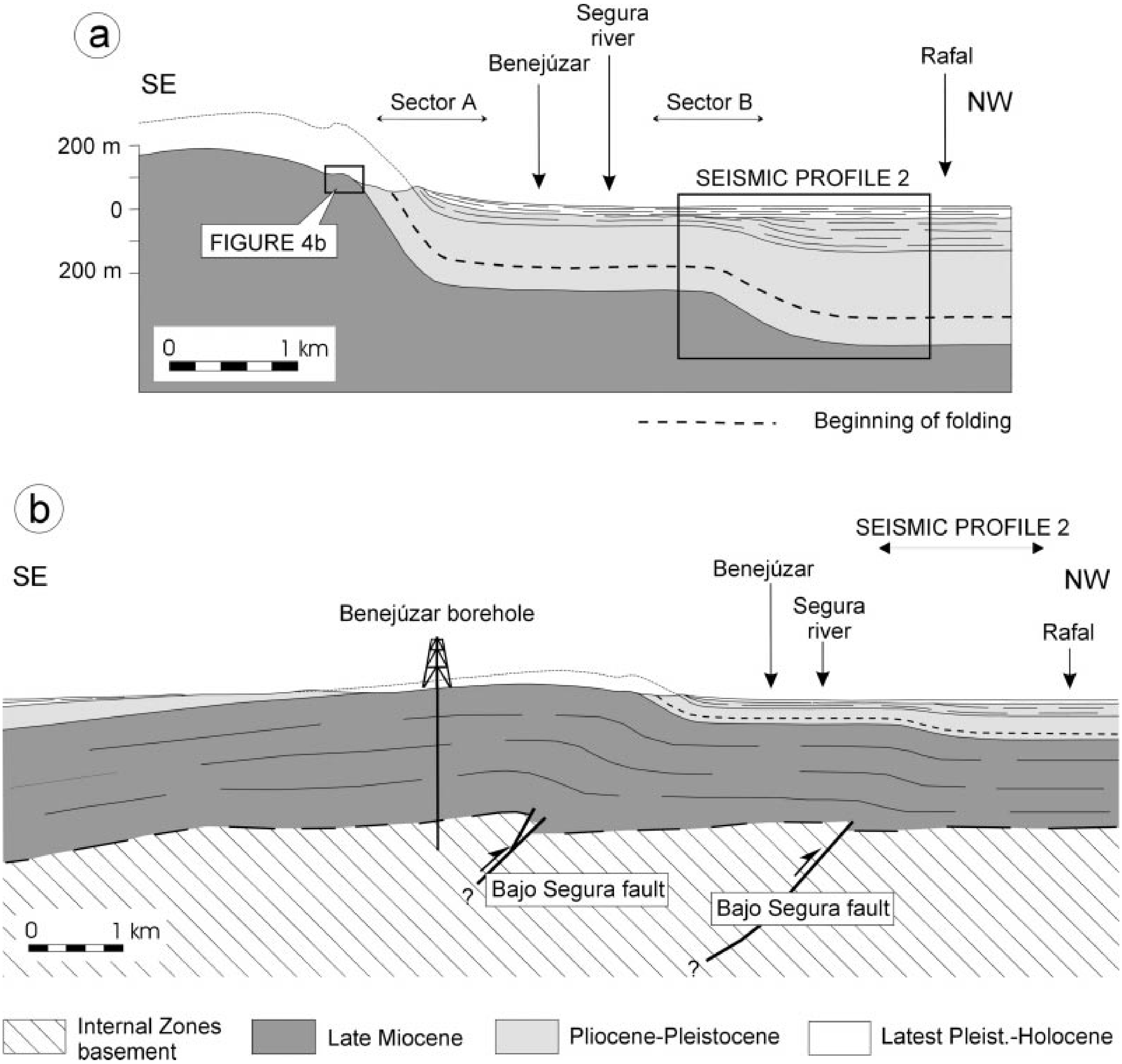

Figure 7. (a) Simplified sketch of the northern sector of the Benejúzar anticline, with the positions of profile SP-2 and fold of Figure 4b (note vertical scale exaggerated). (b) Interpretative geological cross-section of the Bajo Segura blind reverse fault showing a splay pattern.

to the rapid sedimentation rates that occurred in the basin (between 1.9 and 3.7 mm yr^{-1}), with respect to the last eustatic sea-level rise (Soria *et al.* 1999). Today, this recent sedimentary unit covers the whole of the northern subsiding trough, and obscures the geomorphological evidence of activity of the Bajo Segura Fault. Its recent age, probably less than 20 000 yr, is insufficient for this unit to have been appreciably deformed. Consequently in the seismic profiles these recent sediments appear practically horizontal showing only a slight increase in thickness towards the north.

SP-3 (Fig. 8), which runs transverse to the San Miguel de Salinas Fault, exhibits folding of the infilling of the Bajo Segura Basin, as well as a lateral variation of the thickness of strata from the middle of the Pliocene. Another of the notable features is the greater level of subsidence of the western sector in the vicinity of the Hurchillo anticline. This agrees with surface geological observations, which also show a progressive increase of deformation westwards in the successive anticlines. Consequently, this lateral variation in thickness in these strata towards the west can be related exclusively to the activity of the Bajo Segura Fault. Therefore, the San Miguel de Salinas strike-slip fault would likely behave as a transfer fault and consequently not extend further to the northwest into the Bajo Segura basin (Fig. 9). Although no high-resolution

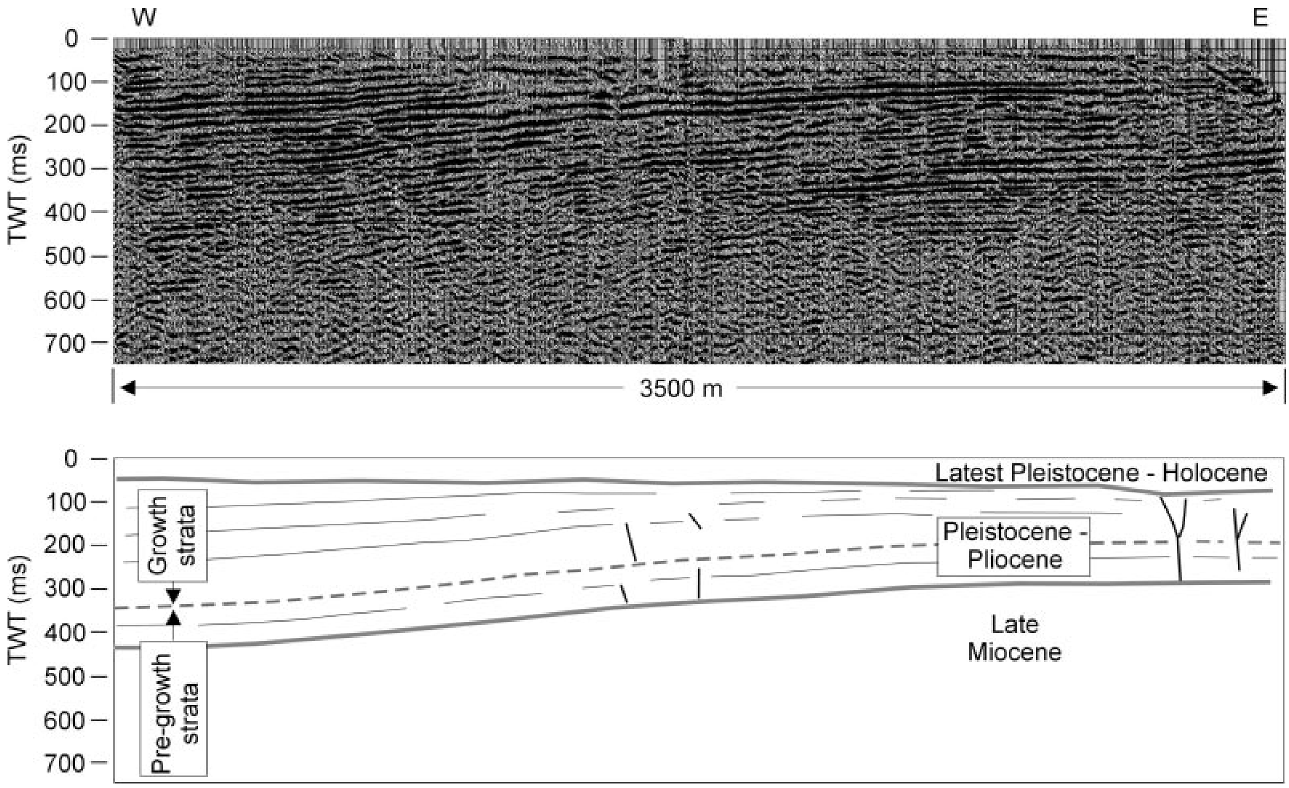

Figure 8. High-resolution seismic profile and interpretative scheme of SP-3. For location, see Figure 2.

seismic profiles have been collected in the continuation of the Torrevieja and Guardamar faults, these NW–SE parallel faults could also be considered as transfer faults.

5. Conclusions

In the three high-resolution reflection profiles produced in this study we have observed how the Plio-Quaternary sediments were deformed by the activity of the Bajo Segura blind reverse fault (eastern Betic Cordillera, southeastern Spain). We have identified various growth synclines in these seismic profiles, which are filled with upper Pliocene–Quaternary deposits.

On the basis of the pre-growth and growth strata (syntectonic strata) of these synclines, we deduce that this fault began its activity during the deposition of the Segura Conglomerate Formation, whose base is Early Pliocene in age. From this result, the Bajo Segura Fault started its activity before the time proposed by Taboada, Bousquet & Philip (1993), approximately four million years ago. Therefore, the Bajo Segura Fault is a seismogenic blind fault with a slow slip rate which agrees with its low seismic activity.

The only materials that are not apparently deformed are those of the last unit filling the Plio-Quaternary basin of the Bajo Segura. These Holocene–Late Pleistocene sediments are more than 30 m thick and have not had time to be appreciably deformed. The rapid sedimentation of these materials linked to the last eustatic sea-level rise obscures some geomorphological traces of the recent activity of this fault. Nonetheless, the fault continues to be active today as shown by the seismicity associated with it. The fault is probably responsible for the various historical earthquakes that had MSK intensities of between VII and X: the 1523 Guardamar del Segura, the 1746 Rojales, the 1829 Torrevieja and the 1919 Jacarilla-Benejúzar earthquakes.

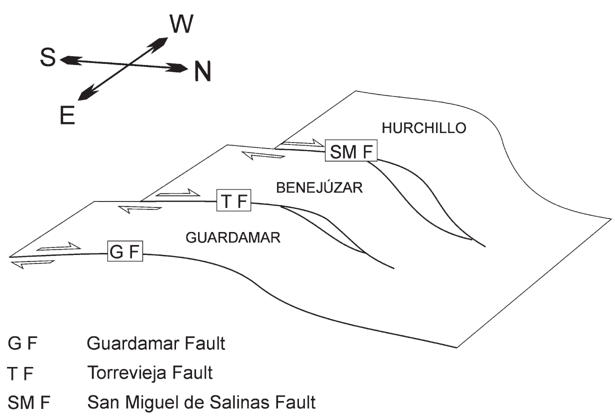

Figure 9. Simplified sketch showing the right-lateral NW–SE faults interpreted as transfer faults of the Bajo Segura Fault.

Seismic profile 2, made in the north of the

Benejúzar anticline, highlights the complex geometry of the forelimb of this fold. We interpret these irregularities in the geometry of the Benejúzar anticline as being related to an imbricate system of blind thrusts with several splay faults close to the surface.

On the other hand, seismic profile 3 shows no clear evidence of the recent activity of the San Miguel de Salinas Fault to the north of the Bajo Segura Fault. We believe this is because this NW–SE fault was a transfer of the Bajo Segura Fault, which is now the main active fault in the area.

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