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Quantification of vertical movements in the eastern Betics (Spain) by comparing levelling data

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Abstract

Comparison of precision levelling data carried out at different times is a technique that allows the quantification of recent vertical movements. We used the precision levelling data from the Instituto Geográfico Nacional of Spain to improve our understanding of the recent tectonic evolution of some areas in the southeastern Iberian Peninsula (eastern Betics), where significant deformation has occurred during the last century. The resulting movements are presented in recent vertical movement profiles. Profiles with significant movements are discussed, taking into account the geologic and seismic features of each zone. These profiles are: Alicante–Albacete, Alicante–Almería, Larva (near Jaén)–Almería and Almería–El Palo (near Málaga).

The results obtained point to the existence of important tectonic deformation rates near the main tectonic structures crossing the profiles. The main tectonic anomalies expressed in constant rates of vertical velocity are: a 2 mm/year step near the ENE–WSW-trending Valldigna–Jumilla fault zone (between Alicante and Albacete); a 0.9 mm/year step located in the NNE–SSW-trending Cocón–Terreros fault zone (between Murcia and Almería); a subsidence of about 1.5 mm/year of the Almería Basin zone that can be related to NW–SE and E–W faults; a step of 1 mm/year related to the ENE–WSW-trending Guadahortuna fault (between Granada and Jaén); a 1 mm/year step associated with the ENE–WSW-trending Cádiz–Alicante fault zone (near the Granada area); and a 1.4 mm/year step related to the tectonic activity of the NW–SE- and NE–SW-trending system of faults that affect the Iberian coast of the Alborán Sea (Almería and Granada zone).

The anomalies related to the ENE–WSW- to E–W-trending structures are associated with reverse faults, whereas the anomalies related to the faults oriented in a NE–SW or NW–SE direction are associated with strike-slip faults with a normal component of vertical movement. These movements are consistent with the present-day Betics stress tensor determined with different methodologies, such as the focal mechanism analysis and microstructural and geomorphological studies, that indicate the existence of a maximum horizontal compression in a NNW–SSE direction together with a perpendicular extension.

If we consider the rates of vertical deformation to be constant in time and if we consider that all the accumulated stress results in big earthquakes ($M \cong 6.0$) with no ductile deformation, an estimate of the minimum return periods for major earthquakes can be made. The return periods, which range between 500 and 1200 years, depending on the zone, should be regarded as new information in the assessment of seismic hazard. These values are in agreement with those deduced from the seismic catalogues of the areas where there is sufficient information.

Keywords: active faults; Eastern Betics; precision levelling data; Recent vertical movements

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1. Introduction

Comparison of precision levelling data measured at different times has been made in diverse areas of the world to quantify recent vertical tectonic deformations. In this study we use the precision levelling data from the Instituto Geográfico Nacional (IGN, Spain) to quantify vertical deformations in order to improve our understanding of the areas in southeastern Spain, where significant tectonic deformation has occurred during the last century.

The area studied, the eastern Betic Cordillera (Fig. 1), which is located in the western part of the Mediterranean sea, was formed during the Alpine orogeny owing to the NNW–SSE continental collision of the African and the Eurasian plates. The Betic chain has been classically divided into External and Internal zones. The External zones (Prebetic and Subbetic domains) are constituted mainly by Mesozoic to Tertiary sediments deposited along the margins of the Iberian plate. The Internal zone is made up of different materials (sedimentary and metamorphic), ranging in age between Palaeozoic and Tertiary, originally deposited at some distance from the Iberian peninsula. During the Alpine orogeny, the Internal zones shifted to the west, colliding with Iberia at the end

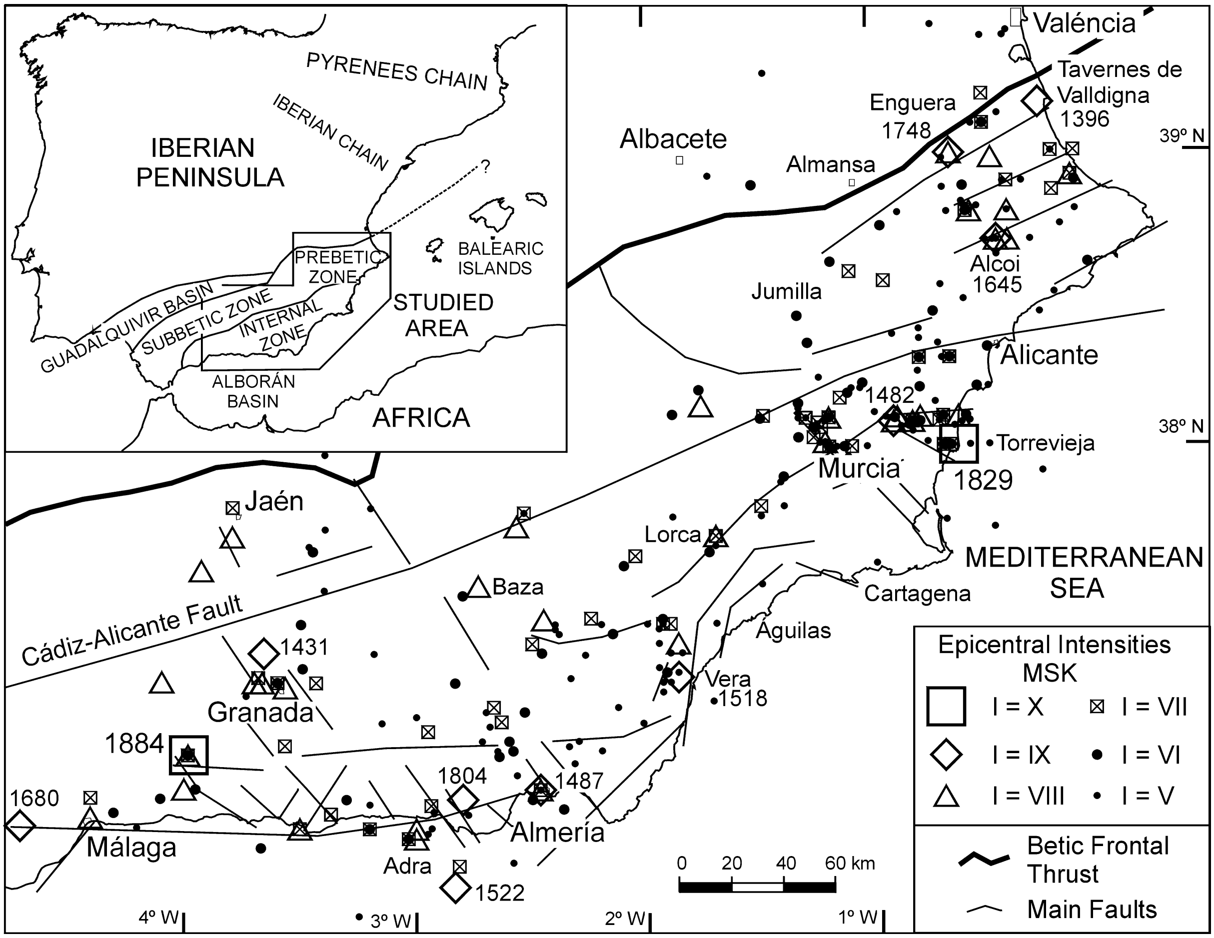

Fig. 1. Location map of the study area and macroseismic earthquake epicentres felt in southeastern Spain since 1396 with an epicentral intensity greater than IV (MSK scale) (Mezcua and Martínez Solares, 1983; Bisbal, 1984; IGN, 1995). The main active faults are also indicated (Boccaletti et al., 1987; Sanz de Galdeano et al., 1995 and others).

of the Middle Miocene. Given this relative right lateral movement between Internal and External zones, strike-slip faults played an important role in the configuration of the Betic orogen (Boccaletti et al., 1987; Larouzière et al., 1988; Sanz de Galdeano, 1990; Meghraoui et al., 1996; Lonergan and White, 1997).

A foreland basin was formed between Iberia and the Betic chain (Guadalquivir Basin), and different basins (piggy-back and intramontane basins), mainly associated with strike-slip and normal faults, were formed during Neogene times (Boccaletti et al., 1987; Sanz de Galdeano and Vera, 1992). At the same time the Alborán basin was developed between Iberia and Africa.

During Late Neogene and Quaternary times the approximately N–S convergence between Iberia and Africa continued. Three main systems of faults have been active during these periods: E–W to ENE–WSW, NE–SW and NW–SE. These faults have undergone different movements according to the orientation of the regional stress field, which has oscillated between NW–SE and N–S since Neogene times (Ott d'Estevou and Montenat, 1985; Boccaletti et al., 1987; Sanz de Galdeano, 1990; Silva et al., 1993; Meghraoui et al., 1996).

At present, the eastern Betics can be regarded as one of the most tectonically active zones in the Iberian Peninsula. It is characterised by a moderate seismicity and has been affected by $I>$ VIII (MSK) earthquakes in historical times (Mezcua and Martínez Solares, 1983; Bisbal, 1984). The macroseismic epicentres with an $I>$ IV are shown in Fig. 1, together with the main active faults (Sanz de Galdeano, 1983, 1990; Buforn et al., 1995; Sanz de Galdeano et al., 1995). In Fig. 1 four areas with high seismic activity can be distinguished: the Enguera–Alcoi–Tavernes de Valldigna zone located in the northeastern corner; the Murcia–Torrevieja zone in the eastern area; the Almería–Adra zone located at the southern edge; and the Granada area in the western part. Other seismogenic zones with a lower concentration of epicentres are the Lorca–Vera area and the Málaga zone. Recently, in 1993–94, two $M \cong 5$ earthquakes took place in Adra (Almería) and in 1999 another $M \cong 5$ earthquake struck the town of Mula (Murcia). Nevertheless, no $M>5.5$ earthquakes have been recorded in this area since the Spanish seismic network was set up (Buforn et al., 1995; Ramírez et al., 1998).

Fig. 1 shows that a good correlation exists between the epicentres and the main faults with Quaternary activity. The analysis of the Spanish seismic catalogue (Mezcua and Martínez Solares, 1983; Bisbal, 1984) shows that the whole zone has been affected by 12 intensity IX earthquakes with an irregular time distribution in the last 600 years: four earthquakes during the 1390–1500 period, two in the 1501–1600 period, two between 1601 and 1700, one between 1701 and 1800, and three earthquakes in the 1801–1900 period. This time distribution indicates that some periods undergo greater seismic activity than others, and that the whole zone has not been affected by destructive earthquakes in the last 100 years, which is the period of our study.

Geological studies demonstrate the presence of recent tectonic activity, which could be related to a NNW–SSE to N–S nearly horizontal compression together with an E–W extension (García Dueñas et al., 1984; Boccaletti et al., 1987; Montenat, 1990; Sanz de Galdeano, 1990; Galindo-Zaldívar et al., 1993; Meghraoui et al., 1996; Lonergan and White, 1997, and others). This stress field is also determined by most of the focal mechanisms of recent earthquakes occurring in this zone (Coca and Buforn, 1994; Buforn et al., 1995; Ramírez et al., 1998; Ministerio de Fomento, IGN, 1999).

This stress field is associated with the present-day convergence between the African and Eurasian plates [of about 0.5 cm/year in this area (Meghraoui et al., 1996)]. A large part of the induced deformation should be concentrated around the major faults of the Betic orogen. ENE–WSW to E–W reverse faults with a strike-slip component of movement are dominant in the External zones (García Dueñas et al., 1984; López Casado et al., 1987). NW–SE and NE–SW strike-slip faults with a vertical component of movement, and E–W reverse faults are important in the Internal zone. NW–SE and NE–SW normal faults with a strike-slip component are the most common faults in the southernmost part of the study area, the Alborán sea (Sanz de Galdeano, 1983, 1990; Boccaletti et al., 1987) (Fig. 1).

The analysis of the vertical movements allows us to determine the faults where a major vertical movement has accumulated within the last century. It should be pointed out that some faults may have an important strike-slip component, which is not observed when comparing the levelling data. For this reason, and in order to control the horizontal movements, a GPS network was set up and measured for the first the time in May 1997 within the zone (Colomina et al., 1998). The analysis of the horizontal displacements to be obtained with new measurements of this network will be useful in assessing the relationship between the horizontal and vertical movements of the main faults of the Eastern Betic orogen.

2. Data acquisition and methodology

The Spanish first order levelling network has been measured twice by the IGN since 1872. The lines levelled between 1872 and 1922 were included in the Spanish Precision Levelling Network, and those levelled between 1925 and today have been incorporated into the Spanish High Precision Levelling Network. All the Spanish lines were independently double levelled and measured with precision values in accordance with the rules of the International Association of Geodesy. Thus, until 1912 the probable kilometric error accepted could not exceed 3 mm/$\sqrt{\text{km}}$, and after the 17th General Conference of the International Association of Geodesy, held in 1912, the random probable kilometric error allowed was 1 mm/$\sqrt{\text{km}}$ and the permitted systematic kilometric error was 0.2 mm/km (Lallemand, 1914). For this reason, the Spanish levelling lines are useful in obtaining recent vertical movements, as has been done with similar data around the world (Brown and Oliver, 1976; Vanicek, et al., 1980; Reilinger and Brown, 1981; Fourniguet, 1987; Hodgkinson et al., 1996).

In this study we analyse all the first order levelling lines of the southeastern part of the Iberian Peninsula, which amount to more than 4000 km (Fig. 2). The vertical movements were obtained by using the differences in height, between the benchmarks, observed along the forward and the backward levelling paths obtained from the original books of the IGN archives. We recalculated the systematic and random kilometric errors of all the levelling lines using the Lallemand (1889) expressions [Eqs. (1) and (2)] because the uncertainty of the levelling measurements was calculated differently in accordance with the year of the survey (Giménez et al., 1996).

According to the Lallemand (1889) expression, the systematic kilometric error σ (mm/km) of a section with length L (km) is:

$$\sigma = \frac{S}{L}, \tag{1}$$

where S (mm) is the systematic part of the accumulated discrepancy along the considered section.

Lallemand's expression for the probable random kilometric error η (mm/$\sqrt{\text{km}}$) of the section of the line of length L is:

$$\eta = \frac{1}{3}\sqrt{\frac{\sum_{i=1}^{N} \frac{\Delta_i^2}{l_i} - \frac{S^2}{L}}{N}}, \tag{2}$$

where Δ_i (mm) are discrepancies, the difference between forward and backward levelling between each benchmark, l_i (km) the distances between benchmarks, and N the number of benchmarks in the section.

The standard deviation (SD) in millimetres of the difference in height between every two benchmarks was obtained with Bomford's (1987) formula:

$$\mathrm{SD} = \sqrt{\eta^2 D + \sigma^2 D^2}, \tag{3}$$

where η and σ are the random and systematic kilometric errors obtained from Lallemand's formulae in Eqs. (1) and (2) respectively and D is the distance between the two benchmarks.

The sections were determined taking into account the possible presence of systematic tendencies in the accumulation of the discrepancies along the line. This was possible because the raw data used provided all the discrepancies and distances

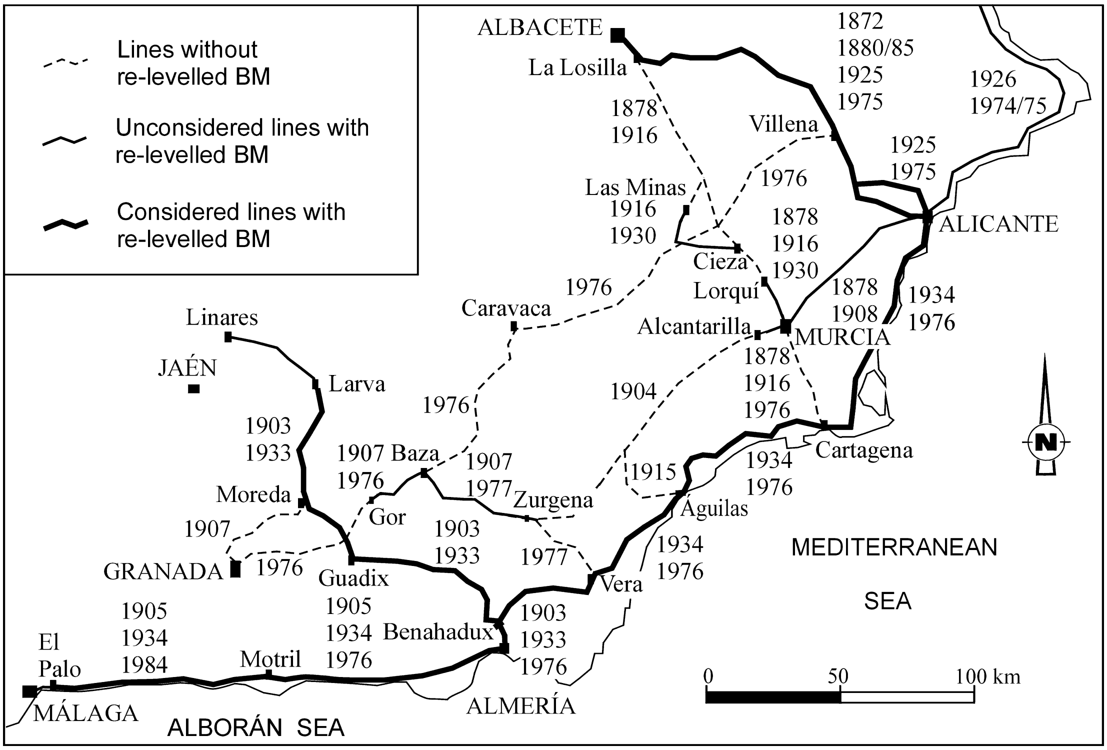

Fig. 2. Studied levelling lines of the southeastern part of the Iberian Peninsula. Dashed lines: levelling lines levelled only once or with no re-levelled benchmarks; thin lines: levelling lines levelled more than once but with an insufficient number of re-levelled benchmarks or with large errors; thick lines: levelling lines that have a sufficient number of re-levelled benchmarks to be interpreted.

between the different benchmarks. Given that each of the different sections with their corresponding systematic kilometric error is considered in a single levelling line, it is possible to separate the sections with high values of systematic kilometric error from the rest. Moreover, as the contribution to the standard deviation of the systematic error increases as a function of D, and the random error as a function of $\sqrt{D}$ [Eq. (3)], the SD obtained between benchmarks with these expressions can be regarded as one of the most pessimistic.

The main characteristics of the lines used to construct the recent vertical movement profiles that will be discussed here, which amount to approximately 2500 km (thick lines, Fig. 2), are shown in Table 1. They are: the origin and end of each line, the year of the levelling survey, the length of the line, the origin and end of the different defined sections of the line and the systematic and random kilometric errors of each of these sections. The largest systematic kilometric error obtained is -1.2 mm/km (first section of the Alicante–Albacete line, 1880/85) but in some sections it is absent, and the random kilometric error ranges between 0.1 and 1.2 mm/$\sqrt{\text{km}}$.

The recent vertical movements were calculated by comparing the differences in height between two common benchmarks obtained in different years and measured along the same path. Of the available 4000 km of levelling lines, 1500 km (thin and dashed lines, Fig. 2) are not discussed here. About 500 km of lines cannot be used to obtain vertical movements because they were only levelled once. Around 1000 km can be used to obtain vertical movements, but the results are not presented in this study for two main reasons: they do not have sufficient linear density of re-levelled benchmarks to interpret the movements satisfactorily; the errors affecting the data are greater than the vertical movements obtained (Giménez, 1998).

Table 1
Main features of the levelling lines studied: origins and ends of the lines, year of the levelling survey, length of the line, origin and end of each section characterised by a systematic accumulation of discrepancies between forward and backward levelling, and systematic and random kilometric errors of each of the defined sections

Levelling line (origin–end)	Survey year	Length (km)	Origin and end of sections (km)	Systematic kilometric error (mm/km)	Random kilometric error (mm/$\sqrt{\text{km}}$)
Alicante–Albacete	1872	172.9	0–29.5	−0.7	0.9
			29.5–172.9	0.8	1.2
Alicante–Albacete	1880/85	192.8	0–69.2	−1.2	0.9
			69.2–99.4	0.8	0.7
			99.4–192.8	−0.8	0.9
Alicante–Albacete	1925	213.1	0–213.1	0.1	0.7
Alicante–Albacete	1975	185.9	0–22.6	0.1	0.1
			22.6–62.3	−0.3	0.4
			62.3–84.4	0.4	0.3
			84.4–185.9	0	0.3
Alicante–Almería	1934	350.9	0–111.2	0.2	0.4
			111.2–244.8	0.3	0.6
			244–350.9	−0.2	0.6
Alicante–Cartagena	1976	121.8	0–49.9	0.3	0.3
			49.9–69.4	−0.3	0.5
			69.4–121.8	0.2	0.3
Cartagena–Vera	1976	138.7	0–138.7	0.2	0.6
Almería–Vera	1976	109	0–109	0.4	0.5
Linares–Almería	1903	179.4	0–179.4	−0.3	0.9
Linares–Almería	1933	181.4	0–73.7	−0.2	0.8
			73.7–181.4	0.4	1.1
Almería–Málaga	1905	221.5	0–68.7	0	1.1
			68.7–221.5	−0.7	1.1
Almería–Málaga	1934	233.7	0–12.5	1	0.5
			12.5–119.2	0	0.7
			119–233.7	−0.4	0.7
Almería–Motril	1976	120.2	0–59.6	0.3	0.4
			59.6–93.3	−0.1	0.4
			93.3–120.2	0.2	0.3

The recent vertical movement profiles were constructed by adding the vertical movements between each two consecutive benchmarks along the line, where the first benchmark is considered to be stable. As we are looking for localised tectonic anomalies between benchmarks, we refer the error bar that affects the movement to the previous benchmark. Referring the error bar to the origin of the line is useful for geodetic purposes, as this provides information on the propagation of the errors along the line, which does not constitute the subject of this study. Thus, in all the profiles discussed the error bars that affect the movement are equal to two SDs in relation to the previous benchmark [two times the quadratic sum of the SD obtained with the Eq. (3), 95% confidence]. The vertical movements obtained between two consecutive benchmarks smaller than the error bars are not considered significant.

Systematic errors constitute a handicap for levelling data collected elsewhere and their exact origin is difficult to establish (Reilinger and Brown, 1981; Bomford, 1987; Craymer et al., 1995). Some authors have used different methods to eliminate or minimise them (Jackson et al., 1981; Reilinger and Brown, 1981; Stein, 1981; Fourniguet, 1987). Stein (1981) proposed a methodology to eliminate systematic errors arising from the topography. In this study, we plot the topographic profile along the line above each recent vertical movement profile. When a statistically significant systematic correlation between the obtained vertical movements (tilt) and topography (topographic slope) was observed along some of the sections of the line, we corrected it by the method proposed by Stein (1981) (Table 2).

The thick lines in Fig. 2 show the profiles under discussion: Alicante–Albacete, Alicante–Almería, Larva (near Jaén)–Almería, and Almería–El Palo (near Málaga). The main characteristics of these profiles (origin and end of the profile, year of the first and second surveys, elapsed time between surveys, length, linear density of re-levelled benchmarks and the values of the Stein correction) are given in Table 2.

The anomalies that can be observed in a recent vertical movement profile can be attributed to tectonic, surficial or anthropic causes. They can be classified in three categories according to the shape of the anomaly: slope changes, spikes (positive or negative) and steps.

The slope changes are generally associated with regional causes, but their origin is difficult to determine, and, in some cases, can be caused by systematic errors related to the trend of the levelling path (Reilinger and Brown, 1981; Fourniguet, 1987). The two main geological processes that can originate a slope change are a differential compaction of recent sediments and a regional tectonic tilt.

The spikes must be regarded as local anomalies, given that they affect a small number of benchmarks. Negative spikes are commonly attributed to surficial causes (extraction of water, unconsolidated sediments, local subsidence of a building, mining, etc.). On the other hand, positive spikes can be related to halokinetc processes. Spikes can also be ascribed to anthropic causes (anthropic displacement of the benchmark) or to mistakes during the levelling survey. Spikes, therefore, are assigned to non-tectonic causes.

The steps are the anomalies that are most clearly related to tectonic causes. They usually occur near an active tectonic structure and can be preceded by positive or negative spikes (Ruegg, 1994; Bezzeghoud et al., 1995; Hodgkinson et al., 1996). Given our interest in the tectonic anomalies, more attention will be devoted to the steps than to any other anomaly.

3. Alicante–Albacete profile

The levelling line starts in Alicante, crosses the Prebetic zone and reaches the Iberian domain as

Table 2
Main characteristics of the recent vertical movement profiles studied: origin and end of the profile, year of the first and second surveys, elapsed time between surveys, length, linear density of re-levelled benchmarks and the Stein (1981) correction (when done)

Recent vertical movements profile (origin–end)	First survey (year)	Second survey (year)	Elapsed time (years)	Length (km)	Linear density (BM/km)	Stein correction (mm/m)	Correlation factor	Affected sections (from–to)
Alicante–Albacete	1872	1880/85	8/13	172	0.74	0.14	0.8	km 25–km 40
Alicante–Albacete	1872	1925	53	192	0.05	none		
Alicante–Albacete	1880/85	1925	40/45	201	0.07	none		
Alicante–La Losilla	1925	1975	50	174	0.1	none		
Alicante–Almería	1934	1976	42	359	0.11	0.18	0.9	km 115–km 250
Larva–Almería	1903	1933	30	176	0.13	−0.42	0.7	km 0–km 70
						0.36	0.8	km 70–km 176
Almería–El Palo	1905	1934	29	219	0.07	none		
Almería–Calahonda	1934	1976	42	106	0.06	none		

far as Albacete (Figs. 1 and 2). It was levelled four times (1872, 1880/85, 1925 and 1975), allowing the construction of four recent vertical movement profiles (Alicante–Albacete, 1872–1880/85, 1872–1925 and 1880/85–1925, and Alicante–La Losilla, 1925–1975) whose main characteristics are shown in Table 2. The sections between Monforte del Cid and Elda of the 1872–1880/85 profile (Fig. 3) were corrected from the systematic errors related to the topography (Table 2). The other profiles do not show any systematic correlation (Giménez, 1998).

The recent vertical movements of the four profiles are shown in Fig. 3, using the average vertical velocities for comparison. The average vertical velocities were obtained by dividing the vertical movements by the time elapsed between the surveys (Table 2). The four profiles have some differences despite showing two common characteristics.

The local negative and positive spikes between Almansa and Albacete, in the Iberian domain, observed in almost all the profiles (Fig. 3), cannot be attributed to a tectonic origin. The shape of the anomalies (spikes), the low seismicity of the area (Fig. 1) (no destructive earthquakes reported or instrumental seismicity monitored) and the fact that the benchmarks are on soft Neogene materials (Giménez, 1998) support this hypothesis.

In all the profiles, a rise of approximately 2 mm/year of the Prebetic zone in the south in relation to the Iberian domain in the north is also observed (A, Fig. 3). This rise occurs in a wide area (Sax–Almansa, Figs. 3 and 4) and cannot be attributed to a single structure. This rise may be ascribed to the recent tectonic activity of the ENE–WSW-oriented faults that affect the Prebetic materials (Jumilla–Valldigna fault zone and other faults) (Fig. 4). In accordance with the present-

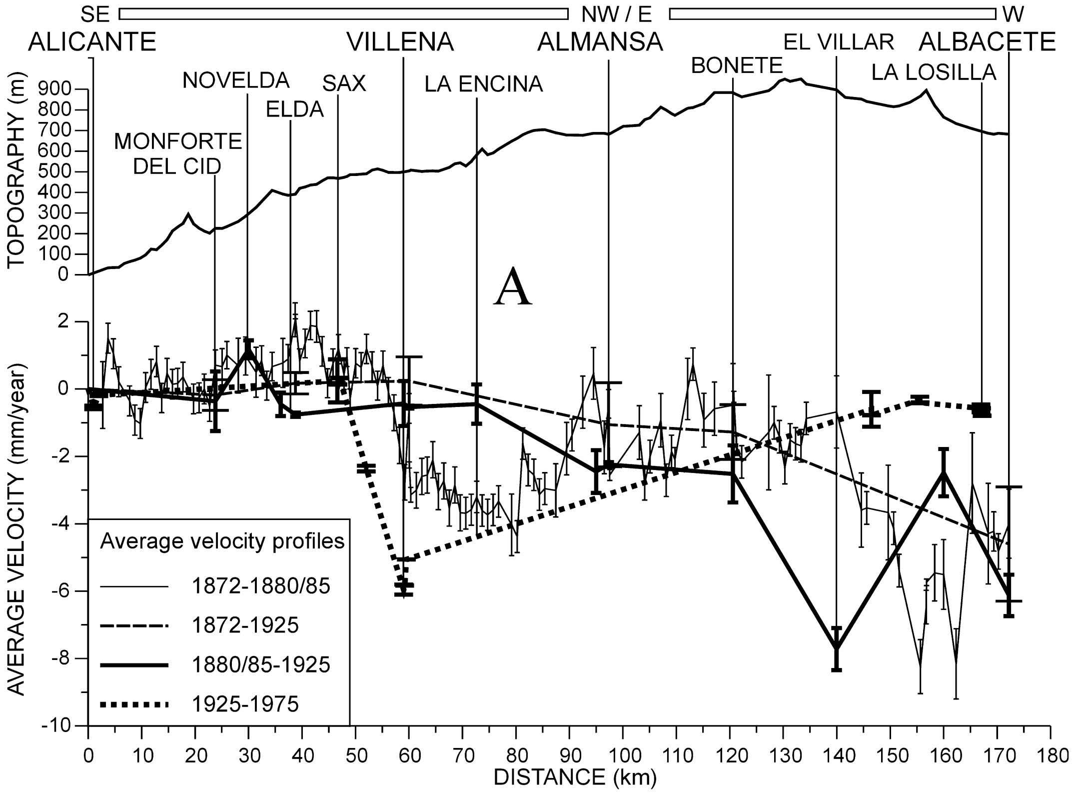

Fig. 3. Average vertical velocities between Alicante and Albacete, with respect to Alicante. Thin line: 1872–1880/85; dashed line: 1872–1925; thick line: 1880/85–1925; thick dotted line (Alicante–La Losilla): 1925–1975. Error bars are equal to two SDs with respect to the previous benchmark. Topography along the line is shown at the top.

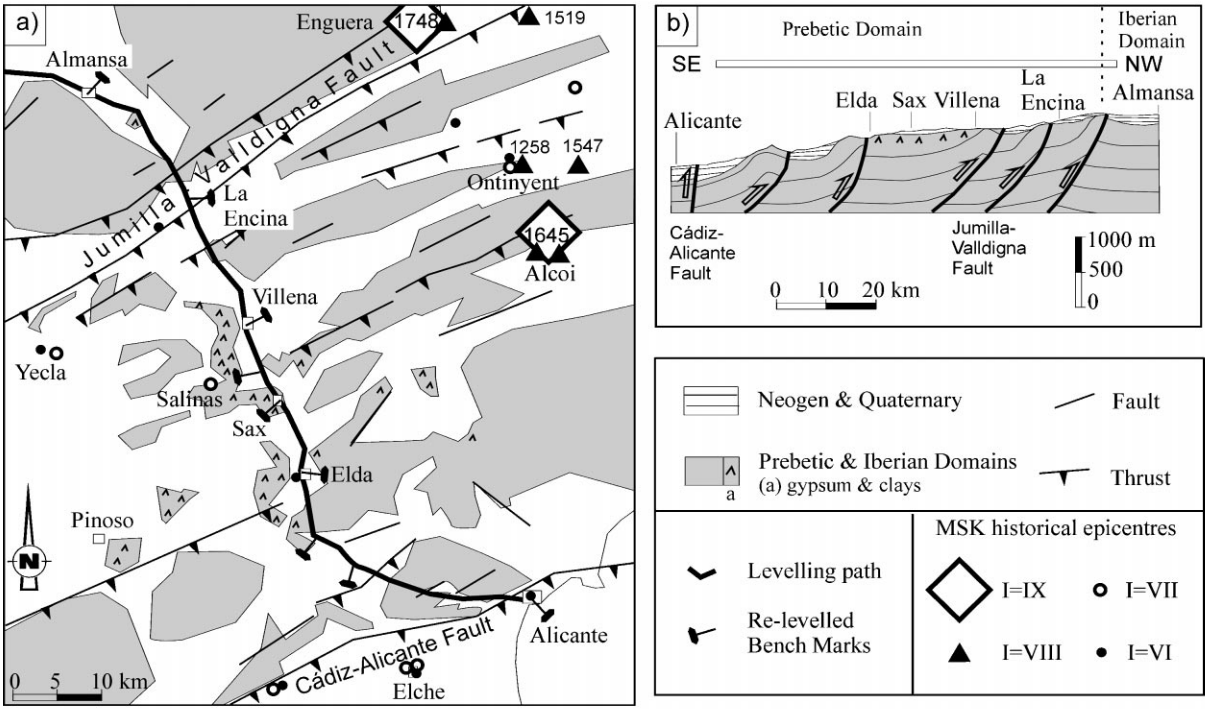

Fig. 4. (a) Geological sketch of the Almansa–Alicante zone showing the location and date of the $I > \mathrm{V}$ macroseismic epicentres together with the levelling line studied and the re-levelled benchmarks used. (b) Simplified cross-section between Alicante and Almansa along the Alicante–Albacete levelling line. (a) and (b) based on López Casado et al. (1987), Sanz de Galdeano et al. (1995) and IGME (1972–1983).

day regional stress field of the Betic Cordilleras these ENE–WSW faults must have inverse movements, which is consistent with the observed rise. Nevertheless, left lateral movements could also be present in these faults (López Casado et al., 1987; Sanz de Galdeano et al., 1995).

In part, we ascribe the subsidence of Villena of about 5 mm/year, in relation to Sax, observed in the 1925–1975 profile (thickest dotted line, Fig. 3) to a non-tectonic origin for a number of reasons. First of all, in the Elda–Sax–Villena area the Triassic gypsum and clays are abundant (Fig. 4), and this kind of material could produce anomalous surface movements. Secondly, the Villena benchmarks compared in the 1925–1975 profile are located on unconsolidated Quaternary sediments, which could undergo movements by accommodation, whereas the Villena benchmarks used in the other three profiles are located on well consolidated Prebetic materials (Giménez, 1998). Nevertheless, some tectonic influences must also be present. These can be related to the recent activity in the ENE–WSW inverse fault located between Sax and Villena that may be associated with the Alcoi earthquake in 1654 (Fig. 4).

The area near the profile was affected by historical seismicity (the $I = \mathrm{IX}$, 1396 Tavernes de Valldigna earthquake; the $I = \mathrm{IX}$, 1645 Alcoi earthquake; and the $I = \mathrm{IX}$, 1748 Enguera earthquake (Mezcua and Martínez Solares, 1983; Bisbal, 1984), which can be associated with the recent activity of the aforementioned reverse-left lateral faults (Figs. 1 and 4) (López Casado et al., 1987; Sanz de Galdeano et al., 1995). Nevertheless, the 1872–1975 period only includes three $I = \mathrm{VII}$ earthquakes in the surrounding area (Yecla in 1896, Salinas in 1916 and Ontinyent in 1945) (Fig. 4). Taking into account the interrelationships between intensities and magnitudes in the Ibero-Mogrebi region (Costa and Oliveira, 1991; López Casado et al., 1995), an $I = \mathrm{VII}$ earthquake corresponds to an $M \cong 5.3$. As the former $I = \mathrm{VII}$ earthquakes took place some kilometres from the profile (Fig. 4), and as an $M \cong 5.3$ corresponds to an approximately 5 km of rupture length with a maximum displacement of 100 mm (Wells and Coppersmith, 1994), these earthquakes cannot account for a coseismic origin of the movements observed between 1872 and 1975. For this reason, the observed rise of the Prebetic zone related to the Iberian Domain may be of interseismic origin; nevertheless, the presence of aseismic creep cannot be disregarded. Further evidence of recent tectonic activity around these faults and additional levelling surveys are necessary to confirm this hypothesis.

4. Alicante–Almería profile

This levelling path, levelled for first time in 1934 and re-levelled in 1976, follows the coast road for over 350 km from Alicante to Almería, and crosses the towns of Cartagena, Águilas and Vera (Fig. 2). Fig. 5 shows the original recent vertical movement profile (thin line) and the one corrected by systematic errors related to the topography (thick line) between Alicante and Almería with respect to Alicante. The Stein (1981) correction was only applied between Cartagena and Vera (Table 2). The main characteristics of this profile are given in Table 2. The profile shows three main anomalies, indicated by capital letters (B, C, and D, Fig. 5).

Anomaly B is a negative spike of the San Javier benchmarks of about 200 ± 20 mm, an average velocity of 4 mm/year. The San Javier benchmarks are located in a Neogene–Quaternary basin controlled mainly by NW–SE normal faults and filled with a large amount of sediments (Somoza et al., 1989; Montenat, 1990; ITGE, 1993). The absence of significant seismic activity in the area (no $I > \mathrm{V}$ earthquakes have been reported, Fig. 1), the shape of the anomaly (localised negative spike) and the presence of unconsolidated Holocene sediments in the San Javier zone lend support to a non-tectonic

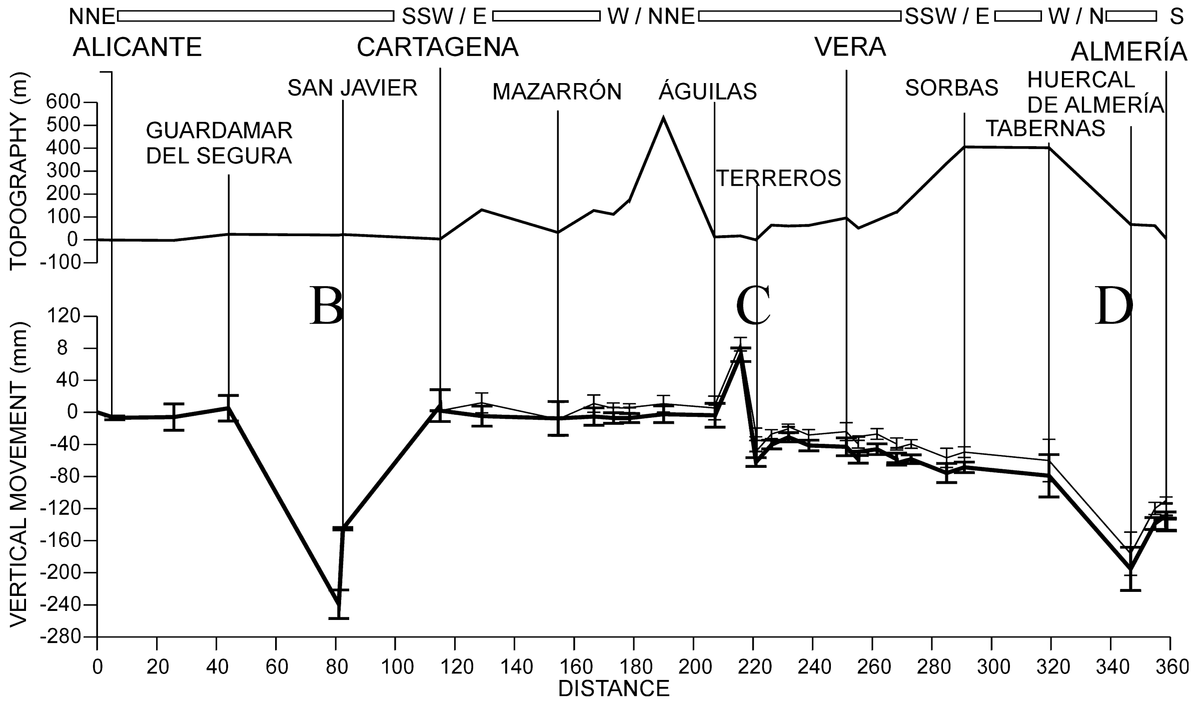

Fig. 5. Recent vertical movement profile between Alicante and Almería, with respect to Alicante, obtained between 1934 and 1976. Thin line: original movements. Thick line: movements corrected with the Stein method. Error bars are equal to two SDs with respect to the previous benchmark. Topography along the line is shown at the top.

origin for this anomaly. Moreover, the small linear density of re-levelled benchmarks between Guardamar del Segura and Cartagena (Fig. 5) makes the interpretation of this anomaly uncertain.

Anomaly C, a negative step between Águilas and Terreros of about 40 ± 8 mm (0.9 mm/year of average vertical velocity), preceded by an anomalous positive spike of 90 ± 10 mm, divides the whole profile into two parts. The northern section (Alicante–Águilas) is characterised by an absence of tilt and the southern one (Terreros–Tabernas) has a negative tilt of -0.5 mm/km (Fig. 5). The origin of this negative tilt between Terreros and Tabernas is uncertain, but it could be attributed to systematic errors.

Two different structures in the area could account for the Águilas–Terreros anomaly. One possible explanation for the positive spike preceding the negative step is that the anomaly is associated with the recent activity of the E–W reverse faults in the area (Fig. 6). This hypothesis is supported by the results of the modelling of vertical movements in reverse faults that demonstrate the presence of positive spikes in the hanging wall (Ruegg, 1994; Bezzeghoud et al., 1995). Nevertheless, anomaly C could also be associated with the NNE–SSW Cocón–Terreros fault zone, the most significant structure in this area (Fig. 6). Geological studies demonstrate that the Cocón–Terreros fault has been moving in Neogene and Quaternary times mainly as a left-lateral strike-slip fault, although vertical movements in this fault zone are also present (Goy and Zazo, 1986; Coppier et al., 1989, 1990; Griveaud et al., 1990; Silva et al., 1993).

A coeval oblique movement (left lateral plus normal) in the Cocón–Terreros fault, together with a reverse movement in the E–W-trending faults (Fig. 6), could account for the C anomaly. This coeval movement is in accordance with the regional stress field of the Betic Cordillera (NNW–SSE compression together with a perpendicular extension).

Although anomaly C seems to be attributed to

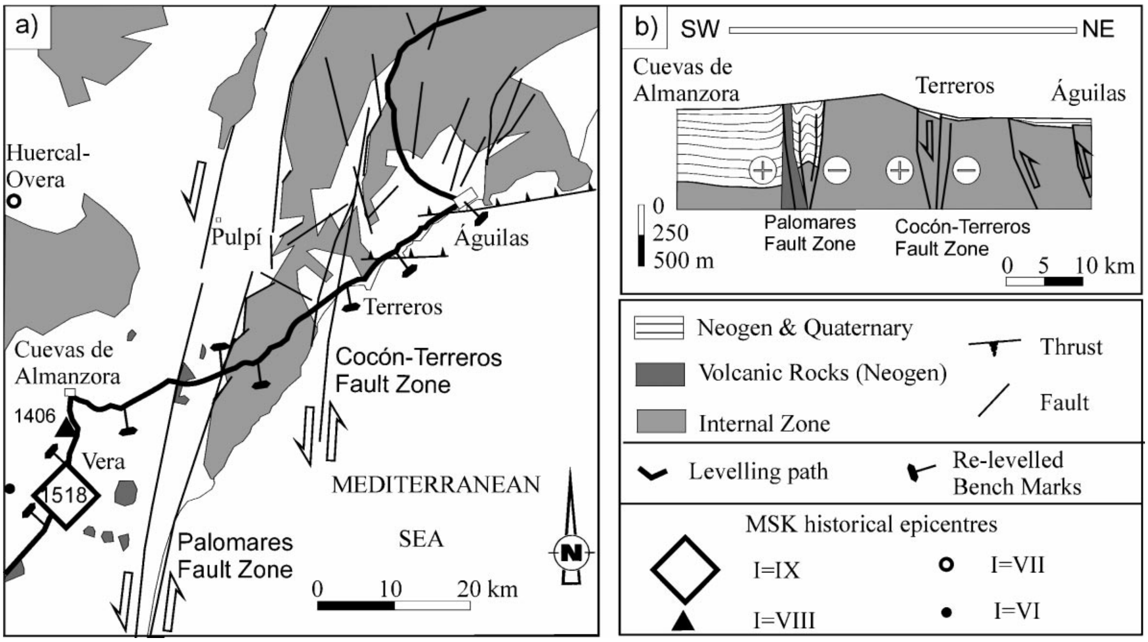

Fig. 6. (a) Geological sketch of the Águilas–Vera zone showing the location of the $I > \mathrm{V}$ macroseismic epicentres together with the levelling line studied and the re-levelled benchmarks used. (b) Simplified cross-section between Águilas and Cuevas de Almanzora along the Alicante–Almería levelling line. (a) and (b) based on Montenat (1990), Sanz de Galdeano et al. (1995) and IGME (1972–1983).

a tectonic origin, as it took place above one of the most important structures in the area, no relevant seismicity has been reported in its proximity in the last century or in historical times (Figs. 1 and 6) (Mezcua and Martínez Solares, 1983). This seismic quiescence of the Cocón–Terreros fault zone contrasts with the recent activity attributed to the Palomares fault zone, which runs parallel to this fault (Fig. 6). The 1518 intensity IX earthquake, which destroyed the town of Vera, and other earthquakes felt in the area (Mezcua and Martínez Solares, 1983) (Figs. 1 and 6) are attributed to the Palomares fault zone. A possible explanation for the absence of historical seismicity reported in the Cocón–Terreros fault, a semi-desert area, is that the seismicity of this fault zone has been associated with the Palomares fault zone (destruction of the town of Vera in 1518, Fig. 6), resulting in a shift of the reported seismicity from the Cocón–Terreros fault zone to the Palomares zone.

Another result obtained from this profile is that vertical movements near the Palomares fault zone are practically insignificant (Figs. 5 and 6). This result is consistent with the fact that this fault has undergone an important left lateral strike-slip movement in Neogene and Quaternary times (Bousquet, 1979; Sanz de Galdeano, 1983, 1990; Weijermars, 1987; Montenat, 1990; Silva et al., 1993). Nevertheless, owing to the presence of 500 m of Neogene sediments in the Vera Basin (Fig. 6), the presence of recent vertical movements on this fault was expected.

Anomaly D is a sinking of the Huercal de Almería benchmark (110 ± 10 mm, 4 mm/year) and the Almería city benchmarks (55 ± 15 mm, 1.5 mm/year) with respect to the Tabernas benchmark (Fig. 5). We regard this anomaly as a tectonic sinking of the Almería Basin in relation to Tabernas of approximately 1.5 mm/year. The negative spike of the Huercal de Almería benchmark could, in part, be due to a non-tectonic origin, since this benchmark is on unconsolidated Quaternary river terraces (Sanz de Galdeano, 1996) that could have undergone recent compactions.

The tectonic subsidence of the Almería basin should be associated with the recent activity of the NW–SE normal faults that affect the Quaternary sediments of this basin (Montenat, 1990; Sanz de Galdeano, 1996). These faults account for the moderate seismicity that characterises the Almería basin, which is distributed in an almost NW–SE direction (Fig. 1). Destructive earthquakes, such as the 1487 intensity IX earthquake that destroyed the town of Almería, have also been reported in this basin (Mezcua and Martínez Solares, 1983).

Unfortunately, the use of tide gauge data to confirm the relative subsidence of Almería in relation to Alicante and Cartagena within the study period is not possible. In fact, the only reliable tide gauge data are those from Alicante harbour, whose data are uninterrupted obtained from 1871 to the present day. On the other hand, the Cartagena and Almería tide gauges were set up in 1977 (Acinas, 1993). Thus, it is not possible to adjust the vertical movements along the coast with the tide gauge data and, therefore, to confirm the subsidence of Almería in relation to Cartagena within the 1934–1976 period.

It should be pointed out that the profile under consideration does not show any anomaly in the Guardamar del Segura–Torrevieja zone (Fig. 5). The absence of vertical movements in this zone was unexpected, given that this is one of the most seismically active areas in southeastern Iberia. Between Murcia and Torrevieja several $I >$ VIII earthquakes have been felt (Fig. 1). The most destructive of these earthquakes occurred in Torrevieja in 1829, achieving an $I =$ X (Muñoz and Udías, 1991). Moreover, the geological studies of this zone provide strong evidence of recent tectonic activity mainly related to E–W reverse faults and NW–SE oblique faults (Boccaletti et al., 1987; Goy and Zazo, 1989; Somoza et al., 1989; ITGE, 1993; Taboada et al., 1993; Alfaro, 1995). A possible explanation for the absence of detected vertical movements in the Guardamar del Segura–Torrevieja zone is the lack of re-levelled benchmarks in this area.

5. Larva–Almería profile

The levelling line runs along the railway line between Linares and Almería and was levelled in 1903 and in 1933 (Fig. 2). Fig. 7 shows the original recent vertical movement profile (thin line) and

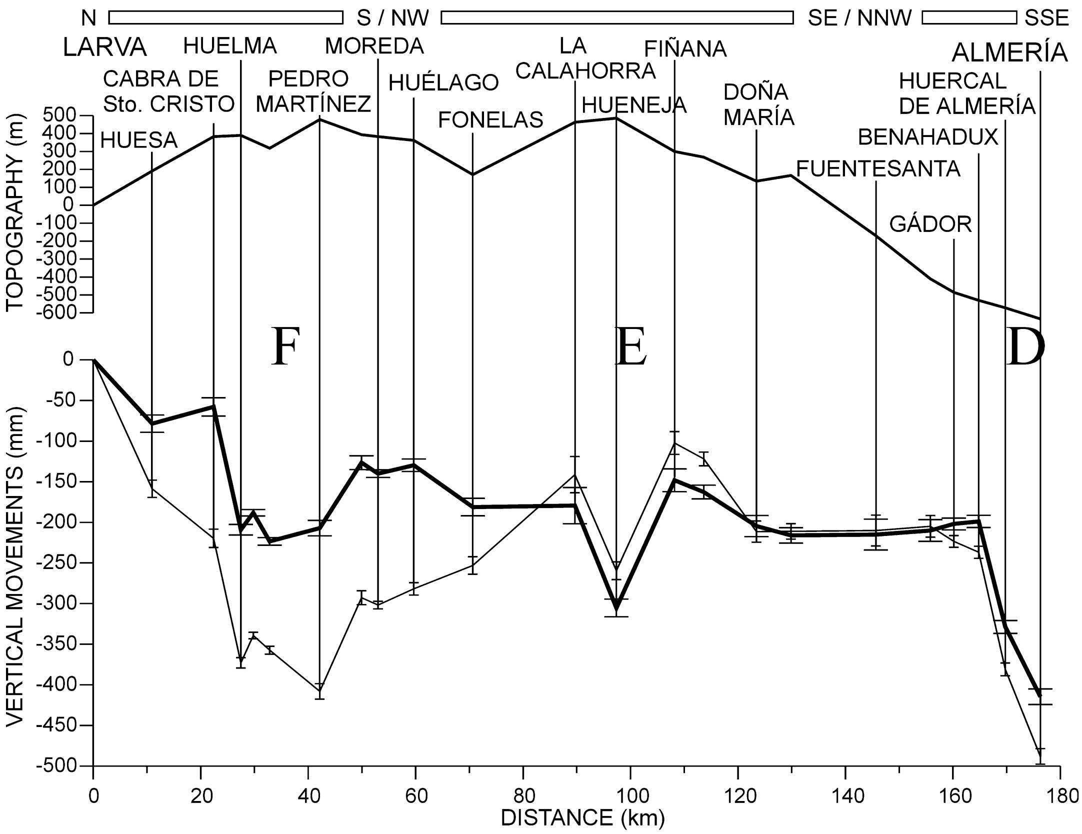

Fig. 7. Recent vertical movement profile between Larva (near Jaén) and Almería, with respect to Larva, obtained between 1903 and 1933. Thin line: original movements. Thick line: movements corrected with the Stein method. Error bars are equal to two SDs with respect to the previous benchmark. Topography along the line is shown at the top.

the profile corrected by the systematic errors related to the topography (thick line) between Larva (near Jaén) and Almería. Three main anomalies indicated by capital letters in Fig. 7 (from south to north D, E and F) are present in both profiles. The main characteristics of these profiles are given in Table 2.

It should be pointed out that there is a considerable difference between the corrected vertical movements of this profile (thick line, Fig. 7) and the original ones (thin line, Fig. 7). Nevertheless, the main anomalies (steps), which could be attributed to a tectonic origin, diminish after correction. The difference between the profiles is due to the high values of the Stein correction (Table 2) and to the fact that the levelling path has a high topographic slope (Fig. 7).

Anomaly E, a negative spike of about -150 ± 15 mm, which affects the Hueneja benchmark (E, Fig. 7), should be associated with non-tectonic movements owing to its morphology, the absence of significant seismicity in the area (Fig. 1), and the fact that the Hueneja benchmark is located on soft and young sediments that can undergo considerable compaction. The small linear density of re-levelled benchmarks in this section of the profile does not permit a more accurate interpretation of this subsidence.

The southern anomaly (D, Fig. 7) is a large subsidence of the Almería basin benchmarks (Huercal de Almería and Almería) of -200 ± 15 mm, with respect to Benahadux. This anomaly coincides with anomaly D of the Alicante–Almería profile discussed above (Fig. 5).

As in the case of this profile, we attribute a large part of this anomalous subsidence to surficial movements. The absence of $I>$VI earthquakes between 1903 and 1976 (Mezcua and Martínez Solares, 1983) supports this hypothesis. Given the difficulty in evaluating these surficial movements, we assume a value of 1.5 mm/year for the tectonic subsidence of the town of Almería not influenced by shallow processes. This value is the same as the one obtained for the sinking of the Almería benchmark in relation to the Tabernas one (Fig. 5).

We attribute the tectonic subsidence to the recent activity of the NW–SE normal faults that characterises this zone (Fig. 8). The activity of these NW–SE normal faults during the Quaternary is evident since these faults cut the recent fluvial sediments of the Almería basin (Sanz de Galdeano, 1996). In historical times, this zone was affected by $I>$VII earthquakes, such as the 1487 intensity IX earthquake that destroyed the town of Almería (Figs. 1 and 8). Nevertheless, within the period of study (1903–1976), the area has only been affected by four $I=$VI earthquakes. Three were felt between 1913 and 1926, and the other in 1950 (Mezcua and Martínez Solares, 1983).

The E–W reverse faults in the surrounding areas of this anomaly (Fig. 8) could also account for the rise of the northern Almería Basin and Tabernas zone in relation to the southern Almería basin. As already stated for the C anomaly, a coeval movement of these two kinds of structure is possible and consistent with the present-day regional stress tensor (compression in a NNW–SSE direction and perpendicular extension). In fact, the focal mechanism of the last significant earthquake, which took place in 1984 at the Sierra Alhamilla (Fig. 8) with an $M\cong 5.0$, can be associated with a WNW–ESE-oriented thrust with some right lateral component of movement (Buforn et al., 1995). Nevertheless, a NW–SE linear distribution of the historical epi-

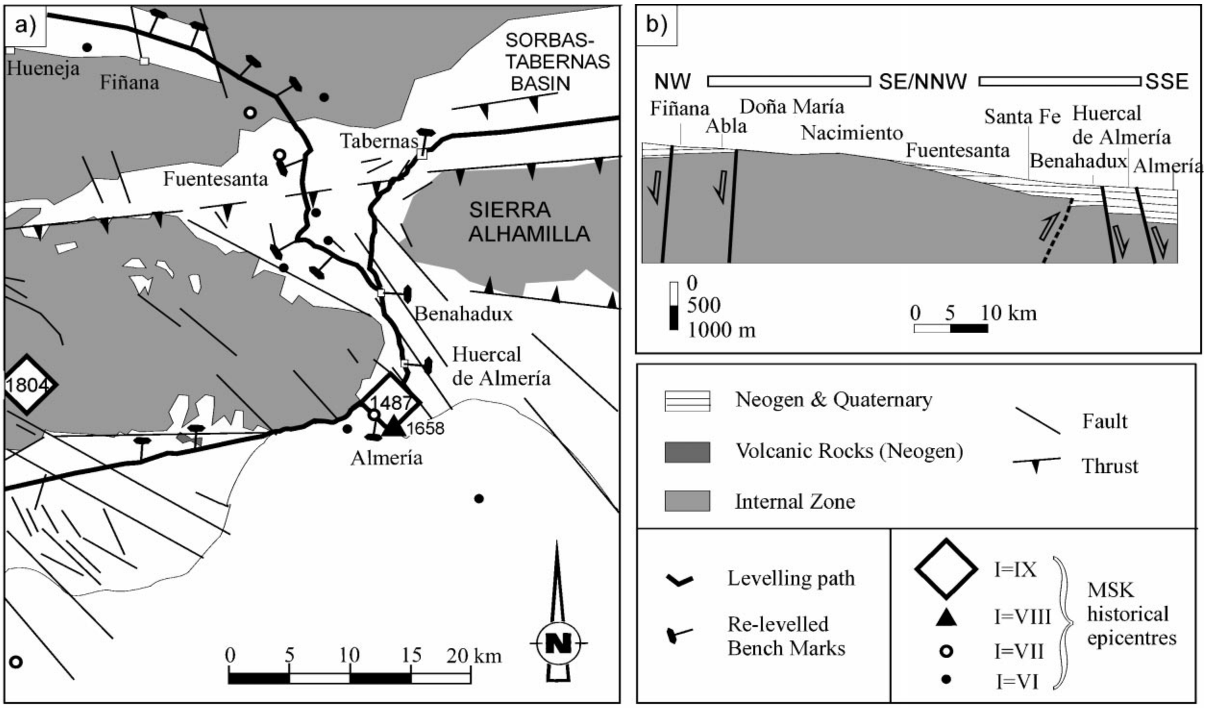

Fig. 8. (a) Geological sketch of the Tabernas and Almería basins showing the location of the $I>$V macroseismic epicentres and the levelling lines studied. (b) Simplified cross-section between Fiñana and Almería benchmarks along the Larva–Almería levelling line. (a) and (b) based on Montenat (1990), Sanz de Galdeano (1990) and IGME (1972–1983).

centres (Fig. 1) highlights the importance of the NW–SE faults in this area.

In the northern part of the profile we observe a sinking of the Huelma–Pedro Martínez block of -150 ± 10 mm in relation to Cabra de Santo Cristo in the north, and a sinking of -70 ± 10 mm in relation to Moreda in the south (F, Fig. 7). These high vertical movements contrast with the low seismicity of the area, given that no destructive earthquakes have been reported (Figs. 1 and 9). Given this low seismicity, we must attribute a considerable part of these movements to non-tectonic processes. Nevertheless, a part of these anomalies must be of tectonic origin since they coincide with two of the most important faults crossing the profile. Unfortunately, the available data do not allow us to determine how much of the deformation is due to tectonic processes and how much is due to surface processes.

We relate the southern step to the Cádiz–Alicante fault zone, oriented in a ENE–WSW direction, and the northern step to the Guadahortuna fault (Figs. 7 and 9), which runs some kilometres further north of the Cádiz–Alicante fault zone with the same orientation (Estévez and Sanz de Galdeano, 1983; Sanz de Galdeano, 1983, 1990; Sanz de Galdeano et al., 1995). These steps are compatible with a reverse component of movement of these faults, which is also compatible with the regional stress field. This is also consistent with the focal mechanisms of earthquakes associated with the Cádiz–Alicante fault (Buforn and Udías, 1991; Carreño et al., 1991; Buforn et al., 1995; Ramírez et al., 1998), located at some distance from this zone, e.g. the recent $M \cong 5$ earthquake in Mula in 1999, which can be associated with an inverse movement on the Cádiz–Alicante fault (Ministerio de Fomento, IGN, 1999; IGN, personal communication).

6. Almería–El Palo (Málaga) profile

The levelling line runs along the coastal road between Almería and Málaga, and was levelled

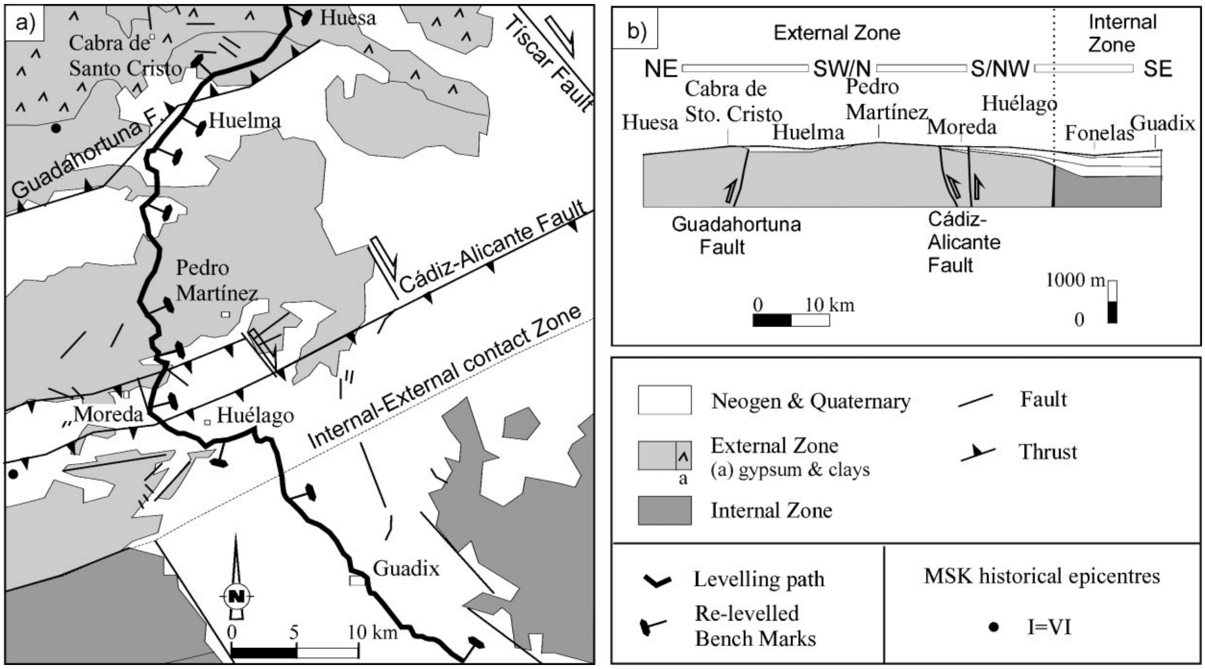

Fig. 9. (a) Geological sketch of the Huesa–Guadix zone showing the location of the levelling line studied. (b) Simplified cross-section between Huesa and Guadix along the Larva–Almería levelling line. (a) and (b) based on Boccaletti et al. (1987), Sanz de Galdeano (1990) and IGME (1972–1983).

three times (1905, 1934 and 1976/84) (Fig. 2). The two vertical movement profiles Almería–El Palo (near Málaga) (1905–1934) and Almería–Calahonda (1934–1976), expressed as average vertical velocities, are presented in Fig. 10. The principal characteristics of these profiles are shown in Table 2.

The main feature of the Almería–El Palo (1905–1934) profile (thick line, Fig. 10) is the regional sinking of its central part, the Adra–Salobreña block, in relation to the Almería and the Almuñécar benchmarks (G, Fig. 10). Four different steps can be considered in this wide anomaly: a negative step of -30 ± 20 mm from Almería to Adra; a negative step of about -70 ± 40 mm from Adra to La Rábita; a positive step of 50 ± 25 mm from Calahonda to Salobreña; and a positive step of 50 ± 22 mm from Salobreña to Almuñécar. An interpretation of this anomaly is the sinking of two different blocks: a large block between Adra and Salobreña, sinking 1 mm/year in relation to Almería and Almuñécar, and an inner block, between La Rábita and Calahonda, which sinks 2 mm/year in relation to Adra and Salobreña (Figs. 10 and 11).

Anomaly G is not observed in the most recent Almería–Calahonda (1934–1976) profile (thin line, Fig. 10). Nevertheless, if we compare the 1905 levelling line with the 1976 line we obtain a sinking of 100 mm of the Calahonda benchmark in relation to the Almería benchmark, which is equivalent to an average velocity of 1.4 mm/year. This 1905–1976 vertical velocity between Almería and Calahonda is more reliable than the 1905–1934 or the 1934–1976 velocities, since the longer the time between the surveys the more representative the velocities obtained.

We relate these vertical movements to the recent activity of the NW–SE and NE–SW normal faults in this zone of the Alborán coast (Fig. 11) (Sanz de Galdeano, 1983, 1990; Martínez Díaz and Hernández Enrile, 1997). Uplifted marine terraces and young sediments affected by this system of faults provide evidence of its activity (Goy and

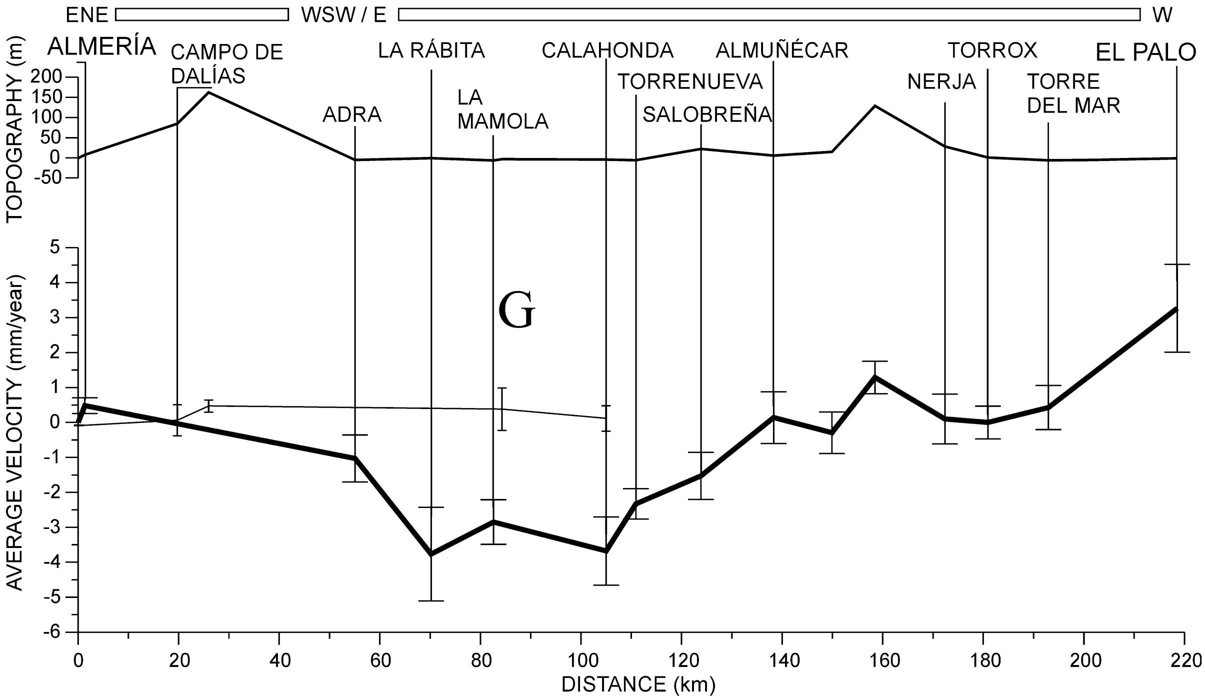

Fig. 10. Average vertical velocities between Almería and El Palo with respect to Almería. Thick line: 1905–1934 average velocities; thin line: 1934–1976 average velocities. Error bars are equal to two SDs with respect to the previous benchmark. Topography along the line is shown at the top.

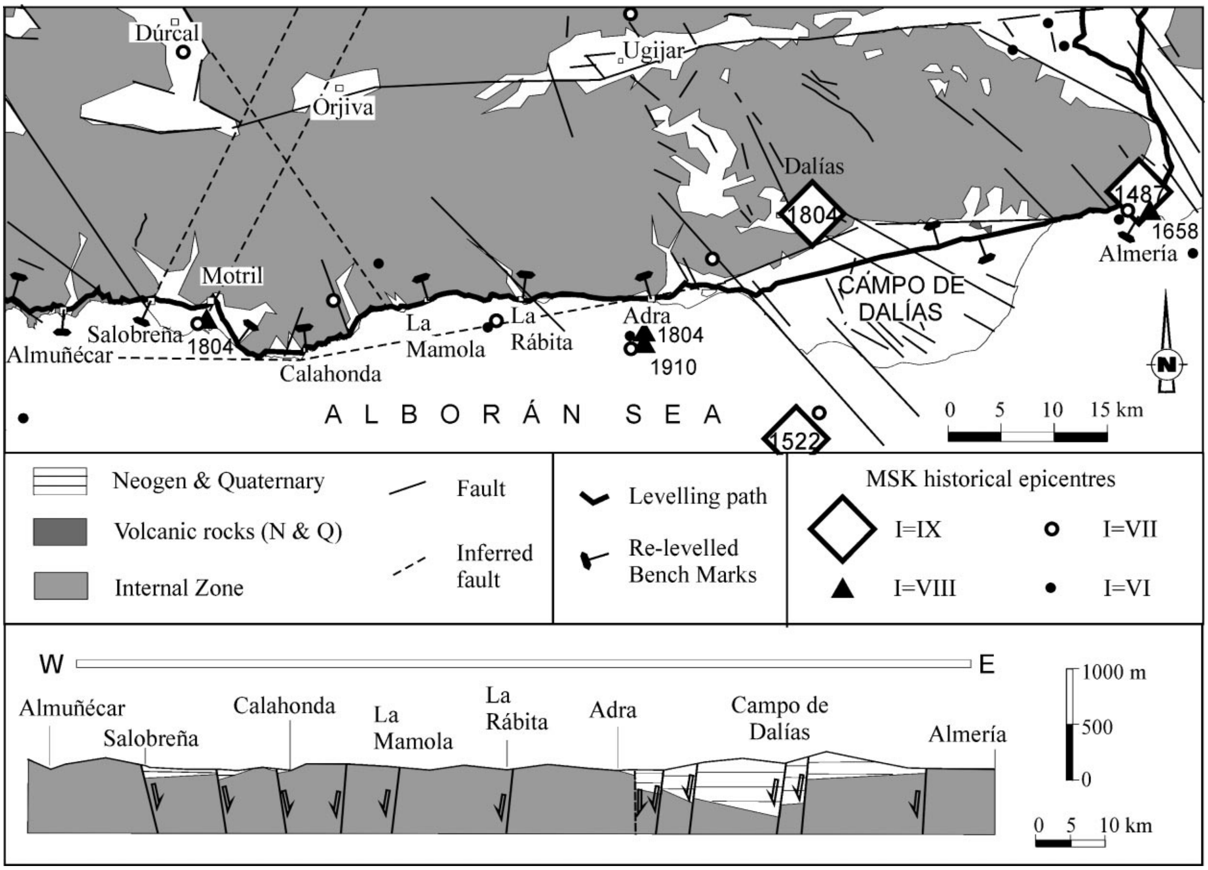

Fig. 11. (a) Geological sketch of the Almuñécar–Almería zone showing the location of the $I>\mathrm{V}$ macroseismic epicentres and the levelling line studied. (b) Simplified cross-section between Almuñécar and Almería along the Almería–Málaga levelling line. (a) and (b) based on Boccaletti et al. (1987), Sanz de Galdeano (1990) and IGME (1972–1983).

Zazo, 1986; Rodríguez-Fernández and Martín-Penela, 1993; Martínez Díaz and Hernández Enrile, 1997). This fault system may account for the destructive earthquakes of the area [two $I=$ IX earthquakes in historical times: one in 1522 located offshore and the other in 1804, at Dalías; Figs. 1 and 11 (Buforn and Udías, 1991; Buforn et al., 1995; IGN, 1995; Rueda et al., 1995)]. The last seismic crisis of this area occurred in 1993–94 with two $M\cong 5.0$ ($I=\mathrm{VII}$) earthquakes, followed by a sequence of aftershocks. These earthquakes can be related to the NW–SE fault located between Adra and the Campo de Dalías (Fig. 11), since their focal mechanisms indicate a normal right-lateral movement along the fault and the distribution of the aftershocks clearly defines the orientation of the fault plane (Rueda et al., 1995; Martínez Díaz and Hernández Enrile, 1997).

The absence of vertical movements between 1934 and 1976 is consistent with the absence of seismic activity in this period, which contrasts with the relatively high activity between 1905 and 1934. Thus, whereas an $I=\mathrm{VIII}$ earthquake affected the town of Adra in 1910, and three $I=\mathrm{VII}$ earthquakes (one in the sea opposite La Rábita in 1913, and two aftershocks of the 1910 Adra earthquake), and five $I=\mathrm{VI}$ earthquakes were felt along the Almuñécar–Adra zone between 1910 and 1922 (Figs. 1 and 11), no $I>\mathrm{V}$ earthquakes were reported in this zone between 1934 and 1976 (Mezcua and Martínez Solares, 1983; Giménez, 1998).

The sinking of La Rábita in relation to Adra in the 1905–1934 profile (Fig. 10) could have been caused by a coseismic movement of the $I=\mathrm{VIII}$ 1910 earthquake and its aftershocks. Indeed, given the interrelationships between intensities and magnitudes in the Ibero-Mogrebi region (Costa and Oliveira, 1991), an $I=\mathrm{VIII}$ earthquake may achieve an $M\cong 5.8$, and an $I=\mathrm{VII}$ earthquake could achieve an $M\cong 5.3$. If we consider the empirical relationships between magnitude and average surface displacement (Wells and Coppersmith, 1994), the $M\cong 5.8$ earthquake may attain a surface displacement of between 50 and 100 mm.

The vertical movements between Almuñécar and Calahonda (Fig. 10) may also have been caused by the seismic activity that occurred between 1910 and 1922. Surficial processes could have influenced the sinking of the Calahonda–Salobreña benchmarks in relation to those of Almuñécar, given that their location is on Plio-Quaternary sediments, which may have undergone recent compaction. In contrast, the Almuñécar benchmark is on well consolidated Betic materials (Fig. 11).

Unfortunately, as in the Alicante–Almería profile, the use of tide gauge data to confirm the subsidence along the Alborán coast within the study period is not possible. In this case, the Almería tide gauge was set up in 1977 and the Málaga one (set up in 1942) has never been referred to a benchmark (Acinas, 1993). For this reason, it is not possible to confirm the subsidence of the Alborán coast benchmarks within the 1905–1976 period using the tide gauge data.

7. Conclusions

The comparison of the available IGN levelling lines measured since 1872 indicates the existence of significant vertical movements mainly located on tectonic structures showing neotectonic activity features and seismicity (Mezcua and Martínez Solares, 1983; Sanz de Galdeano, 1983, 1990; López Casado et al., 1987; Sanz de Galdeano et al., 1995; Giménez, 1998).

Some of the vertical movements obtained have been related to surface processes (compaction of young sediments or considerable water extractions). The spikes located between Almansa and Albacete (Fig. 3), and the anomalies B (Fig. 5) and E (Fig. 7) should be ascribed to a non-tectonic origin. We base our hypothesis on the absence of seismicity, the nature of the sediments making up the benchmarks' substrata, and on the shapes of the anomalies. Unfortunately, in the absence of data on water withdrawal it is not possible to attribute the subsidence to an increase in water exploitation. But, in the course of the last century, human activity in the area studied has grown, which implies a greater exploitation of subsurface water, especially in a semi-arid region such as southeast Spain.

The main vertical movements, attributed to a tectonic origin, are indicated in a geological sketch of the eastern Betics in Fig. 12. From north to south and from east to west they are: 2 mm/year (anomaly A) related to the ENE–WSW Jumilla–Valldigna fault system (Prebetic zone); 0.9 mm/year (anomaly C) associated with the NNE–SSW Cocón–Terreros fault and to E–W reverse faults (Internal zone); 1.5 mm/year (anomaly D) related to the NW–SE faults of the Almería basin and to E–W reverse faults (Internal zone); and 1.4 mm/year (anomaly G) associated with the NE–SW and NW–SE faults system of the Alborán coast zone (Internal zone) (Fig. 12). We estimate a value of 1 mm/year (anomaly F) for the vertical movement of tectonic origin associated with the ENE–WSW Cádiz–Alicante and Guadahortuna faults (Subbetic zone).

The spatial distribution of these tectonic movements indicates that the anomalies in the External zone (Prebetic and Subbetic domains) are related to the ENE–WSW faults (Cádiz–Alicante, Guadahortuna and Jumilla–Valldigna faults) (Fig. 12). Moreover, the anomalies located in the Internal zone may be associated with the NE–SW- and NW–SE-oriented faults (Almería basin and Alborán coast faults) and approximately N–S faults (Cocón–Terreros fault), which, in some cases, could undergo a coeval movement with approximately E–W faults (Fig. 12).

The present-day Betic stress tensor, determined with different methodologies (microstructural data, geological studies and earthquake focal mecha-

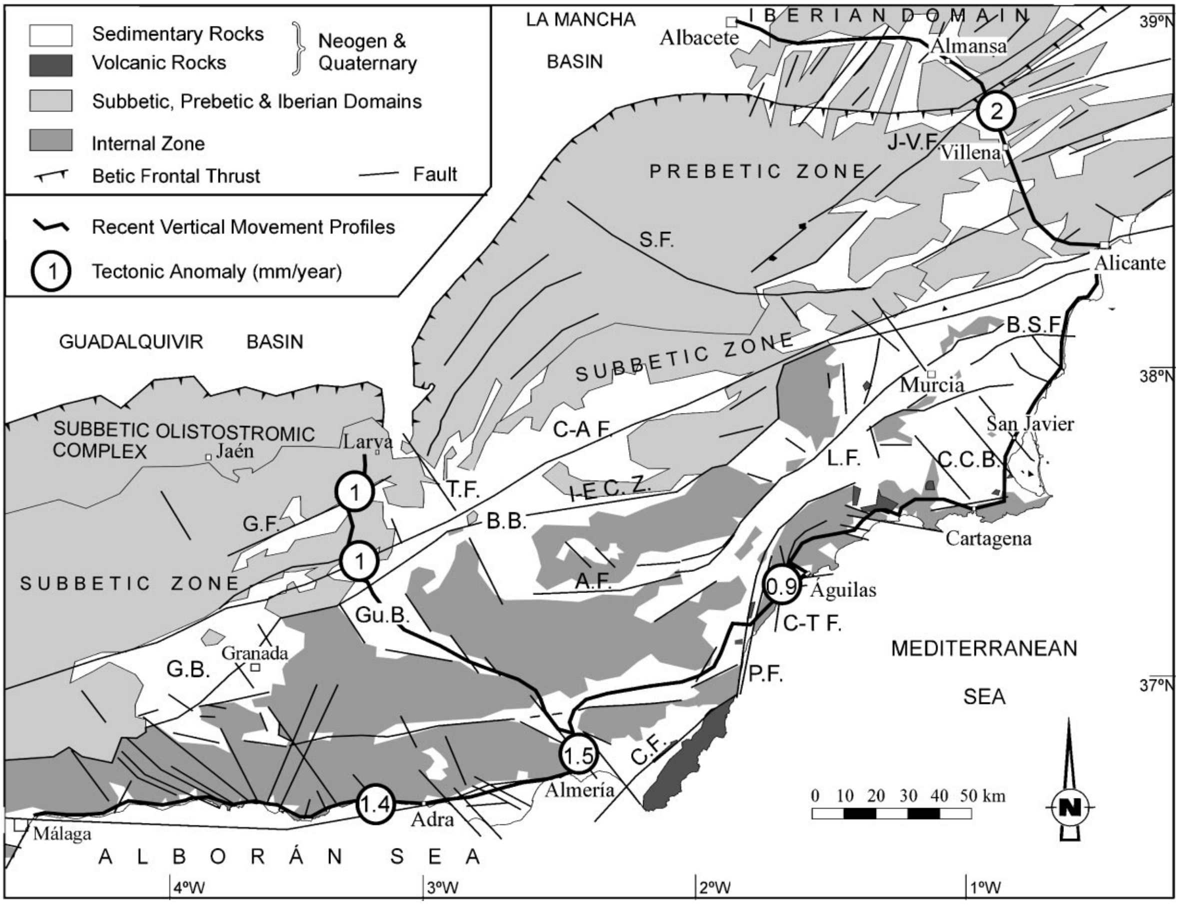

Fig. 12. Geological sketch of the southeastern Iberian Peninsula [based on Boccaletti et al. (1987), López Casado et al. (1987), Montenat (1990), Sanz de Galdeano (1990) and IGME (1972–1983)], with the tectonic vertical anomalies obtained in millimetres per year. B.B.: Baza Basin; C.C.B.: Campo de Cartagena Basin; G.B.: Granada Basin; Gu.B.: Guadix Basin; A.F.: Almanzora Fault; B.S.F.: Bajo Segura Fault; C–A F.: Cádiz–Alicante Fault; C–T F.: Cocón–Terreros Fault; C.F.: Carboneras Fault; G.F.: Guadahortuna Fault; J–V F.: Jumilla–Valldigna Fault; L.F.: Lorca Fault; S.F.: Socovos Fault; T.F.: Tíscar Fault; I–E C. Z.: Internal–External Contact Zone.

nisms) (Boccaletti et al., 1987; Sanz de Galdeano, 1990; Galindo-Zaldívar et al., 1993; Buforn et al., 1995; Ramírez et al., 1998), shows the existence of an approximately NNW–SSE compression together with an ENE–WSW extension. According to this stress tensor, the E–W to ENE–WSW faults must have an approximately pure inverse movement, and the NE–SW, NW–SE and N–S faults must move as strike-slip faults or as normal faults with a strike-slip movement, which are our proposed vertical movements.

On the assumption that these observed rates of vertical deformation are constant in time, and assuming that all the accumulated stress results in large earthquakes, with no ductile deformation, a preliminary estimate of the minimum recurrence periods for destructive earthquakes ($M > 6.0$) could be given, bearing in mind that 1 m of displacement corresponds to an $M \cong 6.5$ earthquake (Wells and Coppersmith, 1994).

For anomaly A (2 mm/year), between Sax and Almansa, the return period obtained is 500 years and this value is in agreement with the return period deduced from the information of the seismic catalogue. For anomaly C (0.9 mm/year), related to the Cocón–Terreros fault zone, the minimum return period is about 1200 years. For anomaly D (1.5 mm/year), in the town of Almería, and for anomaly G (1.4 mm/year) on the Alborán coast, the return period is about 700 years. The return periods over 600 years cannot be confirmed since they exceed the period of time for which the historical seismic catalogue is considered reliable (Mezcua and Martínez Solares, 1983; Bisbal, 1984; Giménez, 1998).

The return periods ranging between 500 and 1200 years should be regarded as additional information in the assessment of seismic hazard, given that no quantification of recent deformations has been made in the zone to date. Nevertheless, it should be borne in mind that the return periods obtained could be smaller than those proposed here since the seismogenic faults of the Betic orogen have a strike-slip component (oblique faults), which, in some cases, could be greater than the vertical component obtained in our study.

Some of the values of the vertical anomalies obtained in southeastern Spain are high in relation to the seismic activity of the area. Nevertheless, similar values of vertical velocities have been found in areas with an analogous seismic activity. In the northeast of Spain, where the seismicity is lower than in the southeastern Betics, vertical velocities between 1 and 3 mm/year have been found (Giménez et al., 1996), and in France and Switzerland, with a seismic activity comparable to that of Spain, vertical velocities of 1 mm/year have been obtained (Gubler et al., 1981; Fourniguet, 1987; Jouanne et al., 1995). These relatively high vertical velocities must be considered to be of interseismic origin in the absence of any important earthquakes in these areas. Nevertheless, the presence of aseismic creep could also be a possible explanation. The problem is that in these areas there are no data on coseismic slips, as no recent important earthquakes have occurred. Therefore, it is not possible to know which portion of these vertical displacements will be released in a future earthquake, and which will be absorbed as aseismic creep. Further levelling measurements and field studies on neotectonic activity are necessary to assess the seismic potential of these faults.

Acknowledgements

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