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Flexural Interaction and the Dynamics of Neogene Extensional Basin Formation in the Alboran-Betic Region

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Abstract. Quantitative tectonic modelling demonstrates an interaction of flexure of the lithosphere underlying the western Betics with crustal thinning in the Alboran Basin and flank uplift in the Internal Zone. In the eastern Betics the flexural response is overprinted by post-thrusting extensional events. Lateral variations in thermal structure and rheology of the lithosphere along strike of the Betics shed light on changes in tectonic configuration and are consistent with evidence for lateral variations in the mode of extension in the Alboran Basin. Flexural modelling and subsidence analysis of Neogene basins in the Internal Zone of the Betics, with spatial development controlled by contrasts in lithosphere rheology, demonstrate that at least two extensional events have affected the orogenic evolution of the Betics. The first event appears to reflect Oligocene–Early Miocene rifting observed throughout the Western Mediterranean. The second phase, which caused the present configuration of the Betics, corresponds to Tortonian–Recent extension centered in the Alboran Basin.

Introduction

The study of lithosphere dynamics responsible for the tectonic evolution of the Alboran-Betic region by means of quantitative geodynamic modelling has only recently begun (e.g. van Wees and others 1992; Peper and Cloetingh 1992; van der Beek and Cloetingh 1992). This region underwent a complex history of repeated extensional and compressional tectonic phases (Bakker and others 1989; De Jong 1991) and offers an almost unique natural laboratory to study the dynamics of extensional basin formation in a regime of overall convergence. Flexural and gravity modelling and quantitative subsidence analysis of Neogene basins sheds light on the existence of lateral variations in rheological properties of the Betic lithosphere as well as on the timing of events that have controlled the dynamics of extension in the Alboran Basin.

During and after Late Cretaceous times convergence of the African and Eurasian plates was induced continuing up to the present (Vegas and Banda 1982; Spakman 1990). Within this large-scale collisional setting spatially and temporally localized extension led to the formation of a number of rifted basins in the western Mediterranean. During Oligocene–early Miocene times rifting took place in the western Mediterranean and oceanic crust was formed in the Ligurian, Sardino-Balearic, and North Algerian basins (reviews by Rehault and others 1984; De Jong 1991). In the Internal Zone of the Betics, extension took place together with high temperature–low pressure metamorphism and intrusion of ultramafic rocks (Bakker and others 1989; Platt and Vissers 1989; De Jong 1991). Contemporaneous with or shortly after the extensional episode in the Alboran Domain, nappes of the Internal Zone started to overthrust the Iberian margin to the north (Sanz de Galdeano 1990). The emplacement of the thrust nappes of the Internal Zone led to thrusting and north-vergent folding in the foreland. Following the emplacement of the Internal Zone thrust complexes, a period of strike–slip faulting affected the Betic-Rif orogen. The onset of strike–slip tectonics is envisaged to be caused by blocking of thrust movements and continued convergence of Africa and Iberia (Sanz de Galdeano 1990). These strike–slip movements controlled the formation of a number of Neogene intramontane pull-apart basins and also accommodated renewed subsidence of the Alboran Basin (Comas and others 1992). After the main tectonic events in the Betics, the region underwent rapid uplift from the late Tortonian–Pliocene onward.

Flexure of the Lithosphere Underlying the Betics and Interaction with Extension in the Alboran Basin

Van der Beek and Cloetingh (1992) modelled the isostatic response of the Iberian lithosphere to loading by the Internal Zone and Subbetic overthrusts along a number of profiles

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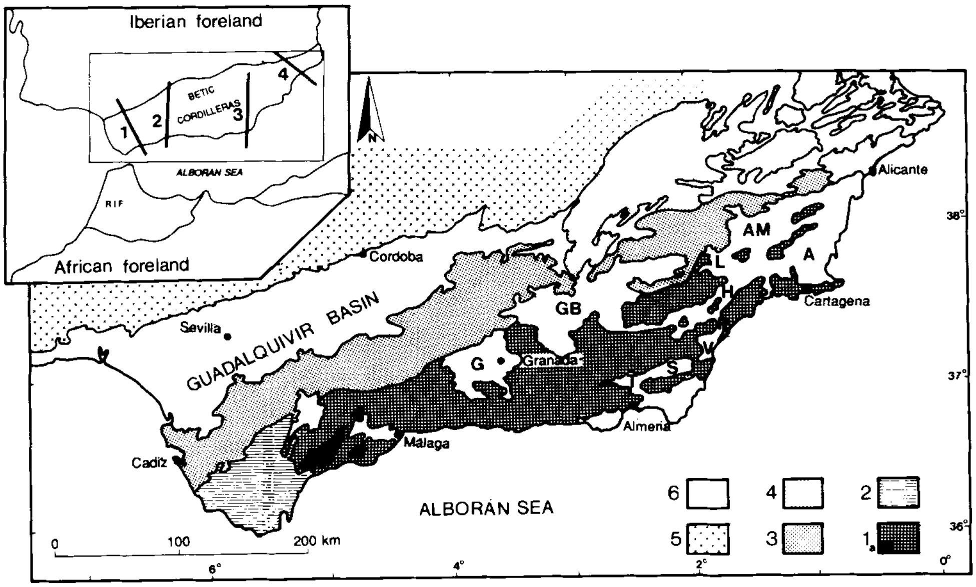

Figure 1. Generalized geological map of the Betic Cordilleras. Key: 1, Internal Zone (1a Ronda peridotites); 2, Campo de Gibraltar flysches; 3, Subbetic; 4, Prebetic; 5, Iberian Meseta; 6, Neogene basins (including the Guadalquivir foreland basin). A, Atalaya (Murcia) Basin; AM, Alhama de Murcia Basin; G, Granada Basin; GB, Guadix-Baza Basin; H, Hinojar Basin; L, Lorca Basin; P, Pulpi Basin; S, Sorbas Basin; T, Tabernas Basin; V, Vera Basin. Inset: tectonic sketch map of the Alboran-Betic region showing the locations of the selected profiles for flexural and gravity modelling.

transecting the Alboran-Betic region (Fig. 1), constrained by seismic profiles across the orogen (Banda and others 1992). A broken-plate model was adopted in the flexural analysis of the Betics, with the position of the coastline defining the termination of the underthrusted Iberian lithosphere. The analysis showed that the flexural wavelength of the Neogene Guadalquivir foreland basin requires an effective elastic thickness (e.e.t.) on the order of 10 km, which is less than e.e.t. estimates obtained for most other Alpine chains (McNutt and others 1988), but in the same range as e.e.t. values obtained for the Ebro foreland basin of the Pyrenees (Zoetemeijer and others 1990). As shown by Zoetemeijer and others (1990), low values for the e.e.t. of the lithosphere underlying the Ebro Basin reflect the weakening effect of elevated temperatures. Similarly, the inferred low values of the e.e.t. for the lithosphere of the Betics suggest that a heating event has affected the region before overthrusting took place. Thermo-mechanical modelling of the pre-Oligocene Betic rifted margin (Peper and Cloetingh 1992), however, only supports a moderate reduction of the e.e.t. in the Paleogene to values on the order of 30 km. It appears, therefore, that the low present-day values of the e.e.t. inferred from the flexural analysis of the Betics cannot be attributed to the Mesozoic extension that affected the Betic margin. This strongly suggests that Oligocene–early Miocene extension, which is recognized in the whole western Mediterranean area, has drastically lowered the e.e.t. of the southern Iberian lithosphere.

The observed lithospheric deflection requires a distributed additional vertical load acting on the plate. Flexural models incorporating a distributed load acting over the total width of the overthrust area are shown in Figure 2. This load distribution is consistent with thrusting of the Internal Zone of the Betics onto a rifted margin constituted by the External Zones. The predicted thickness of overthrusting units in the internal Betics (on the order of 10 km) is also in good agreement with estimates for the cumulative thicknesses of the Internal Zone thrust units and with the presence of a prominent seismic reflector, interpreted as a detachment surface (Banda and others 1992).

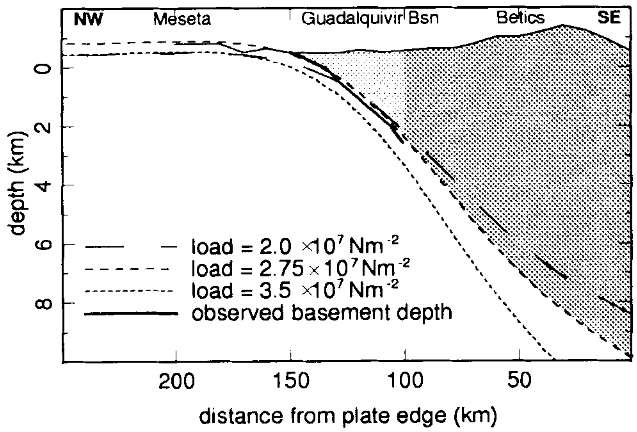

Figure 2. Flexural model of the response of the western Betic lithosphere to thrust loading by the Internal Zone and Subbetic overthrusts. Calculated deflection including distributed subsurface load forces acting over the first 100 km of the profile. Effective elastic thickness of the lithosphere e.e.t. = 10 km; density of topographic load $\rho = 2{,}750\ \mathrm{kgm^{-3}}$.

Of particular interest is the interaction of flexure induced by the Betic thrust sheets and lithospheric extension in the Alboran basin. The geometry of the Alboran Basin is well known from seismic and well data, presented by a number of papers in this volume (e.g. Comas and others 1992; Campos and others 1992; Jurado and Comas 1992; Woodside and Maldonado 1992). The IGME (1987) isopach map was used to constrain the thickness of Neogene sediments in the Alboran Basin and to obtain estimates for crustal thicknesses assuming local isostasy. The inferred crustal thicknesses of 17–20 km, which are in agreement with seismic refraction data, were combined with the results of the flexural analysis to calculate synthetic gravity profiles. These models, however, failed to reproduce the observed gravity pattern throughout the Internal Zone and Subbetic, most noticeably the coastal gravity peak (see dotted line Fig. 3a). The results are also not compatible with seismic refraction data for this part of the Betics as these data indicate that the maximum crustal thickness is not located at the coastline, under the

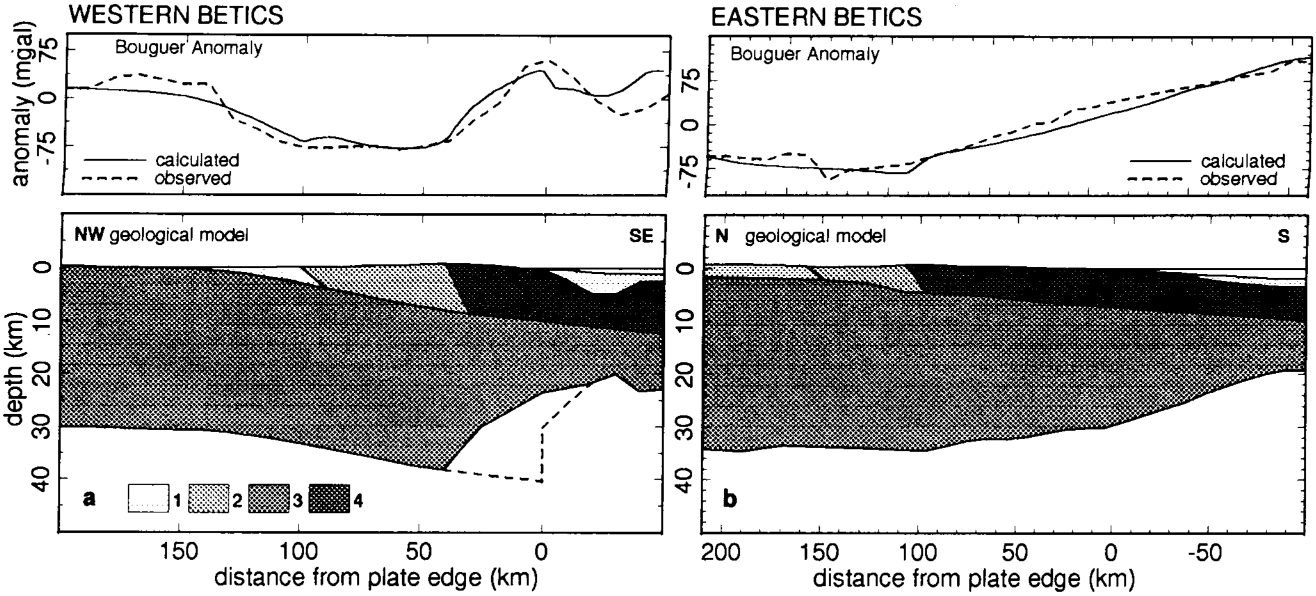

Figure 3. Gravity models for the Betic Cordilleras. a: Western Betics: gravity anomalies calculated for a model of flexure and crustal attenuation in the Internal Zone and Alboran Basin. Stippled lines indicate crustal configuration with non-attenuated underthrusted Iberian lithosphere. b: Eastern Betics: model of local isostatic response and crustal thinning in the Alboran Sea. Shading: 1, Guadalquivir (ρ = 2,400 kgm^{-3}) and Alboran (ρ = 2,200 kgm^{-3}) basin sediments; 2, External Zone sediments (ρ = 2,650 kgm^{-3}); 3, Iberian crust (ρ = 2,850 kgm^{-3}); 4, Internal Zone and Alboran crust (ρ = 2,850 kgm^{-3}). Density of Iberian subcrustal lithosphere 3,300 kgm^{-3}, Alboran subcrustal lithosphere 3,250 kgm^{-3}.

Internal Zone, but rather somewhat to the north of it (Banda and others 1992; Torné and Banda 1992). Crustal thinning was obviously not restricted to the Alboran Basin but also affected the underthrusted Iberian plate. Incorporation of the effect of crustal thinning in the seaward end of the Iberian plate leads to a good fit to the gravity data (Fig. 3a).

The crustal thinning required to fit the gravity anomalies has interesting mechanical consequences. Pre- or post-thrusting crustal thinning could provide an explanation to account for additional loads required to fit the modelled deflection. The additional load that results from the amount of crustal thinning of the underthrusted Iberian plate in the Internal Zone required to fit the observed gravity anomalies is, however, much larger than the hidden load obtained from the modelling of the deflection, and is also distributed more toward the free end of the plate (Fig. 3). To explain both the deflection and the gravity anomaly pattern obviously requires the existence of a dynamic mechanism capable of sustaining the significant load associated with crustal thinning.

As discussed further on, the Internal Zone of the Betics has experienced an uplift of at least 200 m since the Tortonian, simultaneous with extension and subsidence of the Alboran Basin. It is likely that this uplift is associated with attenuation in the Internal Zone of the Betics, which has thereby become an uplifted flank of the Alboran Basin (Fig. 4). The gravity anomaly pattern observed in the western Betics suggests a mechanical coupling between the uplift of the Internal Zone of the Betics and extension in the Alboran Basin, probably as a result of crustal scale detachment (Weissel and Karner 1989) or "necking" of the lithosphere (Braun and Beaumont 1989; Kooi 1991). The modelling results suggest important lateral changes in the mode of extension and the depth of necking from west to east along the Alboran Basin. As shown in Figure 4, a deeper level of necking implies an enhanced topographic elevation at the flank of the rift basin. The present topography supports an increase in the depth of necking in a westward direction, reflecting the presence of stronger subcrustal lithosphere in the western part of the Alboran-Betic region, with a pronounced decrease in the predicted strength in an eastward direction along strike of the Betics.

In the eastern Betics the gravity profile can be adequately modelled by a local (Airy) isostatic response of the lithosphere to the load of the Internal Zone (Fig. 3b). This implies that in the eastern Betics extensional (weakening) events post-date the main overthrusting phase and overprint the flexural response. Clearly, both Oligocene–early Miocene and Late Miocene–Recent stretching in the Alboran Basin and Valencia Trough left their imprint on the mechanical properties of the lithosphere underlying the Betics.

Thermo-Mechanical Properties of the Lithosphere in the Alboran-Betic Region

Depth-dependent rheological profiles through the lithosphere (Cloetingh and others 1982; McNutt and others 1988) provide another source of information on lithosphere dynamics. The strength of the lithosphere is strongly dependent on its composition and thermal structure. Strength profiles of the lithosphere underlying the Alboran-Betic region were constructed by van der Beek and Cloetingh (1992) to test the conspicuously low value of the e.e.t. and the along-strike variation in mechanical properties predicted by the flexural and gravity models.

The strength profiles are based on surface heat flow data published by Albert-Beltrán (1979), with high overall val-

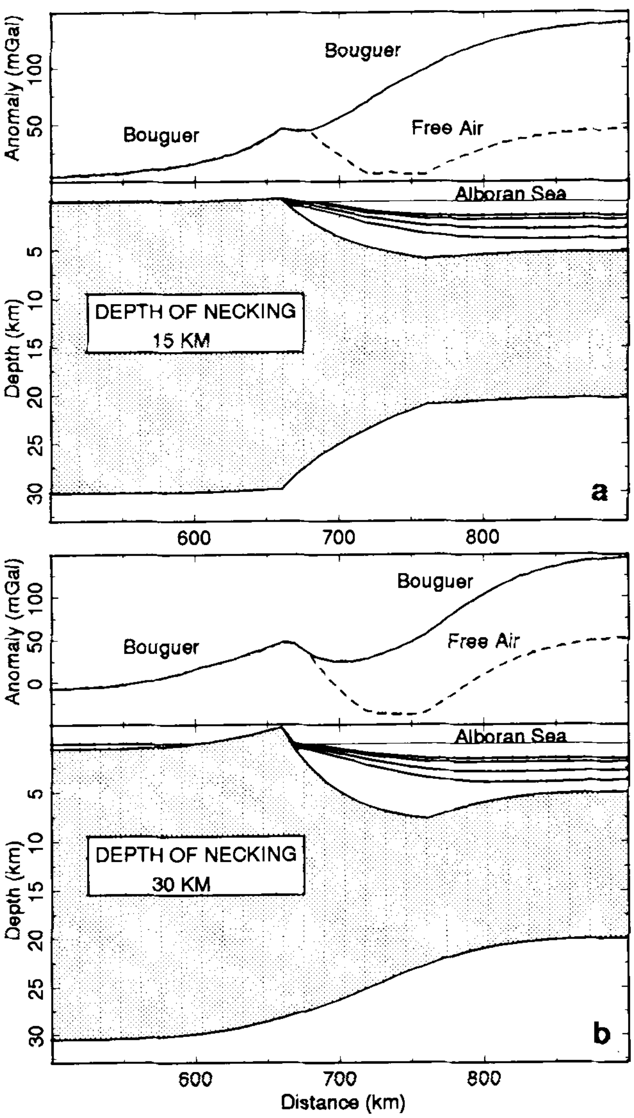

Figure 4. Predictions from a model of lithospheric necking associated with extension in the Alboran Sea. Different depths of necking (Kooi 1991) have a large effect on the magnitude of vertical motions associated with flank uplift induced in the Betics as a result of extension in the Alboran Sea. The predictions of the model can be tested by their capability to produce the correct ratio of syn-rift to post-rift sediments. a: Predicted gravity anomaly pattern and crustal structure for a model with a necking depth of 15 km. b: Predicted gravity anomaly pattern and crustal structure for a model with a necking depth of 30 km.

ues (in excess of 70 mWm^{-2}) throughout the Betics and extremely high values (90–100 mWm^{-2}) in the Gulf of Cadíz in the west and the Alicante–Cartagena area in the east. Although locally these high values may be caused by ground water circulation (Fernàndez and Banda 1989), the longer wavelength patterns of heat flow with an increase in heat flow from west to east seem well established. The increase in heat flow toward the east is consistent with the occurrence of Neogene volcanics predominantly in the eastern Betics. The rheological models are based on maximum and minimum heat flow values, adopting a three layer model (upper crust with a quartzite rheology, lower crust with a diorite rheology, and subcrustal lithosphere with an olivine rheology) with constant thermal conductivity and heat production in each layer. The depths of the boundary between upper and lower crust and the Moho depth are based on seismic refraction profiles (Banda and others 1992).

Inspection of Figure 5 shows a striking dissimilarity in strength distribution between the western and eastern Betics. In the western part of the Betics, the rheological profile suggests that the upper crust and part of the lower crust have maintained a limited strength. The models predict a reduction in strength for the lower part of the upper crust, promoting the development of a thrust detachment at this depth interval, which is relatively constant throughout the Betics. According to the rheological models, the lower crust has zero strength, predicting an important detachment zone between the upper lower crust and the subcrustal lithosphere, which is consistent with results of two dimensional *P-T-t* models for the Internal Zone of the Betics (van Wees and others 1992). The strength contribution is divided equally between the upper crust and upper lower crust on one hand, and the subcrustal lithosphere on the other. Upon application of bending stresses to this profile, the mechanically strong part (MSL) of the subcrustal lithosphere constitutes the elastic core of the bending plate. The MSL has an equivalent thickness of approximately 10 km, which is consistent with e.e.t. values predicted by the flexural models.

The eastern profile through the Betics points to a completely different rheology. Here, the upper crust still has some strength, but as a result of high temperatures the lower crust has no strength. Although the Moho is relatively shallow in this profile, the elevated temperatures have reduced upper mantle strength effectively to zero. The lower boundary of the MSL coincides with the Moho in the Internal Zone of the eastern Betics. Only in the Alboran Sea and the Valencia Trough, where Moho depths are very shallow (less than 20 km) the subcrustal lithosphere has some strength left in its upper part. The rheological profile suggests local isostasy and inability to support any flexural stresses in the eastern part of the Betics. The eastern Betics, the area for which we infer a very weak lithosphere, is also the site of extensive formation of small Neogene pull-apart basins. An interesting feature illustrated in Figure 5 is that the lithospheric strength predicted by the models in the Alboran Sea is much larger than the lithospheric strength in the internal and external Betics. The location of a zone of minimum lithospheric strength in the internal Betics favors a shift of the locus of present and future extension to this area, which is consistent with preferential location of Late Neogene pull-aparts as well as the observed concentration of seismicity in the Betic continental lithosphere (Udias 1988). It appears also that the locus and trends of recent strike–slip faulting are governed by the transition zone between relatively strong attenuated Alboran lithosphere and weaker thickened Betic lithosphere (see also De Jong 1991).

It thus seems that the results of the rheological modelling are consistent with predictions from the flexural and gravity analyses. The models support a strong variation in rheological properties along-strike of the Betics. The destruction of the flexural foreland basin in the eastern part of the Betics can be explained by the anomalous temperature structure that results in a nearly complete loss of strength of the lithosphere.

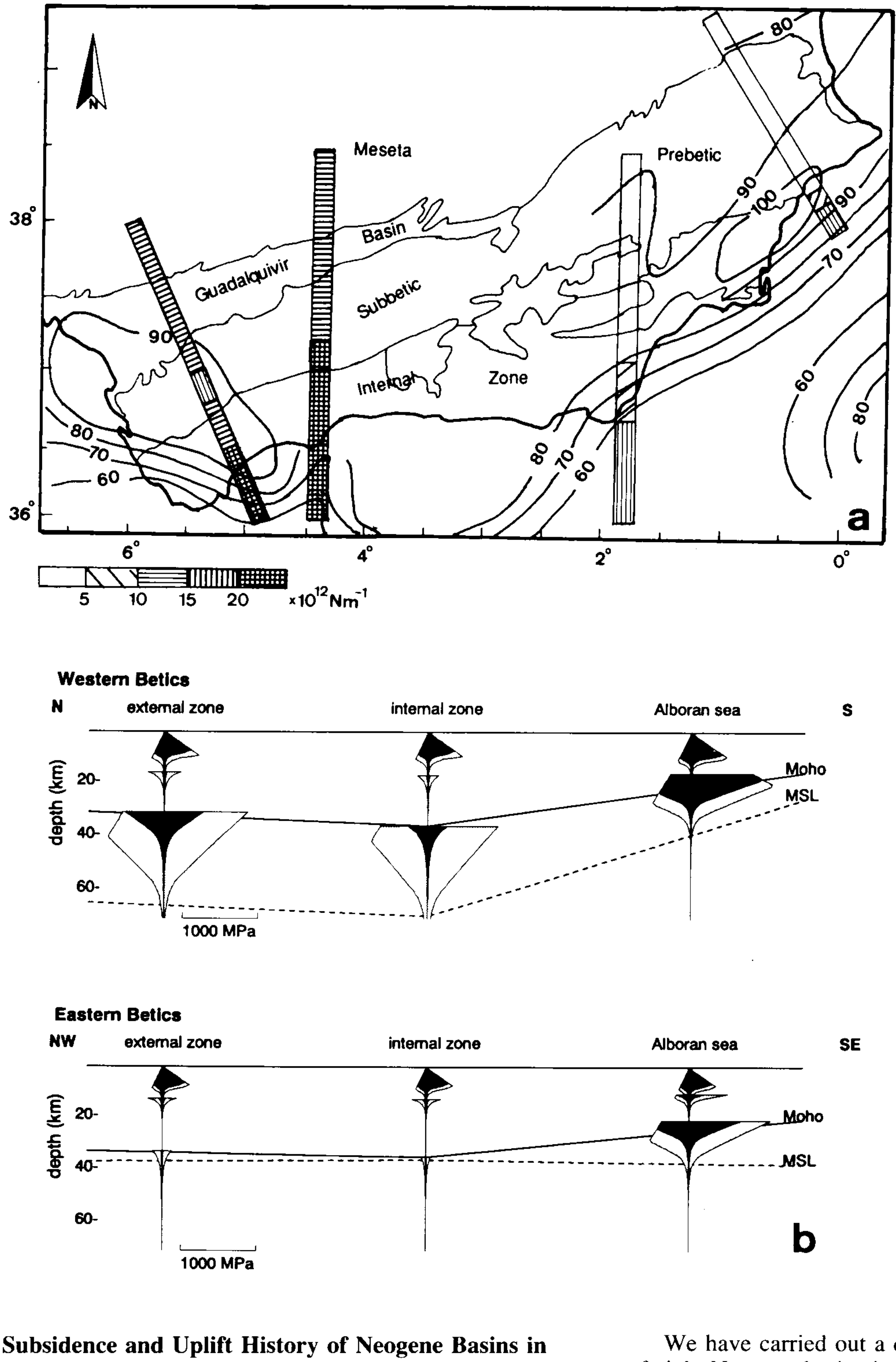

Figure 5. Lithospheric strength variation through the Betics. a: Map showing variation in the total integrated strength of the lithosphere, superimposed on heat flow data (after Albert-Beltrán 1979). b: Lithospheric strength profiles calculated for the External Zone, Internal Zone, and Alboran Sea areas of the western and eastern Betics. Light and darker shading indicate strength profiles corresponding to minimum and maximum heat flow estimates, respectively. Heat flow estimates range from 70–90 mWm^{-2} in the western Betics to 80–100 mWm^{-2} in the eastern Betics. A layered lithospheric model was used with a quartzite upper crust, diabase lower crust, and olivine subcrustal lithosphere. Also shown are the Moho depth and the lower boundary of the mechanically strong part of the lithosphere (MSL), corresponding to a ductile strength of 50 MPa in the subcrustal lithosphere (after van der Beek and Cloetingh 1991).

Subsidence and Uplift History of Neogene Basins in the Internal Betics

The lateral variation in structural characteristics of the Neogene basins in the Internal Zone of the Betics, with a strong contrast in spatial scale from approximately 20 km wide pull aparts in the west to approximately 5 km wide pull-aparts in the east, appears to be controlled by the lateral variation in plate rheology. The rheological models as well as the results obtained from the flexural and gravity analyses point to a striking dissimilarity in the mechanical properties of the lithosphere between the eastern and western Betics.

We have carried out a quantitative subsidence analysis of eight Neogene basins in the Internal Zone of the Betics. These are the Tabernas, Sorbas, Vera, Pulpi, Lorca, Hinojar, Alhama de Murcia, and the Atalaya (Murcia) basins (Fig. 1). Backstripped curves are compared with subsidence curves predicted by forward modelling leading to estimates for crustal and lithospheric stretching.

The Neogene basins have been the subject of intensive structural and sedimentological research (e.g. Montenat and others 1987; Bon and others 1989; Kleverlaan 1989). The basins occur in a setting of regional strike–slip tectonics as pull-aparts or as horst-graben basins in both the External and

Internal zones of the Betics (De Larouzière and others 1988; Geel and others 1992). The main structural features are the generally left lateral strike–slip zones, which trend northeast–southwest (e.g. Alhama de Murcia and Carboneras faults). The activity of these fault zones can be traced from Late-Burdigalian times, initiating directly after the emplacement of the Betic thrust sheets.

A major distinction can be made between Burdigalian–Serravallian and Late Neogene strata. The Burdigalian–Serravallian is strongly deformed and imbricated with the Betic substratum, whereas the Late Neogene sediments are relatively undeformed. A major tectonic event has been inferred in the lowermost Tortonian (Bon and others 1989). This is also apparent in the subsidence history of the Alboran basin (Docherty and Banda 1992). Some folding and faulting of Late Neogene sequences occurs in some basins (the Tabernas Basin, Kleverlaan 1989; the Hinojar Basin, Montenat and others 1987), whereas other basins are relatively undisturbed since Tortonian times (e.g. the Mazarron Basin, De Larouzière and others 1988). A minor intra-Tortonian tectonic event can be inferred from angular unconformities in the Atalaya and Alhama de Murcia basins. This feature may be a prelude to general uplift in the Messinian. An intra-Tortonian unconformity has also been reported for the Guadix-Baza and Granada basins (Estévez and Sanz de Galdeano 1980).

As shown below, tectonic subsidence occurred in all Neogene basins with a maximum of approximately 1,000 m in the Sorbas and Atalaya basins. Most Late Neogene basins developed in zones of weakness where strongly deformed Older Neogene sediments crop out. Following a phase of initial subsidence, a different evolution of the Neogene basins took place, with rapid deepening during Tortonian times associated with subsidence outpacing the sediment infill, leading to sediment starved basins (Pitman and Andrews 1985). The culmination of magmatic activity in the Tortonian coeval with rapid basin subsidence during this period stresses the importance of thermal processes for the tectono-sedimentary evolution of the Late Neogene basins. It will be shown that the timing of tectonic events inferred from the subsidence analysis is consistent with most data on the structural and sedimentological evolution of the Neogene basins.

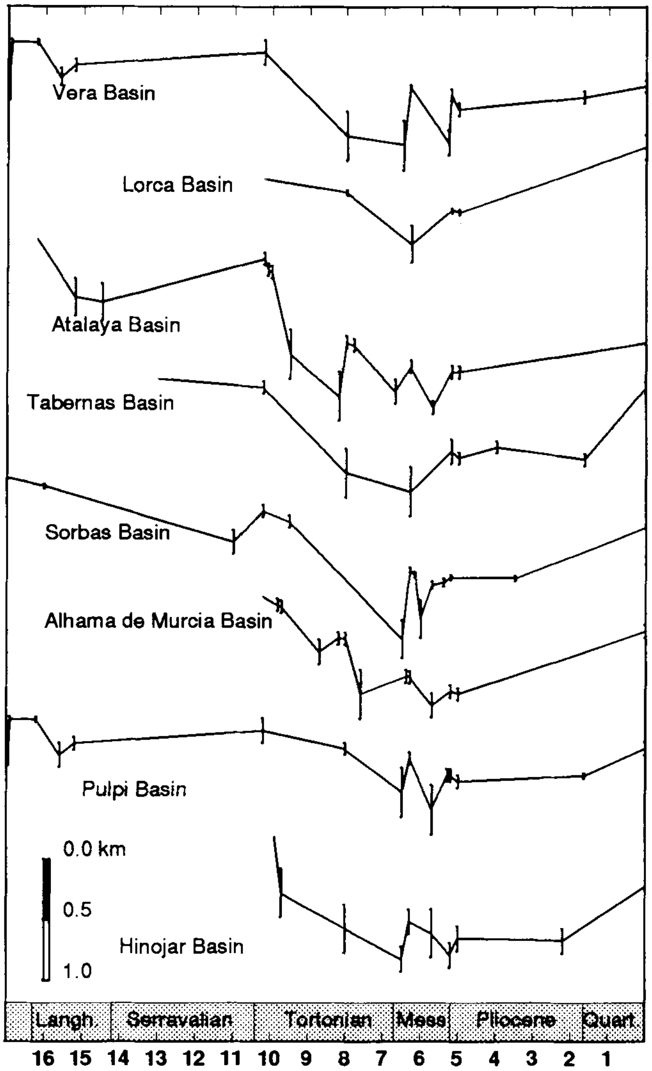

Figure 6. Curves of tectonic subsidence for eight Late Neogene basins in the Internal Zone of the Betics. The curves are constructed from backstripping sections incorporating estimates for paleobathymetry. Sea level fluctuations being of the order of 100 m have only a modest effect on the tectonic subsidence and are ignored.

Backstripping Analysis of Neogene Basins

The tectonic subsidence has been calculated using backstripping techniques, adopting an Airy model for isostasy in the calculations. Although undoubtedly an oversimplification, the presence of weak lithosphere underlying the basins, inferred from the gravity and flexural modelling described before, as well as the extensive development of fault systems surrounding the basins is in reasonable agreement with this assumption. Furthermore, assumptions on the strength of the lithosphere affect only the long-term shape of the subsidence curves and do not influence the short-term changes in subsidence that are our major concern in view of the timing of tectonic events that interrupt the long-term trends in subsidence. Eustatic sea level changes are not incorporated in the analysis as their effect on the tectonic subsidence is modest and as their interpretation in terms of a strictly eustatic mechanism is not unique (e.g. Cloetingh and others 1985). Estimates of paleobathymetry are based on sedimentological and micropaleontological data.

Figure 6 shows curves of tectonic subsidence derived from the backstripping analysis. During Tortonian times, subsidence occurs in small pull-apart or horst-graben basins (Montenat and others 1987; De Larouzière and others 1988), with a tectonic subsidence on the order of 500 m in the Lorca Basin and a maximum tectonic subsidence on the order of 1 km in the Sorbas and Atalaya basins. The inferred subsidence rates are consistent with earlier findings by De Larouzière and others (1988) suggesting an association of horst-graben basins (Lorca, Mazarron) and pull-apart basins (Vera, Hinojar) with the occurrence of low and high subsidence rates, respectively.

General uplift with a maximum of 600 m in the Sorbas Basin occurred at the end of Tortonian times (7.5–6.5 m.y.a.), coeval with a phase of compressive deformation.

As pointed out by Weijermars and others (1985), folded Tortonian sediments covered by undisturbed Messinian sediments, faults transecting Tortonian deposits which are sealed by Messinian sediments, as well as change of paleocurrents reflect a compressive phase during the Late Tortonian. With the exception of the Lorca and Tabernas basins, subsidence occurred at the beginning of Messinian times, followed by major uplift at the end of Messinian times. The latter uplift coincides with the Messinian salinity crisis. Although this feature is generally correlated with two South Atlantic glacial events occurring between 5.7 and 5.1 m.y.a. (McKenzie and Oberhänsli 1985), it seems that tectonic processes also made a major contribution. Various estimates exist for the magnitude of the associated drop in sea level. The depths of the canyons in the pre-Messinian sediments reach a maximum of approximately 250 m in the Agua-Amarga Basin, but evidence for extensive Messinian sub-areal erosion is lacking in the basins. At the beginning of Pliocene times, marine sediments are deposited in all the studied basins, with an exception for the Lorca Basin. The exact timing of the transition from marine to continental sedimentation is not well documented. The turning point in the Vera Basin is estimated at 1.65 m.y.a. (Völk 1967). From the Messinian-Pliocene transition until present maximum uplift is approximately 700 m in the Tabernas Basin, whereas minimum uplift of 125 m occurs in the Vera Basin. Detailed studies of the Quaternary sedimentary record in the Betics by Goy and others (1992) have demonstrated two phases of rapid tectonic reactivation during the Early Pleistocene and at the boundary of Early–Middle Pleistocene times. The early Pleistocene tectonic event coincides with a widespread regression in the Early–Middle Pleistocene, whereas the Early–Middle Pleistocene tectonic events amplified the ongoing uplift, with exception of the Alicante-Murcia region where rapid subsidence was induced (Goy and others 1992).

Forward Modelling of Subsidence of the Neogene Basins

Forward modelling of the tectonic subsidence is based on a non-instantaneous stretching model (Cochran 1983), which has been modified to incorporate the effects of lateral heat flow and depth-dependent stretching. As has been demonstrated by Pitman and Andrews (1985), the effect of lateral heat flow is of particular importance for the subsidence of small-sized pull-apart basins. Synthetic subsidence curves were calculated for both the uniform stretching model and for a model of two-layered stretching with different stretching factors β and δ for subcrustal and crustal stretching, respectively. Values for crustal thicknesses are based on data from Banda and Ansorge (1980), which yield an average thickness of 23 km for the crust to the east of the Palomares fault system and a 29-km-thick crust underlying the Sorbas and Tabernas basins. Forward modelling of subsidence was restricted to the Sorbas, Tabernas, and Hinojar basins. We refrain from a quantitative analysis of the Burdigalian–Serravallian stratigraphy due to the incompleteness of the record for this particular time slice. Crustal stretching factors with values between 1.1 and 1.2 for the Sorbas and Tabernas basins and between 1.1 and 1.45 were adopted for the Hinojar Basin. Subsequently, the pre-extension crustal thickness can easily be calculated. Lithospheric stretching factors are also included but are of minor influence. This is due to the small scale of the basins (with a maximum width of about 10–12 km for the Sorbas Basin) where the lateral heat flow is largely in excess of the vertical contribution to the basin heat flow. Adopting stretching events of 2 and 3.5 m.y.a. duration, we have calculated the subsidence for intervals of 1, 2, 3.5, 5, 6.5, and 10 m.y. after the initiation of stretching.

Figure 7 shows the comparison of backstripped curves of tectonic subsidence with the forward model. In the Tabernas Basin, the synthetic curve with a crustal stretching factor $\delta = 1.1$ (and eventually $\beta = 1.1$) provides the best fit to the observed subsidence, whereas in the Sorbas Basin a best fit is obtained for a $\delta = 1.15$ (and eventually $\beta = 1.15$). As demonstrated by Figure 7, a better fit is obtained for models adopting a slightly prolonged duration of rifting (3.5 m.y.). The models point to an average pre-rifting crustal thickness of 33 km for the Sorbas and Tabernas basins. For the Hinojar Basin a best fit with the observed tectonic subsidence is obtained for a δ between 1.15 and 1.2, implying a pre-extension crustal thickness of 28 km. In general a reasonable fit to the initial part of the subsidence curves can be obtained with models invoking a crustal stretching slightly in excess of the subcrustal stretching. The models fail to predict the subsequent part of the subsidence curves, which are characterized by abrupt phases of uplift. This feature is a consequence of the fact that stretching models for pull-aparts are intrinsically taking only into account the thermal consequences of the basin formation event and associated subsidence, ignoring the mechanical aspects that play a crucial role in faulting-induced uplift of pull-aparts. The models are, however, quite useful to investigate the crustal thinning associated with basin formation, which may occur on a larger spatial scale than the basins themselves. Furthermore, the rapid uplift phases displayed in Figures 6 and 7 are characteristic for an interplay of variations in the stress field and basin development in a strike–slip regime. The analysis strongly suggests that the differences in present crustal thickness are not the result of extension during Tortonian times, but due to earlier phases. Figure 7d and e also shows results for the Hinojar Basin for a 33-km-thick crust (equivalent to the pre-extension thickness of the crust underlying the Sorbas and Tabernas basins) stretched with $\delta = \beta = 1.45$, values that are required to yield the present crustal thickness of 23 km. The misfit between the predicted subsidence and the observed subsidence argues against the existence of an equal crustal thickness prior to Tortonian time.

Discussion and Conclusions

A crucial feature of the onshore record in the Alboran-Betic region is the occurrence of two major extensional events that have affected the Betics during the orogenic phase of their evolution, both leaving their imprint on lithospheric rheology. Extension and heating during Oligocene–early Miocene times lowered the e.e.t. of the Iberian lithosphere considerably, giving rise to a hot and weakened crust to be overthrust by the Internal Zone thrusts. The Tortonian–Pliocene extension and uplift modified the picture again,

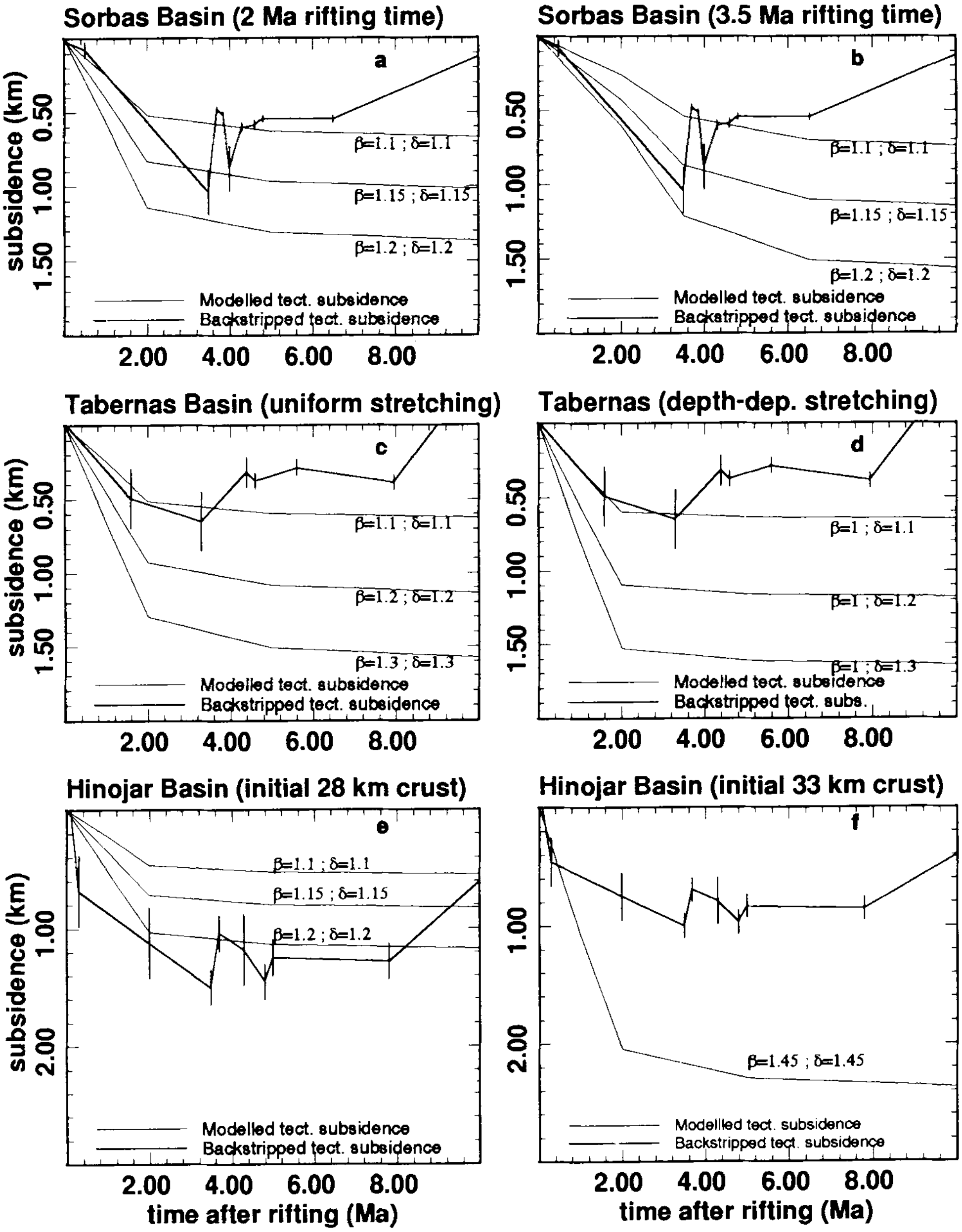

Figure 7. Synthetic subsidence curves compared with observed tectonic subsidence from backstripping analysis for the Sorbas, Tabernas, and Hinojar basins. The effect of lateral heat flow is incorporated, whereas Airy isostasy is assumed. The latter assumption does not affect the pattern of short-term vertical motions. Note the large discrepancies between the modelled and observed tectonic subsidence that arise from high values of stretching for the Hinojar Basin (e, f).

producing flank uplift and a further thinning of the underthrusted plate in the western Betics. In the eastern part of the Betics the effect of extension in the Alboran Basin and the Valencia Trough resulted in a strength of zero for the lithosphere and attainment of local isostasy. The Alboran Basin developed during two (Sanz de Galdeano 1990) or even three stretching events (Comas and others 1992). The first stretching phase is of early Miocene age, the second of Tortonian age, and the third of Pliocene age. Especially the second stretching phase is of major importance, being coeval with the development of the pull-apart and horst-graben basins in southeastern Spain. As pointed out above, it appears that the crust underlying the eastern pull-apart basins was already thinned during an extensional event prior to Tortonian times (see also Banda and Ansorge 1980; Sanz de Galdeano 1990).

A pull-apart opening of the Alboran Basin has been proposed by Vegas and Banda (1982). This mechanism is supported by the contemporaneous development of small-scale pull-apart basins in the Betic area and explains the development of extensional structures in a regime of overall convergence. The older Neogene sediments were probably deposited in a strike–slip related setting (Bon and others 1989), which suggests a pull-apart opening for the Alboran Sea during the first phase of localized stretching. The left-lateral fault zone in southeastern Spain is continuing across the Alboran Sea into the Eastern Rif in Morocco (Morley 1987; De Larouzière and others 1988; Woodside and Maldonado 1992) also reflecting a possible pull-apart mechanism for the Alboran Sea (Maldonado and others 1992). The development of this fault zone postdates the first stretching event in the Alboran Sea (Early Miocene) as the present-day juxtaposition of the Internal and External Zone was first established during the Burdigalian (Sanz de Galdeano 1990).

As pointed out earlier, the basins in the eastern Betics are characterized by a larger length/width ratio than the western basins. Our analysis suggests that this feature is the near-surface tectonic expression of a thinned and hot lithosphere in the eastern Betics. The substantial uplift of the Guadix-Baza and the Granada basins coeval with uplift of the Neogene basins more to the east discussed here reflect the regional nature of the record of vertical motions. The uplift could have presented a trigger mechanism for the Messinian salinity crisis, whereby uplift and erosion is amplified by the drop in sea level itself. Similar rapid anomalies exist in the Late Neogene subsidence history of the southeastern Levant margin in the eastern Mediterranean, possibly related to changes in stress regime (G. Tibor, personal communication 1991). It appears that a new stretching phase at the beginning of the Pliocene (Comas and others 1992) could have terminated the uplift, restoring the connection between the Atlantic and Mediterranean. Different mechanisms have been proposed to explain the Pliocene–Recent uplift. Estévez and Sanz de Galdeano (1980) attributed the uplift of the Guadix-Baza and Granada basins to contemporaneous north–south compression and isostatic uplift of the Guadix-Baza and Granada basins to contemporaneous north–south compression and isostatic uplift of the Betic chain. These authors interpret the various compressional and extensional structural features as being the result of an extensional Tortonian–Early Pleistocene phase followed by a compressional stage from Late Pleistocene onward. This interrelation is consistent with observed structural inversion and generalized uplift of the Alboran ridge from Late Pliocene to present time (Campos and others 1992). Kenter and others (1990) proposed thermal doming as a mechanism to explain the Prebetic uplift after upper Miocene times. It seems that the flank uplift associated with extension in the Alboran Sea proposed here provides an internally consistent mechanism for the record of vertical motions, whereby the oblique character of extension has accommodated an important strike–slip component. The accommodation of crustal structure to the long-wavelength coupling of Alboran Basin and Betic Cordilleras had led to a pattern of differential motions on a smaller scale leading to the formation of pull-aparts, with spatial scales controlled by lithospheric rheology. The lateral variation of mechanical properties along-strike of the Betics, inferred from our analysis, are important for understanding the dynamics of extensional basin formation in an overall convergent setting.

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