

Geophysical and geological constraints on the evolution of the Guadalquivir foreland basin, Spain

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Abstract: This paper presents a compilation and reinterpretation of available geophysical and geological data recently acquired for the ENE–WSW Guadalquivir foreland basin, located on the northern margin of the Betic orogen in southern Iberia. The data include seismic reflection and refraction profiles, well logs, gravity, geoid, surface heat-flow data and field observations. The deep structure of the southern Iberian margin is characterized by large variations in crustal thickness and high heat-flow values, which result in a very low lithospheric rigidity for the whole area. Geoid and gravity data show that deformation affected the crust and the lithospheric mantle differently, producing anomalous mass distributions that could act as subsurface loads. Seismic sequence analysis of the basin infill has permitted the re-assessment of the depositional sequential arrangement of the sediments deposited from Late Langhian–Early Serravallian to Messinian. They are arranged in six sequences and do not show any E–W progradational pattern indicating that during this period the acting loads moved essentially in a NNW direction. A careful analysis of the southern border of the basin shows that the ‘so-called olistostromes’ correspond to lateral diapirs of squeezed Triassic evaporites and internally imbricated Miocene wedges. We discuss the results obtained in terms of palaeo-geographic environments, time distribution and nature of acting loads, and constraints for future basin modelling approaches.

The development of orogenic belts involves vertical loads being imposed on the lithosphere which reacts by deflecting elastically, forming a foreland basin. Modelling foreland basins requires an understanding of (1) the spatial and temporal distribution of surface and subsurface tectonic loads; (2) the geometry and composition of the basin basement; (3) the thickness, composition and palaeo-environments of the major stratigraphic units of the sedimentary infill; (4) the spatial and temporal variations in the mechanical properties of the lithosphere.

The Guadalquivir Basin is one of the youngest European foreland basins which formed as a consequence of the latest stages (Miocene–Recent) of the Alpine Orogeny. It is located in the southern Iberian Peninsula with its northern, foreland margin being the Iberian Massif and its southern, hinterland margin being the Betic Mountain chain (Fig. 1). In spite of the numerous studies carried out for hydrocarbon exploration and academic research purposes, many

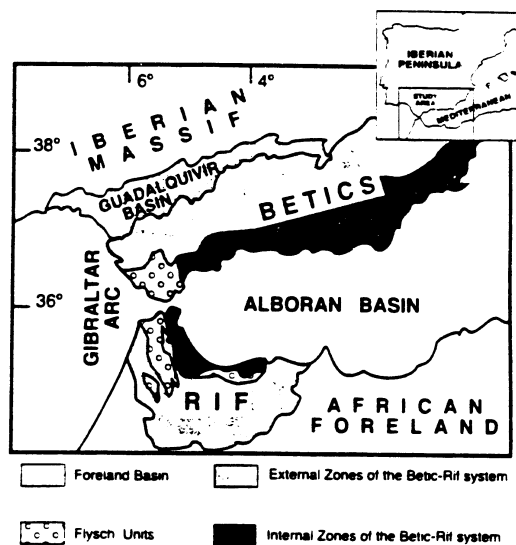


Fig. 1. Geological sketch map of the study area.

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aspects concerning the evolution of the Guadalquivir Basin still remain under debate.

Major discussions arise related to: (1) the age of the sediments that unconformably overlie the basement, which could be Late Langhian–Early Serravallian (e.g. Perconig 1960–62; Saavedra 1964; Ríaza & Martínez del Olmo 1996) or Mid-Tortonian (e.g. Perconig 1971; Sierro *et al.* 1996); (2) the origin and extent of the main prograding directions of the depositional systems which can be attributed to either eustatic changes or tectonic uplift (e.g. Sierro *et al.* 1996; Ríaza & Martínez del Olmo 1996); (3) the nature and mechanisms of emplacement of the so-called 'Olistostromic Unit' that could correspond either to mega-elements emplaced by gravitational sliding (e.g. Perconig 1960–62; Martínez del Olmo *et al.* 1984; Suárez-Alba *et al.* 1989) or to lateral diapirs emplaced by squeezing of Triassic materials, which would have also produced a Miocene frontal wedge (this paper; Berástegui *et al.* this volume); and (4) the composition and geometry of the basement below the Betics, which is poorly constrained (e.g. IGME 1987; Banks & Warburton 1991).

The mechanical properties of the lithosphere are mainly defined by the crustal thickness and the thermal regime (e.g. Ranalli 1994; Burov & Diament 1992). Partial information on the crustal structure and thermal regime in the study area comes from combined seismic and gravity studies and heat-flow surveys carried out in different parts of the southern Iberian margin (e.g. Torné & Banda 1992; Banda *et al.* 1993; ITGE 1993; Polyak *et al.* 1996). However, it is necessary to put together all the available information in order to produce a regional image of the crustal and lithospheric thickness variations over the whole area.

The aim of this paper is to outline some constraints on the present-day structure and Neogene evolution of the Guadalquivir Basin and surrounding areas rather than to develop a self-consistent model, which cannot be achieved from present knowledge. We present a compilation and re-interpretation of geological and geophysical data based on field observations, seismic reflection and refraction profiles, oil-well logs, gravity, geoid and surface heat-flow data. The paper focus on: (1) the deep structure of the whole area including the southern Iberian Massif, the Guadalquivir Basin, the Betic Chain and the Alboran Sea; (2) the architecture of the Guadalquivir Basin, its extension, sequence stratigraphy, and basement geometry; and (3) the nature of the allochthonous, chaotic bodies that are emplaced on the southern border of the basin. A companion paper by Berástegui *et al.* (this volume) deals with the structure and

tectonosedimentary evolution of the southern border of the Guadalquivir Basin.

Regional tectonic setting

The main geological units that characterize the southern part of the Iberian Peninsula are: the Betic mountain chain, the Guadalquivir foreland basin, and the Alboran Sea. The Betic Chain is the northern segment of an arcuate orogen that continues westwards across the Gibraltar Arc into the Rif Chain (Fig. 1). The inner part of this orogen is occupied by the Alboran Sea extensional basin. The tectonic evolution of the whole area, which constitutes the westernmost part of the Alpine Chain, was controlled by the relative movement between the African and Eurasian plates since Late Mesozoic times. Plate-motion studies from Dewey *et al.* (1989) suggest that this part of the plate boundary experienced about 200 km of roughly N–S convergence between Mid-Oligocene and Late Miocene times, followed by about 50 km of WNW-directed oblique convergence in Late Miocene to Recent time.

The major palaeogeographic elements forming the Betics–Gibraltar Arc–Rif system belonged to four pre-Miocene domains, which were well delimited at the beginning of the Neogene (Balanyá & García-Dueñas 1988): (1) and (2) are the External Zones of the Betic–Rif chain corresponding to the inverted Mesozoic continental margins of the Iberian and African plates, respectively; (3) the Flysch Units, which are made up of allochthonous sediments; (4) the Internal Zones of the Betic–Rif chain, composed of a polyphase thrust stack that includes three high-pressure–low-temperature metamorphic nappe complexes (e.g. Bakker *et al.* 1989; Tubia & Gil-Ibarguchi 1991).

Late Cretaceous and Palaeogene convergence caused substantial crustal thickening in the Internal Zones and generated an orogen by collisional stacking. Whether this thickening occurred at the present-day Alboran Sea basin or further to the East is still under debate. The Internal Zones represent the disrupted and extended fragments of this pre-Miocene orogen (Balanyá & García-Dueñas 1987, 1988; Platt & Vissers 1989; Monié *et al.* 1991; Vissers *et al.* 1995). The External Zones and the Flysch Units reflect continued crustal shortening during the Miocene, whereas crustal extension occurred in the Internal Zones of the orogen. This shortening began in the lower Aquitanian and continued into the Late Miocene (García-Dueñas *et al.* 1992; Comas *et al.* 1992).

Miocene extensional detachment systems and

fault-bounded sedimentary basins of Miocene age are superimposed upon the continental collision of the Internal Zones (e.g. Galindo Zaldívar *et al.* 1989; Platt & Vissers 1989; García-Dueñas & Balanyá 1991; García-Dueñas *et al.* 1992). This Miocene extensional phase was accompanied by a distinctive low pressure–high-temperature metamorphism (Zeck *et al.* 1992). The crustal thinning over much of the region, both on- and off-shore is likely to be a result of this phase of extension.

Different hypotheses have been formulated to account for the geodynamic evolution of the southern margin of the Iberian Peninsula including models involving a back-arc origin (Zeck *et al.* 1992; Royden 1993), mantle delamination (Channell & Mareschal 1989; García-Dueñas *et al.* 1992; Docherty & Banda 1995), extensional collapse (Dewey 1988; Vissers *et al.* 1995), and rifting (Cloetingh *et al.* 1992). Up to now, however, none of these models have been successfully tested to fit the available surface and subsurface data.

The Guadalquivir basin formed in an overall environment of plate convergence as the fore-land basin to the central and western Betics. This convergence, however, is not directly reflected in the kinematics either of the surrounding mountain chains or in the extension of the Alboran basin. In fact, the present-day Guadalquivir basin correlates only with the later steps (Miocene–Recent) of this tectonic history that developed from Late Cretaceous times.

Regional geophysical data

During the last years several geophysical surveys have been carried out along the southern margin of the Iberian Peninsula. These surveys include deep seismic refraction, wide-angle and reflection profiles, gravity and heat flow. In this section we present a compilation of those datasets that have a predominantly crustal- and lithospheric-scale significance, namely Bouguer gravity anomalies and geoid height maps, crustal thickness and surface heat-flow.

Bouguer gravity anomalies and geoid height maps

Gravity and geoid data primarily reflect variations in the density distribution of the Earth's interior. Gravity anomalies, because of the inverse square law of the gravity field, are particularly sensitive to density variations at crustal levels. In contrast, under the assumption of local isostatic equilibrium, the geoid anomaly is proportional to the density-moment function

(Haxby & Turcotte 1978) and therefore is more sensitive to density variations at sub-crustal levels. With the aim of highlighting the major features of crustal and lithospheric structure along the southern margin of the Iberian Peninsula, we have mapped both Bouguer gravity anomalies and geoid height.

The Bouguer anomaly map (Fig. 2) has been constructed using available data from the 'Bureau Gravimétrique International', from the Spanish 'Instituto Geográfico Nacional' and from available ship tracks including a cruise carried out by research vessel *RD Conrad* in the Alboran Sea. Additional data points at sea have been taken from Morelli *et al.* (1975). These data have been reduced following the same procedure as Torné *et al.* (1992). Figure 2 shows that the Bouguer anomaly, at the Guadalquivir Basin, is characterized by a gentle South-South-eastward decrease of about 60–70 mGal that reflects the basement topography fairly well. Towards the Betics, the Bouguer anomaly decreases down to -120/-130 mGal associated with the existence of a crustal root, and increases rapidly towards the south to more than +180 mGal in the easternmost Alboran Basin as a response of a prominent crustal thinning. In the western Alboran Basin, the Bouguer anomaly yields negative values, which reflect the combined effect of crustal thinning and large sediment accumulations (up to 6–7 km thick).

The geoid height map has been constructed using available data from the Deutsche Geodätische Kommission (Brennecke *et al.* 1983). These data include gravimetric geoid determinations off-shore and on-shore with a coverage of $6' \times 10'$ arc. Figure 3 shows the contoured map of the resulting geoid heights. The most striking feature is the high gradient across the Guadalquivir Basin, which amounts to 0.1 m km⁻¹. In this area the geoid anomaly decreases by 6 m towards the Betics. Such anomalies are common in continental margins, and are related to the thinning of continental crust towards the oceanic crust. However, since there are no major changes in crustal thickness across the Guadalquivir Basin (see Fig. 4), this geoid anomaly must be related to deeper structures. A similar trend is observed in North Africa where the minimum geoid height (39 m) is localized on the African–Atlantic margin.

Crustal thickness

The southern Iberian Peninsula has been the objective of numerous deep seismic experiments, which include refraction, wide-angle and reflection. The crustal thickness values compiled

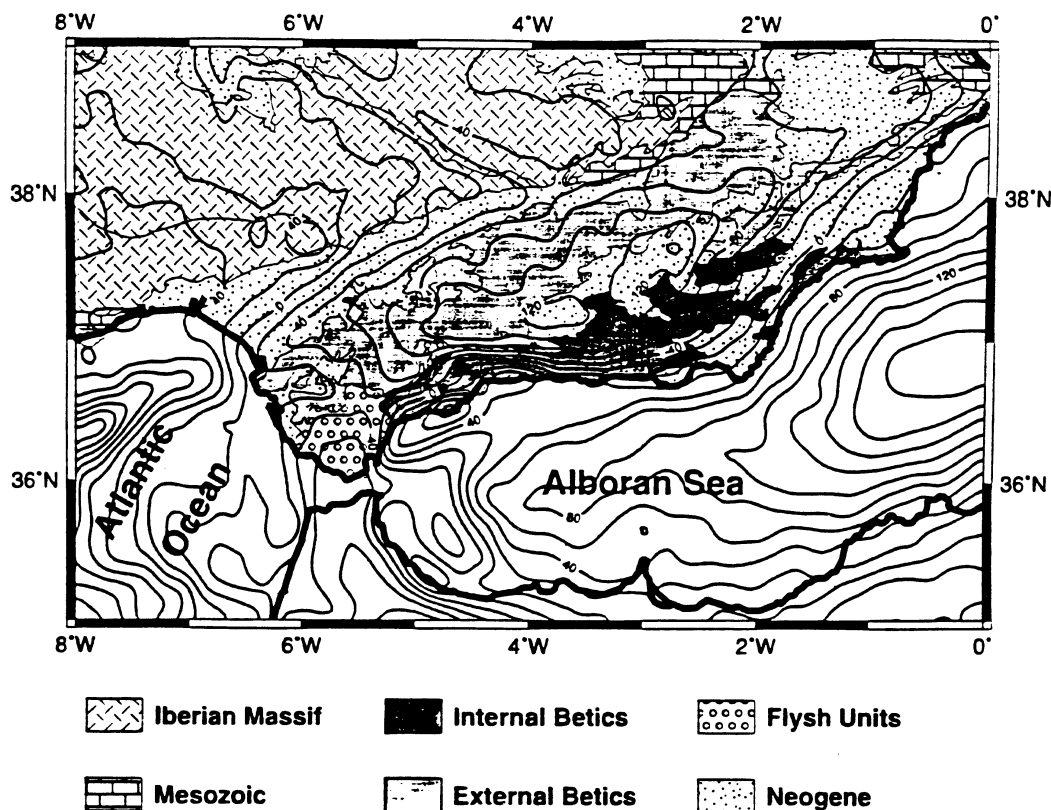


Fig. 2. Bouguer anomaly map. Isolines every 20 mGal. Compiled from 'Bureau Gravimétrique International', Spanish 'Instituto Geográfico Nacional' and Morelli *et al.* (1975).

in this section come primarily from seismic refraction and wide-angle data. The contoured map of the Moho depth (Fig. 4) obtained from the above mentioned data has been filtered and smoothed and therefore shows the main features and trends of the crustal structure in the study area. The Iberian Massif is characterized by a 32–34 km thick crust with a Pn velocity of 8.0–8.1 km s⁻¹ (Banda *et al.* 1981, 1993; Banda 1988; Suriñach & Vegas 1988; ILIHA 1993). In the western part of the Iberian Massif and close to the northern border of the Guadalquivir Basin, González *et al.* (1993) propose a crustal thickness of about 29 km increasing up to 31 km towards the Gulf of Cadiz.

In the Central-Eastern Betics seismic data indicate that the Moho deepens up to 38 km under the Internal Betics (Banda & Ansorge 1980; Banda *et al.* 1993). Deep multichannel seismic data show noticeable differences in the reflective character of the crust between the External and the Internal Betics (García-Dueñas *et al.* 1994). The External Betics are characterized by an almost transparent upper

crust and a weakly reflective lower crust that seems to thin out towards the SE. In contrast, the Internal Betics show a prominent reflector in the upper crust, which is interpreted as a detachment surface, and a moderate reflectivity in the lower crust with dipping reflectors in its central part. The crustal structure obtained for the westernmost Betics (Gibraltar Arc) is characterized by a Moho depth of about 31 km and a very thick sedimentary cover (up to 10 km towards the Gulf of Cadiz) with large lateral variations (Medialdea *et al.* 1986).

A pronounced crustal thinning is observed from the Betics to the Alboran Sea. Different seismic profiles acquired near the shoreline (Banda & Ansorge 1980; Medialdea *et al.* 1986; Barranco *et al.* 1990) show a crustal thickness of 23–24 km. The crustal structure in the Alboran Sea is poorly constrained, since the only available data come from seismic experiments shot in 1974 (Hatzfeld 1976; Boloix & Hatzfeld 1977) and in 1979 (Suriñach & Vegas 1993) which show that the Moho lies at about 15 km depth in the central part of the basin. Combined seismic and

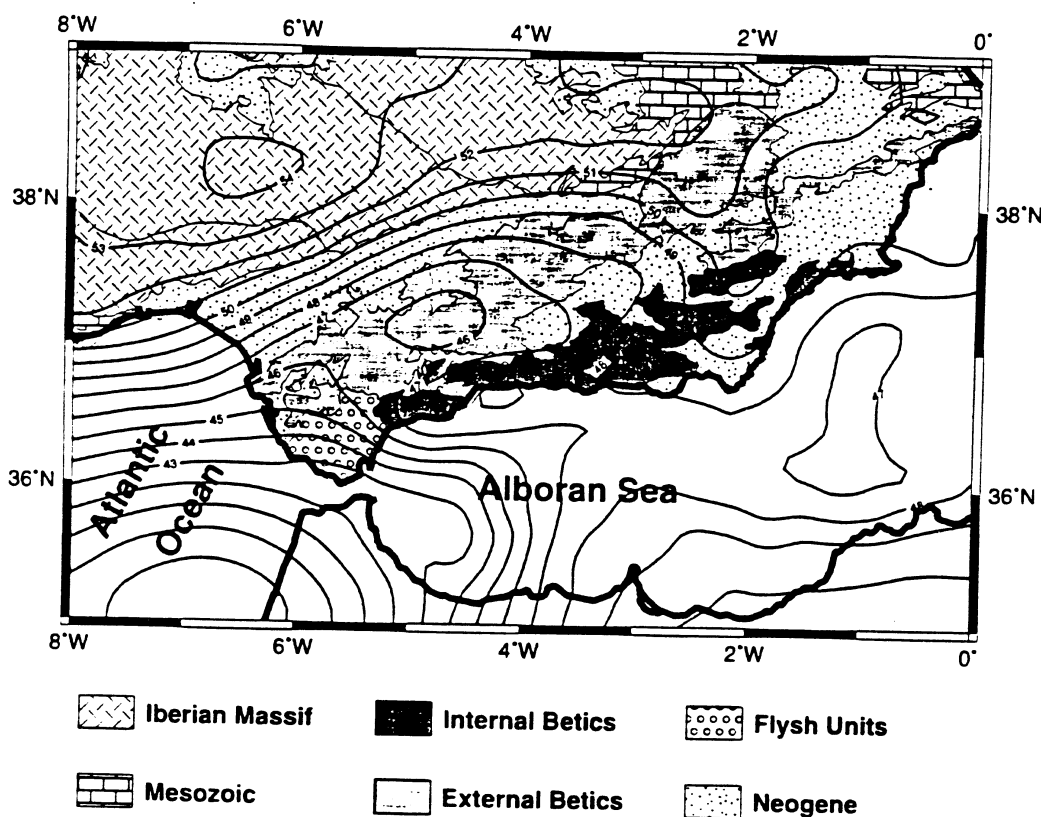


Fig. 3. Absolute geoid height map. Isolines every 1 m. Compiled from Brennecke *et al.* (1983).

gravity studies suggest that the thinning observed from the Betics to the Alboran Sea is mainly produced over a narrow area (30–35 km wide) which resembles the pattern observed in transform margins (Torné & Banda 1992; Torné *et al.* 1992; Watts *et al.* 1993). To the east however this thinning occurs over a much broader zone of about 120 km (Torné & Banda 1992).

Surface heat-flow

The thermal data available in southern Spain come from thermal gradient determinations carried out in oil wells (Albert-Beltrán 1979; Banda *et al.* 1991) and water exploration wells (ITGE 1993), and from sea-floor heat-flow measurements in the Alboran Sea (Polyak *et al.* 1996). Thermal gradients obtained in water exploration wells were corrected for topographic and palaeoclimatic effects. A number of thermal conductivity measurements were also performed on rock-samples representative of the main lithologies to calculate the surface heat-flow in water wells (ITGE 1993). Heat flow

in oil wells has been calculated by multiplying the mean thermal gradient, deduced from bottom hole temperature (BHT) data, by a constant thermal conductivity of $2.1 \text{ W m}^{-1} \text{ K}^{-1}$ (Albert-Beltrán 1979).

Figure 5 shows the heat-flow distribution obtained in the study area. The high scatter observed in heat flow data indicates an active ground-water circulation as is evidenced in some thermometric logs recorded in water wells (Fig. 6). Thermal perturbations due to ground water are particularly noticeable along the northern border of the Guadalquivir Basin and the Betic Chain. Thermal data from oil wells confirm these results and yield temperature gradient values ranging from 20 to 45 mK m^{-1} in the Guadalquivir Basin, and from 13 to 21 mK m^{-1} in the External Betics. The stack of the BHT data (Fig. 7) shows that fluid circulation is not restricted to shallow depths (few hundred metres) but it is also evident at depths up to 5 km. In spite of that, a regional thermal pattern characterized by a surface heat-flow that varies from $70\text{--}80 \text{ mW m}^{-2}$ in the south of the Iberian

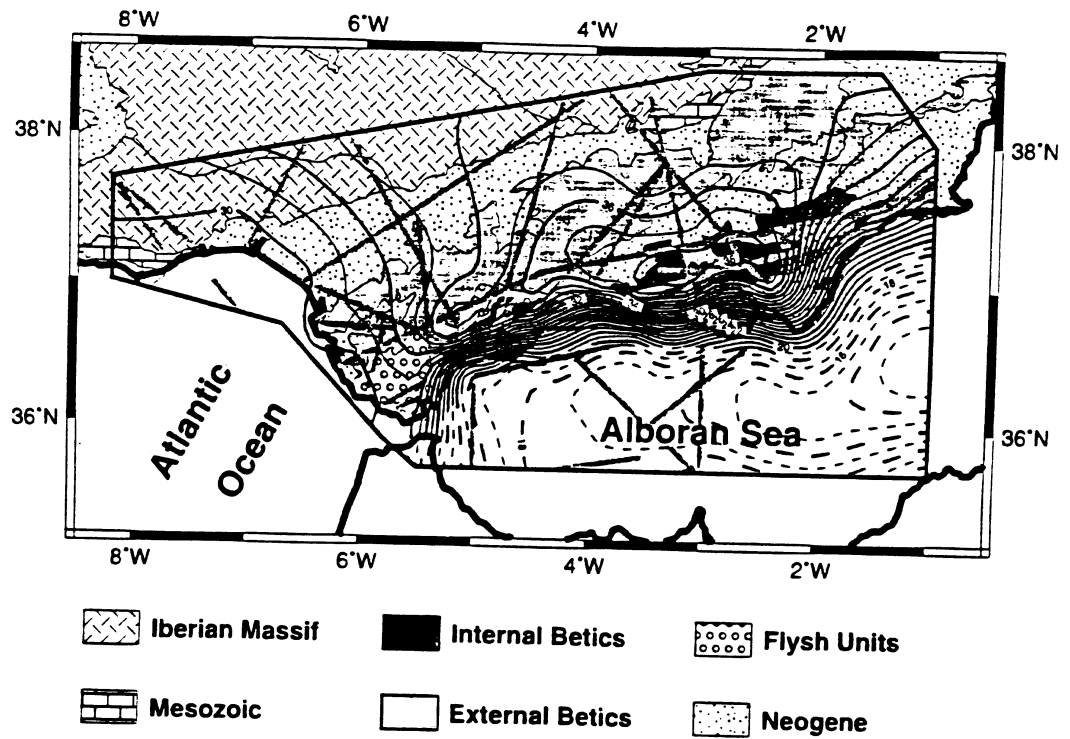


Fig. 4. Moho depth map. Isolines every 1 km. Grey thick lines indicate the location of seismic refraction profiles.

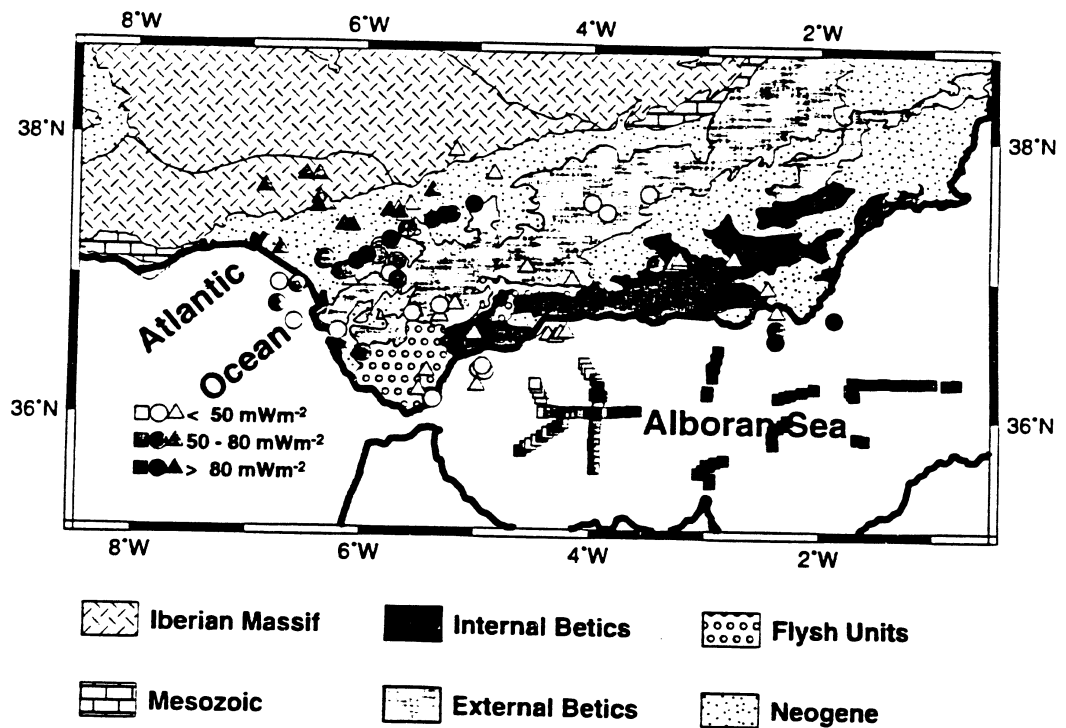


Fig. 5. Surface heat flow map in mW m⁻². Triangles indicate measurements from water exploration wells. Circles indicate measurements from oil exploration wells. Squares indicate sea-floor measurements.

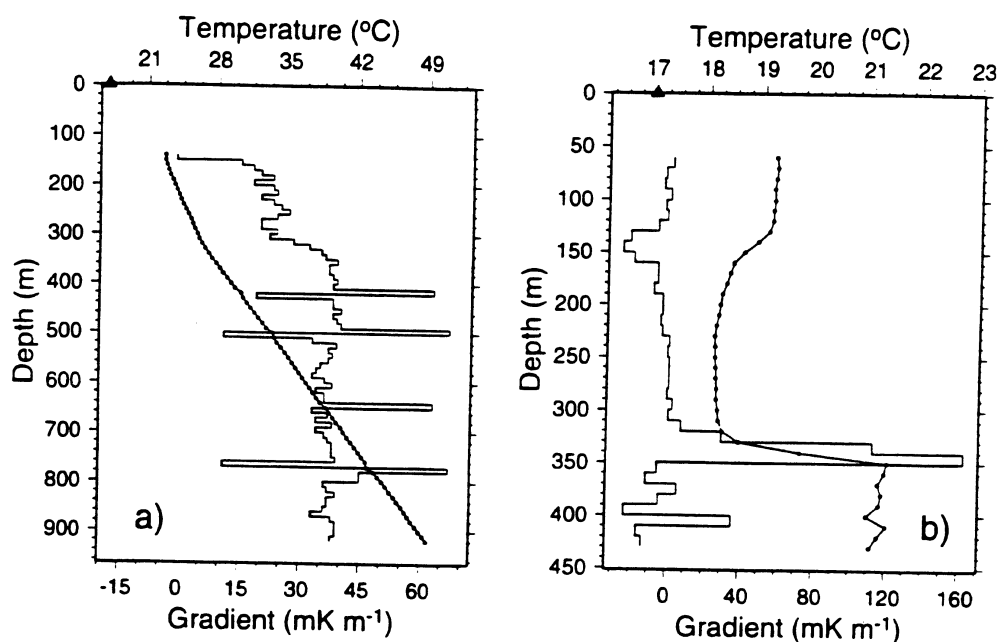


Fig. 6. Thermometric logs recorded in water exploration wells. Dotted line indicates temperature-depth log. Stepped line indicates thermal gradient-depth log. (a) Example of linear temperature log measured at the western part of the Guadalquivir Basin. Only perturbations of short wave-length associated with fractures are evident. (b) Example of highly perturbed thermometric log measured in a Neogene basin (Almeria) located at the southeastern Betic Cordillera. Circulation of cold water between 130 m and 330 m and perturbations associated with fractures between 350 m and 430 m are evident.

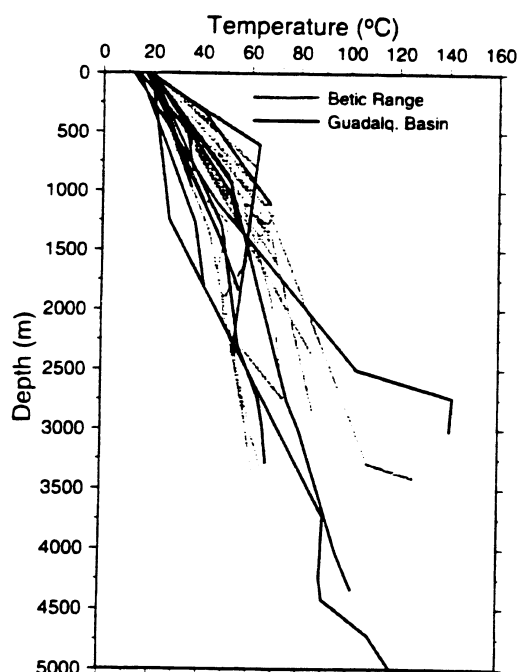


Fig. 7. Stack of bottom-hole temperature data obtained from oil exploration wells.

Massif, to 80 mW m⁻² in the Guadalquivir Basin, and to 40–50 mW m⁻² in the External Betics can be inferred. The few measurements carried out in the Internal Betics also show low heat-flow values (< 50 mW m⁻²). However, further to the south, in the Alboran Sea, the heat-flow shows very high values increasing both in a W–E and N–S direction from about 50 mW m⁻² to 120 mW m⁻².

Geology of the Guadalquivir Basin

Previous interpretations of the basin infill

From early works (see Perconig 1960–62) it is widely accepted that the Neogene infill of the Guadalquivir Basin consists of marine marls including sandy intercalations deposited above a 'basal calcarenite' ('grès à *Heterostegina costata*'), which unconformably overlies a pre-Miocene basement.

Regional interpretations (e.g., Perconig 1960–62; Martínez del Olmo *et al.* 1984; Roldán García & García Cortés 1988; Suárez-Alba *et al.* 1989; Sierro *et al.* 1996; Riaza & Martínez del Olmo 1996) agree that a northern passive margin (the Iberian Massif) provided a clastic

infill to the basin, and a southern active margin (the External Zones of the Betic Cordillera) provided a gravitational infill. The clastics derived from the northern margin were re-distributed by turbiditic currents along the major axis of the basin (ENE-WSW) and finally deposited in the deepest areas (close to the southern margin) forming small, relatively sand-rich stacked lobes interbedded with blue marls and clays. According to these authors, during Late Tortonian times, gigantic chaotic masses of rocks were emplaced by gravitational sliding into the basin from the External Zones of the Betic Cordillera as olistostromes, mega-turbidites or mega-elements, responsible for the N-S narrowness of the basin. These rock masses mainly consist of Triassic evaporites, clays and limestones, and blocks of upper Cretaceous to Palaeocene limestones. In spite of the general agreement on the mode of emplacement of these units, other mechanisms can be considered as discussed below.

Riaza & Martínez del Olmo (1996) arranged the sedimentary infill of the basin into five tectono sedimentary units using seismic and well data, and tied them to the emplacement of the olistostromes. In contrast, Sierro *et al.* (1996), from outcrop observations and micropalaeontological data, defined five offlapping depositional sequences forming a westward progradational set. Both stratigraphic models show strong discrepancies (See Table 1 for a summary).

Although the dating of the Neogene sedimentary infill has been investigated by several authors (e.g. Perconig 1960–62, 1971; Saavedra 1964; Perconig & Granados 1973; Flores & Sierro 1989; Sierro *et al.* 1993), the results obtained show important discrepancies that

span 5 Ma (about 30% of the age of the basin). Perconig (1960–62) proposed that the oldest sediments (the aforementioned 'grès a *Helicostegina costata*') were Helvetian in age (currently Langian–Serravallian). Later, Perconig (1971) attributed a Tortonian age to these sediments. Finally, Sierro *et al.* (1996) proposed that these 'basal calcarenites' are diachronous.

All the above-mentioned uncertainties led us to propose an alternative, self-consistent geological framework, which includes a re-interpretation of the basin infill using seismic stratigraphy, and an analysis of the nature and mode of emplacement of the materials in the southern margin of the basin.

A reinterpretation of the Guadalquivir Basin infill

A total of about 1400 km of seismic profiles together with data from 35 exploration hydrocarbon wells (Fig. 8) were interpreted following the usual procedures in seismic-sequence analysis (i.e. Mitchum *et al.* 1977; Vail 1987).

The lithological composition and physical properties of the sediments and their lateral variations were studied on six selected wells by inversion of the geophysical well logs. Additional information from the corresponding company well reports was also used. Two well-to-well correlations were performed at the westernmost and central parts of the Guadalquivir Basin (Figs 9 and 10) to study the transition from the Betics to the foreland basin. The main lithologies in each well together with the gamma-ray and sonic logs are displayed in these figures. Figure 9 outlines the lithologic composition of the 'so-called olistostromes' (hereinafter referred to as the chaotic unit) in the westernmost Guadalquivir Basin and its lateral thickness variations. Betica 14-1 well shows that the chaotic unit overlies undisturbed Miocene sediments, and mainly consists of undercompacted shales and clays with intervals (up to 160 m thick) of Triassic evaporites. Miocene to Pliocene sediments are recognized at the uppermost part of the section. The thickness of the chaotic unit decreases dramatically from 2600 m (Betica 14-1) to 100 m in the Casa Nieves-1 well located about 20 km to the northwest, and is not recognized further north at the Villamanrique-1 well. In all three wells, the lowermost sediments overlying the autochthonous basement correspond to the 'basal calcarenite' previously recognized by Perconig (1960–62). In the central part of the basin (Fig. 10), the Nueva Carteya-1 well, located on the External Betics, drilled more than 3000 m of Mesozoic carbonates overthrusting

Table 1. Summary of stratigraphic models from Riaza & Martínez del Olmo (1996); Sierro *et al.* (1996) and Berástegui *et al.* (this volume)

AGE	Riaza & Martínez del Olmo, 1996	Sierro <i>et al.</i> , 1996	Berástegui <i>et al.</i> , this volume
QUATERNARY — 1.65	Ode sequence		
PLIOCENE	MARISMAS GROUP	Sequence E	
5.2		Sequence D	
Messinian 6.3	ANDALUCÍA GROUP	Sequence C	Sequence 6
	BETICA GROUP	Sequence B	Sequence 5
Tortonian		Sequence A	Sequence 4
10.2			Sequence 3
Serravallian	ATLANTIDA GROUP		Sequence 2
15.2			Sequence 1
Langhian			

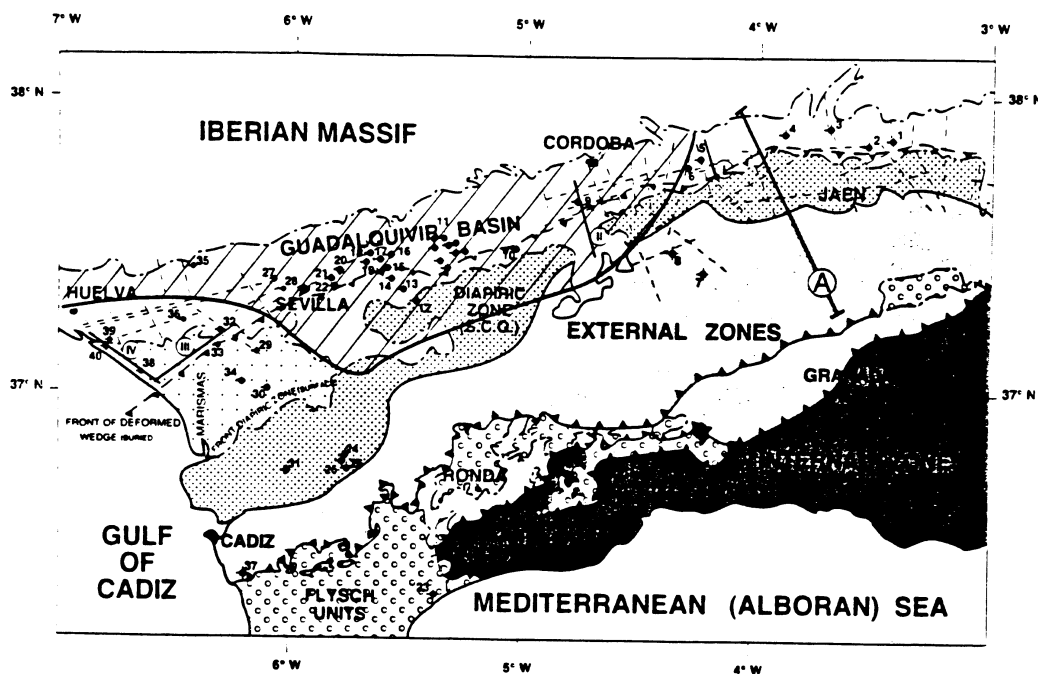


Fig. 8. Location map of subsurface data. Dashed lines indicate the location of seismic profiles used in this study. Solid lines indicate the location of interpreted seismic lines shown in this paper: I (Fig. 12); II (Fig. 16); III (Fig. 15); IV (Fig. 13). Segment 'A' indicate the location of Martos cross section (Fig. 17). Oil-wells: 1. Baeza-1; 2. Baeza-2; 3. Baeza-4 or Bailén; 4. Villanueva de la Reina or Baeza-3; 5. Rio Guadalquivir K-1; 6. Bujalance; 7. Rio Guadalquivir H-1; 8. Nueva Carteya-1; 9. Rio Guadalquivir N-1; 10. Ecija 1 and 2; 11. Córdoba A-1 to A-7, Córdoba B-1 and B-2, and Córdoba C-1; 12. Carmona 6; 13. Carmona-5; 14. Carmona-4; 15. Carmona-3; 16. Carmona-2; 17. Sevilla-3; 18. Carmona-1; 19. Sevilla-1; 20. Ciervo; 21. Sevilla-2; 22. Sevilla-4; 23. Cerro Gordo-3; 24. Bornos-3; 25. Bornos-1; 26. Angostura-Bornos; 27. Salteras-1; 28. Castilleja; 29. Isla Mayor; 30. Bética 14-1; 31. Bética 18-1; 32. Villamanrique; 33. Casa Nieves; 34. Sapo-1; 35. Villalba del Alcor-1; 36. Almonte-1; 37. Chiclana; 38. Asperillo; 39. Huelva-1; 40. Moguer-1. Striped area indicates the pre-Mesozoic basement overlain directly by Neogene.

Miocene sediments. Towards the N and NW, at the Rio Guadalquivir N-1 and Rio Guadalquivir K-1 wells, respectively, the drilled sections correspond to autochthonous Miocene shales with poorly compacted sands.

The top of the pre-Neogene basement, as imaged from well data and seismic profiles, dips gently ($2-4^\circ$) towards the SE beneath the basin, whereas below the thrust belt, where the Iberian crust is more heavily loaded, an increase in depth of as much as 10° is expected. Towards the southern margin of the basin, the seismic character of the top of the basement is lost below the thrust belt — this basin margin is not defined by basement structure, but by the thrust front. Figure 11 shows a smoothed contour map of depth to basement obtained from well data, seismic profiles and cross sections (Banks & Warburton 1991; Berástegui *et al.* this volume).

In most of the basin, the basement consists of Palaeozoic sediments in varying states of

metamorphism and, below the central area of the basin, intrusive rocks occur also, similar to those cropping out in the Iberian Meseta. In the southwesternmost areas (Marismas), the Palaeozoic rocks are overlain by a partially eroded cover of Mesozoic strata, ranging in age from Triassic to upper Cretaceous, which have been drilled by the Moguer, Almonte, Asperillo, Casa Nieves and Isla Mayor wells (see Fig. 8 for location). In the easternmost area, a partially eroded Triassic cover was drilled in the Bailén-1 and Baeza-2 wells. Figure 8 also displays a map of the Neogene subcrop on which can be observed the present-day boundaries of the Mesozoic cover.

On seismic profiles the materials forming the pre-Neogene basement are involved in normal faulting (Figs 12 and 13). These faults, striking roughly NE-SW, die out in the lower part of basin fill, in the first sequence that shows thickening into the basin. Fault offsets are generally less than 100 ms (two-way travel time), and there

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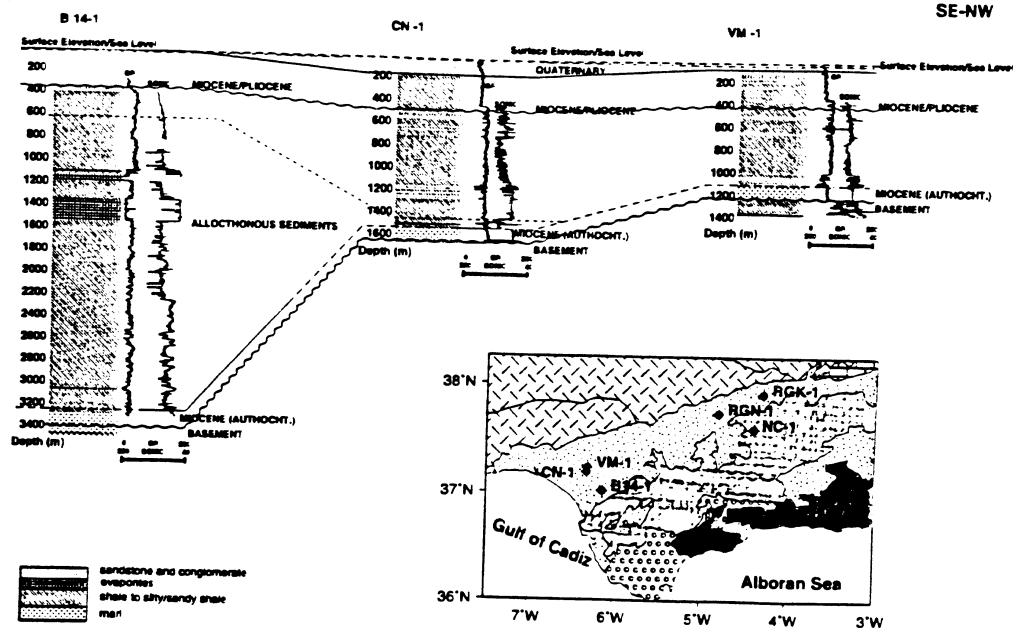


Fig. 9. Correlation section across selected wells in the westernmost Guadalquivir Basin. Allocthonous under-compacted sediments are recognized at the SE tip of the section, in the Betica 14-1 (B14-1) well, which progressively disappear towards the NW in the Casa Nieves-1 (CN-1) and Villamanrique-1 (VM-1) wells. Main lithologies, gamma-ray log (GR) expressed in API units, and sonic log ($\mu\text{s}/\text{ft}$) are shown for each well.

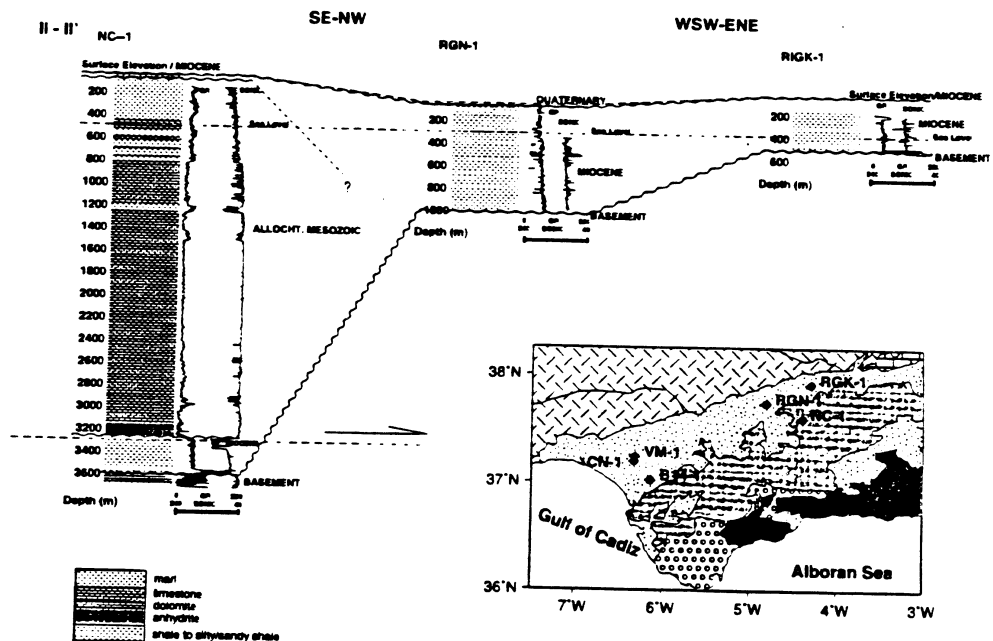


Fig. 10. Correlation section across selected wells from the Central Betic units that overthrust the autochthonous Guadalquivir Basin sediments at the Nueva Carteya-1 (NC-1) well towards the unperturbed basin interior at the RioGuadalquivir N-1 (RGN-1) and RioGuadalquivir K-1 (RGK-1) wells. Main lithologies, gamma-ray log (GR) expressed in API units, and sonic log ($\mu\text{s}/\text{ft}$) are shown for each well.

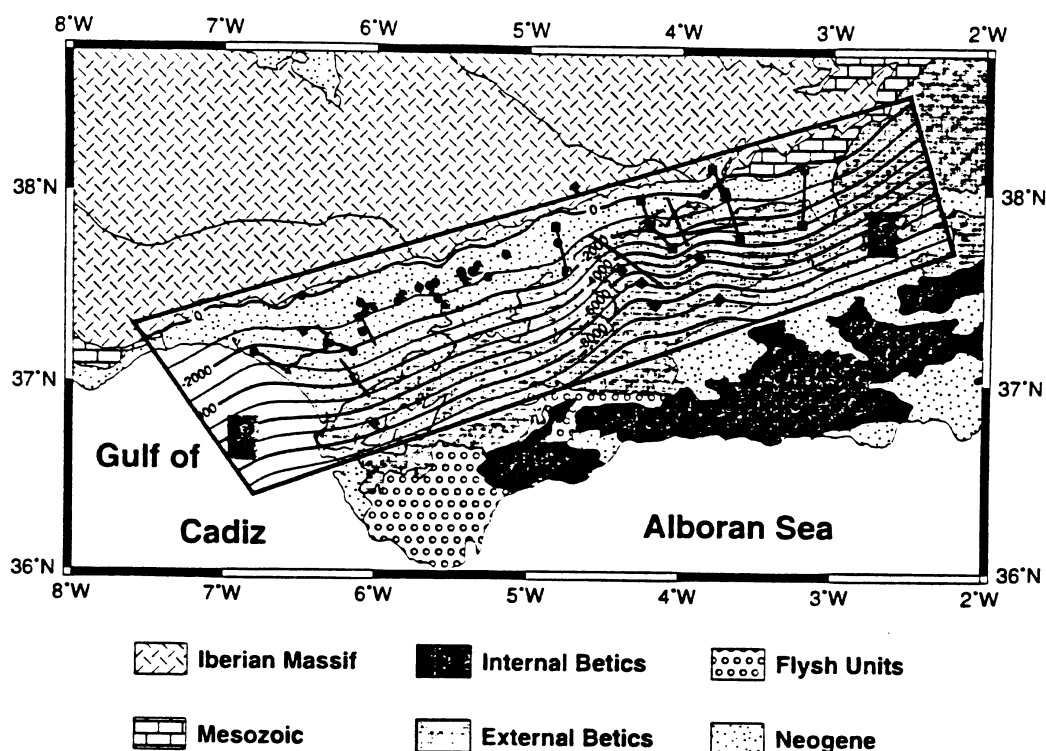


Fig. 11. Depth of the Palaeozoic basement map of the Guadalquivir basin referred to the sea level. Isolines every 1000 m. The data used come from oil wells (circles), seismic lines (squares), and cross-sections (diamonds) from Banks & Warburton (1991) and Berástegui *et al.* (this volume).

is a preponderance of faults downthrowing to the south. However, some large north-throwing faults are observed (Fig. 12), which have probably resulted from crustal arching when the tectonic load was emplaced during early Mid-Miocene (Langhian) times, thus the set leaves a longitudinal 'central high'. In a few places there is slight evidence of compressive reactivation of the faults (basin inversion), but this is not thought to be a major process in this basin.

The Neogene sedimentary infill is here arranged into six seismic-stratigraphic, depositional sequences bounded by unconformities and their correlative conformable boundaries, recording the time span from Late Langhian to Late Messinian. Because of the aforementioned dating uncertainties, we have tied the identified sequences to the standard Exxon cycle-chart (Haq *et al.* 1987) (Fig. 14) taking as a datum the well-known pre-Pliocene erosion. The nature of the boundaries, seismic facies, thicknesses, lithologies, sedimentary environments and ages attributed to each sequence are summarized in Table 2. Table 1 shows the correlation of the here-defined sequences to previous works. In

contrast to Siirro *et al.* (1996), from the set of studied seismic profiles (see Fig. 8) we cannot recognize any NE-SW progradational arrangement of the Late Langhian to Messinian set of sequences. Conversely, the Late Messinian to Plio-Quaternary deposits show a remarkable westward progradational pattern in the Marismas area (Fig. 15). The absence of the 'central high' in the westernmost part of the basin results in thickness variations of the sedimentary sequences from east to west.

The southern margin of the Guadalquivir Basin

As mentioned above, previous works agree that the most important infill supplied by the southern margin of the basin consisted of gigantic masses of chaotic materials that were emplaced by gravitational sliding.

Seismic profiles acquired recently show that the chaotic unit is formed by two kinds of seismic fabrics. The southern half is seismically non-coherent and corresponds to Triassic evaporites drilled in wells (e.g. Betica 18-1, Bornos-1, Bornos-3). The northern half consists of a set of

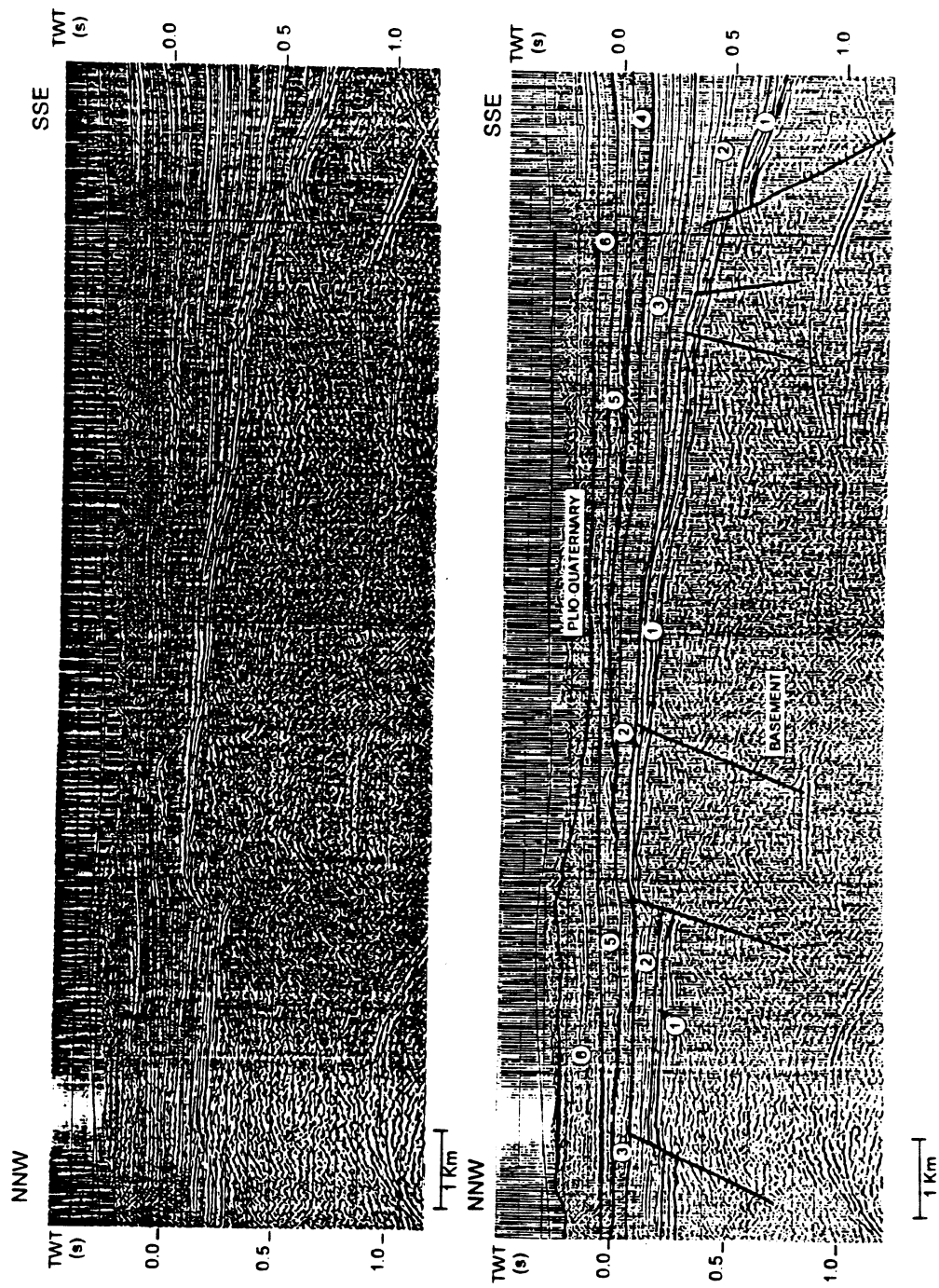


Fig. 12. Profile 1 (line 89-01). The interpreted version shows extensional structures involving the basement and Neogene sequences 1 and 2 (see text). Numbered sequences correspond to Tables 1 and 2.

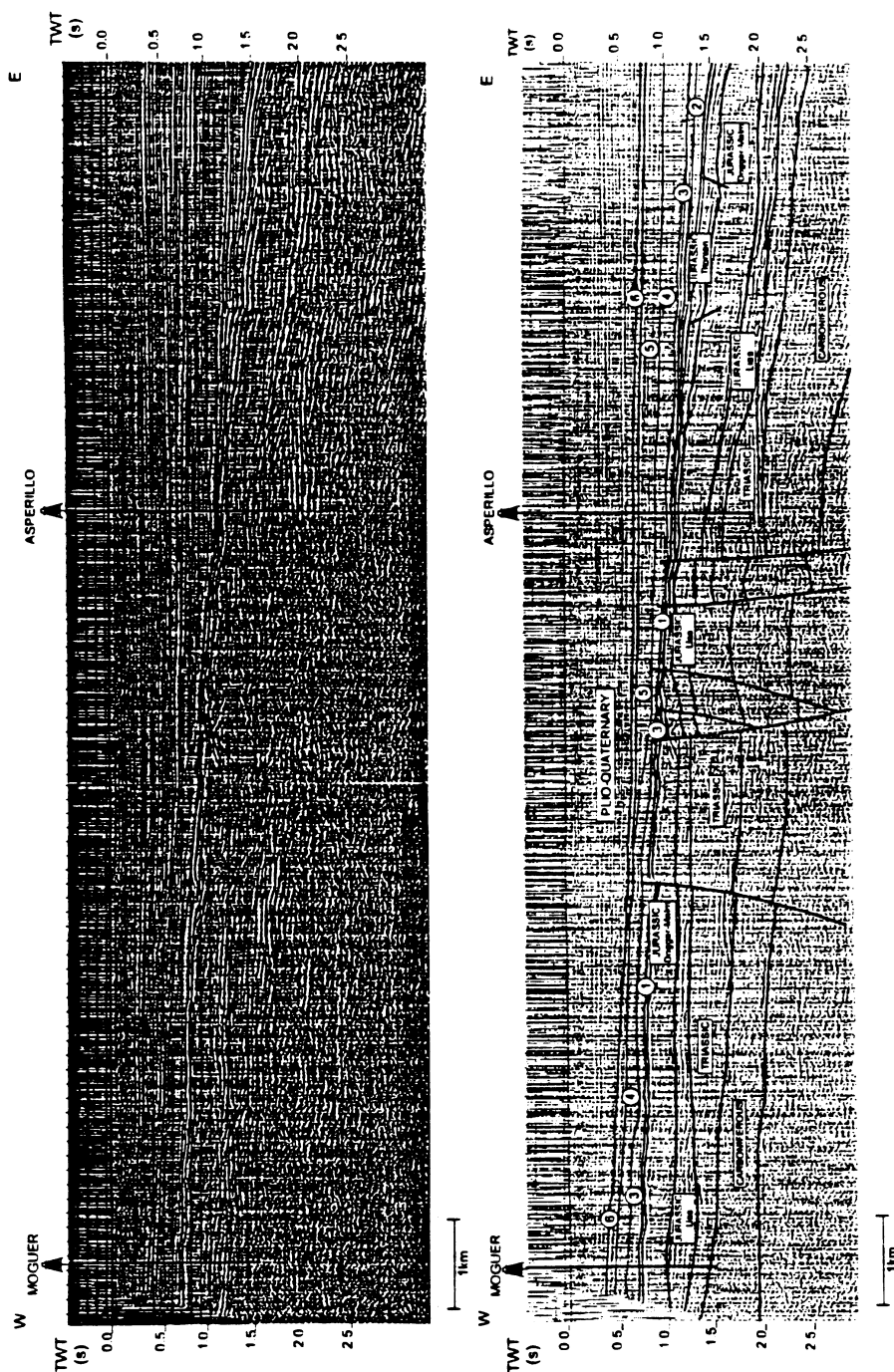


Fig. 13. Profile IV (line MA2) located in the Marismas area. The interpreted version shows the Palaeozoic structure, Mesozoic cover and Neogene sequences. Numbered sequences correspond to Tables 1 and 2.

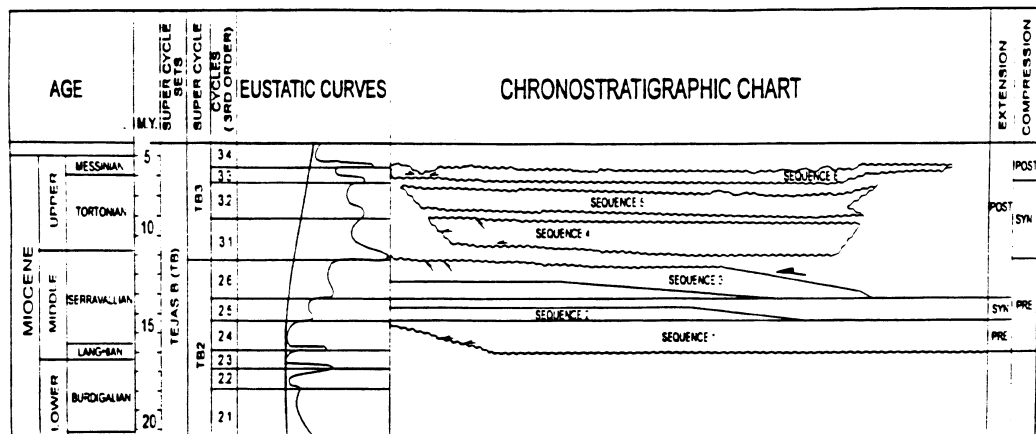


Fig. 14. Cycle chart showing the established sequences and its correlation to the standard cycle chart (Exxon). Sequences are also correlated to the basement extension and compression.

imbricate thrust slices involving Miocene sediments (e.g. Isla Mayor-1, Carmona-4, Ecija-1-2), displaying a wedge-shaped structure (Fig. 16). Moreover, it can be observed that the southernmost, more internal, seismically non-coherent part, is beneath the Mesozoic limestones forming the External Zones of the chain, and that its contact with the frontal Miocene imbricates can be interpreted as a more or less complex reverse fault, or as a diapiric contact. To summarize, from the integration of field, seismic and well data, we propose that the 'so-called olistostromes' are the result of squeezing of Keuper materials from below the External Zones (Fig. 16) that pushed the Miocene sediments ahead, thus forming the frontal deformed

wedge. The processes involved include evaporite lateral diapirism, glacier-like flow and cap-rock formation. The chaotic character of this unit in outcrop corresponds to the above-mentioned cap-rock formation, together with small vertical evaporite developments that can involve the overlying Miocene sediments. This interpretation differs from those given by previous authors in that: (1) the 'so-called olistostromes' are not a single body but encompass an internal Triassic part and a frontal Miocene deformed wedge; (2) their emplacement does not correspond to gravitational sliding but to a lateral diapiric mechanism; (3) they do not form part of the basin sedimentary infill. A wider interpretation and discussion about the origin and

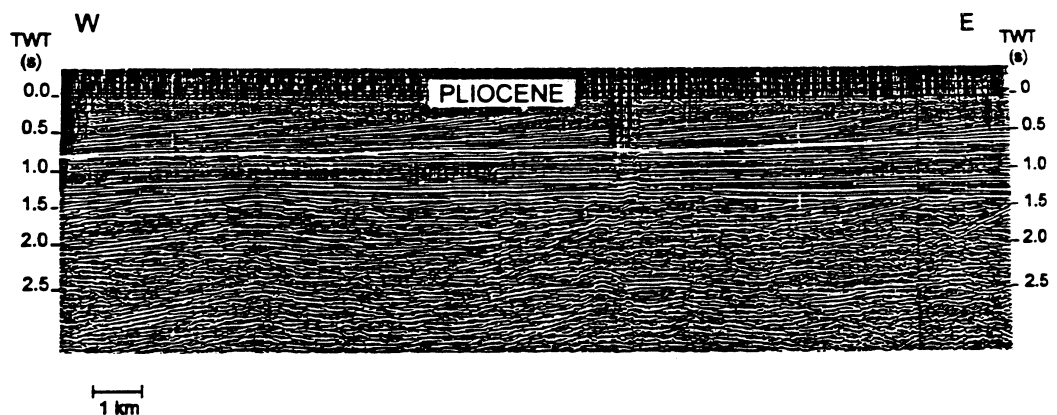
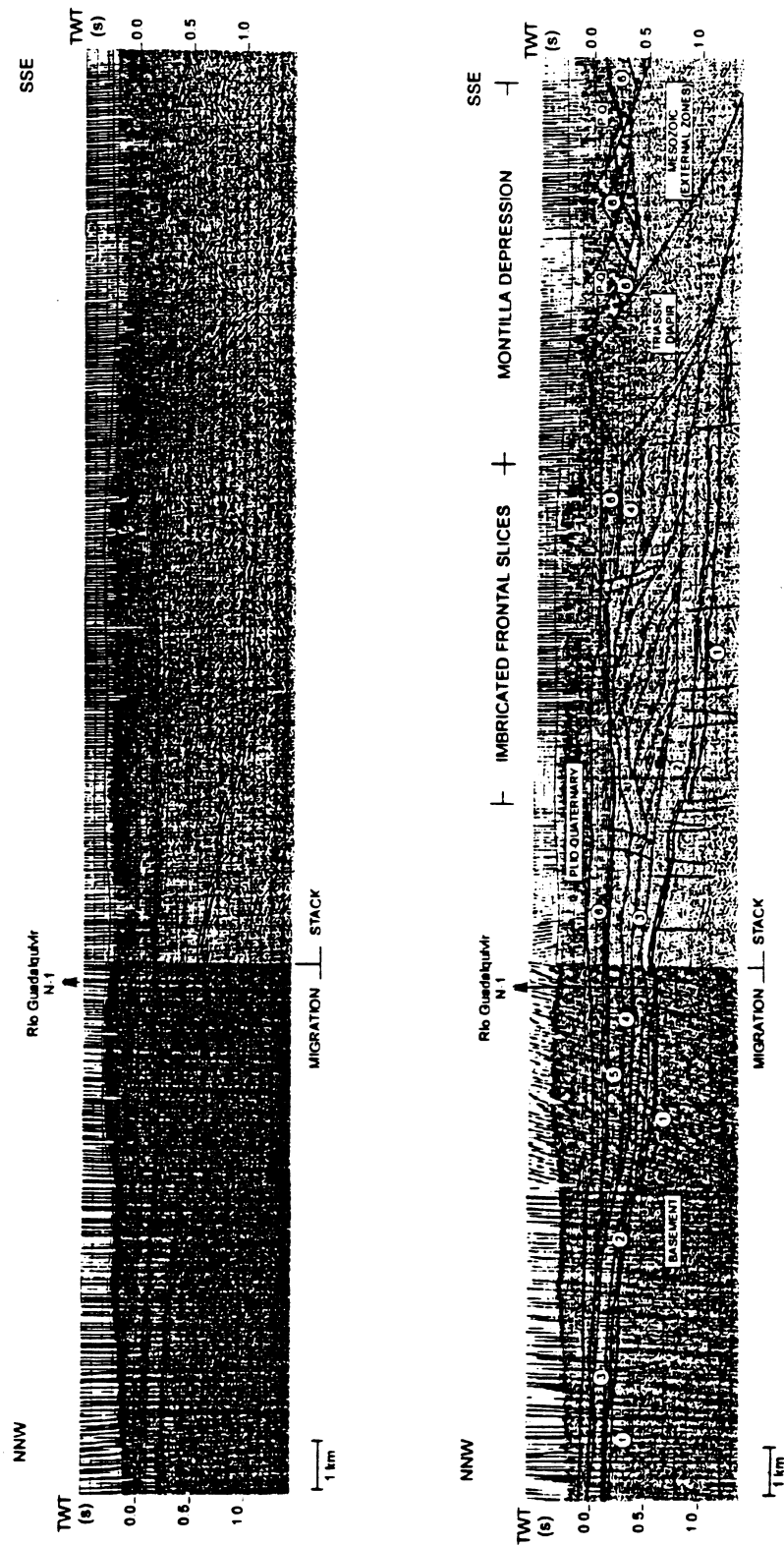


Fig. 15. Profile III (Line MA-4). Pliocene to Quaternary progradational stratal pattern towards the West (Marismas area).



mechanisms of emplacement of this frontal unit is presented by Berástegui *et al.* (this volume).

The NW–SE cross-section displayed in Fig. 17 (see Fig 8 for location) summarizes the tectonostratigraphic zones of the Guadalquivir Basin and External Betics. Details on the basement dip, structure of the frontal imbricates and lateral diapir, as well as the arrangement of the External Betics are shown.

Discussion

The evolution of the Guadalquivir Basin is closely related to the formation of the Betic Chain and the Alboran Sea. This relation was already pointed out by van der Beek & Cloetingh (1992), who presented the only attempt to model the flexural response of the Guadalquivir Basin. These authors considered the present-day basement deflection under topographic loads associated with the External and Internal Betics and used gravity modelling to constrain the resulting crustal structure. Several important features were derived from this work: (a) very low elastic thickness values equivalent to 10 km in the western Betics and nearly zero in the eastern Betics; (b) the necessity to invoke subsurface loads; (c) the necessity to invoke an Oligocene–Early Miocene extensional event affecting the margin before the main phase of overthrusting; (d) a qualitative relationship between elastic thickness and rheology that was controlled by the thermal regime.

The role of the crustal structure and thermal regime on the rigidity of the continental lithosphere and therefore on its flexural response has been established by different authors (e.g. Beaumont 1979; Bodine *et al.* 1981; Burov & Diament 1992). The combination of high heat-flow and thick crust results in a low value of the total lithospheric strength. The heat-flow data (Fig. 5) show a thermal pattern characterized by a clear eastwards increase in heat flow (up to 125 mW m⁻²) in the Alboran Sea (Polyak *et al.* 1996). The western part of the Guadalquivir Basin is also characterized by rather high heat-flow values (70–85 mW m⁻² on average), whereas the available data in the Betics show strong perturbations due to groundwater circulation, that completely mask the deep thermal signature. Nevertheless, the regional thermal pattern together with the crustal thickness variations (Fig. 4) suggest that the present-day elastic thickness across the Guadalquivir Basin and the Betics should decrease towards the east as inferred by van der Beek & Cloetingh (1992).

An outstanding feature deduced from the interpretation presented is the non-existence of

gigantic olistostromic masses in the southern border of the basin as has been claimed by previous authors. According to Berástegui *et al.* (this volume) these bodies are, in fact, the result of tectonically squeezed Triassic materials and Miocene deformed frontal wedges. This interpretation has strong implications for the palaeogeography. The presence of olistostromes in the southern margin of the basin has led authors to propose that the pre-Guadalquivir Basin corresponded to a foredeep in order to have the necessary palaeo-relief for their deposition. As a consequence, Early Miocene palaeogeographic schemes have been characterized by deep waters and a frontal trough (e.g. Sanz de Galdeano & Vera 1992). However, it is quite difficult to reconcile this environment with the subsidence of the basement and with the observed stratigraphy. The new interpretation of the southern margin of the Guadalquivir Basin does not require deep waters and is more tectonically consistent with the evolution of the orogenic loads, the geometry of the sedimentary basin-fill, and with the thermomechanical behaviour of the lithosphere.

According to van der Beek & Cloetingh (1992), the origin of subsurface loads acting in the Internal Betics is related to the sharpness of the crustal towards the Alboran Sea. This allowed them to account for the extra load, associated with the replacement of crustal material by denser mantle, making it compatible with observed Bouguer gravity anomaly. However, further gravity models, constrained by deep seismic data, show that the crustal thinning from 34–35 km to 20–22 km is produced over an area 15–30 km wide (Torné & Banda 1992; Torné *et al.* 1992), which is noticeably narrower than that proposed from flexural modelling. This steep thinning affects the northern margin of the Alboran Sea except its easternmost part as is evident from the Moho depth map (Fig. 4). Therefore, subsurface loads associated with the crust–mantle transition if any, should be of less significance.

The necessity of subsurface loads to fit the basement deflection together with the assumption of deep palaeo-bathymetries in the Betic front led van der Beek & Cloetingh (1992) to propose that the margin should have undergone a rifting event prior to the Betic overthrusting. From the arguments presented above, we think that the existence of such an Oligocene–Early Miocene rifting event is highly questionable, at least in the Central Betics.

To date, no attempts have been made to numerically model the progressive evolution of the Guadalquivir Basin. The geometry of a

foreland basin as well as the architecture of its sedimentary fill records the main tectonic features related to thrust sheet displacements, crustal shortening and associated changes in the thermo-mechanical properties of the lithosphere. Most of the work carried out in this project has been directed toward establishing the main features that characterize the evolution of the Guadalquivir Basin which are: (a) initiation of subsidence; (b) time distribution of surface loads; and (c) lithospheric structure and subsurface loads.

Initiation of subsidence. A major problem in understanding the evolution of the Guadalquivir Basin is the determination of the time at which the first sediments were deposited. The results obtained from our seismic stratigraphic interpretations indicate that the oldest sediments overlaying the basement are Late Langhian although radiometric dating is necessary to confirm this age. This sequence extends to the south below, at least, the Miocene wedge and the lateral diapir (formerly called olistostromes). However, the presence of older sediments further to the south cannot be ruled out since compression initiated at Late Cretaceous thus producing a progressive northward migration of the foreland basin. Probably, the sediments filling this pre-Guadalquivir basin were incorporated to the hanging wall of the frontal thrusts. This picture is actually very similar to that imaged on seismic profiles at the most frontal part of the External Zones of the Betic Chain.

Time distribution of surface loads. The main surface loads acting in the Guadalquivir Basin correspond to the External and Internal Betics. The interpretation of the available data has permitted a better definition of the depth to basement towards the SSE (Figs 11 and 17). In these figures it can be seen that the Mesozoic and Palaeozoic basements reach up to 7 and 10 km depth respectively below the External Betics and dip below the Internal Betics. The sedimentary infill of the Guadalquivir Basin indicates that from Late Langhian to Messinian the acting loads were preferentially displaced in a NNW direction since no E-W onlaps and progradations are evident. The situation could have been radically different from Messinian to Recent as eastwards progradations are recognized in the western part of the basin together with a huge Pliocene erosion in its eastern part. These facts indicate that the Guadalquivir Basin probably underwent a differential uplift in its eastern border which could be related to the

regional Pliocene uplift that affected most of the Mediterranean Spanish coast (Sanz de Galdeano & Vera 1992; Janssen *et al.* 1993).

Lithospheric structure and subsurface loads. Different studies have shown that the load produced by thrust stacking (surface load) is in some cases too large (Ganga Basin and Himalaya; Lyon-Caen & Molnar 1983, 1985) or too small (Pyrenees and Apennines; Brunet 1986; Royden 1988) to fit the observed basement deflection and gravity anomaly. As a consequence, it is necessary to invoke the existence of subsurface loads or bending moments. A plausible cause for this extra load could be the redistribution of mass at deep crustal and lithospheric levels during tectonic shortening (e.g. Brunet 1986; Royden 1988). Since the density contrast between the crust and the lithospheric mantle and between the mantle and the asthenosphere has an opposite sign, the resulting net load will depend on the lateral and vertical distribution of strain. Deep seismics, gravity and geological data indicate that the southern margin of the Iberian Peninsula underwent a large amount of tectonic deformation that affected different crustal levels. Furthermore, heat flow and geoid data show that deformation is not restricted to the crust but also affected the upper mantle. The mass distribution in the crust differs noticeably from that in the upper mantle as evidenced when comparing gravity and geoid data. It is therefore possible that subsurface loads resulting from mass redistribution over time may have played an important role in determining basement subsidence and the associated sedimentary pattern in the study area.

In summary, the compilation and re-interpretation of available data have permitted the improvement of the present-day knowledge of the Guadalquivir foreland basin and to change radically some of the previous interpretations. The results obtained from the presented work put important constraints on further numerical models of the basin. Clearly, there are still some aspects that remain unresolved, such as the quantification and identification of the acting loads and the resulting flexural rigidity; the role of the formation of the Alboran Sea and the associated unloading; the transition from the Atlantic to the Mediterranean and the continuation of the Guadalquivir Basin into the Gulf of Cadiz; and the nature of the vertical movements that the basin seems to have experienced from Pliocene to Recent. Ongoing studies dealing with some of these topics are being developed by the institutions involved in this project.

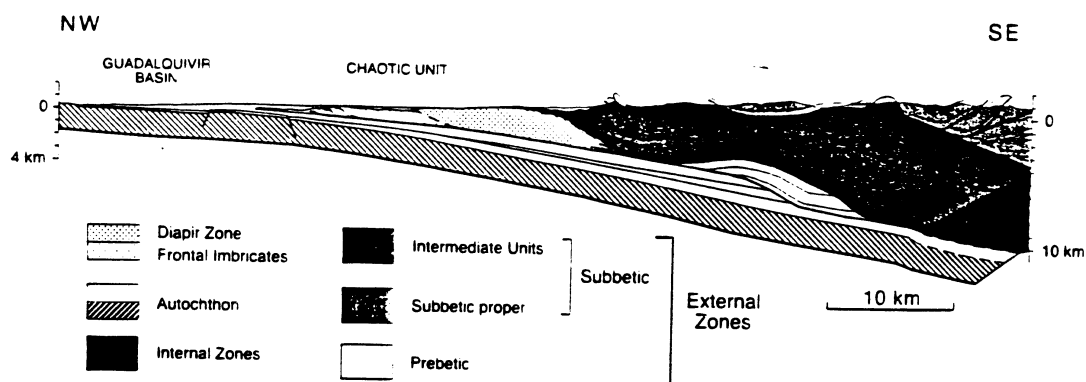


Fig. 17. 'Martos' cross-section showing the tectonostratigraphic units and the extrusion of the diapir zone along the base of the Intermediate Units.

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