The Valencia Trough: geological and geophysical constraints on basin formation models

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ABSTRACT

The Valencia Trough, located between the Spanish mainland and the Balearic Promontory, is one of the Cenozoic extensional basins of the Western Mediterranean which developed in a region of convergence between the European and African plates. The Valencia Trough began to subside during the late Oligocene-early Miocene along the Mediterranean side of Spain, coeval with a phase of compression which affected its southeastern margin, formed by the Balearic Promontory. This rifting phase was followed by a period of post-rift subsidence. During the Plio-Quaternary, extensional tectonics and minor volcanic activity resumed along the Spanish margin of the Trough. This phase of extension is, however, not recorded in the central parts of the basin. The wealth of geological and geophysical data collected from the Valencia Trough during the last decades provides a precise image of its crustal structure; however, its deep lithospheric configuration is still poorly known.

The Valencia Trough is characterized by a strongly attenuated continental crust, except in its northeasternmost part where oceanic crust is probably present. It is underlain by an anomalous low-velocity uppermost mantle, the lateral extent and thickness of which are still under debate. Kinematic models of basin development have been quite successful in describing some aspects of the central parts of the Trough, though not of the entire basin and particularly not for its southern region. As these models failed to integrate the complex plate interactions which governed the development of the Valencia Trough, they must be regarded as simplistic. The Valencia Trough hosts an oil province which is largely restricted to the Ebro delta.

INTRODUCTION

The Valencia Trough is a NE-SW oriented triangular shaped basin which is located between the Spanish mainland and the northeastern prolongation of the Betic Cordillera, the Balearic Promontory (Fig. 1). The continental crust underlying this trough was consolidated during the Hercynian orogeny. During the Mesozoic break-up of Pangea,

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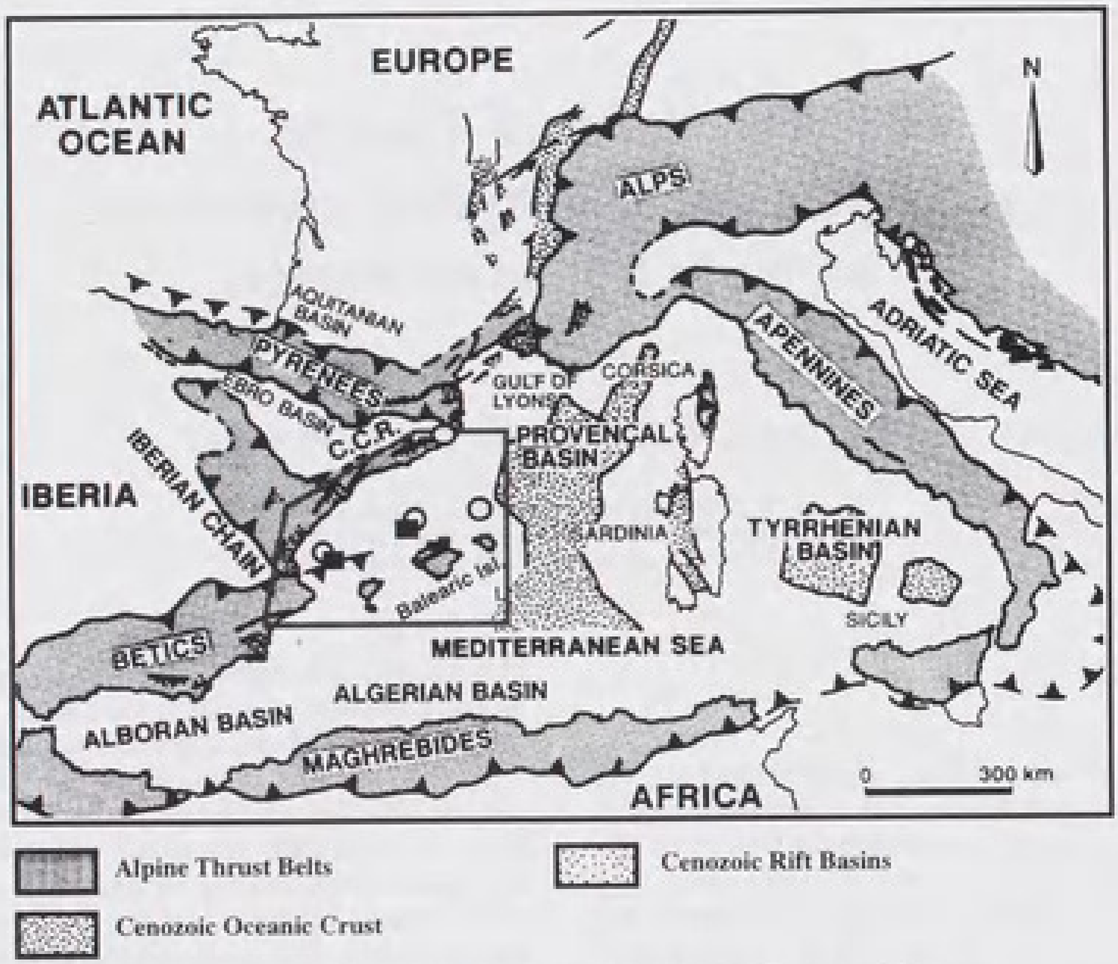

FIG. 1. Location map of the study area showing main geological features of the Western Mediterranean (modified after Banda and Santanach, 1992b). Valencia Trough is outlined by heavy grey line. C.C.R.: Catalan Coastal Ranges. Black squares: calcalkaline magmatism (30-15 Ma); Open circles: alkaline magmatism (15-0 Ma). (location of volcanic outcrops from Martí et al.,1992).

this crust underwent repeated extensional events, controlling the subsidence of graben structures. During the latest Cretaceous and Paleogene, intraplate compressional stresses caused inversion of the Iberian Chain, the Catalan Coastal Ranges and their off-shore equivalents (Fig. 1); during this process, Mesozoic extensional crustal thinning was apparently largely recovered.

The present day structure of the Valencia Trough is thought to result from a late Oligocene-early Miocene rifting event which was coeval with a phase of compression confined to the southeastern margin of the basin, formed by the Balearic Promontory. This extensional phase affected mainly the northwestern part of the basin, as evident by the development of a series of horst and graben structures, bounded by ENE-WSW trending normal faults. Whereas the horsts are held up by a variety of Palaeozoic and Mesozoic rocks, the grabens were filled by late Oligocene-early Miocene shales (Torres and Bois, 1993). In contrast, the Balearic part of the basin is characterized by a series of SE-NW trending thrusts and reverse faults which developed during a Late Oligocene to Middle Miocene compressional phase (Roca and Desegaulx, 1992). Subsequently, these compressional structures were tensionally reactivated, resulting in the development of horst and graben structures, as seen on the Island of Mallorca (Fig. 1). For further details the reader is referred to Banda and Santanach (1992a).

The Valencia Trough has been the target of extensive geological and geophysical investigations by the petroleum industry and academic institutions (Fig. 2). During the 1970's and 1980's, the Catalonian shelf was intensely explored for hydrocarbons. The recording of extensive reflection-seismic surveys and the drilling of over 90 wells (Fig. 2a) resulted in the discovery of a number of small and one large oil fields, having cumulative ultimate recoverable reserved of the order of 250 to 300 x 106 bbls of oil. Most of these accumulations are contained in extensional fault blocks and buried hills, upheld by karstified Mesozoic carbonates. These structures are sealed by middle Miocene basinal shales. Hydrocarbon charge is provided by Mesozoic source-rocks as well as by late Oligocene-early Miocene shales which were deposited during the early rifting stage of the Valencia Trough. These data sets provide valuable information on the sedimentary record of the Valencia Trough and its subsidence and thermal evolution.

The first academic geophysical experiments commenced in the early 70's with the acquisition of two seismic refraction profiles, located North and South of the Island of Mallorca (Hinz, 1972; Gobert et al., 1972), followed up by a seismic refraction/wide-angle reflection experiment along the Balearic Promontory (Banda et al., 1980). During 1988 the VALSIS experiments were carried out to determine the lithospheric configuration of the basin. During a first cruise (VALSIS-I) heat-flow measurements were acquired along four transects crossing the axis of the Trough (Fig. 2b; Foucher et al., 1992). During a second cruise (VALSIS-II), twelve deep multichannel seismic-reflection profiles (CDP), eight wide-aperture multichannel profiles (COP) and six expanded spread profiles (ESP) were recorded (Figs. 2c and 2d). Marine seismic data were complemented by land recording of shots (Gallart et al., 1990). An additional refraction/wide-angle reflection experiment was carried out during the summer of 1989 along three profiles crossing the basin (P-I, P-II, and P-III of Fig. 2d; Dañobeitia et al., 1992). For a detailed discussion of CDP results data the reader is referred to Mauffret et al. (1992), Maillard et al. (1992) and Torné et al. (1992). The ESP results are discussed by Pascal et al. (1992) and Torné et al. (1992) and the wide-angle data by Gallart et al. (1990) and Dañobeitia et al. (1992). COP results were presented by Collier et al. (1994). In 1992, the crustal structure of the Valencia Trough was investigated by coincident steep and wide-angle reflection data (Fig. 2c) under the auspices of the Spanish Estudios Sísmicos de la Corteza Ibérica (ESCI) Program (Gallart et al, 1995; Vidal et al., 1995).

The results of these experiments show that the Valencia Trough is characterized by a strongly attenuated continental crust which is underlain by an anomalous low-velocity upper mantle (7.6 to 8.0 km/s), except in its northeasternmost part where oceanic crust is probably present. In the central part of the basin, the crust has a thickness of about 15-16 km; towards its margins it increases asymmetrically to average values of 20-22 km along the Iberian coast and about 24 km below Mallorca. Along the flanks of the basin, the upper and middle crust are characterized by an almost transparent layer with velocities ranging from 6.1 to 6.4 km/s. In contrast, the lower crust is variably reflective below the flanks of the basin and has velocities in the 6.4 to 6.9 km/s range, whereas it is almost absent under its axial parts.

Information on the configuration of the lithosphere-asthenosphere boundary comes primarily from modelling results. Modelling of the central part of the basin shows that the lithosphere thins towards the axis of the basin to values in the 60 to 65 km range (e.g., Watts and Torné 1992a; Zeyen and Fernàndez, 1994). Moreover, surface-wave studies favour thinning of the lithosphere towards the central part of the basin (Marillier and Mueller, 1985). There is no information, however, on the position of the lithosphere-asthenosphere boundary in the southern parts of the Trough, and also in the North at its transition to the oceanic Provençal basin (Fig. 1).

Direct evidence for volcanic activity comes from outcrops and exploration wells (Lanaja, 1987) and DSDP Site 123 (Ryan et al., 1972). Reflection-seismic and aeromagnetic data provide indirect evidence for additional volcanic centres (e.g., Mauffret, 1976; Maillard et al., 1992; Martí et al., 1992; Galdeano et al., 1974) (Fig. 1). Following Martí et al. (1992), Cenozoic magmatism in the area is characterized by two volcanic cycles which are clearly separated in time and by their petrology and tectonic setting. The first volcanic cycle (late Chattian-early Burdigalian) coincides

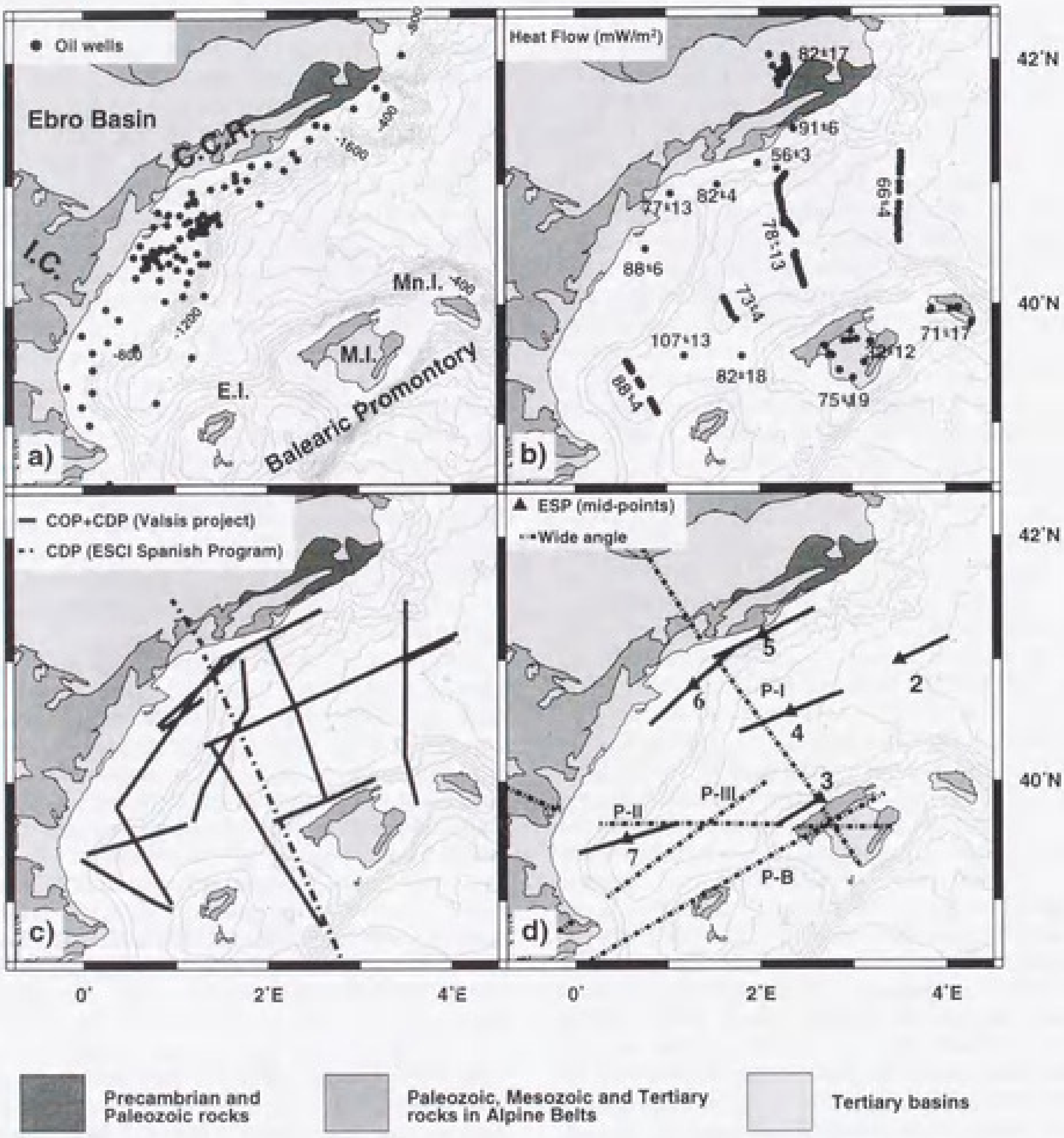

FIG. 2. **a)** Location of hydrocarbon exploration wells along the Ebro platform and Spanish margin. C.C.R.: Catalan Coastal Ranges; I.C.: Iberian Chain; E.I: Island of Eivissa; Mn.I.: Island of Menorca; M.I.: Island of Mallorca.
b) Heat flow determinations in mW/m^2.
c) Track lines of deep multichannel seismic profiling. Thick lines: Valsis-II CDP/COP profiles. Dashed-dotted line: ESCI coincident steep and wide-angle reflection profile.
d) Thick lines: Valsis-II ESP Profiles (triangles show mid-point locations). Dashed-dotted lines: wide-angle/refraction seismic profiles.

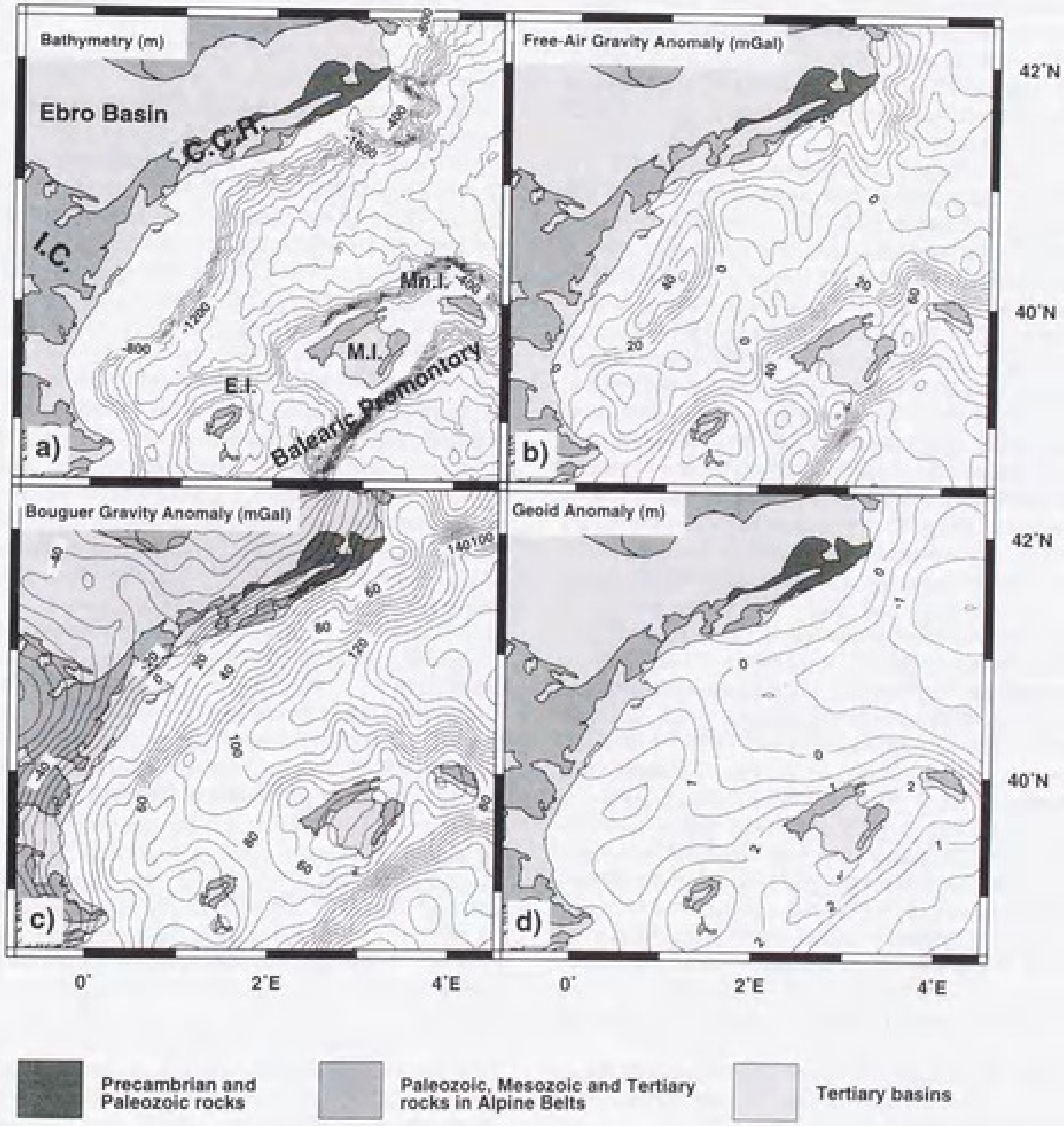

FIG. 3. **a)** Bathymetry of Valencia Trough, 200 m contour intervals.
b) Free-Air gravity anomaly map based on all available marine gravity data. Contour interval 10 mGal. Abbreviations as in Fig. 2.
c) Simplified Bouguer gravity anomaly map, contour interval 10 mGal (after Torné et al., 1992). Data on Iberia are based on Casas et al. (1987) and on Mallorca on IGME (1981).
d) Geoid anomaly map, contour interval 0.5 m. The map is based on GEOMED (e.g., Sevilla, 1992). A regional field based on the OSU91A model to degree and order 12 has been removed from the observed data prior gridding.

with the initial, main phase of rifting and is characterized by calcalkaline andesitic and pyroclastic rocks. The second cycle (Tortonian to Recent) is characterized by poorly differentiated alkali-basalts and was accompanied by a minor phase of extensional tectonics.

Paleomagnetic investigations suggest a 20^{o} early-middle Miocene clockwise rotations of the islands of Mallorca and Menorca relative to the Catalan Coastal Ranges, coinciding with the emplacement of the Betic-Balearic thrust sheets. A further late Miocene-Pliocene rotation of up to 20^{o} may be related to extensional faulting. However, it can not be excluded that part of these rotations are related to whole lithospheric movements (Parés et al., 1992). These authors point out that clockwise rotation in the Balearic Islands is in disagreement with most of the models proposed for the evolution of the Western Mediterranean, and that the total amount of rotation is too large to be accounted for by crustal extension in the Valencia Trough.

In summary, the various studies of the basin, using different geological and geophysical approaches, have resulted in a wide range of geodynamic hypotheses. These range from back-arc extensional mechanisms, related to northwestward subduction of oceanic lithosphere (e.g., Bocaletti and Guazzone, 1974; Mauffret, 1976; Banda and Channel, 1979; Cohen, 1980; Horvath and Berckhemer, 1982) to intra-continental rifting, related to horizontal movements of crustal blocks and seafloor spreading (e.g., Auzende et al., 1973; Rehault et al., 1985) and rift propagation from the Alpine forelands across the Alpine megasuture (Ziegler, 1988, 1992). Recently, Fontboté et al. (1989) and Roca and Desegaulx (1992) postulated that development of the Valencia Trough could be explained by foreland-type mechanisms, whereas Doblas and Oyarzun (1990) proposed that its origin is controlled by a major extensional detachment surface, cutting the crust and lithosphere, and upwelling of the asthenosphere.

In this paper we summarize the present-day crustal and lithospheric configuration of the Valencia Trough and focus on modelling results and difficulties and limitations which have been encountered when applying "classical" extensional models to explain the origin and evolution of this basin.

GEOPHYSICAL OBSERVATIONS

In this section we present a compilation of the various geophysical data sets which provide constraints on modelling the evolution of the Valencia Trough (Figs. 2 and 3). Figure 3a illustrates the triangular shape of this basin and its opening to the Northeast where water depths reach values of up to 2500 m, whereas in its southwestern parts they not exceed 1200 m. The axial trough is flanked by narrow shelves, except in the area of the Ebro delta (Fig. 3a).

Up to the VALSIS-I survey, information on the thermal regime of the area was limited to temperature gradients obtained from on-shore and offshore water and oil wells. These indicate that areas adjacent to the Trough are characterized by large temperature gradient variations, probably related to ground-water circulation (Fernàndez and Banda, 1989; Fernàndez et al., 1990). Similarly, heat-flow values for the eastern part of the Ebro basin (Cabal and Fernàndez, 1995) and the Spanish shelf (Negredo et al., 1995a) are also high variable and range from 55 to 90 mW/m^2. The islands of Mallorca and Menorca are characterized by background heat flow values of about 70-80 mW/m^2 and 75-90 mW/m^2, respectively (Fernàndez and Cabal, 1992). Results of the VALSIS-I survey (Foucher et al., 1992), which are not corrected for the thermal blanketing effect of sediments, indicate for the axial part of the basin heat-flow values varying from 88 mW/m^2 in the Southwest to 66 mW/m^2 in the Northeast at the transition to the Provençal basin, and thus demonstrate a significant decrease in heat-flow values towards deeper waters (Fig. 2b).

Free-Air gravity data (Fig. 3b) show that the axial parts of the Trough are dominated by values around 0 mGal whereas on its flanks maximum values of about 40 mGal are reached. This may suggest that the regional features of the study area are in local isostatic equilibrium; this is in accordance with various modelling results which show that the lithosphere has acquired little or no strength since rifting (e.g. Watts and Torné, 1992b; Zeyen and Fernàndez, 1994). Bouguer gravity data shows that the Trough is associated with a gravity anomaly high of about 100-150 mGal (Fig. 3c). 2D gravity modelling by Watts and Torné (1992a) shows that this gravity high can be explained by the combined effect of mantle and crustal thinning.

Figure 3d gives a map of geoid anomalies derived from GEOMED (e.g., Sevilla, 1992). Since the geoid is more sensitive to deep mass distribution than gravity, this can help in better deciphering the topography of the base of the lithosphere. Figure 3d shows that the Valencia Trough is associated with a relatively broad negative geoid anomaly which increases in magnitude toward the northeastern, whereas both flanks, and particularly the Balearic Promontory, are associated with positive geoid anomalies of up to 2 m. A first evaluation of this geoid anomaly low favours the hypothesis that the lithosphere is thinner under the central part of the Trough.

CRUSTAL AND LITHOSPHERIC STRUCTURE

In the following we discuss the sedimentary fill of the Valencia Trough, its upper and lower crustal configuration and the structure of the lithosphere/asthenosphere boundary.

Sedimentary Record and Basement Structure

Following Soler et al. (1983), the stratigraphic record of the Valencia Trough and surrounding areas is characterized by a major unconformity separating the Palaeozoic-Mesozoic basement from its Oligocene to Quaternary sedimentary cover (Fig. 4). On the Spanish shelf, Hercynian deformed Palaeozoic sedimentary and metamorphic rocks are uncomformably overlain by Permian and Mesozoic series, consisting of carbonate, siliciclastic and evaporite rocks (Torres and Bois, 1993). Rapid lateral thickness variations and facies changes indicate that these sediments accumulated in tensional basins which developed in conjunction with the opening of the Tethys Ocean (e.g. Ziegler, 1988; Fontboté et al., 1989; Maillard et al., 1992). On the islands of Mallorca and Eivissa (Fig. 2a), Middle Jurassic-Late Cretaceous series were developed in a slope and base of slope facies, reflecting their location along the Tethys passive margin (Banda and Santanach, 1992b).

The latest Cretaceous and Paleogene phase of intraplate compression was responsible for the inversion of the Mesozoic basins and uplift of the present-day off-shore parts of the Valencia Trough (Fig. 1). Inversion of the Iberian Chain was accompanied with the development of a series of NW-SE and E-W striking thrust faults (Guimerá, 1984; Guimerá and Alvaro, 1990) whereas the Catalan Coastal Ranges evolved in response to convergent wrench movements along NE-SW striking faults (Anadón et al., 1985). In the off-shore, Paleogene rocks are generally absent, except in the Barcelona graben (Bartrina et al., 1992) where continental or transitional deposits are present. In contrast, widespread Eocene to Oligocene lacustrine carbonates and lignites occur on the island of Mallorca (Ramos-Guerrero et al., 1989).

The Oligocene to Quaternary sedimentary fill of the Valencia Trough can be subdivided in four depositional sequences, separated by unconformities (Fig. 4b; García-Siñeriz et al., 1979; Soler et al., 1983; Anadón et al., 1989; Clavell and Berastegui, 1991).

On the western flank of the Trough, the lower sequence, spanning late Oligocene to Langhian times, consists of basal continental-transitional clastics and shales, which accumulated in fault-bounded shallow basins, and the transpressive early Miocene marine shales and carbonates of the Alcanar formation. The latter was deposited after the first rifting stage (Chattian-Aquitanian) and during the Betics compressional phase (Torres and Bois, 1993) and oversteps the block-faulted relief of the Valencia rift (Fig. 5). On the southeastern flank of the basin, Chattian-Aquitanian sediments consist of shallow-water carbonate and clastic rocks (Rodríguez-Perea, 1984; Anglada and Serra-Kiel, 1986) whereas Burdigalian and Langhian series consist of pelagic and calcareous turbidites that were deposited during the thrust deformation of the Balearic Promontory.

The second sequence spans Serravallian to early Messinian times. On the Balearic Promontory it is represented by carbonates deposited under a

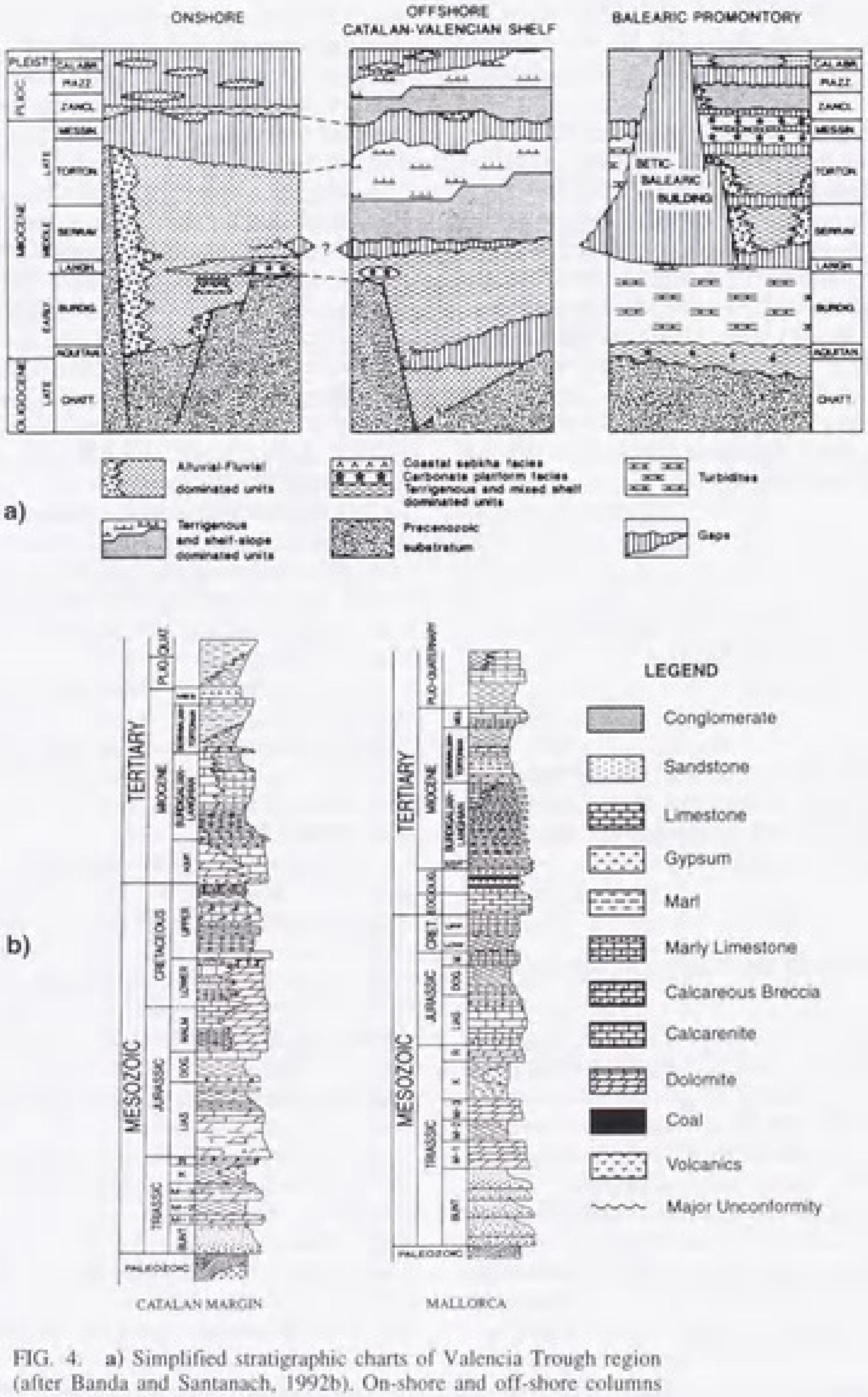

FIG. 4. **a)** Simplified stratigraphic charts of Valencia Trough region (after Banda and Santanach, 1992b). On-shore and off-shore columns after Bartrina et al. (1992).
b) Stratigraphic columns of the Spanish margin and Mallorca (after Torres and Bois, 1993).

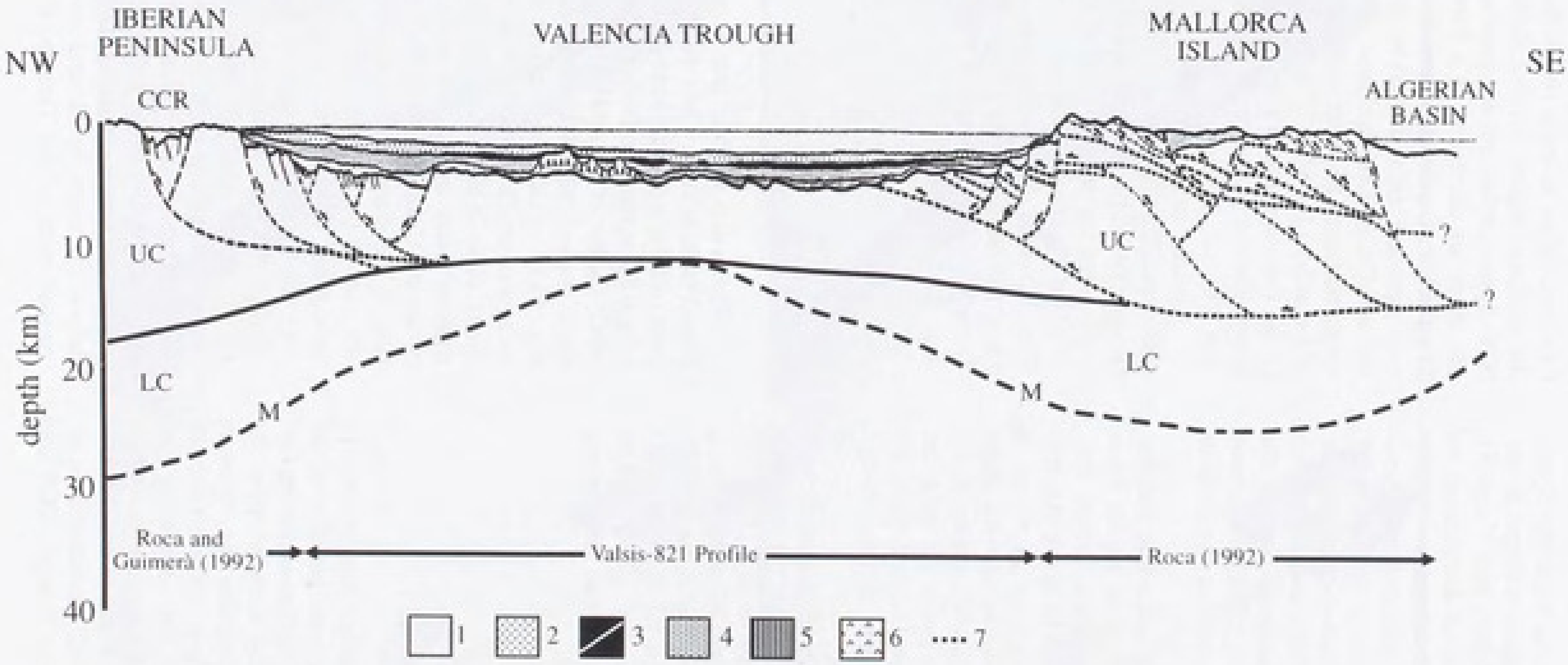

FIG. 5. Regional cross-section through Valencia Trough region along CDP line 821. For location see Fig. 8. (after Torres et al., 1993). UC: Upper crust; LC: Lower crust; M: Moho. 1 = water; 2 = Ebro Group (Pliocene-Quaternary); 3 = Messinian; 4 = Castellon Group (Serravallian-Tortonian); 5 = Lower Neogene (Aquitanian-Langhian); 6 = Volcanics; 7 = Main geodynamics features. Dashed line indicates approximate location of crust-mantle boundary.

tectonically quiet regime, whereas from the Spanish coast, a major deltaic complex, referred as the Castellon Group, prograded into the Valencia Trough, characterized by rapid deepening in response to post-rift thermal subsidence.

During the Messinian, a major drop in sea-level gave rise to the development of high relief unconformities on the continental shelves and the deposition of variably thick halites and minor sulphates in the central and northeastern parts of the Trough (Mulder, 1973; Ziegler, 1988). Sequence three is therefore only represented in the deepest parts of the basin.

The forth sequence, which spans late Messinian-Quaternary times, corresponds to the Ebro Group which, similar to the Castellón Group, consists of a major deltaic complex building out into deeper waters from the Spanish coast. However, it records in coastal and shelf areas a renewed phase of extensional tectonics that was accompanied by the extrusion of alkaline volcanics, forming the Columbretes Islands. Similar extensional faults are no evident in the central parts of the Trough (Banda and Santanach, 1992b).

Figure 6a provides a structural map at the base of the Cenozoic sedimentary fill of the Valencia Trough (Lanaja, 1987; Maillard et al., 1992) and Figure 6b gives an isopach map of the Cenozoic strata. The structure map illustrates the broadly saucer shaped configuration of the Cenozoic Valencia Trough. The isopach map, in combination with the bathymetric map, shows that this basin is clearly partly sediment starved.

Upper and Middle Crust

The available geophysical data permit to image the present day crustal configuration of the Trough (Figs. 7, 8 and 9). Reflection and refraction seismic data show that along both margins the upper-middle crust, almost reflection free, varies in thickness between 6-10 km and has velocities of 6.1-6.2 km/s (Figs. 7 and 9). The overlaying pre-rift Mesozoic carbonates are characterized by velocities ranging between 5.4 to 5.9 km/s (Pascal et al., 1992; Torné et al., 1992; Dañobeitia et al., 1992). Across the axis of the Trough, COP and CDP data allow to trace two different scenarios. In the southern region, seismic data show a series of NW dipping reflectors at upper/middle crustal levels; these are attributed to a Mesozoic basin (e.g. Mauffret et al., 1992; Torné et al., 1992) which may represent the southeastern prolongation of the Iberian Chain. The thickness of the upper/middle crust, without Cenozoic sediments, is in this area of the order of 7-8 km (Fig. 8a and P-III of Fig. 9). In the central parts of the Trough there is no evidence for the presence of thick Mesozoic series (Fig. 8b).

Seismic refraction/wide-angle reflection data also reveal that the upper/middle crust thins from the southwestern off-shore regions in a northeasterly direction towards the central areas of the Trough (P-III of Fig. 9). In contrast, profiles P-I and P-II (Fig. 9) reveal that the thickness of the upper/middle crust does not vary significantly across the Trough; this is in accordance with the ESP data (e.g., Pascal et al., 1992).

Lower Crust

Reflection seismic data show that beneath the Ebro Platform the 6-7 km thick lower crust is characterized by good reflectivity, involving 1-4 km long subhorizontal reflectors (Fig. 7a; Torné et al., 1992; Collier et al., 1994). In contrast, the 9-10 km thick lower crust of the Mallorca margin (P-I of Fig. 9) is variably reflective, showing disrupted reflectors which are difficult to trace along the profile (Collier et al., 1994; Fig. 7b). Considering the shallow water and lack of near-surface low-velocity layers, Collier et al. (1994) favour that disruption of the lower crustal reflectors is genuine and not caused by multiple interference. Towards the axis of the Trough, the reflective lower crust thins very rapidly where it appears to be missing (Torné et al., 1992) or to be reduced to a 1-2 km thick layer (P-I of Fig. 9), and displays a moderate velocity gradient of 0.1 s^{-1} (Dañobeitia et al., 1992). These results are confirmed by coincident steep and wide-angle reflection profiles, which show that lower crustal reflectivity diminishes below the slope-break and vanishes towards the central parts of the Trough (Gallart et al., 1995;

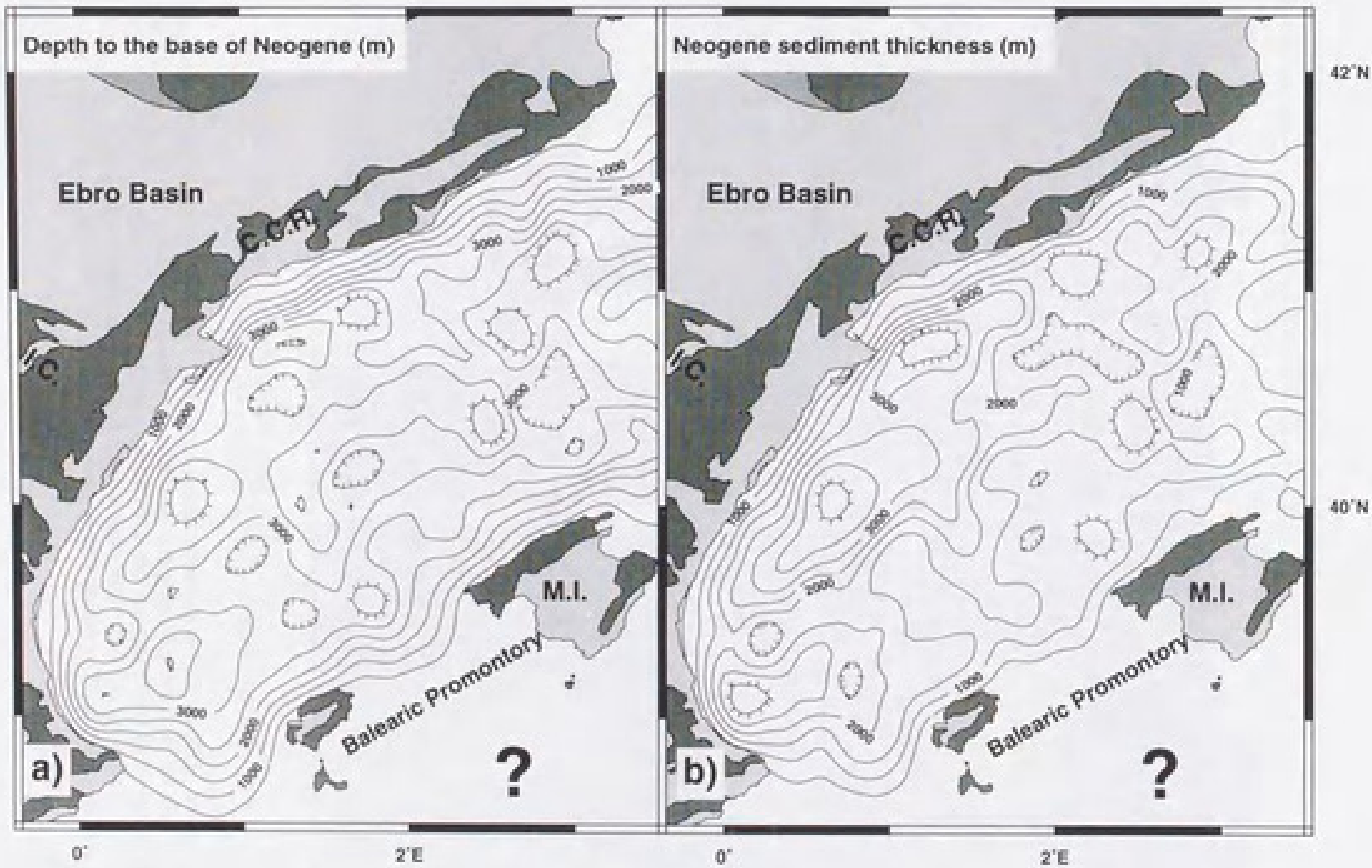

FIG. 6. **a)** Depth to the base of Neogene, contour interval 500 m. **b)** Neogene sediment thickness, contour interval 500 m. Compiled from Maillard et al. (1992) and Lanaja (1987). Abbreviations as in Fig. 2.

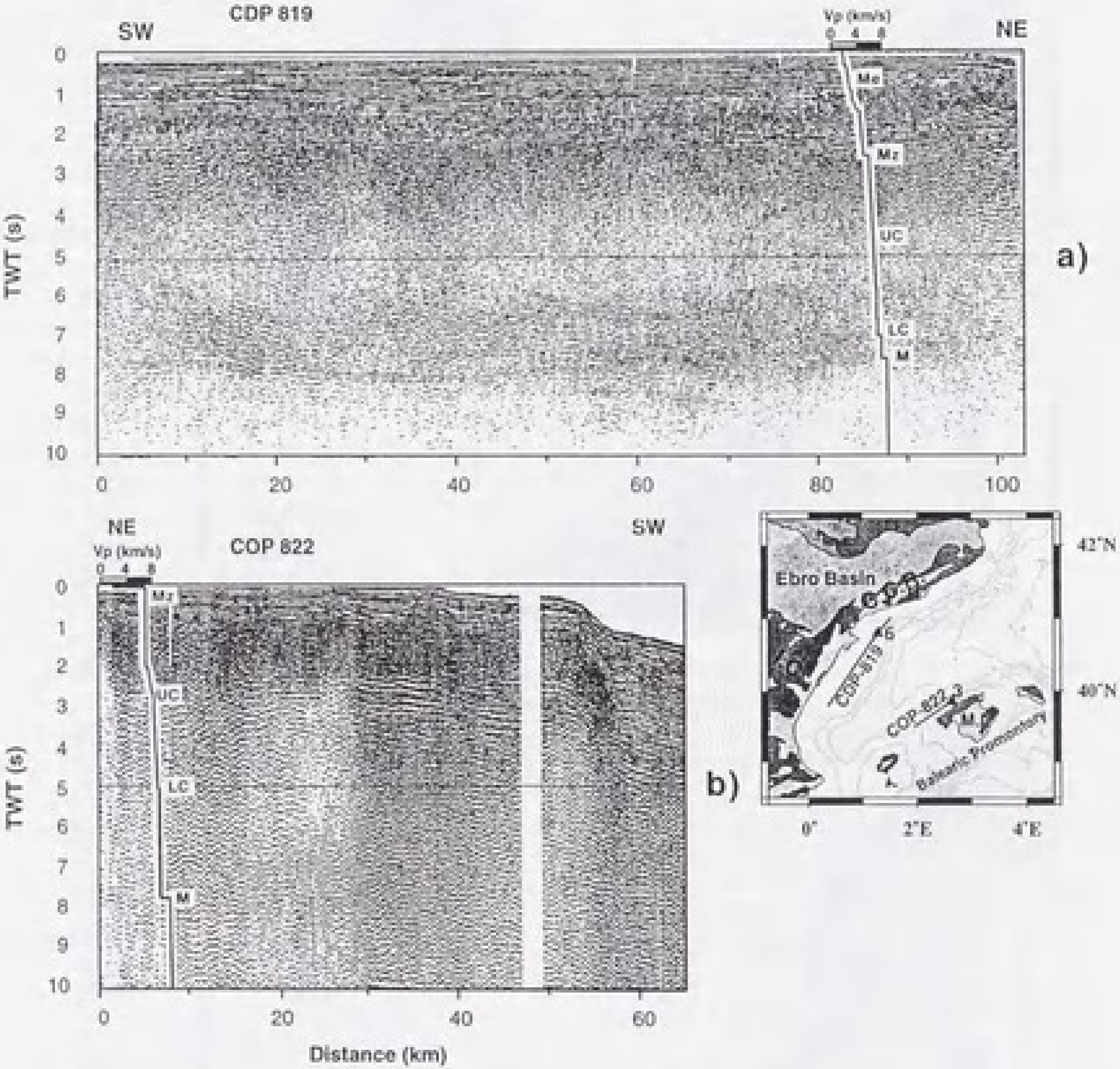

FIG. 7. **a)** Unmigrated CDP line 819 with velocity solution from ESP-6.
b) Unmigrated COP line 822 with velocity solution from ESP-3. No vertical exaggeration at 4.1 km/s. Inset shows location of seismic sections. Triangles give mid-point locations of ESP-6 and 3. Abbreviations as in Fig. 2. COP profiles from Collier et al. (1994), ESP results from Pascal et al. (1992) and Torné et al. (1992).

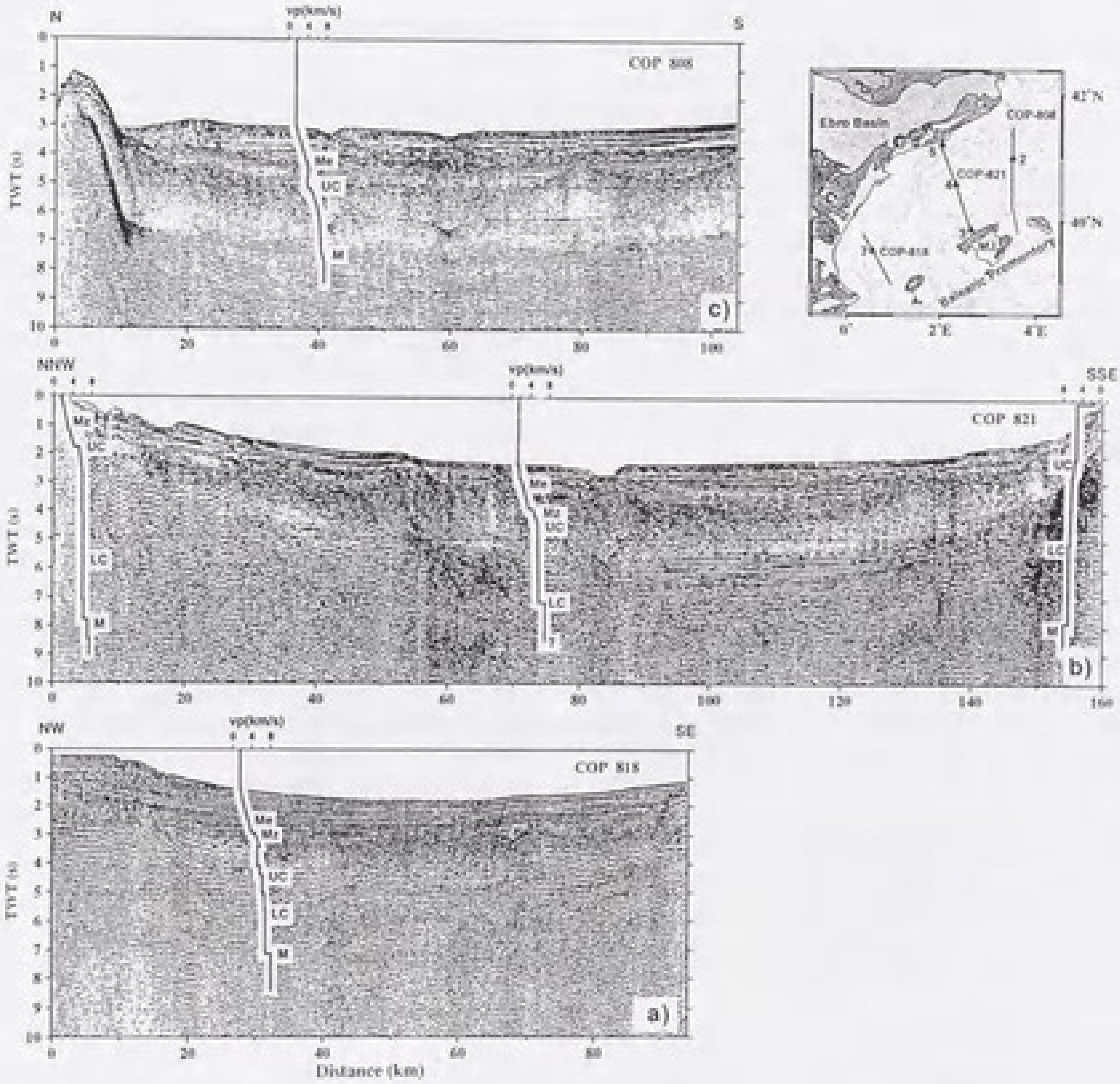

FIG. 8. **a)** Unmigrated COP line 818 with velocity solution from ESP-7. **b)** Unmigrated COP line 821 with velocities solutions from ESP-3, 4 and 5.

c) Unmigrated COP line 808 with velocity solution from ESP-2. No vertical exaggeration at 4.1 km/s. Me: Messinian; Mz: Mesozoic; UC: Upper Crust; LC: Lower Crust; M: Moho. Inset shows location of seismic sections. Triangles give mid-point locations of ESPs. Abbreviations as in Fig. 2. COP profiles from Collier et al. (1994), ESP results from Pascal et al. (1992) and Torné et al. (1992).

Vidal et al., 1995). In the southern parts of the basin, the lower crust is 5 km thick and is characterized by average velocities of 6.8 km/s (Pascal et al., 1992).

Watts et al. (1990) argue that the highly reflective lower crustal layer predates the mid-Tertiary extensional event; as such, underplating processes, related to the Cenozoic extension, could not cause the observed reflectivity of the lower crust. This view is supported by Collier et al. (1994), who based on the analysis of the lower crustal reflectivity patterns in different parts of the Trough, determined that Cenozoic extension significantly weakened or even destroyed the lower crustal reflectivity.

Moho Topography

In the area of the Valencia Trough, the crust/mantle boundary is reasonably well constrained by seismic and gravity data. Figure 10 gives a smoothed depth map of the Moho which is based on an integration of seismic data and gravity modelling results. The Moho raises gradually from a depth of 27-30 km under Iberia to 15-16 km beneath the Trough axis and descends toward the Baleares to a depth of 22-24 km. The Moho shallows from 18-19 km at the southwestern end of the basin to about 13-14 km at its northeasternmost end where it opens into the Provençal Basin. In cross-section, the Trough is slightly asymmetric, having a steeper flank towards the Baleares (Fig. 10).

In off-shore areas, velocities of the uppermost lithospheric mantle range from 7.7 to 7.9 km/s, whereas on-shore Iberia, velocities of 8.1 km/s are recorded. The upper-mantle velocity increases from 7.7-7.8 km/s beneath the axial parts of the Trough to 7.9-8.0 km/s towards the mainland, whereas beneath the Balearic Promontory, they remain in the 7.7-7.8 km/s range.

On COP the Moho can be traced throughout the basin (Figs. 7 and 8; Collier et al., 1994). The reflection signature of the Moho varies beneath the different parts of the basin and can be correlated with differences in the amount of stretching. Cenozoic extension may have modified the reflection character of the Moho.

Lithosphere-Asthenosphere Boundary

Information on the configuration of the lithosphere/asthenosphere boundary comes primarily from 2D modelling of the central parts of the Trough, using gravity and geoid anomalies along a profile extending from the Ebro basin to the South-Balearic basin (Watts and Torné, 1992a; Zeyen and Fernàndez, 1994). Watts and Torné (1992a) pointed out that the two margins of the Trough are characterized by different structural styles; the Spanish margin is a rift-type margin whereas the Balearic margin appears to be a constructional margin which is underlain by a broad region of lithospheric thinning. Zeyen and Fernàndez (1994) conclude that the shallowness of the lithosphere/asthenosphere boundary indicates that the causal rifting event had terminated only very recently, as previously suggested by Morgan and Fernàndez (1992). Surface-wave and tomography studies (Marillier and Mueller, 1985; Spakman, 1990) show that the Trough lies in a region of lithospheric thinning and anomalous low-velocity sublithospheric upper-mantle, characteristic for the western Mediterranean.

BASIN MODELLING

Subsidence Analysis

In an effort to isolate tectonic subsidence from the effects of sedimentary loading during the evolution of the Valencia Trough, backstripping analyses were carried out by several authors (Watts et al., 1990; Bartrina et al., 1992; Roca and Desegaulx, 1992) on the basis of wells located on the western margin of the Trough. The observed tectonic subsidence curves show an exponential

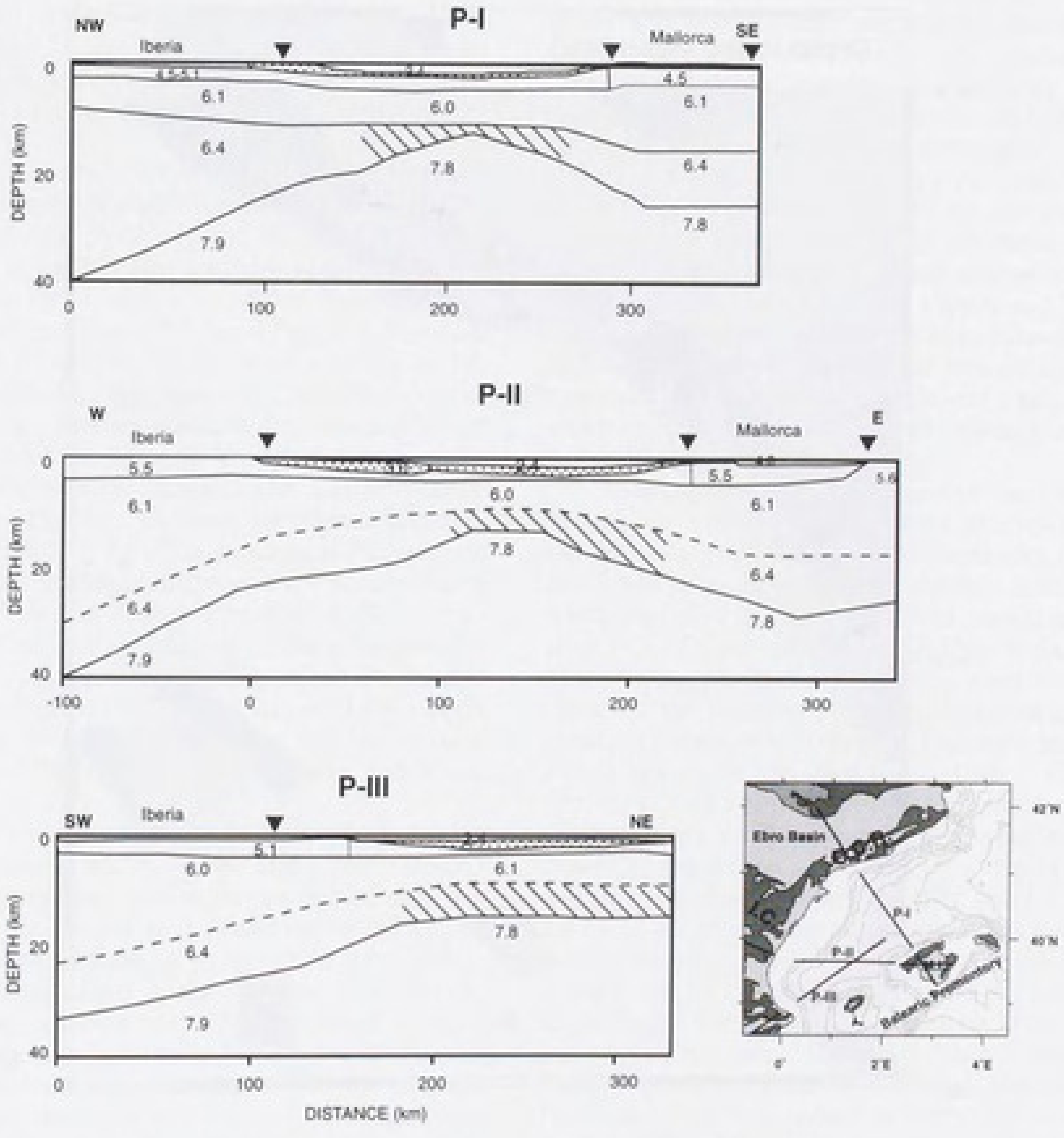

FIG. 9. Velocity-depth crustal models along profiles P-I, P-II, and P-III. Stippled zones indicate Neogene sediments. Dashed lines mark the transition between the upper and lower crust. Inclined stripped pattern denotes a gradient of 0.1 s^{-1} in the lower crust. Triangles indicate shore-line location. Values show P-wave velocities in km/s. Inset gives location of profiles (after Dañobeitia et al., 1992).

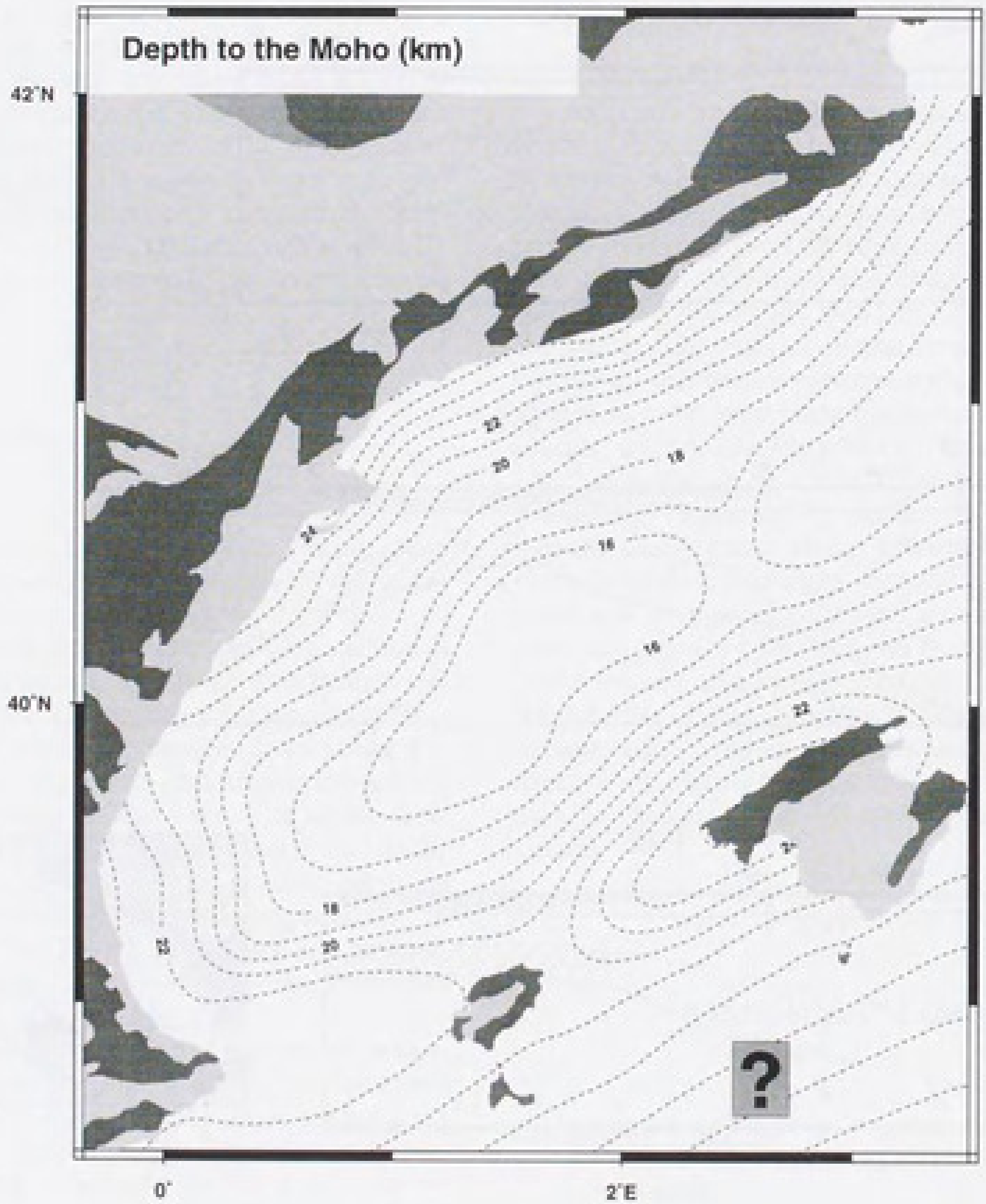

FIG. 10. Smoothed depth to the Moho map, contour interval 1 km. Compiled from results of Banda et al. (1980), Dañobeitia et al. (1992), Gallart et al., (1990), Pascal et al. (1992), Torné et al. (1992) and Zeyen et al. (1985).

trend with total tectonic subsidence values in the range of 1.4 to 1.6 km. 1D subsidence results also show that it is difficult to separate the late Oligocene-early Miocene syn-rift from the post-rift subsidence (Watts et al., 1990; Roca and Desegaulx, 1992). The shape of the subsidence curves must be carefully analyzed, as inaccuracies in palaeo-waterdepth estimates result in significant uncertainties (e.g, Watts et al., 1990; Bartrina et al., 1992).

Spatial variations in the tectonic subsidence along a regional transect considering CDP line 821 were analyzed by Watts and Torné (1992a) and Torres et al. (1993) who concluded that the form of the backstripped curves is similar, irrespective of the elastic thickness (Te), providing that Te values of 5 and 25 km and that corresponding to the 450°C isotherm, are assumed. Such quantitative subsidence analyses confirm the regional broad subsidence of the Valencia Trough and its accentuation to the northeast towards the continent-ocean transition (Fig. 11). Flexural subsidence analyses indicate uplift of the Catalan Coastal Ranges and the Balearic Islands, contemporary with subsidence with the Valencia Trough. Detailed studies, incorporating fine stratigraphic and palaeo-waterdepths analyses, are able to distinguish an initial phase of rapid subsidence (30-15 Ma) followed by a post-rift phase, characterized by lower subsidence rates (Roca and Desegaulx, 1992; Torres and Bois, 1993).

A 3D backstripping analysis of the entire region, carried out by Watts and Torné (1992b) using seismic and well data, confirmed that the Trough corresponds to a broad region of subsidence which is flanked by uplift in the Catalan Coastal Ranges and in the Balearic Promontory. Maximum tectonic subsidence values of 4.2-4.4 km are reached in the NE at the continent-ocean transition (e.g., Pascal et al., 1992), whereas elsewhere tectonic subsidence values range between 1 and 3 km (Fig. 11).

Numerical Modelling

Numerical models applied to the study area are far from complete and self-consistent. Nevertheless, they provide valuable information on the evolution of the Valencia Trough.

Two key features of this basin are difficult to handle with "classical" extensional models, namely the observed crustal and lithospheric asymmetry across and along its axis, and the fact that the initial rifting phase was coeval with compression along the Balearic margin. The majority of the numerical approaches, so far performed, omitted both facts and thus result in the assumption of simplified models. The difficulties encountered in modelling are particularly acute for the southern region of the Trough, where also the surface heat-flow values are consistently higher and the tectonic subsidence less than expected (Watts and Torné, 1992a). Therefore, numerical approaches were applied to the central parts of the Trough and concentrated on determining the pre-rift lithospheric conditions, the duration of the rifting stage, and the amount of lithospheric stretching.

Keeping in mind that the area of the Valencia Trough was uplifted and subjected to erosion during the Paleogene, Morgan and Fernàndez (1992) attempted to evaluate the lithospheric conditions which prevailed in the western and central regions prior to the Oligocene-Miocene rifting. A formulation of lithospheric buoyancy was used to back-calculate the possible pre-extension lithospheric structure, consistent with mid-Tertiary elevation and lithospheric strength constraints. This 1D approach was applied to different lithospheric columns along a profile from the Ebro basin to the centre of the Valencia Trough. For the Spanish margin, stretching factors ranging from 1.45 to 1.87 and an initial crustal thickness between 27 and 35 km were arrived at, whereas for the centre of the Trough these values are 2.9-4 and 26-36 km, respectively. The estimated stretching factors can be reduced by about 10%, assuming erosion of 1 km of pre-rift sediments. Although Morgan and Fernàndez (1992) proposed differential stretching for the Valencia Trough, where $ß_{crust}>ß_{mantle}$ in the centre of the Trough but $ß_{crust}<ß_{mantle}$ under the Spanish margin, uniform stretching in the centre of the Trough can also fit the model, provided an erosion of about 1.5 km of pre-rift sediments is acceptable.

A second approach, based on a 1D pure-shear stretching model, was explored by Foucher et al. (1992) using as constraints measured heat-flow

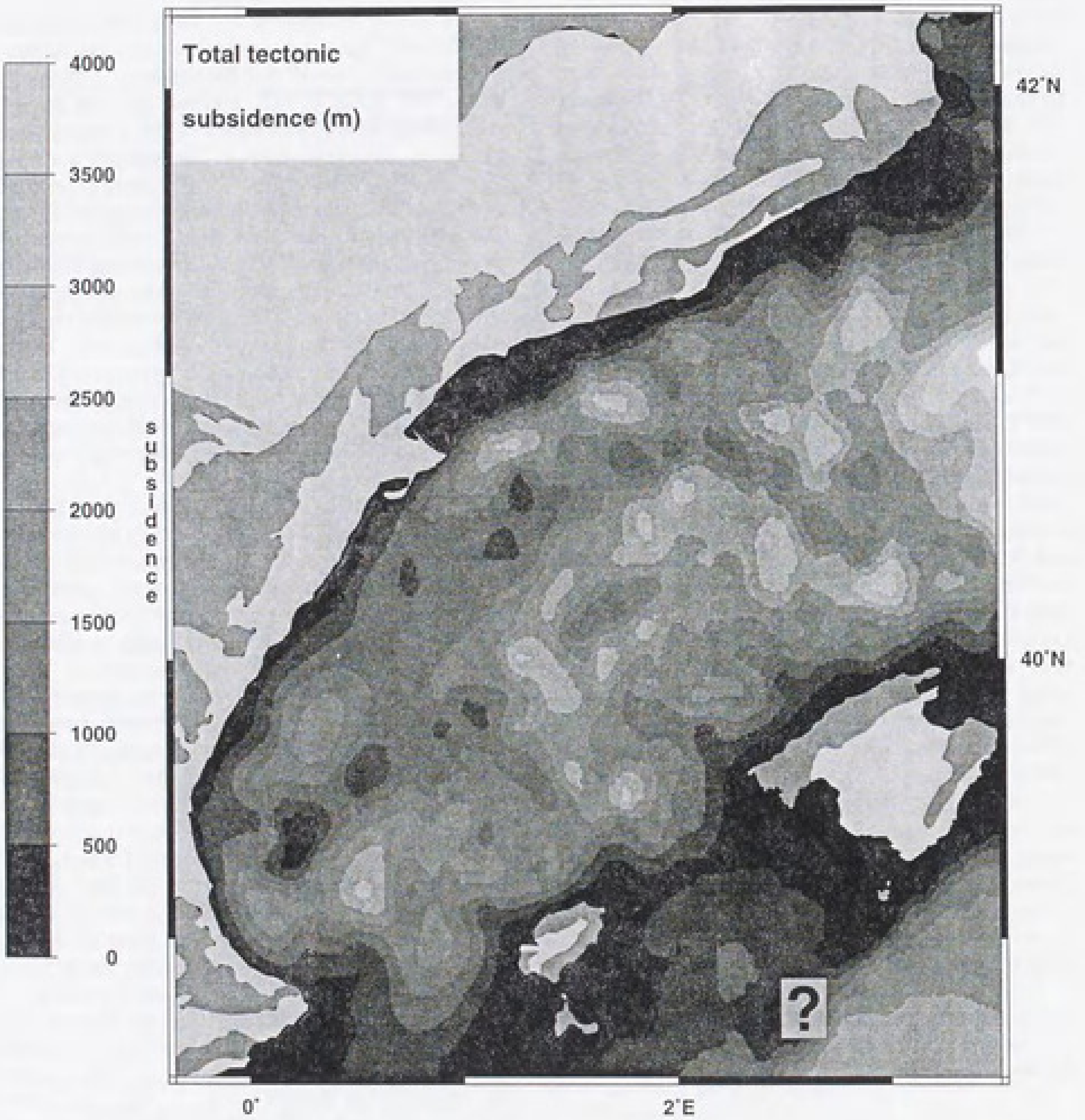

FIG. 11. Tectonic subsidence/uplift map, contour interval 500 m. Based on flexural backstripping of sediment thicknesses given in Fig. 6b. Parameters used: elastic thickness (Te) of 5 km, water, sediment and mantle densities of 1030, 2400 and 3300 kg/m^3, respectively. Modified after Watts and Torné (1992b).

data and bathymetry along three transects located in the central parts of the Trough (for location see Fig. 2b). Their results show that the northeastern half of the Valencia Trough could be successfully explained by a single rifting event lasting from 28 to 22 Ma with crustal stretching factors of 3.5 and 3.3 for the northern transects. However, this approach fails to explain the relatively high heat flow and shallow water depths observed in the southern part of the Trough (transect T4 of Fig. 2b), even when a multi-stage Neogene rifting event with different initial crustal and lithospheric thicknesses is considered. Foucher and co-workers speculate that this may be the result of a recent Pliocene-Quaternary event which would favour a southward propagation of the rift activity.

Fernàndez et al. (1995) attempted to model the southern Valencia Trough, applying a 1D uniform stretching model constrained by thermal and palaeothermal data. Their model takes into account the thermal effects of sedimentation/erosion, compaction, mineral composition and heat production. This model suggests that the SW Valencia Trough underwent a complex geodynamic history, including three Mesozoic rifting events, a Paleogene compressional and an uplift phase, causing erosion of about 5 km of Late Jurassic and Cretaceous sediments, and a late Oligocene-early Miocene extensional phase.

Several 2D numerical models were applied along different transects located in the central region of the Valencia Trough. These models, based on a kinematic approach, are mainly constrained by the basement structure, crustal and mantle stretching factors and surface heat-flow data. The first model, presented by Watts and Torné (1992a), was performed along a transect extending from the Ebro basin to the South Balearic basin, coinciding off-shore with CDP line 821. The total tectonic subsidence obtained from a 2D backstripping analysis and the measured heat flow were compared with that obtained from a 2D non-uniform finite stretching model. The best fit shows a homogeneous stretching with a b factor increasing from 1.4 beneath the Spanish margin to 3.0 at the centre of the Trough. However, on-shore, below the Catalan Coastal Ranges, the observed tectonic uplift requires a broad region of mantle stretching (β_{mantle}=1.4) extending well beyond the region of crustal stretching. It was assumed that the rifting episode started 24 Ma ago and had a duration between 8 and 16 Ma, and that the initial crustal and lithospheric thickness were 31.2 and 125 km, respectively. A combined geoid and gravity model, where a temperature-dependent mantle density is considered, was used to better constrain the present-day geometry of the lithosphere below the Balearic margin. The model results reveal asymmetry at crustal and subcrustal levels between the flanks of the Trough and, that the region of lithospheric thinning is much broader than the width of the initial rift and extends far beyond the Balearic Promontory.

Torres et al. (1993) modelled the off-shore areas of the Trough along CDP line 821, using a 2D uniform stretching model, considering local isostasy, and the loading and thermal effects of sediments. Unlike Watts and Torné (1992a), it was assumed that the Valencia Trough underwent a first rifting event between 25.2 to 20.0 Ma, which had minor effects on the deep basin and affected mostly the Spanish margin, an that a second rifting event between 15.2-10.2 Ma, coeval with the opening of the Tyrrhenian basin, was responsible for the present-day Moho uplift. However, there is no clear reflection-seismic evidence for this second rifting event. These authors also conclude that, in contrast to the interpretation given by Fontboté et al. (1989) and Roca and Desegaulx (1992), the post mid-Miocene development of the basin does not conform to a flexural foreland-type mechanism.

Finally, Jansen et al. (1993) proposed a 2D necking model along two profiles crossing the central part of the Valencia Trough. Basement subsidence, Moho depth and gravity anomalies were calculated for different elastic thicknesses, duration of rifting and necking depths. Results support a rifting model with a low elastic thickness (5-20 km), an intermediate depth of necking (17-33 km) and a finite duration of the stretching event (16 m.y.), propagating southwestward. Rifting would have started 24 Ma ago in the northeastern profile (Mallorca-Barcelona) and 20 Ma ago in the southwestern profile (Mallorca-Ebro Delta). A Pliocene uplift, caused by additional mantle thinning, is proposed to fit the present-day Moho depth and uplift in the Valencia Trough and the Iberian-Mediterranean margin. Whether this uplift is related with the Plio-Quaternary extensional phase is not evident.

DISCUSSION

The Valencia Trough is one of a several extensional basins located in the western Mediterranean region, which developed under a compressional regime. It differs, however, from other rifted basins of the western Mediterranean, such as the Tyrrhenian and South Balearic basins, in that extension has not progressed to crustal separation. Available geological and geophysical data provide a reasonably well constrained image of its present-day crustal structure. It is now well accepted that the Valencia Trough is characterized by a strongly attenuated continental crust, underlain by an anomalous low-velocity upper mantle, and that its lithospheric structure shows asymmetry both at crustal and sub-crustal levels. There is still some debate, however, among the different authors on the cause and magnitude of extension and on the evolution of the Trough.

A major problem in understanding the evolution of the basin is the poor knowledge on the structure of the lithosphere and configuration of the crust before the late Oligocene extensional phase. It is well established that during the Mesozoic break-up of Pangea the area underwent repeated extensional events and that, during Late Cretaceous and Paleogene times, intraplate compressional stresses caused inversion of most of the extensional Mesozoic basins. However, whether or not the crust recovered its pre-Mesozoic thickness as a consequence of basin inversion is still a matter of debate. Therefore, the first question that has to be solved concerns the effect of Mesozoic extension and Paleogene compression on the lithospheric configuration of the Valencia Trough, prior to the onset of Oligocene-Miocene extension.

The Oligocene to Recent evolution of the Trough is characterized by a first rifting stage (late Oligocene-early Miocene) which can be explained either by a back-arc model (the Valencia Trough evolved in a back-arc position relative to the Kabylian-Calabrian arc) or by southward propagation of the European rift system across the West-Mediterranean fold belts. During the early-middle Miocene, Balearic thrusting counteracted extensional forces and aborted rifting. After locking of the Balearic thrust front, extension resumed during the latest Miocene and persisted into the Pleistocene.

Assuming that the Trough is indeed a rift-type basin and forms part of the Cenozoic rift system of Western and Central Europe, there are still several questions that need to be addressed, such as the initiation, duration and mechanism of the Oligo-early Miocene rifting event, the amount of stretching, and rift-related processes such as lower crustal reflectivity, underplating, Moho rejuvenation, thermal regime, etc.

Timing and Duration of Rifting

Surface geological and reflection seismic data show that crustal extension commenced during Chattian(?)-Aquitanian times with the deposition of the first syn-rift sediments and the development of a block-faulted relief along the western flank of the Valencia Trough. To the South, however, the first syn-rift sediments record an upper-Langhian age. This suggests that the rifting propagated from North to South, or that the southern areas had a higher topographic relief when rift activity commenced. Geological data also show that in the northern and central parts of the Trough the rifting phase persisted into Langhian-Serravallian times (Roca and Desegaulx, 1992). This indicates that the main rifting activity lasted 8-10 Ma. Subsidence analysis do not help too much in deciphering the duration of rifting since, as mentioned above, it is difficult to separate the Oligocene-early Miocene syn-rift from the post-rift phase. This underlies the proposal of different durations of the rifting stage, ranging from 6 m.y. (Foucher et al., 1992) to 8-16 m.y. (Watts et al., 1992a) and even to multi-stage Neogene events (Torres et al., 1993).

Mechanisms of Rifting

Numerical models attempt to establish the mechanisms of lithospheric extension. Two end-member models are available, the pure-shear (McKenzie, 1978) and the simple-shear model

(Wernicke, 1985). In the study area, most of the available geophysical data favours a pure-shear mechanism, since there is no clear evidence in support of a simple-shear model. This does not rule out, however, that simple shear deformation is restricted to the upper/middle crust and is combined with pure shear deformation at deeper levels (Lister et al., 1991), though such a model has not yet been tested. Simple shearing would explain some major upper crustal structural features, such as low angle faults and fault-block rotations observed in the upper/brittle part of the crust. Although the pure-shear model has been successfully applied to off-shore areas, a differential stretching mechanism is required to fit the uplift of on-shore areas. In this context, Cabal and Fernàndez (1995), based on thermal evidences from the easternmost Ebro basin, proposed that during middle Miocene to Recent times thinning of the mantle lithosphere occurred beyond the zone of actual rifting and extended some distance to the West of the Catalan Coastal Ranges.

Stretching Values

The amount of Oligocene and younger lithospheric stretching was obtained mainly from the crustal configuration and subsidence studies. Assuming a pre-rift crustal thickness of 30-35 km, crustal stretching factors, ranging from 1.4-1.55 for the western flank of the Trough and 3.2±0.25 for central areas, and upper-crustal thinning ratios of up to 2.1 were obtained. This value is much larger than upper-crustal extension ratios deduced from structural analysis which give values of up to 1.4-1.5 (Roca and Guimerà, 1992). The observed differences between extension and thinning ratios may be explained by assuming that the thinned crust is partially inherited from the Mesozoic rifting events. On the other hand, Morgan and Fernàndez (1992) suggest that upper crustal stretching factors in the 1.8 to 2.55 range, can be expected if a mid-Tertiary topographic relief between 0 and 500 m is assumed. Finally, it can not be excluded that the observed discrepancies between upper crustal extension by faulting and mid to lower crustal attenuation involved a Neogene destabilization of the Moho and its upwards displacement by magmatic delamination of the lower crust (Ziegler, 1992, 1995).

Rift Related Processes

Collier et al. (1994) established a correlation between the lower crustal/Moho reflectivity and the degree of crustal attenuation and concluded that extension could significantly weaken or even destroy the reflectivity of the lower crust (see also Watts et al., 1990), but enhanced the reflectivity of the Moho. Where the lower crust is very thin, its reflectivity and the Moho reflector are weak or non existent. In the centre of the Trough, the absence of a reflective lower crustal layer and the presence of a single lower crustal reflector (reflector X), which coincides with a P-wave velocity increase from 6.4 to 7.8 km/s, has led to Collier et al. (1994) to propose that this reflector represents the top of a crustal transition zone, composed of crustal and mantle material. Further evidence for intrusion of mantle material into the base of the crust is the observed high-velocity gradient in the lower crustal layer (Dañobeitia et al., 1992). The occurrence of a crust-mantle transition zone was already postulated by Banda et al. (1992) in an effort to explain the observed difference between upper and lower crustal attenuation and the presence of anomalous upper mantle velocities recognized throughout the basin, the thickness of which is of the order of 20 km, as deduced from gravity modelling (Torné and Banda, 1988).

The thermal regime of the Trough, as summarized in Fig. 2b, is not too well constrained by measurements which show considerable variations in the central regions of the Trough. This makes it difficult to decipher whether this area is characterized by intermediate or high heat flow values. Moreover, the background heat flow of the Balearic Promontory is quite similar to that of the Trough axis, except on Menorca where a slight increase is recorded. This regional heat flow pattern is in accord with modelling results which show that the region of lithospheric thinning extends beneath the Balearic Promontory (Watts and Torné, 1992a; Zeyen and Fernàndez, 1994); as such, the latter can not be regarded as the conjugate margin of the Iberian margin.

CONCLUSIONS

Although basin modelling has been quite successful in imaging some aspects of the central parts of the Trough, it was less successful on a basin wide scale and particularly for the southern areas. The underlying reason is, that kinematic models applied do not account for the complex tectonic evolution of the area. This concerns mainly the alternation and nearly contemporaneous extension and compression and the possible southward rift propagation. Some of these aspects have been explained in a step-like manner rather than incorporating all of them into a self-consistent model. Advective heat transport, radiogenic heat production, melt generation and sediment thermal blanketing are not contemplated in most of the models, yet they may be important factors in controlling the evolution of the basin.

On the other hand, lithospheric deformations imposed on these kinematic models are not constrained by constitutive equations. Depending on the initial lithospheric structure, the strain rates obtained from stretching factors and the duration of the rift stage are at odds with the thermo-mechanical behaviour of lithosphere. As pointed out by Negredo et al. (1995b), thermo-mechanical constraints on kinematic models may result in different styles of rifting but can also invalidate a preconceived mode of deformation. Fully dynamic models are more self-consistent since deformation is calculated by coupling constitutive and thermal equations (e.g. Bassi et al., 1993), yet the high nonlinearity of the equation renders the results very sensitive to the initial conditions, making it difficult to reproduce the present-day crustal structure of a given extended area.

Therefore, we conclude that current basin modelling techniques do not allow to properly account for the evolution of the Valencia Trough. In addition, even assuming that these techniques are capable to handle the main tectonic aspects, there are still some gaps in our knowledge of the study area such as:

- Is the Valencia Trough an extensional feature on its own? An important aspect when modelling the Trough is whether it should be considered as an "extensional" feature on its own, or should be considered as a "branch" of a much wider extensional region covering the western Mediterranean. If the latter is correct, then the Trough would form part of the Gulf of Lyons, Corsica-Sardinia rift system which was active prior to the late Aquitanian-early Burdigalian opening of the Algero-Provençal Basin (Ziegler, 1992).

- What was the pre-rift lithospheric configuration of the Trough? It is not clear whether or not the Paleogene compressional phase was large enough to restore the thinned Mesozoic lithosphere to its initial conditions. In other words, is the present-day lithospheric structure mainly the result of the Neogene rifting? or is it partially inherited from Mesozoic extension?. The Alpine deformation of the area occupied by the Valencia Trough is still poorly understood. Therefore, interactive forward and backward models must be developed which take into account various degrees of Mesozoic extension and Paleogene inversion and pre-rift erosion.

- Is the present-day lithospheric structure the result of a finite rifting episode or a multistage rifting? As pointed out earlier, subsidence analysis do not permit to clearly separate syn-rift and post-rift phases; correspondingly different durations of rift activity have been proposed. This is mainly due to the lack of knowledge of several parameters, which strongly influence backstripping results, such as palaeo-bathymetry, precise timing and amount of erosion, pre-Neogene basement morphology and density variations. The superposition of a thrust loading phase on the southeastern parts of the Trough is an additional complication factor. In this respect, stress-induced lithospheric deflections may also have played an important role (Cloetingh and Kooi, 1992).

- What is the configuration of the lithospheric mantle and the lithosphere-asthenosphere boundary? Information on the structure of the lithospheric mantle and the topography of the base of the lithosphere comes only from thermal modelling and surface-wave studies. There is no information on the deep structure of the lithosphere along the basin axis and its transition to the oceanic Algero-Provençal basin. The lateral extent and thickness of the low-velocity anomalous upper mantle is unknown. Passive and active source seismology in the form of deep seismic soundings and intermediate tomographic inversion schemes may help to outline the topography of the base of the lithosphere and to image the shape of the low-velocity upper mantle layer.

- Was the Moho a passive marker throughout Cenozoic extension? There is some evidence that the geophysically defined crust/mantle boundary was destabilized during Oligocene and younger rifting. The differences observed between the magnitude of crustal extension by faulting and crustal thinning could at least partly be explained by an upward displacement and rejuvenation of the Moho. In this respect, the presence of an anomalous low-velocity uppermost mantle or "transitional" layer could be explained by the presence of partial melts which may have interacted with the lower crust. However, whether the top or the bottom of this anomalous layer correspond to the present crust/mantle boundary, remains to be investigated.

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