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Some geophysical constraints to dynamic processes in the Southwestern Mediterranean

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Abstract
The total tectonic subsidence, thermal state and seismotectonic regime have been analysed to better constrain the dynamic processes which originated the basins of the Southwestern Mediterranean. It is argued that backarc extension and oceanic spreading are the possible and main processes which took place within a compressional framework, driven by the interaction between the African and European plates. As inferred by both subsidence and heat-flux data, in the central part of the Algerian-Balearic basin the crust is oceanic, 20 Ma old on average, originated by a spreading phase, which also affected the Ligurian-Provençal basin. The Alboran basin, which is underlain by stretched continental crust, shows an intermediate seismic activity and a few deep events, explainable by a gravitational collapse of cold lithosphere. After a review of the most recent geodynamical hypotheses, an evolutionary scheme is attempted envisaging the lateral continental escape of the Gibraltar arc. Within a convergent tectonic framework, some lithospheric material could translate almost perpendicular to the convergence direction, and undergo a lateral subduction process, secondary to the main boundary between plates.

Key words *marginal basins – heat-flux and seismotectonic data – lateral extrusion model – Algerian-Balearic and Alboran basins – Betic cordillera-Rif system*

1. Introduction

Several studies showed that the present structural setting of the northwestern sector of the Mediterranean is a result of a complex superposition of processes such as continental collision, subduction, crustal stretching, rotation of microplates, and sea-floor spreading which generated different and contrasted geodynamical environments. Recently, the analysis of tectonic subsidence, thermal flux and seismotectonic data from this area, allowed us to outline the boundaries of the oceanic domain, and to give information on the presence of a crust with intermediate characteristics, contributing to a better knowledge of the structural setting and the style of deformation of the lithosphere underlying the basin (Pasquale *et al.*, 1994, 1995a).

In this paper, such an analysis is carried out for the southwestern part of the Mediterranean. This area is examined in relation to the main processes of extension and ocean spreading which occurred in the northwestern sector, within a tectonic framework of convergence between the African and European plates. Some fundamental geophysical constraints are taken into account in discussing the most recent geodynamical interpretations, and attempting a new evolutionary scheme. Particular em-

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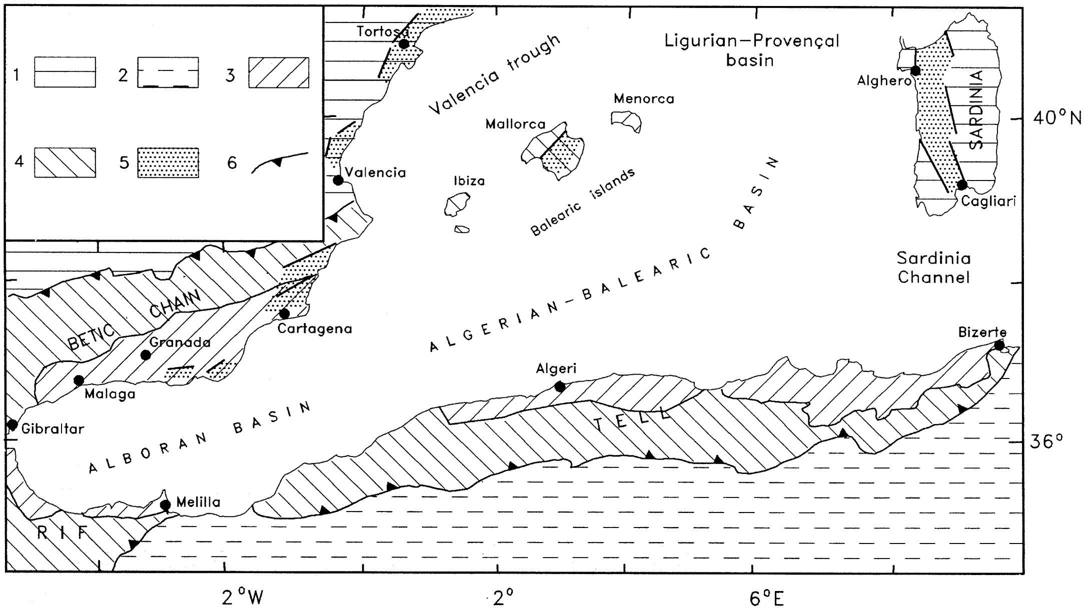

Fig. 1. Southwestern Mediterranean basins and main structural elements of the surrounding area. Foreland and foredeep of the European (1) and African (2) plates; internal (3) and external (4) zones of the Betic cordillera and the Rif-Tell chain; Cenozoic rift (5); thrust front (6).

phasis is put on which kind of evidence is to be investigated in order to improve the proposed model.

Figure 1 shows the schematic structural setting of the Southwestern Mediterranean. The area comprises the Algerian-Balearic basin, which continues towards the north into the Ligurian-Provençal basin and is bounded to the east by the Sardinia channel, and the Alboran basin. To the south and the west, the marine realm is surrounded by the Gibraltar arc, formed by the Betic cordillera-Rif system, and the Tell chain, facing the Alboran and Algerian-Balearic basins. The internal zones of these mountain systems consist mainly of Paleozoic tectonic units overlaid with Mesozoic terrains. They were deformed during the main phases of the Alpine orogeny and successively rejuvenated in Paleogene-Miocene times. The external zones are, instead, formed by carbonatic sediments and platform sequences deformed during the Miocene (*cf.* Boccaletti *et al.*, 1990). The foreland and the syntectonic foredeep extend behind the outer edges of the chains. The Balearic islands represent the natural continuation of the Betics towards the northeast, whereas to the East Sardinia is mainly formed by crystalline massifs of Hercynian age.

Extension processes which affected the area are mainly mirrored by the seismic structure and gravity anomalies. The central Algerian-Balearic basin is characterised by a 5 km thick crust, overlaid with a 4.5 km thick sedimentary cover. The crustal features seem oceanic, similarly to those observed in the Northwestern Mediterranean (Hinz, 1973; Pasquale *et al.*, 1995a, 1996). P-wave velocity ranges between 6.0 and 7.4 km/s, and in the uppermost mantle is 8.0 km/s. The Bouguer anomaly is positive and exceeds 200 mGal. The crust underlying the Alboran basin is continental, 13-20 km thick, and the upper mantle shows anomalously low velocity of 7.6-7.9 km/s (Banda *et al.*, 1983). Horsts and grabens, trending E-W and parallel to magnetic anomalies due to volcanic rocks (Galdeano *et al.*, 1974), make the sea-floor topography irregular (Dillon *et al.*, 1980). A negative Bouguer anomaly of 130 mGal affects the Gibraltar arc and the westernmost part of the basin (Bonini *et al.*, 1973).

2. Subsidence

Provided that the basins were built up by extension processes, additional information on the nature and structure of the underlying crust can be obtained from the total tectonic subsidence (TTS), *i.e.* the pre-rift elevation of the continental crust minus the present-day basement depth corrected for the load effect of sediment. TTS accounts for the initial subsidence due to stretching and the thermal subsidence due to a progressive return to thermal equilibrium of the lithosphere (*cf.* Pasquale *et al.*, 1995a). We calculated TTS from bathymetry observations by means of the method of Crough (1983), which allows removal of the sediment load through data of two-way sediment reflection times, under the assumption that the local Airy isostasy is applicable. This method, based on velocity and density measurements along deep sea drill-holes, accounts for a non-uniform change in density with depth.

The loading effect of the sediments on the continental margins could be also calculated by considering the flexural loading of a thinned elastic or viscoelastic plate (Karner and Watts, 1982). However, the method applied by us yields nearly equivalent results, as in the deep basins under examination sediments and crustal thickness are laterally uniform (Bessis, 1986; Jemsek, 1988). A bias could arise from the reflection records used in plotting bathymetry and basement isochron maps. If these records can be read to 0.02 s and the acoustic wave-velocity of both unconsolidated deep-sea sediments and water is assumed to be on the order of 1.5 km/s, then errors on these

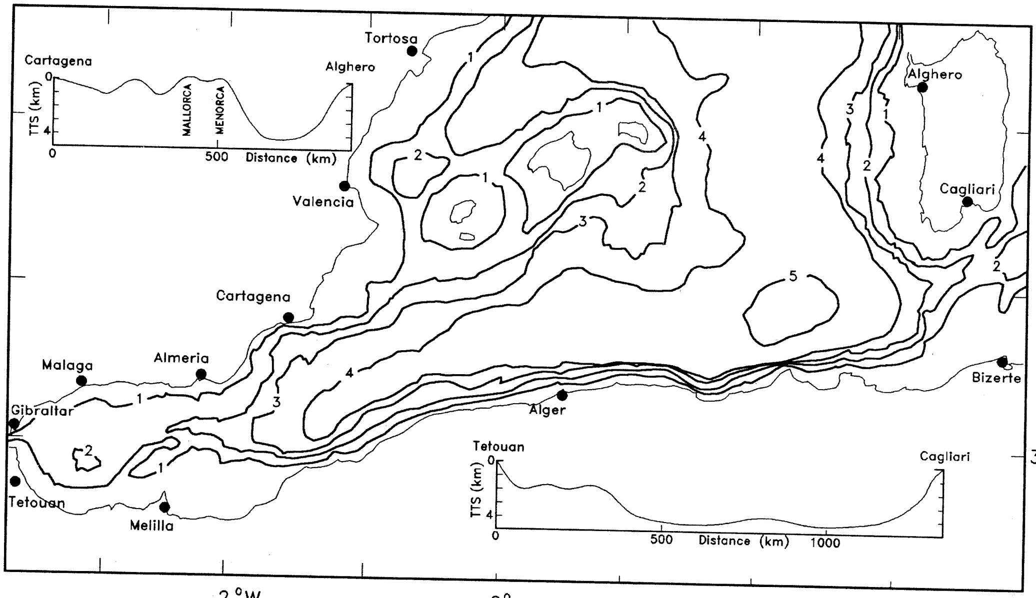

Fig. 2. A contour map of the regional total tectonic subsidence (isolines in km), and cross-sections showing lateral variations in the Algerian-Balearic basin, the Valencia trough and the Alboran Sea.

maps are about 30 m (Schroeder, 1984). Moreover, thermal coupling between the sediment layer and the basement does not affect the subsidence by more than a few tens of metres and consequently can be ignored (Alvarez *et al.*, 1984). The different uncertainties imply that TTS estimates have an accuracy of 50-100 m (see Chiozzi, 1995, for a detailed discussion).

Two-way travel time data were derived from the basement isochron map by Réhault *et al.* (1984). They were locally integrated with detailed basement isochrons from multi-channel reflection data recently acquired, in particular, in the Valencia trough (Mauffret *et al.*, 1992), in the western side of the Alboran Sea (Morley, 1993), and in the Sardinia Channel (Nicolich, 1989). Sediment thicknesses and the basement depth from deep boreholes, in the western Sardinian margin (Ryan *et al.*, 1978a), in the Alboran Sea (Ryan *et al.*, 1978b; Morley, 1993) and in the central part of the Algerian-Balearic basin (Hsü *et al.*, 1978), highlight the geometry of the basement and give further constraints to TTS estimates.

The TTS regional pattern and two representative cross-sections are shown in fig. 2. West of Sardinia and along the Northern African margin, lateral variations of TTS are larger than in the Balearic Promontory margin as well as in the Valencia trough and the Alboran Sea. There is a wide area, bounded by the 4 km TTS isoline, between Sardinia and the Alboran Sea, shown in the Tetouan-Cagliari cross-section. This zone becomes narrower to the southwest, towards the Alboran domain. TTS exceeds 5 km only in the Southern Algerian-Balearic basin, in relation with a larger sediment accumulation. In the Valencia trough and the Alboran Sea, TTS gently increases eastward, to maximum values of about 4 km, as shown in the Cartagena-Alghero cross-section. This indicates a continuation of the two areas towards the Ligurian-Provençal and Algerian-Balearic basin, respectively.

3. Crustal domains and heat flux

We demonstrated for the Northwestern Mediterranean that TTS values of 3.4 and 4.1 km represent the boundaries of the continental margins and the oceanic crust, respectively (Pasquale *et al.*, 1994, 1995a). The extension of such a criterion to the investigated area makes it possible to call apart different domains in the crust underlying the basins. The boundaries of the crustal domains are shown in fig. 3. In order to discuss them in relation with the thermal features, we have reviewed the available heat-flux data.

Thermal data for the Algerian-Balearic basin, the Sardinia Channel, Sardinia, and the eastern zone of the Tell-Atlas system have been extracted from the file compiled by Cermák *et al.* (1992). Measurements were corrected for two main perturbations: thermal blanketing caused by sedimentation, and the influence of paleoclimatic variations. The sedimentary correction increases the measured heat flux by up to 30%, and the paleoclimatic correction by 8-10 mW/m^2. Details on data validation and correction criteria are given by Verdoya (1992).

Data from the other areas are scattered in several papers. In order to make the marine dataset homogeneous, measurements from the Valencia trough (Nason and Lee, 1964; Hutchison *et al.*, 1985; Foucher *et al.*, 1992), the Alboran Sea and the southern margin of the Balearic Promontory (Erickson, 1970; Takherist and Lesquer, 1988) were processed to eliminate paleoclimatic perturbations. Corrections for a few deep-sea drilling measurements from the eastern side of the Balearic Promontory (Erickson and von Herzen, 1978), were, instead, hard to quantify.

Most heat-flux values in mainland areas (Iberian peninsula, Balearics, Rif-Tell) are poorer in quality, as either deduced from estimations of thermal parameters combined with direct measurements (Albert-Beltrán, 1979; Takherist and Lesquer, 1988; Fernàndez *et al.*, 1989; Rimi, 1990) or affected by water circulation (Fernàndez and Cabal, 1992). For these reasons no correction was attempted.

In outlining the regional pattern of the surface heat flux, shown in fig. 4, data were dealt with differently. In the marine realm, we have rejected a few measurements having poorer quality or not obeying Chauvenet's criterion,

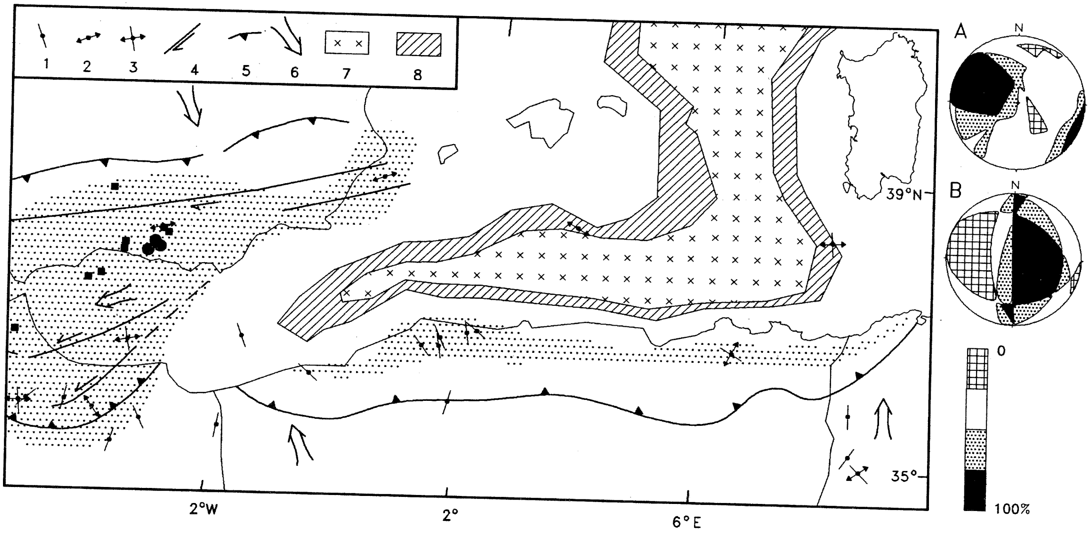

Fig. 3. Crustal domains, seismic areas and stress directions. The stippled areas indicate the zones with maximum concentration of seismic events with surface-wave magnitude equal to or grater than 4.0, in the period 1900-1990. 1 = Maximum horizontal principal stress of reverse faults; 2 = Minimum horizontal principal stress of normal faults; 3 = Maximum and minimum horizontal principal stress of strike-slips (all obtained from fault-plane solutions, *in situ* measurements, and geologic indicators); 4 = Strike-slip faults; 5 = Reverse faults; 6 = Plate movements; 7 = Oceanic crust; 8 = Transitional crust. In the right side, right-dihedral diagrams (equal area projections, lower hemisphere) for seven focal mechanisms of intermediate earthquakes whose epicentres are represented by squares (A), and three focal mechanisms of deep earthquakes whose epicentres are represented by circles (B); below, percentages of dihedra in compression.

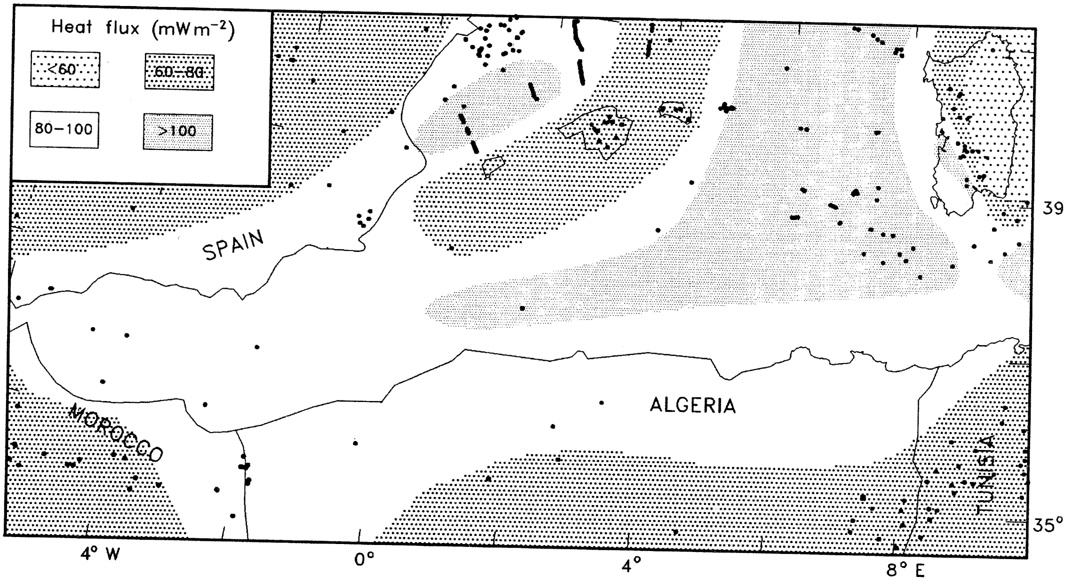

Fig. 4. Measurement sites (dots) and grey-contoured heat-flux map of the Southwestern Mediterranean.

i.e. extremely high or low values likely due to thermal refraction around high-conductivity structures or convection in sediments. Due to their lower quality, heat-flux values from the mainland were taken into account only as a boundary condition for contouring adjustments. In the Valencia trough, near Barcelona, heat-flux data from off-shore exploration wells were neglected, because of their large variations in temperature gradients presumably related to water circulation (Fernàndez and Banda, 1989). In principle, a statistical interpolation criterion was used, but for areas lacking of observations we also considered the structural setting, and to minimise uncertainties in peripheral zones, heat-flux values adjacent to the investigated area were taken into account (*cf.* Takherist and Lesquer, 1988; Rimi, 1990; Banda and Santanach, 1992; Della Vedova *et al.*, 1995).

The regional surface heat flux of the marine realm shows the highest values in the Central Algerian-Balearic basin as well as in the Sardinia Channel (> 100 mW/m^2). The heat flux (about 100 mW/m^2) decreases towards the northeastern part of the Valencia trough. Lower heat-flux values (80-100 mW/m^2) occur in the Alboran Sea and the Southwestern Algerian-Balearic basin. In the mainland, it ranges from 75 to 95 mW/m^2 in the Betic cordillera-Rif chain and the Tell-Atlas domain, and from 60 to 80 mW/m^2 in the African and European foreland. In the Balearic Promontory, the heat flux is on the order of 60 mW/m^2, as well as in Sardinia, excluding the Cenozoic rift zone which shows higher values.

The heat-flux pattern in the marine realm confirms the differences in the crust nature inferred from the TTS criterion. Table I shows the mean heat flux and the number of observations for each crustal domain. In principle, across the continental margin the larger the heat flux, the thinner the crust. This matches predictions of a thermal model proposed by Pasquale *et al.* (1995b), and based on a crustal extension mechanism by simple stretching. However, the mean heat flux of the continental margin is slightly higher than that of the stretching model, mainly because of the higher values observed in the Sardinian-African margin of the basin. The best agreement occurs for the Iberian-Balearic continental margin.

In the oceanic domain, the mean heat-flux value (107 mW/m^2) indicates a 20 Ma old crust, an age consistent with most models of ocean spreading (Pasquale *et al.*, 1996) and paleomagnetic results (Vigliotti and Langenheim, 1995) for the Western Mediterranean. Between the continental and oceanic domain a transitional belt with intermediate heat flux (105 mW/m^2) and composition is interposed. Wide variations in the average thermal conditions are found, particularly in the Sardinian-African margin, where data are very close to the oceanic boundary.

Table I. Surface heat flux q (in mW/m^2) in the crustal domains of the Southwestern Mediterranean basins: n = number of observations; s.d. = standard deviation.

Crust type	Domain	n	q	s.d.	Range
	Iberian-Balearic margin	7	80	28	42-126
Continental	Sardinia-Africa margin	8	95	15	83-110
	Total	15	88	23	42-126
	Iberian-Balearic margin	18	104	16	74-139
Transitional	Sardinia-Africa margin	11	107	14	89-131
	Total	29	105	15	74-139
Oceanic	Bathyal plane	20	107	18	90-148

4. Seismotectonic features

In this section we analyse the tectonic stress orientation and the seismic activity. One of the principal axes of the stress tensor being approximately vertical, the orientation of the stress ellipsoid is defined by specifying the azimuth of one of the subhorizontal principal stress axes, obtained from earthquake focal mechanisms, *in situ* stress measurements and geological indicators. Most of the analysed stress data derive from a compilation by Rebaï *et al.* (1992) of more than 1000 stress indicators in the Mediterranean region. Data were integrated with the analysis of focal mechanisms of intermediate and deep earthquakes (Buforn *et al.*, 1991) and results of recent studies on brittle microstructures (Galindo-Zaldívar *et al.*, 1993). The earthquake catalogue of Morocco, Algeria, Tunisia, the Alboran Sea and the Southern Iberian Peninsula (Benouar, 1994) was used as data source for the seismicity study.

Among 54 focal mechanisms of earthquakes and stress measurements, we have selected 20 fault-plane solutions, characterised by a low number of inconsistent readings and the best azimuthal distribution of stations compared to the focus, and three *in situ* stress data of good to very good quality. Among the different available geological indicators, we have considered a few tens of microtectonic measurements at 11 different zones, which showed a coherent distribution in space of fault planes.

Seismically active areas and stress directions are shown in fig. 3. Earthquakes in the uppermost 30 km occur in the Betic chain, with maximum concentration in the inner part as well as in the Rif chain and the western part of the Alboran basin. North of Algeria there is a seismic belt which is usually considered as the plate boundary between Eurasia and Africa (Buforn *et al.*, 1991). At 30-120 km depth, many earthquakes occur, mainly clustered in the southernmost part of Spain, west of the Alboran basin and north of Morocco. Seismic activity at 630-650 km depth (only three events in 1954, 1973, 1990, respectively) is present in Southern Spain.

In a first approximation, compression and tension axes of each focal mechanism of shallow earthquakes were identified for the greatest and least principal stress direction, and only the two axes which were closer to the horizontal plane were considered. The direction of the maximum horizontal stress, trending roughly NNW-SSE, is a consequence of the convergent motion of the Eurasian and African plates, and is consistent with the rotational motion of the African plate about a pole located at 21°N and 20°W (Argus *et al.*, 1989). Caught between the African plate and the Iberian block, the Gibraltar arc, affected by active right-lateral faults to the north and left-lateral faults to south, displays a relatively complex stress field pattern. In the Central-eastern Betics, focal mechanisms show subhorizontal tensional axes trending E-W. Excluding small local anomalies, in Morocco the maximum horizontal stress axis is roughly perpendicular to the Rif thrust sheets.

Focal mechanisms of intermediate and deep earthquakes were separately analysed by superimposing mechanisms in order to determine a zone of unit sphere denoting compression or distension (*cf.* Angelier and Mechler, 1977). Results estimated from focal mechanisms of earthquakes with depth greater than 30 km indicate a compression dipping 30° towards WNW. The deep earthquakes show a compressional axis plunging 50° towards the east and a subhorizontal, tensional stress axis plunging towards the west.

5. Geodynamical hypotheses

The most commonly accepted view is that the examined area is a result of lithospheric stretching originated by subduction processes beneath both the inner zones of the Tell chain and west of the Gibraltar arc. In particular, the Alboran region represents a crucial zone, as its evolution cannot be seen separately from the Africa-Europe interaction, and is somehow related to the eastern Atlantic tectonics. Different hypotheses were formulated to explain these processes. The following is a synthesis of the main and more recent geodynamic models.

5.1. *Microplate model*

Many researchers (*e.g.*, Andrieux *et al.*, 1971; de Smet, 1984; Le Blanc and Olivier, 1984; Rebaï *et al.*, 1992; Vegas, 1992) proposed that the Alboran region is formed by a microplate, bounded by dextral-transpressive zones to the north and sinistral-transpressive zones to the south, moving towards the west in relation to the convergence between Africa and Europe (fig. 5a). This hypothesis might explain the migration of the internal units towards the northwest and southwest in the Betics and the Rif, respectively. However, the Alboran region is widely and deeply deformed so that it is difficult to envisage it as a microplate, which, instead, should be deformed only partially at its margins.

If one considers this region as the westernmost part of a hypothetical intermediate or Mediterranean plate (a sort of Apulian plate, transversely very wide), this model can be considered a derivative of the «three-plate model» invoked by Hsü (1989) for the kinematic reconstruction of the Mediterranean. In principle such a model could work, but it is not totally convincing when applied locally to the Betic cordillera-Rif system.

5.2. *Extensional collapse model*

Assuming that extension structures in the Alboran basin are coeval (Neogenic) with the radial pattern of overthrusting around the Gibraltar arc, Platt and Vissers (1989) formulated a model consisting of the following stages of development (fig. 5b):

– collisional phase (pre-Neogene): the relative north-south convergence between Africa and Europe led to the collision of the continental margins, forming an orogen of Alpine type, located in the present-day Alboran area. During this phase (Upper Cretaceous-Paleogene), due to the subduction of Africa beneath the Iberian block (Horváth and Berckhemer, 1982), a crustal thickening (doubling) should have taken place, yielding a more than 50 km thick crust and forming cold lithospheric roots;

– detachment phase: such roots, gravitationally unstable, could have been detached through delamination (the process is described by Bird, 1978, and discussed by Houseman *et al.*, 1981, in terms of convection), and then sank in the mantle. The root detachment caused, as a reaction, a rise in the topography and an increase in the gravity potential energy of the orogen. As a consequence, vertical stresses exceeded horizontal ones (the latter due to plate convergence) and the region began to stretch;

– extensional phase: after sinking, lithospheric roots were replaced by asthenospheric material (Lower Miocene) and the subsequent stretching was accompanied by shortening and overthrusting, almost radially, in the surrounding regions (the Betics and the external Rif). Extension in the inner area (Alboran basin) is, instead, accompanied by a high subsidence rate.

Considering the peridotic bodies of the Gibraltar arc as mantle equivalents of metamorphic core complexes usually associated with arc-shaped orogenic systems, Doblas and Oyarzun (1989) proposed a slightly different scheme, again based on the gravitational collapse due to an overthickened Betic orogen. The process would have caused exhumation of mantle peridotites and asymmetric extension, maximized towards west.

In our opinion, this model shows some inconsistencies:

a) it requires contemporaneity between extension and overthrusting. But this does not match the available evidence. Seismic refraction data (Mulder and Parry, 1977) show that extension does not affect Neogenic sediments of the Alboran basin (it could have affected the basement in earlier times, but this cannot be seen in seismic profiles, and other data are not available). As the crustal thickness is now 13-20 km, there is no doubt that extension occurred. Structures observed towards the mainland indicate that extension probably occurred in the Late Oligocene-Lower Miocene and migrated towards the mainland during the Middle Miocene;

b) it implies lithospheric thickening before stretching; however this is not always necessary,

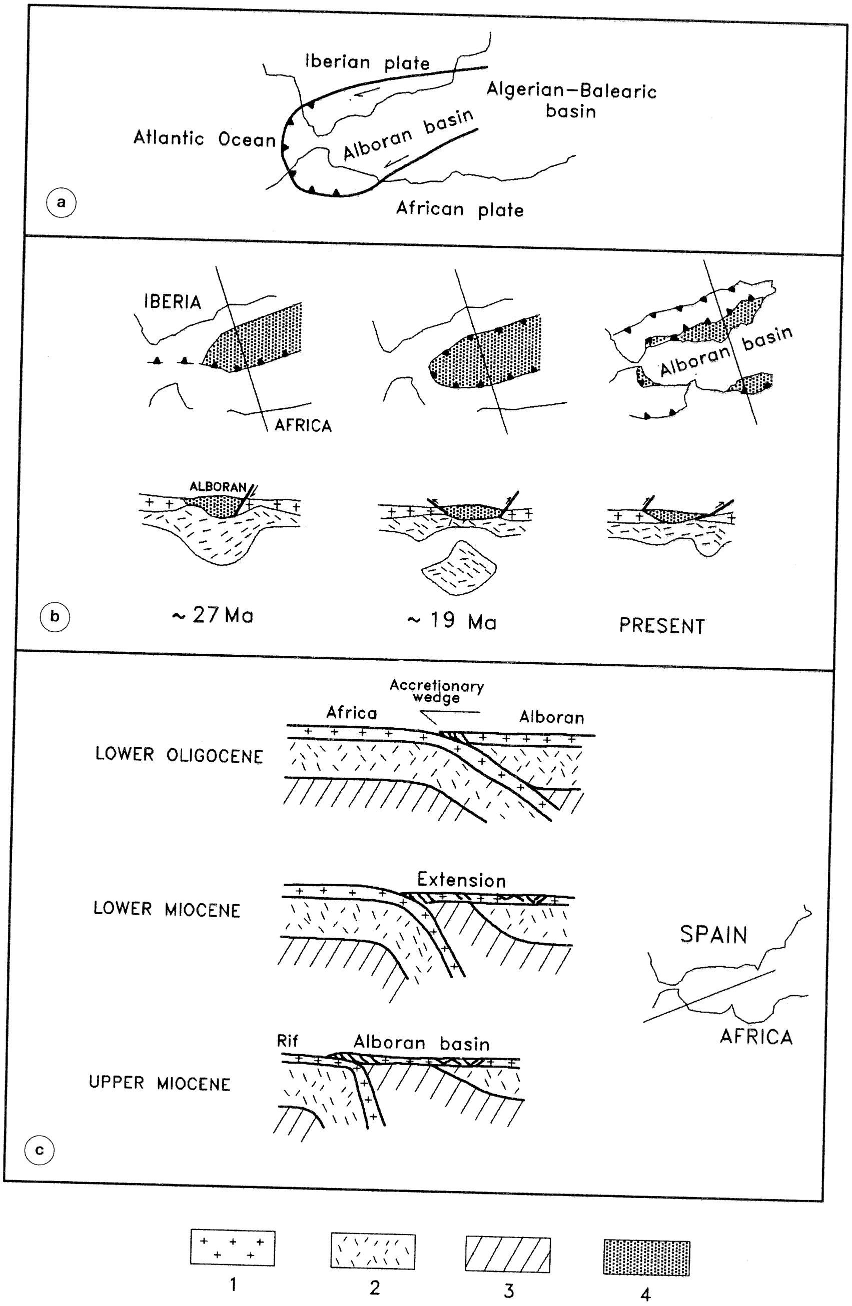

Fig. 5a-c. Models of tectonic evolution of the Southwestern Mediterranean. Geodynamic hypothesis of (a) microplate dispersal (Vegas, 1992); b) extensional collapse of thickened continental lithosphere (Platt and Vissers, 1989); and c) backarc extension (Morley, 1993). 1 = Continental crust; 2 = Lithospheric mantle; 3 = Asthenosphere; 4 = Collisional ridge.

as observed in several extensional areas (*cf. e.g.*, Green *et al.*, 1986; Keach *et al.*, 1989).

The uncontemporaneity between extension and compression is argument in favour of a backarc-extension model (*cf.* Malinverno and Ryan, 1986).

5.3. *Backarc basin model*

Morley (1993) tried to explain the geodynamical evolution of the region according to the mechanism described by Doglioni (1991, 1992), by invoking the subduction and roll back of the African plate (fig. 5c). This caused extension in the Alboran backarc basin and compression in the external front of the accretionary wedge of the Rif which thrust over the foreland. An upwelling of mantle materials originated a surplus of heat and then thermal subsidence (sag basin).

However, this interpretation is not exhaustive as:

a) Morley himself stresses that this reconstruction fits only the evolution of the Rif, but does not explain the migration and movements towards the northwest of the internal units of the Betics;

b) this interpretation is mainly based on the subduction of the African plate beneath Europe, but there is no clear evidence from seismic tomography. Blanco and Spakman (1993) recognised the presence of a deep lithospheric body whose dip is indeed difficult to ascertain, being nearly vertical;

c) a mantle flowing towards the east, invoked to justify these subduction processes, is not able to explain the westward migration of the tectonic wave which implies a subduction opposed to that predicted by the model.

6. Proposed evolutionary model

In view of the limitations described above and the complex structural setting of the area, it is more reasonable first to establish leading ideas for the resolution of the problem. The fundamental and widely accepted constraints to be taken into account for any geodynamical interpretation are:

- the continuation of the Betic cordillera-Rif system across the Gibraltar Straits and the westward overthrust of this orogenic system since the Lower Miocene (Horváth and Berckhemer, 1982);
- the beginning of compression in the arc almost contemporaneous with subsidence (*i.e.*, extension) in the Alboran basin;
- extension in the Alboran basin coeval with the opening of the Algerian-Provençal basin which, in turn, is related to the north-dipping subduction of the Apulian-African plate (*e.g.*, Vegas, 1992);
- the age of the oceanic domain in the Algerian-Balearic basin, on average 20 Ma, as can be deduced from surface heat-flux data;
- the existence of an early orogen, derived from an Alpine phase (Cretaceous-Paleocene-Eocene?) antecedent to the Betic cordillera-Rif system, and extension in the Alboran region, both inferred from *P-T-t* paths of internal metamorphic complexes of the Betics (van Wees *et al.*, 1992);
- subsidence and heat flux in the Algerian-Balearic basin consistent with values of an oceanic crust (*cf.* Pasquale *et al.*, 1996), suggesting that the basin is marginal and thus linked to the evolution of the Ligurian-Provençal basin.

Our favourite hypothesis is based on idea that, due to a convergent tectonic framework, some material could be squeezed and laterally pushed away, translating almost perpendicular to the convergence direction, within a lateral subduction process, secondary to the main boundary of the plate (*cf.* Royden, 1993a).

6.1. *Lateral extrusion model*

Our reconstruction begins from a pre-Neogenic phase during which the convergence between Africa and Europe generated a subduction of Alpine type, *i.e.* the European plate subducted beneath the African one (fig. 6). Between the plates we can speculate about the presence of a thin oceanic lithosphere or a stretched continental margin. The latter hy-

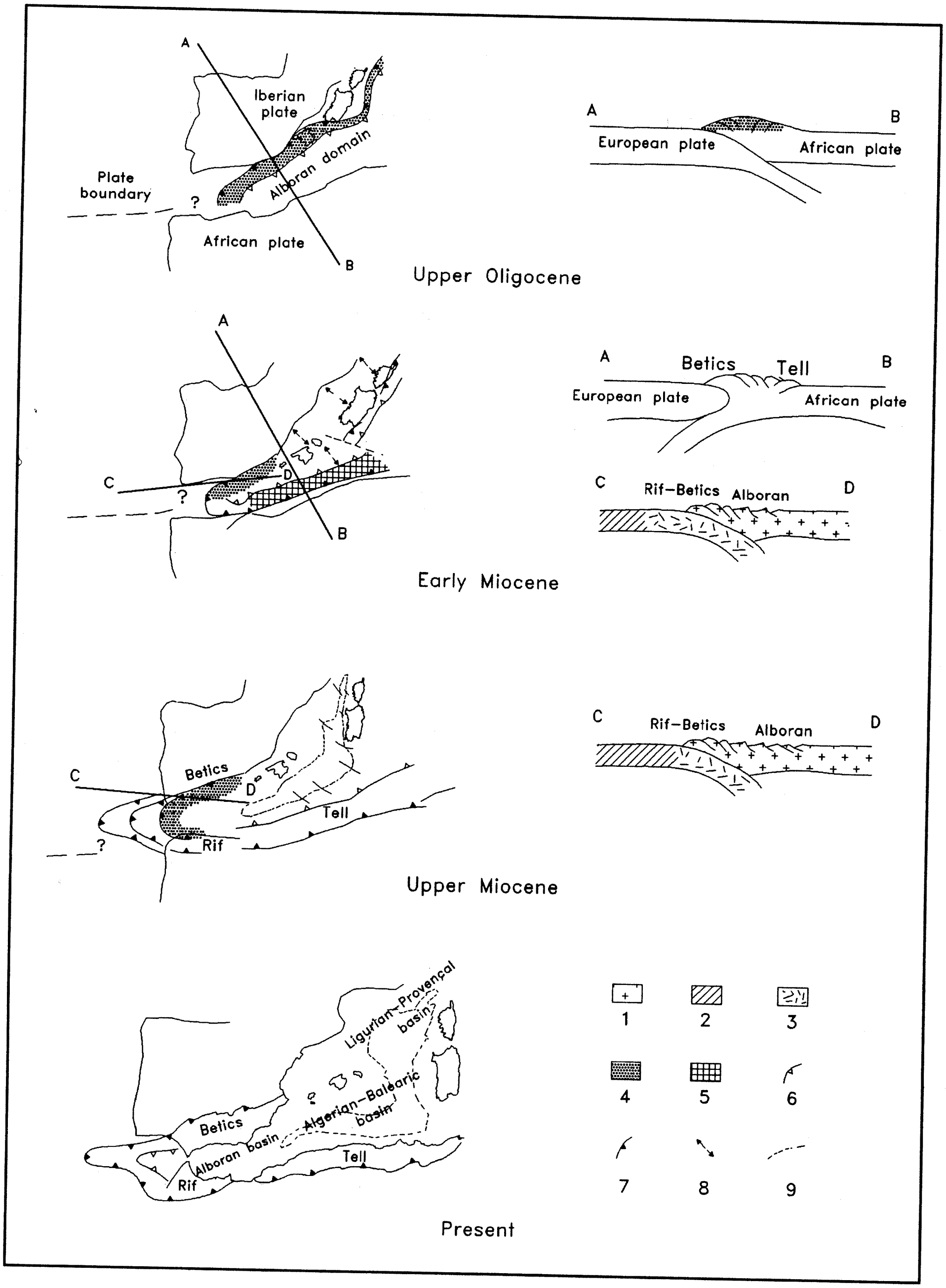

Fig. 6. Model of continental lateral escape for the Pre-Neogene to Present evolution of the Southwestern Mediterranean. 1 = Continental lithosphere; 2 = Oceanic lithosphere; 3 = Continental margin; 4 = Betic cordillera-Rif system; 5 = Tell chain; 6 = Subduction boundary; 7 = Thrust front; 8 = Lithospheric stretching; 9 = Oceanic domain boundary.

pothesis seems more reliable, as in the Rif-Betics (as well as in the whole north African system) there are no ophiolites (Smith and Woodcok, 1982). The process of convergence and subduction of the Iberian margin should be marked by the Alpine metamorphism (van Wees *et al.*, 1992): subduction occurred along the boundary between the plates, ending somewhere to the west in the Azores-Gibraltar line. The presence of bulges and hollows between the margins could have caused an initial bending.

In the Aquitanian-Burdigalian, the formation of the Algerian-Balearic basin, as well as that of the Ligurian-Provençal basin, implied the inversion of the subducted slab towards Europe. This could be due to the complete consumption of the thinned Iberian margin and the actual collision between the two continental blocks. The inversion could be accounted for by differences in the lithospheric thickness (*cf.* Doglioni, 1991; Royden, 1993b), in this case playing against the African margin. The convergence between Africa and Europe (*cf.* Dewey *et al.*, 1989) could have insulated, within the collision zone, crustal, or more generally, lithospheric materials which were squeezed between the converging margins and laterally extruded (*cf.* McKenzie, 1972; Dewey and Sengör, 1979; Sengör *et al.*, 1985; Sengör, 1993). If material thrusts over a thin continental or oceanic lithosphere, the gravity driven action of the subducting plate (slab pull) intervenes (Royden, 1993a,b). Our hypothesis is that the deeper lithospheric levels were also involved, as testified by exhumation of mantle peridotites 22 Ma B.P. in the Gibraltar arc (Obata, 1979; Priem *et al.*, 1979).

Overthrusting towards the external zones of the Betic cordillera-Rif chain began in the Lower-Middle Miocene and terminated in the Upper Miocene. This process was accompanied by extension and, contemporaneously, subsidence in the Alboran basin and Southern Iberia. The present-day western boundary of the Rif-Betics should lie in the Atlantic ocean, about 800 km west of Gibraltar (Lajat *et al.*, 1975), identified by an arched line connecting the outermost thrust sheets. According to Royden (1993b), this is consistent with an eastward-dipping, very narrow subduction beneath the arc, representing the lateral escape towards the Atlantic, and the subduction rate is estimated to be higher than the relative motion between Africa and Europe. This extensional-compressional system is very close to being defined as a local system, only partially obeying global tectonic rules, because it could be in relation with the Azores triple junction which changes eastward from a ridge into a transform fault, with large strike-slip motion of right-lateral character.

While west of Gibraltar subduction should still be active, the process has now ended beneath the Rif-Tell zone. The Algerian-Balearic basin is quiescent as well, as revealed by the lack of seismic activity. Eastward-dipping subduction during the last 5 Ma could have been accommodated by relative north-westward movements of Africa to Europe (*cf.* Dewey *et al.*, 1989).

7. Discussion

The crust beneath the Algerian-Balearic basin was affected by a complex tectonothermal history signed by continental stretching, the subsequent rotation of the Corsican-Sardinia block, and the formation of an oceanic crust in the bathyal zones. Its origin, as well as the Alboran continental basin, should be seen in the light of a relative convergence between the African and European plates, producing, from the one hand, extension in the basins and, on the other, overthrusting in the Tell and the Gibraltar arc. In this context, the Alboran basin should be considered as a result of a dynamic process characterised by compression and subsequent stretching.

Tectonothermal events are reflected by the nature and composition of the crust as well as the surface heat flux. However, if an evolutionary model of the Southwestern Mediterranean is attempted, several problems arise. Up to now all models proposed in literature show evident limitations. To us, the mechanism envisaged by Royden (1993a) could be a good basis to outline a reasonable evolutionary scheme.

However, one of the crucial points to be clarified first is the pattern of the plate boundary between Africa and Europe. An eastward-dipping and westward-retreating subduction would require a «spoon-like» lithosphere, downwarped and narrowly bent; as the geometry of the contact zone between plates is not clearly resolved (*cf. e.g.*, Grimison and Chen, 1986; Sartori *et al.*, 1994), it is not simple to visualise such a subduction. West of Gibraltar, there should be an ocean-ocean collision zone where an actual plate boundary is hard to distinguish, as if two ocean lithosphere blocks, thermally and mechanically identical, were juxtaposed.

The seismic activity is another puzzler as:

a) it does not constrain enough the continuation of the Gibraltar arc below the Atlantic. While an extensional regime should be expected at least in the inner parts of the arc, like that occurring, for example, in the Northern Apennines (Pasquale *et al.*, 1993), the seismotectonic regime is clearly compressive. Moreover, seismic events are mainly concentrated south of the Iberian margin, and do not follow any arched pattern;

b) it does not make possible the visualisation of the dip of the subducted lithosphere. Subcrustal seismic events with focal depth of 30-120 km around the Alboran basin occur along a sub-vertical plane;

c) it does not make it possible to visualise a continuous lithospheric slab. At 660 km depth there again occur earthquakes, but there exists a seismic gap for 500 km. Royden (1993b) interpreted such a seismic activity as a proof of an active subduction beneath the Gibraltar arc, but Grimison and Chen (1986) demonstrated that also a detached fragment of lithosphere, a gravitationally and thermally unstable «blob», could have a brittle behaviour. The latter interpretation is consistent with seismic tomography evidence (*cf.* Blanco and Spakman, 1993).

Moreover, before concluding beyond doubt that the Alboran region and the Betic cordillera-Rif arc belong to a local system which escapes the global dynamics, more details on relations and interactions between plates west of the Gibraltar Straits are necessary.

8. Conclusions

We have presented a set of geophysical data from marine and continental areas of the Southwestern Mediterranean. If a simple stretching mechanism is assumed to model the extensional processes which have occurred since Miocene times, TTS results account for crustal thinning in the Alboran basin and ocean spreading in the Algerian-Balearic basin. The different crustal domains inferred from subsidence analysis match the thermal regime. Heat flux is higher in the bathyal zones indicating ages around 20 Ma for the oceanic crust. Across the continental margins, the thicker the crust, the lower the heat flux. The present-day stress field, inferred from earthquake focal mechanisms, *in situ* stress measurements and geological indicators, is mainly controlled by the convergence of the Eurasian and African plates.

The maximum horizontal stress direction trends NNW-SSE. The Gibraltar arc shows a relatively complex pattern with subhorizontal tensional axes trending E-W in the Central-eastern Betics, while the maximum horizontal axis is roughly perpendicular to the Rif chain in Morocco.

Different models, proposed to account for the evolution and the present-day setting of the area, have been discussed. There are several pieces of evidence which argue against evolutionary schemes dealing with the Alboran region as a microplate or interpreting extension and overthrusting in terms of extensional collapse or classical backarc processes. This study draws the attention to a further possible mechanism.

During the convergence motion between the two main plates, lithospheric materials could have been insulated within the collision zone and laterally extruded westwards, causing extension and subsidence in the Alboran basin and overthrusting in the Betic cordillera-Rif system. Although basic evidence, such as the geometry of the two plates and the pattern of the seismic activity, is still open to question, our model is consistent with some fundamental geophysical and geological constraints.

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