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Rifting and thermal evolution of the Northwestern Mediterranean

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Abstract
The structural setting of the Northwestern Mediterranean stems from tectonothermal processes which reflect on the nature of the crust. The Oligocene to Present evolution is here analysed with a thermal model which takes into account the significant extension of the continental lithosphere before the onset of sea-floor spreading in the bathyal zone. Subsidence data were used to set the boundaries of the oceanic realm which was compared with previous reconstructions inferred from other geophysical evidence. The thermal features of the transitional crust that lies between the oceanic crust and the stretched continental margins were also outlined. The Ligurian-Provençal basin is a marginal basin, whereas only the continental crust is expected in the Valencia trough. An evolutionary sketch of the study area that accounts for the observed subsidence and heat flux is proposed.

Key words *rift – marginal basin – thermal model – oceanic and transitional crust – Mediterranean Sea*

1. Introduction

Rifting basins are regions characterized by continental thinning and rising of asthenospheric material which cause consequent changes in the physical properties of the lithosphere. Much geophysical evidence characterizes such areas: low seismic velocity, low-density upper mantle, enhanced heat flux, volcanic activity, deformations and earthquakes with fault-plane solutions of tensional type. Mechanisms yielding lithosphere stretching can be of three basic types:

– mechanical thinning, in response to a regional tensional stress field, with passive rise of asthenosphere;
– thermal thinning with heat transfer through the lithosphere base by both convection and conduction;
– diapiric rising of asthenosphere material into the lithosphere.

The efficiency of each mechanism, for which various models of lithosphere stretching can be formulated, and the detailed variations produced by the extensional events can sensibly differ (Verdoya *et al.*, 1994).

Due to its tectonic features, the Northwestern Mediterranean is highly suitable for treating these geodynamic concepts. In this paper, we studied its evolution by means of models which, besides continental stretching processes, account for the development of a marginal basin. The analysis of the total tectonic subsidence, which is given by the difference between the pre-rift elevation of the continental crust and the present-day basement depth after removing the sediment load effect, allows the determination of the boundaries of the different types of crust, the stretching rate, and thus to account for the geodynamics of the region.

2. Tectonic and structural setting

The Mediterranean Sea consists of several basins differing in age and origin. Its northwestern part, which is analyzed in this study, is formed by the Ligurian-Provençal basin and the Valencia trough (fig. 1). The genesis of such areas is a result of very complex processes which involved, besides stretching in the margins, production of magma as well as formation, in the deepest zones, of new crust differing from the former in physical-chemical characteristics.

There is general agreement that the formation of the Ligurian-Provençal basin took place within an Oligocene-Miocene rift regional system which yielded the development of a marginal basin. The extensional processes is thought to be related to the subduction of the African-Adriatic plate beneath the European plate and the drifting of the Corsica-Sardinia block. However, different hypotheses have been formulated about the time when the basin opened, its original position, and the rotation and kinematics of the Corsica-Sardinia block. This is because the nature and structure of the crust in the marine realm have not yet been exhaustively defined. Therefore, models explaining the Corsica and Sardinia displacement and mechanisms of basin opening and spreading run the risk of becoming more or less speculative (Pasquale *et al.*, 1994).

The Valencia trough lays southwest of the Ligurian-Provençal basin. It is located between the Balearic ridge, which is considered as a prolongation of the Betic thrust belt, and the

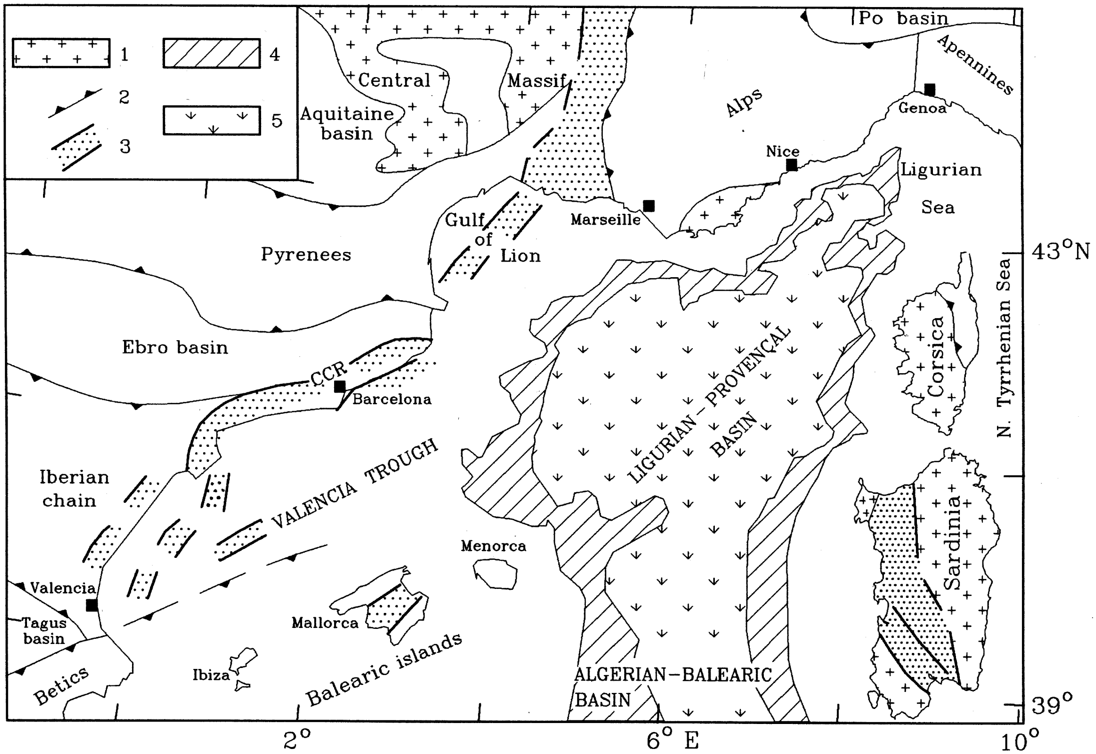

Fig. 1. Main structural features of the Northwestern Mediterranean and crustal type boundaries determined in this paper. 1: Palaeozoic basement; 2: overthrust; 3: Cainozoic rift; 4: transitional crust; 5: oceanic crust.

Iberian Peninsula. The trough, albeit roughly coeval with the basin, is interpreted as related to the west European rift-system or to subduction processes due to the Africa-Europe convergence, otherwise it should be viewed as a foreland basin of the Betic belt during Early Miocene times, superposed on the rift system of Oligocene-Early Miocene age (Torres *et al.*, 1993).

Seismic, gravity and magnetic observations have given the first evidence of the oceanic crust in the Ligurian-Provençal basin (Burrus, 1984; Réhault *et al.*, 1984). Le Douaran *et al.* (1984) and Pascal *et al.* (1993) demonstrated that the continental crust gets thinner from the coast line (about 25-30 km) to the deepest zones (about 8 km). In the central zone of the Ligurian-Provençal basin, the acoustic basement reveals *P*-wave velocities ranging from 5.8 to 6.9 km/s, which are typical of Layer 3 of the oceanic crust; velocity of 5.2-5.3 km/s, which characterizes basaltic layers, is almost absent. The lower crust in the Valencia trough shows velocity values of 6.6 km/s, except the southern part of the trough where the heat flux is anomalously high and velocity is 6.4 km/s. Below the crust-mantle discontinuity, seismic velocity of 7.8-7.9 km/s is present, indicating an anomalous mantle (Torné *et al.*, 1992).

Bouguer gravity anomalies (120-220 mGal) are directly connected to the rise of mantle materials, with consequent upwarp of the Moho to a depth of 12-15 km, and crustal thinning up to a 3-5 km. In the central part of the Valencia trough, the negligible free-air anomalies indicate prevailing isostatic equilibrium. On the contrary, in the bathyal plain of the Ligurian-Provençal basin, positive values account for mass excess or further sinking of the area (Torné *et al.*, 1992). Magnetic features typical of oceanic crust are not clearly highlighted as the regional field trend is remarkably affected by local anomalies (over 200 nT), due to magmatic intrusions, which do not show any clear pattern of a sea-floor spreading (Galdeano and Rossignol, 1977). This leads to the hypothesis that spreading took place in a very short time or through mechanisms which did not generate standard magnetic anomalies with elongated shape and parallel trend.

3. Subsidence analysis

3.1. *Modelling*

More detailed information on the nature and spatial distribution of the crust is necessary to understand the processes which affected the examined area. The extensional tectonics which yielded the buildup of the Ligurian-Provençal basin and the Valencia trough, seems to have left a signature not only in the structure, but also in the enhanced heat flux, affected by a strong transient component. Since their formation, these zones have undergone high subsidence, which is testified by the remarkable accumulation of syn- and post-rift sediments (Chiozzi *et al.*, 1994).

Among the different extensional models which have been formulated (uniform stretching, depth-dependent extension, dyke intrusion or melt segregation and lateral variation of stretching; see Fowler, 1990, for a summary), McKenzie's (1978) pure shear model represents a simple mechanical thinning of the lithosphere in response to a regional extensional stress field. Several authors used such a model for some sectors of the Northwestern Mediterranean and calculated that it accounts well for both the present-day heat flux and subsidence (see Pasquale *et al.*, 1994 and references therein). Here, the uniform extension model together with the cooling ocean plate model allow us, albeit in a first approximation, to characterize the nature of the crust that underlies the region and to map the ocean-continent boundary.

The evolution of the study area may be divided into two stages. The first stage is represented by the origin of a continental rift with thinning of the crust and lithospheric mantle, and asthenosphere upwarping. At the same time, initial subsidence by isostatic rebound took place, because of the density change which results from stretching and temperature increase of the uppermost mantle.

The second stage involves a passive process caused by the crust and upper mantle comeback to thermal equilibrium with consequent lithosphere contraction which results in a long-term thermal subsidence. Initial subsidence plus thermal subsidence constitute the total tectonic subsidence.

In this model, stretching is instantaneous and uniform, and the lithosphere thickness H is reduced by a factor β. If the compressibility effect on density ρ_c and ρ_H of the crust and lithospheric mantle, respectively, is neglected, the initial subsidence S_i is given by (Le Pichon and Sibuet, 1981; Chiozzi *et al.*, 1994):

$$S_i = \frac{H\rho_a - h\rho_c - (H-h)\,\rho_H}{\rho_a - \rho_w}\left(1 - \frac{1}{\beta}\right) \qquad (3.1)$$

with

$$\rho_a = \rho_m\,(1 - \alpha T_a)$$

$$\rho_c = \rho_{co}\left(1 - \frac{\alpha}{2}T_a\frac{h}{H}\right)$$

$$\rho_H = \rho_m\left(1 - \frac{\alpha}{2}T_a - \frac{\alpha}{2}T_a\frac{h}{H}\right)$$

where ρ_m and ρ_{co} are the lithospheric mantle and crust density at room temperature, ρ_a and T_a the asthenosphere density and temperature, ρ_w the water density, α the thermal expansion coefficient and h the crust thickness.

After more than 200 Ma since rifting, the lithosphere would attain thermal equilibrium conditions with a maximum total tectonic subsidence S_∞ as a function of the present crustal thickness expressed by the equation:

$$S_\infty = h\,\frac{\rho_H - \rho_c + \rho_m\,(\alpha/2)\,T_a + \varepsilon}{\rho_a - \rho_w}\left(1 - \frac{1}{\beta}\right) \qquad (3.2)$$

where

$$\varepsilon = -\frac{\rho_m - \rho_{co}}{\beta}\left(\frac{\alpha h}{2H}T_a\right)$$

can be neglected since it yields an error in the order of 0.5%.

Values for ρ_{co}, ρ_m, ρ_w and α proposed by Sclater *et al.* (1980) have been used for the Northwestern Mediterranean, as they are very similar all over the continental margins. The results of seismic surveys indicate that the crustal thickness h is 25-30 km in the areas surrounding the basins, but considering that the crust underwent a former thinning (Mesozoic), we have chosen h = 25 km. The lithosphere thickness H is 90 km at regional level (Pasquale *et al.*, 1990; Suhadolc *et al.*, 1990) and T_a has been set up to 0.9 times that of the mantle solidus (Pasquale *et al.*, 1994). It follows that eq. (3.1) becomes:

$$S_i = 3.7\left(1 - \frac{1}{\beta}\right) \quad \text{[km]} \qquad (3.3)$$

and eq. (3.2):

$$S_\infty = 6.5\left(1 - \frac{1}{\beta}\right) \quad \text{[km]}\,. \qquad (3.4)$$

As the Ligurian-Provençal basin and the Valencia trough are about 20 Ma old (Burrus, 1984), the thermal subsidence, which follows approximately an exponential law with time constant $\tau = H^2/(\pi^2\,\chi)$ and mean thermal diffusivity of the lithosphere χ = 32 m^2/a (Parsons and Sclater, 1977), should have attained 46% of its maximum value. Equation (3.4) thus becomes:

$$S_{t\,=\,21\mathrm{Ma}} = 5.0\left(1 - \frac{1}{\beta}\right) \quad \text{[km]}\,. \qquad (3.5)$$

3.2. *Implications on the crust nature and structure*

A value of total tectonic subsidence of 2.5 km, that is the depth of the isostatic equilibrium level of the asthenosphere beneath the midocean ridges (Pasquale *et al.*, 1993), can be attained, according to eq. (3.3) for β = 3.2. By solving eq. (3.5) for such a maximum stretching rate, one obtains a present-day subsidence value of 3.4 km, which represents the boundary of the continental crust. Although there could be oceanic crust behind this limit, it occurs only for subsidence of 4.1 km at least, as predicted by the models of formation and cooling of oceanic plates (Sclater *et al.*, 1980). This indicates that between the two crusts there is a crust with transitional characteristics. The minimum thickness of the stretched continental crust is about 8 km, whereas the lithosphere is 30 km thick. For thicknesses lower than such values, the crust should be highly fractured and magma intrusions may make it structurally and petrographically intermediate between continental and oceanic.

To know the experimental total tectonic subsidence, which is useful to define the boundaries of the crust types, basement identification, the mass budget of the sedimentary column and the assumption of a suitable model of isostatic compensation are necessary. As it is impossible to have, for the study area, a detailed knowledge of the stratigraphy of the sedimentary cover, we used Crough's method (1983) which accounts for the density and porosity change with depth and the two-way travel time of acoustic waves. The latter parameter was deduced from basement isochron maps, which have integrated locally by data on sediment thickness obtained from seismic profiles and geologic-stratigraphic analyses. To calculate the total subsidence, it was assumed that the local isostatic compensation is of Airy's type. We did not use a flexural model, mathematically more complex, of an elastic or viscoelastic plate, as lateral variations of the sediment and crust thickness of the bathyal zone are not substantial. The application of such a model should give almost equivalent results or, at most, the difference should not be greater than the error on the subsidence estimate, that is about 100 m. A detailed map of the total tectonic subsidence, deduced from the available data, is depicted in fig. 2.

Figure 1 shows the above mentioned isolines of total tectonic subsidence that delimit

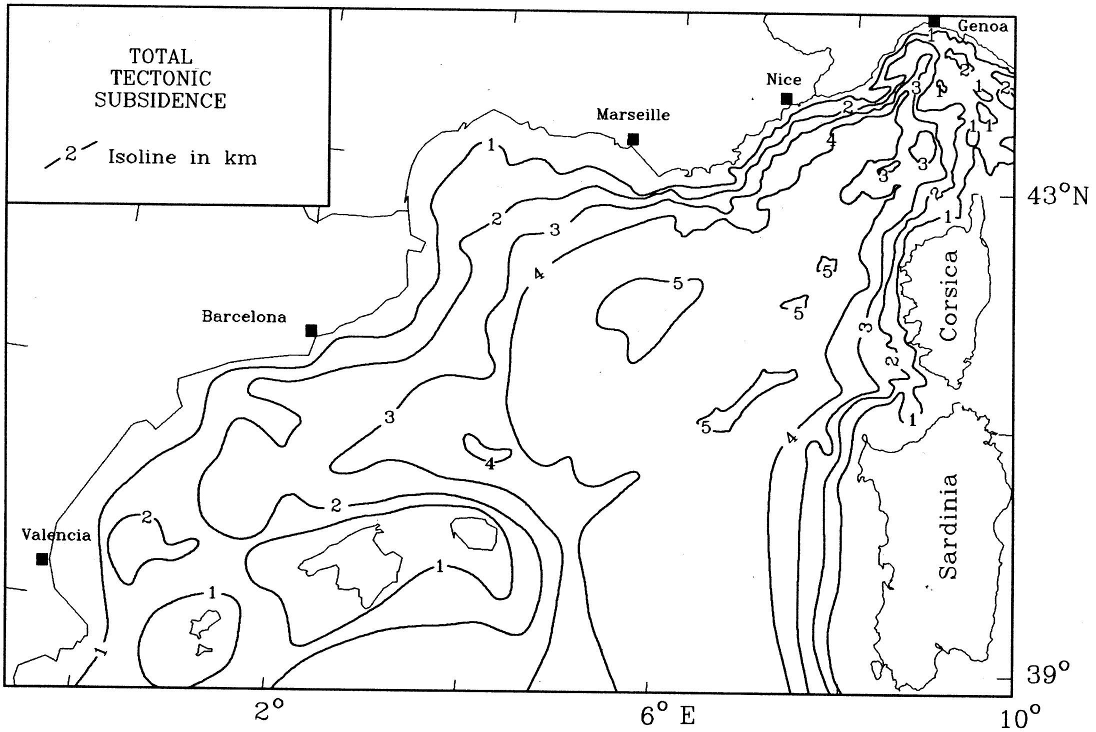

Fig. 2. A contour map of total tectonic subsidence.

the boundary of the stretched continental crust and the oceanic domain, respectively; between the two realms, a crust with intermediate features should be present. The stretched continental margins show a general decrease in width from south to north, which is much more evident from the Valencia trough to the Ligurian Sea than along the western margin of the Corsica-Sardinia block. The transitional crust forms a relatively narrow belt with wider zones in the southwestern part of the Ligurian Sea, and east of the Valencia trough and the Balearic islands. The oceanic domain has irregular shape with maximum width and subsidence (about 5 km) between the Gulf of Lion and the Corsica-Sardinia block, whereas it is narrower between the Balearic islands and Sardinia, and beneath the Ligurian Sea.

4. Discussion

Table I shows the mean heat-flux values from the stretched continental margins to the oceanic area. The data set has been extracted from the catalogue by Cermák *et al.* (1992), and from Burrus and Foucher (1986) and Foucher *et al.* (1992) whose data have also been corrected for the paleoclimatic effect as described in Pasquale *et al.* (1994). The thermal flux pattern in the Ligurian-Provençal basin seems to testify the existence of different crustal types; in the oceanic domain the mean heat flux is in good agreement with Sclater *et al.*'s (1980) relation between heat flux and age. The transitional crust is characterized by heat flux ranging within the typical values of ocean and continent, but closer to oceanic values.

In particular, the heat-flux values predicted are in good agreement with the observations only on the northwestern margin of the Ligurian-Provençal basin. Along the Corsican-Sardinian western margin it is observed a heat flux of about 100 mW/m^2. This produces an asymmetric thermal pattern, which is evident not only in the continental stretched crust, but also in the transitional one. At first sight, one could be induced to deal with such asymmetry according to Wernicke's (1981) model, hypothesizing a large-scale simple shear along a low-angle detachment fault which dips shallowly southeast under an actively retreating Corsican-Sardinian block. Wang *et al.* (1989) have extensively explored the thermal consequences of such model for the evolution of the Tyrrhenian Sea. Based on the hypothesis that the basin was opened by detachment of the Calabrian arc away from the Sardinia margin, these authors slightly modified the model so that fault cuts only the upper and middle crust but merges subhorizontally into lower crust, below which pure shear may occur. However, there is no evidence of a low-velocity zone at any level within the continental lithosphere beneath the Corsican-Sardinian block. The detachment level from the underlying medium such that the block can undergo substantial rotation must therefore be sought at the base of the lithosphere, in the upper mantle at depth between about 60-70 km (Blundel *et al.*, 1992). Moreover no normal fault is evidenced beneath the Corsican-Sardinian block, at present seismically quiescent, contrary to what occurs in the Calabrian arc, which is the most seismically active area in the Central Mediterranean. Seismicity in the Ligurian-Provençal basin is present only in the continental margins north of Corsica, denoting a compressional regime

Table I. Number of observations and mean values of heat flux for the Ligurian-Provençal basin and the Valencia trough; in brackets standard deviation.

Area	Number of observations	Heat flux (mW/m^2)
LIGURIAN-PROVENÇAL BASIN		
Continental crust		
Northwestern margin	63	81 (17)
Corsica-Sardinia margin	41	98 (15)
Total	104	88 (16)
Transitional crust	81	101 (19)
Oceanic crust	100	105 (20)
VALENCIA TROUGH	82	84 (10)

(Pasquale *et al.*, 1994). The hypothesis of the presence of detached upper plate is then difficult to demonstrate. As the thermal anomaly is very large in wavelength and it lays on the whole western side of the Corsica-Sardinia block, a subcrustal origin could be a reliable explanation.

On the Ligurian-Provençal basin margin, between Nice and Marseille (fig. 3), there is an area of remarkable subsidence excess (200-800 m) which can be compared with that already observed by Burrus *et al.* (1987) in the bathyal part of the Gulf of Lion. A better fit may be obtained by means of a model accounting for differential stretching of the lithosphere (Royden, 1986). If mantle thinning were three times that of the crust, the subsidence excess observed could be justified. However, according to the results inferred by studying focal mechanisms of earthquakes (Pasquale *et al.*, 1994), such an excess of subsidence may be evidence in favour of a compressional stress regime on the margin.

Figure 3 compares the shape and width of the oceanic crust here defined and that determined by means of different techniques. The general trend matches that reported by Réhault (1981) and Burrus (1984). Nevertheless, they supposed a sudden transition from continental to oceanic crust. Also, taking into account the transitional crust, the previous boundaries are almost entirely in an internal position compared to the boundary of the continental margins. Substantially, the greatest differences with the oceanic crust determined from aeromagnetic observations and reflection seismics (Réhault, 1981) are beneath the Ligurian Sea and correspond with the prolongation of the

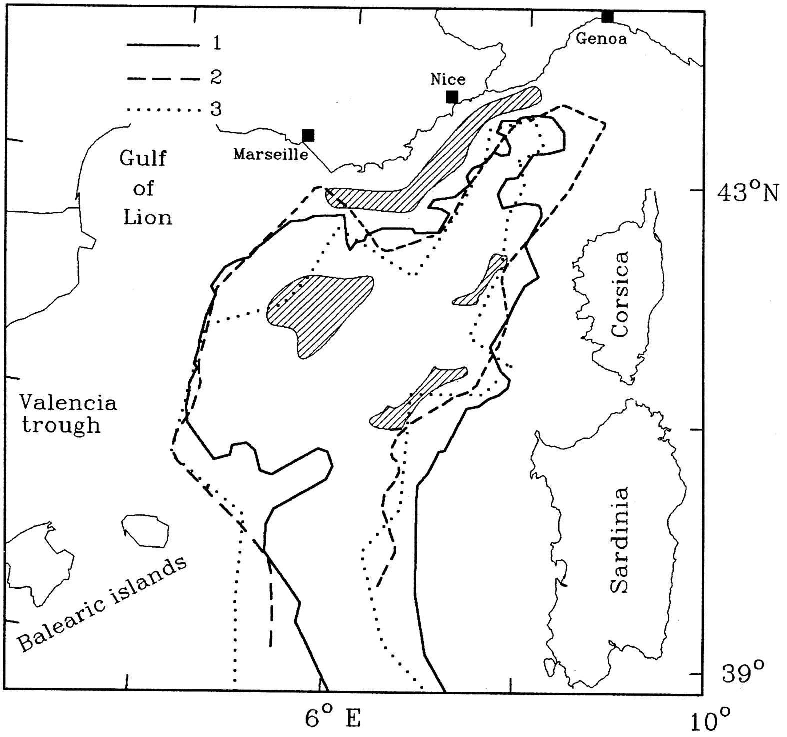

Fig. 3. Predicted ocean boundaries (1) compared with the oceanic crust (2) by Réhault (1981) and (3) by Burrus (1984). Hatching indicates areas with remarkable subsidence excess.

Balearic promontory, where our oceanic crust is narrower by some tens of kilometres. Off the Gulf of Lion the oceanic crust boundary deviates from that proposed by Burrus (1984) by a few tens of kilometres.

Within the oceanic realm there are sectors with remarkable subsidence excess (about 1 km). This is not surprising as it frequently occurs in most of the marginal basins which can be distinguished from the typical oceanic areas also by such a feature (Anderson, 1980; Sclater *et al.*, 1980). Réhault *et al.* (1984) and Jemsek *et al.* (1985) hypothesized that in the Ligurian-Provençal basin this might be due to an oceanic crust that is thinner than normal. An alternative explanation can be formulated from the high seismic velocity at depth of 90-100 km observed by Egger (1992) beneath the basin, which could represent relics of subducted lithosphere. According to Anderson (1989) the presence of cold materials beneath a marginal basin could produce additional sinking in the ocean floor and thus subsidence excess.

Figure 4a-c sketches the main evolutionary steps of the Northwestern Mediterranean region. After the Upper Eocene collision of the Adriatic block against the European plate which caused the formation of the Alpine chain with emplacement (obduction) of ophiolitic thrust-sheets in Corsica, in the Upper Oligocene northwestern-dipping subduction marked the onset of the Apennines orogeny and continental rifting between Corsica and the Palaeozoic European basement.

In the Early Miocene, the continental crust broke and new crust of oceanic nature began to spread out in the Ligurian-Provençal basin, while the Apennine accretionary wedge, consisting of stacking of the upper layers of the subducting plate together with syntectonic sediments, was overthrusting the Adriatic plate. Such events result from a single dynamic process which simultaneously produced both compressional and extensional tectonic realms characterized by a well-defined thermal regime.

In the Middle Miocene sea-floor spreading in the Ligurian-Provençal basin ceased. This process was accompanied by a very fast eastward migration of Corsica and Sardinia as far as their present position and by intense subsidence. The extensional magmatism east of Corsica about 15 Ma ago (Serri *et al.*, 1993) clearly dates the first extensional episodes which protracted till the Present in Northern Tyrrhenian area. Extension superimposes the formerly compressional structures of the inner zones of the Apennines Northern arc (Mantovani *et al.*, 1992) and increases the surface heat flux.

Retreating of the subduction boundary and rolling back of the subducted slab are invoked to change the tectonic setting from range buildup to crustal thinning and could explain eastward propagation of the tectonic wave as well as magmatism and thermal anomalies (Malinverno and Ryan, 1986; Doglioni, 1991; Royden, 1993; Pasquale *et al.*, 1994). The very fast ocean spreading in the Ligurian-Provençal basin, and then the high subduction rate of the Adriatic plate, supports the idea that the lithosphere slab could have been fragmented and remnants are now «floating» in the upper mantle west of Corsica accounting for subsidence excess in the oceanic realm.

5. Conclusions

The tectonic subsidence of the Northwestern Mediterranean extensional basins is strictly connected to their thermal evolution. A simple model of uniform stretching accounts well, in a first approximation, for the dynamic processes which led to the formation of the Ligurian-Provençal basin and the Valencia trough. Such a model, along with the total tectonic subsidence data, represents an indirect approach for the determination of the nature of the crust.

It has been found that the critical stretching factor should equal 3.2. Over this extension rate the continent-ocean transition should be represented by a gradual change in the petrophysical properties, similarly to what inferred was from recent data collected along passive margins of oceanic areas (Whitmarsh and Sawyer, 1993).

To describe the evolutionary history of the crust in the Ligurian-Provençal basin it is nec-

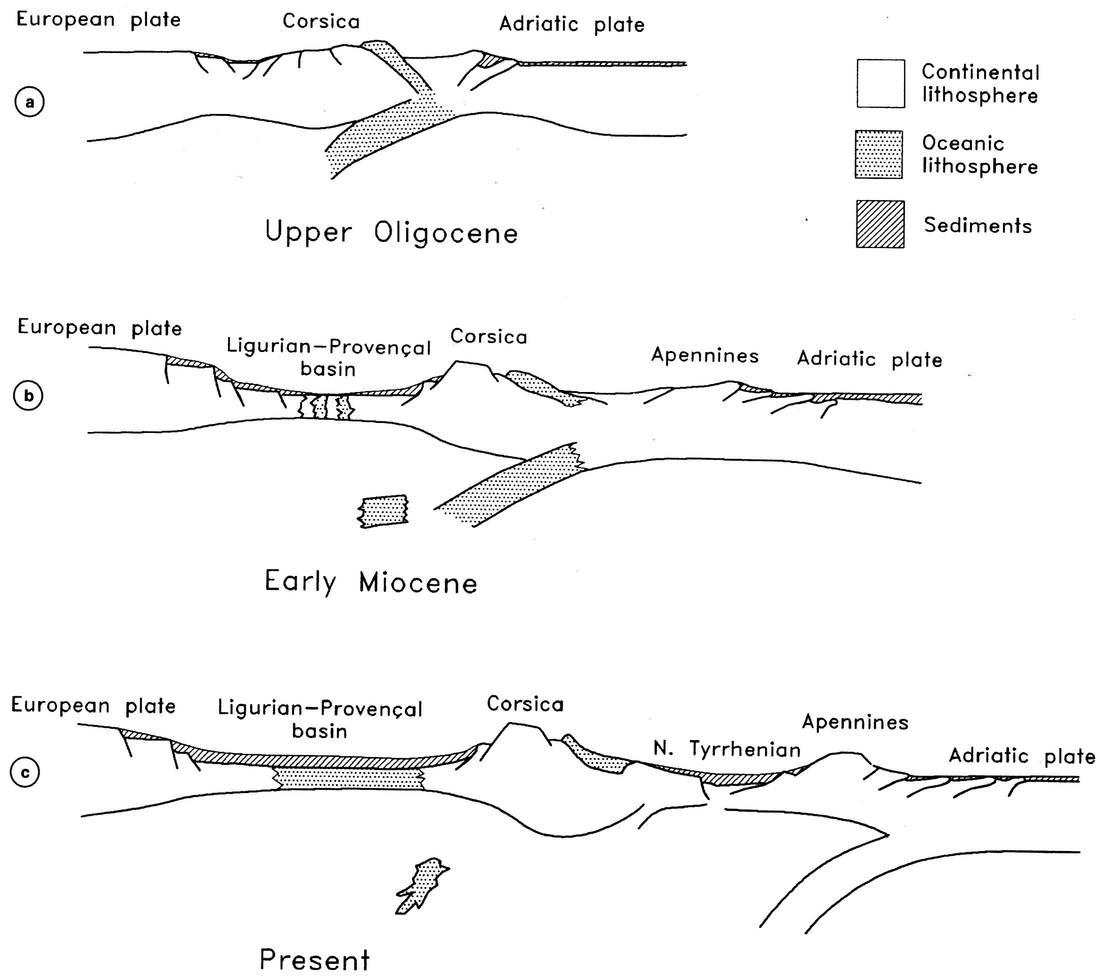

Fig. 4a-c. Evolutionary scheme of the Northwestern Mediterranean from the Upper Oligocene to Present. a) Lithosphere cross-section trending NW-SE through the European plate, Corsica and the subducting Adriatic plate (Upper Oligocene). b) Lithosphere cross-section trending NW-SE from the European plate to Corsica and WNW-ESE from Corsica to the Adriatic plate (Early Miocene). c) Lithosphere cross-section trending NW-SE from the European plate to Corsica and W-E from Corsica to the Adriatic plate (Present).

essary to invoke, besides continental stretching, ocean spreading processes which may occur only by 4.1 km, at least, of total subsidence. In the Valencia trough, that shows relatively low subsidence values, only continental thinning took place with no formation of oceanic crust. The regional trend of total tectonic subsidence as well as recent seismic results (de Voogd *et al.*, 1991) in the central and deepest part of the Ligurian-Provençal basin, seem to confirm the lack of a clear spreading centre through which new crust formed. Consequently, the opening of such basin very likely took place through a diffuse spreading.

The origin of the Northwestern Mediterranean is viewed within a tectonic framework of convergence between the European and the African-Adriatic plates. The tectonothermal events which occurred in the Oligocene-Miocene fit both the structure and composition of the crust, as well as the surface heat flux. The main assumption of the back-arc model is based on the Neogene subduction of the Adriatic plate whose boundary, initially located east of the Corsican-Sardinian block, progressively migrates eastward together with the front of the Apennines.

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