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SEISMIC AND HEAT FLOW STUDY OF THE SOUTHERN ADRIATIC BASIN

Abstract. From the interpretation of a large number of regional seismic reflection lines it is seen that the Southern Adriatic basin is an old depression, generated in the Mesozoic, when huge widespread rifting phases took place in the central-eastern Mediterranean Sea. An initial stretching occurred in the Middle Triassic with extensional deformations that thinned the crust of the Ionian Sea - Eastern Mediterranean and began to detach the Adria plate (Apulia) from the North African plate.

In the Middle-Upper Jurassic (178 to 150 m.a.) a second rift phase produced the most impressive and important extensional deformations, with generation of oceanic crusts such as in the Ionian and Eastern Mediterranean Seas, and drastic crustal thinning with deep basins. The Southern Adriatic is one of these Mesozoic deep continental basins that now constitutes a foredeep at the contact between the Southern Dinarides and Northern Hellenides orogenic systems. Seismostratigraphic information shows that the sequence from Trias to Lias thins notably from the Apulian margin to the deep basin, and is affected by numerous distensive faults. The succession dating from Dogger to Oligocene, in the deep basin, is very thin, continuous and of deep basin deposition. Stretching processes begun at about 178 m.a., continued very active until 150 m.a. with some terminal, less important movements until 120 m.a., thinning the crust from the 30 km of the Apulian Platform to the approximately 19-20 km of the Southern Adriatic Basin. Miocene and Plio-Pleistocene sediments thicken considerably into the basin. At the eastern side of the Southern Adriatic Basin are the buried front of the Dinarides thrusts to north and those of the Hellenides to the south, generated from late Oligocene to Middle Miocene. Mesozoic evaporites are involved in the thrusting tectonics.

Using all data furnished by seismic exploration, the Authors give a full explanation of the high heat flow values, according to time and rate of lithospheric stretching processes and associated thermal evolution. At about 150 m.a. the lithosphere reduced to about 35 km by thinning. Subsequent rethickening of the LID caused by cooling has led to an increase in the lithosphere to about 80-90 km at present.

INTRODUCTION

The first seismic exploration of the Southern Adriatic for scientific purposes was conducted several years ago (1972) in the framework of a large deep water project involving the entire Mediterranean Sea. Data obtained from the Southern Adriatic are illustrated in various papers, together with other Mediterranean regions (Finetti and Morelli, 1973; Finetti, 1982; Finetti and Del Ben, 1986; Finetti et al., 1987). The thick, well reflecting, sedimentary sequence of the Southern Adriatic Basin was immediately evident and impressive.

On the basis of identifiable seismic reflection characteristics elsewhere calibrated, the main reflectors and their chronostratigraphic attribution were recognized over two decades ago. With the successive progress in knowledge of the Adriatic reflecting sequence in general, and of the tectonic deformation involved, a finer more reliable seismic stratigraphy was obtained from the geophysical exploration.

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A very important contribution was furnished by the detailed public seismic exploration by ENI on the Italian offshore area of the Adriatic. Some other data then became available from the Yugoslavian side (Dragasevic, 1983; Frank et al., 1983 and others), so that it is now possible to outline a regional stratigraphic and structural setting for the whole Adriatic, more or less seismically controlled.

Some borehole data, in the literature, contributed to clarifying the main seismic stratigraphy, especially for the Neogene-Quaternary sequence and in a lesser manner for the Mesozoic ones. Moreover, a detailed study of the Quaternary sequence of the entire Italian Adriatic Sea area and its evolution has been published by AGIP geoscientists (Dondi et al., 1985).

Since 1966, in the Southern Adriatic, near the Apulian coastal area, a deep offshore seismic refraction investigation (Finetti et al., 1966) was conducted with the purpose of studying the crustal characteristic of the area. These data, together with other successive DSS profiling investigations and the stretching computation data from seismic reflection interpretation allowed a reconstruction of the crustal relationships between the Apulian Platform and the deep Southern Adriatic Basin.

Heat flow measurements (Della Vedova and Pellis, 1991) showed that the Southern Adriatic Basin is characterized by relatively high values. Using the stretching tectonics deformation shown by the seismic exploration data, the Authors in this paper intend to explain such high HF values. This is done starting from a rate and time analysis of the crustal lithosphere thinning (and connected asthenosphere uplifting) obtained seismically, and reconstructing the consequent thermal evolution up to the present.

STRATIGRAPHIC AND STRUCTURAL SETTING

A regional tectono-structural reconstruction of the studied area shown in Fig. 1 was performed by interpretation of the complete public domain seismic datasets of ENI for the Italian side of the Adriatic, and the MS scientific lines (see Fig. 1 for their locations). Other data for the Yugoslavian side could only be obtained from seismic lines and structural geology reported in the literature. Therefore, the seismic control of the area behind the median line is rather scarce and the reconstructed structural map of Fig. 9 in this part must be considered schematic.

Interpretation of the seismic datasets was performed using the following selected key chronostratigraphic horizons (Figs. 2 and 3):

- Base Pleistocene (Horizon ‘A1‘)
- Base Plio-Pleistocene (Horizon ‘A2‘)
- Base Messinian (Horizon ‘B‘)
- Top Oligocene Carbonate
- Top Mesozoic (Not picked in Figs. 2 and 3)
- Top Trias
- Acoustic Basement.

Identification of these horizons is sometimes rather easy and fully reliable, such as horizons ‘A1‘, ‘A2‘, ‘B‘ and Top Carbonate (Oligocene Scaglia), because they are substantially characteristic. Top Lias and Top Trias are seismically connected to distant reliable calibrations. Top Basement, in the relevant part, is identified on poor and scarcely characteristic reflectors.

In this paper, only the Time-Contour Map of Fig. 9 which shows the top of Mesozoic, that sometimes coincides or is very close to the top of Paleogene carbonate, is included.

To illustrate in more immediate manner the structural and stratigraphic conditions in the Southern Adriatic Basin and its Italian and Albanian margins, we describe our interpretation of seismic line MS-30, running from the Apulian Margin to the Northern Albanian Shelf (Figs. 2 and 3). The western part of MS-30 (Fig. 2) shows the tectono-stratigraphic setting of the Apulian Margin, starting from the Murge coast. The eastern half of MS-30 (Fig. 3) shows the

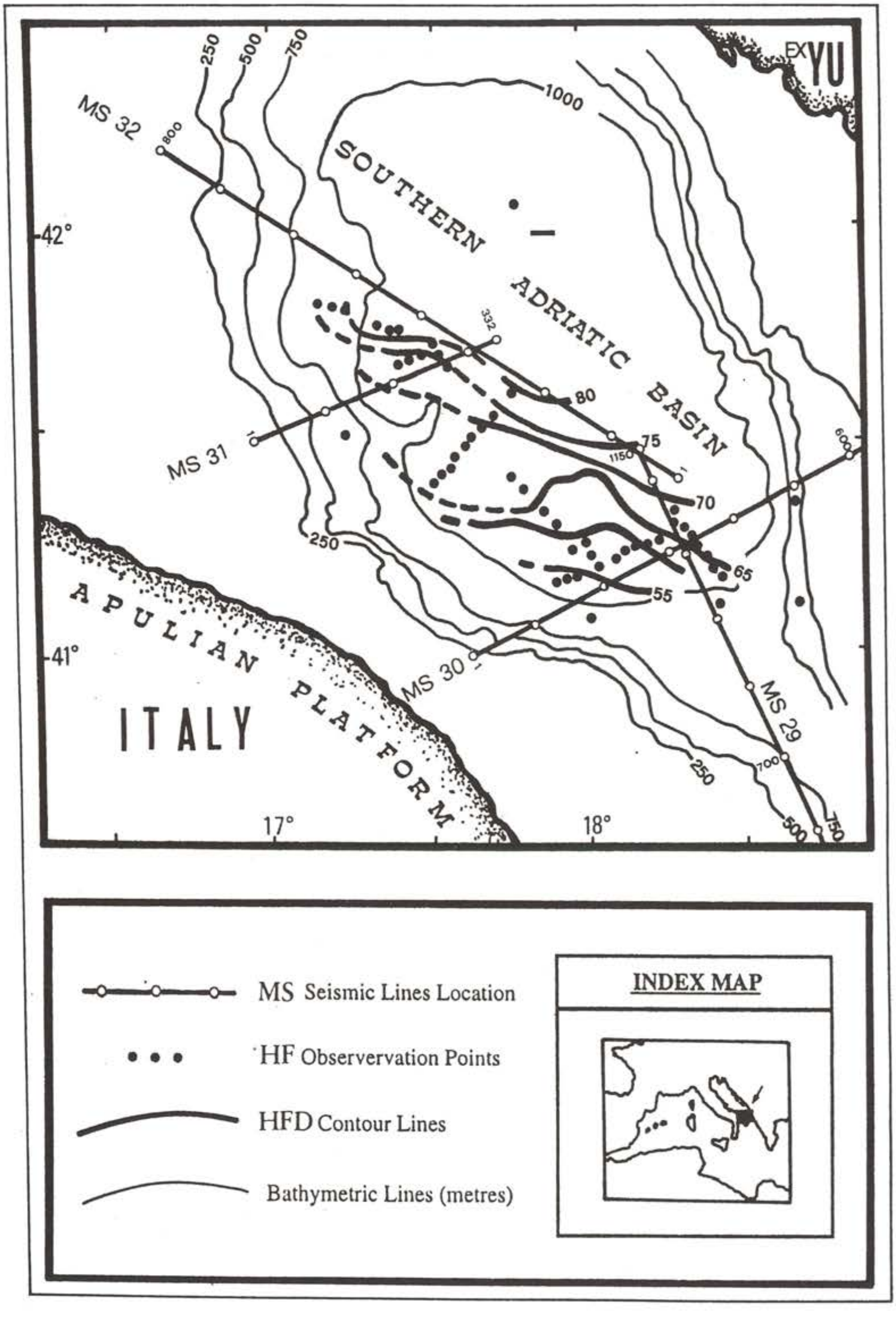

Fig. 1 — Area of Study with bathymetry (in meters), location of MS Seismic Lines, and HF observation points reported in the literature. HFD values are corrected for sedimentation.

deep basin of the Southern Adriatic and the outermost compressive deformation of the Northern Hellenides at their contact zone with the Southern Dinarides.

Seismic stratigraphy

On the Apulian shelf area (Fig.2) the basement is tentatively identified at a depth of 4.3 s which, according to the seismic velocities obtained, corresponds to a depth of about 10 km. Over the basement, lies a thick (1.3 s, about 4 km) Trias dolomitic-evaporitic (Burano formation) sequence followed by 0.65 s (about 2 km) of Lias carbonate sediments. The existence of possible clastic sediments of Permian age on the basement is not to be excluded. Lias is followed by predominant carbonate layers of age ranging from Middle Jurassic to Oligocene (Scaglia formation), for a total expected thickness here on the upper Apulian shelf of about 0.9 s (about 2.2-2.4 km). At the western extremity of the line (Fig. 2, left side), Oligocene is overlain by a thin Upper Miocene (0.3-0.5 km), covered by 1 s (0.9 to 1 km) of Plio-Pleistocene. Moving seawards, it is very interesting to note the change in thicknesses when passing from the upper shelf of the Apulian Platform to the deep basin.

The Trias sequence, very thick on the shelf, thins progressively on the slope zone (Fig. 2), and in the deep basin (Fig. 3) it becomes much more reduced (from 1.3 to 0.4 s). In the compressive tectonic zone of Fig. 3, where the front of the Hellenides buried thrusts occurs, the increasing thickness of the Trias can be explained as a combination of thrusting deformation with salt mobilization under horizontal tectonic pressure.

The Lias interval seems to change little across line MS-30, and has a minimum thickness on the lower Apulian Margin of the basin. On the contrary, the interval from base of Dogger to top of Oligocene carbonate, over a very long interval of time (from 178 to 23 m.a.), thins drastically from the shelf zone to the upper slope, passing from about 1 s to less than 0.35 s. In the zones of the basin where this deep sea deposition sequence, continuous the from Dogger to Oligocene, is thinnest, its thickness even reduces to only 0.12-0.15 s (about 250-300 meters).

The pre-Messinian Miocene seismic interval is very thin on the Apulian shelf edge shown in Fig. 2 (about 0.1 s, equivalent to about 150 m), and thickens progressively and strongly on the Apulian slope to 1.2-1.3 s in the deep basin (about 1800-2000 m). Seismic data clearly indicate that after a long time interval of condensed continuous deposition in a deep Southern Adriatic Basin (Dogger to Oligocene), during the Miocene (Aquitanian to Serravallian) fast syn-orogenic deposition took place that not only filled the foredeep of the Hellenides-Dinarides completely, but also covered the slope and the outermost Hellenides thrusts (Figs. 2 and 3).

The Messinian interval is very characteristics almost everywhere in the Mediterranean, and rather easy to seismically identify. In the examples shown of Figs. 2 and 3, the Messinian interval varies in thickness from about 0.1 to 0.25 s (about 150 to 250 m). But on the upper shelf, or on the highs of paleoslope zones successively foundered in Pliocene times, the Messinian interval can be missing (non-deposited) or much thinner than indicated above.

Over the Miocene lies a relatively thick Pliocene that reaches a maximum thickness of 1.1-1.2 s (1300-1600 m) in the deep basin (Fig. 3), followed in continuity by a thick Quaternary of 0.4-0.5 s (about 350-500 m). The Plio-Pleistocene is substantially flat in the deep basin, but thickens on the Albanian shelf area of Fig. 3 to 1.7 s (about 1900-2000 m) for the Pliocene and 0.8 s (about 700 m) for the Quaternary respectively.

Structural setting

The investigated area is composed of three tectono-stratigraphic units: a foreland (Apulian Platform), a foredeep (Southern Adriatic Basin) and the frontal thrusts of the Southern Dinarides-Northern Hellenides Belts at their contact zone (Figs. 2, 3 and 9). In the SW area of the tectonic map in Fig. 9, the Apulian Platform is overlain by the Southern Apennine Foredeep and the Apennine Calabrian Arc thrust belt, which are not geologic features pertinent to this paper.

The outcropping Apulian Platform shows a regionally rather tabular structural setting, and a notable thickening of the Cretaceous-Jurassic carbonate sequence from the Gargano area to the SE extremity of the Apulian Peninsula. The Southern Adriatic margin of the Apulian Platform is affected by numerous extensive faults (Figs. 2 and 3), with more or less evident moderate rotation of blocks and back-tilting. Some faults are limited to the basement and immediately overlying cover, but the major part displaces the entire carbonate sequence. This does not mean that crustal extensional tectonics took place at the end of carbonate deposition (Oligocene). In fact, fault displacement analysis indicates that some faults were active only with the first stretching phase (Middle Triassic), some others were created by the second phase (Middle Jurassic), and others, the majority, created by the first phase, were then reactivated by the second. Finally, the Lower Miocene compressive geodynamics (Dinarides-Hellenides), with its thrusting and consequent rotational foundering of the foredeep area, also reactivated several pre-existing extensive faults.

The tectonic map of Fig. 9 shows the regional setting of the Southern Adriatic Basin and surrounding geological provinces. Seismic line MS-30 (Figs. 2 and 3) crosses the basin at its deepest part for the top carbonate. At its NE extremity, the line (Fig. 3) shows the buried front of Northern Hellenides (locally also named Albanides).

In the area from the Dugi Otok basin to the Palagruza high (Fig. 9) the structural picture is complicated by a combination of Dinaride compressive tectonics and halokinetic reactions of the Mesozoic evaporites. The structural scheme in the map gives here a simplified picture.

Two major and seismically evident strike-slip faults affect the Southern Adriatic area: the Tremity fault and the Gargano fault (Fig. 9). The first, trending NE-SW, in the Tremity Islands zone is transpressive, so creating an elongated structural high. The Gargano fault trends W-E and creates transpressive and transtensive zones with structural highs and lows elongated around the fault plane.

A time analysis of deformation produced by these strike-slip faults shows that their activity is coeval with the Apennine orogenesis. The Gargano uplift in literature (Finetti, 1982) is reported as a diapir-like feature where the Triassic anhydrite created the structural high in Plio-Pleistocene times under the horizontal tectonic pressure of the Apenninic north-eastward movements determined by the Apulian margin subduction. It is reasonable to suppose that the Gargano fault and, probably also that of the Tremiti Islands, played a role in the horizontal shearing deformations at the base of the anhydrite layers.

In a larger context it is interesting to note that the whole emerged Apulian Platform area, from Gargano to the SE extremity of Otranto, has been uplifting from Middle Pliocene to the present. Major elevations are located in a band parallel to the Adriatic coast, some 30 km further inland. More precisely, the area from the Ofanto fault to the Brindisi-Taranto connection line is that of the most notable uplifting (up to over 670 m). Seismic exloration indicates that the Triassic evaporite on the Apulian platform forms a very gentle, slightly asymmetric dome. The asymmetry is Adriatic - vergent on Murge, and Ionian - vergent on its SE offshore extension. Taking into account that the Apulian Platform, from the Ofanto fault to Otranto (Murge area), on its SW - side is horizontally compressed by the active Apennine thrust-belt, while on the opposite NE - side there is the deep Southern Adriatic basin where no compressive tectonics takes place, it seems evident that the Apennine thrust pressure has slightly thichened the Triassic Anhydrite of the Murge area with Adriatic - verging gentle asymmetry, so contributing to the uplifting process (Upper Pliocene-Pleistocene). On the other hand, Doglioni et al. (1994) explain the Murge structure as a flexural bulge due to subduction of the Adria plate at the passage from thin oceanic to thick continental crust. Southeast of the Otranto fault, the offshore extension of Apulia (Fig. 9) presents an orogenic context remarkably different from that of Murge area. Here, the NE - side of the platform is in evident close contact with the Hellenides thrusts, while on its SW - side the Calabrian Arc thrusts are diverging and going off. So, the Hellenides are pressing the offshore Apulian extension south-westwards. The Otranto strike slip fault, evident on seismic data, is generated by the above described opposed tectonic pressures.

North of the Gargano-Tremiti Islands area, the axis zone of the Apulian platform is located in the middle of the Adriatic, and both the SW - and NE - sides are overthrusted in a more or less symmetric manner by the Apennine and the Dinarides orogenic systems respectively. For this reason, here Apulia does not uplift, and especially in Upper Pliocene-Pleistocene times was substantially foundering.

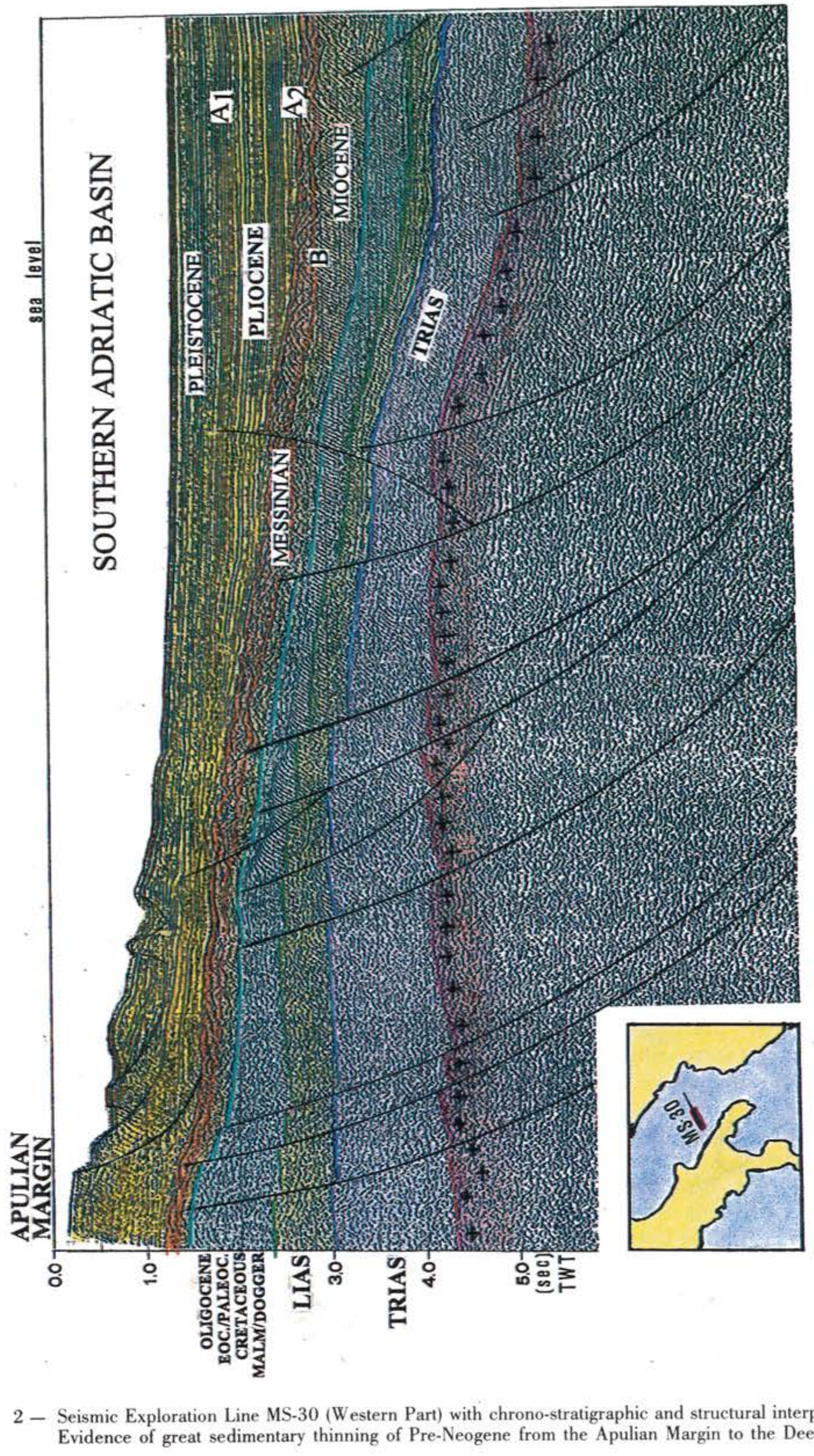

Fig. 2 — Seismic Exploration Line MS-30 (Western Part) with chrono-stratigraphic and structural interpretation. Evidence of great sedimentary thinning of Pre-Neogene from the Apulian Margin to the Deep Basin.

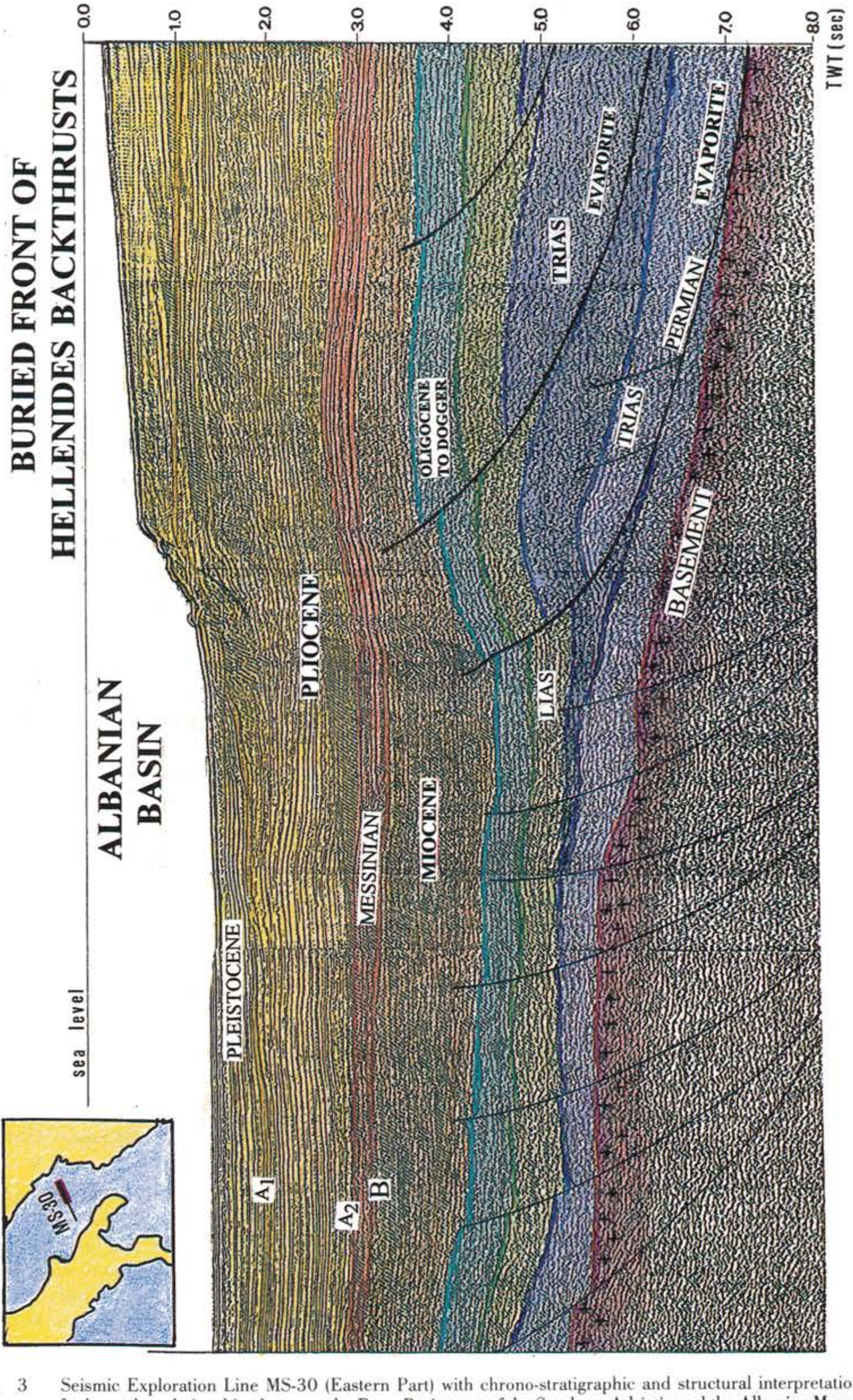

Fig. 3 Seismic Exploration Line MS-30 (Eastern Part) with chrono-stratigraphic and structural interpretation. It shows the relationships between the Deep Basin area of the Southern Adriatic and the Albanian Margin with the buried front of the Hellenides thrusts of Late Oligocene-Lower Miocene age.

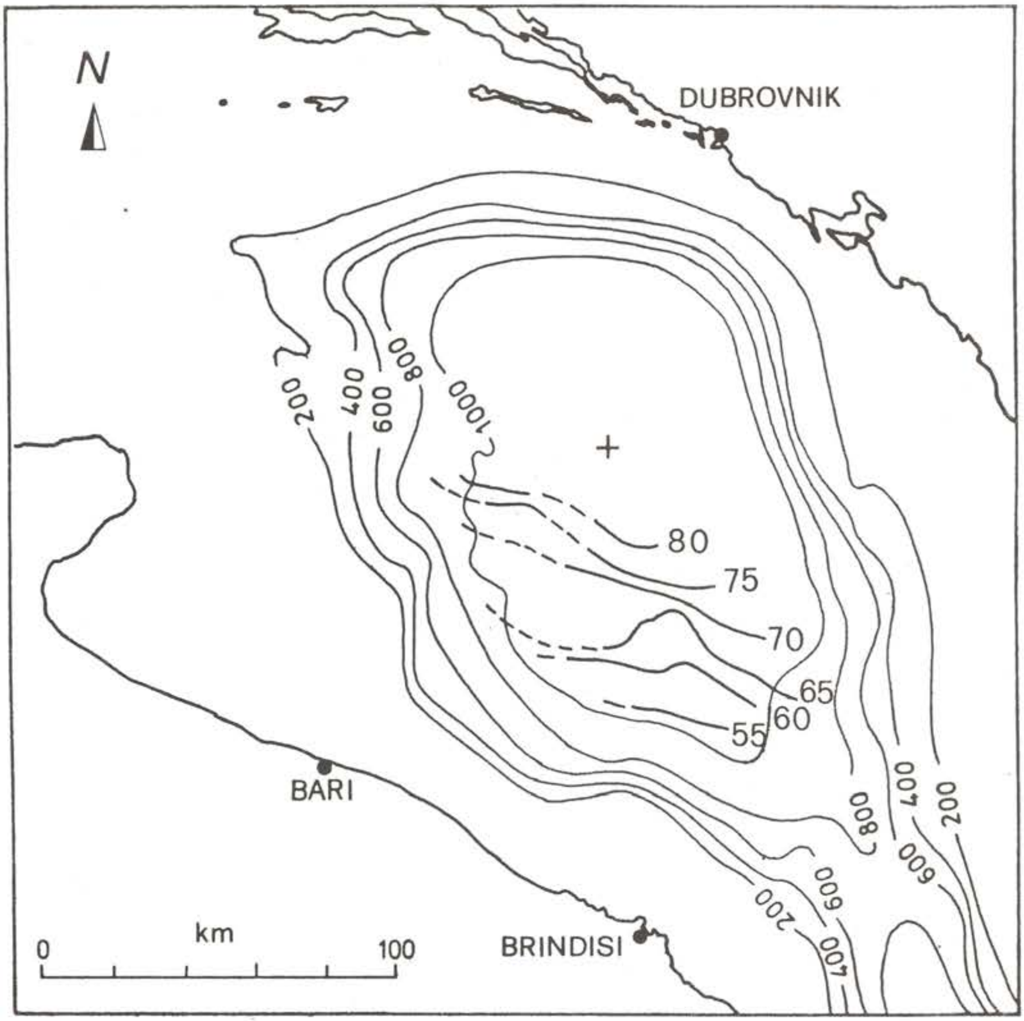

Fig. 4 - Map of the heat flow density (in mWm^{-2}) corrected for sedimentation. Thin lines are the isobaths in meters.

TIME ANALYSIS OF STRETCHING AND COMPRESSIVE PHASES

A careful time analysis of the regional tectonic deformation processes leads to the conclusion that the deep Southern Adriatic basin is part of an old trough created in Mesozoic times by two main lithospheric stretching phases.

As above mentioned, the first took place during the Middle Triassic when the basin started to deepen. But the most important occurred in the Middle Jurassic and continued into the first part of the Upper Jurassic (178 to 150 m.a.) with a strong lithospheric reduction (to a minimum of about 35 km) and crustal thinning from about 30 to 19-20 km in the deep basin area. These main stretching phases observed in the studied area are not just local geodynamics but constitute a widespread process at a megametric scale in the Central Mediterranean and also involve major plates with plate boundary and intraplate deformations.

After the lithospheric and crustal thinning, for a long time (about from 150 to 25-23 m.a.), the Southern Adriatic remained permanently a deep water basin, quietly trapping sediments at a very low sedimentation rate, without significant tectonic perturbations. The area of the

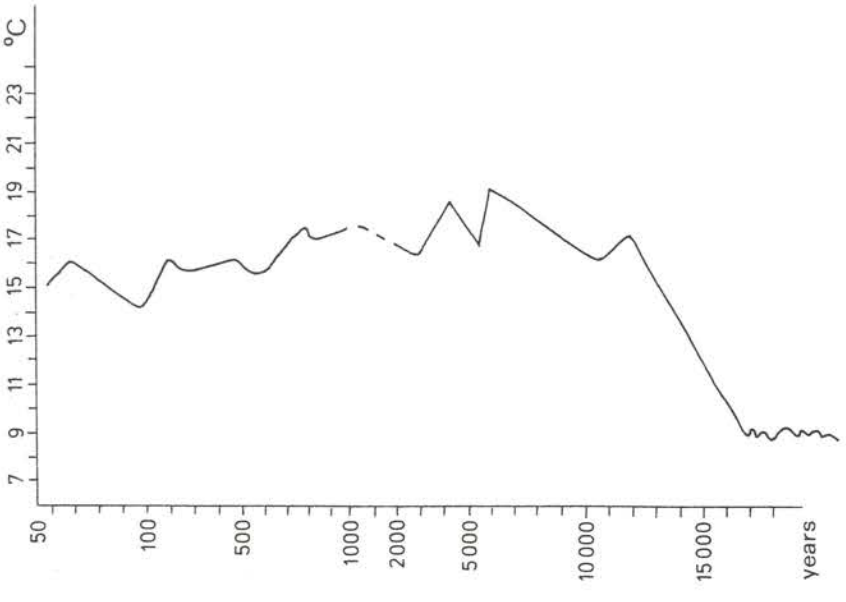

Fig. 5 - The inferred palaeo-temperature curve of the southern Adriatic sea.

deep basin, during this interval of geologic time was much wider than it is at present.

In the Late Oligocene the compressive tectonic movements of the external Dinarides and Hellenides initiated, and the eastern area of the deep basin began to subduct. This continued in the Lower and Middle Miocene with a classic thrusting deformation, of which the front is shown in Figs. 2 and 3. Successively, in the Upper Miocene and later, the frontal thrusts did not move any further outwards because they were obstructed and the crustal shortening was absorbed by reactivated, out of sequence, more internal blocks and duplexing processes.

PALEOCLIMATIC CORRECTION OF HEAT FLOW DATA

Fig. 4 shows the heat flow map of the southwestern sector of the South-Adriatic Basin. The values are corrected for sedimentation, pore water advection and radiogenic heat production by Cenozoic sediment deposition (Della Vedova and Pellis, 1990). It is observed that the heat flow density (HFD) increases from normal values (55-60 mW m^{-2}) in the south to more than 80 mW m^{-2} in the north-western sector of the depression.

As the depth of the basin is only 1000 m, it is necessary to calculate the influence of the paleotemperature variations on the heat flow mesurements. In fact, Herman (1988) maintains that the temperature of the intermediate and deep water in the Eastern Mediterranean during the last ice age was 3-4°C lower than at present.

The correction for the paleotemperature variations is made in three steps:

i) reconstruction of paleotemperature variations at the sea surface;

ii) propagation of those variations to the basin bottom;

iii) penetration of the damped variations in the bottom sediments during sedimentation.

I) During the cruise when the heat flow measurements were made, the bottom sediments were cored at several points down to about 6m. Mesurements of the thermal conductivity on the core samples gave $\lambda=0.85$ W m^{-1} K^{-1} at the sea bottom and 1.1 W m^{-1} K^{-1} at 6 m depth (Della Vedova and Pellis, 1990). A study of the paleontological fauna allowed Chiri (1990) to obtain the paleotemperatures at the sea surface over the time interval 1,000-15,000 years

Table — Main harmonic components.

component	P	A
1st	2500 y	1.25°C
2nd	270 y	0.25°C
3rd	110 y	1.00°C

b.p., and the sedimentation rate $u=2\text{-}5\cdot10^{-4}$ m y^{-1}. For more recent years, Caldara and Pennetta (1992) reconstructed the temperature variations of the last millennium in the Apulian lowland from historical and sedimentological information.

The results of both papers are put togther in Fig. 5. We observe that a temperature restoration of about 10-12°C occurred 15,000 years ago, at the end of the last ice age, followed by smaller oscillations to the present.

II) According to many authors (see, for instance, Mosetti, 1979) the propagation of a thermal disturbance from the surface into the sea can be studied by assuming the Fourier equation of heat conduction with a thermal diffusivity k some order of magnitudes greater than that of the still water ($1.44\ 10^{-7}\ m^2\ s^{-1}$).

According to this working hypothesis, we can consider the last glaciation in the Eastern Mediterranean as a thermal wave with amplitude Ao=6°C and period P=45,000 years, lasting from about 60,000 to 15,000 years b.p., which reduced at 1,5-2°C at the sea bottom (3,000 m). As the temperature amplitude decreases exponentially with depth by

$$A=A_o\ exp\left(-\alpha\ z\right) \qquad \alpha=\sqrt{\frac{\pi}{kP}}\ , \tag{1}$$

putting z=3000 m, we obtain the thermal diffusivity $k=1.6\cdot10^{-5}\ m^2\ s^{-1}$ of the sea water.

The Fourier analysis of the temperature curve of Fig. 5, from 12,000 years ago to the present, gives the main harmonic components of the variation, as reported in the Table.

From eqn. (1) with $k=1.6\cdot10^{-5}\ m^2\ s^{-1}$, we find that the amplitude of the first component reduces to 0.25°C at 1,000 m., while the others can be neglected.

III) In a sedimentary basin, sedimentation and temperature variations at the surface occur at the same time. Mongelli and Zito (1993) have shown that it is possible to carry out the two corrections on the temperature gradient separately, using the method of Benfield (1949) for the sedimentation, and the following correction for the paleoclimatic change:

$$\left(\frac{\partial T}{\partial z}\right)_{z=0}=A\left[\frac{u}{2k}\cos\omega t-a^{\frac{1}{2}}\cos\left(\omega t+\frac{\psi}{2}\right)\right], \tag{2}$$

$$a=I\ \frac{1}{4k^2}\sqrt{u^4+16\ \omega^2\ k^2}; \qquad \psi=tg^{-1}\frac{4\omega k}{u^2}\ , \tag{3}$$

where A is the amplitude of the harmonic component of the paleoclimatic change; $\omega=2\pi/P$; P is the period of the component; k the thermal diffusivity of the sediments (10-30 $m^2\ y^{-1}$); and u is the sedimentation rate.

Application of eqn. (2) to the first component gives a positive correction to the value, already corrected for sedimentation, of 5-6 mW m^{-2} at each point.

Paleoclimatic variations at the sea bottom due to the last glaciation may be considered as a double-step temperature variation, both of 3-4°C in amplitude, the first negative starting 60,000 years ago, and the second positive 15,000 years ago.

By using for each step the equations (Mongelli and Zito, 1988)

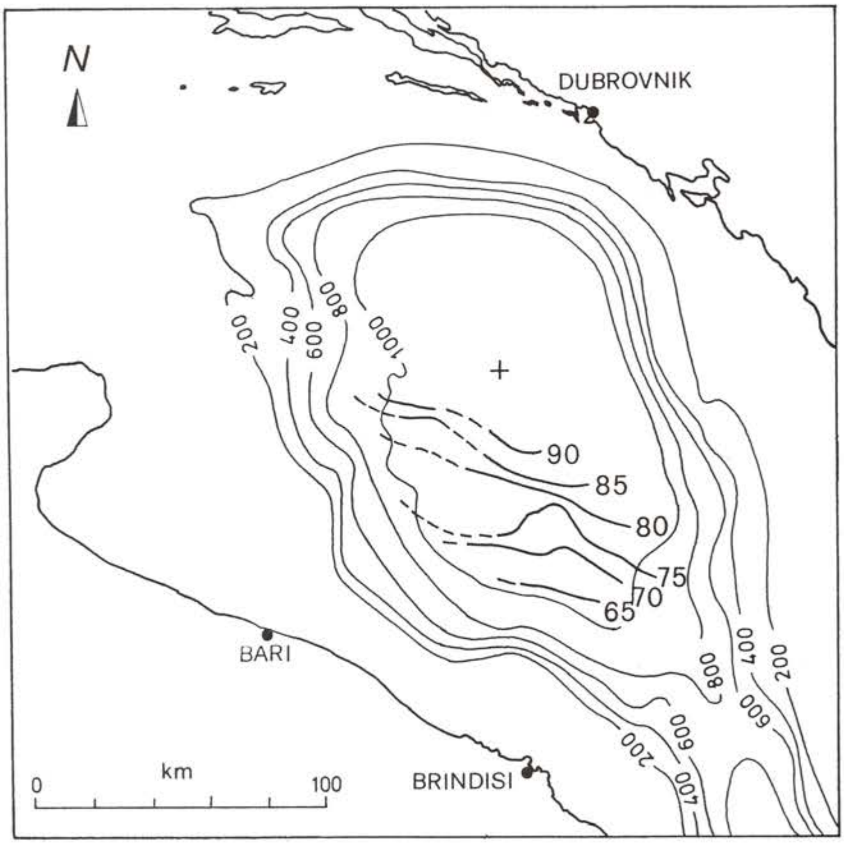

Fig. 6 - Map of the heat flow density (in mWm $^{-2}$) corrected for both sedimentation and past climatic change. Thin lines are the isobaths in meters.

$$\Delta T=\Delta T_0 \left(1-erf\frac{z}{\sqrt{\pi k t}}\right), \tag{4}$$

$$\left(\frac{\partial T}{\partial z}\right)_{z=0} = \frac{\Delta T_0}{\sqrt{\pi k t}}, \tag{5}$$

we obtain a positive correction of 3-4 mw m^{-2} at each point.

Fig. 6 shows the new map with the HFD values corrected for the sedimentation and the past climatic change.

INTERPRETATION OF HEAT FLOW DATA

In the first section of this paper it has been shown that the Southern Adriatic is an extensional basin created in the Mesozoic. McKenzie (1978) was the first to study the heat flow in an extensional basin, by assuming uniform (crustal and lithospheric) extension and thinning. McKenzie's model has been expanded by other workers to include features such as non-uniform extension sediment loading, thermal blanketing and lateral processes. With these models it is possible to obtain the extension parameters by knowing the age of the basin (or viceversa), by using the heat flow data and the sedimentation (or subsidence) history of the basin.

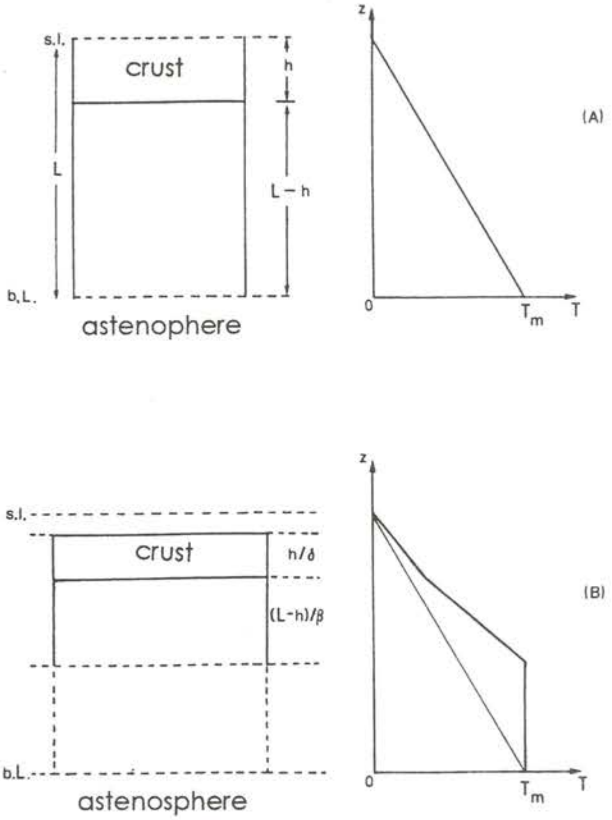

Fig. 7 - Two-layer extension model: β is the stratching factor of crust and δ is the stretching factor of the LID. A) initial conditions; B) conditions after extension (s.l. = sea level; b.l. = base of the lithosphere).

Unfortunately, information on the sedimentation history of the South Adriatic basin is not available; on the other hand, seismic research has shown that the crust of the Apulian plate reduced from 30 km to 20 at about 150 m.a. The simple uniform extension model of McKenzie cannot explain a heat flow density of 65-90 mW m^{-2} by an extension of $\beta = 1.5$ at 150 m.a.

The non-uniform extension model of Royden and Keen (1980) assumes (Fig. 4) that the brittle crust stretches by a factor δ and the ductile LID by a factor β ($\beta \geq \delta$), whereas the asthenosphere rises up and, as a result, the heat flow density increases istantaneously. If L is the width of the stable lithosphere, and h that of the crust, after stretching the crust reduces to h/δ and the LID to $(L-h)/\beta$. The stretching is followed by a cooling and rethickening of the LID, and a decrease of the heat flow at the surface.

We can consider the lithosphere as a slab whose upper surface, $z=L$, is constantly at temperature $T=0$ and the lower surface, $z=0$, at $T=T_1$. If the heat of crustal origin is not considered, the temperature during the cooling is given by (Royden and Keen, 1980)

$$T=T_1\left(1-\frac{z}{L}\right)+T_1\cdot\sum_{n=1}^{\infty}\frac{2}{n\pi}\;(-1)^{n+1}\,x_n\,\sin\left(\frac{4\pi z}{L}\right)\exp\left(-\frac{n^2\,\pi^2\,kt}{L^2}\right), \quad (6)$$

where

$x_n=(\delta-\beta)\ \sin\ (n\pi x)+\beta\sin\ (n\pi G)$ is n-th Fourier coefficient of the initial temperature distribution;

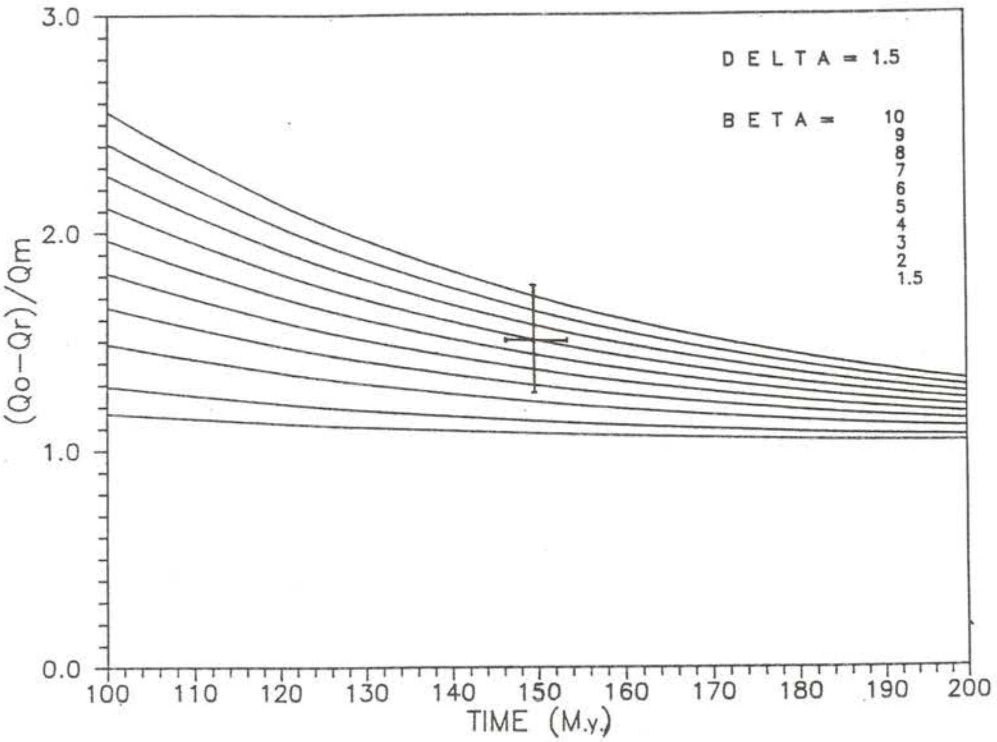

Fig. 8 - Trend of the ratio between the pre-stretching crustal to LID HFD versus time for the fixed value of $\beta=1.5$ and δ ranging from 1.5 to 10.

$H=h/L\delta$;

$G=(h/L)\ (1/\delta-1/\beta)+1/\beta$;

k is the thermal diffusivity ($k=20\ km^2\ Ma^{-1}$, Zito et al., 1993).

Now, indicating by

Q_o the surface (corrected) heat flow;

Q_r the heat flow contribution of crustal origin of the stable pre-stretch crust;

Q_m the heat flow contribution coming from the stable pre-stretch LID,

we obtain

$$\frac{Q_o-Q_r}{Q_m}=1+2\sum_{1}^{\infty}\left[\frac{\beta-\delta}{n\pi}\sin(n\pi H)+\beta\sin(n\pi G)\exp\left(-\frac{n^2 t}{\tau}\right)\right]. \quad (7)$$

Q_r and Q_m can be obtained from the Pollak and Chapman (1975) relations:

$$Q_m=0.6\ Q_{os}\ ,\qquad Q_r=0.4\ Q_{os}\ ,$$

where Q_{os} is the heat flow of the pre-stretch stable lithosphere; and $\tau=L^2/\pi^2k$ is the time constant of the lithosphere (67 M.a.) for L = 115 km.

For the South Adriatic Basin we have

$Q_o=70\text{-}90\ mW\ m^{-2}$, considering only its central sector;

$Q_r=0.40Q_{os}$; and $Q_{os}=55\text{-}60\ mW\ m^{-2}$, the heat flow of the stable Apulian plate.

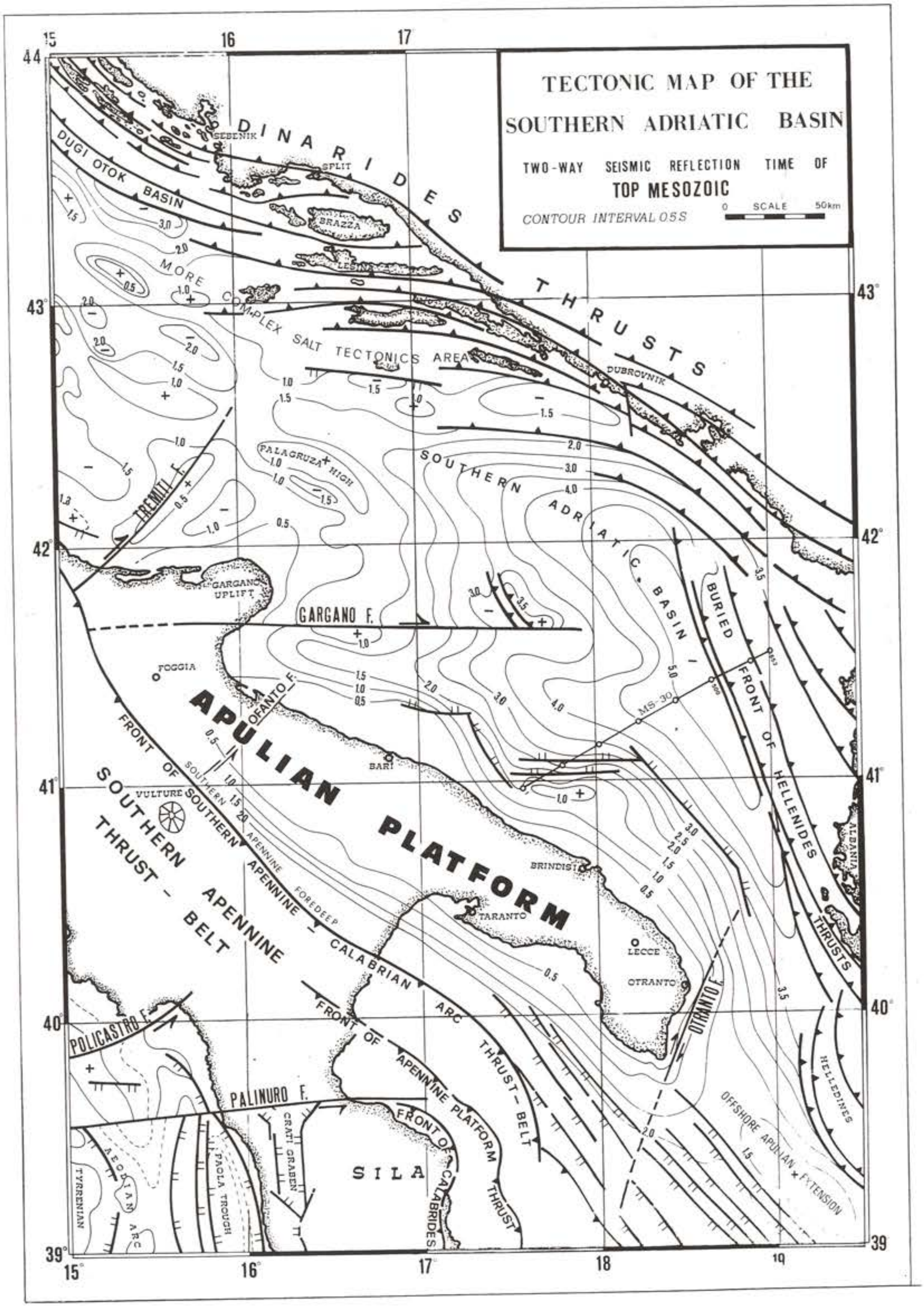

Fig. 9 — Tectonic map of the Southern Adriatic Basin with contour lines of the seismic reflection time from Top of Mesozoic. In the Tyrrhenian Sea contours refer to top of basement of the Calabrides thrusts.

Thus

$Q_r = 24$ mW m^{-2};

$Q_m = 36$ mW m^{-2};

$(Q_o - Q_r)/Q_m = 1.3\text{-}1.8$;

and $\delta = 1.5$ from seismic research.

Fig. 8 shows the plot of eqn. (7), assuming $\delta = 1.5$. The cross represents the South Adriatic Basin; from its position we obtain a value of $\beta = 7$. This means that the stretching reduced the LID from 90-95 km to about 15 km and the whole lithosphere from 115 km to about 35 km. This is a very favourable condition for oil maturation.

During rethickening, the crust remains thinned, while the LID increases downwards. At the present, after 150 m.a., that is about 2.2 τ, we can deduce that the base of the LID has not yet reached its primitive depth of about 115 km. Taking into account that the crust has been reduced to 20 km, and assuming for the LID a long-term exponential restoration, we can argue that the lithosphere in the Southern Adriatic Basin still remains thinned to about 80-90 km.

REFERENCES

Benfield A.E.; 1949: *The effect of uplift and denudation on underground temperatures*. J. Appl. Phys., **20**, 66-70.

Caldara M. and Pennetta L.; 1992: *Interpretazione paleoclimatica di dati preistorici e storici relativi all'entroterra del Golfo di Manfredonia*. Mem. Soc. Geol. It., **44**, 197-207.

Chiri C.; 1990: *Studi sul bacino d'Otranto: variazioni paleoclimatiche ed implicazioni geotermiche*. Tesi di Laurea. Università di Bari (Italy).

Della Vedova B. and Pellis G.; 1990: *Thermal regime of the South-Adriatic basin: preliminary results*. Atti del 7° Convegno GNGTS, Roma 1988, **3**, 1403-1408.

Doglioni C., Moangelli F. and Pieri P.; 1994: *The Puglia uplift: An anomaly in the foreland Apenninic subduction due to bucking of a thick continental lithosphere*. Tectonics, **13**, 1309-1321.

Dondi L., Rizzini A. and Rossi P.; 1985: *Recent Geological Evolution of the Adriatic Sea*. In: Geol. Evol. Medit. Basins. Stanley D.J. and Wezel F.C. eds, Springer-Verlag.

Dragasevic T.; 1983: *Oil Geologic Exploration in the Montenegro Offshore in Yugoslavia*. Journal of Jugoslav Commettee of the World Petroleum Congresses, **XXXIV** (7-8) 397-403.

Finetti I., Bellemo S. and De Visentini G.; 1966: *Preliminary Investigation of the Earth's Crust in the South Adriatic Sea*. Boll. Geof. Teor. Appl., **8**, 2-39.

Finetti I., Bricchi G., Del Ben A., Pipan M. and Xuan Z.; 1987: *Geophysical Study of the Adria Plate*. Mem. Soc. Geol. It., **40**, 335-344.

Finetti I. and Del Ben A.; 1986: *Geophysical Study of the Tyrrhenian Opening*. Boll. Geof. Teor. Appl., **28**, 75-155.

Finetti I. and Morelli C.; 1973: *Geophysical Exploration of the Mediterranean Sea*. Boll. Geof. Teor. Appl., **15**, 291-342.

Finetti I.; 1981: *Geophysical Study on the Evolution of the Ionian Sea*. Sedimentary Basins of Mediterranean Margins. C.N.R. Italian Project of Oceanography, 465-484.

Finetti I.; 1982: *Structure, Stratigraphy and Evolution of Central Mediterranean*. Boll. Geof. Teor. Appl., **24**, 247-312.

Frank G., Kriz J. and Vlasic B.; 1983: *Results and Directions in Hydrocarbon Exploration of the Adriatic Offshore*. Journal of Jugoslav Commettee of the World Petroleum Congresses, **XXXIV (7-8)** 387-396.

Herman Y.; 1988: *Late quaternary palaeoceanography of the Eastern Mediterranean: the deep sea record*. Marine Geology, **15**, 68-77.

McKenzie D.P.; 1978: *Some remarks on the development of sedimentary basins*. EPSL, **40**, 25-32.

Mongelli F. and Zito G.; 1988: *Effect of recent temperature change on shallow geothermal measurements*. Geothermics. **17**, 765-776.

Mongelli F. and Zito G.; 1993: *The contemporary effect of erosion/sedimentation and past climate on the geothermal gradient*. Studia Geoph. et Geod., **37**, 258-174.

Mosetti F.; 1979: *Fondamenti di oceanologia e idrologia*. UTET Torino.

Pollack H.P. and Chapman; 1975: *On the regional variation of heat flow, geotherms, and lithospheric thickness*. Tectonophysics, **38**, 279-286.

Ricchetti G. and Mongelli F.; 1980: *Flessione e campo gravimetrico della micrapiastra apulia*. Boll. Soc. Geol. It., **93**, 431-436.

Royden L. and Keen C.E.; 1980: *Rifting process and thermal evolution of the continental margin of eastern Canada determined from subsidence curves*. EPSL, **51**, 343-361.

Zito G., Mongelli F. and Loddo M.; 1993: *Temperature dependence of the thermal parameters of some rocks*. Boll. Geof. Teor. Appl., **25**, 437-445.