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Thermal effects of the dynamic activity from the Ligurian Sea to the Eastern Alps

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Abstract
We discuss the thermal field in connection with the structural and dynamic framework from the Ligurian Sea to the Eastern Alps. Information on thermal data is briefly summarized and a new heat-flux value for the Northern Apennines is given. In the Variscan and the convergent Alpine units, the thermal flux is around 60-85 mW/m^2, except for the Pedealpine-Adriatic Homocline and the more external arcuate systems of the Southern Alps and Northern Apennines, showing much lower heat-flux values, which may be partly due to the thermal effect of post-Miocenic overthrusting. Values higher than 85 mW/m^2 occur in the internal Apennines zone and in the Ligurian Sea, which is interpreted as a marginal basin formed after lithospheric stretching processes which took place 21 Ma ago. The long wavelength thermal anomaly laying between the Apennines and the Alps does not only account for the subduction processes which led to Moho overlaps, but also for the lithosphere root beneath the Po basin, representing the remnant of a deep-reaching subduction episode.

Key words *thermal modelling – overthrusting – continental stretching – lithosphere root – Alps – Apennines system*

1. Introduction

The lithosphere thermal structure is still largely unknown, although it has a basic role for the understanding of the dynamics of the processes which caused tectonic events such as orogenesis, continental stretching or oceanic basin formation. This is mainly due to the thermal data, which are not easily attainable and always available for all the geological provinces. For steady-state conditions, the surface thermal flux is given by the sum of two components: the heat flux arising from the mantle and that generated by radiogenic source decay of crustal materials. An additional transient component appears as a thermal perturbation caused by tectonic events accompanied by upwelling of asthenospheric mantle material, plate or crust overlaps, crustal subsidence or uplift. The study of the thermal effects of these events therefore supplies useful elements about the dynamic activity of the lithosphere in the recent past.

This paper analyzes the contribution of the dynamic processes to the lithospheric thermal budget from the Ligurian Sea to the Eastern Alps (fig. 1), along and adjacent to a profile presently studied within the framework of the CROP Project, financially supported by CNR and other Italian public agencies, dealing with the deep structure of the crust (Morelli, 1992). A heat-flux data set derived from the catalogue compiled for the EGT Project (Cermák *et al.*, 1992) was used to define the thermal field pattern. We shall describe the heat-flux data in relation to their structural context and discuss the thermal field deduced through their interpolation. Extent and intensity of recent tectonic events which perturbed the thermal flux will be estimated and models formulated in order to supply further information on the dynamic processes which affected the examined area.

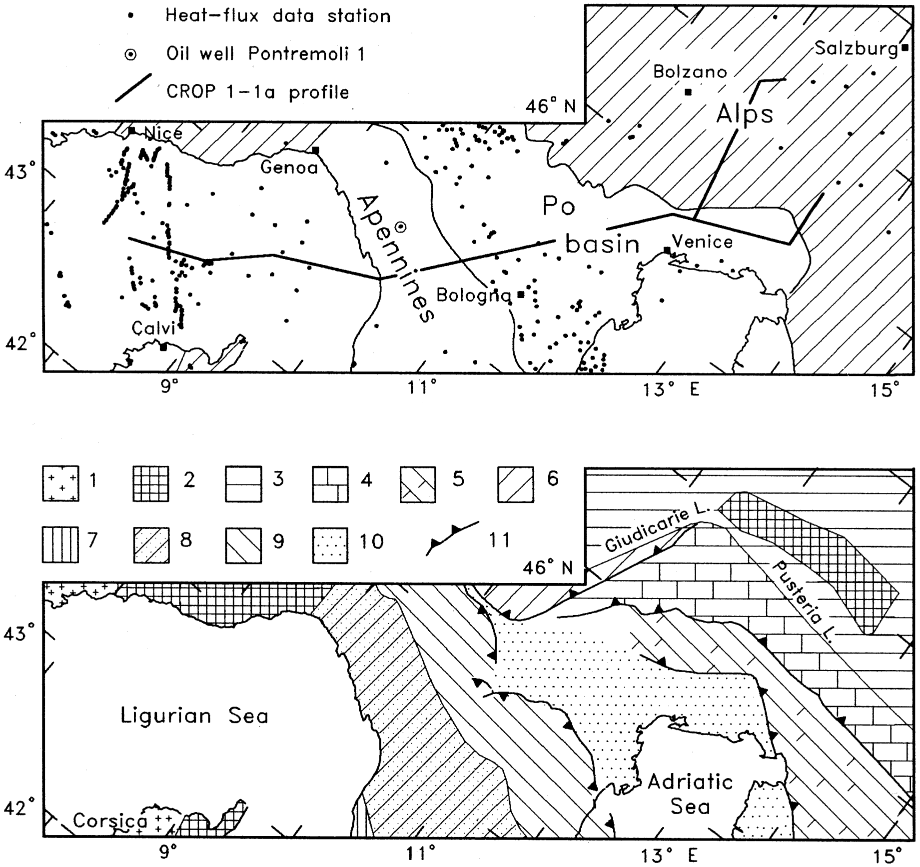

Fig. 1. Heat-flux measurement stations of a 200 km wide belt, extending from the Ligurian Sea to the Eastern Alps, centred along the CROP 1-1a profile. Below, structural elements (Pieri and Groppi, 1981; Castellarin and Vai, 1986; Pasquale *et al.*, 1993): Maures-Estérel and Corsica Variscan massifs (1); Alpine successions, Liguride complex and Tauern window (2); Austroalpine zone (3); Southern Alps: internal-intermediate arc (4), external arc (5), intermediate arc (6); Apennines successions: peri-Tyrrhenian zone (7), internal (8) and external (9); Pedealpine-Adriatic Homocline (10); overriding fronts (11).

2. Review of thermal data

The area in fig. 1 has been divided into tectonic provinces having a well defined structure, age and distinct thermal regime. Mean heat-flux values and range, sorted by province and measurement method, are reported in table I. Data having low quality or not obeying Chauvenet criterion were not taken into account in the statistics. More than 170 determinations pertain to measurements through oceanographic method carried out in the Ligurian Sea and Alpine lakes. A wide number of data (105) comes from temperatures measured at the bottom of oil wells, located in the Po basin. The conventional on-land measurement data set (25 as a whole) also contains data from tunnels. Uncorrected observations have been reprocessed to eliminate the main perturbation effects.

Determinations pertaining to the Variscan massifs of Maures-Estérel and Corsica are corrected for topography and palaeoclimatic effects. Globally, the heat flux for these provinces averages about 80 mW/m^2, with higher values next to the western margin of Corsica, whereas the Provençal margin shows lower values, comparable to the average (60-70 mW/m^2) of the Variscan units of Central Europe (Pasquale *et al.*, 1990).

The eight values belonging to the Alpine successions and Liguride complex obtained by means of conventional on-land methods are on average of the same order of those of the Variscan provinces. On the contrary, one lacustrine determination in the Tauern tectonic window would indicate a value of about 95 mW/m^2. Data are generally corrected for topography and palaeoclimatic effects.

The Austroalpine and the internal-intermediate Southalpine arc data set gives mean values of about 80-85 mW/m^2 and is rather homogeneous as measurements are entirely of lacustrine type. These values have been expressly reprocessed for thermal property contrast between basement and sediments, short and long period bottom temperature variations and sedimentation following Finckh's (1983) technique. Data previously uncorrected for palaeoclimatic changes have been on average increased by 10%, on the base of the surface thermal history model discussed by Pasquale (1985).

The Northern Apennines are characterized by strong lateral variation of the thermal field. In the peri-Tyrrhenian zone, which corresponds to the inner zone of the Apennines and includes the Tuscany-Latium geothermal region, the few available data, corrected for sea-effect and palaeoclimatic variations (Loddo and Mongelli, 1979), give a mean heat flux quite high (about 110 mW/m^2). North-east of this zone, there extends the internal zone of the Apennines, whose heat flux ranges between 60 and 95 mW/m^2. The new determination based on data supplied by AGIP in the oil well Pontremoli 1 (fig. 1 and 2) gave a value falling within this interval of variation.

Table I. Number of measurement sites n, mean values of heat flux q_0, standard deviation s.d. and range, in mW/m^2, from observations relative to the analyzed provinces. Values have been sorted according to the measurement method: conventional on land (A), from bottom-hole temperature (B) and oceanographic (C).

Province	A				B				C			
	n	q_0	s.d.	range	n	q_0	s.d.	range	n	q_0	s.d.	range
Maures-Estérel and Corsica massifs	8	79	15	66-104								
Alpine successions and Liguride complex	8	83	13	60-105					1	96		
Austroalpine zone									5	87	13	72-102
Internal-intermediate Southalpine arc									4	79	14	67-98
Intermediate Southalpine arc					17	39	6	32-52				
Peri-Tyrrhenian zone	3	107	5	105-113								
Internal Apennines zone	4	82	16	60-95	1	68						
External Apennines zone	2	29	2	27-30	73	36	7	27-60				
Pedealpine-Adriatic Homocline					14	45	6	34-56				
Ligurian Sea									166	94	21	47-154

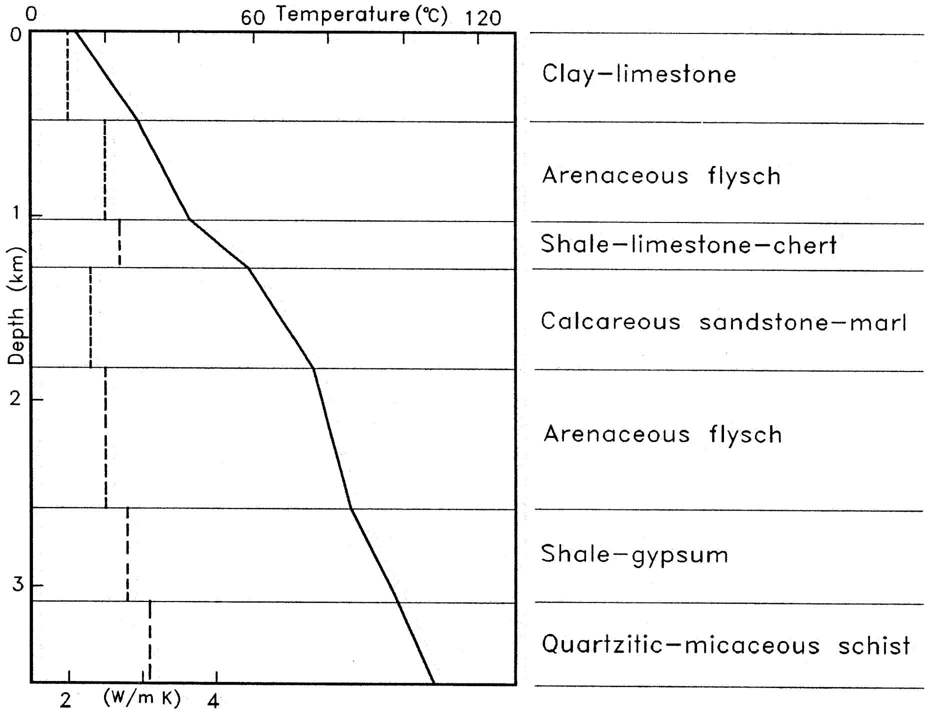

Fig. 2. Temperature-depth profile (solid line) of the oil well Pontremoli 1 (44.367°N, 9.863°E), for a heat flux of 68 mW/m^2 and layer thermal conductivity (hatched line) varying from 2 and 3.1 W/(m K).

Neglecting the radiogenic heat production and schematizing the stratigraphy through homogeneous lithological layers of known thermal conductivity, the temperature-depth profile which best fits the temperature of 108 °C, measured at a depth of 3520 m, was found for a surface heat flux of 68 mW/m^2. Thermal conductivity has been computed from the weighted mean of the thermal conductivity of the main lithotypes forming the layers, as deduced from laboratory measurements (Pasquale and Verdoya, 1990).

Whereas the external arc of the Southern Alps is lacking in heat-flux determinations, a wide number of values is available for the external zone of the Apennines and for the intermediate arc of the Southern Alps. These measurements, almost entirely coming from bottom-hole temperature observations corrected for sedimentation effect, indicate mean heat flux of about 30 and 40 mW/m^2, respectively (Pasquale and Verdoya, 1990), in agreement with those determined by means of conventional measurements along the external range of the Apennines (Mongelli *et al.*, 1981).

Between the Alps and the Apennines we find the undeformed part of the Po basin, consisting of the Pedealpine-Adriatic Homocline. Here, determinations entirely derived from temperature measurements in oil wells give values slightly higher than those observed along the buried fronts of the chains, attaining on average 45 mW/m^2.

All the data belonging to the Ligurian Sea are corrected for the effect due to the Pliocenic-Quaternary sedimentation. In agreement with the model proposed by Jemsek (1988), which takes into account the climatic history of the Western Mediterranean during the last 0.7 Ma, we applied a palaeoclimatic correction of 9 mW/m^2 to the measurements uncorrected for such an effect. The mean heat-flux value of about 95 mW/m^2 is significantly high and the individual values range between a minimum of about 50 and a maximum of 150 mW/m^2.

3. Models and results

The regional pattern of the surface thermal flux reported in fig. 3 results from the processing of all the available data. In zones where the spatial distribution of observations was sufficiently homogeneous, interpolation geostatistical techniques have been used (see Pasquale *et al.*, 1993), whereas for the provinces where observations were scarce or even lacking, we have also taken into account the structural setting. In order to minimize the uncertainties in the peripheral zones, heat-flux values adjacent to the investigated area were considered. The following is an analysis of the thermal field and its relation with the effects of stretching, oceanization and overthrusting occurred through the main units.

3.1. *Ligurian Sea*

The Ligurian Sea is interpreted as a marginal basin resulting from stretching processes which affected the Western Mediterranean from Eocene to lower Miocene time (Biju-Duval *et al.*, 1978; Dercourt *et al.*, 1985). Structurally, in the deeper and southernmost part it is characterized by an oceanic crust 10-12 km thick, which lays between two continental margins with crustal thickness increasing towards the coast (Le Douaran *et al.*, 1984).

High heat-flux values dominate almost all the Ligurian Sea, especially south of the line Nice-Calvi, where the thermal flux overcomes 110 mW/m^2. The heat-flux pattern along this traverse is shown in fig. 4. Whereas on the Western Corsica margin heat flux tends to be relatively high (80-90 mW/m^2), on the Provençal margin it decreases to about 70 mW/m^2. This asymmetric pattern of the thermal field was already noticed by other researchers (Jemsek *et al.*, 1985; Burrus and Foucher, 1986), on the base of a number of data smaller and not always corrected for the main disturbances. The asymmetry cannot be explained by different radiogenic heat production as the zones with lower thermal flux have higher heat generation (Lucazeau and Mailhé, 1986). The seismic structure indicates a crystalline basement with P-wave velocity ranging between 4.5-6.8 km/s and a sedimentary cover of 5-6 km at most. From the Provençal continental margin to the Corsica one, between Nice and Calvi, there is a crust about 5 km thick, whose probable nature is not completely

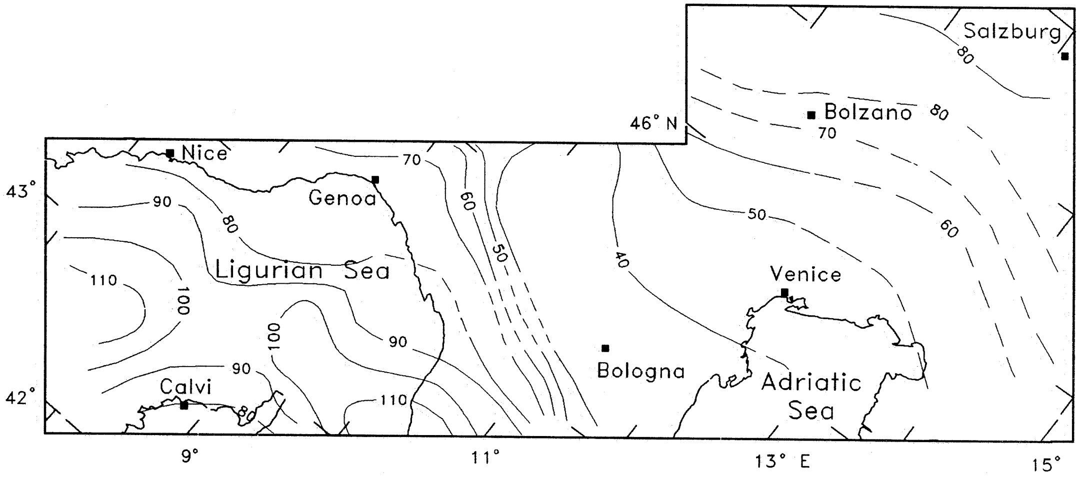

Fig. 3. Regional thermal-flux field, in mW/m^2. Uncertain isoline is hatched.

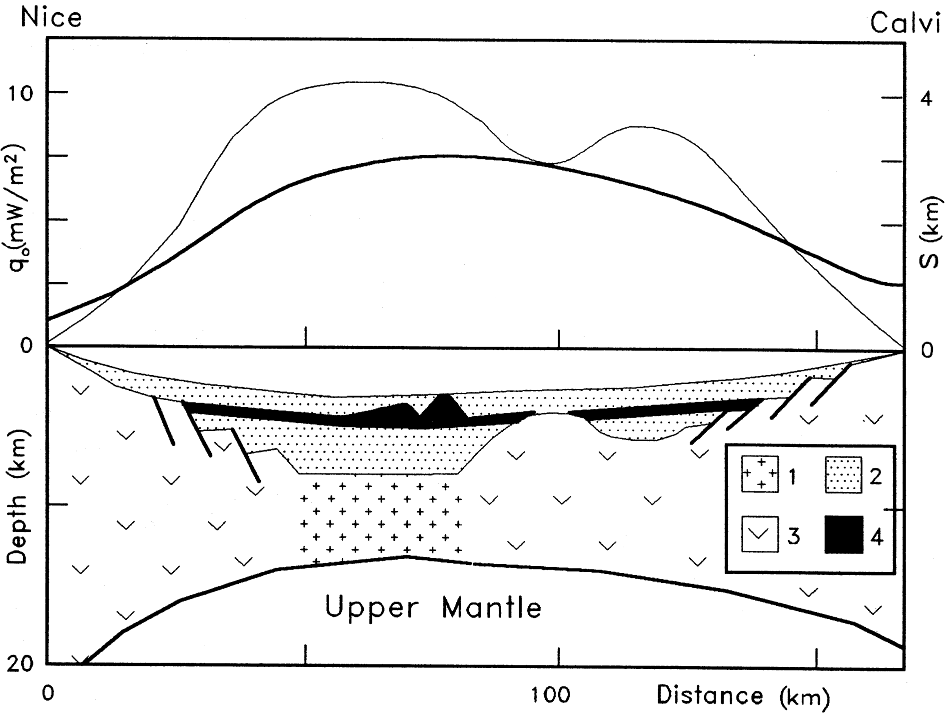

Fig. 4. Thermal flux q_0 (thick line) and total tectonic subsidence S (thin line) from Nice to Calvi. Lithospheric structure after Le Douaran *et al.* (1984): sub-oceanic crust (1); sediment (2); continental margin (3); Messinian salt or evaporites (4).

oceanic, being characterized by seismic velocities (5.2-6.0 km/s) lower than the typical ones of the oceanic crust noticed southward (Le Douaran *et al.*, 1984).

The evolution of the Ligurian basin can be described through McKenzie's (1978) subsidence model: instantaneous stretching of the continental lithosphere by a factor $\beta > 1$ is accompanied by isostatic compensation to the thinning and rising of asthenospheric hotter material, producing an initial subsidence and a thermal perturbation; afterwards, a cooling with time t causes thermal subsidence, lithospheric mantle thickening and thermal flux decreasing.

Such a model has been applied adopting values for the crust and upper mantle density and thermal expansion coefficient as proposed by Le Pichon and Sibuet (1981), since they are similar for all the margins. Although the present crustal thickness next to Provence and Corsica ranges from 25 to 30 km (Hirn, 1980; Egger *et al.*, 1988), we have chosen a value of 25 km for the stage preceding the Oligocenic-Miocenic stretching as a Mesozoic crustal thinning has probably affected these zones (Burrus and Bessis, 1986). The regional thickness of the lithosphere has been assumed to be 90 km as in the zones adjacent to the basin it varies from 75 to 110 km, according to seismic (Panza *et al.*, 1980) and thermal data (Pasquale *et al.*, 1990). The temperature at the lithosphere base has been supposed to be equal to 9/10 of the mantle solidus, considering that the crust was partially oceanized after stretching.

Figure 5 reports the model results in terms of a relationship between attenuation factor β, initial subsidence and total tectonic subsidence, for a basin 21 Ma old (Burrus and

Foucher, 1986) and for $t=\infty$. The difference between the total tectonic subsidence and the initial one gives the thermal subsidence. Assuming an initial subsidence of 2.5 km, which corresponds to the asthenospheric isostatic equilibrium level (Le Pichon and Sibuet, 1981), one obtains $\beta = 3.1$ and a total tectonic subsidence of 4.4 km for $t=\infty$ and of 3.3 km for a time equal to the basin age. This means that when $\beta > 3.1$ the asthenospheric material should be able to rise for lithostatic pressure and to break through a thinned continental crust to form new crust. However, according to Sawyer (1985), for subsidence values greater than this breaking limit, a sudden formation of crust with oceanic features is not likely to occur, but a transitional type crust forms. Therefore, the total tectonic subsidence value to which the formation of oceanic crust corresponds must be greater than 4.1 km, as one deduces from models of formation and cooling of lithospheric plates (Parsons and Sclater, 1977).

Along the Nice-Calvi cross-section (fig. 4), the total tectonic subsidence indicates structural conditions close to the oceanic realm. Subsidence, determined from seismic stratigraphy and bathymetry data (Rehault, 1981) and corrected for the sediment burden (Crough, 1983), tends to attain the limit of 4.1 km only in a narrow region at the middle part of the profile.

Another indication is given by the relationships between basin age, stretching and heat flux. The latter is the sum of three components: equilibrium heat flux from the mantle (about 33 mW/m^2), transient heat flux depending from the extension amount β and heat flux given from the ratio between radiogenic heat production of the crust q_c and β (McKenzie, 1978). For $q_c \approx 35$ mW/m^2, as found in the Variscan crust of the Corsica-Sardinia block (Pasquale *et al.*, 1990) and for average stretching $\beta \approx 2$, one obtains a heat flux (about 85 mW/m^2) of the same order of that observed in the stretched continental margins. The zone with total tectonic subsidence greater than 4.1 km fits in with the Parsons and Sclater's (1977) relation, which for a basin 21 Ma old gives heat flux around 105 mW/m^2, as actually observed in the central part of the profile.

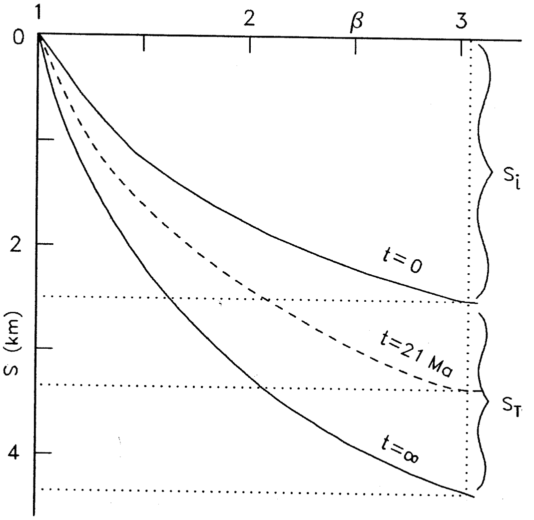

Fig. 5. Relationship between subsidence S and stretching factor β for the Ligurian basin at time $t=0$, $t=21$ Ma and $t=\infty$. S_i initial subsidence and S_T thermal subsidence.

3.2. *Northern Apennines*

A detailed representation of the thermal field in the northern margin of the Apennines and part of the Po basin is shown in fig. 6. This latter sector, particularly in correspondence of the buried arcs of the external Apennines zone, is clearly dominated by low heat flux (about 30-40 mW/m^2). Thermal flux tends to increase toward the undeformed part of the basin, consisting of the Pedealpine-Adriatic Homocline, attaining values around 40-50 mW/m^2, and toward the internal zone of the Apennines with values greater than 70 mW/m^2, explained by lithosphere stretching (Mongelli *et al.*, 1989). Globally, the basin sector pertaining to the external folds of the Apennines and to the Homocline seems to be closed by the 50 mW/m^2 isoline.

The thermal field pattern in the external zone of the Apennines should be strongly conditioned by its complex structural setting, whose fundamental features are well known

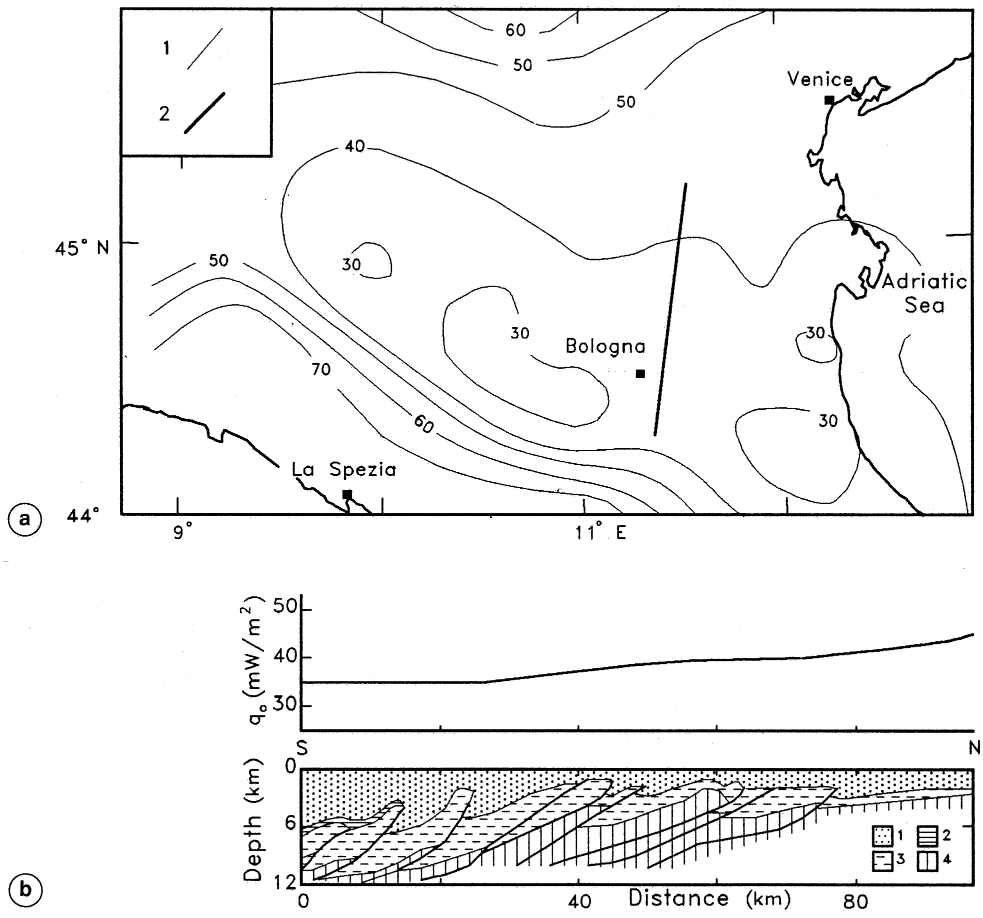

Fig. 6. a) Heat flux of the Northern Apennines and part of the adjacent Po basin: isoline in mW/m^2 (1); layout of a geological cross-section (after Pieri and Groppi, 1981) along the buried zone of the Apennines (2). b) Heat-flux pattern q_0 through the cross-section: Quaternary and Pliocene (1); upper Miocene (2); Miocene and Paleogene (3); Mesozoic (4).

(Pieri and Groppi, 1981; Patacca and Scandone, 1985; Castellarin and Vai, 1986). The orographic border of the chain does not match the north-verging structural front, which extends for several kilometres beneath the Quaternary sediments of the Po basin, forming the external zone of the Apennines (fig. 1). Such a structural setting was produced by migration of a chain-foredeep system, through overthrusting fronts more and more externally displaced (Ori and Friend, 1984). This process took place from the end of Miocene to lower Pleistocene time through several tectonic episodes which caused shortening and overthrusting progressively migrated toward north-east (fig. 6).

Remarkable accumulation of Neogenic deposits, having sometimes thickness greater than 8 km, occurred in correspondence of the buried arcs of the Apennines, sensibly disturbing the thermal gradient. Sedimentation reduced the heat flux of more than 30%, in relation to the thickness of the sedimented layer and the deposition time (Pasquale and Verdoya, 1990). Although the correction of this perturbation may have been underestimated as only applied to the more recent sedimentary event, the low thermal field is unlikely to be solely ascribable to the accumulation of sediments. Based on Brewer's (1981) mathematical model, Mongelli *et al.* (1989) demonstrated for the Northwestern Apennines that the heat flux is sensibly reduced by friction heat dissipation and thermal relaxation because of overthrusting. The same kind of analysis has been here adopted to evaluate the order-of-magnitude of the thermal field perturbations due to recent overthrusting inside the Po basin. For this purpose, besides assumptions on the physical parameters of medium, it has been necessary to define overthrusting duration time, nappe thickness, their displacement and geometry.

On the base of structural data by Pieri and Groppi (1981), the compressional phase which led to the present structural setting can be schematized with a first episode, between Messinian and lower Pliocene time, followed by an important second one in upper Pliocene-lower Pleistocene time. The main detachment surfaces seem to be within Neogenic terrain and next to the Mesozoic-Tertiary boundary, but some surfaces occur to greater depth and could be located at the Mesozoic basement and sometimes in the crystalline basement too (Cassano *et al.*, 1986). Therefore, in view of the difficulty in defining the real depth of the detachment level, we have assumed, on the base of the structural cross-section of fig. 6, a nappe 6 km thick, including the cover and some upper levels of the Mesozoic successions displaced during the Miocenic-Pliocenic compressional event. Before modelling the Pliocenic-Quaternary overthrusting, we have increased the nappe thickness of 1 km in order to take into account the lower Pliocene sedimentation.

The evaluation of the shortening amount of the thrust fronts is similarly difficult. In fact the overall shortening depends on the deep layers chosen as reference level and it would be as greater as the assumed detachment level is deeper. Moreover, displacement of the overthrust blocks varies from the inner zones to those closer to the Homocline. It has been assumed an overall mean shortening of about 25% for the older event and of about 10% for the more recent one (Pieri and Groppi, 1981).

Figure 7 shows the surface heat-flux variation with time, resulting from the model of a nappe which horizontally moves with a constant velocity and friction coefficient ranging from 0.2 to 0.6 as proposed by Byerlee (1978) and Brewer (1981). We have taken values of 1.8 W/(m K) and 10^{-6} m^2/s for the nappe thermal conductivity and diffusivity, 2500 kg/m^3

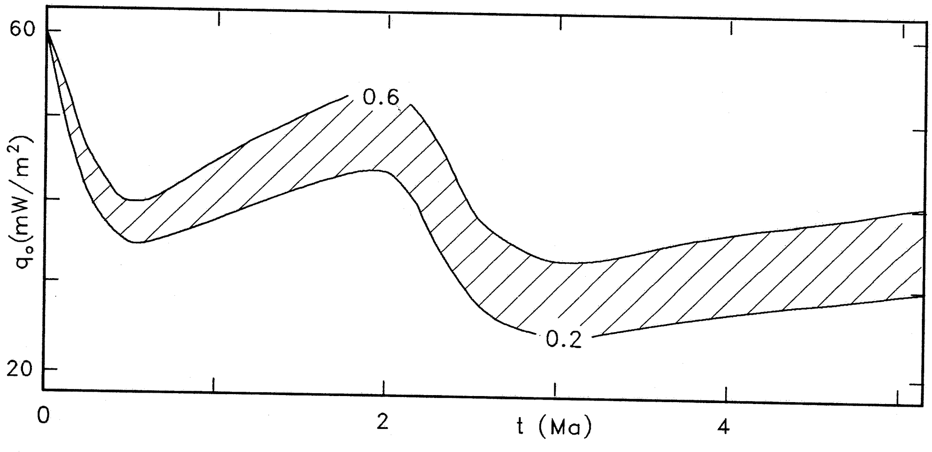

Fig. 7. Heat-flux variation q_0 with time t during the last 5 Ma, in the external zone of the Apennines, due to two overthrusting episodes, for a friction coefficient from 0.2 to 0.6.

for the density and 1 kJ/(kg K) for the specific heat, on the base of measurements carried out on core samples of the sedimentary successions of the Po basin (Pasquale and Verdoya, 1990). The reference heat flux assumed as an equilibrium value for the lithosphere is equal to 60 mW/m^2, as proposed by Mongelli *et al.* (1989). The effect due to the radiogenic sources has been neglected.

Considering a mean friction coefficient of 0.4, heat flux initially decreases of about 40%. 2 Ma after the beginning of the overthrusting, it increases to about 50 mW/m^2. The perturbation generated by the second phase of displacement produces a further decrease in the heat flux, which at present assumes values from 30 to 40 mW/m^2, in good agreement with the experimental observations.

3.3. *Eastern Alps*

The Eastern Alps consist of several overthrust nappe units with different polarities, which make particularly complex the structural pattern of this part of the Alpine chain. The Giudicarie-Pusteria tectonic line separates the Austroalpine northward verging units and the underlying basement, consisting of the Alpine successions of Tauern tectonic window, from the Southern Alps unit (fig. 1). The latter consists of wide arcuate systems southward verging, whose asymmetric pattern can be related to the presence of intrusions of Variscan granites and of volcanic rocks of Permian and Paleogenic age. These intrusions reacted as a rigid block to the advancing of the Southalpine front (Castellarin and Vai, 1986).

In the studied area the internal-intermediate and intermediate arcs of Paleogenic-Miocenic age form the northernmost portion of the Southalpine. The external arc, completely buried beneath the Pliocenic-Quaternary cover of the Po basin, has the same age (upper Miocene-upper Pliocene) of the external zone of the Apennines and solely extends behind the front of the above mentioned arcuate systems.

From a structural point of view, these arc systems have polarity opposite to the Apennines, with which they share the foreland, corresponding to the Pedealpine-Adriatic Homocline. Whereas the external arcs of the Apennines are originated by the overriding on to the undeformed foreland, the Alpine arcs result from the northward underthrusting of the Adriatic crust. Therefore, it is possible to hypothesize a mechanism of active subduction for the Southalpine front and truly passive subduction for the Apennines.

Structural and evolutionary analogies between the Southern Alps external arc zone and the coeval buried front of the Apennines make possible to apply the same kind of thermal modelling carried out for the Po basin. Using the same physical parameters and a thrust sheet displacement halved with respect to the Apennines, the present heat flux should result around 50 mW/m^2. In the remaining provinces, the heat flux varies from a minimum of 45 mW/m^2, in correspondence of the Apennines foreland, to about 80 mW/m^2 for the Austroalpine zone, showing a south-north increasing trend (fig. 3).

4. Discussion and conclusions

The models of post-Miocenic overthrusting, where frictional heating is generated along a planar slip zone, and post-Paleogenic stretching of continental lithosphere, which produced thinning and passive upwelling of hot asthenosphere and back-arc spreading, predict remarkable thermal anomalies for the investigated area.

The high heat flux with strong transient component in the Ligurian Sea and peri-Tyrrhenian zone is due to subduction and back-arc extension processes which led to lithospheric stretching with formation of the Ligurian marginal basin and the Apennines-Tyrrhenian system (fig. 8). A stretching model more complex than the one proposed would imply depth-dependence of the attenuation factor, which is generally greater in the ductile part of the lithosphere than in the upper crust, and igneous intrusions in the lower continental crust subject to deformation (Royden *et al.*, 1983). However, it was demonstrated that a horizontal intrusion only controls the variation

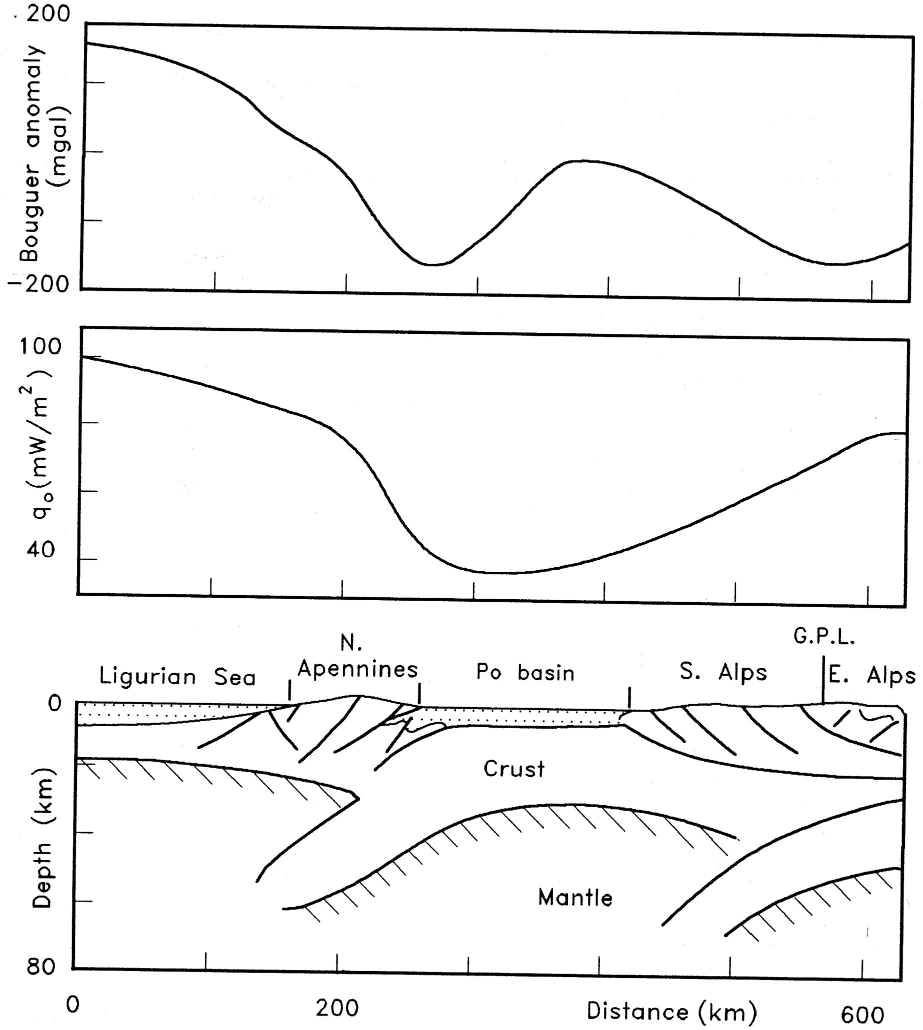

Fig. 8. General pattern of the Bouguer gravity anomaly (after Klingelé *et al.*, 1991) and heat flux, together with schematic cross-section illustrating the plate interaction from the Ligurian Sea to the Eastern Alps (after Giese *et al.*, 1992; Giese and Buness, 1992). G.P.L.=Giudicarie-Pusteria Line.

of the crustal volume and the initial subsidence, but the heat flux and the thermal subsidence remain as a function of the attenuation factor (McKenzie, 1984). This implies that the limit of the transitional crust deduced from the total tectonic subsidence could be slightly modified, whereas the one corresponding to the oceanic crust would remain unchanged, as depending on heat flux and age of the rifting process. The enhanced heat flux of the Ligurian Sea contrasts with the decidedly low flux of the provinces extending from the external zone of the Apennines to the intermediate Southalpine arc. This involves strong lateral variation of the mechanical field through the effect of temperature on fracture and flow properties in the crust and upper mantle (Pasquale *et al.*, 1993).

The heat flux of 40-50 mW/m^2 in the central part of the Po basin corresponding to the Pedealpine-Adriatic Homocline cannot be ascribed to the overthrusting effects, which only affected the external zones of the ranges. After modelling the thermal effect due to sources reside inside the crust, a long wavelength anomaly of low heat flux still remains between the Alps and the Apennines. The origin of this anomaly must be searched in the close coupling between lithosphere regional thermal state and processes of convergence connected to the developing of the Alps-Apennines system (fig. 8).

The Alps and Apennines chains record two subduction events which differ both in time and style and produced crustal thickening and complex Moho overlaps, controlled by plate convergence (Mantovani *et al.*, 1992; Giese *et al.*, 1992). The Alps result from the Africa-verging subduction of the European block started in Cretaceous time and the Tertiary collision of this block against the Adriatic one. The south-westwarding subduction of the Adriatic slab in Oligocene time produced a second crustal overlap and the formation of the Apennines accretionary wedge. This latter process was accompanied by anticlockwise rotation of Corsica-Sardinia block and formation of the asymmetric back-arc Ligurian basin. At present the Apennines are characterized by gradual eastward propagation of rifting, due to the continuous retreating of the subduction hinge of the Adriatic slab (Scandone *et al.*, 1990; Doglioni, 1991). This tectonic process is reflected by the high thermal flux of the peri-Tyrrhenian zone. Compressive tectonic regime and lower heat flux are confined in the thrust front zone of the buried external chain of the Apennines, showing a few pure reverse fault seismic focal mechanisms (Pasquale *et al.*, 1993). Active subducted slab beneath the chain has been outlined through tomography images computed starting from the digital waveforms of teleseismic events (Amato *et al.*, 1993).

Within such a geodynamic framework, the decrease of heat flux between the Alps and the Apennines could be explained by isotherm downwarping in the lithosphere due to a subducted and downward transported lithospheric slab having temperature lower than the surrounding material. In fact, in correspondence of the observed heat-flux minima, surface wave dispersion studies and more recently seismic tomography studies (Mueller and Panza, 1986; Spakman, 1990) have revealed the continuation to greater depths of the subduction processes. A denser mantle lithosphere root about 200 km deep, strongly dipping beneath the Po basin, has been modelled by Werner and Kissling (1985) to fit gravimetric data (fig. 8). In 1988, the same authors proposed a dynamic model of root sinking in the mantle, down to about 300 km, which produces the same presently observed rates of uplift in the Alps and subsidence in the Po basin. The global thermal effect could therefore result from both a more recent lithospheric root beneath the Alps and a dominant deep-reaching lithospheric root beneath the Po basin, remnant of an earlier subduction episode.

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