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THERMAL CONSTRAINTS TO THE GEODYNAMIC PROCESSES IN THE SOUTHERN TYRRHENIAN

Abstract. We determined temperature profiles at various depths of the Ionian plate, sinking in an isothermal mantle beneath the southern Tyrrhenian. We used an analytical model whose boundary conditions take into account the relation between the maximum depth of seismicity and the “thermal parameter” $L_{th}$ of the slab, which is a product of the age of the subducted lithosphere and the vertical component of the convergence rate. By considering that the maximum depth of the earthquakes within the slab is 600 km, a $L_{th}$ of 4725 km was found. For a subduction rate equal to spreading rate, the corresponding assimilation and cooling times of the microplate are about 7 and 90 Myr, respectively. The thermal model assumes that the mantle flow above the slab is parallel and equal to the subducting plate velocity (6 cm/yr), and that the heat conduction down the slab dip can be ignored. The critical temperature, above which the slab cannot sustain the stress necessary to produce seismic events, was determined from the temperature conditions governing the rheology of the oceanic plate. The minimal potential temperature at the depth of the deepest earthquake is of 730 °C and occurs at a distance of about 23 from the upper surface of the slab.

INTRODUCTION

The study of the seismic activity together with the thermal regime of the lithosphere may produce a more complete picture of the tectonic processes. Such an analysis becomes complicated for areas thermally perturbed by recent or even still ongoing geodynamic processes. In order to call apart the different effects and reconstruct their evolution with time, to analyse separately each event is a possible approach. The southern Tyrrhenian falls within this category of areas. The thermal features of the subducting Ionian slab are an important constraint for understanding its geodynamic evolution and the present-day setting. The thermal state, together with the knowledge of the tectonic regime, thermo-mechanical parameters, and the composition and structure of the slab is fundamental for reconstructing the rheological stratification and for interpreting the complex distribution of the shallow and deep seismic activity.

VINCOLI TERMICI AI PROCESSI GEODINAMICI NEL BASSO TIRRENO

Riassunto. Sono stati determinati profili termici a varie profondità nella placca ionica in subduzione in un mantello isotermico sotto il Tirreno meridionale, per mezzo di un modello analitico le cui condizioni termiche al contorno tengono conto della relazione tra la profondità massima della sismicità e del “parametro termico” $L_{th}$, dato dal prodotto dell’età della litosfera subdotta per la componente verticale della velocità di convergenza. Considerando che la massima profondità dei terremoti nella piastra in subduzione è 600 km, $L_{th}$ risulta 4725 km. Per una velocità di subduzione uguale alla velocità di espansione, i corrispondenti tempi di assimilazione e di raffreddamento sono di circa 7 e 90 Ma, rispettivamente. Il modello termico assume che il flusso del mantello, sopra il piano di subduzione, è parallelo ed uguale alla velocità della placca in subduzione (6 cm/a), e che la conduzione di calore lungo la direzione d’immersione della piastra può essere ignorata. La temperatura critica, sopra la quale la piastra non è in grado di sostenere la tensione necessaria alla generazione di terremoti, è stata determinata dalle condizioni termiche che governano la reologia della placca oceanica. Il valore minimo della temperatura potenziale, alla massima profondità sismica, si trova ad una distanza di 23 km dalla superficie superiore della piastra ed è pari a 730 °C.

INTRODUCTION

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Several numerical and analogical models were so far proposed to depict the dynamics of the Tyrrenian subduction zone (e.g. Giunchi et al., 1996; Faccenna et al., 1996), whereas the inference of the thermal structure is still at an early stage. It was only approached by studying the temperature distribution within the Ionian slab with a conductive heating model (Pasquale et al., 1999 and 2003a). Nevertheless, the thermal conditions of the subducting lithosphere and the surrounding mantle are a key-information to understand, besides earthquake distribution, magma generation in the back-arc area (Sicilian-Calabrian margin). In this paper, we try to improve our previous thermal investigations by means of an analytic model, which takes into account the effects of the dynamic interaction between the slab and the surrounding mantle. We use an original approach, which allows for an initial thermal boundary layer in the mantle wedge as well as above the subducting slab.

**Fig. 1 -** Geometry, orientation and co-ordinate system of the analytic thermal model of the Ionian slab descending beneath the southern Tyrrenian. Positive $x$- and $y$-axes are into the slab and in its down-dip direction. The $x$-axis is perpendicular to the slab surface and is negative out into the overriding mantle. The temperature of the slab as it subducts into the asthenosphere ($y=0$) is defined in eq. (1). The slab extends infinitely in the $z$-direction (so $\partial T/\partial z = 0$).

**ANALYTICAL MODEL**

The thermal structure of the subducting Ionian slab was determined by using an analytical model as that proposed by Davies (1999), which we adapted with adequate boundary conditions, established by considering the rheological behaviour of the oceanic plates (Pasquale et al., 2003b). The model assumes that the mantle above the slab flows parallel to the subducting plate and at the same velocity $v_y$, and that the conduction down the slab dip can be ignored. The Ionian slab geometry and co-ordinate system are shown in Fig. 1. The geometry has been deduced from the distribution of intermediate and deep seismicity (between 60 and 600 km) in the subduction zone, occurred from 1985 to 2000 (Pasquale et al., 1999; Selvaggi, 2001). At shallow depth, the seismogenic layer is close to the slab upper surface. In the slab
The deepest part, seismicity is low and more scattered. Also, the slab sinks at an angle of about 75° to 350-400 km and of 50° at greater depth.

The required boundary conditions are:

\[
\begin{align*}
\mathcal{G} &= \mathcal{G}_1, & x &\leq -d \\
\mathcal{G} &= \mathcal{G}_0 - \frac{x}{d} (\mathcal{G}_1 - \mathcal{G}_0), & -d &\leq x \leq 0 \\
\mathcal{G} &= \mathcal{G}_0 + \frac{x}{H_{th}} (\mathcal{G}_1 - \mathcal{G}_0), & 0 &\leq x \leq H_{th} \\
\mathcal{G} &= \mathcal{G}_1, & x &\geq H_{th}
\end{align*}
\]

(1)

as \( y \to \infty \), \( \mathcal{G} \) (all \( x \)) \( \to \mathcal{G}_1 \)

\( x \to \infty \), \( \mathcal{G} \) (all \( y \)) \( \to \mathcal{G}_1 \)

where \( H_{th} \) is the thickness of the subducting thermal lithosphere, \( d \) the initial thickness of the boundary layer in the mantle that occurs at the point where the flow is largely perpendicular to the slab before it begins to descend parallel to the slab, \( \mathcal{G}_1 \) the mantle temperature away from the slab and \( \mathcal{G}_0 \) the temperature of the upper surface of plate as it enters the asthenosphere.

If we assume a steady state and

\[
\frac{\partial^2 \mathcal{G}}{\partial y^2} \ll \frac{\partial^2 \mathcal{G}}{\partial x^2}
\]

(2)

the heat transfer equation reduces to

\[
\frac{\partial \mathcal{G}}{\partial y} = \frac{\chi}{v_y} \frac{\partial^2 \mathcal{G}}{\partial x^2}
\]

(3)

where \( \chi \) is the thermal diffusivity. Thus, indicating with \( f(x) \) the foregoing boundary condition, the solution is

\[
\mathcal{G} = \left( \frac{4 \pi y \chi / v_y}{2} \right)^{1/2} \int_{-\infty}^{\infty} f(x') \exp \left[ -\frac{(x-x')^2}{4y\chi/v_y} \right] dx'
\]

(4)

**MODEL RESULTS**

The thermal conditions at the boundaries of the subducting slab were fixed on the basis of rheological considerations. Studies on the bending of oceanic plates have shown that the temperature-dependence of the lithosphere rheology is controlled by the ratio \( \gamma \) of the critical temperature \( \mathcal{G}_c \), above which no earthquake occurs, on the melting temperature \( \mathcal{G}_m \). As the maximum depth of earthquakes within an oceanic lithosphere far away from the subduction zone is about 45 km (Chen and
Molnar, 1983), and at such a depth $\theta_c$ is 600 °C (Pasquale et al., 2003b), we found that $\gamma$ is 0.56 and the depth-dependence $z$ of $\theta_c$ is

$$\theta_c(z) = 0.56 \theta_m(z)$$  \hspace{1cm} (5)

where $\theta_m$ is the mantle melting temperature (in Kelvin) as inferred from data by Stacey (1977). We calculated a critical temperature of 990 °C at the lower boundary of the model. Consequently, by subtracting the temperature increase of 135 °C due to the latent heat of the olivine-spinel phase change at 400 km depth (Turcotte and Schubert, 1971) a value of $\theta_0 = 450$ °C was set in order to fit the lower boundary thermal conditions.

On the basis of geological data, Pasquale et al. (1999) argued that the velocity of the Ionian plate is about 6 cm/yr, Here, we attempt to infer the subduction rate $v_y$ on other independent pieces of evidence. $v_y$ is related to the “thermal parameter” $L_{th}$ of a descending slab defined as

$$L_{th} = t_c v_y \sin \alpha$$  \hspace{1cm} (6)

where $\alpha$ is the dip angle of the slab and $t_c$ is the cooling time required for the oceanic plate to move from a spreading centre to a trench (Kirby et al., 1991). On the basis of a number of observations for several worldwide subduction zones, Gabatov and Kostaglodov (1997) reported a set of values of $L_{th}$, $t_c$ and $D_m$. The latter is the maximum depth of seismic events within the slab. From their dataset, we only considered the following values for some subduction zones with uncertainty in $D_m$ and $L_{th}$ smaller than 40 and 300 km, respectively, in the seismicity maximum depth range of 400-700 km:

<table>
<thead>
<tr>
<th>Subduction zone</th>
<th>$D_m$(km)</th>
<th>$\delta D_m$</th>
<th>$L_{th}$(km)</th>
<th>$\delta L_{th}$</th>
<th>$t_c/t_{ass}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan (~ 42° N)</td>
<td>541</td>
<td>10</td>
<td>4180</td>
<td>280</td>
<td>8.8</td>
</tr>
<tr>
<td>Japan (~ 40° N)</td>
<td>588</td>
<td>35</td>
<td>4590</td>
<td>300</td>
<td>8.9</td>
</tr>
<tr>
<td>Southern Kuriles (~ 45° N)</td>
<td>460</td>
<td>10</td>
<td>4420</td>
<td>150</td>
<td>13.6</td>
</tr>
<tr>
<td>Southern Kuriles (~ 44° N)</td>
<td>400</td>
<td>15</td>
<td>4420</td>
<td>150</td>
<td>15.1</td>
</tr>
<tr>
<td>Southern Kuriles (~ 43° N)</td>
<td>400</td>
<td>10</td>
<td>4140</td>
<td>140</td>
<td>13.5</td>
</tr>
<tr>
<td>Marianas (~ 19° N)</td>
<td>700</td>
<td>39</td>
<td>4990</td>
<td>170</td>
<td>13.4</td>
</tr>
<tr>
<td>Marianas (~ 18° N)</td>
<td>650</td>
<td>10</td>
<td>5000</td>
<td>140</td>
<td>15.4</td>
</tr>
</tbody>
</table>

$\delta D_m$ and $\delta L_{th}$ are uncertainties in the estimates of $D_m$ and $L_{th}$, respectively. $t_{ass}$ is the time required for the subducting plate to lose the ability of generating earthquakes since it began to subduct.

By assuming that the subduction rate is equal to the spreading rate, we obtained for the ratio between $t_c$ and the assimilation time $t_{ass}$ (Shiono and Sugi, 1985), a value of $12.7 \pm 2.7$. Moreover, the maximum depth of the seismic activity is related to $L_{th}$ as follows

$$D_m = \frac{2}{7} L_{th} - 750$$  \hspace{1cm} (7)

for $400 < D_m < 700$ km.

The maximum depth of the seismic events within the Ionian slab is 600 km. This leads to a thermal parameter of 4725 km. Since the assimilation time of the Ionian
slab is 7 Myr (Pasquale et al., 1999), one obtains a cooling time of about 90 Myr and, for a 60° average dip angle of the slab, a subduction rate of 6 cm/yr. The parameters used for the calculations and the obtained results are:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum depth of seismicity</td>
<td>D_m 600 km</td>
</tr>
<tr>
<td>“Thermal parameter”</td>
<td>L_th 4725 km</td>
</tr>
<tr>
<td>Average dip angle</td>
<td>α 60°</td>
</tr>
<tr>
<td>Subduction rate</td>
<td>ν_y 6 cm/yr</td>
</tr>
<tr>
<td>Cooling time</td>
<td>t_c 90 Myr</td>
</tr>
<tr>
<td>Assimilation time</td>
<td>t_ass 7 Myr</td>
</tr>
</tbody>
</table>

A geotherm was calculated in the undeformed part of the slab (Ionian abyssal plain) by taking a thickness of 70 km for the mechanical boundary layer, a surface heat flux of 42 mW/m², an asthenosphere potential temperature of 1300 °C, an adiabatic gradient of 0.6 mK/m and a mantle kinematic viscosity of 10⁷ m²/s. The calculated temperature-depth distribution compared to the mantle melting temperature indicates the decoupling between lithosphere and asthenosphere occurs at 105 km depth, corresponding to a temperature of 1275 °C (Pasquale et al., 2003b).

Fig. 2 shows temperature profiles of the slab, whose geometry is reported in Fig. 1, and the surrounding thermal boundary layer of mantle. We used a value of 20 km for the thickness of the boundary layer and assumed that the origin of the calculation (x = 0) is at 50 km depth. As the model was performed for an isothermal mantle, the
calculated temperature values are in terms of potential temperature, and the value of \( \vartheta_c \) at the depth of 600 km corresponds to a potential temperature of about 730 °C. The temperature profiles, taken at various depths, illustrate not only the heating of the slab down dip, but also the cooling of the mantle wedge. The minimum temperature within the slab tends to shift down dip away from the upper surface. At 600 km depth, the distance is about 23 km (Fig. 3). The minimum temperature increases by 280 °C in the 50-600 km depth range and affects the seismic distribution in the depth region.

**Fig. 3 -** Minimum temperature in the slab (a) and its distance from the slab-surface (b) plotted as a function of y-direction.

**DISCUSSION AND CONCLUSIONS**

The surface heat flux in the southern Tyrrhenian is regionally higher, albeit lower than that expected for a cooling ocean plate. This confirms the young age and the marginal nature of the basin. The oceanic crust in the abyssal plain is thermally perturbed, probably because of fluid circulation below the sea floor. The stretched margins are affected by a complex mechanism of heat transfer, mainly due to magmatic intrusions and related fluids perturbing the surface thermal field (Pasquale et al., 2003a).

The proposed thermal model of the plate subducting beneath the basin takes account of the thickness, convergence rate, dip angle and physical features and seismogenetic zones of the slab. By considering an appropriate adiabatic gradient in the mantle and the latent heat due to phase changes, the thermal field within the subducting lithosphere is so that the potentially seismogenetic portion tends to shift with depth within the slab.

Once the Ionian lithosphere thickness and the temperature at its base are established, the main difficulty in reconstructing the thermal structure of the subducting slab is to determine the subduction rate and the initial minimum temperature as the slab subducts into the asthenosphere. For a vertical temperature gradient in the mantle, the slab heating should depend mostly on the vertical component of the convergence rate. If the temperature is the principal parameter
controlling the occurrence of deep earthquakes, the maximum length of the down dip seismic activity along a subducting slab, with given values of velocity and age, is a function of the dip angle. The adiabatic heating should raise more rapidly the temperature inside a steep slab rather than in a gently dipping one. Thus, the “thermal parameter” is connected to the maximum depth of seismicity. The application of the relation between these two parameters, obtained for seismicity profiles across subduction zones of marginal basins, gives for the Ionian slab a velocity of 6 cm/yr, in agreement with what deduced with other methods.

The difficulties arising in assessing the cooling time of the plate, defined as the time required for the ocean plate to move from the spreading centre to the trench, can be overcome by hypothesizing a subduction rate equal to spreading rate. If this is true, a direct proportionality of assimilation time to the cooling time is obtained. The critical potential temperature at which deformation of oceanic lithosphere is accompanied by earthquakes in the slab, defined as a fraction (0.56) of the melting temperature of the upper mantle, is $730 \pm 70 \, ^\circ$C and the uncertainty in the initial minimum temperature can attain a maximum of 100 °C. This will involve that the error on the temperature in the slab is in the range 70 - 100 °C.

The adopted model requires that the temperature in the asthenosphere wedge above the subduction slab (Tyrhenian basin) is equal to the asthenosphere temperature beneath the stable part of the plate the lithosphere (Ionian basin). However, Pasquale et al. (2003a) suggested that the thermal budget and the occurrence of extensional magmatism in the former area could be explained only if a moderately warmer asthenospheric wedge is invoked. We assumed in our model normal thermal conditions for the asthenosphere at both sides of the slab. Therefore, the calculated temperatures in the descending plate can be underestimated, but the maximum deviation should be of 100 °C.

Despite of these limitations, the proposed model represents a first attempt to depict the thermal features in the deepest part of the Ionian subduction zone. The mantle was considered isothermal and the heat sources within the slab were neglected. The results can be used as a basis to produce thermal models of the entire subduction zone, i.e. by taking into account also the shallow parts where the overriding plate is rigid. Besides, in relation to the seismic activity, a thermal model of the Ionian subduction may be of fundamental importance for the understanding of the magmatic processes that occur in the Tyrhenian area.

REFERENCES


Pasquale V., Verdoya M., Chiozzi P.; 2003b: Thermal structure of the subducted Ionian slab (in prep.)