Modelling the thermal perturbation of the continental crust after intraplating of thick granitoid sheets: a comparison with the crustal sections in Calabria (Italy)

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Abstract – Thick granitoid sheets represent a considerable percentage of Palaeozoic crustal sections exposed in Calabria. High thermal gradients are recorded in upper and lower crustal regional metamorphic rocks lying at the roof and base of the granitoids. Ages of peak metamorphism and emplacement of granitoids are mostly overlapping, suggesting a connection between magma intrusion and low-pressure metamorphism. To analyse this relationship, thermal perturbation following granitoid emplacement has been modelled. The simulation indicates that, in the upper crust, the thermal perturbation is short-lived. In contrast, in the lower crust temperatures greater than 700 °C are maintained for 12 Ma, explaining granulite formation, anatexis and the following nearly isobaric cooling. An even longer perturbation can be achieved introducing the effect of mantle lithosphere thinning into the model.

Keywords: Hercynian Orogeny, continental crust, thermal metamorphism, numerical models, Calabria Italy

1. Introduction

High thermal gradients in low-pressure metamorphic belts are often ascribed to the heat released during crystallization of granitoid tabular intrusions emplaced in the middle crust (Lux et al. 1986; Montel et al. 1992; Finger & Clemens, 1995), thus corroborating the concept of regional-scale contact metamorphism. In Calabria, a close connection between Hercynian low-pressure metamorphic terrains and thick granitoid intrusions has been recently hypothesized from field observations and geochronology of the crustal sections exhumed after Tertiary tectonics (Schenk, 1980, 1981; Grässner et al. 2000). Upper crustal rocks record high thermal gradients (Grässner & Schenk, 1999; Borghi Colonna & Compagnoni, 1992) that reach the remarkable value of 60 °C km⁻¹ in Aspromonte (Fig. 1). In the intermediate portion of the crustal sections, at palaeodepths greater than 7 km, late Hercynian granitoids are widespread (Fig. 1). The outcrop pattern of the Sila and Serre granitoids suggests that they are characterized by a notable lateral extent and a tabular geometry. The composition of the granitoids ranges from tonalite to leucogranite, for a cumulative thickness of 7–13 km (Schenk, 1980; 1990; Caggianelli, Prosser & Rottura, 2000; Caggianelli & Prosser, 2001), with the more mafic types prevailing at deeper levels. Underneath the granitoid intrusions, migmatitic paragneisses and granulites occur. They record thermal gradients lower than in the upper crust but still high (Schenk, 1989; Grässner & Schenk, 2001). They range from 33 to 28 °C km⁻¹, at palaeodepths of 20–28 km in Serre and reach the value of 49 °C km⁻¹ at a palaeodepth of 15 km in Sila. Available geochronological data indicate a close match between the age of granitoid intrusion and age of peak metamorphism in rocks lying above and below the granitoids (Grässner et al. 2000, and references therein). At least for the Serre crustal section, intrusion and peak metamorphic ages, obtained with different geochronological methods, are bracketed between 290 and 304 Ma. In Sila, dates are similar (Ayuso et al. 1994; Grässner et al. 2000), except for the upper crust, where Acquafredda et al. (1992) calculated a Rb–Sr whole rock isochron on paragneisses and micaschists pointing to an age of 326 ± 6 Ma.

In recent years the general evidence in favour of the tabular geometries of granitoid bodies has increased (see Cruden, 1998, and Petford & Clemens, 2000, for a review). In addition, a crustal structure similar to that observed in Calabria, and an analogous connection between huge granitoid intrusions and low-pressure metamorphism, has been proposed for the Mesozoic magmatic arc in the western United States (Barton et al. 1988). Thus the thermal effect of the intrusion of huge tabular granitoids in the middle crust is worthy of examination.

The present paper aims to simulate, by numerical calculations, post-intrusion thermal perturbation of a model crust, with a structure similar to that in the
cross-sections exposed in Calabria. The principal objective is to check whether the thermal perturbation caused by granitoid intraplating is compatible with observed metamorphic effects in the upper and lower crust, as formerly suggested by Grässner & Schenk (1999).

2. A crustal model from the Calabrian cross-sections

Cross-sections of the continental crust, shaped by late Hercynian metamorphic and magmatic events, are exposed in Sila (Grässner & Schenk, 2001; Caggianelli & Prosser, 2001) and Serre (Schenk, 1980). Tilting and exhumation of both sections are related to Late Oligocene–Early Miocene tectonics, as indicated by fission track dating of zircon and apatite (Schenk, 1989; Thomson, 1994). In addition, Oligocene–Miocene conglomerates and arenites from Serre and Sila (Stilo-Capo d’Orlando Formation in Cavazza, 1989, and Paludi Formation in Bonardi, De Capoa & Perrone, 1995) are mostly composed of clasts from the crystalline basement. This is consistent with a rapid exhumation rate during Oligocene and Miocene times.

Both cross-sections share important lithological similarities, as was formerly recognized by Quitzow (1935) and Dubois (1971). A simplified crustal sequence is proposed below.

The upper crust, broadly of metapelitic to metamorphic composition, is made up of two metamorphic complexes of low to medium grade intruded by weakly foliated granodiorites. Rock types are represented by phyllites, micaschists and paragneisses with minor intercalations of metavolcanic rocks and marble (Acquafredda et al. 1987). In the neighbourhood of the granitoids a sharp contact aureole is present. Pressure estimates for the emplacement level of the granitoids, obtained by Al-in-Hbl barometry and on the basis of the mineral assemblage in contact metamorphic rocks, range from 170 to 250 MPa (Caggianelli, Prosser & Di Battista, 1997; Grässner & Schenk, 1999; Caggianelli & Prosser, 2001). The middle crust consists essentially of granitoids ranging in composition from tonalite to leucogranite (Rottura et al. 1990). A tabular shape of the intrusions, except for the leucogranites, is hypothesized on the basis of the outcrop pattern and attitude of the magmatic foliation. Tonalites and minor dioritic, noritic and gabbroic rocks are more abundant in the neighbourhood of the contact with lower crustal rocks. Pressures at the emplacement level of deeper granitoids along the Sila and Serre sections (Fig. 1) by Al-in-Hbl barometry are 400–540 MPa, respectively (Caggianelli, Prosser & Di Battista, 1997).

The lower crust mainly includes metapelites, metarenites and metabasites. Rock types, from the base upwards, are represented by mafic granulites with minor peridotites, felsic granulites and migmatitic paragneisses with minor amphibolite and marble intercalations (Schenk, 1981; Schenk, 1990; Caggianelli et al. 1991). In the deeper levels, the lower crust records peak temperatures of 770 and 800 °C and pressures of 600 and 750 MPa, in the Sila and Serre sections, respectively (Schenk, 1989; Grässner & Schenk, 2001).

3. Tectonic context for the emplacement of the granitoids

Several lines of evidence suggest that, during Late Carboniferous to Early Permian times, the European continental crust underwent thinning after the Hercynian orogeny (e.g. Matte, 1991; Carmignani
intrusion of granitoid magmas in a continental crust

4. Thermal model

The simplified model proposed here relies on the conductive heat dissipation of a thick (13 km) tabular intrusion of granitoid magmas in a continental crust having a thickness of 30 km. To allow one-dimensional modelling, it is postulated that the tabular intrusion is horizontal and with infinite lateral extent. In addition, it is assumed that magma intraplating took place in a single stage and instantaneously. This assumption is, of course, a simplification but could be permitted if times required to fill large sheet-like plutons are short (<1 Ma), as calculated by Clemens & Mawer (1992) and Cruden (1998).

The model is based on the heat flow equation that includes contributions from heat conduction and heat production:

\[
\frac{dT}{dt} = \frac{k}{c\rho} \frac{d^2T}{dz^2} + \frac{A}{c\rho},
\]

where \( T \) is temperature in K, \( t \) is time in s, \( z \) is depth in m, \( k \) is thermal conductivity (2.5 W m\(^{-1}\) K\(^{-1}\) for all crustal rocks and 3.3 W m\(^{-1}\) K\(^{-1}\) in the upper mantle), \( c \) is heat capacity (1000 J kg\(^{-1}\) K\(^{-1}\)), \( \rho \) is density in kg m\(^{-3}\) and \( A \) is radiogenic heat production in W m\(^{-3}\) (see Fig. 2 for values).

In addition, the effect of the latent heat of crystalization was considered for the granitoid layer at temperatures decreasing from 850 to 650°C. To take into account this contribution, an effective heat capacity was introduced in equation (1) in place of the true magma heat capacity, following the approach suggested by Spear (1993).

Considering that granitoid magmas were probably partially crystallized at the time of the intrusion it seemed appropriate to fix the effective heat capacity to a value 2.5 times that of true heat capacity.

The effect of heat advection due to erosion is not considered here. In fact, the thermal history is rebuilt for the first 10 or 40 Ma after the end of the magma intrusion event, when the erosion rate of the Calabrian crust was modest (Schenk, 1989; Caggianelli, Prosser & Rottura, 2000).

Solution of the equation (1) was obtained by the finite-difference method, imposing as initial conditions a surface temperature of 0°C and a temperature at the base of the lithosphere (\( z = 100 \) km) of 1350°C. The initial geotherm, calculated by equation given in Philpotts (1990), is based on a multi-layer crust, with values of surface heat flow and reduced heat flow from the mantle appropriate for an extensional regime during magma intrusion (Fig. 2). The granitoid layer was divided into three sub-layers of equal thickness having initial temperatures of 850, 800 and 750°C to represent distinct sheet-like intrusions of tonalitic to granitic composition. The lower crust was divided into two sub-layers of equal thickness having different values of radiogenic heat production, to take into account differences between migmatitic paragneisses and granulites. Calculations were performed with the Stella® software package, adopting the 4th-order Runge–Kutta algorithm.
5. Results

In Figure 3 the perturbed geotherm has been traced at convenient time intervals after the granitoid intra-plating. It results in a maximum increase in temperature of about 250 °C in the upper crust and about 200 °C in the lower crust.

In the upper crust, despite the huge volume of magma intruded below, thermal perturbation is rapid, and produces a peak surface heat flow of 169 mW m⁻². After 0.5 Ma the temperatures close to the contact with the granitoids are already falling and after 1 Ma the temperature is decreasing everywhere.

In the lower crust, negative slopes of the geotherm can be observed 0.25, 0.5 and 1 Ma after the intrusion of magma. At these stages, heat flows downward from the granitoids into the underlying crust. After c. 2 Ma the geotherm regains an overall positive slope and heat flows upward everywhere. However, the base of the lower crust is still heating because the thermal gradient attenuates near the contact with the granitoids, generating a bottleneck in the heat flow. Finally, after 5 Ma the geotherm has a convex-upward profile and slowly cools to approximate a steady-state condition.

In Figure 4, model temperature–time curves are given for upper (a) and lower crustal levels (b) and for the intervening granitoids (c). Here, thermal history is limited to the first 10 Ma following intrusion. In the lower crust thermal inversion takes place during the first 2 Ma after intrusion. This is due to the more rapid heating of the lower crustal rocks closer to the contact with granitoids.

Peak metamorphism is significantly diachronous at different crustal levels. A comparison of the temperature–time curves for the upper crust (Fig. 4a) and for the lower crust (Fig. 4b) indicates that thermal maxima occurred later in rocks lying below the intrusion, as might be expected from the insulation effect of the overlying crust + granitoids. The delay increases as deeper levels of the lower crust are considered. This depends on the rate of heat transfer, more rapid in upper crust than in lower crust, in response to the different value of the thermal gradients across roof and base of the granitoid layer. For this reason, peak temperatures in the upper crust are reached within 0.9 Ma, whereas peak temperatures of 739 and 802 °C, at depths of 23 and 29 km, are attained after 3.0 and 4.1 Ma, respectively. Peak thermal gradients amount to 66–68 °C km⁻¹ in the upper crust and to 28–32 °C km⁻¹ in the lower crust. These values are in good agreement with the inferred gradients (Schenk, 1989; Grässner & Schenk, 2001). However, in the model, the effect of the partial melting is not considered. This would buffer temperature increase in response to the absorption of the latent heat of melting. For this reason, obtained peak temperatures may be overestimated. An attempt to quantify the effect of partial melting was made incorporating in the model the contribution of the latent heat of melting for the metapelitic lower crust. In the case of wet melting this effect should be considered for temperatures higher than 650 °C. Latent heat of crystallization of partial melts was also considered. The result is a decrease of peak temperatures of about 20 °C and a 0.4 Ma delay in reaching peak conditions.

Cooling curves of the granitoids are shown in Figure 4c. A cross-cutting of the tonalite and granodiorite curves occurs after about 0.3 and 0.8 Ma. In this interval an inversion of temperatures takes place. This is due to the initial slower cooling rate of the central granodioritic sheet screened by the external tonalite and granite sheets.
6. Discussion and conclusions

The results of the conductive thermal model suggest that intraplating of thick granitoid sheets in the Hercynian Calabrian crust could produce a vast thermal perturbation. This confirms Grässner & Schenk’s (1999) proposal, explaining metamorphic effects in the upper and lower crust with advective heat transport by large granitoid intrusions in the middle crust. The model indicates that thermal maxima in the upper and lower crust are differently delayed with respect to the intrusion age. Peak temperatures in the upper crust are achieved in less than 1 Ma, whereas in the lower crust they are attained 3–5 Ma after intrusion. In the following paragraphs, results are discussed separately for the upper and lower crust. Finally, a possible improvement of the model is proposed.

The upper crust is affected by a significant temperature increment of about 250 °C near the contact with the granitoids, with thermal gradients comparable with the observed values. The critical point is the short duration of the thermal perturbation simulated by the model. For example, a temperature greater than 400 °C is maintained for less than 1 Ma at depths of 5–7 km. This seems crucial in relation to the coarse grain size (up to 2 cm for andalusite) observed in the upper crustal rocks from Sila. Even though the average growth times for millimetre-sized porphyroblasts in regional metamorphism may be quite short (0.1–1 Ma, according to Cashman & Ferry, 1988), the duration of the calculated thermal perturbation could be inadequate to develop the observed coarse grain size. This problem could be solved by including in the model the effect of extensional tectonics. Borghi, Colonna & Compagnoni (1992) suggest that long-lasting heating of the upper crust in Sila could be linked to extension operating before the intrusion. Alternatively, if extensional tectonics outlasted intrusion of granitoids, the related mantle lithosphere thinning could favour a more persistent thermal perturbation in the upper crust with respect to the model proposed here.

The lower crust is affected by a temperature increment of about 200 °C, and by a thermal perturbation significantly longer than in the upper crust. In fact, at the base of the lower crust temperatures higher than 700 °C are maintained for c. 12 Ma. Peak temperatures of about 740–800 °C reproduced by the model are in close agreement with values obtained by geothermometry. Granulite formation and the widespread partial melting observed in the migmatitic paragneisses

Figure 3. Perturbed geotherms calculated at appropriate time intervals (numbers on curves in Ma) after the intraplating of the granitoids. The initial conditions are represented by the heavy dashed lines. The Al₂SiO₅ phase diagram after Holdaway (1971) is reported as a reference.
are also justified by the thermal perturbation. As a further check, the isobaric cooling (IBC) path observed in the Serre and Sila high-grade metamorphic rocks (Schenk, 1989; Grässner & Schenk, 2001) can be compared with the thermal relaxation of the transient geotherm computed with the model (Fig. 5). Analysis of Schenk's $P$–$T$–$t$ paths reveals that the cooling rates in the Serre rocks were of 3–5 °C Ma$^{-1}$ for the first 40 Ma of IBC. Model calculations indicate higher average values of 5 to 6 °C Ma$^{-1}$. This indicates that thermal perturbation might be slightly underestimated in the model. Even in this case a more persistent thermal effect could be ascribed to the influence of extensional tectonics outlasting intrusion of granitoids.

Thus, analysis of results of the model suggests both for the upper and lower crust that a better fit to observed temperatures could be obtained incorporating the effect of extensional tectonics. To evaluate this, mantle lithosphere thinning was tentatively introduced in the model. A thinning of 1 mm a$^{-1}$ ongoing for 20 Ma after intrusion is adequate to obtain a good match with Schenk’s data in the lower crust (Fig. 6). In contrast, mantle lithosphere thinning produces a negligible change in the upper crust.

Summing up, the model satisfactorily reproduces peak temperatures estimated for the metamorphism in the Calabrian lower crust. Taking into account the influence of extensional tectonics, the results can be optimized also for the persistence of the thermal perturbation. However, results of the model appear not conclusive for the origin of the regional scale metamorphism in the upper crust.

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References


Modelling the thermal perturbation of the continental crust


