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Curie temperature depths in the Alps and the Po Plain (northern Italy): Comparison with heat flow and seismic tomography data

Fabio Speranza[a,*], Liliana Minelli[a], Alessandro Pignatelli[a], Matteo Gilardi[b]

[a] *Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Roma, Italy*
[b] *ENI S.p.A., Exploration & Production Division, Via Emilia 1, 20097 San Donato Milanese, Italy*

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ABSTRACT

We report on the spectral analysis of the aeromagnetic residuals of the Alps and the Po Plain (northern Italy) to derive the Curie point depth (CPD), assumed to represent the 550 °C isotherm depth. We analysed both the aeromagnetic residuals of northern Italy gathered by Agip (now Eni) and the recent EMAG2 compilation. We used the centroid method on 44 and 96 (respectively) 100 × 100 km^2 windows considering both a random and a fractal magnetization distribution, but found that, at least for the Alps, the fractal model yields unrealistically shallow CPDs. Analyses considering a random magnetization model give CPDs varying between 12 and 39 km (22 to 24 km on average considering the two data sets) in the Po Plain, representing the Adriatic-African foreland area of the Alps, in substantial agreement with recently reported heat flow values of 60–70 mW/m^2. In the Alps, the Eni data set yields shallow CPDs ranging between 6 and 23 km (13 km on average). EMAG2 analysis basically confirms the "hot" Alpine crust, but reduces it to three 50–100 km wide patches elongated along the chain, where CPDs vary between 10 and 15 km. Such "hot" Alpine domains occur just north of maximum (50–55 km) crustal thickness zones of the Alps and correspond to low seismic wave velocity anomalies recently documented in the 20–22 to 35–38 km depth interval, whereas no relation is apparent with local geology. Assuming an average crustal thermal conductivity of 2.5 W/m °C and a steady-state conductive model, CPDs from the hot zones of the Alps translate into heat flow values of 110–120 mW/m^2, and to a basal heat flow from the mantle exceeding 100 mW/m^2 that is significantly greater than that expected in a mountain range. Thus we conclude that the steady-state conductive model does not apply for the Alps and granitic melts occur at ~15–40 km depths, consistently with seismic tomography evidence.

1. Introduction

A correct assessment of the thermal state of mountain belts is one of the most relevant targets of Earth sciences, as it is fundamental to model uplift and exhumation, and ultimately to understand the dynamics of mountain chains. Cenozoic-age orogens are composed of thick (50–70 km) crust formed during the last 60 Ma, thus in principle highly radiogenic and hot (Jackson et al., 2008). From the point of view of metamorphic geology, small orogens (such as the Alps) are considered to be cold, while large orogens (such as the Himalayan-Tibetan system) are characterized by hot crust and widespread lower crustal melting (Jamieson and Beaumont, 2013).

Data from the Italian Alps yielded heat flow values ranging between 45 and 80 mW/m^2 (Cataldi et al., 1995; geoThopica database at http://geothopica.igg.cnr.it/Fig. 1a), suggestive of a cold to intermediate crust, but recent data compilations and re-evaluations by Pasquale et al. (2012, 2014) raised heat flow values from the internal part of the Alps to 80–90 mW/m^2 (Fig. 1b). However, heat flow data of the Italian Alps were gathered either in shallow wells (depth < 1 km) or by road/railways tunnels, thus likely biased by shallow hydrological circulation of cold meteoric waters (e.g. Forster and Smith, 1989).

In the past, Jaboyedoff and Pastorelli (2003) considering geological-metamorphic evidence tried to assess the water circulation perturbation of the heat flow in the Swiss Alps by 1D thermal simulations. They suggested that low heat flow values in the Swiss Alps (< 70 mW/m^2 in areas of high topography) might reflect large amounts of cold groundwater circulating into the high-relief massifs and lowering internal temperatures. They stressed that heat flow map of Switzerland (Medici and Rybach, 1995) clearly shows an inverse correlation between heat flow values and topography, and that heat flow values gathered above 800 m a.s.l. are sys-

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* Corresponding author.
E-mail address: fabio.speranza@ingv.it (F. Speranza).

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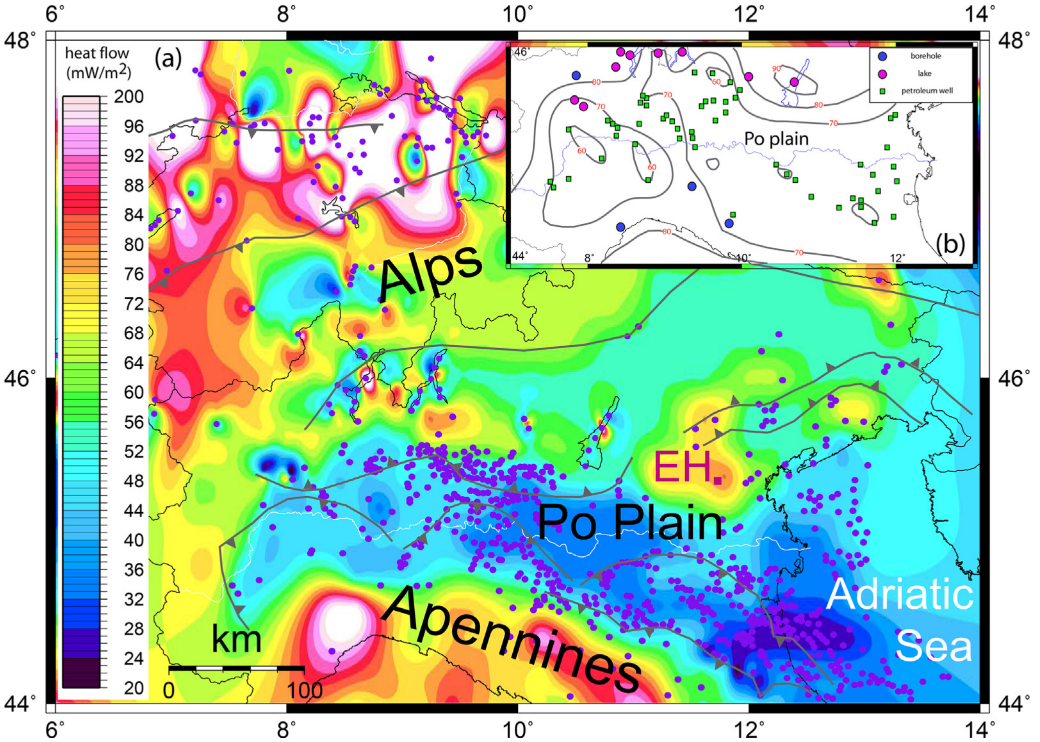

Fig. 1. a) Heat flow map of northern Italy (Cataldi et al., 1995; GeoThopica database, http://geothopica.igg.cnr.it/), Switzerland (Medici and Rybach, 1995), and neighbouring regions (Global Heat Flow Database of International Heat Flow Commission, http://www.heatflow.und.edu/). Data points are in purple. Abbreviations: EH Euganei Hills. Updated heat flow values by Pasquale et al. (2012, 2014) are shown in b.

tematically lower than 90 mW/m^2. Hydrological perturbation is confirmed by the observation of large descending cold-water flows in the Simplon, Mont-Blanc, and Gotthard tunnels (e.g. Jaboyedoff and Pastorelli, 2003 and references therein). Jaboyedoff and Pastorelli (2003) substantially confirmed previous suggestions by Oxburgh and England (1980), and estimated the water "cooling effect" to be approximately 0–50% of the total heat flow values. Water circulation would be also responsible for local hot springs and high (> 100 mW/m^2) heat flow patches of northern Switzerland (Fig. 1a), located in regions just north of the Alps characterized by high permeability and allowing the upraise of water coming from relevant depths.

The potential bias affecting classical heat flow measurements carried out in orogens hosting high-permeability rocks and wide shallow aquifers is also confirmed by the recent work of Chiodini et al. (2013) on the central Apennines of Italy. This region has been always considered cold by classical heat flow measurements, yielding values as low as 30–40 mW/m^2 (Cataldi et al., 1995). Yet Chiodini et al. (2013) demonstrated that considering the difference between spring temperatures and temperatures inferred for recharge waters, the heat flow of the central Apennines exceeds in fact 300 mW/m^2.

The determination of the Curie point depth (CPD) by spectral analysis of magnetic residuals has the potentiality to solve this problem, and document the real thermal state of mountain belts. In fact, ferromagnetic minerals of rocks become paramagnetic above a given Curie temperature, and their magnetic susceptibility drops by several orders of magnitude. Thus the lithosphere becomes virtually non-magnetic below CPD, where rocks get hotter than the Curie point of the dominant ferromagnetic mineral.

As magnetite and low-Ti titanomagnetite are the main ferromagnetic minerals of the deep continental crust (Frost and Shive, 1986; Shive et al., 1992), and their Curie temperature is in the 500–600 °C temperature range at pressures expected at ∼20 km depth (Schult, 1970), the determination of the CPD in a given area translates into the 500–600 °C isotherm depth determination (e.g. Blakely, 1988; Tanaka et al., 1999; Chiozzi et al., 2005; Li et al., 2010, 2013; Ravat et al., 2011; Wang and Li, 2015; among many others). As such temperatures occur at depths (10–50 km) where heat flow bias due to shallow/geothermal water circulation is avoided, CPD may represent a significant proxy of the thermal state of the crust. In this paper we provide the CPDs of the Alps and the Po Plain (northern Italy), evaluate their consistency with documented heat flow values, and compare them with recent seismic tomography results obtained in the Alps.

1.1. Geological setting

The Alps (Fig. 2) are the result of late Cretaceous-Tertiary indentation of Adria (a promontory of Africa) into Europe (Argand, 1924). Subduction of Europe below Adria (Piromallo and Faccenna, 2004) yielded an asymmetric orogen, characterized by a wider and thicker nappe stack verging towards Europe, and a smaller wedge with southern vergence resting over the Adria plate (Consiglio Nazionale delle Ricerche, 1991; Rosenberg and Kissling, 2013). The arc-shaped Alpine chain is connected to the Apennines, and both are tectonically stacked over the Adria block, forming a sort of horseshoe-shaped orogenic re-entrant. The Adria foreland, locked between the two facing belts, is covered by thick terrigenous Neogene sediments of the Po Plain (Fig. 2). The crust is up to 50–55 km thick below the Alps, while it decreases to 25–30 km in correspondence of the European foreland, and to 30–40 km in the Po Plain and northern Adriatic Sea (Spada et al., 2013). On the European side of the Alps, the Moho gradually deepens southward from 25 to 50–55 km, while in the Po Plain an abrupt step is observed between normal Adriatic foreland thickness of 35–40 km and the zone of maximum Alpine crustal thickness of 50–55 km. In the western Po Plain, the Moho shallows up at 10–15 km in correspondence

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