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Thermal structure of a vanishing subduction system: an example of seismically-derived crustal temperature along the Italian peninsula

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SUMMARY

The active tectonic processes in convergent margins confer a high degree of complexity to the crust. Determining the thermal structure is, therefore, key to better elucidate the nature of those processes. In order to reconstruct the thermal structure of the crust beneath the Italian peninsula, we combine the most recent and accurate shear-wave velocity model that is currently available with thermodynamic modelling, assuming a global average crustal composition with no lateral variations. Our model, presented in terms of Moho temperature and crustal thermal gradients, shows a very good agreement with the known thermal anomalies associated with the backarc spreading related to the Apennine subduction. Importantly, we envisage a new anomalous region of high Moho temperatures in NW Italy ($T > 800$ °C at 30 km), at the transition between the Alps and Apennine orogens. The lowest temperatures of our model, corresponding to geothermal gradients <19 °C km^{-1}, are obtained in the still active but slow-convergent portion of the northern Apennine. Moho temperatures increase moving southwards along the Apennine chain, an observation that is coherent with the evidence of ceasing subduction and consequent rebalancing of the depressed isotherms along the slab. Our results suggest that a thermal structure in different tectonic settings can be inferred with acceptable uncertainties based on absolute seismic velocity models. In this sense, our approach can be extended to any other region.

Key words: Composition and structure of the continental crust; Crustal imaging; Seismic tomography; Continental margins: convergent; Crustal temperature.

1 INTRODUCTION

The temperature of the crust and lithospheric mantle at a convergent margin is complex, being altered by the downwelling of cold lithosphere material into the mantle. As such, the thermal field is depressed in the subduction zone and raised in backarc regions (Currie & Hyndman 2006). Subduction velocity, shear stress along the plate contact (Peacock 1996), delamination of the lithospheric mantle from the crust (Bird 1979) are all factors that can spatially vary (Kincaid & Griffiths 2003) and influence the temperature field. Moreover, the temperature at depth can be a function of the specific stage of the convergence process, affecting the rheological behaviour of the involved plates, their seismicity and its spatio-temporal evolution.

In literature, the inference of lithospheric temperatures often relies on heat flow measurements only or with complementary data, such as gravity and seismic velocities (Zeyen *et al.* 1994; Sobolev *et al.* 1997; Fullea *et al.* 2009; Simmons *et al.* 2009). While these approaches might be adequate in old, stable continental areas (Chapman 1986; Jaupart & Mareschal 2010), their utility in regions characterized by recent and ongoing tectonic activity is limited. In fact, several issues undermine the reliability and applicability of temperature estimates from heat flow. For example, the local topographic and geological setting can diminish the local heat flow because of the percolation of meteoric water, whereas fluid upwelling can increase heat flow. Moreover, since borehole data are sparse and often extremely shallow (reaching a few hundred meters depth), their vertical and lateral representativeness is rather poor in most cases.

Both laboratory experiments and thermodynamic modelling (Christensen & Mooney 1986; Rudnick & Fountain 1995; Birch 1961) show that temperature exerts a major control on the elastic behaviour of rocks. Anomalies in seismic velocities can be therefore used for inferring temperature at depth. However, also chemical composition, water content and mineral association, contributes to the bulk seismic properties of rocks. Thermodynamic modelling consists in a quantitative approach that considers the simultaneous contribution of these variables, leading to more robust estimates of temperature from seismic velocities. By employing thermodynamic modelling in our previous work (Diaferia & Cammarano 2017), we have shown that a different chemical composition within the same crustal layer is not expected to produce a substantial change in seismic velocities and, therefore, on temperature inference (in the order of tens of degrees, according to our calculation). As a consequence, the more pronounced, first-order effect driven by temperature might justify the overlook of chemical change for the sake of temperature inference at a crustal depth. Based on this premise, we convert shear wave velocities (V_S) into crustal temperature, obtaining the Moho thermal structure and thermal gradients across the Italian Peninsula.

The Italian Apennines chain is a key tectonic site to understand the way the temperature field is depressed over a complex active margin. In fact, the style and mechanism of convergence change dramatically along strike over a few hundreds of kilometres. Beneath the northern Apennines, the Adria Plate is slowly subducting/delaminating beneath the Tyrrhenian side. In the Central Apennines, subduction probably vanished a couple of million years ago and slab most probably broke off (Wortel & Spakman 2000; Picotti & Pazzaglia 2008). Finally, active oceanic subduction is underway under Calabria. All these lateral changes may cause the variation of the thermal field along strike.

Our analysis provides a new picture of the temperature field and geothermal gradient over the Apennines as well as the Alps. A particularly interesting result we anticipate is the high value of the Moho temperature, showing a rather uniform distribution, with a value exceeding 800 °C. Exceptions are limited to a small region on the Tyrrhenian side. This high value and the rather uniform Moho temperatures are due to the fact that in regions with lower temperature gradient the Moho is deeper and vice versa. Moreover, we identify an anomalously hot Moho in correspondence of recent/active volcanic activity, in the Molasse basin as well as below the Piedmont area (NW Italy).

2 DATA AND METHOD

We convert V_S at depth into temperature with thermodynamic modelling, thus accounting for the nonlinear relationships between seismic properties of a mineralogical aggregate and the pressure–temperature conditions at depth. Seismic velocities are from Molinari *et al.* (2015a), obtained through the inversion of phase and group velocities of Rayleigh waves from 1-yr long recording of ambient noise. The optimal sensitivity for crustal depth is assured by the 5–45 s period range of the retrieved Rayleigh waves. For inversion, a neighbourhood algorithm (Sambridge 1999; Wathelet 2008) is used at each location in a grid of 0.25° spacing. Further details can be found in Molinari *et al.* (2015a) and references therein. In Fig. 1 some essential characteristics of Molinari *et al.* (2015a) are summarized. For example, the four horizontal slices (10, 20, 30 and 50 km) in panel (a) highlight the low-velocity structure associated with the Alpine and Apennine orogens. Conversely, higher velocities correspond to the Tyrrhenian Sea where a thin oceanic crust is expected. As shown in panel (b), crustal and mantle domains are easily discriminated given the sharp separation in terms of seismic velocities. Those in the crust do not exceed 3.9 km s^{-1} and distribute bimodally, with a rather long tail of low- to very low-velocities that are encountered in thick sedimentary basins (i.e. Po Plain). Crustal thickness (i.e. Moho depth) is largely varying , spanning from 15 to 50 km (mean = 31 km).

We use thermodynamic modelling to predict the absolute temperatures at depth from seismic velocities. Predictions are made via `Perple_X` (Connoly 2009), a code based on Gibbs free energy minimization that solves iteratively the thermodynamic equations of state, computes the association of stable minerals and the seismic properties of the mineral aggregate, for any P–T condition. For each of the minerals constituting the modelled rock, the V_P and V_S are a function of the adiabatic bulk modulus (K) and density (ρ), both related to the derivatives of the Gibbs free energy with respect to pressure and temperature. More specifically:

$$K = -\frac{\partial G}{\partial P}\left\{\frac{\partial^2 T}{\partial G^2}\left[\frac{\partial^2 G}{\partial P^2} + \left(\frac{\partial}{\partial P}\frac{\partial G}{\partial T}\right)^2\right]\right\}^{-1} \tag{1}$$

$$\rho = N\frac{\partial P}{\partial G}, \tag{2}$$

where G is the Gibbs free energy and N is the molar weight. Regarding the shear modulus μ:

$$\mu = \mu_0 + T\frac{\partial \mu}{\partial T} + P\frac{\partial \mu}{\partial P} \tag{3}$$

where μ_0, $\frac{\partial \mu}{\partial T}$ and $\frac{\partial \mu}{\partial P}$ are constants evaluated through laboratory experiments. Given the compressional and shear wave velocities of each mineral composing the modelled rock, its bulk seismic properties are calculated through the Voigt–Ross–Hill (Hill 1952) averaging scheme. For our specific application to the crustal domain, we implement the thermodynamic database from Holland & Powell (1998), augmented with the experimentally constrained shear moduli provided by Hacker & Abers (2004), including the experiments from Ohno *et al.* (2006) regarding the peculiar behaviour of quartz at its transition from the α to β form around 580 °C. At each location, the crust is subdivided into three layers (upper, middle, and lower crust) of equal thickness. The chemical composition of these layers is assumed as the global average proposed by Rudnick & Gao (2003). We account for the presence of water at crustal depth adding 1 wt .% H_2O to the aforementioned (dry) composition. The addition of water lowers the solidus temperature, allowing partial melting at crustal temperatures. For the sake of temperature inference, we keep the water content fixed because a variable degree of hydration does not substantially affect the thermodynamic calculations of shear-wave velocities in the P–T space (Diaferia & Cammarano 2017). The higher sensitivity of V_S to temperature rather than to chemical composition implies that the assumption of a unique chemical composition does not translate into significant uncertainty when inferring temperature from thermodynamic modelling (Diaferia & Cammarano 2017).

We correct the observed V_S to account for porosity, using the empirical formulae proposed (Castagna *et al.* 1985; Vitovtova *et al.* 2014). In agreement with previous findings (e.g. Guerri *et al.* 2015), temperature estimates in the upper and middle crust are even 200 °C higher than plausible temperatures (e.g. assuming an average 30 °C km^{-1}). The reasons for this result are several. The applied porosity correction probably underestimates the actual porosity effects at these depths (Diaferia & Cammarano 2017). In addition, it is likely that in the shallow portion of the crust, lateral variation in the chemical or mineralogical composition can be relevant, due to metastability, chemical contamination by sedimentary compositions, causing V_S that are lower than those modelled with thermodynamics at these depths. The temperatures inferred in the upper crust are in most cases excessive and thus discarded from our analysis.

We derive the crustal temperatures by matching the observed V_S profiles from Molinari *et al.* (2015a) with the velocities in the P–T space obtained from thermodynamics. The match between observed and calculated V_S always spans a range of temperatures (rather than a single value), representing the uncertainty of the temperature inference. It is worth noting that such uncertainty does not account for the inherent approximation made in thermodynamic modelling nor for the uncertainty in the minerals' properties that constitute the thermodynamic database. Finally, thermal gradients are obtained

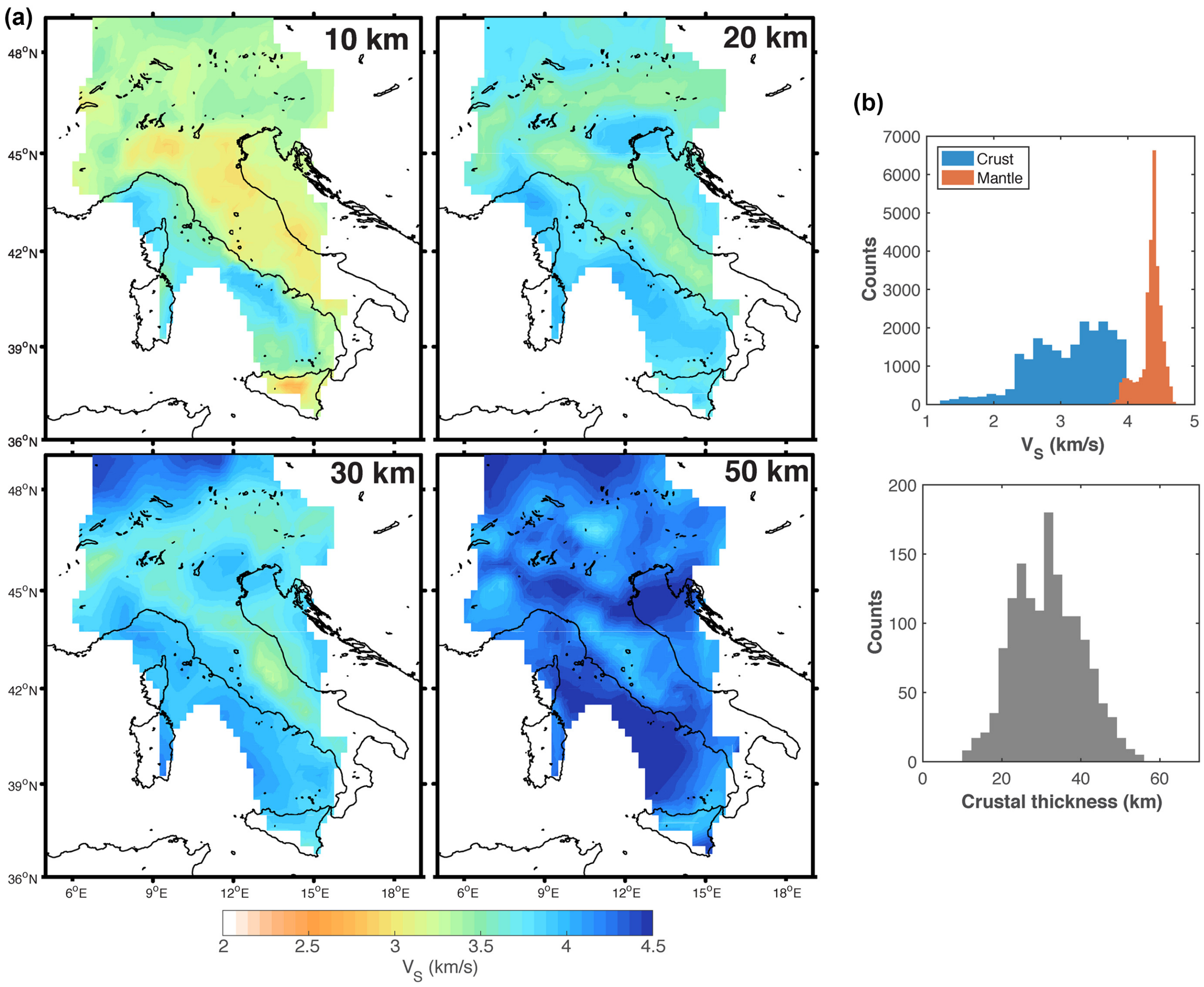

Figure 1. (a) Maps of shear wave velocities at depths of 10, 20, 30 and 50 km. (b) Upper side: histogram of shear wave velocities associated with the crust and mantle, respectively. The bi-modal distribution of crustal velocities is associated with the abundance of thick sediment bodies with low- to very low-velocities (e.g. Po Plain). Lower side: histogram of the crustal thickness.

by fitting the inferred temperatures with a robust linear equation. A surface temperature of 18 °C is assumed and data weighting is according to the uncertainty of inferred temperature.

3 RESULTS AND DISCUSSION

In Fig. 2 (left), we show the Moho depth according to the shear-wave velocity model of Molinari *et al.* (2015a). At these depths we calculate the temperature using thermodynamic modelling (Fig. 2, right). We observe the highest Moho temperatures (>850°) in the Alps and Apennines chains, where the Moho reaches greater depths (>40 km). Such a hot Moho underneath the Apennines is consistent with the high temperatures invoked by Mele *et al.* (1996) to explain the strong attenuation of Pn phases. Analogous to our findings, (Schutt *et al.* 2018) found temperatures above 850 °C at locations with a thick crust in the Western United States. A clear correlation between Moho depth and its temperatures is evident in the scatter plot (Fig. 2, upper side). The majority of data points lie along the 21 °C km^{-1} geotherm that can be considered, therefore, as an average geothermal gradient across the Italian peninsula. The uncertainty on Moho depth can be assumed to be rather small since the model from Molinari *et al.* (2015a) has been built incorporating a suite of different geophysical models that provide good constraints on the Moho depth and structure. As an example, a Moho at 30±2 km with a thermal gradient of 20 °C km^{-1} translates into a temparutre of 618 ± 60 °C. With the reasonable approximation that the Moho depth uncertainties are spatially homogeneous, the spatial characteristics of the thermal structure we present in this paper are thus preserved.

3.1 Good correlation with existing data?

In the scatter plot in Fig. 2, a small yet a relevant portion of the inferred Moho temperatures lies far from the 21 °C km^{-1} average gradient, suggesting anomalously hot Moho and higher geothermal gradients. In Fig. 3, we highlight such zones showing the temperatures at the Moho as a difference with respect to the reference thermal gradient of 21 °C km^{-1}. The envisaged anomalous zones perfectly correlate with the well-known Italian magmatic provinces.

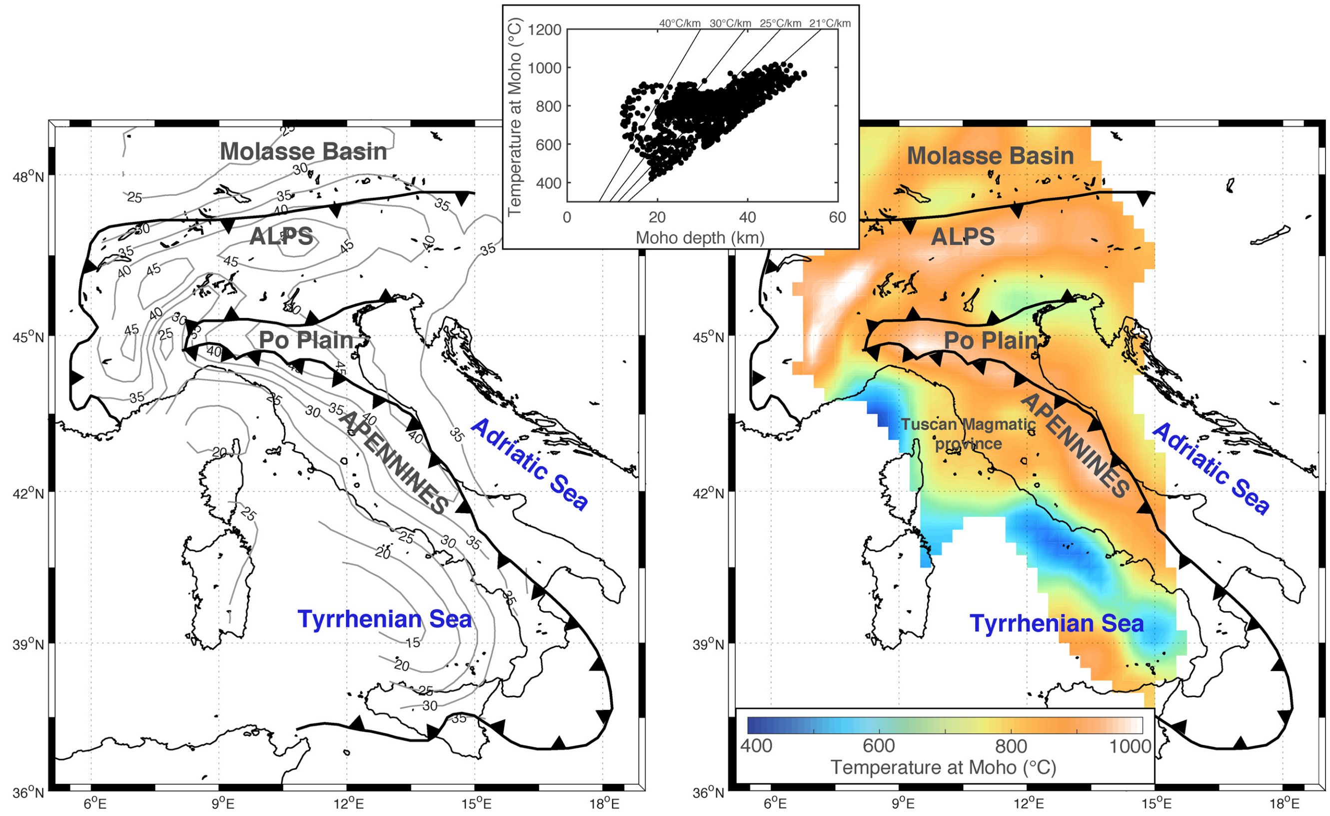

Figure 2. Left: contour plot of the Moho depths obtained from the shear-wave velocity model of Molinari *et al.* (2015a). Right: temperature at the Moho, obtained from the shear-wave velocities and thermodynamic modelling, assuming the chemical composition of Rudnick & Gao (2003). The highest temperatures (exceeding 900 °C) correspond to thickened portion of the crust along the Alpine and Apennine belts. On the top, the scatter plot of temperature and depth of the Moho shows that the majority of the data are correlated and lie along the 21 °C km^{-1} geotherm. Data points with low correlation lie along hotter geotherms and depict an anomalously hot Moho.

The anomaly with the largest extent corresponds to the Tuscan magmatic province, where both intrusive and extrusive events occurred in the past 8.5 Ma because of the subduction process along the Apennines (Peccerillo & Frezzotti 2015). The area is characterized by a high heat flow [>100 mW m^{-2}, (Della Vedova *et al.* 2001)] exploited through major, high enthalpy geothermal fields (Larderello, Travale-Radicondoli and Monte Amiata) for electricity production (Cataldi *et al.* 1995). The vigorous upwelling of steam and hot water is also documented in hundreds of exploration boreholes (ViDEPI—http://unmig.sviluppoeconomico.gov.it/videpi/videpi.asp, shown in Fig. 3), and suggests the ongoing stagnation of melts within the shallow crust. The thermal anomaly we find at the Moho (>250 °C higher than the reference temperature) suggests a deeper source for the heat, of which the stagnating partial melts within the upper crust are only the shallow expression. Such a hot Moho results in rather high geothermal gradients (see Fig. 4), in the order of 40–45 °C km^{-1} in the whole province.

According to our results, the strongest thermal anomaly lies under the Southern Tyrrhenian Sea. Here the shallow Moho (10–15 km depth) exceeds 800 °C, resulting in a peak geothermal gradient above 50 °C km^{-1}. The Tyrrhenian basin opened due to the counterclockwise rotation of the Apenninic compressive front in the past 15 Ma (Carminati *et al.* 1998; Faccenna *et al.* 2001; Carminati *et al.* 2010). The moderate crustal thickness and high heat flow support the hypothesis of a relevant crustal thinning and extensive spreading (Cataldi *et al.* 1995), followed by basaltic volcanism in the abyssal plain (e.g. Marsili and Vavilov seamounts) in addition to the calc-alkaline, subduction-related volcanism in the nearby Aeolian Arc. It is worth noting that the presence of a hot crust–mantle boundary has been suggested to explain the strong attenuation of Sn phases observed here by Mele *et al.* (1997). Though the amount of thermal anomaly that we envision in this basin appears plausible, in a thin crust the role of porosity can still have an effect on seismic velocities in the lower crust, leading our method to overestimate the Moho temperature. Therefore, we suggest considering our calculated temperature here as upper bounds.

Another thermal anomaly is observed in the northern Alpine foreland, which corresponds to the Molasse basin. Here the station coverage is limited, resulting in low spatial resolution. However, the below-average shear wave velocities found in this area suggest a Moho temperature of ∼800–900 °C (for a Moho ranging between 25 and 30 km depth), compatible with an average geothermal gradient of ∼32 °C km^{-1} (Agemar *et al.* 2012). The area has the most promising geothermal potential in Germany (Schellschmidt *et al.* 2010) because of the karstified, south-dipping Jurassic limestone aquifer underlying the whole basin (Birn 2013). At depths between 1.5 and 5 km, the temperature of the aquifer ranges between 85 and 140 °C and has permitted extensive exploitation of heat and, recently, electricity generation (e.g. Unterhaching power plant, Wolfgramm *et al.* 2007). It is worth noting that the amount and the extent of the thermal anomaly indicate a deep heat source for such geothermal area.

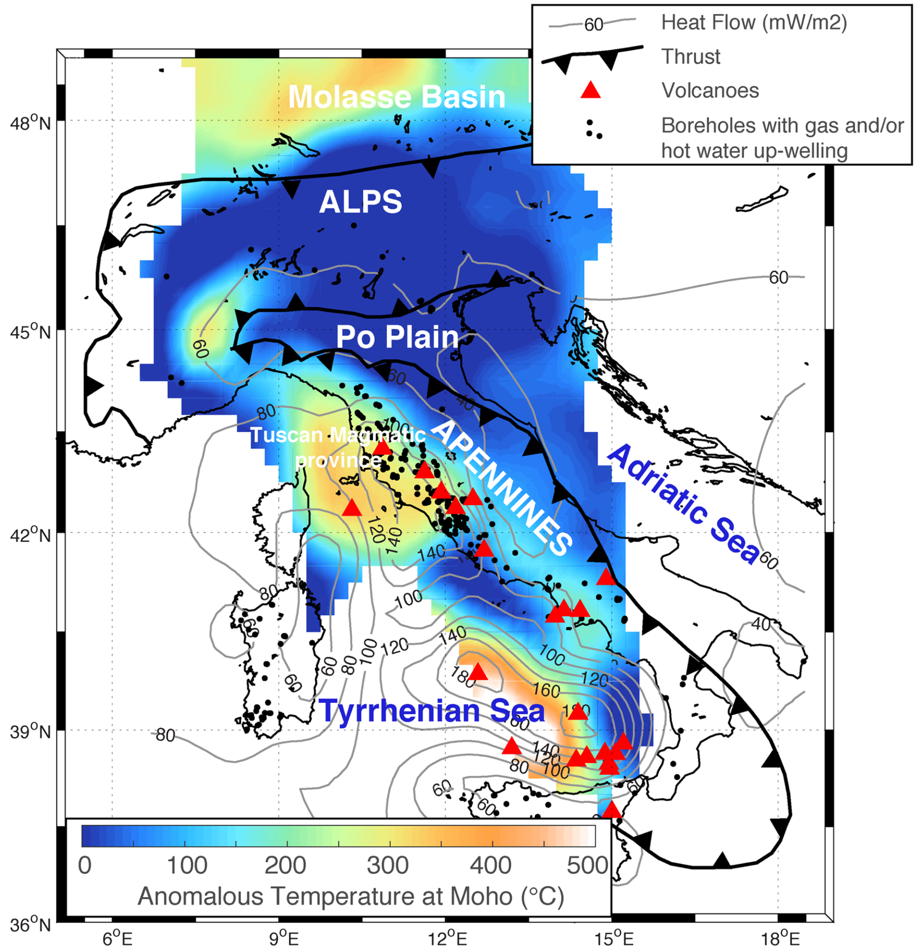

Figure 3. Absolute temperature anomaly of the Moho with respect to a reference gradient of 21 °C km^{-1} (see the scatter plot in Fig. 2). Colour bar is saturated at the lower bound (i.e. negative values and 0 have the same blue colour). The areas showing an anomalously hot Moho represent well the magmatic provinces of the Italian peninsula. Here, the highest values of heat flow are found, with diffuse past and current volcanism, and evidences of hot water and gas in boreholes drilled for geothermal exploration. Other areas with anomalous Moho temperature correspond to the Molasse basin and the Piedmont region, at the junction between the Apennines and southern Alps thrusts .

3.1.1 Anelasticity as a source of uncertainty

According to our findings, the crust might be in near-solidus conditions in several areas. Thus, it can be argued that the overlook of possible (intrinsic) anelastic effects can lead to an unreliable estimate of absolute temperature. While it is true that near-solidus rocks can anelastically attenuate seismic waves, crustal domains have, in general, higher Q (Karato 1993), thus being less attenuating than the shallowest crust and the underlying mantle. Even in the case of a highly attenuating mantle domain, Cammarano & Guerri (2017) proved that the overall uncertainties on the V_S structure are greater than those arising by neglecting viscoelastic dissipation of seismic waves. It is worth noting that we use a V_S model built through the inversion of Rayleigh waves. Such surface waves are a combination of compressive and shearing motion and then are less attenuated than Love waves whose motion is purely of shear-type (Kovach 1978). In those areas with an anomalously hot crust, as the Tyrrhenian basin, earlier studies (Craglietto *et al.* 1989) suggested a $Q = 100$ for the entire lithosphere, compared to $Q = 250$–300 in the Apennine. Using eq. (5) in Karato (1993) (with $\alpha = 0.2$, $V_{\mathrm{arm}} = 3.8$ km s^{-1} and assuming a frequency-independent Q), a $Q = 100$ would translate in a 0.037 m s^{-1} (0.97%) decrease in V_S, which is roughly half the uncertainty on the inverted V_S at 35 km depth in the Molinari *et al.* (2015a) model. Therefore, the neglect of anelastic effects leads only to second-order uncertainty compared to the ambiguity of surface waves inversion. As an example, at 35 km depth a $V_S = 3.8$ km s^{-1}, with an estimated uncertainty of $\sigma = 0.063$ km s^{-1} (Molinari *et al.* 2015a), would translate into a temperature range of 507–637 °C. However, uncertainty as such does not invalidate the characteristics of the thermal structure we highlight, since spatial patterns (and their interpretation) would be preserved. Possible values of $Q < 100$ in the upper crust of volcanic regions can lead to a substantial anelastic decrease of V_S. However, by considering only lower crustal velocities, we avoid the temperature inference to be biased towards higher values due to the overlook of anelastic effects.

3.2 A newly imaged thermal anomaly in NW Italy

The anomalies discussed so far well agree with the volcanism, heat flow anomalies, the tectonic and geodynamic setting of the Italian peninsula and neighbouring regions. Interestingly, we also identify a new, minor anomaly in correspondence of northwestern Italy (Piedmont region). Here, we obtain a Moho temperature exceeding 800 °C at ∼25 km depth. This region is sandwiched between the Alpine chain to the west and the Apennines to the east, with a Moho

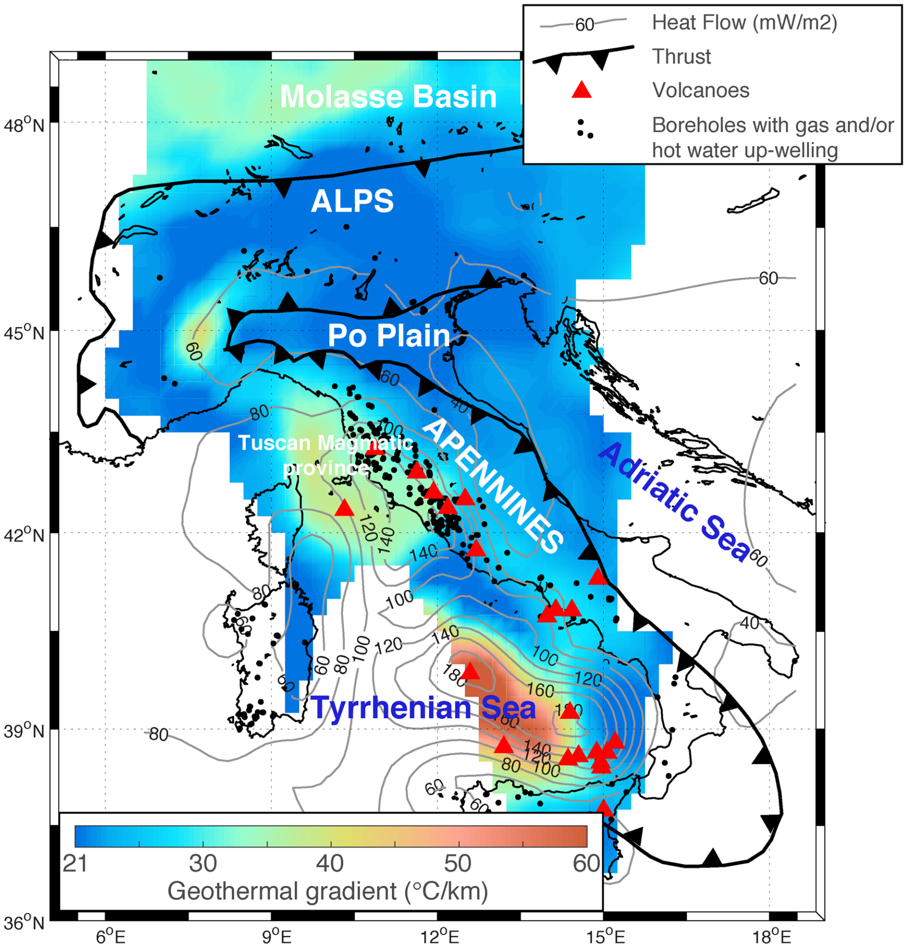

Figure 4. Map of the geothermal gradient inferred from thermodynamics using shear-wave velocities. High values (>40 °C km^{-1}) are found in the Tuscan and Tyrrhenian magmatic provinces. Relatively hot gradients are also found in the Molasse basin and in the Piedmont region, at the junction between the Apennines and southern Alps thrusts .

that rapidly deepens at >40 km depth at both sides. The reported heat flow is not anomalous and did not motivate any assessment for the geothermal potential of the area. Assuming a purely conductive heat transfer (Chapman 1986), the average heat flow in the area ($\sim$65 mW m^{-2}, see Fig. 3) implies 680 °C at the Moho, around 100 °C lower than our estimates. We speculate that the reason for such discrepancy can be ascribed either to (i) the inadequate assumption of pure conductive heat trasfer or (ii) to an underestimated heat flow that, obtained through an insufficient number of boreholes, fails to represent the complexity of the area with its several, but localized, hot fluids ascend (Dominco *et al.* 1980). Both the hydrogeological and geochemical characteristics of the localized thermal springs in the area seem to support our observations. The hydrothermal system of Acqui Terme, with a water outlet of 9 l s^{-1} at 70 °C (Dominco *et al.* 1980), is located on the southern border of the thermal anomaly we discovered. Geochemical evidence suggests that the fluids originate from a geothermal reservoir at 2–3 km depth and 130–140°, and, while ascending, cool down by mixing with percolating meteoric water (Marini *et al.* 2000). The reservoir is trapped underneath a sequence of tertiary marine sediments (comprising gypsum-bearing evaporites) that acts as an effective seal (Marini *et al.* 2000). Sparse local springs (such as Acqui Terme) occur, therefore, only where permeability increases, that is, along localized NW and W-trending, normal and strike-slip faults (Piana *et al.* 1997) that cross the entire sedimentary overburden. Our temperature estimates agree with the bottom-hole temperatures of the few boreholes drilled for oil and gas exploration (ViDEPI—http://unmig.sviluppoeconomico.gov.it/videpi/videpi.asp), indicating medium to high geothermal gradients that are compatible with our findings. For example, a temperature of 109 °C at 3802 m is found at the 'Sommariva del Bosco 001' borehole (gradient: 28 °C km^{-1}). In 'Valghera 001', at 732 m the registered temperature was 34 °C. In conclusion, our findings would suggest the necessity of more in-depth studies of the area for clarifying the origin of its thermal anomaly and its implication in the context of the transition from the Alpine to Apenninic orogen. Vignaroli *et al.* (2008) propose that this area and the nearby Voltri Massif on its southern side have undergone a substantial extension during the counter-clockwise migration of the Apenninic front, favoured by the toroidal flow of the asthenospheric mantle during the roll-back of the Adriatic slab.

A compositional rather than a thermal anomaly causing the low V_S in the Piedmont area cannot be fully excluded. Speranza *et al.* (2016) imaged a large magnetic anomaly (>50 nT) that is explained with the presence of a large serpentinized body at shallow depth. Since V_S and V_P decrease with the degree of serpentinization

(Christensen 2004), such metamorphism may explain the low velocities seen in this area (Molinari *et al.* 2015a; Zhao *et al.* 2015). Coincidentally, the latter interpret such low velocities as indicative of a serpentinized Adriatic mantle ('Ivrea Body', Closs & Labrouste 1963) reaching crustal depth, above the subducting continental slab of the European Plate. In this scenario, the role of temperature can still be relevant, though of second order. In fact, Speranza *et al.* (2016), after filtering out the magnetic effect induced by the shallow serpentized body, retrieved shallow Curie temperature ($\sim$550 °C) that implies high geothermal gradients ($>$40 °C km^{-1}), comparable to those we obtain from seismic velocities and thermodynamics. Such temperatures can be explained with the upraised geotherms due to the emplacement of the Adriatic mantle at crustal depth. Thus, the existing geophysical evidence and our finding does not seem contradictory and suggests a mixed contribution of lithological and temperature-driven effect in generating low seismic velocities in the Piedmont region, owing to its peculiar position in the context of the Alpine–Apennine transition.

3.3 Varying thermal structure along strike: the case of the Apennine orogen

With the envisioned thermal structure across the Apennine chain, several observations can be made in the context of the geodynamic evolution of the area. The transition from the Central to Northern Apennine (slightly above the 44° parallel) is accompanied by a decrease in the Moho temperature (around 100°), while its depth remains the same ($\sim$40 km) along the orogen front. Consequently, the geothermal gradient decreases northwards by 3–4 °C km^{-1}, reaching values as low as 19 °C km^{-1} within the Po Plain, where the front of the thrust is underneath a thick sedimentary cover (Molinari *et al.* 2015b). This is the only part of the Apennine system where the subduction of the Adriatic slab is ongoing, as suggested by the compressive seismicity and geological evidence (Doglioni *et al.* 1999; Chiarabba *et al.* 2005; Minelli & Faccenna 2010; Bennet et al. 2012), with an overall convergence rate in the order of mm yr^{-1} (Picotti & Pazzaglia 2008). Faccenna *et al.* (2001) have shown that the entire Apennine subduction system must have decreased its convergence velocity from a peak of few cm yr^{-1}, when the oceanic crust was entirely consumed and more buoyant continental crust started to be subducted. Such a low convergence rate must enhance the heat transfer by conduction through the lithosphere, rebalancing the isotherms [once depressed due to the subduction of the cold slab (Peacock 1996)] and gradually increases the geothermal gradient. This scenario is consistent with the geothermal gradients we observe, being substantially higher than those inferred for the initial, fast-convergent stage of the Apennine subduction.

What is the fate of a subduction system when the positively buoyant continental crust can be no longer subducted? The answer can be found southwards, in the Central Apennines, where we find higher crustal temperatures and hotter geothermal gradients. The current seismicity suggests an extensional regime connected to the uplift of the entire area. Slab break-off might have occurred, or subduction might have culminated in the delamination of cold lithospheric material (Wortel & Spakman 2000; Gvirtzman & Nur 2001). The higher geothermal gradients that we observe along strike seem to favour the latter scenario. Indeed, the foundering of the cold, gravitationally unstable lower lithosphere might have led to the upward and eastward migration of hot asthenospheric material, increasing temperature underneath the orogen and explaining the thermal anomaly at the Moho ($>$100 °C). Regarding temperature-driven gravitational instability, Jagoutz & Behn (2013) and Jull & Kelemen (2001) showed that if the temperature at Moho is $>$900 °C, a density contrast $\leq$300 kg m^{-3} can lead to the foundering of 1–10 km of lower crust in a 1–10 Ma time window due to the activation of vertical viscous flow. This implies that a hot orogen might be affected by the delamination of dense portion of the deep crust into a more buoyant upper mantle. This process might be particularly evident in the thickest portion of the orogen where the Moho depths exceed 45–50 km and the density of lower crust reaches the highest values ($>$3000 g cm^{-3}, according to our thermodynamic calculation).

A mantle wedge that is closer than expected to the chain has been recently pointed out by Piana Agostinetti & Faccenna (2018) through the analysis of active/passive seismic data. However, while the role of asthenosphere in contributing to the thermal structure and uplift of the Central Apennine might remain speculative, the extent and characteristics of the nearby Tuscan Magmatic province must invoke a deep source of heat. As a matter of fact, the strong attenuation (Mele *et al.* 1996), low V_P (Di Stefano *et al.* 2009), high heat flow (Della Vedova *et al.* 2001) and the relevant thermal anomalies we observe suggest an upwelling of hot asthenosphere (reaching depths as shallow as $\sim$50 km), the same that might pervade eastwards, intrude and replace the delaminated portion of the lower crust underneath the Central Apennine orogen.

4 CONCLUSIONS

We used shear wave velocities and thermodynamics to retrieve the thermal structure of the crust in the Italian peninsula, presented in terms of temperature at the Moho and geothermal gradients. Our methodology helps remedy the data scarcity and other limitations of temperature extrapolation from heat flow measurements.

The highest Moho temperatures are found at the base of the thick crust along the Alps and Apennines, a scenario that reconciles with the attenuation of refracted Pn phases observed in other studies.

Using the average $\sim$21 °C km^{-1} geotherm as a reference, we have imaged the zones of anomalously high temperature at the Moho. These regions correspond to the well-known magmatic Italian provinces, namely, the Tuscan area and the Tyrrhenian basin. We also highlight a thermal anomaly at the base of the crust in the Molasse basin (Southern Germany), known for its relevant geothermal potential.

We find the smallest, yet relevant, anomaly in the Piedmont region (NW Italy), at the transition between the Alpine and Apennine belts. This zone is not regarded as a potentially interesting location for geothermal exploitation. However, well-documented hot-fluid upwelling and hydrogeological evidence indicate a geothermal gradient that is higher than the average for the Italian peninsula. The hypothesis of a thermal anomaly does not contradict the possible presence of a shallow serpentinized upper mantle that, besides the high crustal temperature, might contribute to explaining the low seismic velocities recorded.

Crustal temperatures increase moving southwards along the Apennine chain. This can be an evidence of the ceased convergence along the central Apennine, as opposed to the northern Apennine where the cold slab is still slowly subducting. In spite of the apparently strong assumption of a chemically homogeneous lower crust for the thermodynamic calculation, our approach has shown the capability of imaging lateral variation of the crustal thermal structure of the Italian peninsula. In view of the geologic and tectonic complexity of the studied area, we foresee that our methodology can be applied also to other regions. Our approach can bypass the limitations and scarcity of heat flow measurement, and contribute towards a better understanding of crustal behaviour, evolution and relation with the mantle underneath and neighbouring plates.

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