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Data integration and conceptual modelling of the Larderello geothermal area, Italy

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Abstract

In the frame of the Integrated Method for Advanced Geothermal Exploration (IMAGE) Project, a reliable exploration and resource assessment workflow was implemented on the basis of an integrated and multidisciplinary approach. Our study addressed to a better understanding of the thermal structure of the deepest part of the Larderello geothermal field (Southern Tuscany, Italy) by integrating structural, geological, geochemical, geochronological, petrological and geophysical data. With the aim to characterize the reservoir located nearby an important seismic reflector (the K-horizon), we systematized the available data and, successively, we applied a numerical thermal modelling approach to test our hypotheses and concepts.

Keywords: data integration; conceptual modelling; geothermal reservoir; heat source; Larderello area

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1. Introduction

Due to the growing interest in the technological development of unconventional geothermal resources, interdisciplinary geoscientific activities have been focused on the southwestern part of the Larderello-Travale Geothermal Area (LTGA), i.e. the Lago Boracifero locality, also referred as Lago area (Fig. 1). In the LTGA, two main geothermal reservoirs exist: the “shallow reservoir” hosted in the evaporite-carbonate units (about 0.7 – 1.0 km b.g.l. on average and with temperature from 150°C to 260°C) and the “deep reservoir” hosted in the metamorphic succession and Neogene granitoids (about 2.5 – 4.0 km b.g.l. and with temperature from 300°C to 350°C) [1,2]. Fluids dominantly of meteoric origin at vapor phase circulate in both reservoirs [3]. The meteoric recharge occurs through the carbonate outcropping formations; besides a lateral input from the regional aquifers surrounding the hydrothermal reservoirs is also assumed, presumably induced by the actual exploitation process [2,3].

In the Lago area, the occurrence of high temperature and high pressure fluids hosted below the hydrothermal systems currently under exploitation has been established in the frame of a deep exploration program carried out in the early 1980s. In particular, the San Pompeo 2 well encountered fluids with a temperature > 400°C and reservoir pressure far above 24 MPa, in a fractured zone at about 2900 m [4]. The main objective of this well was to verify whether exploitable fluids exist in correspondence to the anomalies detected by reflection seismic surveys. In fact, the 2D and 3D seismic exploration activities carried out in the last decades provided evidences of two distinct seismic markers, referred to as “H-horizon” and “K-horizon”, discontinuously characterizing the entire LTGA. Drilling data show that in some cases (especially in the Travale area) the H-horizon is located in correspondence of the thermo-metamorphic aureole of Neogene granitoids [5] and many wells produced super-heated steam from this level. The deeper K-horizon has similar amplitude pattern, but locally showing bright spot features, and a more continuous spatial extension with respect to H-horizon. The nature and the origin of the K-horizon are still under debate [4,6,7], as it has not yet been drilled with the presumable exception of the San Pompeo 2 well. The thermobaric conditions extrapolated at this level (P ≈ 30 MPa and T > 400°C) do not seem to be compatible with the deep geothermal reservoir so far exploited characterized by a sub-hydrostatic pressure controlled by its current super-heated steam condition [2]. In order to improve the understanding of the physical conditions in the zone corresponding to the K-horizon, we systematized the available information from different geoscientific sources, briefly discussed in the following.

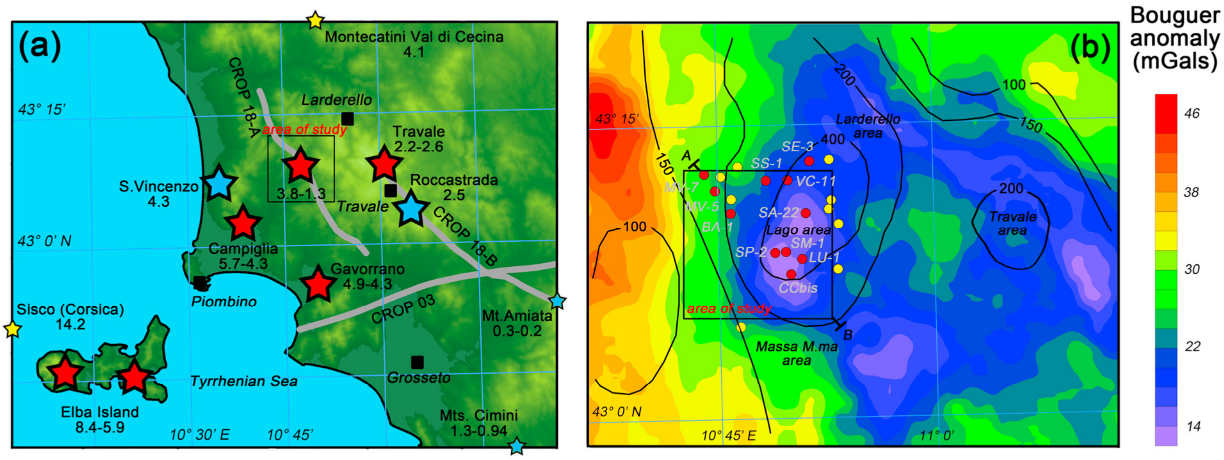

Fig. 1. (a) Location of the area of study. The sub-volcanic mafic (yellow stars), acid intrusive (red stars) and extrusive (cyan stars) centers and their ages (in Ma) are showed. The out-of-area magmatic sites referred to in the text are also reported (small stars) along the map borders; (b) Bouguer anomaly map of the Larderello-Travale Geothermal Area together with the heat flow isolines of the regional anomaly (in mW/m^2, modified from [20]). The studied boreholes and the NW-SE cross-section (A–B) are reported. Red circles are the deep wells of Table 1 (BD-1: Badia 1, CCbis: Carboli CBIS, LU-1: Lumiera 1, MV-5: Monteverdi 5, MV-7: Monteverdi 7, SM-1: San Martino 1, SP-2: San Pompeo 2, SA-22: Sasso 22, SE-3: Selvaccia 3, SS-1: Serrazzano Sperimentale 1 and VC-11: Valle Cornia 11). Yellow circles are additional wells used for the reconstruction of the Neogene-Pleistocene composite granitoid.

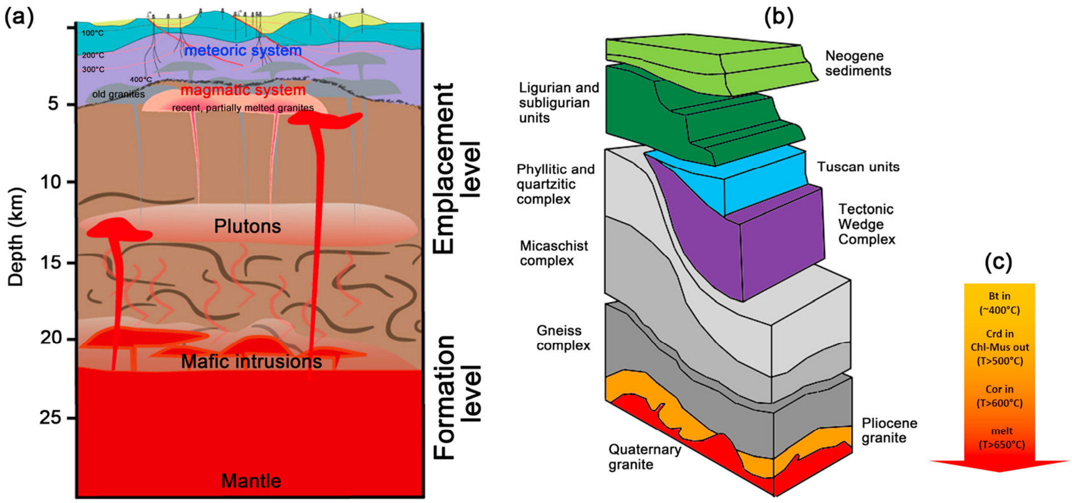

Fig. 2. (a) Schematic crustal section below Larderello-Travale Geothermal Area and magma emplacement conceptual model, (b) structural-stratigraphic framework and the modelled geological surfaces, (c) Temperature evidences from the mineral assemblage of the Plio-Quaternary HT-LP metamorphism (Bt: Biotite, Crd: Cordierite, Chl: Chlorite, Mus: Muscovite, Cor: Corindum).

Table 1. $^{40}Ar/^{39}Ar$, K/Ar and Rb/Sr ages of Larderello biotite (Bt), Muscovite (Mus) and Tourmaline (Tour) of Metamorphic (Met) or Magmatic (Mag) origin. The available in-hole temperatures (T) are also reported.

Well	Depth (m)	T (°C)	Age (Ma)	Method	Mineral	Reference
Badia 1	3450		1.6	$^{40}Ar/^{39}Ar$	Met. Bt	[31]
Carboli CBIS	4200	425	1.2	$^{40}Ar/^{39}Ar$	Mag. Mus	[32]
Carboli CBIS	4304	425	1.3	$^{40}Ar/^{39}Ar$	Mag. Mus	[32]
Lumiera 1	2237		3.3	$^{40}Ar/^{39}Ar$	Met. Mus	[33]
Monteverdi 5	2843	330	3.8	$^{40}Ar/^{39}Ar$	Mag. Bt	[34]
Monteverdi 7	3483	335	3.8	K/Ar	Mag. Bt	[35]
San Martino 1	2722		3.0	$^{40}Ar/^{39}Ar$	Met. Bt	[31]
San Pompeo 2	2718		2.5	$^{40}Ar/^{39}Ar$	Met. Mus	[33]
San Pompeo 2	2962	> 420	1.3	K/Ar	Hyd. Tour	[36]
San Pompeo 2	2962	> 420	1.6	K/Ar	Hyd. Bt	[36]
Sasso 22	2502	350	3.1	K/Ar	Met. Bt	[37]
Sasso 22	2636		3.5	K/Ar	Met. Bt	[37]
Sasso 22	3530		3.3	Rb/Sr	Met. Bt	[37]
Sasso 22	3800		3.2	K/Ar	Met. Bt	[37]
Sasso 22	4028	400	3.1	Rb/Sr	Met. Bt	[37]
Selvaccia 3	3506		3.6	$^{40}Ar/^{39}Ar$	Met. Bt	[33]
Serrazzano Sperimentale 1	2242	280	1.6	Rb/Sr	Met. Bt	[37]
Serrazzano Sperimentale 1	2242	280	2.5	K/Ar	Met. Bt	[37]
Valle Cornia 11	2946	340	2.9	K/Ar	Met. Bt	[36]

2. Magma emplacement conceptual model

The geothermal anomaly characterizing the LTGA should be therefore framed in the magmatic and tectonic evolution of the inner Northern Apennines, also characterised by the so-called Tuscan magmatic province [10]. It consists of a series of mafic to acid intrusive and extrusive centers scattered through the southern Tuscany and the Tuscan archipelago (Fig. 1). The emplacement time spans from 14.2 Ma at Sisco (Corsica) to 0.3 – 0.2 Ma at Mt. Amiata (Italy). Due to the spatial and temporal evolution of the post-collisional phase of the inner Northern Apennines, the two monzogranitic plutons partially exposed in the western (Mt. Capanne, 6.9 Ma old) and eastern (La Serra-Porto Azzurro, 5.9 Ma old) sectors of the Elba Island represent an exceptional example of exhumed fossil geothermal systems developed from the cooling of plutonic masses. As the granitic intrusions are supposed to be the primary heat source of the deep-seated geothermal systems in southern Tuscany, in the frame of the IMAGE Project several structural, petrological and fluid inclusion studies have been performed in the Elba Island, as a proxy of the actual geothermal system of Larderello [11].

Fieldwork and laboratory analyses provided data for the fossil magmatic system, e.g. fracture networks and relation with the mineralization in the hosting rocks, the physical (temperature and pressure) conditions and the composition of the fluids circulating from the early magmatic until the final hydrothermal stages. These data represented essential constraints to perform a geothermal characterization of the actual magmatic system existing below the Larderello area. In this context, a conceptual model of magma emplacement has been refined and a schematic crustal section representative of the LTGA is shown in Fig. 2.

The variable partial melting of the mantle is responsible for the successive injections of mafic magmas into the continental crust, which in turn induced an increase of isotherms, crustal anatexis and a variable degree of mafic-acid magma mingling. The produced hybrid melt emplaced at middle-crustal levels (the "Plutons" in Fig. 2) and fed the magmatic system. The intermittent injections of mafic magma through the entire crust furnished the heat to sustain the prolonged cooling time at the different emplacement levels.

Considering the tectonic and magmatic framework in which the actual geothermal system is located, the Larderello magma source is assumed to fall in this general context, although the granite samples reached through boreholes do not exhibit petrographic, geochemical or isotopic features indicating a mass contribution of mantle-derived magmas. These latter are, however, suggested by the mantle signature of He isotopes data [12] and the findings of hybrid granites with mafic enclaves, or mafic intrusive bodies in future drillings cannot be ruled out [10].

3. Geothermal exploration proxies

In our study, the characterization of the structural setting represented a key activity. We realized in Petrel environment a 3D geological model, covering an area of 14 × 14 km^2, by the integration of the available stratigraphic, structural and seismic information [13]. The structural-stratigraphic framework as well as the modelled geological surfaces are summarized in Fig. 2. The geological and structural setting results from the interplay among thinning of the previously over-thickened crust and lithosphere, extensional tectonics and magmatism. The 3D reconstruction of the shallow geological structures was based on seismic profiles, borehole data from the National Geothermal Database [14], structural and geological information, whereas the main deep crustal features have been constrained by active source seismic data acquired within the CROP Project [15,16], seismic tomography, magnetotelluric survey [17,18], Bouguer anomaly [19] and heat flow data. The geophysical observations allowed to set the depth of the Mohorovičić discontinuity around 22 – 25 km [20 and references therein] and to estimate the lithosphere to be about 40 km thick [21]. The effects of regional extension, magmatic intrusion, uplift and fluid circulation are responsible for the high background heat flow in the order of 200 mW/m^2 (Fig. 1) with two main local maxima, one centered close to the Lago and Larderello areas (up to 1000 mW/m^2), and another (up to 500 mW/m^2) in the Travale area, to the east of Larderello [22].

The seismicity of the LTGA has a low magnitude (< 3) and a cut-off depth set at about 8 km (although few events have a hypocentral depth of 10 – 15 km). The maximum peak hypocenter distribution exhibits positive correlation with the K-horizon and due to the high temperatures (i.e. > 400°C), this reflective horizon was interpreted as a kinematically active rheological boundary separating the upper brittle from the lower ductile crust [23]. Recent 3D microearthquake tomography [24,25] imaged the seismological parameters (the Vp, Vs structure and the deduced Vp/Vs, Vp × Vs anomalies) in the first 8 km of the crust. The K-horizon lies within a low Vp zone; some earthquake clusters are visible within the underlying high velocity (Vp) structure. The low Vp/Vs values dominating the exploited hydrothermal reservoir are interpreted as due to steam-bearing formations, whereas other higher and sparse Vp/Vs values at shallow depths and characterized by low Vp ×Vs, are probably related to either condensation or recharge zones. The analysis of the Vp ×Vs image suggests that the K-horizon [23] delineates a transition zone towards formations with a relatively lower crack accumulation and/or porosity. Despite no high Vp/Vs ratios have been identified along the K-horizon, the presence of overpressurized fluids cannot be ruled out due to the inherent resolution of the tomography images. A middle-crustal low velocity body (LVB) in the centre of the geothermal area was inferred by tomographic inversions of teleseismic and local earthquakes. The top of the LVB is constrained at about 10 km depth by a reduction of the bulk velocity of the order of 15 – 18 % as inferred by teleseismic travel-time residuals [8] and by a low (< 5 km/s) Vp anomaly [9]. The Bouguer anomaly map (Fig. 1) highlights a wide low gravity anomaly with values lower than 25 mGals that encompass the whole LTGA, with local gravity minima of 15 mGals (e.g. in the Lago area). In spite of the dense carbonate formations outcropping in the area, a deep and low-density source is required to justify this gravity anomaly. Several authors [e.g. 26,27] recognized, in the CROP (deep crustal) reflection seismic profiles, zones with homogeneous velocity distribution and low contrast of acoustic impedance (i.e. transparent areas). The shallow transparent areas have been associated to felsic magmatic bodies, also encountered in local geothermal boreholes, whereas the deep transparency correlates with the top of the LVB (Fig. 3). Furthermore, the inversions of previously and newly acquired MT measurements [28,29] revealed a deep low resistivity anomaly in correspondence of the LVB (Fig. 3). The LVB may be interpreted as the occurrence of a hot (low density and low velocity), partially molten (conductive), isotropic magma body (transparent seismic facies) emplaced at middle-crustal level.

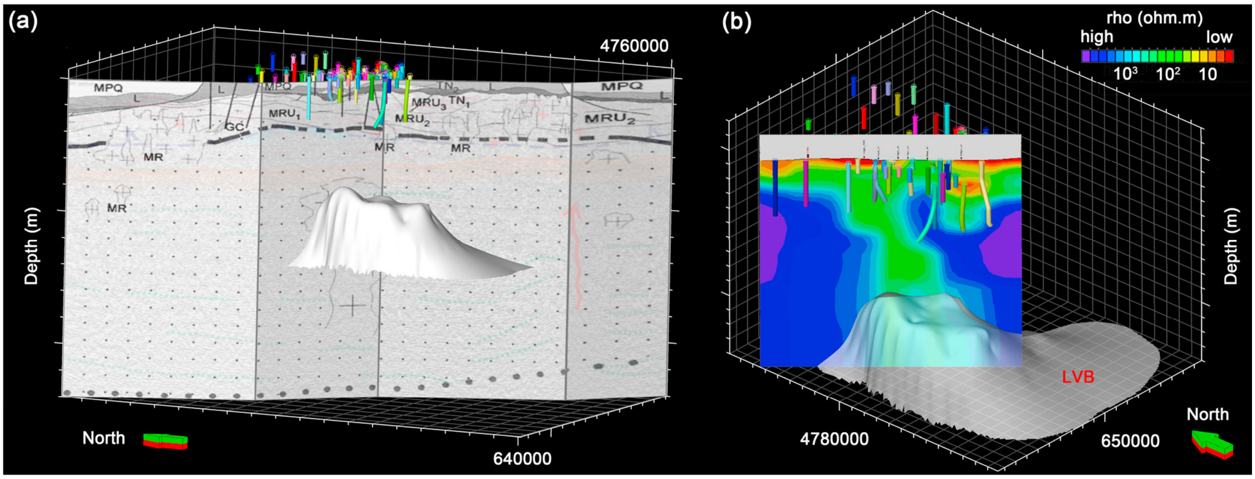

Fig. 3. (a) Portion of the interpreted CROP 18-A seismic section; (b) resistivity structure along the NW-SE section (A-B) in the area of study (see Fig. 1). The Low Velocity Body (LVB, velocity model from [8]) and the studied deep boreholes are also reported.

At Larderello Neogene-Pleistocene granitoids were drilled within the metamorphic basement in some deep wells. The granite emplacement produced thermo-metamorphic aureoles with characteristic mineral assemblages (Fig. 2) as function of the distance from the heat source and type of the hosting rock [30]. The granitic system can be described as a magmatic complex built up over an approximate time span of about 2.5 Ma (from 3.8 to 1.3 Ma) by multiple intrusions of isotopically and geochemically distinct anatectic magmas. In Table 1 the available geochronological data are summarized (see Fig. 1 for borehole locations). A reconstruction of the Neogene-Pleistocene composite granitoid is here proposed based on the occurrence of a thermal metamorphic rim in deep drillings and direct evidences of drilled dikes and/or laccolites (Fig. 4). The characterization of fluids trapped as inclusions above the studied magmatic system (Elba Island and Larderello) gave indications on their sources (magmatic, metamorphic and meteoric) and useful information regarding the evolution of the hydrothermal system.

In particular, the metamorphic (aqueous-carbonic) and magmatic (Li-rich brines) fluids, representative of the magmatic stage, were trapped under near lithostatic (74 – 135 MPa) and high temperature (420 – 650°C) conditions [10,30]). If the K-horizon origin is supposedly related to recent magmatic events, the early stage fluids of magmatic and thermo-metamorphic origin, as those studied in the fossil geothermal systems of the Elba Island and Larderello, image the actual, or very recent, physical condition determining the reflective horizon.

Table 2. Thermo-physical properties of rocks and melts used in the numerical simulation.

Lithothermal Units	Porosity	TC [W/(m K)]	Density [kg/m^3]	Heat Capacity [J/(kg K)]	Radiogenic Heat [μW/m^3]
Cover (Neogene & Ligurian)	0.1	2.5	2400	900	1.0
Tuscan	0.06	3.0	2700	850	0.5
TWC	0.05	3.5	2800	900	0.8
Metamorphic basement	0.01	3.0	2770	850	2.0
Intrusive bodies					
melt	-	2.5	2500	1300	-
solid	-	3.0	2650	850	2.0

4. Numerical modelling

Once a conceptual model consistent with the available data has been created, it can form the framework of a subsequent numerical model. Our initial numerical strategy was mainly based on the history matching of the detected past thermal climax controlled by the Neogene-Pleistocene magma input, in order to forecast the present-day temperature distribution around a hypothetic, and very recent magmatic intrusion (but similar in size, emplacement temperature and other physical characteristics) at a depth of the order of 2.5 – 5 km. We used a 3-D thermal model that numerically simulates the temperature variations in a layered crustal section, induced by the occurrence of intrusive bodies over a time span of 5.3 Ma (Fig. 4). The thermal evolution of the model is governed by the heat transfer equation:

$$\rho C_p \frac{\partial T}{\partial t} = k \nabla^2 T + A + Q \tag{1}$$

where ρ is the density, C_p is the specific heat, T is the temperature, t is the time, k is the thermal conductivity, A is the radiogenic heat generation and Q is the magmatic heat source. The heat equation is solved by the FEM method and we applied specific temperature-dependent thermal properties to the rocks [38] (Table 2), a constant surface temperature, a fixed heat flux at the base of the model (70 mW/m^2) and a temperature-dependent heat flux across the intrusion boundaries. The latter is calculated according to Newton's law of cooling [39]:

$$Q = h \cdot \left(T_{mag} - T\right) \cdot f(t) \tag{2}$$

where Q is the heat flux, h is the convection heat transfer coefficient, T_{mag} is the magma emplacement temperature and T is the external temperature. Distinct heat sources, located inside the modelled domain (Fig. 4), provided the thermal loading. The duration of each magmatic event is modelled multiplying the heat source term (Eq. 2) with an arbitrary pulse function $f(t)$ (Table 2). Since the end of the magmatic event, the release of latent heat of crystallization (L) has been taken into account by incorporating an effective specific heat (C_{eff}) instead of the true specific heat (C_p) for the temperature interval of crystallization (ΔT_m):

$$C_{eff} = C_p + \frac{L}{\Delta T_m} \; . \tag{3}$$

The middle-crustal heat source (i.e. the LVB) was assumed active from the Pliocene to the present time. We supposed that the heat sources could maintain themselves by a continuous replenishment of heat induced by intermittent injections of mafic magmas from below. According to Dini et al. [10], the middle-crustal melts emplaced under lithostatic conditions for temperature close to 850°C. At shallow levels, the emplacement of the granitoids, nowadays cooled, took place through successive, randomly distributed, magma injections. In a first approximation, the emplacement of the Neogene-Pleistocene composite granitoid in the time interval 3.8 – 1.3 Ma was modelled as a single thermal event. Following our initial hypothesis, we assumed that the upper portion of the K-horizon mimics the shape of a recent intrusion and we positioned its top few hundred meters (i.e. 500 m) below the seismic marker. This intrusion emplaced below the Neogene-Pleistocene granitoids and induced a continuous heat input in the time interval 1.3 – 0.3 Ma. This recent magma body partially intruded the old granitoids as shown in Fig. 4.

Although the top surfaces of the crustal granitoids are constrained by direct and/or geophysical evidences, the bottom surfaces are highly undetermined. The uncertainties regarding the real volume of the granitoids influence the cooling time and the amount of latent heat released during the crystallization. Nevertheless, the main parameters controlling the thermal climax reached above the Neogene-Pleistocene granitoids are the distance from the top of the intrusive body and its emplacement temperature.

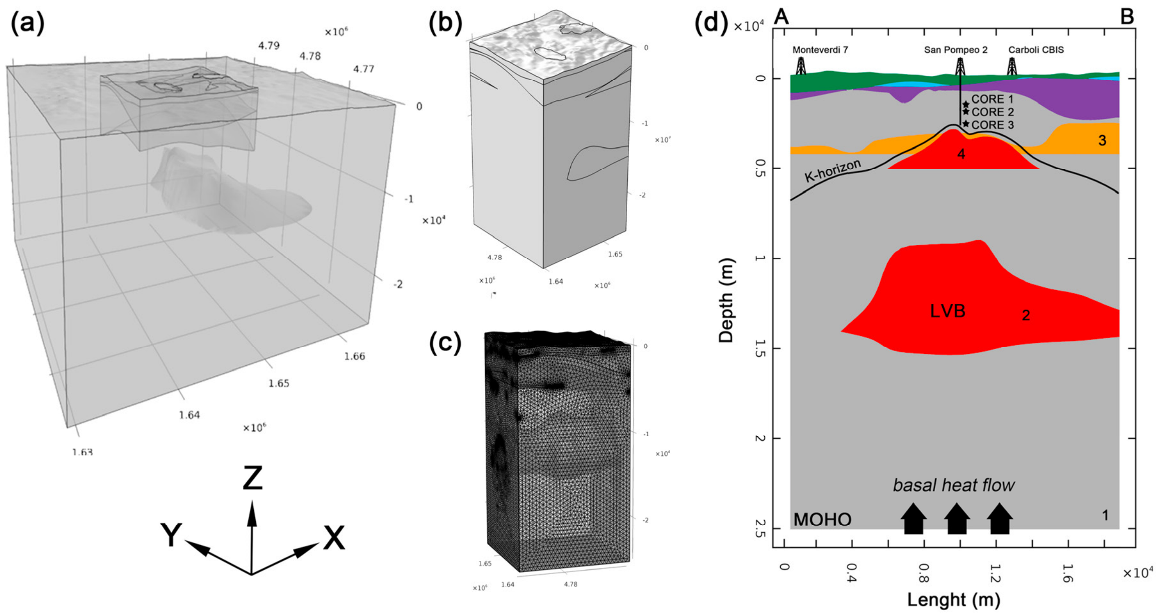

Fig. 4. (a) 3D view of the modelled domain beyond the volume of interest in order to avoid the effects of the finite, thermally insulating, lateral boundaries in the heat diffusion. (b) 3D geometry of the study area, (c) numerical mesh, (d) 2D section from the 3D model (profile A-B of Fig. 1). The heat sources are: 1) deep roof of the system, 2) middle-crustal granitoid, 3) Neogene-Pleistocene composite granitoid and 4) recent granitoid. The projected locations of some boreholes and the position of the core samples of San Pompeo 2 well are shown.

Table 3. Thermo-physical properties of melts and duration of magmatic events used in the numerical simulation.

Heat source properties	Duration (Ma b.p.)	Liquidus (°C)	Solidus (°C)	L (kJ/kg)	T_{mag} (°C)
Middle-crustal pluton	5.3 - 0	850	550	500	850
Shallow granites (old)	3.8 – 1.3	850	550	500	650
Shallow granites (recent)	1.3 – 0.3	850	550	500	650

The borehole temperatures measured along the San Pompeo 2 well in the metamorphic basement were used as thermal constraints to validate the numerical results to the actual time (Fig. 5). The thermal evolution was compared with the petrological information of three deep core samples, used as control points (core 1: –2189 m b.s.l., core 2: –2380 m b.s.l. and core 3: –2700 m b.s.l.), coming from the same well. Those metamorphic samples have characteristic mineralogical assemblages for increasing temperatures from 490±40°C (core 1 and 2) to 600±30°C (core 3). Fig. 5 shows the simulated temperature vs time for the three, above mentioned, control points. The present-day depth of the core samples does not correspond to the past position as the LTGA experienced an average Pliocene uplift rate of about 0.2 mm/yr [33]. Because of this uplift, the displayed temperature curves refer to the three control points that move upward during time. When the deep heat source emplaced 5.3 Ma ago at the middle-crustal level (10 – 15 km), it induced in the shallower levels (i.e. 2.5 – 3.5 km) only a smooth temperature increase of about 80°C in a time interval of 1.0 Ma. Successively, from 3.8 to 1.3 Ma, the shallow magma emplacement controlled the rapid temperature increase of the rocks and the attainment of the thermal climax. At the end of this phase, we assumed a new magma input, which continuously supplied heat for 1.0 Ma. The modelled temperature decrease is partially due to its slightly deeper emplacement level. Finally, the cooling phase during the last 0.3 Ma is responsible of the temperature decrease down to actual values of 350 – 400°C in the depth interval 2700 – 2100 m b.s.l.

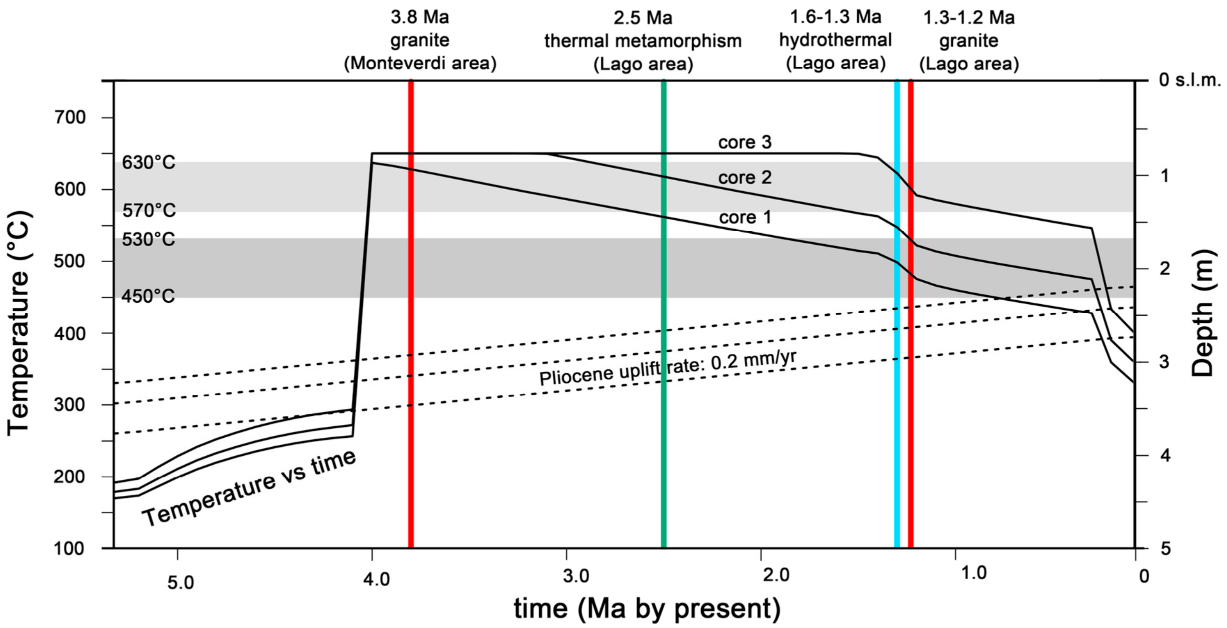

Fig. 5. Modelled thermal evolution of the area around the San Pompeo 2 well. Continuous lines are the temperature (left axis) vs time experienced by the core 1, 2 and 3 of the same well during the last 5.3 Ma. Dashed lines are the depth (right axis) vs time trajectories of the same core samples resulting from an average Pliocene uplift rate of 0.2 mm/yr. The ages of the main magmatic (red), thermo-metamorphic (green) and hydrothermal (cyan) events are also reported.

5. Conclusions

The developed conceptual model is a representation of the current best understanding of the studied geothermal system, consistent with all known data and information. The analysis of these geoscientific data allowed defining the main elements for the numerical model. Our basic numerical approach represent an initial model that can be refined and improved as more data becomes available. Actually, the validation procedure based only on the thermal and petrological data coming from the San Pompeo 2 well. Therefore, the results are representative of a sector around the selected borehole rather than the whole area of study.

The main conclusions are the following:

- The middle-crustal magmatic body, i.e. the LVB constrained by the geophysical data at about 10 km depth, cannot explain alone the observed thermal anomaly. The actual temperatures and the thermal climax recorded by the metamorphic cores rely to the emplacement of magmas at shallower levels (most likely in the depth range 2.5- 5 km).
- Although there is no direct evidence of the location of the actual magmatic intrusions, the measured temperature in the San Pompeo 2 well are consistent with the possible existence of a cooling magmatic intrusion that roughly mimic the shape of the deep seismic marker (the K-horizon).
- The study of the Elba Island granitoid, as a proxy of the Larderello deep-seated geothermal system, gave us the correct thermal constraints (e.g. the magma emplacement temperature) to develop our initial numerical model.
- Based on the numerical results, a temperature above the supercritical point nearby the K-horizon is envisaged.
- Although a continuous heat supply has been modelled, due to the average uplift rate of 0.2 mm/yr the core samples experienced a rather monotonous cooling from their thermal climax (3.8 Ma) to the present.

Acknowledgements

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