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Conductive heat flow pattern of the central-northern Apennines, Italy

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Abstract

We analyzed thermal data from deep oil exploration and geothermal boreholes in the 1000-7000 m depth range to unravel thermal regime beneath the central-northern Apennines chain and the surrounding sedimentary basins. We particularly selected deepest bottom hole temperatures, all recorded within the permeable carbonate Paleogene-Mesozoic formations, which represent the most widespread tectono-stratigraphic unit of the study area. The available temperatures were corrected for the drilling disturbance and the thermal conductivity was estimated from detailed litho-stratigraphic information and by taking into account the pressure and temperature effect. The thermal resistance approach, including also the radiogenic heat production, was used to infer the terrestrial heat flow and to highlight possible advective perturbation due to groundwater circulation. Only two boreholes close to recharge areas argue for deep groundwater flow in the permeable carbonate unit, whereas most of the obtained heat-flow data may reflect the deep, undisturbed, conductive thermal regime.

1. Introduction

The Apennines chain plays a key role to understand general tectonic concepts and deformation mechanisms within the Mediterranean region (Figure 1). The evolution of the chain from the late Oligocene to the present is characterized by migration of an accretionary wedge roughly northeast, accompanied since the late Miocene by a change of tectonic regime, from compression to extension (Malinverno and Ryan, 1986; Royden, 1993; Lavecchia et al., 2003; Pasquale et al., 2010).

The terrestrial heat-flow pattern can be considered as both a piece of evidence and an interpretive key of the processes that have occurred in this young and active deformation area. On the other hand, the thermal structure may play a fundamental role in controlling the physical properties and consequently the geodynamics of the lithosphere (see, Pasquale et al., 1993; 1997). Heat flow is the only observable geophysical quantity related to the thermal effects of the regional tectonics. This parameter is particularly difficult to deal with, because it may include both transient components related to the tectonic history and geological noise originated by a variety of shallow and deep processes, which can be of different origin and hide the deep conductive heat flow (e.g. Pasquale et al., 2012; Chiozzi et al., 2017).

The first heat-flow maps of Apennines and adjacent seas were published by Mongelli et al. (1991), Cataldi et al. (1995) and Pasquale et al. (1997). Later on, additional heat flow data were provided by the Geothermal Atlas of Europe (Hurtig et al., 1991) and by the compilation in the frame of the European Geotraverse Project (Cermak et al., 1992). These data were distributed unevenly and, sometimes, not corrected for the main thermal disturbing effects (sedimentation, erosion, uplift, subsidence, paleoclimatic change) that have affected the mountain chain and surrounding sedimentary basins. Moreover, data affected by groundwater circulation and igneous intrusion from recent magmatism were not filtered out.

Della Vedova et al. (2001) enlarged the database especially with new thermal data from hydrocarbon exploration wells and produced a map of the observed (uncorrected) heat flow. Furthermore, they attempted to obtain the deep heat flow pattern (undisturbed and conductive) by means of extrapolation thermal gradient of the deepest boreholes. However, no detail was given the distribution, number of data sets used for the inference of the deep heat flow pattern, assumptions on thermal conductivity and heat production of the sediment cover. Moreover, the effect of deep groundwater circulation is approached qualitatively. Therefore, the deep undisturbed heat flow is in some areas rather speculative.

A first effort to produce a heat flow map of the central-northern Apennines on the basis of data corrected for the main thermal disturbances was made by Pasquale et al. (2010). The database was extracted from Cermak et al (1992) and Pasquale et al. (1997), and all observations included corrections for blanketing caused by sedimentation, paleoclimatic variations

and topography. Moreover, the data that were suspected of being affected by underground water movements were rejected. However, data coverage along the Apennines chain was not particularly satisfactory, thermal conductivity information was scarce and temperature measurements from oil wells were roughly processed.

In this paper, we review the available thermal database from Pasquale et al. (2010) and analyze new available information deriving from deep temperature records, in the 1000-7000 m depth range, carried out in oil and conventional geothermal wells. We focus on the deepest temperature data similarly to what suggested by Della Vedova et al. (2001) as they may better reflect the undisturbed conductive thermal regime of the lithosphere. However, since most of available deep temperatures were measured in the permeable carbonate Paleogene-Mesozoic layers, the influence of the regional groundwater circulation on the thermal regime is investigated.

To treat thermal data recorded from deep wells we use a new approach as recently suggested by Pasquale et al. (2012 and 2014). This approach consists in rigorously selecting thermal data, i.e. rejection of boreholes with less than two temperature records at different depths and treating thermal disturbances due to drilling with a technique specifically calibrated for the Apennines foreland basins (Pasquale et al., 2008). A further improvement in data processing consists in estimating thermal conductivity by taking into account porosity and anisotropy variations with depth due to the overburden of the sediment and temperature effect. Moreover, the radiogenic heat from both natural gamma-ray logs and gamma-ray spectrometry measurements on core samples is evaluated. Both the revised and the new heat-flow data provide a new preliminary pattern of the terrestrial heat flow.

2. Geological setting and thermal data

The central-northern part of the Apennines chain (Figure 1) includes two main structural domains with different tectonic and geophysical features, resulting from the superposition of extensional deformation on a pre-existing compressional architecture: to the west, the Tyrrhenian domain (TD) and to the east the Adriatic domain (AD). TD is characterized by a thinned lithosphere, shallow seismicity (generally of extensional type) and volcanism. AD has thicker lithosphere and shows a complex seismic pattern. Under the chain axis, earthquakes occur in the uppermost crust along extensional faults, and light-moderate seismicity of compressive character takes place in the deep crust and at subcrustal depths. East of the chain, shallow seismic events, with strike-slip and thrust motions, suggest still active compression (e.g. Carminati and Doglioni, 2012; Chiarabba et al., 2014; Chiarabba and Gori, 2016).

Carbonate Paleogene-Mesozoic formations represent the major and widespread tectono-stratigraphic unit of the study area. They crop out mostly in the central-southern part, whereas to the north they are buried beneath Paleogene-Neogene siliciclastic sediments (Figure 1). The stratigraphic sequence along the Apennines chain axis as inferred from three deep drillings (Pieve Santo Stefano 1, Mt. Civitello 1 and Varoni 1) is depicted in Figure 2. From bottom to top, we find the Paleogene-Mesozoic layer, consisting of an Early Jurassic carbonate platform, overlain by pelagic limestones with subordinated marly levels (Jurassic-Oligocene) and evaporites (Late Triassic), constituted by alternating layers of anhydrites and dolomites (Burano formation). In well Pieve Santo Stefano 1, the Burano formation is interbedded with calc-alkaline andesitic volcanic products (Anelli et al., 1994;

Heinicke et al., 2006; Bicocchi et al., 2013), whereas in Mt. Civitello 1 and Varoni 1 wells, this formation is made up by a sequence of alternating sulphates (anhydrites and gypsum) and dolostones (e.g. Speranza and Minelli, 2014; Trippetta et al., 2013; Porreca et al., 2018).
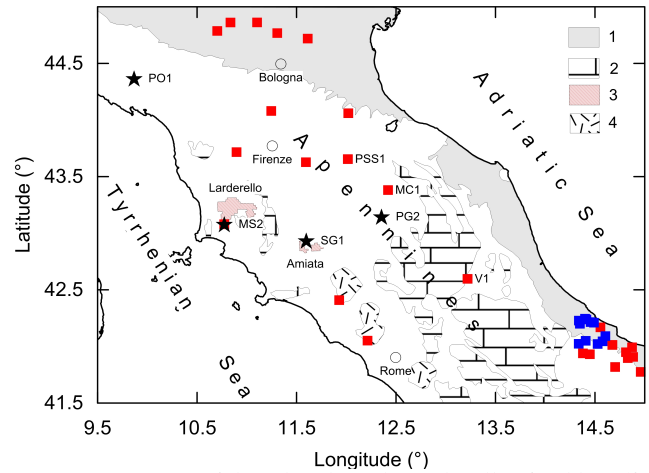

Figure 1 - Location of the oil and geothermal wells of Table 1 (full squares: blue from Pasquale et al. (2010) and red new wells). Pieve S. Stefano 1 (PSS1), Mt. Civitello 1 (MC1) and Varoni 1 (V1) wells shown in Fig. 2. Black stars indicate the wells drilled metamorphic basement: Pontremoli 1 (PO1), Perugia 2 (PG2), Massa 2 (MS2) and Seggiano 1 (SG1). 1 – Plio-Quaternary deposits; 2 - Pre-Pliocene carbonates exposed in the Apennine chain; 3 - Larderello and Mt. Amiata geothermal areas; 4 - major subaerial Quaternary volcanoes.

The Paleogene-Mesozoic unit is covered by the Paleogene-Neogene lithological group that includes the Messinian-Lower Pliocene sandstones (Laga flysch) and a thick marly succession, made generally from alternating layers of clays, sandstones and marls (referred to as Tuscan and Umbria units). In Pieve Santo Stefano 1, the stratigraphic sequence ends with the Ligurian units, consisting of Jurassic ophiolites covered by Cretaceous pelagites and Eocene calcareous flysch, crop out and piled up during the Miocene (Mirabella et al., 2008; 2011).

In both AD and TD domains, the thermal effects due to sedimentation, fluid circulation and thrusting may drastically change the temperature distribution in the uppermost few kilometers of the crust (e.g. Pasquale et al., 2012). Since groundwater flow, thermo-tectonic perturbations, such as sedimentation and overthrusting, still affect the thick sedimentary formations of the central-northern Apennines, we attempted to find thermal data from the crystalline basement, which should be under an undisturbed, conductive thermal regime. Besides detailed information on lithostratigraphy, temperature data for the central-northern Apennines and geophysical logs are directly available and consultable in the master logs of the ViDepi Project (http://unmig. sviluppoeconomico.gov.it) of the Italian Ministry of Economic Development and in the compilation of Agip (1977).

After a careful analysis of data sources, we found that the Permian crystalline basement was encountered in several geothermal wells in the geothermal areas of TD, which unfortunately are strongly affected by advective/convective heat transfer. Far from the geothermal fields, only four wells (Pontremoli 1, Perugia 2, Massa 2 and Seggiano 1) reached the metamorphic basement (Anelli et al., 1994; Bally et al., 1986; Figure 1), but only Massa 2 satisfies the condition that at least two temperature records are available and thus suitable for further analysis. Moreover, it must be stressed that, from the late Oligocene to the present, the Paleozoic crystalline

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basement of TD is generally affected by a change of tectonic regime, from compression to extension, which may have perturbed the thermal regime (e.g. Verdoya et al., 2005).
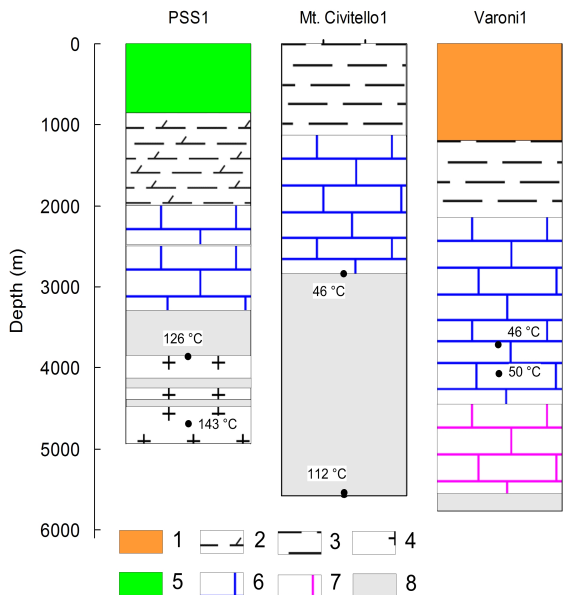

Figure 2 - Stratigraphic column of Pieve S. Stefano 1 (PSS1), Mt. Civitello 1 and Varoni 1 wells synthesizing the sedimentary sequence of the central-northern Apennines chain (see Fig. 1 for location). 1 – Laga flysch (syn-orogenic siliciclastic deposits, Upper Miocene–Pliocene); 2 – Tuscan siliciclastic units (Oligocene-Early Miocene); 3 – Umbria turbidites units (alternating layers of sandstones and marls, Miocene); 4 - volcanic andesites (Oligocene-Miocene); 5 – Ligurian units; 6 – Carbonate multilayer (early Jurassic-Oligocene); 7 – Triassic dolomites; 8 – Triassic evaporites (Burano formation). Full black circle corrected BHT.

Besides the foregoing databases, we reviewed the bottom hole temperature (BHT) data from oil wells reported by Pasquale et al. (2010). From this database, we selected only wells with at least two BHT records in the deepest geological formations drilled in the investigated area (Figure 1), which therefore were always measured in the deep carbonate layers. In summary, most of the deepest available temperature values were thus measured in the permeable carbonate Paleogene-Mesozoic formations, which may be affected by groundwater flow. After this selection, our database includes BHTs from thirty-four oil wells in the AD and temperature data from three geothermal boreholes in the TD (see Figure 1).

It is important to stress that some of the selected boreholes showed significant deviation from the vertical. Since master logs report the measured depth along the borehole path, in case of directional drilling it is crucial to correct the depth to obtain the true vertical depth. Among the existing methods, we applied the minimum curvature method that uses inclination and azimuth information. This method assumes a curved wellbore over the course length from one survey point to another (Burgoyne et al., 1991). Among the analyzed boreholes, the Suviana 1 well was the one more largely deviating from the vertical. After an approximately vertical section down to about 4 km, it deviated with a total displacement northward of about 2.2 km and a final inclination of 50° within the targeted carbonate horizon. Against a final measured depth of 7810 m, after the correction the true vertical depth was 7131 m. This correction increased the temperature gradient by about 5%.

Tables 1a and 1b lists the temperature data recorded in the Paleogene-Mesozoic unit, namely forty-three values of BHTs,

after correction for mud circulation, and seven values of stabilized temperature from geothermal boreholes. BHT data were corrected with two different approaches, depending on the information available in the well reports. For twenty-six temperature data, only one couple of BHT and shut-in time values, i.e. the time elapsed between cessation of the mud circulation and the temperature, was available. In this case, we inferred the formation temperature T with the empirical relation

$$T = BHT + (16.3z - 2.1\,z^2)ln\left(1 + \frac{1.7 + 0.05z + 0.10z^2}{t_e}\right) \quad (1)$$

where the shut-in time t_e is expressed in hours, depth z in kilometers, and for $t_e < 10$ hours an additional temperature correction of 2 °C is necessary (Pasquale et al., 2008). In general, the correction for the circulating mud ranged from 4 to 10 °C.

The remaining BHT data (sixteen values) were suitable for a classic Horner plot correction (Lachenbruch and Brewer, 1959) since a set of multiple temperatures measured at the same depths but at different times were available for each well. The temperature values corrected with this method were directly available on the master logs. For several boreholes, wherein mud circulation and shut-in time were also available, it was possible to crosscheck the correctness of the inferred formation temperature.

After correction, it clearly appears that, at any depth, there is a remarkable difference of the deep temperature between the TD and AD domains, and the temperature is higher in the Tyrrhenian domain (Table 1). Figure 3 presents the values of corrected temperature versus depth in the different domains. The difference increases with depth and, at about 3500 m depth, it can be as large as 200 °C. This means that the scatter of temperature is not caused solely by errors in BHT data, but it is likely caused by regional variation in thermal conditions across the investigated area.

In general, the thermal gradient in the Paleogene-Mesozoic carbonate formations (Figure 3) decreases from about 80mK m^{-1} in the Tyrrhenian domain to 20mK m^{-1} in the external side of the Adriatic domain. In particular, temperature pattern in the wells of the Tyrrhenian domain is linear, with the exception of well Certaldo 4, located near the external boundary of TD (Figure 1). In the Apennines chain, the temperatures are more scattered. In the northern sector of the belt, Suviana1, Pieve S. Stefano 1 and Pratomagno 1 wells provide a geothermal gradient of about 35mK m^{-1}, which is higher respect to that of Mt. Civitello 1 (24mK m^{-1}) and Varoni 1 (11mK m^{-1}), located in the central sector. In the external side of AD, the thermal gradient is of the same order of magnitude both in the northern (19mK m^{-1}) and in the south- eastern (18mK m^{-1}) sides.

3. Surface heat flow

Since the Paleogene-Mesozoic layer consists of carbonate, likely permeable, rocks, it might be affected by regional groundwater circulation. Consequently, we expect that the temperature measured in this layer might be affected by advection or convection. To investigate this hypothesis, we analyzed whether deviations from a purely conductive temperature-depth distribution occur.

Under steady-state heat conduction, through a horizontally layered Earth that includes heat production, the variation of temperature with depth can be determined with (Funnel et al., 1996):

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$$T = T_o + \sum_{i=1}^{n} \left(\frac{q_{i-1} \Delta z_i}{k_i} - \frac{A_i \Delta z_i^2}{2k_i} \right) \qquad (2)$$

where T_o is the surface ground temperature, $q_{i-1} = q_i + A_i \Delta z_i$, Δz_i, k_i and A_i are the thickness, thermal conductivity and heat production for the ith depth interval, q_i and q_{i-1} are the heat flow at the base and the top of the ith interval.

The *in situ* thermal conductivity, k_i, can be estimated by assuming the geometric mixing model and a decrease of porosity with depth z as proposed by Pasquale et al. (2017):

$$k_i = \left[1.8 + (k_o - 1.8) \left(\frac{1}{\alpha T + \beta} - \delta \right) \right]^{[1-(\phi_o \exp(-bz))]} k_w^{\phi_o \exp(-bz)} \quad (3)$$

where ϕ_o is the surface porosity, k_o the matrix conductivity at 20 °C, b the compaction factor, T the temperature and k_w the water thermal conductivity that is assumed to change with temperature as proposed by Deming and Chapman (1988). Values of coefficient α, β, δ are 0.002732, 0.7463 and 0.2485, respectively.

Using equations. (2) and (3), one can generate geotherms for specific values of surface heat flow, based on thermal conductivity and heat production assumed for each interval Δz_i=20 m. In this calculation, the only value that is unknown is the surface heat flow. The best estimate of surface heat flow can be found by minimizing the root-mean-square error RMSE between the calculated temperature and the corrected observed temperature.

Table 1a - Corrected temperature from oil boreholes and geothermal wells (Massa 2, Sabatini 9dir, Marta 3) measured in the Paleogene-Mesozoic carbonate formations (see also Figure 1). The different methods used to correct for mud circulation are also reported.
1 – new data; 2 - revised data (Pasquale et al., 2010).

Well	Latitude N	Longitude E	Elev. m	Depth m	Temp. °C	Temp. Correction	Ref
Bignardi 1	44.8623	11.1034	20	3330	78	Horner method	1
S. Giovanni 1	44.8615	10.8359	20	4193	87	Horner method	1
Bagnolo in Piano 3	44.7871	10.7031	31	4645	98	Horner method	1
Bagnolo in Piano 3	44.7871	10.7031	31	4996	103	Horner method	1
Spada 1	44.7679	11.3062	16	4263	102	Horner method	1
Suviana 1	44.0800	11.2458	670	6029	195	Horner method	1
Suviana 1	44.0800	11.2458	670	6491	214	Horner method	1
Sarsina 1	44.0601	12.0204	106	4757	108	Horner method	1
Sarsina 1	44.0601	12.0204	106	5763	134	Horner method	1
Certaldo 4	43.7165	10.8967	23	2644	114	Horner method	1
Pieve Santo Stefano 1	43.6547	12.0159	560	3878	126	Horner method	1
Pieve Santo Stefano 1	43.6547	12.0159	560	4708	143	Horner method	1
Prato Magno 1	43.6275	11.5943	680	4149	127	Horner method	1
Mt. Civitello 1	43.3814	12.4199	570	2828	46	Horner method	1
Mt. Civitello 1	43.3814	12.4199	570	5562	112	Horner method	1
Massa 2	43.0795	10.7734	220	1218	125	-	1
Massa 2	43.0795	10.7734	220	1618	143	-	1
Massa 2	43.0795	10.7734	220	2070	177	-	1
Massa 2	43.0795	10.7734	220	2548	211	-	1
Varoni 1	42.5972	13.2190	1160	3740	46	Horner method	1
Varoni 1	42.5972	13.2190	1160	4095	50	Horner method	1
Marta 3	42.4092	11.9288	345	1940	172	-	1
Marta 3	42.4092	11.9288	345	2530	197	-	1
Lanciano 1	42.2450	14.4000	250	2738	81	Pasquale et al. (2008)	2
Lanciano 1	42.2450	14.4000	250	2871	86	Pasquale et al. (2008)	2
Lanciano 2	42.2383	14.4133	242	2743	81	Pasquale et al. (2008)	1
Castelfrentano 5	42.2283	14.3383	144	2802	97	Pasquale et al. (2008)	2
S. Maria 1	42.2150	14.4567	136	2511	79	Pasquale et al. (2008)	2
S. Maria 2	42.2100	14.4900	20	2392	77	Pasquale et al. (2008)	2
Castelfrentano 6	42.2000	14.3483	328	2959	75	Pasquale et al. (2008)	2
Villanfonsina 1	42.1683	14.5550	175	3195	88	Pasquale et al. (2008)	1
Scerni 1	42.0915	14.6044	173	1761	68	Pasquale et al. (2008)	2
Sabatini 9dir	42.0512	12.2136	240	3318	300	-	1
Furci 2	42.0496	14.4067	283	1705	71	Pasquale et al. (2008)	2
Gissi 1	42.0450	14.5767	200	2225	79	Pasquale et al. (2008)	2
Bomba 2	42.0233	14.3367	357	1504	53	Pasquale et al. (2008)	2
S. Buono 1	42.0217	14.5267	227	2256	70	Pasquale et al. (2008)	2
Cupello 19	42.0133	14.6750	95	3136	88	Pasquale et al. (2008)	2
Cupello 19	42.0133	14.6750	95	4992	126	Pasquale et al. (2008)	2
Mt. Antico 1	41.9928	14.8728	166	1682	67	Pasquale et al. (2008)	1
Mt. Cilfone 2	41.9490	14.8117	200	2366	75	Pasquale et al. (2008)	1
Rosello 1	41.9386	14.3789	810	2966	75	Pasquale et al. (2008)	1
Messer Marino 1	41.9308	14.4484	765	3564	87	Pasquale et al. (2008)	1
Guglionesi 1	41.9072	14.8831	165	2365	69	Pasquale et al. (2008)	1
San Leucio 1	41.8968	14.8299	336	2456	73	Pasquale et al. (2008)	1
Castelmauro 2	41.8183	14.7027	690	3621	96	Pasquale et al. (2008)	1
Castelmauro 2	41.8183	14.7027	690	3729	105	Pasquale et al. (2008)	1
Rotello 2	41.7750	14.9600	310	2591	80	Pasquale et al. (2008)	1
Torrente Tona 1	41.7331	15.0781	197	1941	72	Pasquale et al. (2008)	1
Mt. Rotaro 2	41.6778	15.0724	192	2493	78	Pasquale et al. (2008)	1

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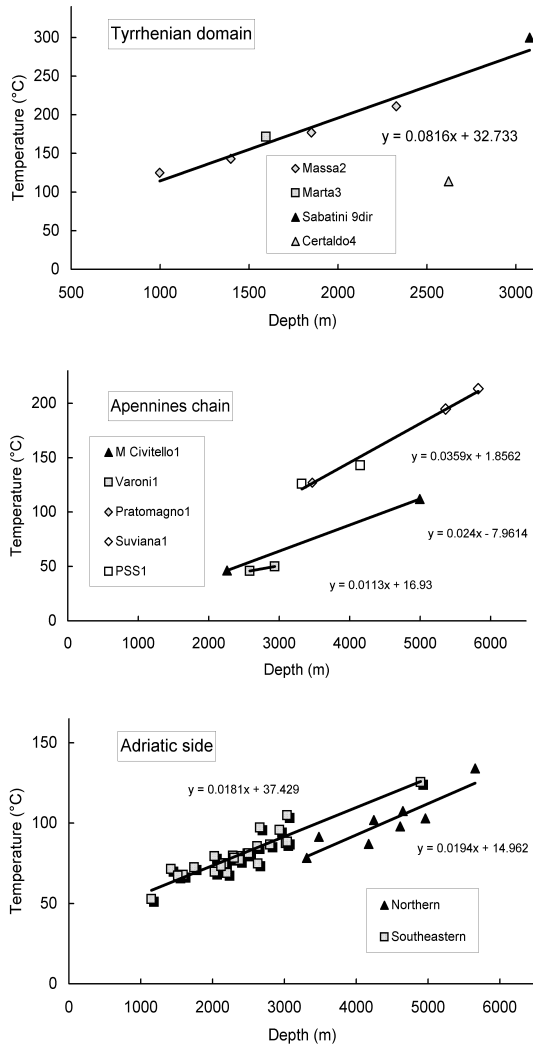*International Journal of Terrestrial Heat Flow and Applied Geothermics. VOL. 2, NO. 1 (2019); P. 37-45.*

Figure 3 - Plot of the corrected temperature vs. depth of the wells reported in Table1 of the Tyrrhenian domain and the Adriatic domain: Apennines chain, northern sector and southeastern sector of the Adriatic side. Temperature depths are referred to the sea level.

To infer whether the thermal regime is conductive or not, this approach requires at least two temperatures in the convective/advective layer to be available. From our dataset (Table 1) only eleven boreholes satisfy this requirement and were thus used in the analysis. For the surface ground temperature, we assumed that it is on average 3 °C warmer than the long-term mean annual air temperature (15 °C) in the investigated area (Costantini et al. 2013) and that temperature decreases with elevation at a rate of 0.7 °C/100 m (Powell et al., 1988). Values assumed for ϕ_0 and b (eq. 3) for estimating thermal conductivity were 0.180 and 0.396 km^{-1} in carbonate rocks and argillaceous limestones, 0.284 and 0.216 km^{-1} in sandstones calcarenites, 0.298 and 0.461 km^{-1} in marls and calcareous marls and 0.293 and 0.379 km^{-1} in clay, shale and silty clays, respectively. In case of clay lithotypes (e.g. Plio-Quaternary layers), anisotropy was taken into account according to the approach suggested by Pasquale et al. (2011).

To correct water and matrix thermal conductivity for temperature effect, we used a preliminary temperature gradient inferred in each well from the linear regression of temperature-depth data. Values of matrix thermal conductivity for the lithotypes of the stratigraphic columns were assumed from laboratory measurements on core specimens recovered from oil wells of the northern Apennines (Pasquale et al., 2011; Pasquale et al., 2017).

In sedimentary basins, with thick sequences of especially muds and shales, sediment heat production must be considered as a factor contributing to the overall geothermal flow (e.g. Rybach, 1986). No core sample was available for the investigated boreholes. Thus, the radiogenic contribution was evaluated for each lithology either from compilations experimental data of the northern Apennines (Pasquale et al., 2012) or by converting available gamma-ray logs in six wells (Sarsina 1, Pieve S. Stefano 1, Mt. Civitello 1, Varoni 1, Suviana 1, Bagnolo Piano 3) into heat production using the relationship by Bucher and Rybach (1996).

By applying equations. (2) and (3) we calculated temperature profiles which best match the corrected BHTs. The fit is rather good in most of the boreholes, with the exception of Mt. Civitello 1, Marta 3 and Massa 2 (Table 2), which show RMSE larger than the maximum uncertainty (5 °C) assumed for BHT data (Deming and Chapman, 1988; Funnell et al., 1996; Chiozzi et al., 2017). Figure 4 shows the results of two example wells (Sarsina 1 and Mt. Civitello 1), together with the variation with depth of the input parameters (porosity, thermal conductivity and radiogenic heat production). Sarsina 1 illustrates a good fitting between calculated temperature and BHT data, whereas Mt. Civitello 1 shows an example of the large deviations between data and modeled temperature profiles. Generally, in the uppermost two-three kilometers, the compaction effect is larger than the temperature effect and, for the same lithotype, this causes an increase of thermal conductivity with depth. Both wells show that the maximum values of thermal conductivity occur in carbonate formations. Discontinuities in the trends of the input thermo-physical parameters (Figure 4) are due to changes in lithology.

Table 2 lists the surface heat-flow values obtained by minimizing BHT data together with the average thermal conductivity for the selected wells.

The largest values of heat flow (>100 mW m^{-2}) were obtained in the Tyrrhenian domain, in the boreholes Massa 2, located near to the geothermal field of Larderello, and Marta 3, in the quaternary volcanic area of central Italy (Figure 1). The lowest values were mostly found in holes located close to the Paleogene-Mesozoic formations cropping out in the central Apennines (Figure 1).

Table 2 - Surface heat-flow values (HF), heat-flow range (HFR) for the wells that have at least two temperatures recorded in the Paleogene-Mesozoic carbonate of Table 1. k is thermal conductivity and RMSE the root-mean-square error.

Well	Depth m	k W m^{-1} K^{-1}	HF mW m^{-2}	RMSE K	HFR mW m^{-2}
Bagn. P. 3	5046	2.51	56*	0.7	49-62
Suviana 1	7131	2.47	77	3.1	68-87
Sarsina 1	5714	2.48	50	5.3	44-57
Pieve S.S. 1	4936	2.45	71	3.5	62-80
Mt Civ. 1	5581	2.76	43	14.3	38-53
Massa 2	4341	2.49	182	2.5	159-203
Varoni 1	5766	2.81	27	1.6	22-32
Marta 3	2347	1.85	131	5.3	112-150
Lanciano 1	2880	2.31	67*	1.4	56-74
Cupello 19	4996	2.66	66*	0.8	58-74
Castelm. 2	3754	2.38	57	3.4	49-66

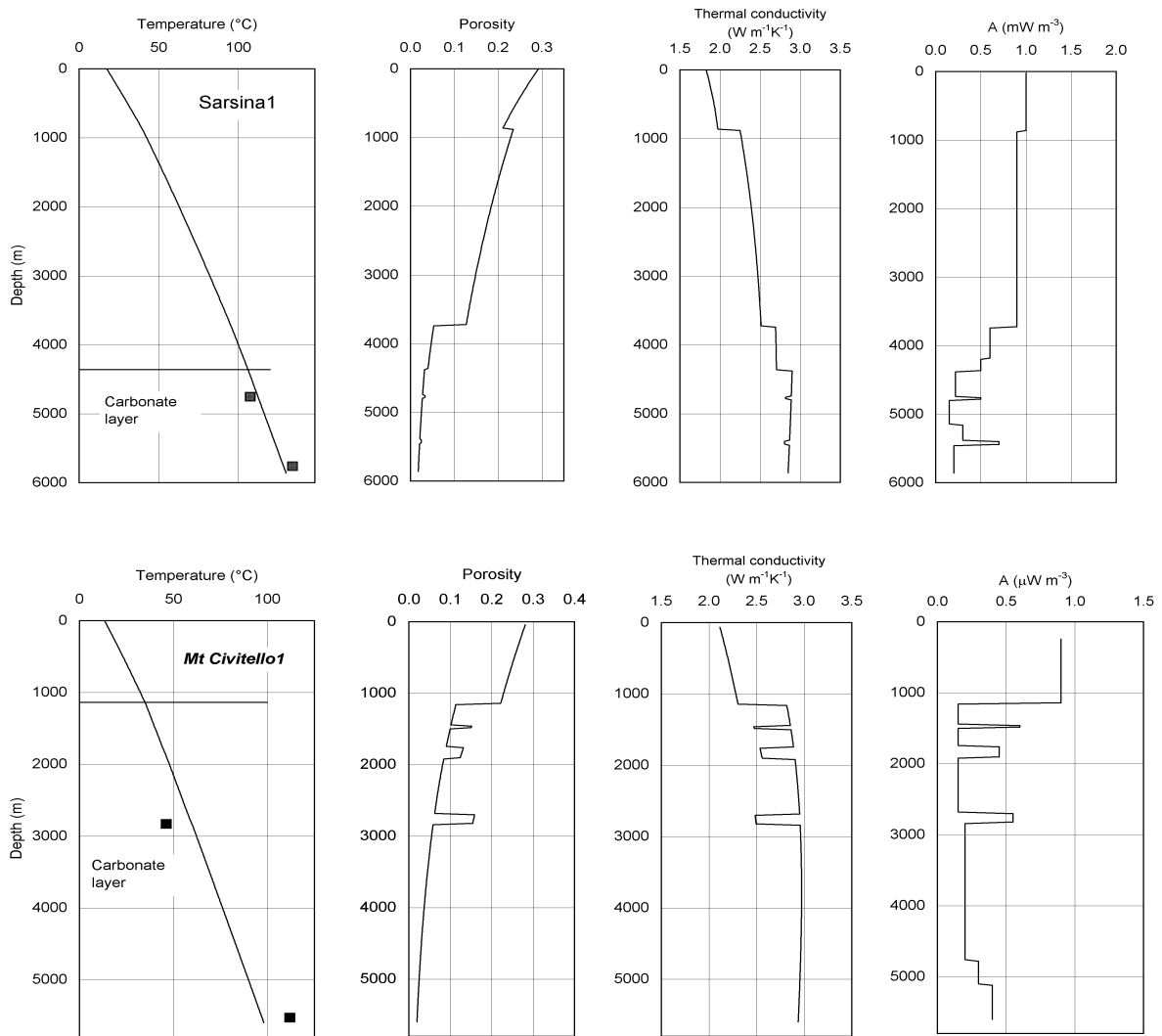*Corrected for sedimentation

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Figure 4 - Calculated geotherms, obtained by minimizing BHT data (see text and Table 2), plotted against corrected BHTs (black square) and physical properties (porosity, thermal conductivity and radiogenic heat production (A) for the Sarsina 1 and Mt. Civitello 1 wells.

4. Discussion and conclusions

The results of processing of the thermal data from the Paleogene-Mesozoic carbonate unit shows that heat flow decreases from the TD (130-180 mW m^{-2}, boreholes Marta 3 and Massa 2) towards the axis of the Apennines chain (70 mW m^{-2}, boreholes Suviana1 and Pieve S. Stefano 1; Figure 5 and Table 2).
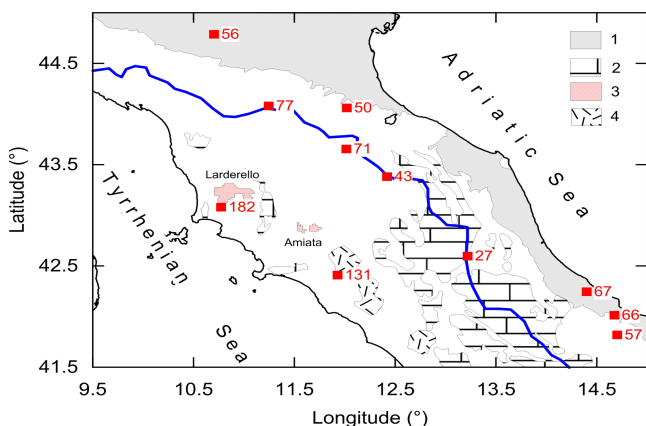

Figure 5 - Heat flow values (in mW m^{-2}) as inferred from selected thermal data of deep boreholes (see also Table 2). The Apennines watershed is also indicated (blue line). Details as in Fig. 1.

The lowest values were found in the boreholes of the eastern side of the Adriatic domain (50-60 mWm^{-2}, boreholes Sarsina 1, Lanciano 1, Cupello 19, Castelmauro 2 and Bagnolo P. 3). Along the chain, the heat flow seems also decreasing from north (Suviana 1 and Pieve S. Stefano 1) to south (Mt. Civitello 1 and Varoni 1). Since thermal conductivity is relatively homogeneous among the different lithological units (Table 2), the E-W and N-S variation of heat flow should be mainly controlled by variation in temperature gradient.

The minimization method that we applied is based on the assumption of steady state purely conduction and therefore it could discriminate the thermal regime of the deep carbonate units. Even if we found a general agreement between observed and calculated temperatures, thus indicating a likely conductive thermal regime in the deep carbonate layer, some boreholes showed significant deviations. A possible cause might be advection or convection.

Deviation from conductive thermal regime seems particularly evident in borehole Mt. Civitello 1, which showed the largest RMSE misfit (Figure 4). A possible mechanism of heat transfer in the deep carbonate formations might lie in the thermal convection. A number of theoretical studies stresses that thermal convection may occur in permeable formations, like the deep carbonate units, under normal thermal gradients. The presence of convective fluid flow was demonstrated for

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the carbonate permeable layers of the northern Apennines by Pasquale et al. (2013). However, Mt. Civitello 1, is close to a likely recharge zone, i.e. the Paleogene Mesozoic outcrops of the central Apennines (Figure 1) and thus it is more likely BHTs in this hole to be affected by advective processes.

The minimization approach seems thus able to resolve the type of thermal regime. However, it must be stressed that this also depends on the number of available temperature measurements. For an ideally continuous temperature-depth log, deviation from pure convection would be clearly revealed, whereas for few and sparse BHTs, as it occurs in most of the boreholes, the interpretation may be speculative.

Additional bias may arise in case of few and too closely spaced BHTs. This is particularly evident in the Varoni 1 well. In this borehole, despite the misfit between calculated and observed temperatures is minimum, thus arguing for a conductive thermal regime, the inferred heat flow is unreasonably low (Table 2) for a young and of normal thickness continental crust (e.g. Sclater et al., 1980; Hamza et al., 2008; Pasquale et al., 2017). This result may be a consequence of the uncertainty (of the order of $\pm$3-5 °C) that intrinsically affect BHTs and of the fact that the temperatures were recorded within an interval of only 350 m (Table 1). Therefore, the determination of thermal gradient and consequently the interpretation heat flow in Varoni 1 well is highly questionable. A similar consideration can be applied to Bagnolo in Piano 3, Lanciano 1 and Castelmauro 2. However, the heat flow value obtained for these holes is consistent with the heat flow values of the Adriatic domain.

The uncertainty in the inferred heat flow depends on the uncertainty on the BHT data, thermal parameters of the rocks (conductivity and heat production) and the assumed value for ground surface temperature. Paleoclimate can have additional effect on the inferred heat flow. Majorowicz and Wybraniec (2011) proposed a depth-dependent correction curve for south–southwestern Europe. The paleoclimatic correction as a response to five glacial cycles since 600 kyr ago with glacial–interglacial surface temperature amplitude of 7 °C would imply a heat-flow increase, which smooth with depth. The correction is about 5 mWm^{-2} at depth less than 1200 m and becomes negligible at depth larger than 2000 m. Thus, in principle an additional paleoclimate correction of 2-3 mWm^{-2} should be applied to borehole Massa 2.

Bottom hole temperatures (BHT), recorded in oil well, generally suffer from inherent biases which may affect the heat flow determinations (e.g. Hermanrud et al., 1990). Thermal disturbance that occurs during circulation or drilling is a main problem. Among the number of models proposed to correct BHTs for this bias (see e.g. Deming, 1989, for a review), we used the approach proposed by Pasquale et al. (2012; 2014). To circumvent possible error sources and improve the quality of interpretations, we selected only those boreholes with at least two bottom-hole temperatures and detailed information on lithostratigraphy were available. An estimate of the error in corrected BHTs depends on the magnitude of the BHT correction, as well as on systematic and random errors in the actual BHT measurement (Speece et al., 1985). We estimate the average error to be 3-5 °C (Deming and Chapman, 1988; Funnell et al., 1996; Chiozzi et al., 2017). This error is quite large as compared to that of continuous thermal logging with precision temperature devices in shallow holes. However, the lack of high-resolution continuous temperature logs is compensated by the deepest range in temperature measurements.

The knowledge of in-situ thermal conductivity is fundamental to obtain reliable heat-flow estimates. Thermal conductivity was estimated by means of an approach that is based on stratigraphic data and taking into account the temperature dependence of the matrix and pore fluid conductivity and the porosity variation with depth. Better estimates can be obtained if the matrix thermal conductivity is measured in the laboratory. Unfortunately, core samples were not available for the investigated holes. We thus used values of thermal conductivity measured by Pasquale et al. (2011; 2012) for lithotypes of the same geological formations encountered in our boreholes. A likely estimate of the error on the assumed thermal conductivity at any depth range is $\pm$0.25 W m^{-1} K^{-1}.

The inclusion of a sediment heat productivity term in the heat flow determination typically causes an increase of 2-4 mWm^{-2} in the steady state heat flow. The error on the estimation of the radiogenic heat production from gamma-ray logs can be as large as 10% (Bucher and Rybach, 1996). We may assume that the same uncertainty lies also in the estimations based on the heat production data measured on core samples collected by Pasquale et al. (2012). Our estimate of the mean annual ground temperature is likely in error by no more than 1-2 °C (see e.g. Lee et al., 1996).

A sensitivity analysis was carried out on the heat flow results obtained with the minimization approach. By combining values of the maximum errors of BHTs, thermal conductivity, heat production and ground surface temperature, the likely uncertainty of heat flow values was obtained (Table 2). The uncertainty varies from 5 to 23 mW m^{-2} and on average for all the dataset across the investigated area is < 15%.

Although the number of data that survived the rigid selection criteria (at least two available BHTs in the carbonate and/or crystalline basement) is relatively small, the inferred heat flow pattern (Figure 5) should represent the deep, conductive heat flow. Similarly, to early studies, the new heat flow data put into evidence that there is an eastward lateral variation in heat flow from 180-70 mW m^{-2} to the 70-50 mW m^{-2}. The high heat-flow area, mainly covering the TD, is consistent with the extensional processes, involving lithosphere thinning and recent volcanism that have affected this tectonic domain (Verdoya et al., 2005). The lower values, mainly occurring in the AD, correspond to a compressive tectonic realm related to the recent overthrusting of the Apennines chain (e.g. Pasquale et al., 2010). Compared to early studies, the area with heat flow > 70 mW m^{-2} seems more extended eastwards and the new data of the AD exhibit values larger by 10-15 mW m^{-2}.

Unfortunately, the heat flow in the central part of the Apennines chain remains little defined. The only one borehole providing reliable information (Mt. Civitello 1) argues for an advective thermal regime. This part of the mountain chain is characterized by outcrops of carbonate units, which may act as recharge areas of regional aquifers. This argument is in favor of an advection-dominated thermal regime all over this part of the chain.

In summary, the analysis of the deepest available thermal data led to an improved picture of the heat flow pattern of the central-northern Apennines. Even if the temperatures recorded in some boreholes within the Paleogene-Mesozoic carbonate layers seem reflecting an advective thermal regime, away from the recharge areas the new heat-flow data, albeit sparse, may give an insight into the deep crustal heat-flow pattern. The new data substantially confirm the increase of heat flow from the western, internal portion of the Apennines chain (Tyrrhenian domain) to eastern, external part (Adriatic domain), but also point out that the Adriatic domain is characterized by larger values that inferred in early studies. As the latter domain is

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seismically active, we suggest that the new thermal pattern could reopen the discussion on the relation between rheological properties and earthquake distribution in the external part of the Apennines chain.

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