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Thermal conductivity of rocks and regional mapping

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ABSTRACT

In the low enthalpy geothermal field a proper plant design is fundamental in order to ensure an efficient exchange of heat, avoiding sizing errors of field probes resulting in a loss of energy efficiency or excessive costs. Therefore, it is, among others, important to know the thermal conductivity (λ, $Wm^{-1}K^{-1}$) of rocks and sediments involved by ground heat exchangers, providing a distribution map to be associated to other fundamental parameter maps useful for geothermal system planning.

Aim of this paper is to highlight the need for a reasoned choice of heat conductivity values to be assigned at regional and local scale. In fact, laboratory measurements in dry and wet conditions give the λ value belonging to a specific sample. To up-scale the laboratory data to a regional scale we must take into account the different lithologies forming the lithological units represented on geological maps. Moreover, it is necessary to consider the presence of water and the influence of the entire stratigraphic sequence on the subsoil generally involved by geothermal pumps and affected by heat exchange performance.

Thermal property tests were carried out in laboratory (dry and wet condition) by using specific equipment, on more than 200 samples collected in four regions of southern Italy (Calabria, Campania, Apulia and Sicily) in the frame of the VIGOR Project, aimed at assessing the geothermal potential. The λ values of rocks and loose materials previously obtained from the screening of international literature have been validated by comparison with those directly measured on samples.

A reasoned λ value were then assigned to the most representative geological units, selected according to the largest areal extent (km^2) and the highest population density, and thermal conductivity maps were produced and related to the possible development of geothermal solutions in the territory.

1. INTRODUCTION

In Italy, in recent years, the use of low-enthalpy geothermal energy for heating and cooling purposes of residential and commercial units increased mainly in the northern regions (Lo Russo et al 2011; Gemelli et al 2011). In the southern ones, the development of these solutions involves primarily the cooling phase during summer season (Magraner et al 2010, Galgaro et al 2012, Mendrinos et al 2012). To assess the ground ability to exchange heat with buildings, a better knowledge of the thermal properties of the subsoil is necessary (Yasar et al 2008, Sharqawy et al 2009, Pouloupatis et al 2011, Liebel et al 2012). In detail, conduction is the principal mode of heat transmission in the earth. Therefore, a correct evaluation of the thermal conductivity of rocks is fundamental to properly size borehole heat exchangers and related pumps (Robertson 1988, Clauser and Huenges 1995, Banks 2012). This feature is one of the main input parameters in geothermal modeling since it directly controls the steady state temperature field and is a reference value to validate data obtained by indirect control methods applied in situ (hydrogeological and geothermal exploration).

In a first phase of our study, a general review of the thermal conductivity values described in literature for rocks and loose materials has been performed (Majorowicz et al 1987; Lee and Deming, 1998; Vosteen et al 2003; Waples and Waples 2004a; Waples and Waples 2004b; Davis et al 2007; Gruescu et al 2007; Alishaev et al 2012). Data regarding about 90 lithologies were organized in a reference database. However, at local scale, the different climate and environmental condition, together with the structural and geological features of the territory can modify porosity (i.e. water content), texture and homogeneity of the material, leading to thermal conductivity values

significantly different from those defined from literature.

On this regard, an overview of the geological and hydrogeological features of the four regions involved in the VIGOR Project (Calabria, Campania, Apulia and Sicily) has been performed. Relying on the Geological Map of Italy, scale 1:250.000 edited by ISPRA, the igneous, metamorphic and sedimentary outcrops can be easily recognized (Fig.1). The figure clearly shows that sedimentary rocks and deposits are dominant everywhere, magmatic rocks are located in the volcanic areas of Sicily (Mt. Etna) and Campania (Campi Flegrei-Ischia Island) whereas almost all metamorphic rocks can be found in northern Sicily and in Calabria.

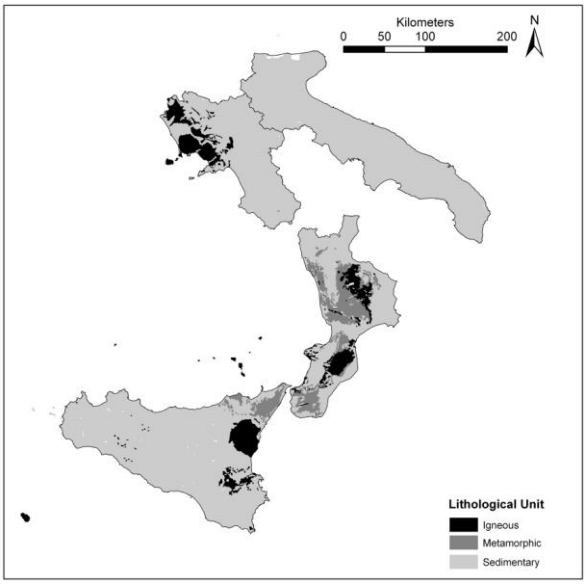
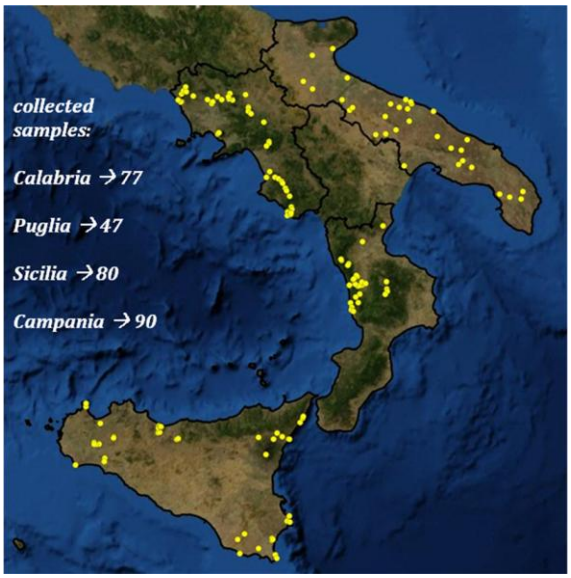


Figure 1: Areal distribution of the igneous, metamorphic and sedimentary rocks outcrops in the southern Italian regions involved in the VIGOR project (scale 1:250.000).

To validate at local scale the λ ($Wm^{-1}K^{-1}$) values of rocks and loose materials obtained from the screening of international literature, an extensive sampling campaign was carried out in the summer of 2012. Selected samples, representative of the main geological units (i.e. having the largest areal extent and present in the most urbanized areas) were collected all over the territory and tested for thermal conductivity in laboratory (Fig.2). The material taken in situ (about 294 samples) tries to respect, as far as possible, the lithological heterogeneity of the considered geological units, as known from literature. Aim of this work is to create a regional database of thermal conductivity for geological materials, comparable with the one created from literature data. It must be taken into consideration that the presence or absence of water is able to significantly improve the ability to conduct heat, so that particular attention must be paid in the measurement of wet and dry material. The consequence related to the influence of the entire stratigraphic sequence and to the thickness of the subsoil generally affected by geothermal heat exchangers (about 150 m) is treated in other works



(Galgaro et al 2012, Di Sipio et al 2012).

Figure 2: Location of samples.

2. METHODOLOGY

Direct measurements of thermal conductivity were performed in laboratory using a specific thermal conductivity analyzer. The instrument (C-Therm-Tci) measures directly the thermal conductivity and effusivity of materials, based on the modified transient plane source method, and can provide user-input capabilities in the calculation of thermal diffusivity and heat capacity. The system is comprised of a sensor, control electronics and computer software, where the sensor employs a one-sided, interfacial heat reflectance device that applies a constant current heat source to the sample (Fig.3). A known current is applied to the sensor's heating element providing a small amount of heat. The heat provided results in a rise in temperature at the interface between the sensor and the sample – typically lower than 2°C.

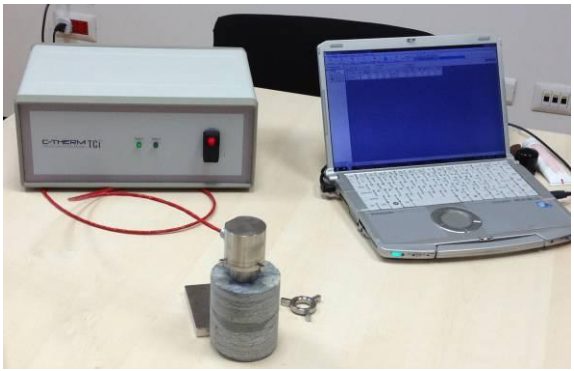


Figure 3: Thermal conductivity analyzer

This temperature rise at the interface induces a change in the voltage drop of the sensor element. Since the rate of temperature increase at the heating element is inversely proportional to the thermal conductivity of

the material, this material property can be determined by measuring the rate of voltage increase when a constant current is applied (C-Therm 2012, Harris and Sorensen 2007, Mikulic et al 2013). Since the sensor needs a good contact with only one side of the sample, before testing each sample must be cut and the obtained surface has to be properly smoothed (Seipold et al 1998, Krishnaiah et al 2004, Park et al 2004, Jougnot et al 2010).

At first, thermal conductivity has been measured on rock samples dried in oven at 70° C for 24h, and then brought into thermal equilibrium with the sensor at stable air-conditioned room temperature (24h, T= 21-23°C). The obtained values are precautionary, as generally it can be assumed that measurements of the wet rock sample yield more realistic results, since the pore volume in situ is usually water saturated. Measurements in wet conditions were then performed on some of the samples hydrated for 96h. Eventually, a statistical evaluation of the recorded data was performed.

3. RESULT AND DISCUSSION

In every region the geological unit with the greatest areal extent has been selected according to the Geological Map of Italy 1:250.000 (Table 1, Fig.4).

Table 1: The geological unit selected (VIGOR Project)

region	geological unit	area (km^2)
Calabria	*Granites and granodiorites – Paleozoic cycle*	2004
Campania	*Clays, limestones and clay unit (turbiditic) - Paleogene*	1864
Apulia	*Skeletal limestones of neritic and carbonate platform facies - Upper Cretaceous*	4955
Sicily	*Clays and marls – middle-lower Miocene*	2924

Each unit consists of several lithologies, formed in different geological period and characterized by different values of conductivity, as granite and granodiorites (*Granites and granodiorites*); clay, marl, calcarenites, limestone (*Clays, limestones and clay unit*); limestone, dolomite, dolomitic limestone, skeletal limestone (*Skeletal limestones of neritic and carbonate platform facies*); clay, marl, calcarenites, limestone (*Clays and marls*). Moreover, these units can be found in every other region but with a smaller extent. However, the outcrops may be subjected to weathering and fracturing phenomena that locally, in the same formation, determine variation of open porosity and, in this way, of the thermal properties of the rocks.

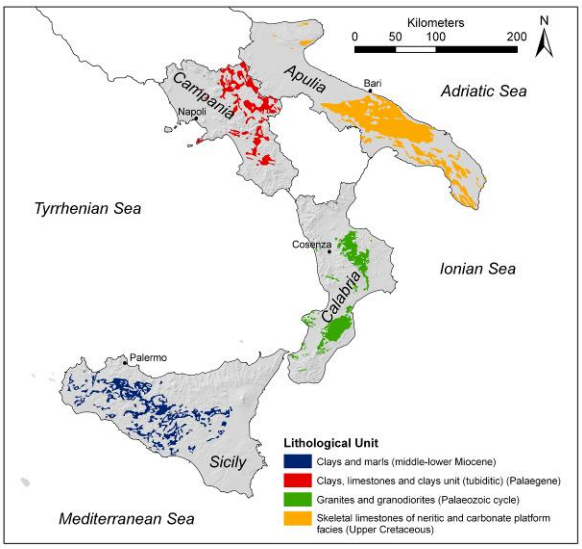


Figure 4: Distribution of the geological unit described in Table 1.

For example, in Calabria the granite units cover large part of the territory and have thickness of more than 30 m (Ietto et al 2007). Due to the different degree of weathering, they are in the form of fresh rock (Fig.5a-c) or of granitic saprolite (Fig.5b-d), characterized by thermal conductivity values similar to those obtained from literature respectively for granite (2.8 $Wm^{-1}K^{-1}$) or dry sand (0.5 $Wm^{-1}K^{-1}$).

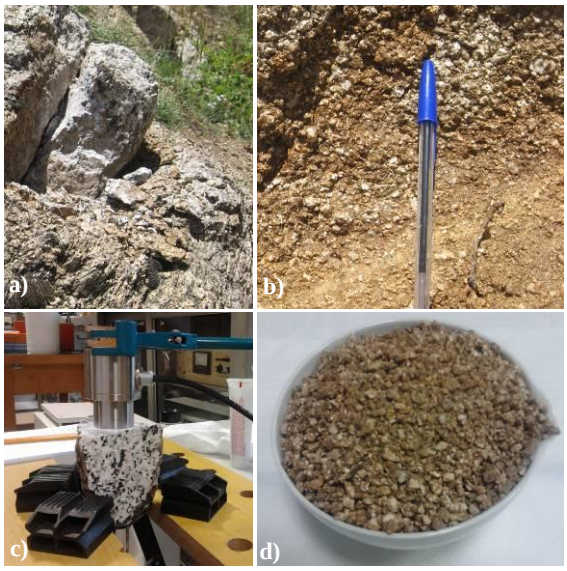


Figure 5: Fresh (a-c) and weathered (b-d) granite in situ (a-b) and in laboratory (c-d)

Therefore, direct thermal measurements performed in situ or in laboratory on natural materials, duly selected according to the geological configuration, are necessary and strict recommended in order to create a regional database representative of the actual condition of the territories, useful for planners, public administrations and operators involved in the geothermal sector.

In detail, for every geological unit identified in Table 1, several samples have been collected and analyzed in

dry condition. All of them have been subjected to at least two series of measurements, each constituted by continuous detection of 8 values. The first two recordings were generally discarded due to possible contact problem between the probe and the analyzed surface, and the remaining six were averaged. The weighted average of the 12 values obtained from the two series of measurements was considered representative of the analyzed sample. The median of the thermal conductivity values defined for the samples belonging to the same geological unit was then attributed to the whole geological formation.

In Calabria, 8 granites and 3 granodiorites have been analyzed resulting in a total of 110 values to be treated statistically. In dry condition the thermal conductivity ranges from 0.4 $Wm^{-1}K^{-1}$ for the most weathered granite (CAL30.1, granitic saprolite, Fig.6a) till 3.5 $Wm^{-1}K^{-1}$ for the hardest samples (CAL22.1, metamorphosed, Fig.6b), while the *Granites and granodiorites* unit has a value of 2.4 $Wm^{-1}K^{-1}$. The *Clays, limestones and clay unit* of Campania, the *Skeletal limestones of neritic and carbonate platform facies* of Puglia and the *Clays and marls* of Sicily show a λ_{dry} of 2.0, 2.5 and 1.6 $Wm^{-1}K^{-1}$, respectively (Fig.6 c-h, Table 2).

Table 2: Thermal conductivity values ($Wm^{-1}K^{-1}$) of the main geological units derived by direct measurements on samples (dry condition).

geological unit	n of samaples	$\lambda_{dry\ min}$	$\lambda_{dry\ max}$	λ_{dry}
Granites and granodiorites	8 granite 3 granodiorites	1.3	3.5	2.4
Clays, limestones and clay unit (turbiditic)	3 marls 1 clay 1 calcarenite 1 sandstone	0.4	3.2	2.0
Skeletal limestones of neritic and carbonate platform facies	7 limestone of Altamura 20 limestone of Bari 3 dolomite of Galatina 1 limestone of Melissano	1.7	3.7	2.5
Clays and marls	2 clay 3 marl	0.9	2.0	1.6

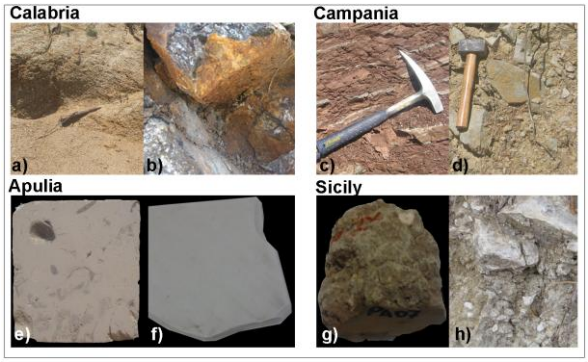


Figure 6: Overview of the rock materials collected to perform direct thermal conductivity measurement in laboratory: weathered and fresh granite (a-b) from Campania; marl and sandstone from Campania; skeleton limestone and limestone of Bari (e-f) from Apulia; clay and marl (g-h) from Sicily.

As you can see in Table 3, as expected, the λ_{dry} assigned are always lower than those derived from the literature screening. In fact, in the subsoil the water saturates the porosity of rocks by increasing their ability to transfer heat. Therefore, according to the procedure described above, some tests on saturated materials were carried out for Calabria and Sicily rocks. In the first case the final λ_{wet} derived from the processing of data belonging to granite and granodiorites increases up to 2.8 $Wm^{-1}K^{-1}$, comparable with the bibliographic one. The samples characterized by the minimum and maximum value of λ_{wet} are always the granitic saprolite (CAL30.1, 1.3 $Wm^{-1}K^{-1}$) and the fresh metamorphosed granite (CAL22.1, 3.9 $Wm^{-1}K^{-1}$). In the second one, the *Clays and marls* unit reaches a λ_{wet} value of 2.8 $Wm^{-1}K^{-1}$, greater than that obtained from literature screening (2.2 $Wm^{-1}K^{-1}$), and in the range 1.30 to 4.2 $Wm^{-1}K^{-1}$. Instead, the data registered in dry condition are significantly lower, ranging from 0.9 till 2.0 $Wm^{-1}K^{-1}$.

Table 3: Comparison between thermal conductivity values ($Wm^{-1}K^{-1}$) measured in dry and wet conditions and derived by literature

geological unit	λ_{dry}	λ_{wet}	λ_{bib}
Granites and granodiorites	2.4	2.8	2.8
Clays, limestones and clay unit (turbiditic)	2.0	-	2.3
Skeletal limestones of neritic and carbonate platform facies	2.5	-	2.9
Clays and marls	1.6	2.8	2.2

4. CONCLUSIONS

The correct determination of thermal conductivity referred to the main geological units of a region, based not just on the data reported in literature but on direct measurements on properly taken samples, requires the knowledge of the geological, structural and hydrogeological features of territories at local scale, due to the presence of several lithologies in a single formation and the existence of the same lithology in different geological units. For example, water saturation considerably improves the heat transfer conduction in the subsoil. Therefore, determining the thermal conductivity values in dry condition is a precautionary measure that allows the design of geothermal plants suited to the actual conditions of the subsoil.

Moreover, the creation of a database dedicated to the measured thermal properties collection is accessible also for the exploitation of geothermal energy resources in medium and high enthalpy, where the

knowledge of thermal conductivity is a key parameters for modeling the potential of deep subsurface structure.

Further development of this work has to take into consideration the influence on thermal conductivity values both of the entire stratigraphic sequence and of groundwater up to a depth of about 150 m, useful for shallow geothermal application. Data directly measured in laboratory on small samples must be validated by outputs derived by Thermal Response Test (TRT) to point out the possibility to extend the information collected at local scale to a wider area, allowing a regional mapping of the thermal properties.

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