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First results of infrared thermography applied to the evaluation of hydraulic conductivity in rock masses

Giovanna Pappalardo[1]

Abstract An innovative methodological approach using infrared thermography (IRT) provides a potential contribution to the indirect assessment of hydraulic conductivity of jointed rock masses. This technique proved a suitable tool to evaluate the degree of fracturing of rock masses along with their discontinuity systems, which expedite water flow within the rock mass itself. First, based on the latest scientific outcomes on the application of IRT to the geomechanics of rock systems, rock mass surveys were carried out at different outcrops (dolostone, limestone and porphyroid) and hydraulic conductivity was empirically assessed through approaches well known in the international literature. Then, IRT campaigns were performed at each surveyed rock mass, with the purpose of evaluating the corresponding Cooling Rate Index, strictly linked to the cooling attitude of the rock. Such index was correlated with the assessed hydraulic conductivity and satisfactory regression equations were achieved. The interesting results show that hydraulic conductivity values are likely to be linked with the cooling behavior of rock masses, which, in turn, is affected by spacing, aperture and persistence of discontinuities.

Keywords Crystalline rocks · Carbonate rocks · Infrared thermography · Cooling Rate Index · Hydraulic conductivity

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Introduction

The hydraulic conductivity of a rock mass is a difficult parameter to define because it is a function of numerous factors (e.g. orientation, persistence, spacing, opening, shape and roughness of discontinuities) and of the uncertainty in rock mass properties (Witherspoon and Gale 1983; Silliman 1989; Weisbrod et al. 1998). The hydraulic conductivity (or coefficient of permeability) is defined as the discharge velocity through a unit area under a unit hydraulic gradient and is dependent upon the properties of the medium, as well as the viscosity and density of the fluid. According to Darcy's law, the quantity of flow through a cross-sectional area of rock can be calculated by

$$q = kiA \tag{1}$$

where q is the quantity of flow; k is the permeability coefficient of the rock, having the units of velocity; i is the hydraulic gradient (head loss divided by length over which the head loss occurs); and A is the cross-sectional area of flow. Water mainly circulates through a network of discontinuities with a primary (e.g. bedding surfaces, schistosity) or secondary (e.g. joints, faults) origin. The flow through the intact rock matrix is usually so low that significant fluid movement can only take place through the fractures (Witherspoon and Gale 1983); therefore, to characterize the hydraulic conductivity of a rock mass, it is essential to consider its fracturing characteristics. According to Zhang (2013), the degree of anisotropy in permeability for the jointed rock mass depends on the distribution of discontinuities and is much higher than that of intact rock, therefore should be carefully evaluated.

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The most common in-situ procedure used to estimate hydraulic conductivity of rock masses is the Lugeon test (Lugeon 1933; Houlsby 1976), which is a constant-head type test performed in an isolated portion of a borehole. Kazemi (1969) proposed a method to estimate the main hydrogeological parameters of aquifers characterized by dual porosity such as the carbonate ones, while for anisotropic aquifers the most common methods have been proposed by Papadopulos (1965), Hantush (1966) and Neuman et al. (1984).

Laboratory tests allow the evaluation of hydraulic conductivity on intact rock specimens characterized by a network of interconnected pores. Through Hoek's cell, is possible to measure the speed of the water flow passing throughout a cylindrical rock specimen (e.g. Pappalardo et al. 2016a). On the other hand, the hydraulic conductivity of rock masses can be assessed also through empirical equations (e.g. Snow 1968; Louis 1974; Rocha and Franciss 1977), assuming that the flow moves along discontinuities, thus it is influenced by their aperture, roughness and persistence.

Kiràly(1969) suggested a methodology to empirically calculate the hydraulic conductivity of fractured rock masses using mathematical formulas, whose terms can be derived through a detailed mapping of the fractures. In fact, discontinuities in rock masses are elements, generated either during the rock formation or as a consequent of brittle deformation, characterized by peculiar geometric features and a set of parameters such as orientation, persistence, trace length, opening, spacing, roughness, weathering and in-filling (ISRM 1978), affecting the water circulation.

Several researchers verified the application of such empirical methodologies in different geological conditions (Snow 1968; Louis 1974; Rocha and Franciss 1977). In particular, an important application of the Kiraly method was performed by Louis 1974 to determine the hydraulic conductivity of rock joints in laminar, transitional and turbulent flow regimes based on laboratory tests in artificial fractures. Although the empirical estimation of permeability in fractured rock masses is usually associated with petroleum, civil and mining engineering, this practice is essential to understand a variety of problems such as possible locations of underground storage sites for contaminated fluids (Lesnic et al. 1997).

Although for relevant engineering works such as dams, Lugeon tests are needed for the direct estimation of permeability, when the extension of the study area is limited, as in the case of most civil engineering projects, the hydraulic conductivity of rock formations may be indirectly estimated by taking into account the main geomechanical parameters measured on outcrops through specific surveys.

Recently, some researchers have tested infrared thermography (IRT) for the study of rock masses, proving that their cooling behavior is related to their degree of fracturing (Mineo et al. 2015a, b; Pappalardo et al. 2016b). With particular reference to rock masses, they established a Cooling Rate Index (CRI), which describes the cooling speed of the rock after a natural heating, highlighting that an intensely jointed rock mass cools down faster than a less fractured one. CRI correlates well to the main geomechanical features of the rock mass, such as the rock quality designation (RQD) and the joint volumetric count (Jv).

Inspired by such recent innovative outcomes achieved by IRT, which designate CRI as a suitable potential index for the study of the rock fracturing, this paper aims at looking for a useful application of CRI for the indirect estimation of rock mass hydraulic conductivity by means of IRT and the empirical methods above mentioned.

In this perspective, in order to test such methodology on different lithologies, six rock masses, both sedimentary and metamorphic (dolostone, limestone, porphyroids), were surveyed in northeastern Sicily (Italy) (Pappalardo et al. 2014; Pappalardo and Mineo, 2015) and underwent detailed geomechanical and IRT characterizations.

The main geomechanical parameters were analyzed through statistical methodologies and CRIs were calculated for each rock mass. Then, hydraulic conductivity was empirically calculated using the equation proposed by Snow 1968, 1969 and Louis 1974, thus taking into account only those methods involving parameters which can be measured in situ.

Results were statistically correlated to IRT outcomes, finding interesting correlations and achieving promising results, which highlight a potentially alternative practice for the estimation of the hydraulic conductivity in rock masses.

Methodology

Aiming at assessing if a relation between the hydraulic conductivity of rock masses and their cooling behavior exists, and looking for an innovative technique for the estimation of such features strongly influenced by fracturing, in this study a detailed survey of the discontinuities has been carried out at six rock masses in northeastern Sicily, according to the ISRM (2007) specifications. Results were used to empirically calculate the hydraulic conductivity, whose values were compared with the outcomes of an IRT survey carried out at the studied rock masses.

Recent studies proved the useful contribution of IRT to assessment of rock mechanics (e.g. Mineo et al. 2015a; Pappalardo et al. 2016b; Mineo and Pappalardo 2016a; Pappalardo and Mineo 2017) highlighting that discontinuity traces in rock masses, along with fractured/crushed sectors, are marked by positive thermal anomalies, while regular planes (with no visible fractures) keep a lower temperature.

First, set and total spacing, aperture, persistence and roughness of discontinuities were carefully measured at jointed outcrops of dolostone, limestone and porphyroid, which are the most representative rock types of the study area (Peloritani

Mountains). At macroscopic scale, discontinuities affect the rock mass in a systematic way, thus they can be statistically grouped into sets according to their strike. In this perspective, field data were statistically processed to define representative parameters for the hydraulic conductivity computation.

The second stage of this work led to the application of the methods proposed by Snow 1968, 1969 and Louis 1974 for the empirical estimation of the hydraulic conductivity of studied rock masses.

At the same time, IRT surveys were carried out for the assessment of the CRI during the night cooling phase of such rock masses, according to Pappalardo et al. 2016b. In particular, thermograms were acquired by an infrared camera, with temperature accuracy calibrated within ± 2 °C or $\pm 2\%$ of reading, a range of measurable temperature between $-20°$ and $+120$ °C, a spectral range of 7.5–13 μm, a field of view of 25–19°, a focal length of 18 mm and a noise equivalent temperature difference (NETD) of 50 mK. The camera was placed on a tripod to ensure its stability during the acquisition phases and had a constant horizontal trim. Acquired thermograms were processed and the average surface temperature of each station was calculated. The results, with reference to both the empirical assessment of hydraulic conductivity and the IRT survey, were correlated to find out if a mutual dependence exists; moreover, the hydraulic conductivity was correlated to the main geomechanical indexes that numerically describe the fracturing of rock masses.

Evaluation of rock mass fracturing

In this section, a report is given on the rock mass survey carried out at six stations according to ISRM (2007) recommendations. These surveys were carried out with the aim of characterize the investigated outcrops from a geomechanical point of view, so as to retrieve the parameters needed for the calculation of hydraulic conductivity. In particular, spacing and aperture parameters were measured in situ and then statistically processed; moreover, the main geomechanical indexes related to the rock mass fracturing (RQD and Jv) were estimated.

Rock mass survey

The surveyed rock masses are characterized by an intense degree of fracturing, due to the complex geological and tectonic history of the Peloritani Mountains (e.g. Ferrara and Pappalardo 2005; Pappalardo 2015). They belong to three different lithologies (dolostone, limestone and porphyroid), and are crossed by seven to ten discontinuity systems (Fig. 1).

In this kind of setting with intensely fractured rock masses, water circulation, especially in the case of carbonate rocks, is enhanced by the presence of numerous discontinuity sets,

particularly if they are interconnected (Pappalardo et al. 2016c). Sub-horizontal systems are present such as bedding surfaces in dolostone and limestone, which are crossed by other sub-vertical sets linked to tectonics.

The measured spacing values were processed through histograms (Fig. 2a–f) showing that frequency has a lognormal distribution at each surveyed rock mass. At the six rock masses studied, on average, spacing is 0.04 and 0.03 m for dolostone, and 0.23 and 0.13 m for limestone, while porphyroid values are about 0.09 and 0.07 m. The lowest values, causing the greater propensity to permeability, are related to dolostone outcrops. For the six rock masses, aperture is 0.29 and 0.32 cm for dolostone, 0.49 and 0.53 cm for limestone, and 0.42 and 1.08 cm at the porphyroids. Aperture, which could be overestimated by surveys on outcrops (due to possible decompression phenomena or the effects of weathering), is particularly significant for the study of water flow within a rock mass, because it conditions the permeability along fracture systems. For aperture values lower than 1 cm, the statistical distribution of retrieved data has a normal trend, while for greater values frequency decreases (Fig. 3a–f).

Rock quality designation and joint volumetric count (Jv)

The intersection between fractures subdivides the rock mass into blocks whose sizes are a function of spacing and orientation – strike and dip of the discontinuity systems. The Jv was introduced by Palmström 1982 as the number of joints in a blast round and it is defined as the number of joints intersecting a volume of 1 m^3. This can be indirectly calculated by using the spacing of the surveyed joint sets according to Eq. (2).

$$\mathrm{Jv} = 1/S_1 + 1/S_2 + 1/S_3 + \cdots + 1/S_n \qquad (2)$$

where S_n is the spacing of a single joint system.

The obtained Jv values are, on average, 171.5, 71.5 and 50 with reference to dolostones, limestones and porphyroids, respectively. Based on the classification proposed by Palmström 2005, limestones and dolostones can be classified as "crushed rock", while porphyroids have a high degree of jointing. The minimum rock volume to take into account for the hydrogeological study of rocks as a homogeneous matter is known as the representative elementary volume (REV) (Bear 1972). This, involving all the discontinuity sets, is strongly related to the unitary rock volume (URV) (Palmström 1982). In particular, for rocks studied herein, URV values are lower than 1 m^3, resulting in a rock mass composed of very small blocks according to ISRM (1978).

Another parameter considered herein is RQD, allowing the evaluation of the mechanical quality of rock masses based on its degree of fracturing. It was developed by Deere (1963) to provide a quantitative estimation of rock mass quality from drill core logs. It is defined as "the

percentage of intact core pieces longer than 100 mm in the total length of core". RQD values calculated along the scanline are lower than 20% for dolostones (very poor), while they are 54 and 49% for limestones and porphyroids respectively (fair).

Hudson and Priest (1979) presented the following mathematical Eq. (3) between RQD and fracture frequency:

$$RQD = 100e^{-0.1\lambda}(1 + 0.1\lambda) \tag{3}$$

where λ is the total joint frequency.

Results are similar to those calculated along the scanline: dolostones (11%), limestones (58%) and porphyroids (41%).

Laboratory experiments have shown that the roughness and aperture of a rock joint are the most important factors governing fluid flow through the joint. Roughness is an important factor in both the mechanical and hydraulic behavior of the rock; in fact, it is inversely proportional to the aperture (Barton et al. 1985). Moreover, Brown et al. (1986) state that rock bridges affect the permeability of a rock mass by

lowering the water flow; however, due to the impossibility of measuring this parameter directly in a flow process, its influence is usually assessed using coefficients such as the relative hydraulic roughness or the physical joint roughness coefficient (JRC). The JRC, proposed by Barton and Choubey (1977) for description of the shear strength of rock joints, is the most used at the moment for normal deformation and shear strength analysis of rock joints (Bandis et al. 1983; Barton and Bandis 1990). Due to the extensive use of JRC in rock mechanics assessments and the possibility to quantify this parameter using the simple methods proposed by Barton and Choubey 1977, this coefficient seems to be a potentially useful practical tool to characterize the hydraulic conductivity of rock joints taking into account the effects of roughness on flow (Barton and de Quadros 1997).

Infrared thermography survey

Infrared thermography (IRT) is a technique that involves the measurement of the surface temperature of objects starting

Fig. 1 Stereoplots of each survey station, with distinction of the main discontinuity sets
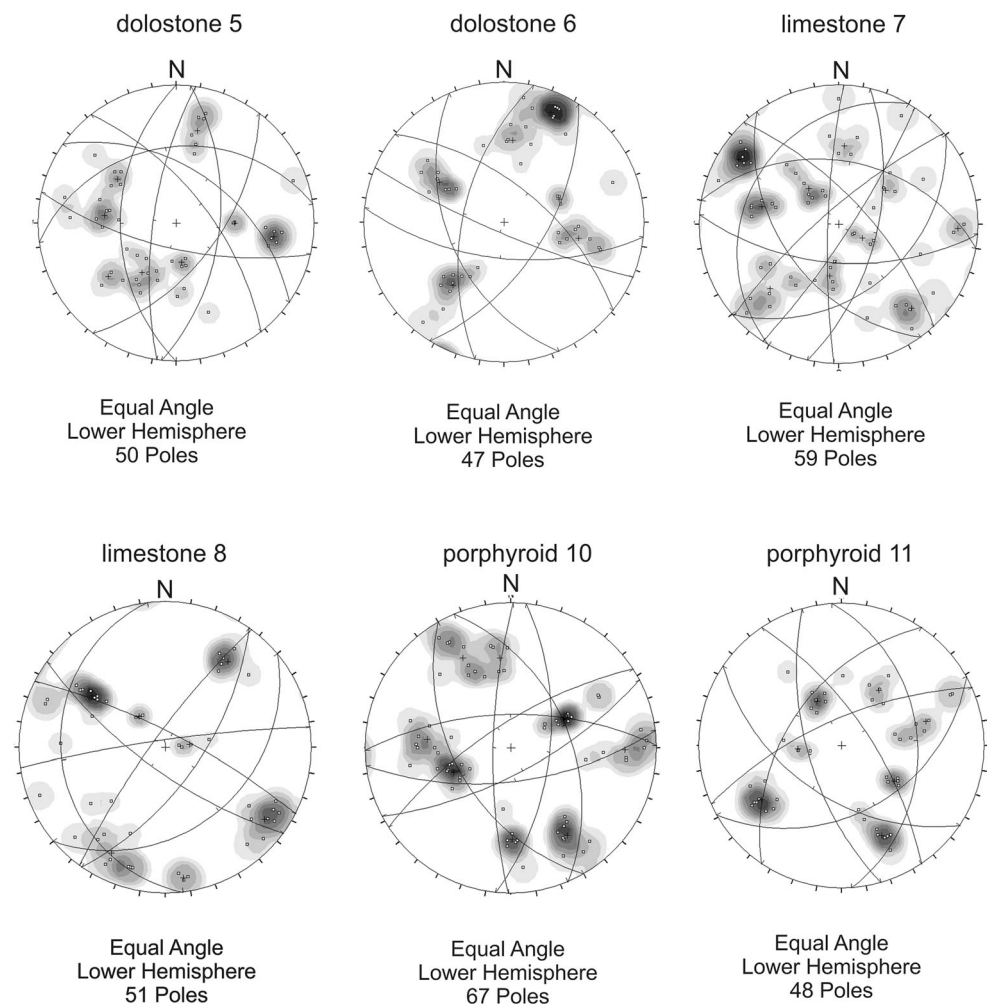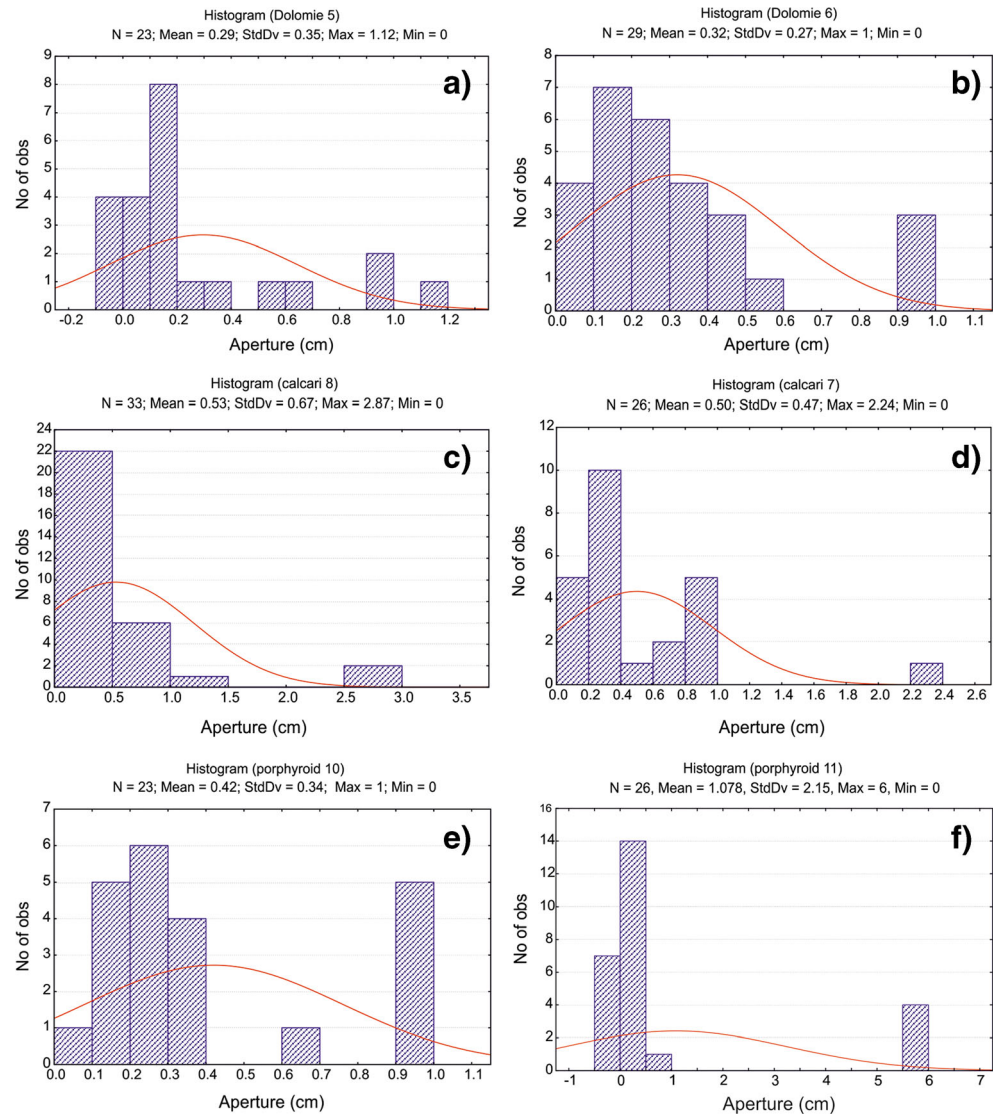
Fig. 2 Main statistical parameters and frequency histogram of the spacing (**a–b** dolostones; **c–d** limestones; **e–f** porphyroids) for all the discontinuity sets

from their emitted thermal radiation (Shannon et al. 2005). This is made of electromagnetic waves mainly falling in the infrared portion of the electromagnetic spectrum (wavelengths ranging between 0.7 and 1,000 μm). Such radiation can be detected by particular devices (thermographic cameras), generally operating in the range of wavelengths as long as 13 μm and able to build color-scaled images, whose pixels represent a specific temperature value. Although this technique is being successfully applied in several fields of science, its use in rock mechanics is a recent practice (e.g. Teza et al. 2012; Baroň et al. 2012). In particular, the recent employment of IRT for the study of rock fracturing started with Mineo et al. 2015b, who studied and compared thermograms of two rock masses at different times, achieving preliminary outcomes. Their work was followed by Pappalardo et al. 2016b, who implemented the surveys and developed the CRI starting from the average surface temperature of surveyed rock masses. This is a measure of the cooling speed of a rock mass after its daily

heating. It is known, by Newton's Law of Cooling, that the rate of change of the temperature is proportional to the difference between the temperature of the rock mass and the ambient temperature.

$$\mathrm{CRI} = \frac{\Delta T}{\Delta t} \qquad (4)$$

where ΔT is the variation of temperature and Δt is the considered time interval.

Pappalardo et al. 2016b found that the higher the degree of fracturing of the rock, the faster its cooling. Moreover, they provided interesting correlations between CRI and the main geomechanical indexes such as the RQD and the Jv, proving that the rock fracturing affects its thermal behavior, thus IRT can be considered a useful tool in the study of rock slopes. In this paper, such correlations are affected by satisfactory R^2, proving the strong link between CRI and the rock fracturing

Fig. 3 Main statistical parameters and frequency histogram of the apertures (**a–b** dolostones; **c–d** limestones; **e–f** porphyroids) for all the discontinuity sets
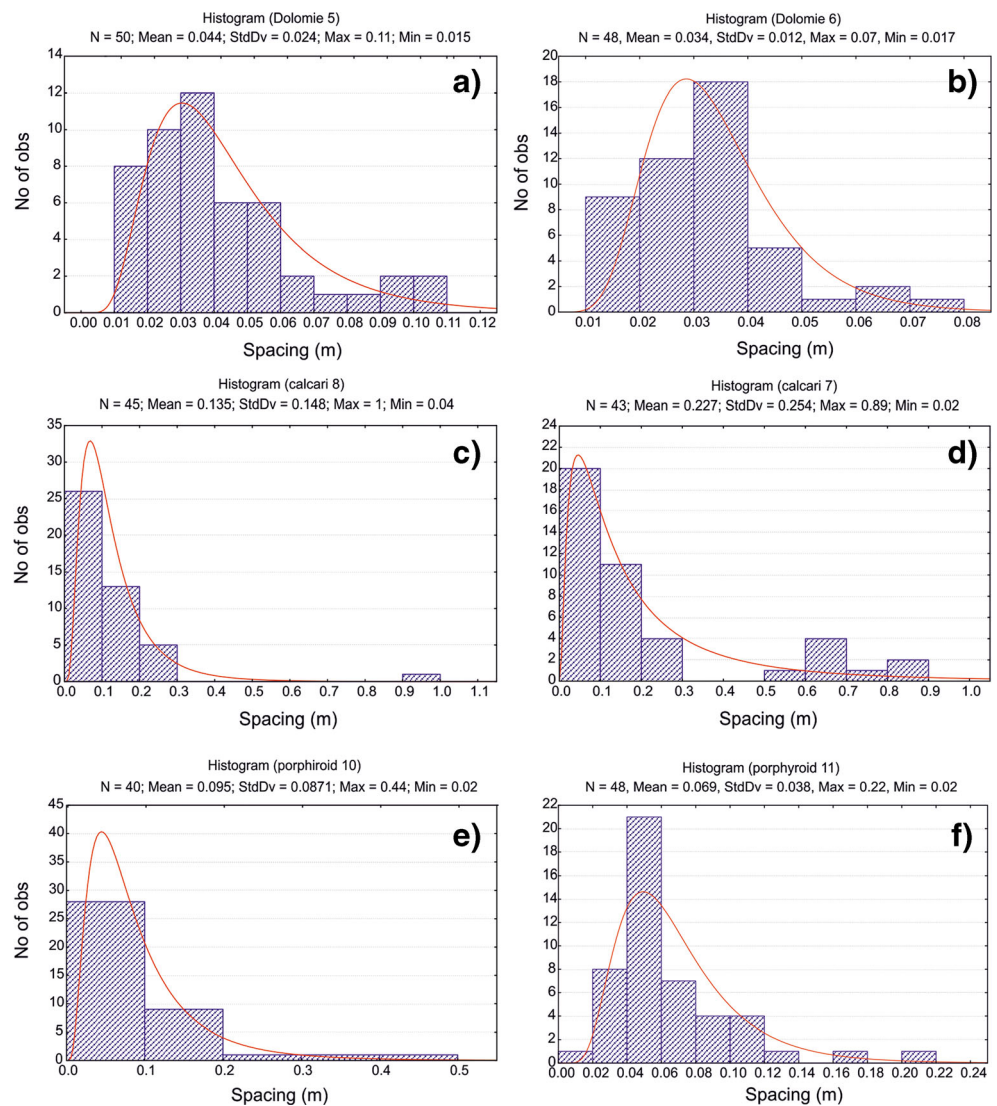
(Fig. 4). In particular, the relation between CRI and RQD is described by a negative trend, as increasing CRIs correspond to a more fractured rock (low RQD); similarly, CRI/Jv shows a positive linear relation, as high CRI values correspond to intensely jointed rock masses.

Moreover, infrared technology was also applied to the study of intact rock specimen in the laboratory, starting from the same principle that the cooling of a rock can provide useful information on its fracturing. In light of this, Mineo and Pappalardo (2016a, b) found interesting relations between CRI and the porosity of intact rock specimens, proving that that the greater the rock porosity, the faster its cooling after an artificial heating phase. This is a relevant topic, because porosity is one of the key properties conditioning the water circulation within a rock (e.g. Fortin et al. 2005; Zheng et al. 2015; Pappalardo et al. 2017).

Given the great matches found between CRI and rock geomechanical parameters, this study looked for a relation with hydraulic conductivity that is strictly connected to the rock fracturing. To this purpose, two IRT imaging campaigns were carried out at all the surveyed rock masses (summer and winter seasons) to acquire thermograms in the nighttime according to Pappalardo et al. (2016b).

Figure 5 shows the comparison between thermograms acquired under different seasonal conditions, highlighting that winter thermograms have a lower resolution due to the lower temperatures reached by rock masses in this season. Dolostone thermograms clearly show the closely spaced discontinuity sets, which are likely to drive the hydraulic flow within the rock mass. Limestone thermograms highlight the presence of a bedding surface along with some dissolution voids (colder area). With respect to porphyroids, the colder areas in thermograms are related to the presence of vegetation growing on the slope face (Fig. 6).

Fig. 4 Correlation between CRI and **a** RQD and **b** Jv for the studied rock masses

a)

y = -0.0151x + 1.2862
R² = 0.74
SD = 0.21

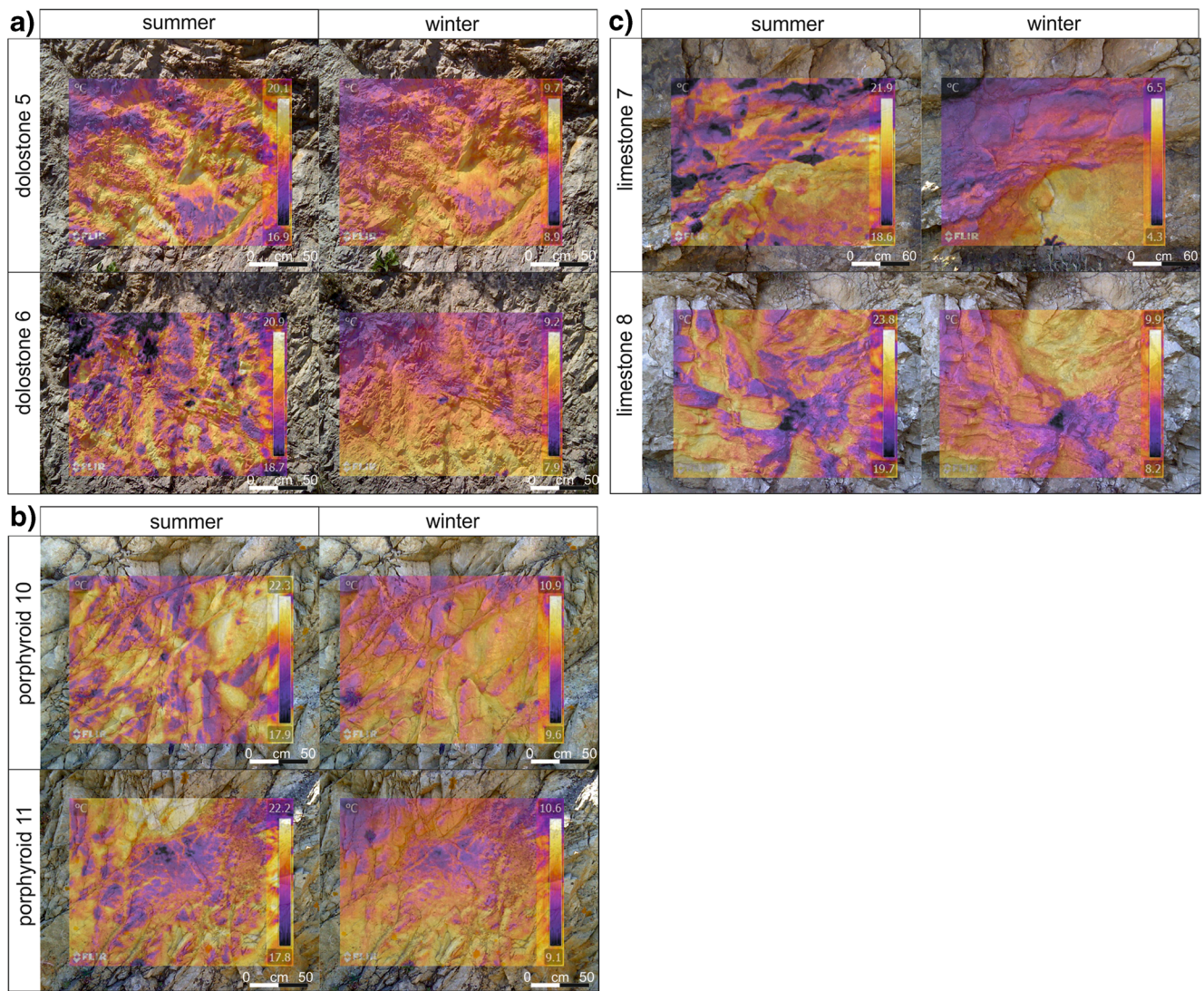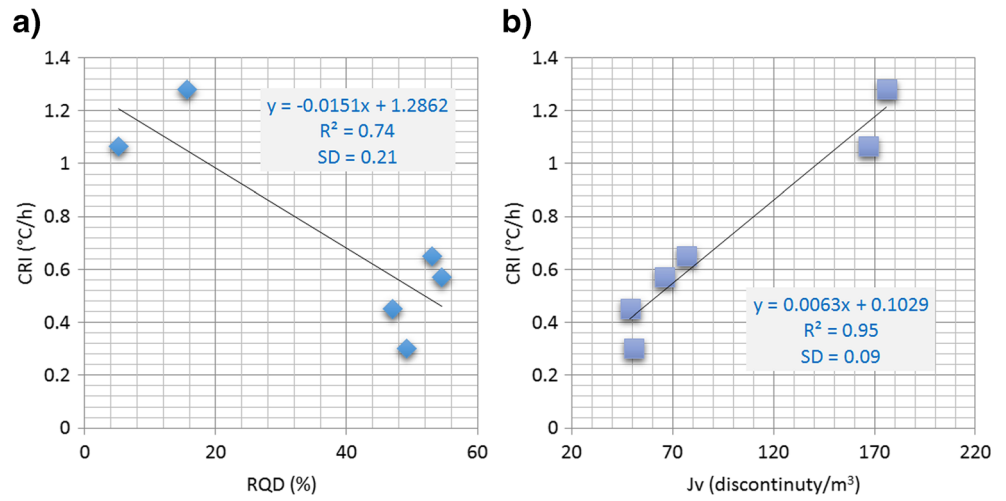b)

y = 0.0063x + 0.1029
R² = 0.95
SD = 0.09

Fig. 5 Comparison between summer and winter thermal images of **a** dolostone, **b** limestone and **c** porphyroid rock masses, overlapped on a digital photo of the rock mass itself

Empirical methods for the estimation of hydraulic conductivity in rock masses

From the hydraulic point of view, rock masses are heterogeneous, anisotropic and discontinuous. Since water circulation mainly occurs along discontinuities, the knowledge of their distribution and their main parameters is of fundamental importance. Several methodologies have been developed during the years correlating structural data to the main hydrogeological parameters. In this paper, deterministic approaches are taken as reference, considering the rock mass as permeable only along fractures.

For fluid flow through rock joints, it is common to consider the joint as composed of two smooth parallel plates and the flow to be steady, single phase, laminar and incompressible. Under these conditions, the joint's hydraulic conductivity may be written (after Poiseulle) as:

$$K = \frac{\gamma e^2}{12\eta} = \frac{ge^2}{12\nu} \tag{5}$$

where e is the hydraulic aperture (m), g is the gravitational acceleration (m/s^2), and η, γ and υ are the fluid kinematic viscosity (1.0×10^{-6} m^2/s for pure water at 20 °C), density (kg/m^3) and dynamic viscosity (10^{-3} Pa/s) respectively.

Snow 1969 and Louis 1974 assume that discontinuities are characterized by spacing and frequency. Thus, for smooth joints and laminar flow regime:

$$K = \frac{N_i g e^3}{12\nu} \tag{6}$$

where N_i is the frequency of the i-th set (m^{-1}).

The percolation threshold empirical method (Wei et al. 1995) assumes that permeability is strictly influenced by joint length (extent) L and spacing (S). The formation is considered permeable when the average length of the joint is greater than twice the total spacing, or else when it is greater than the average spacing of the different joint sets (Clerici and Sfratato 2008), which leads to the formation of a network allowing the water to flow. This method introduces an elementary representative volume so that if the joint length is greater than 10–15 times the spacing, it may be treated as being infinite and permeability may be calculated using an equation assuming the presence of three perpendicular joint systems in the rock formation (Snow 1968):

$$K = \frac{1}{6} \cdot \frac{e^3}{S} \tag{7}$$

where e is the hydraulic aperture of the smooth discontinuity and S is the average spacing of the systems.

According to Barton and Quadros (1997), traditionally, fluid flowing through rock joints can be described by a cubic law, which follows the assumption that the joints consist of two smooth parallel plates. Real rock joints, however, have rough walls and variable aperture, as well as asperity areas where the two opposing surfaces of the joint walls are in contact with each other. According to this, apertures can generally be defined as mechanical (geometrically measured such as with epoxy injection) or hydraulic (measured by analysis of the fluid flow). The hydraulic aperture (e) can be determined both from laboratory fluid-flow experiments and borehole pump tests in the field.

Fig. 6 3D representation of discontinuities at the six surveyed rock masses

dolostone 5

dolostone 6

limestone 7

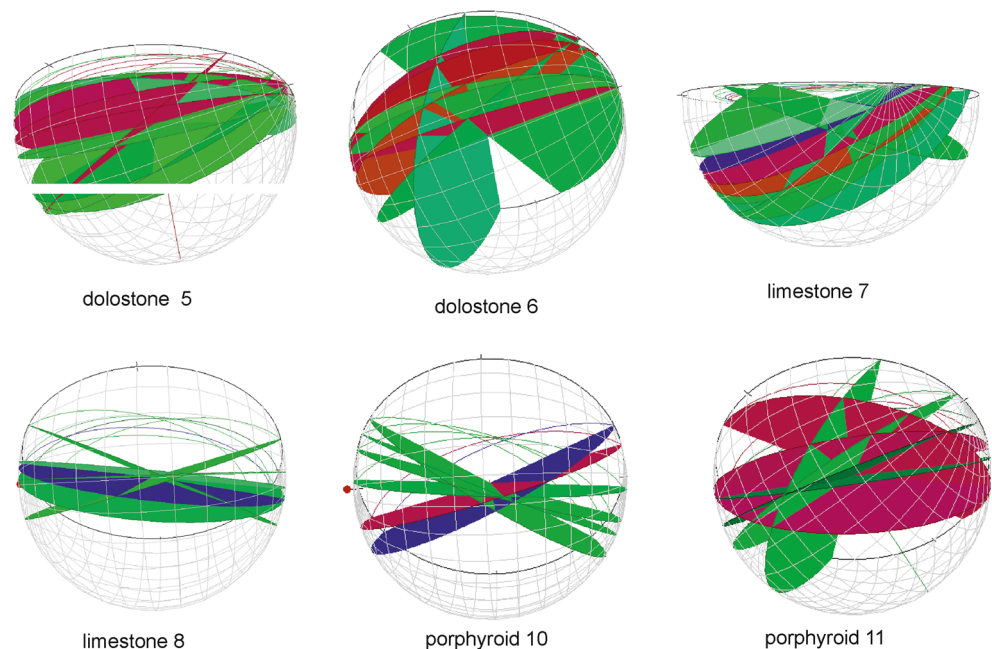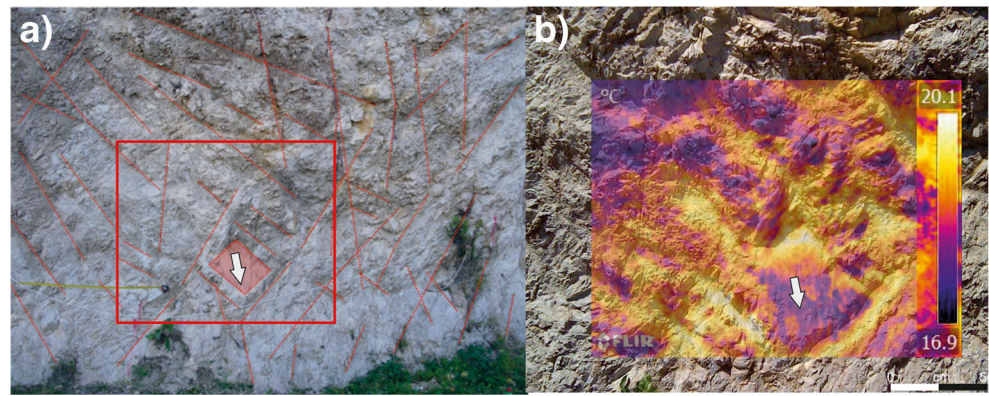limestone 8

porphyroid 10

porphyroid 11

Fig. 7 Main KK (persistent) systems affecting dolostone rock masses: **a** digital photo of the outcrop (red box indicate the area of thermogram in inset (**b**), while the arrow indicates the dip-immersion of the highlighted plane; **b** thermogram of the outcrop

A study by Zimmerman and Bodvarsson (1996) concluded that the hydraulic aperture is less than the mechanical aperture by a factor that depends on the ratio of the mean value of the aperture to its standard deviation. Results by Hakami (1995) showed that the ratio between mechanical mean aperture and hydraulic aperture was 1.1–1.7 for joints with a mean aperture of 100–500 μm. Olsson and Barton (2001), on the basis of experimental data and Barton (1982), proposed the following exponential function, relating the hydraulic aperture to the mechanical aperture and JRC:

$$e = \frac{E^2}{JRC^{2.5}} \tag{8}$$

where E is the mechanical aperture (μm) measured in the field, e is the hydraulic aperture, and JRC is the joint roughness coefficient.

Starting from Louis's Law (1969, 1974) for rough joints, Barton et al. (1985) proposed an empirical relation to correlate the joint roughness coefficient (JRC), with the effective opening of joints:

$$K = \frac{gE^2}{12\nu \left[1 + 8.8 \left(0.5 - \frac{E}{2JRC^{2.5}} \right)^{1.5} \right]} \tag{9}$$

; however, Eq. (9) is only valid when the mechanical aperture is greater than the hydraulic aperture.

Table 1 Hydraulic conductivity according to three empirical methods

Lithology	Site No.	Hydraulic conductivity (m/s)		
		Equation (5)	Equation (6)	Equation (9)
Dolostone	5	2.98×10^{-05}	1.51×10^{-07}	1.07×10^{-05}
	6	8.69×10^{-04}	3.18×10^{-05}	5.17×10^{-06}
Limestone	7	5.36×10^{-06}	4.53×10^{-07}	9.30×10^{08}
	8	2.33×10^{-06}	7.66×10^{-07}	2.49×10^{-08}
Porphyroid	10	3.14×10^{-07}	4.01×10^{-09}	3.21×10^{-09}
	11	4.01×10^{-07}	5.18×10^{-09}	4.85×10^{-09}

When in-filling material occurs within the fractures (sand, silt, clay), the rock permeability is conditioned according to the thickness of such material; thus, laboratory tests will be necessary to evaluate the permeability of the in-filling material. With respect to the case study discussed herein, in-filling is represented by calcite and occurs when the opening is greater than 2 mm. Nevertheless, several experimental studies analyzing the water circulation within a saturated fracture demonstrate that the approximation of a discontinuity as a couple of smooth and parallel surfaces is acceptable from a general point of view.

Results

The rock mass survey at the different outcrops highlighted the presence of seven to ten discontinuity systems, which, along with the close spacing affecting most of these sets, subdivide the rock mass into centimetric rock volumes. Some of these sets are also highlighted by thermograms through positive thermal anomalies, mainly related to the most persistent systems (indicated with KK) in dolostones (warm colors in Fig. 7b). These sets are also affected by a close spacing.

Aperture, spacing and JRC were measured in the six studied stations, in accordance with ISRM (2007)
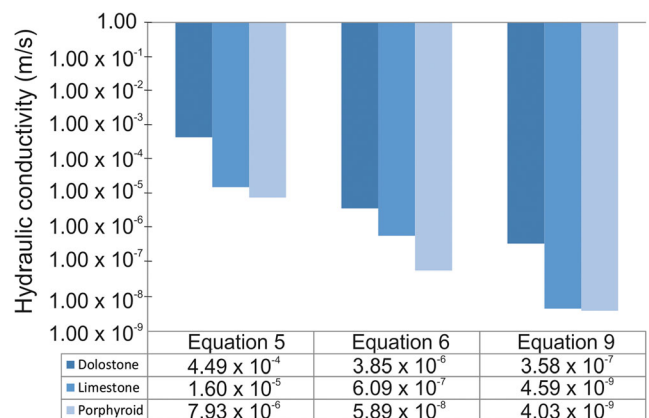

Fig. 8 Hydraulic conductivity values assessed for the three studied lithologies through the considered empirical equations
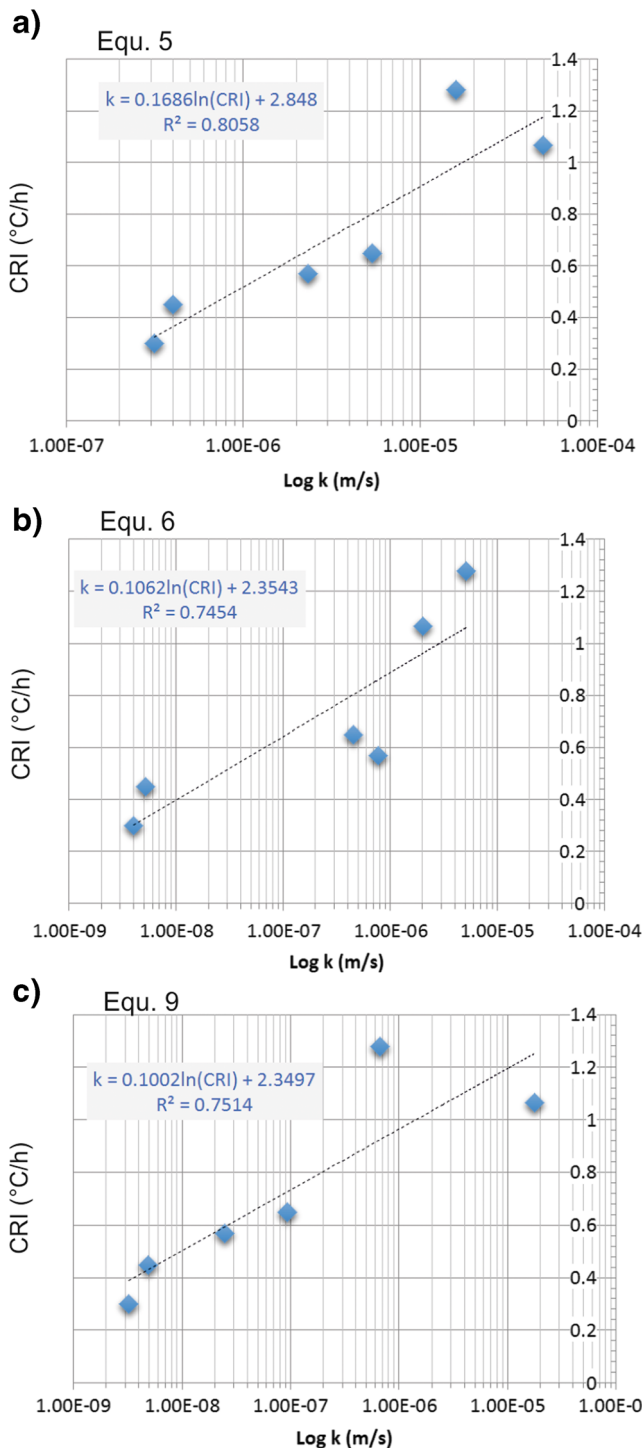
a)

Equ. 5

$k = 0.1686\ln(CRI) + 2.848$
$R^2 = 0.8058$

CRI (°C/h)

Log k (m/s)

b)

Equ. 6

$k = 0.1062\ln(CRI) + 2.3543$
$R^2 = 0.7454$

CRI (°C/h)

Log k (m/s)

c)

Equ. 9

$k = 0.1002\ln(CRI) + 2.3497$
$R^2 = 0.7514$

CRI (°C/h)

Log k (m/s)

Fig. 9 Correlation between K and CRI; K calculated according to **a** Eq. (5), **b** Eq. (6) and **c** Eq. (9)

recommendations. Values in the equations result from the statistical evaluations discussed in section 'Rock mass survey'.

Assessed hydraulic conductivity, through Eqs. (5), (6) and (9), varies according to the considered lithology (Table 1). In particular, Eq. (5) returned the highest conductivity, while the lowest values are related to Eq. (9). Nevertheless, all the three tested methods pointed towards dolostone outcrops as the

most permeable, followed by limestones and porphyroids. Results show differences among the three approaches; in particular, Eq. (5) leads to the greatest permeability in all the lithologies, while Eqs. (6) and (9) give lower values. The least permeable lithology is porphyroids (Fig. 8).

The statistical correlation between K and CRI (Fig. 9) shows satisfactory results, with coefficients of determination (R^2) always greater than 0.74. In particular, the best correlation is achieved when K is calculated through Snow 1968 (Eq. 5), considering only the square opening of discontinuities, followed by Snow 1969 (Eq. 6) and Louis 1974 (Eq. 9). The latter method takes into account the cube opening value, the average set spacing and the JRC. In general, CRI increases along with K, with a positive trend. In fact, both the rock mass cooling and the hydraulic conductivity are proportional to the rock fracturing. The greater dispersion of data occurs at dolostones, where fracturing is associated with some faults.

Values of hydraulic conductivity resulting from Eq. (9) are the lowest, because this method takes into account the roughness along discontinuities. A high roughness value may cause the hydraulic closure of the discontinuity, thus preventing the water circulation enhancing the neutral pressures.

Discussion and conclusions

The assessment of hydraulic conductivity in rock masses is difficult due to the extreme variability of the degree of fracturing. The only in situ methodology aimed at estimating this property in rock masses is the Lugeon test carried out within a borehole. Nevertheless, this may not be representative of the whole rock mass, because it is conditioned by the orientation of the borehole. Another way to estimate the rock mass hydraulic conductivity is based on the application of empirical equations taking into account some geomechanical parameters to be measured on site, leading to time-consuming, and sometimes logistically complex field operations.

For this reason, this paper is aimed at describing a new potential non-invasive technique for the assessment of the hydraulic conductivity from the analysis of the rock face. This pioneering methodology is based on the relation between the hydraulic conductivity of rock masses and their cooling behavior evaluated through IRT. Geomechanical and IRT surveys at three different lithologies (dolostone, limestone, porphyroids) were carried out to estimate the main parameters that characterize rock fracturing (i.e. RQD, Jv, spacing, opening and roughness), and to acquire thermograms of rock masses to estimate their cooling rate (CRI) according to the most recent scientific findings.

Statistical correlation between CRI and RQD/Jv showed a satisfactory positive trend, with particular reference to the one

between RQD and Jv (R^2 = 0.95; SD = 0.09). This is better than the correlation between CRI and RQD (R^2 = 0.74; SD = 0.21), demonstrating that for heavily jointed rock masses (centimetric URV), the Jv parameter is more representative than RQD, because it takes into account the frequency of all the discontinuity sets, unlike RQD, which tends to underestimate these.

In particular, surveyed rock masses are characterized by numerous discontinuity systems, with a close spacing and variable persistence, which condition the rock mass hydraulic conductivity since they all drive water circulation. For this reason, the empirical calculation of permeability has been carried out by considering all the sets occurring in the rock masses. The empirical methods considered herein are by Snow 1968, 1969 and Louis 1974, since in such rock masses, with a low primary porosity of the rock, water mainly circulates through fractures. Among the examined lithologies, dolostones showed a greater hydraulic conductivity due to their close spacing, although the number of discontinuity sets is comparable to the other rock masses. This result has been highlighted also by thermal images and by the CRI computation. This latter, proposed by Pappalardo et al. 2016b, is the variation of the surface temperature of a rock mass per unit of time. The CRI correlated well with the rock fracturing as proved by correlation with the main geomechanical indexes; for this reason, it has been related to the hydraulic conductivity herein. Obtained results show good correlations, proving that such methodology could be regarded as a valid alternative for the assessment of permeability of rock outcrops through geomechanical analysis, representing a potentially quick solution during in situ surveys. In fact, the greater the permeability, the faster the rock mass cooling, because this is strictly connected to the rock fracturing.

It has to be emphasized that this method needs further tests on intensely jointed rock masses to find a representative relation for several rock types, especially where the presence of persistent discontinuities (e.g. faults) could condition the thermal output. At this stage, empirical methods were useful to calibrate IRT as a potentially useful tool for the study of hydraulic conductivity of rock masses and this paper underscores the validity of CRI as an index representative of several rock mass properties.

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