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PRELIMINARY RESULTS FROM MULTITEMPORAL INFRARED THERMOGRAPHY SURVEYS AT THE WIED-IL-MIELAH ROCK ARCH (ISLAND OF GOZO)

GUGLIELMO GRECHI & SALVATORE MARTINO

Sapienza University of Rome - Earth Sciences Department - Rome, Italy;
Corresponding author: guglielmo.grechi@uniroma1.it

EXTENDED ABSTRACT

Le frane in roccia rappresentano uno dei pericoli naturali meno prevedibili a causa della loro impulsività e della spesso trascurabile entità delle deformazioni ad esse propedeutiche. Tali frane, inoltre, sono in grado di determinare scenari ad elevato rischio sia quando impattano infrastrutture antropiche nei contesti urbanizzati, sia quando coinvolgono ambiti naturalistici ad alta frequentazione, quali siti turistici altamente attrattivi. I versanti in roccia si presentano spesso predisposti alle instabilità gravitative a causa della presenza di sistemi di fratturazione che, in virtù della loro densità ed orientazione, influenzano fortemente le caratteristiche di resistenza e deformabilità degli ammassi rocciosi fratturati. In relazione a queste condizioni predisponenti le instabilità di versante, il verificarsi di fenomeni marcatamente transitori, quali terremoti, vibrazioni indotte o forti precipitazioni piovose, può determinare il raggiungimento delle soglie di innesco di fenomeni franosi in tempi considerevolmente ridotti. Su scale temporali più ampie sono però i cosiddetti fattori preparatori ad esercitare una continua, e non trascurabile, azione di graduale danneggiamento e di progressiva riduzione delle proprietà meccaniche degli ammassi rocciosi fratturati. Nel tentativo di comprendere le modalità con cui i fattori preparatori influenzino il comportamento meccanico degli ammassi rocciosi, sono diversi gli studi che hanno tentato di analizzare gli effetti deformativi e di deterioramento delle caratteristiche geomeccaniche provocati in particolare dalle fluttuazioni giornaliere e stagionali della temperatura. Infatti, in contesti meteoclimatici in cui le escursioni termiche diurne superano le decine di gradi, l'effetto del susseguirsi di cicli di riscaldamento e raffreddamento, trascurabile se considerato nel breve termine, è in grado di influenzare il comportamento su lungo termine di ammassi fratturati operando con un processo di *thermal fatigue*: l'entità degli effetti termomeccanici cumulati nel tempo è tale da non poterli omettere dal bilancio dei fattori che contribuiscono al graduale processo di *mechanical weathering* degli ammassi rocciosi. La propagazione di un flusso termico all'interno degli ammassi rocciosi, derivante dalle periodiche fluttuazioni della loro temperatura superficiale, determina il configurarsi di un campo di temperatura le cui variazioni, in termini di intensità delle fasi di riscaldamento e raffreddamento, sono funzione della distanza dall'interfaccia di scambio termico. Tali modificazioni generano delle deformazioni cicliche termo-indotte, la cui entità è massima all'interno delle porzioni più superficiali degli ammassi rocciosi, che sono anche le più predisposte ad instabilità gravitative quali scorrimenti, ribaltamenti o crolli. Il risultato dell'alternarsi di cicli di espansione e contrazione termica induce un fenomeno di progressiva degradazione delle proprietà meccaniche di ammasso che, esplicandosi attraverso processi di neo-fratturazione (micro-fratturazione) e di propagazione di fratture preesistenti, può determinare nel tempo il raggiungimento di deformazioni irreversibili compatibili con le soglie di innesco di fenomeni franosi, quali soprattutto crolli e ribaltamenti. Lo studio di tali processi di instabilità gravitativa in ammassi rocciosi non può dunque prescindere da una caratterizzazione delle forzanti termiche sito-specifiche, il cui livello di dettaglio ed approfondimento deve essere commisurato, in termini di risoluzione spaziale e temporale, alla scala di indagine. Il presente lavoro pone in evidenza i risultati ottenuti a partire dall'esecuzione di due campagne di monitoraggio termografico, dalla durata giornaliera e condotte in condizioni meteoclimatiche differenti (Autunno-Inverno), presso l'arco costiero di Wied-Il-Mielah, situato nel settore nord-occidentale dell'isola di Gozo (Malta). L'acquisizione di immagini termiche ha permesso di ricostruire non soltanto l'evoluzione temporale delle temperature superficiali dell'ammasso roccioso assieme alle relazioni sussistenti con la temperatura ambientale ma, fornendo contemporaneamente una dettagliata distribuzione spaziale delle stesse, ha consentito di valutare le modificazioni del campo di temperature in relazione ai caratteri morfologici della struttura. I risultati così ottenuti evidenziano come la termografia ad infrarossi, essendo una metodologia di indagine remota, non-invasiva e non-distruttiva, rappresenti un valido ed utile strumento per la caratterizzazione del comportamento termico di ammassi rocciosi fratturati.

ABSTRACT

The Mediterranean region is climatically characterized by considerable daily and seasonal temperature fluctuations due to both direct solar radiation and local weather conditions. The long-term mechanical behavior of jointed rock masses can be actively influenced by the superposition of continuous thermal excursions, especially if exceeding the tens of degrees, and thus rock mass systems could be slowly led toward prone-to-failure conditions. With a view to evaluating the entity of thermal forcings acting on a jointed rock arch, consequently characterizing its thermal behavior, two daily InfraRed Thermography (IRT) monitoring surveys were performed in different seasons (Autumn and Winter) at the Wied-Il-Mielah case study (Island of Gozo in the Maltese archipelago).

The obtained preliminary results highlight that the rock mass thermal attitude is strictly related to both the magnitude of the incoming and outcoming heat flux (resulting from the heat-exchange with atmospheric thermal conditions and direct solar radiation) and to the exposure of rock mass surfaces with respect to the incident solar radiation. IRT proved to be a valid remote surveying technique for the definition of the surficial temperature distribution of rock masses, being able to provide useful information in supporting more traditional approaches for the study of thermomechanical effects on rock masses.

Keywords: *infrared thermography, rock mass, thermomechanics, slope stability*

INTRODUCTION

InfraRed Thermography applications in Earth Sciences are mostly related to the passive monitoring of volcanic activity and fumarolic systems (Chiodini *et alii*, 2007; Furukawa *et alii*, 2010; Spampinato *et alii*, 2011) or to the detection of temperature anomalies induced by the presence of geothermal fields (Coppola *et alii*, 2007), nevertheless thermal imaging techniques are mostly being applied in research fields such as Medicine, Chemistry, Civil and Materials engineering (Pappalardo *et alii*, 2016).

Despite the widespread applications of IRT monitoring, its implementation for the study of rock mass instabilities is still limited (Fiorucci *et alii*, 2018). IRT pioneering applications were tested on the study of concretes and rock masses integrity (Clark *et alii*, 2003), laying the basis for the assessment of jointing conditions (Teza *et alii*, 2012) and rock mass geotechnical characterization (Pappalardo *et alii*, 2016), aiming either at the evaluation of the influence of joints attitude on rock masses proneness toward growing instability (Fiorucci *et alii*, 2018) and at the assessment of the related geological hazard due to the potential occurrence of fast to very-fast landslides (Martino *et alii*, 2014). Several studies highlighted that where temperature ranges exceed the tens of degrees, thermally-induced effects related to the superimposition of heating-cooling cycles, negligible if considered in short- to middle-time, can influence rock mass mechanical behavior acting as a thermal fatigue process (Gunzburger *et alii*, 2005; Collins & Stock, 2016): the intensity of thermomechanical effects, cumulated over time, cannot be then omitted from all those factors which actively contribute to the progressive damaging and to the mechanical weathering of rock mass properties (Bakun-Mazor *et alii*, 2013; Gischig *et alii*, 2011a).

Daily temperature fluctuations can exert slight, yet repeated, perturbations of stress fields resulting in a day-to-day cumulative effect, contributing over wide-time scales to lead rock slopes to a prone-to-failure condition.

The comprehension of thermomechanical deformations on jointed rock masses, thus requires the definition of both the amplitude of thermal actions and the spatial distribution of near-surface temperatures (Fiorucci *et alii*, 2018; Greif *et alii*, 2016).

The heat flux propagation can be markedly influenced by rock mass jointing conditions (i.e. fracture density and spatial orientation) (Pappalardo *et alii*, 2016; Fiorucci *et alii*, 2018), acquiring a predominant role in the localization and accumulation of plastic deformation. With the aim to constrain and quantify the effect of direct solar radiation on both the heat balance and surficial temperature distribution fluctuations of rock mass, two IRT daily monitoring surveys were performed on the selected case study of the Wied-Il-Mielah rock arch, located on the Island of Gozo (Malta).

Monitoring campaigns were conducted in October 2018 and January 2019 and thermal images were acquired every hour from 07:00 to 22:00, in order to collect multitemporal frames of the temperature field, thus assessing its variations in time and space through different seasons.

The obtained results represent a preliminary contribution for the characterization of the thermal forcing which continuously acts on this natural structure.

GEOLOGICAL SETTING

The Island of Gozo is the second largest island of the Maltese archipelago, central Mediterranean Sea, and is located about 100 km south Sicily and 290 km north-east of Tunisia (Fig. 1a).

The Maltese archipelago stands on a shallow submarine elevation, the Malta plateau, which is part of the Pelagian Platform, and represents the emergent part of an extensive shallow-water shelf extending from eastern Sicily to the Malta graben (Pedley, 2011; Gigli *et alii*, 2012).

The geological setting of Gozo is characterized by a sedimentary sequence of five litho-stratigraphic units, mainly composed by Oligo-Miocenic limestones and marls (Fig. 1b, 1c) which underwent a strong tectonic uplift related to the Pliocenic opening of the Pantelleria Rift, outcropping all over the island (ALEXANDER, 1988; PEDLEY *et alii*, 2002; GIGLI *et alii*, 2012). From oldest to youngest these units are:

• Lower Coralline Limestone Formation (LCL), a compact and hard grey limestone (late Oligocene – Chattian) whose thickness varies between 100 and 140 m;

• Globigerina Limestone Formation (GL), a soft fine-grained yellow limestone (Miocene – Acquitanian-Langhian) with a thickness up to 200 m;

• Blue Clay Formation (BC), very soft pelagic blue or grey clay marl and limey clay (Middle Miocene – Serravallian), with a thickness variable from 20 up to 75 m;

• Greensand Formation (GS), massive brown to dark green bioclastic limestone (Upper Miocene – Tortonian), with a thickness up to 10 m in central sectors of Gozo;

• Upper Coralline Limestone Formation (UCL), a grey fossiliferous coarse-grained limestone (Upper Miocene – Tortonian-Messinian), up to 160 m thick.

The stratigraphic sequence of the Wied-il-Mielah rock arch is presented in Figure 2. The structure is completely composed by 30 m of the LCL Formation, overlaid by a GL Formation cap, and it is possible to recognize two different members (PEDLEY *et alii*, 2002):

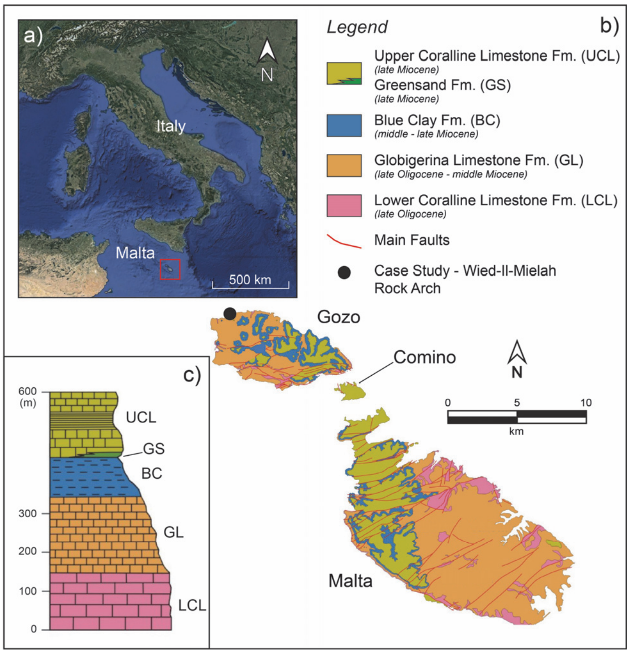

Fig 1 - Geographical setting (a), synthetic geological map (b) and simplified stratigraphic sequence (c) of the Maltese islands (GIGLI et alii, 2012, modified)

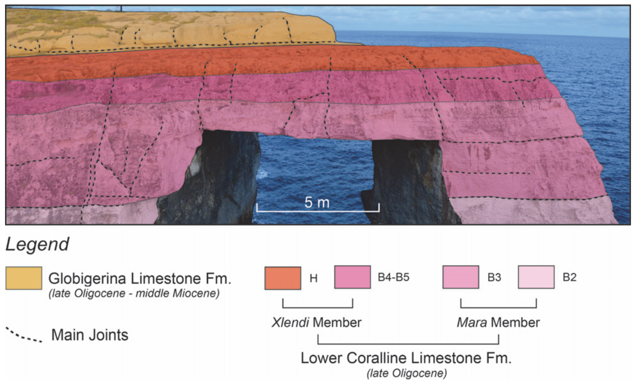

Fig. 2 - Geological sketch of the Wied-Il-Mielah rock arch. Main joints traces have been represented in order to highlight the pervasive jointing condition of the rock mass

• Member A, which is subdivided in 4 facies (A1-A2-A3-A4) and represents the equivalent of the Attard Member, is characterized by almost 20 m of horizontal strata of micritic to fine-grained limestone dominated by calcareous coralline red algae;

• Member B, which is subdivided in 5 facies (B1-B2-B3-B4-B5), is characterized by a 15 m sequence of horizontal to cross-bedded grainstone to packstone (B2-B3) overlaid by packstone to wackestone limestones (B4-B5), equivalent to the Xlendi Member and Mara Member respectively.

The rock arch is delimited by vertical cliffs almost 30 m height and presents a 0°-10°N orientation of its major axis. The whole structure is dislodged in several blocks by the presence of centimetric-wide open joints, whose intersections are able to identify potentially unstable rock sub-blocks, thus in a prone-to-failure condition. According to the ISRM standard (ISRM, 1978), geomechanical surveys of the rock arch were carried out in order to achieve a preliminary characterization of the attitude (dip/dip direction), persistence, spacing, aperture, filling, JCS coefficient (joint surface compressive strength) and JCR coefficient (joint rugosity coefficient) of the main joint sets affecting this structure. Therefore, four main joint sets were identified: J0 (horizontal bedding), J1 (10°N/80-90°), J2 (100°N/80-90°), J3 (35°N/70°).

METHODOLOGY

With a view to understanding and constraining the thermal behavior of the Wied-Il-Mielah rock arch, thermal mapping of the rock mass was performed during daily surveys with seasonal recurrence. In particular, the here presented results are derived from two measurements campaigns that were carried out in October 2018 (Autumn campaign) and January 2019 (Winter campaign), and in both circumstances no rain or significant cloud coverage occurred. Image collection was conducted through a Testo® 885-1 thermal camera, with temperature measuring range between -30°C and 100°C, accuracy calibrated

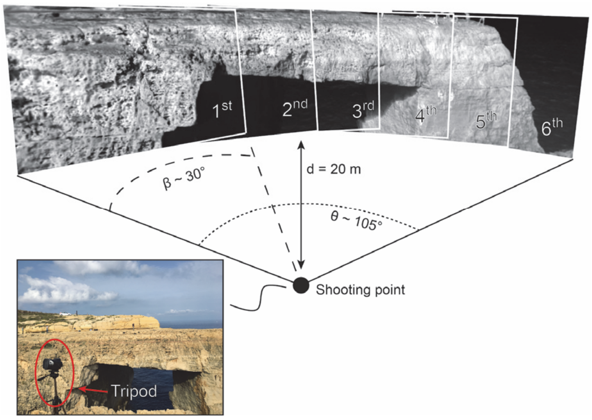

Fig. 3 - Simplified model of the six thermal images georeferencing process. Legend: d = distance of the shooting point from the monitored arch surface; β = horizontal angle of view of the IR camera; θ = total angle of view obtained by overlapping IR images

within ±2% of reading values, field of view (FOV) 30° x 24°, IR resolution of 320 x 240 pixels, Noise Equivalent Temperature Difference (NETD) of 30 mK and maximum geometric resolution of 1.7 mrad. To ensure the camera stability a tripod was employed and placed at a distance of 20 m from the center of the rock arch exposed surface and thus guaranteeing a detailed geometrical resolution in the range of 3-3.5 cm. In order to achieve the replicability of image acquisition and to maintain the same shooting point, markers were fixed both on the rock arch top and on the ground where the tripod was located. Additional instrumentation, consisting in a Kestrel® 5500 portable weather station, was also employed for air temperature and relative humidity fluctuations control and, moreover, the so collected values were settled in the thermal camera proprietary open-source software Testo-IRsoft® for atmospheric correction. The emissivity coefficient of rock mass was assumed equal to 0.94, taking into account typical values for limestones (FIORUCCI *et alii*, 2018). The monitored surface of the arch is characterized by a 0°-10°N direction and then results in an almost perfect eastward exposition. This means that even if considering the variability of sun paths and relative heights in time, the monitored surface is always normally exposed to the direct solar radiation of the first hours of the day during all seasons. Monitoring activities were performed through a standard acquisition of thermal images, consisting in the collection of thermograms every hour from 07:00 (before sunrise) to 22:00 (after sunset). Due to the camera FOV and the relatively close distance from the target, it was necessary to acquire six thermal images by turning the camera on its axis of a 20° angle, covering a total angle of view (θ) of 105° (Fig. 3). Therefore, all the acquired images were manually georeferenced and overlapped in order to obtain a panoramic view of the arch face for every single hour of monitoring (Fig. 3). In the post-processing stage, thermal images were analyzed by comparing the distribution of temperature fluctuations over the day in the two different seasons, focusing on the surficial distribution of temperatures (Fig. 4), and through the extraction of temperature time-series from two control-points representative of the directly exposed rock matrix and of an open joint respectively. (Fig. 4d, 4h).

PRELIMINARY RESULTS FROM IRT SURVEYS

All the presented thermal images show the distribution of temperature values of the monitored rock arch in a false color-scale rendering, covering a surface of the rock mass of about 112 m^2. It has already been observed that while rock surface daily temperature fluctuations are markedly influenced by direct solar radiation, relative exposure and heat exchange between the atmosphere and the rock mass, seasonal drifts more likely depend on local climatic conditions affecting the thermal behavior of the rock mass, in terms of heating and cooling phases (PAPPALARDO *et alii*, 2012; GUNZBURGER & MERRIEN-SOUKATCHOFF, 2011; GREIF *et alii*, 2016; FIORUCCI *et alii*, 2018). From a preliminary observational analysis of both Autumn and Winter thermograms, it is possible to discern a similar thermal behavior of the rock mass in terms of temperatures distribution in heating and cooling stages. In fact, even though several isothermal bands can be identified, thus representing inhomogeneous temperature fields, their spatial distribution appears to comparable in both seasons. During the first hours of the day (Fig. 4a, 4e), usually at sunrise, highest temperatures tend to cluster in correspondence of areas representing either surface morphological irregularities and main joint surfaces or differently oriented sectors with respect to the monitored surface, while lower temperature values are homogeneously distributed on the surface itself. After the heating phase of the rock mass, thus at the daily maximum temperature peak (Fig. 4b, 4f), temperatures invert their distribution with respect to early morning stages, with coldest areas spatially limited to those sectors representing shadowed morphological irregularities and hottest areas representing sectors of the rock mass directly exposed to solar radiation. When the whole arch surface is not anymore exposed to the incident solar radiation, then at sunset (Fig. 4c, 4g), isothermal bands describe a relative temperature field similar to early day stages (Fig. 4a, 4e). The here discussed thermal behavior of the rock mass is also graphically presented in Figure 4d and 4h, where temperature values extracted from two control-points on the IR images, representative for the rock matrix (T_1 – hotspot) and for a rock mass main joint (T_2 – coldspot) respectively, were compared with air temperature time-series (T_3). Temperature time-series clearly highlight how different temperature trends and ranges were experienced by the rock arch during both monitoring campaigns. In fact, while T_1 overwent a thermal excursion of 20 °C and 13 °C, in Autumn and Winter season respectively, T_2 has suffered lower amplitude temperature fluctuations of about 8 °C and 4°C (red and blue dashed lines in Figure 4d and 4h). Moreover, three different daily stages can be identified for both seasons, showing how rock mass temperatures evolve with respect to air temperature. At sunrise and at sunset, then immediately before heating phase start (t_1) and after the first hours of cooling phase (t_3), rock mass temperatures (both T_1 and T_2) are lower than atmospheric temperatures. Instead, due to the intense contribute of solar radiation, rock mass temperature reaches its maximum positive peak to then gradually decrease in time (t_2), passing through two transitional phases of isothermal condition with the outer atmosphere.

CONCLUSIONS

In October 2018 and January 2019, two IRT monitoring field-campaigns were carried out at the Wied-Il-Mielah rock arch, north-western sector of the Island of Gozo, through the acquisition of multitemporal thermal maps of the investigated rock mass. These activities achieved to provide a preliminary characterization of both the thermal behavior of this natural structure, in terms of temporal and spatial evolution of rock surficial temperatures, and of the thermal forcing acting on the rock mass itself. At the light of the obtained results, the

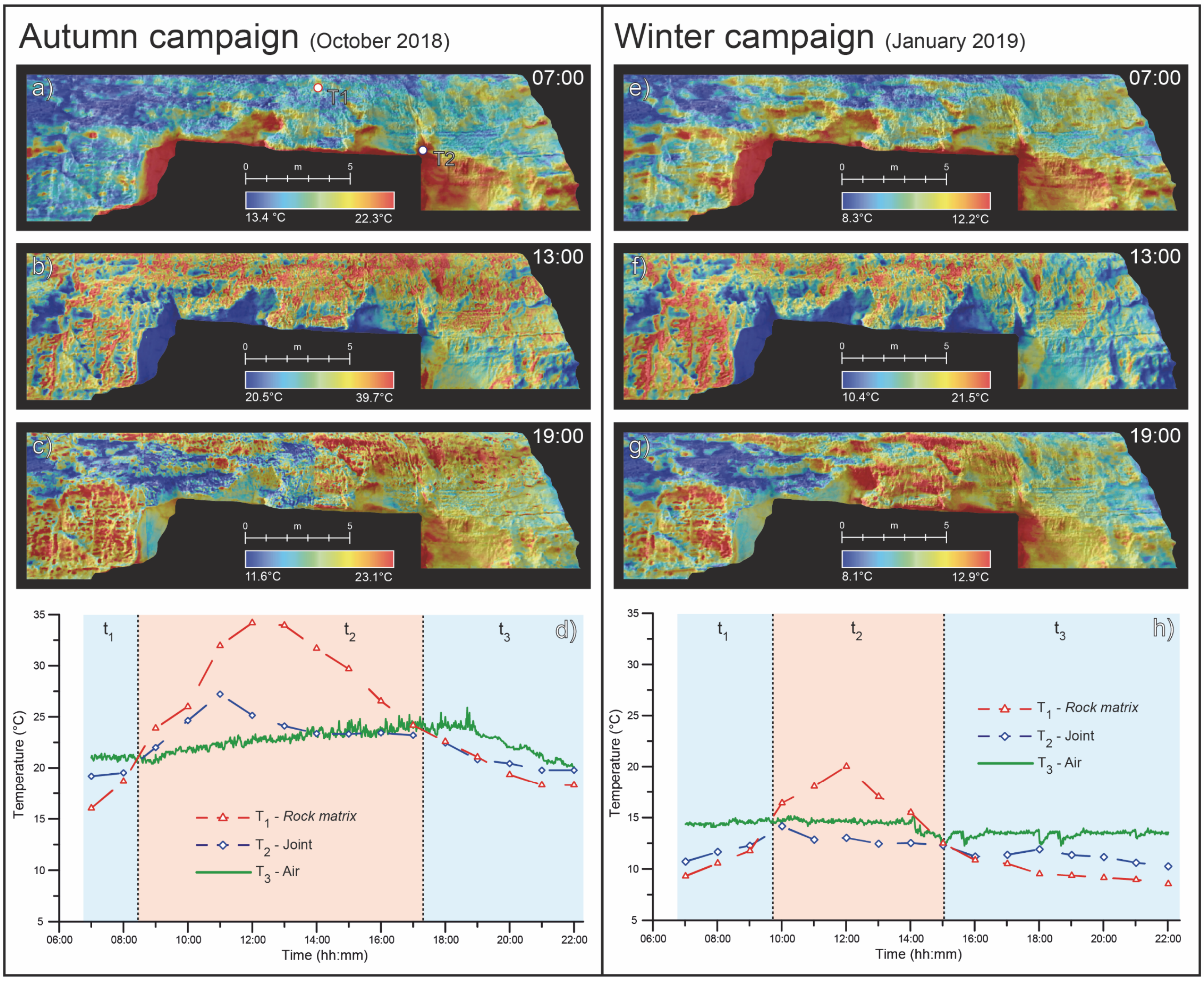

Fig. 4 - Thermal maps of the monitored surface of the Wied-Il-Mielah rock arch for different hours of the day (07:00, 13:00, 19:00). The here presented IR images were obtained during daily monitoring surveys performed in Autumn (a, b, c) and Winter (e, f, g); (d) ,(h): comparison between temperature time-series derived from two control-points on thermal images (T_1 and T_2), whose locations are specified in (a), and air temperature (T_3)

exploitation of InfraRed Thermography monitoring surveying could represent a useful technique to provide key information for several widespread approaches for the investigation of thermomechanical effects on jointed rock masses, such as for numerical modelling methods or for the design of in-situ multiparametrical monitoring systems. Furthermore, an exhaustive characterization of the thermal behavior of the arch could also contribute to assess defensive strategies for this naturalistic heritage, designing conservation interventions aimed at preserving this heritage site from landslide processes.

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