Towards Quantifying Degree of Rock Weathering from Time Series Thermal Images

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February, 2010

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by

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Thesis submitted to the International Institute for Geo-information Science and Earth Observation in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation, Specialisation: (fill in the name of the specialisation)

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Abstract

Weathering degree is often estimated by methods requiring physical tests and expert judgments which are time consuming and depend on accessibility of the targets.

In this study the radiant temperature variation of rock samples and rock masses with time over a day has been looked into for possible quantification of weathering degree.

For this purpose temperature series images monitored over the duration of a day on artificial samples mosaic of Granite, Slate and Mudstone with varying degree of weathering and temperature images acquired from field sites of Slate rock mass slope and Granite rock mass slope were used. These are evaluated using indices obtained from the temperature series for the different weathering classes and compared with the weathering classes determined in the field following geotechnical guidelines. Lowest morning temperature record (*A*), maximum temperature record before direct solar irradiance (*B*), the temperatures after receiving 5, 30 and 80 minutes of direct solar irradiance (*B*, *C*, *D*) and the days peak temperature (*F*) of the rocks and their ratios were used as index .

F/C and *E/C* ratio images gave relatively consistent increasing trend with weathering degree while *B/A* and D/C gave less consistent similar trend. Higher degree of overlap between the range of values for different lithologies were found suggesting possibility of transferable scale of measurement between different sites in the case of *B/A* and *D/C* ratios. The lack of overlap in *F/C* and *E/C* ratios suggests only a relative means of quantification for different sites requiring more reference information on the target to calibrate. In the rock mass outcrops temperature series image a method to represent the temperature inversion between morning and noon time images of weathered and un-weathered parts gave fairly consistent result to the expected.

An attempt has been made to characterize the spectra features of the samples from the different degree of weathering. Apart from the elevated overall emissivity of the samples with weathering no significant change in spectral association could be found.

Key words: Temperature series, degree of weathering, Quantitative, terrestrial IR.

Acknowledgements

The humble offer of the Netherlands Fellowship Program (NFP) for the full scholarship to study in the Netherlands and the will of my employing organization, Geological Survey of Ethiopia (GSE), for letting me further my education is highly regarded.

My deepest gratitude goes to my supervisors Dr. Robert Hack and Chris Hecker for the close, valuable, and welcoming atmosphere of supervision they have given me. I have greatly benefitted from the wits and tips I have gotten. All the comments and suggestions made by the proposal and mid-term assessment committee have benefitted me to consider matters critically.

The correspondence with Ir. Siefko Slob and acquaintance with the field work area by Dr. Marko Huisman is duly acknowledged.

The experience I have shared with fellow students from all corners of the world had given me the unique opportunity of virtual “touring” through the world. All teams of International Institute for Geo-Information Science and Earth Observation, (ITC) are thanked for their service, assistant, and understanding to make my stay as comfortable as possible.

Nevertheless, it suffices to mention the almost eminent jeopardy of the field work due to lack of co-ordination at the beginning regarding the use of certain instruments. It has not been settled by reverting to alternative plans.

Finally I wish all fellow students and the stuff of ITC a prosperous and fruitful future ahead of them.

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1. Introduction

1.1. Background and Problem statement

Weathering or geotechnical degradation of rocks and earth materials at or near the earth surface is an unavoidable process. This implies that all structures built in or on the earth surface are also influenced as these are found on them. Several approaches have been developed over the years to account for this inherent natural process in the design of such structures. The most common are based on standards for a qualitative geotechnical classification of the degree of weathering. The classification is to a large extent subjective and heavily depending on the expertise and experience of the individual in the field. Therefore, it is important to have quantitative, unbiased methods that help to determine the degree of weathering in intact rock and rock masses (and in some cases also for soil and soil masses, although that is not the subject of this research).

In principle, a quantitative degree of weathering can be established using any property that changes unidirectional from fresh to completely weathered through the different levels of degrees of weathering (Arıkan, 2007). A previous work, (Kekeba, 2008), already indicates systematic patterns of temperature changes between early morning and mid day temperature values of rock outcrops with varying degree of weathering. A strong relation between LiDAR intensity and radiant temperatures was also found for units of same degrees of weathering. Nevertheless, the quantification aspect of the degree of weathering was not addressed in the work. As such, sequential record of rock outcrop radiant temperature could be used to quantify its weathering degree based on the thermal response of the rock surfaces with time. Difficulties arising from reaching higher parts or hazardous parts of the target outcrop (slope face), lack of means of continuous measurement in degree of weathering on slope face are some of the other setbacks in the existing method of weathering degree assessment that need to be addressed.

1.2. Research formulation

The changes in physical properties of weathered rocks are well understood from long history of practice and laboratory measurements (Carmichael, 1989), (Gupta, 2000), (Hack, 1997). In general the weathering of rocks is accompanied by loosening of grain to grain contact, increased porosity and lowering of density, alteration of the minerals. These changes can in principle affect the heating and cooling rate of the rocks. A high frequency of rock surface temperature measurement can hence be use to obtain the inherent difference brought about by the variation in the physical properties mentioned above. Hence the objective of this research is to test possibility of using the temperature differences of weathered and un-weathered rocks as measured from field instances over time with diurnal range.

1.2.1. Major Objective

To assess the possibility of developing quantitative degrees of rock mass and intact rock weathering from temperature images for geotechnical purpose. In this regard the following specific targets are formulated to address the overall objective.

1.2.2. Specific Objectives

- To analyze the change in radiant temperature with time as a function of the different weathering degrees, as observed in the field over span of a day.
- To assess the use of radiant temperature derivatives from time series measurements in the form of image to predict the degree of weathering.
- To investigate the role of alteration of the rock materials in the surface temperature variation between different classes of weathering degree, as revealed from the radiant temperature series measurements in the field and reflectance spectra measurements of representative samples.

The questions that need to be addressed with this regard are formulated in the following manner.

1.2.3. Research questions

1. Do different degrees of rock mass weathering show difference in the rate of heating? If yes, what causes the difference?

Hypothesis: Inhomogeneous rock mass show different rate and magnitude of daily cyclic heating and cooling depending on the thermal property of their in homogeneities and the way they form the rock mass. Hence, materials of higher thermal inertia tend to heat up slowly and to lesser extent than those with lower thermal inertia.

2. Can quantitative scales of weathering degree evaluation be derived from the differences in thermal response between weathered and un-weathered rock masses?

Hypothesis: The variation in the pattern of the heating and cooling rate is proportional to the extent of alteration or weathering of the material from the parent material.

3. Can temperature measurements made at far fewer instants in a day than the high frequency of temperature measurements be used to derive valuable information as those of the high frequency?

Hypothesis: Methods which work for temperature measurements of high frequency measurements could be used by extrapolating the measurements to those only taken at strategically practical times of the day.

4. Can the variation in thermal response due to weathering degree be explained by a change in materials composition?

   Hypothesis: A relationship can be established between different weathering classes and the dominant minerals.

1.2.4. Thesis Structure

The thesis is organized into six sections. The first one sets forth the research formulation, where the background and objectives are presented. Following this a section on review of related works is given. The third part deals with the methodology employed to collect the field data, data organization and description of the study area.

Analysis of the data in light of obtaining derivative from temperature series with time to infer the degree of rock weathering is presented in the fourth section. Following this the results of the analysis along with explanation and discussion of the analysis results are given. Finally, conclusions drawn and identified recommendations are presented in the sixth section.

2. Background

2.1. Introduction

Rock weathering process is a dynamic process taking place in response to physical and chemical reactions which may or may not take place concurrently. Physical weathering refers to disintegration of rock material by the action of water, thermal stress, freezing and thawing, and stress configuration change upon unloading or exposure to new environment than under which it was formed. Chemical weathering on the other hand is decaying process of rock material by humidity, moisture and hot climate. Weathering brings about transformation in colour, fabrics, mineralogy, texture, sizes and decomposition to regolith and soil of rock masses. Hence, under the influence of weathering, the strength, density and volumetric stability of the rock will be reduced, while deformability, porosity and weather-ability are increased.

Weathering assessment of rock material has evolved in multi disciplinary fields of study such as rock art heritages preservation, building stones evaluation and geotechnical site investigation for civil infrastructures. Several works are reported to have been undertaken in this regard, (Inkpen et al., 2001), (McKinley et al., 2006). Nevertheless, most works focus on felsic rocks such as Granites. It could be the knock on effect from the coincidental challenge encountered in earlier civil works such as those in Hong Kong, which are situated on extensively weathered Granite, leading to formations in this area be given due attention. The earlier works of Ruxton and Berry in the case of the Hong Kong Granites and other investigators are examples in this regard (Dearman, 1975), (Arıkan, 2007), (Baynes, 1978), (Annon, 1999).

2.2. Weathering description Standards

Various schemes have been adopted to assess the degree of weathering which is still a problem lacking a clear solution on its classification and description (Annon, 1995). Various associations and organizations took it up on themselves to develop their own system of geotechnical standards resulting in various weathering degree classifications schemes (Hencher, 2008). Generally the degree of weathering is assigned for a geotechnical unit in an exposure, or core samples from borehole, based on a set of characteristic properties prescribed in standards. But the lack of common agreed classification system throughout posed often use of different terminology and inconsistency of classification schemes.

Over the years these standards have been revised several times as more information is obtained through experiences, (Annon, 1999), (Annon, 1995), (ISRM, 1981b), (Annon, 1981), (Annon, 2003). They have been the basis of most of the subsequent works on the quantification of weathering degree. The BS 5930:1981 standard has six (6) weathering degree classes: fresh, slightly weathered, moderately weathered, highly weathered, completely weathered and residual soil, (Annon, 1981). In the system, discoloration of the rock material and rock to soil ratio are the main assessment criteria used for the weathering classes determination.

Following BS 5930:1981, amendments were made on it resulting in the BS 5930:1999 standard. Elaborate classification of weathering degree schemes were adopted in this standard. This includes classifying the weathering degree of rocks having different natural competence separately. Hence rocks falling in the category of high competence (strong) are classified based on different criteria than those of weaker rocks. Nevertheless, the implementation is reported to be cumbersome and also the interpretation often misleading. This has been attended in the currently active standard introduced as ISO 14689-1:2003.

In the ISO 14689-1:2003 standard the degree of weathering is once again classified into six classes similar to the earlier version of the BS-1981 standard for the rock mass Only slight change in description used for the slightly weathered class is found in which in the recent classification the extent of rock discoloration is not specified. The *rock mass* weathering grade (from the ISRM, 1978 standard) ranges between 0 for fresh and 5 for residual soil, but runs from 1 to 6 in the BS-1981 version. On the other hand four descriptive classes are recommended for *rock material* weathering as fresh, discoloured, disintegrated, and decomposed, although no scale of weathering grade is given for this scheme.

The standards development by individual countries have recently been integrated into a new system called the Euro code 7, where the number 7 designates the part concerning geotechnical issues. This has been sought to be the de-facto standard for Europe and worldwide in near future.

2.3. Intact rock versus Rock mass weathering

Two types of weathering assessment are used depending on the intention of the assessment, rock mass and intact rock assessment. The major difference is in the case of intact rock weathering the pure continuous rock matrix is considered. The evaluation is based on the core disintegration of the materials making up the rock itself. In rock mass weathering assessment on the other hand emphasis is given to the intact rock as well as the discontinuity in the rock. Both assessments are carried out depending on the purpose. For engineering works that heavily depend on evaluation of the individual rock materials for their integrity, intact rock weathering is implemented. Examples are in assessing cultural heritages, monuments, stones for building blocks. On the other hand in engineering works that require site specific evaluation such as tunnel, retaining wall, and foundation design, the weathering assessment has to give account of the mass weathering rather than the individual blocks of rock.

Three aspects of weathering are prescribed as very important for describing any rock mass for engineering purpose by the British Standard (Annon, 1999): the degree, the extent, and the nature of weathering. The degree indicates intensity of the weathering effect while the extent indicates the area coverage of the weathered region. The nature has to do with expressing the volumetric regularity or irregularity of the change in engineering properties of the rock material (Price, 2009). The fact that weathering progresses from discontinuity planes inward (Price, 1993), (Fookes, 1989a) means that weathering evaluation from the rock mass point of view is essential. This involves qualitative assessment methods. With the trend so far, rock mass and intact rock weathering evaluation is undertaken qualitatively as well as quantitatively. Following are given an account of each approach with some applications in literature.

2.4. Qualitative versus Quantitative Assessments

Change in some physical and engineering geological properties of rock mass take place upon weathering. Some of these reported properties include, decrease in density, unconfined compressive strength, seismic velocity, Schmidt hammer rebound number, rock cohesion, higher moisture content and porosity are just few to list, (Price, 2009), (Huisman, 2006), (Gupta, 2000). These noted changes in property have been utilized to assess the degree of weathering in general, (Ceryan S., 2008) (Gupta, 2000).

Qualitative methods of weathering evaluation are based on the visual inspection of the physical and engineering geological parameters. Some of them could be inferred from index test while others require mechanical tests. The visual evaluation heavily depends on judgment and experience of the expert. The geotechnical standards are based on the visual observation of the outcrop or samples (in the case of borehole cores samples) (Annon, 1995), (ISRM, 1981b), (Annon, 1981), (Annon, 1999), (Annon, 2003), (ASTM, D5878-05). These systems are mainly based on the visual definition of the geological properties, the index properties and the basic mechanical tests, (Ceryan S., 2008).

Some rock mass classification systems incorporate rate of rock mass weathering (Hack, 1997). For example weathering rates have been incorporated when rating the rock mass for underground excavations (Laubscheir, 1990) by reducing the rating of rock mass proportional to its weathering susceptibility. The URCS incorporated the degree of weathering using descriptive terms Micro Fresh, Visually Fresh, Stained, Partly Decomposed, and Completely Decomposed for the first time (KOLOSKI, 1989).

It is not uncommon to see different approaches taken to evaluate weathering degree from the applications point of view. Hence special set of properties attributed to certain weathering degree are often used to evaluate the extent of weathering. For instance, by interpreting light toned surfaces as rain washed and are therefore identified as fresh. In contrast, areas of deposition which appear as darker surfaces were inferred as weathered product accumulation sites (Inkpen et al., 2001). This might not hold always as the case might be in some weathered and dark toned rocks such as pentellic marble and others that are lighter in colour originally.

Four quantitative rates of weathering are summarized by Ceryan (2008). These are single index, relative change of index properties between fresh and weathered rock mass, empirical formula, and statistical analysis of factors indicative of weathering.

In the simplest case, any of the single index are used to quantify weathering on a scale such as point load strength, seismic wave velocity bulk density or other physical and engineering properties of the rock mass. The change however could well be due to other geologic processes than weathering. In addition, these range of the engineering properties predicted for each weathering grade in the boundary often overlap in value (Ceryan S., 2008).

Second classes of quantitative weathering degree assessment rely on relative changes in the index properties between fresh and weathered rock mass. It has been suggested (Arıkan, 2007) that:

> "Simple quantitative degree of weathering scale can be established for any rock property or group of rock properties which change in unidirectional throughout the weathering degree and whose value or values can be readily established in the non-weathered state".

A limitation with such methods is the need for the co-occurrence of fresh and weathered units, which cannot be granted always. As a solution to the case in the absence of fresh outcrops, relative ratios obtained from any other two weathering degrees observation has been suggested to be used in deriving the reduction of the weathering indicator index (Hack, 1997). But still in the case of a single weathering degree observation, it is unavoidable problem.

Based on beforehand knowledge of the expected change in certain properties of materials, several empirical relations have been formulated to predict weathering degree on quantitative scale. This methods work well in conditions where the change in properties are well understood. In situ GRS (Gamma Ray Spectrometry) measurements correlated well with the degree of weathering as characterized by indices obtained from major elements chemical analysis, (Chen, 2007). This method has the limitation to be applied only in rocks of acidic composition which have relatively higher proportion of the radio elements that can be associated with depletion and dispersion characteristics with progress in weathering.

Statistical analysis can be also applied to factors usually involved in contributing to weathering such as factorial analysis, multiple regressions. Although the methods can be applied elsewhere with little bias, the intensive data requirement makes it a matter to be useful only to very important projects (Arikan, 2002).

In other studies increase in water absorption, porosity and permeability due to removal of cementing material and increase in microstructure and macro fracturing with weathering has been used to quantify weathering degree (Gupta, 2000). These methods have profound improvement over the traditional rating of weathering by mere observation and estimation of the weathering degree. Nevertheless, the possibility of finding a quantitative scale that can be readily integrated into geotechnical models calls for further work. Further, a quick look at the literature shows that the quantification of the weathering degrees pertains to the environmental setting of the problem. The methods developed are guided by the prevailing conditions in the field. This often leads to problems of repeatability elsewhere in situations different than they were originally developed for.

In addition, most of the methods are either pervasive or require close or physical contact for the assessment of the rock mass and/or intact rock. Remote and non destructive methods of assessing weathering of rock mass should be the next step in the future with what the advance in technology has to offer.

2.5. Thermal properties of rocks

The total radiant energy arriving at a surface is split into three. Part of it is reflected part of it absorbed and the rest is transmitted (Sabins, 1996), which is in agreement with the conservation of energy. The proportion of each is different from material to material depending on the properties called reflectivity, absorptivity and transmissivity. Nevertheless, only some of these parameters are **conveniently** measurable to be used in determining the type of materials. The interaction of materials with the incoming radiation is often governed by few derived physical properties. These are emissivity, thermal conductivity, thermal capacity and density (Sabins 1996). These have been briefly discussed with the implication of weathering on them.

Remote systems always register lower temperature than the actual surface temperature such as one measured by contact thermometer. The difference is partly due to the property of the materials ability to radiate the receive energy, which is measurable quantity. This quantity is called the emissivity and is used to correct for the differences in the remote measurements of infrared radiation to determine the actual temperature of the body.

The role of thermal conductivity, thermal capacity and density of materials on their thermal property is represented by thermal inertia (Schieldge J. , 1980). The thermal inertia of surface materials are reported to influence diurnal temperature excursions of geologic surfaces (Plaut, 1992). Higher thermal inertia indicates materials that tend to heat up slowly and preserve it for longer time contrary to materials of lower thermal inertia P,[$J.m^{-2}.k^{-1}.S^{-1/2}$]. It is defined as

$P = \sqrt{k\rho C}$ … (Equation 1)

Where, k is bulk thermal conductivity [$W.m^{-1}.K^{-1}$], ρ is bulk density [$Kg.m^{3}$], and C is specific heat capacity [$J.Kg^{-1}.K^{-1}$].

In Equation 1, thermal conductivity (k) is a parameter representing rate of at which heat passes through a material. It represents how well the materials conduct heat. While the thermal capacity (C) is the measure of a materials ability to hold the heat energy stored in it.

Thermal inertia and being a function of the other independent thermal properties is very important in application of delineating materials of varying thermal properties. Weathering of rock has more direct implication to thermal conductivity and this has also been further reviewed.

2.5.1. Thermal inertia

Despite the simple appearance of the expression of the thermal inertia, its determination often involves quite a few functions around it (Sabins, 1996). One way is fitting a model diurnal temperature profile to one acquired over a finite portion of the diurnal cycle at a given location. The albedo and thermal inertia are then varied for the model outputs until they fit with amplitude and phase of the measured (actual) diurnal temperature profile (references in (Mellon, 2001)). The albedo is defined as the proportion of the reflected radiation from a surface upon irradiance (Sabins, 1996). Another method proposed to generate a lookup table of possible temperature values and their corresponding thermal inertia under the different combination of the parameters. These are then use to correlate and find the best fitting thermal inertia for the observed temperature. But the techniques involved require sophisticated analytical computations making it cumbersome to apply.

Simplifying assumptions are hence employed for different studies depending on the objective. For example (Hardgrove et al., 2009), thermal inertia was substituted by similar parameter which can easily be determined from the temperature range and surface albedo of the target. A term called apparent thermal Inertia (ATI) represented by the following equation is introduced:

$$ATI = \frac{1-A}{\Delta T} \quad \text{… (Equation 2)}$$

A is the surface albedo representing the brightness of the surface in the visible band. It is measured as a percentage of the amount of light reflected from the total incoming radiation of the surface. In this context, high temperatures are typically caused by either Sun-facing or low albedo surfaces, while low temperatures are generally surfaces with a high albedo or are in shadow.

In another case, night time temperature variations is used to infer relative differences in the underlying thermal inertia, (THEMIS Public Data Releases, 2009). This is because the temperature variation at night are free of influence from topography and albedo. Hence, it can be used for qualitative study of materials having contrasting thermal inertia.

Thermal inertia has been used in various contexts to study geologic materials. Contrasts in the thermal inertia have been used to delineate alluvial fans using day and night time images alone. For example, (Hardgrove et al., 2009) used the simple notion of inverse relation between thermal inertia and the change in surface temperature of the pre-dawn and mid-day instead of the more sophisticated modelling of the thermal response of terrestrial surfaces developed such as (Watson K., 2000) to map alluvial fans in Carlin, Nevada.

Apart from thermal inertia albedo levels are shown to have the effect of lowering the temperature values, (Mellon, 2001). In studying the effect of albedo on creating thermal stress among rocks (Hall et al., 2005), conditions where bright rocks (high albedo) experience rapid and higher temperature than dark (low albedo) rocks have been observed. This usually takes place in cases when the air temperature is exceeded largely by the rocks hence leading to rapid loss of heat to air. The dark rocks being the first to heat up primarily until they exceed the ambient air temperature, would end up having the highest thermal gradient and hence lose energy unlike the white rocks that are within much smaller thermal gradient with the air temperature and hence continue to heat up instead of losing their heat.

2.5.2. Thermal conductivity effects

In general the thermal behaviour of rocks materials is tuned first of all by whether they are porous or not, (Schon, 1996), (Carmichael, 1989). Non-porous solid rock materials have their thermal conductivity controlled by the thermal properties of the constituent mineral and the internal structures. Still, more variations follow depending on the assemblage of constituent minerals in them. Hence rocks like quartzite, have wide range of thermal conductivity values while crystalline rocks in general have narrower range. Acidic rocks have higher heat conductivity than basic rocks. Loose materials would show the least thermal conductivity.

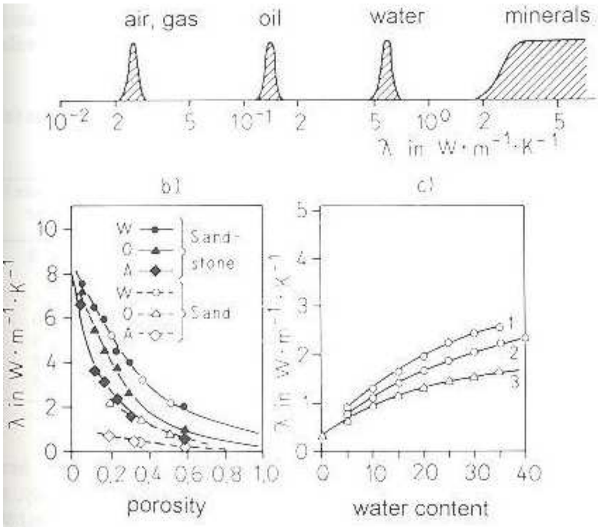


Figure 2-1. Range of average thermal conductivities (λ , [W.m-^{1}.K-^{1}]) for various pore in fills on logarithmic scale (Top). The role of porosity (lower left) and water content (lower right) on the thermal conductivity (λ) of rock materials (adopted from (Schon, 1996)).

On the other hand thermal conductivity of porous rocks are governed by the porosity and the cavity contents. According to references in (Schon, 1996), increase in porosity lowers the overall conductivity of the rock exponentially, (Figure 2.1). Pore constituents influence the thermal conductivity differently depending on the type of constituents. Water being most conductive increases the thermal conductivity of rocks, followed by gas/air and oil in that order. Further, abundance of thermally conductive constituents in the solid parts of porous rock material itself increases its thermal conductivity.

The effect of moisture content on the thermal property of rocks emerges with two arguments. The first is that due to the high thermal inertia of water the moisture content would increase the overall natural thermal inertia of the object. This results in lowering the amplitude of temperature series over a diurnal cycle than when they are dry. On the other hand, experimental evidence has shown the contrary, whereby in fact the temperature profile amplitude is increased in as moisture content increases. These has been attributed to the cooling effect of the moisture (water) instead of raising the overall thermal inertia (Sabins, 1996). This method has been employed to develop tools for mapping geologic materials (Nasipuri et al., 2005).

These are very important observations as they could aid in using the change in temperature of surface materials where weathering is very active. Conductivity of materials is directly proportional to thermal inertia which dictates the temperature fluctuation. Hence materials with higher conductivity with all other thermal parameters kept constant would tend to heat up slowly and to lower extent than those of higher thermal conductivity (Schieldge J. , 1980).

2.5.3. Studies on weathering by remote IR systems

Non destructive remote means of weathering assessment are subject of ongoing research utilizing the different regions of electromagnetic spectrum. Ratio computed for intensity of the reflected lights at 1.8 µm, 1.94µm, and 2.1µm wavelengths on masonry bridge piers made of sandstones which have undergone long history of weathering have been used to determine the degree of weathering indirectly. The ratios of absorbance intensity at 1.94 µm to that of the other two wavelengths is related to moisture content which were then compared with the extent of weathering in the bridge piers (Matsukura, 2000).

Several examples exist in literature that used thermal images in study of rocks and rock mass. Study conducted by (Warke, 1996) shows the importance of surface temperature changes on weathering rate of different rock types. Samples of sandstone and limestone variety which have different albedo were used in their experiment to study the change in surface and subsurface temperature under an artificial radiation from infrared lamps. According to their experiment the temperature fluctuations of the first few millimetres were intense. They further suggested that it can be applied to detection of material behaviour resulting from heterogeneity including the local and differential rock weathering and water content difference.

A study on slope deterioration using thermograph to detect caves behind shot-creted slope has clearly shown possibility of using the method to assess integrity of rock mass (Wu Jian-Hong, 2005). In another case Kononov (Kononov, 2000) studied the temperature gradient measured over loose to solid rocks for mine safety monitoring. Detached and/or hanging blocks of rock have been found to heat up and cool down faster than the intact blocks that are solidly attached to the background.

A detailed report by Senkowski (Senkowski 2008), gives account of the use of thermal images as forensic tools for detecting subtle temperature differences arising from different thermal properties of the underlying material. A new method of studying slope rock masses has also been suggested based on a study conducted in Japan (Takashi, 2003b), (Takashi, 2003a). The study used terrestrial thermal and visible-near infrared images of samples simulating the various degrees of weathering and conditions. In another study rock piles from Molybdenum mine in new Mexico, have been studied using thermal images for presence of heat venting in the pile in relation to the oxidation of pyrite under the pile leading to intensified weathering (Shannon, 2005). In another attempt, infrared spectra has been to detect the moisture content of rock samples in the laboratory to quantify the degree of rock weathering indirectly by inferring the quantity of moisture in hte samples (Matsukura, 2000).

Recently different weathering regimes have been identified by deriving distinct chemical compositional trend from thermal infrared spectra (Michalski, 2006), (Rampe, 2009). Use of thermal spectrometer has been also utilized in monitoring of cultural heritages such as masonry sculptures, rock paintings, and historical buildings (Hall, 2007), (Warke, 1996). An investigation in sedimentary terrain on LiDAR intensity data and surface temperature of weathered outcrop indicated a higher degree of correlation (Kekeba, 2008).

3. Methodology

3.1. Study Area

3.1.1. Location of the Area

This study is conducted in the north eastern part of Spain, in the Catalonian district near the town of Falset. Two measurements are done on the actual road cut slopes while as a third data set rock samples were collected from the same area and measurement of the mosaic taken back at the camp in Cambrils, the base camp.

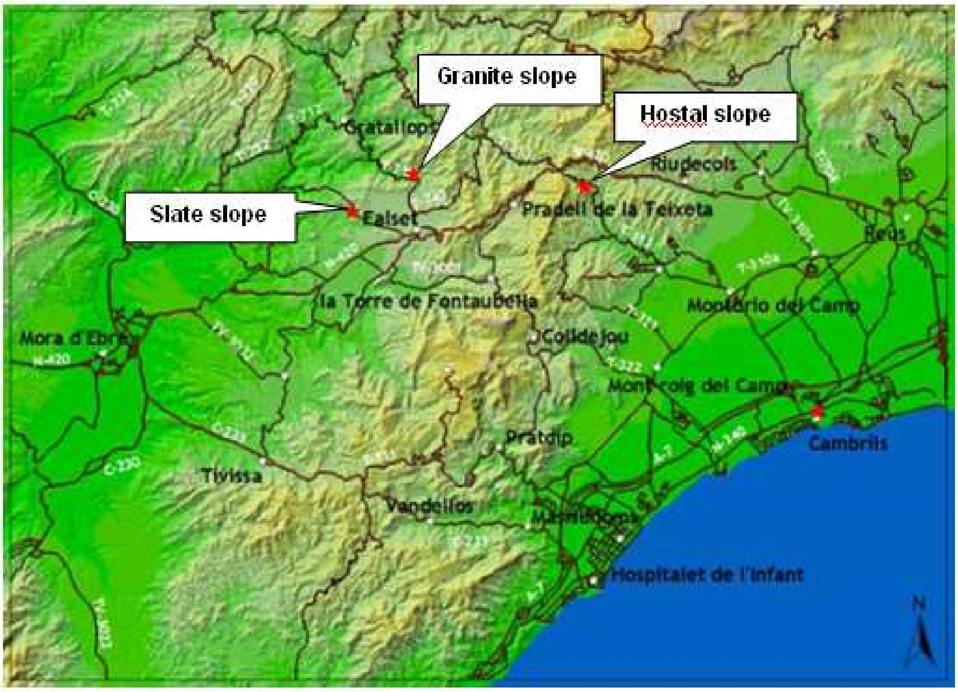


Figure 3-1 Location map of the study area. The red stars are places where live temperature measurements were taken, including the camp on the Mediterranean coastal town of Cambrils, Spain. Map after (Husiman, 2006).

According to Huisman, (Huisman, 2006), the area is underlain by sedimentary sequence of Devonian through quaternary age. Paleozoic formations consisting mainly of slate inter-bedded with micro-conglomerate. Shale and siltstone are also found. The slate underwent a low degree of metamorphism with remnant bedding planes still evident. The carboniferous rocks are intruded by granodiorite and have undergone a contact metamorphism.

The study was conducted on three lithologic units from the Triassic and carboniferous formation. The first one is the granitic intrusions of pre Triassic period into the carboniferous formations. Three types of intrusions are found in this group: granodiorite, granites and aplithik dikes. One of the investigated slopes (the granite slope) falls in the granodiorite intrusions. It is mostly light colure rock and shows morphology of a stock work.

The second site of investigation is located in the carbonaceous age formations of Slates, Sandstones and Greywacke. They are well exposed in the mountainous areas near Belmunt and east of Pradell, especially along the road cut slopes. The temperature measurement for the study was in fact conducted on one such exposures of slate rock mass.

The third rock type used in the study falls in the keuper formation of the Triassic age which consists of Shale and Siltstone inter-bedded with Limestone and Dolomite. In this later case only intact rock samples were used in the study.

3.1.2. Topography

The area of direct measurement in the field is located in a topographically undulating area with wider valleys dominating. Elevation ranges between 300 and 1000 meters above sea level. The dominant vegetation types are Vineyards and Olive trees. Also a fair amount of forest and shrub is found elsewhere.

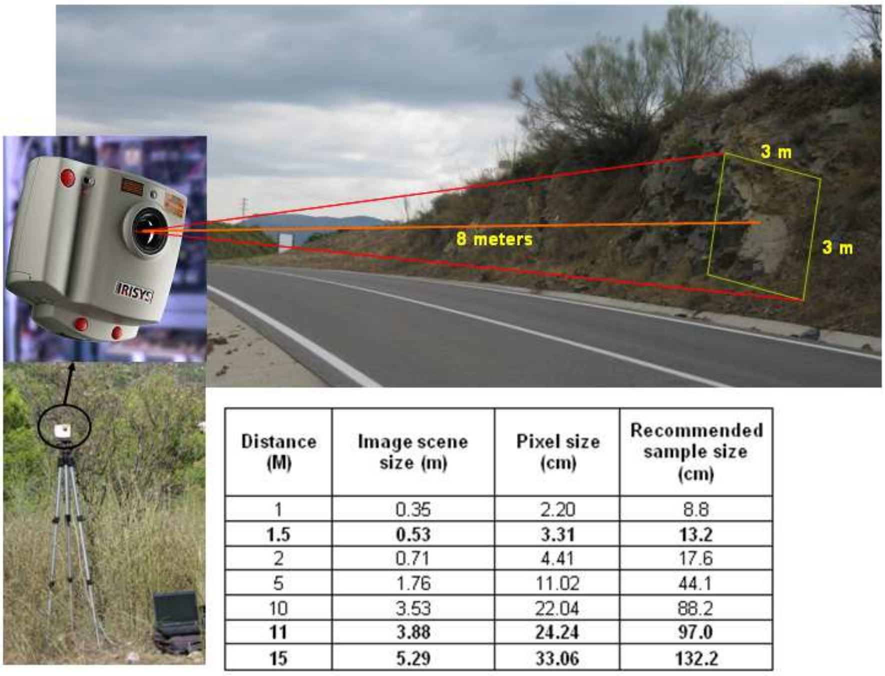
The climate is dry, hot summer with temperature ranging from (15°C to 35°C). Bimodal rainfall patterns exist in the area in April-May and September – October. Nevertheless only in the Slate slopes temperature measurements was a brief slight drizzle encountered.

For the month September, several information on insolation (solar irradiance) conditions are documented based on 22 years of data up to 2005, (Paul W.Stackhouse, 2010) by the Atmospheric Science data Centre of NASA. Some of the parameters from the web site close to the time of field data acquisition both temporally and spatially are available. The monthly averaged insolation incident on a horizontal surface is 4.55kWh/m^2/day, the monthly average for midday is 0.59kW/m^2, and it varies with time from 0.43kW/m^2 at 9:00 GMT, to 0.59 at 12:00 GMT, and 0.38 at 15:00 GMT. The monthly averaged downward long-wave radiative flux is on the other hand 8.50kWh/m^2/day. The average daily temperature range is 7°C while the monthly averaged air temperature at 10 m above the surface of the earth averages 21.3°C ranging between 18.1°C and 25.1°C. The following gives the average air temperature at 10 m above the surface of the earth for indicated GMT times (°C) for the month September when the field measurements were taken.

Average@00 GMT	15.0
Average@03 GMT	13.7
Average@06 GMT	14.2
Average@09 GMT	17.2
Average@12 GMT	19.7
Average@15 GMT	21.0
Average@18 GMT	18.3
Average@21 GMT	16.4

3.2. Instrumentation

IRISYS 1011 thermal camera has been used to acquire the series of thermal images. The camera is recommended to be used reliably for measuring targets having temperature of 15°F to 570°F with sensitivity of 0.3°K. The spectral response range is from 8 to 14 micrometer. It has a 20° horizontal and vertical field of view with 16 by 16 arrays of detectors behind the lenses to project the incoming radiance image on and recalculate the temperature depending on the average emissivity set by user. The dimensions of the scenes covered vary depending on the position of the camera from the target. Generally the camera has a 16 by 16 sensor matrix making it lower in spatial resolution.



Distance (M)	Image scene size (m)	Pixel size (cm)	Recommended sample size (cm)
1	0.35	2.20	8.8
1.5	**0.53**	**3.31**	**13.2**
2	0.71	4.41	17.6
5	1.76	11.02	44.1
10	3.53	22.04	88.2
11	**3.88**	**24.24**	**97.0**
15	**5.29**	**33.06**	**132.2**

Figure 3-2.1Relationship between image size and camera distance from the target (IRISYS 1011).

3.3. Data acquisition

The field work commenced, on September 21, 2009, by exploratory assessment of the potential slopes that show as much variation in weathering degree as possible over a short distance. Those slopes which have been the subject of the previous studies, (Huisman, 2006, Kekeba, 2008) were visited so that sufficient information could be available on the physical characteristics (nature) of the slopes. Hence the three mono-lithologic slopes, which have been called by previous researchers as Bellmunt (Slate slope), a Granite slope and Hostal slope (Mudstone unit), have been chosen. The necessary observation of all the slope exposures attribute were noted and recorded. Nevertheless, actual measurements were made only on the first two leaving out the Mudstone outcrop. Samples of the different degrees of weathering have been collected on the same day for laboratory spectral measurement to assess the compositional relation between the parent materials and the altered products. Hence samples representing different degrees of weathering from three different lithologies and their respective three consecutive degrees of weathering (slightly weathered, SW; moderately weathered, MW; and highly weathered, HW) were obtained from the selected sites. In the process, temperature time series measurements have been acquired alternating between slope exposures and samples mosaic, throughout the field work time.

There is difficulty in the visual recognition of targets due to the lower spatial resolution of the thermal camera. Hence the view extent and spatial resolution had to be estimated for the target based on the camera's field of view (20°) and assuming a minimum of four pixels (for the case of mosaic) to cover individual samples. This has been done for the varying distance of the camera from the targets (table in Figure 3.3).

The samples were carefully selected, labelled and packed separately in Polyethylene bags and stored for measurement back at the camp. Two types of samples were required one for the night and day time temperature acquisition and another for Laboratory spectra measurement. The latter required only a minimum of 3 cm by 3 cm dimension of rock chips. Unlike them, the previous samples required fairly sized dimensions of 10 to 15 cm since the resolution of the camera was not high enough to have sufficient number of pixels covering individual samples of the weathered rocks. As the intension was to assess only surface weathering degree of slopes surface, it was sufficient to only consider the surface area alone, instead of the bulk size, in deciding on the size of samples. Next an account of each of the measurements made in the field is given in the order they were made.

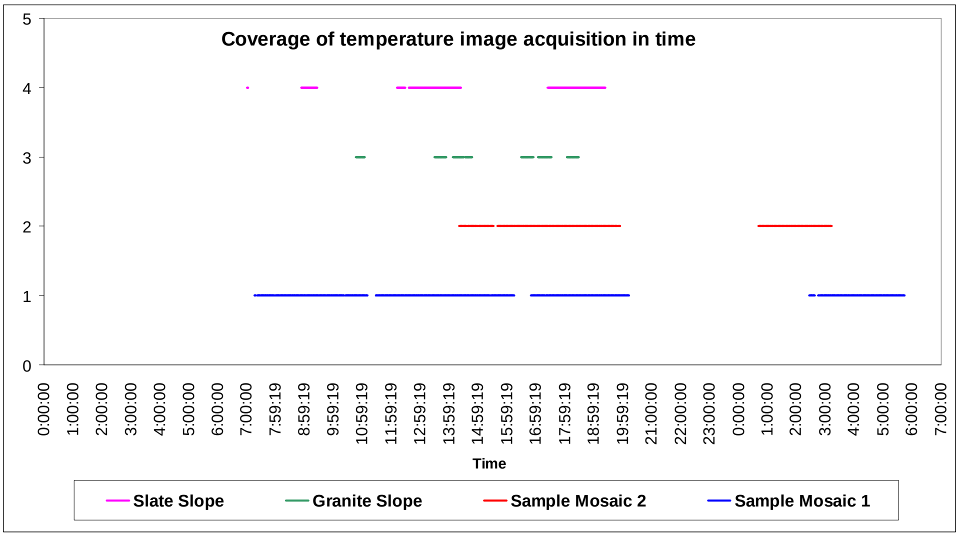


Figure 3-3Temperature imaging coverage of the two slopes and the sample mosaics

3.3.1. Sample mosaics

Temperature measurement of the rock samples was done at the camp, on 23rd of September 2009, by laying rock samples on a balcony. Measurements stared at 07:15 AM local time (GMT+2), right before sunrise. The samples were spread out on card paper on the balcony floor and their temperature was continuously acquired. The relevant irregularities in the acquisition of the temperature profile was documented such as light posts casting shadows onto samples as well as samples shadowing each other for a short while. The measurement continued the whole day until mid night and then well into the morning of the next day, on September 24, 07:00 AM (GMT+2) local time with longer major interruption during the florescent lighting time in the evening. Concurrent logging of the ambient temperature was also taken. The samples layout has been described in the experimental setup section along with the pictures. Also, snapshots of the live measurement of the temperature of sample mosaics and photographic image of the samples spread on the floor were taken to document how the relative position of the samples appears in the temperature image (Picture 3.1).

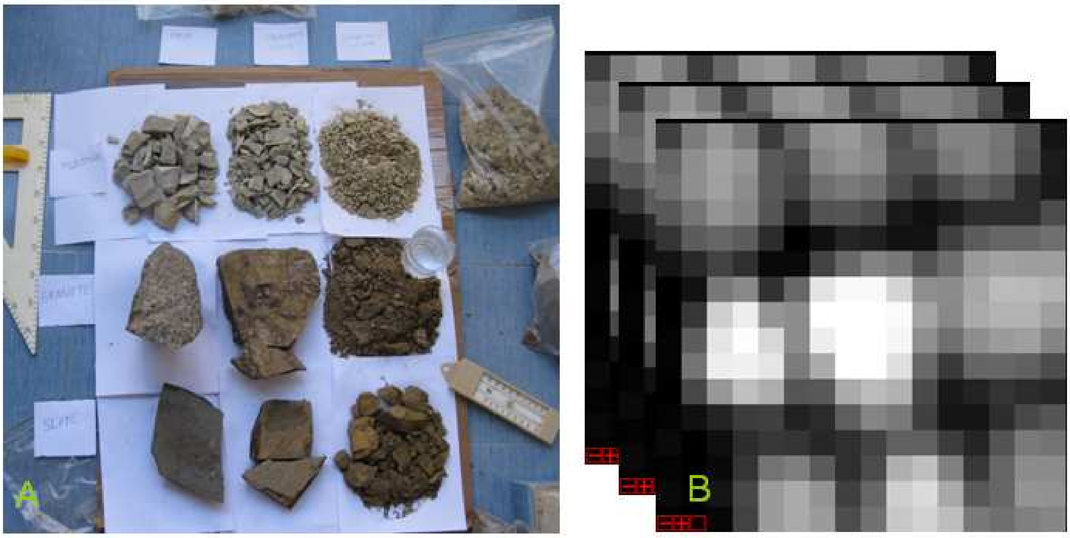


Figure 3-4 Sample mosaics prepared for temperature imaging at the camp (A) and corresponding temperature image (B) in grayscale at time of highest contrast between samples at 04:52 PM.

3.3.2. Slate slope

The first temperature profile measurement was conducted on September 22, on the Slate slope which is located in the carboniferous formation. It consists of slates of variable degree of weathering. The slope is located north-west of the town of Falset along the TP7101 road leading to town of Bellmunt, (0°48’25.22” east, and 41°808’42.82” north). Temperature profile measurement was started well before sun rise at 06:57 AM local time (GMT+2) while sun rise arrived at 07:45 AM local time (GMT+2).

In the Slate slope the camera was set opposite the slope which faces to the north east. Orthogonal blocks of 20 cm to 50 cm dimension make up the slope face, which according to the ISO Standard classification of rock mass structures and block shapes is qualified as Prismatic Block (ISO 14689-1:2003(E)). These make the slope highly variable in the illumination angle of the slope face. The camera was setup 11 meters away on the opposite side of the slope across the local road, giving it a coverage of 3.8 meters by 3.8 meters at a resolution of 24 cm. Along with retrieval of the temperature image, concurrent measurement of the rock surface temperature was taken by contact thermometer at a single point to assist the reliability of the temperature measurement. The slope is a recent road cut composed of Slates that are part of the Meta sandstone, Sandstone and Greywacke formation of carboniferous (Huisman and references therie in). The exposure is relatively short lived which otherwise could not have given the opportunity for any differential weathering of the slope face to be seen. The area of the slope investigated has little or no vegetation except few dried shrubs due to the prevailing dry season at the time especially in some part of the mostly weathered part of the slope.

Temperature log of the slope surface was taken with contact thermometer at variable time interval throughout the acquisition time of the surface temperature with the thermal camera (Annexed). The measurement was interrupted few times for significant lengths of time due to shortage of power supply. Slight drizzle took place around 02:00PM lasting just at the second major interruption of the temperature measurement due to battery power shortage. All the coverage of images with time is shown in Figure 3.3. The weathering degree of the area covered by the thermal camera scene has already been assessed with respect to the BS 1999 standard (1999) and SSPC which is based on the BS 1981 version, giving emphasis to the weathering of the rock mass rather than the intact rock. Also additional samples were obtained from the different weathered units of the slope to check the repeatability of the temperature profile measurement of the weathered samples by comparing them with the previous set of samples already obtained during the previous day.

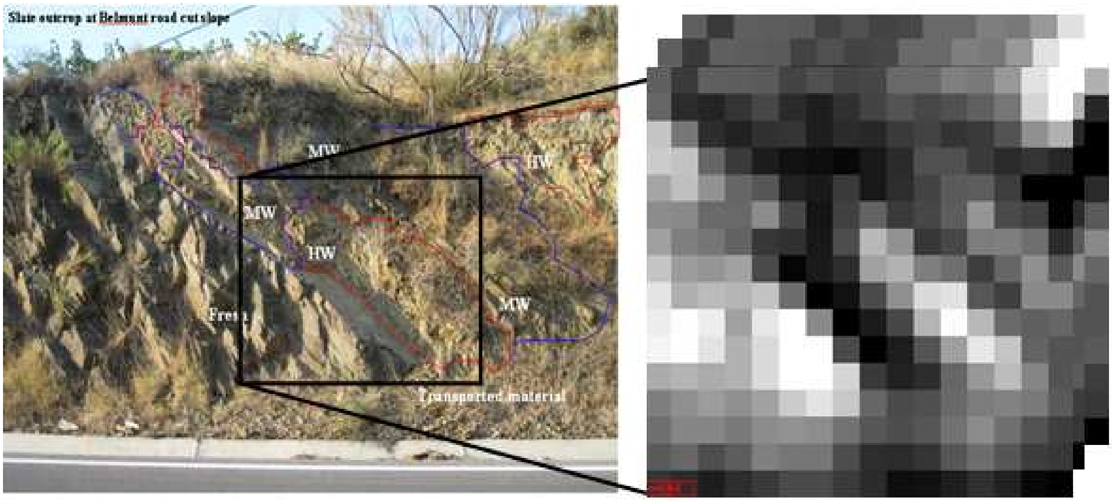


Figure 3-5 Slope cut exposure of the Sates near Belmunt (Left), orthogonal blocks make up the slope face giving it systematic lighting by sun as in the snap shot from the picture on the right.

3.3.3. Granite slopes

The third temperature series measurement conducted was that of the granite slope. The measurement lasted from 09:33 AM until 06:15 PM on September 25, including interruptions due to shortage of power supply and other technical problems.

The slopes in the Granite rock mass slope are part of early Triassic granitoid intrusive (Huisman, 2006). The slopes were imaged from a distance of 14 meters, which would mean that the scene has a

resolution of 30cm and scene coverage of 5m by 5m. The images are acquired continuously and retrieved on Laptop computer. The temperature was also measured with contact thermometer to compare with the overall measurements of the camera and to get the ambient temperature. The measurements from the thermometer are read at regular intervals. The weather condition on the measurement day was sunny. Nevertheless, due to the higher slope height and south facing aspect, the slope face in the granite unit hardly receive any direct solar irradiance; at least for that particular day.
Temperature logging with contact probe as well as comments about irregularities in the acquisition were maintained.

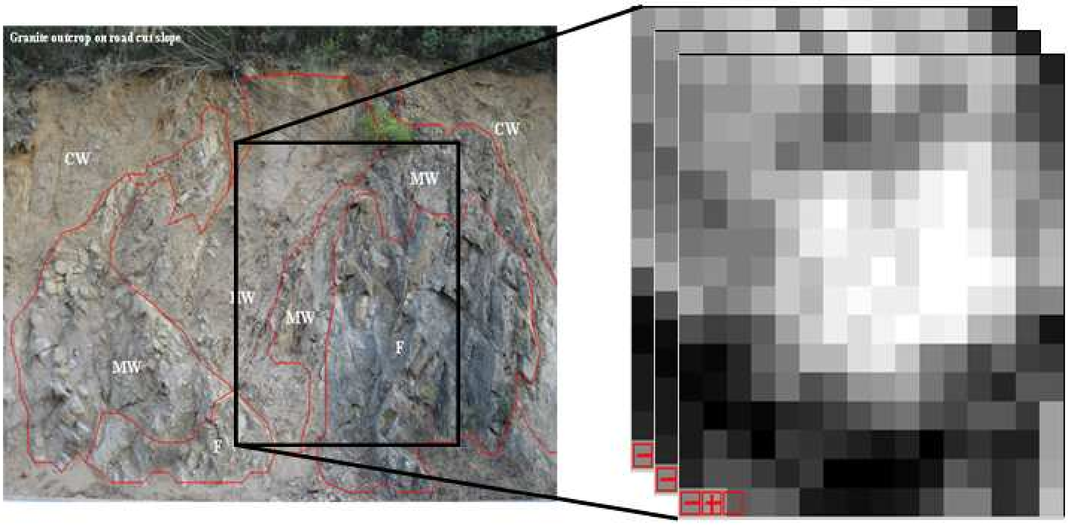


Figure 3-6 Outcrop of the Granitic slope (Left). The figure on the right is approximate scene area of temperature image.

3.4. Sample spectra Analysis of VIS/NIR and TIR

The spectral measurements taken for the VIS/NI (Visible and Near Infrared spectra) and TIR range were analyzed for two purposes. First is the signature matching to identify most probable mineral groups which has been done with the help of TSG® (The Spectral Geologist, © 2007), a tool developed by CSIRO (Common wealth Scientific and Industrial Research Organization) for matching the spectral profile of rocks with existing data base. Secondly the TI reflectance spectrum was used to infer the difference in emissivity between different grades of weathering in the same lithologic unit.

3.4.1. VIS/NIR observations

The spectral profiles of the samples are shown in Figure 3-7. The samples from the Granite rocks showed clear difference in degree of weathering by visual and physical inspection. They are generally light coloured in the fresh state but become greyish brown on weathering. The interpreted result of TSG indicates the presence of Illite, chlorite and Phengite in all the measured spectra of the samples ranging from fresh to highly weathered.
The slate samples have dark grey colour when fresh but the weathered samples have light brownish crust. The highly weathered types show soil like property but with intact original structure. The spectral signature of the fresh samples shows the presence of Kaolinite, Muscovite and Fe-chlorite. The moderately weathered samples spectra have spectral signatures of Montmorillonite, Halloysite and

dry vegetation probably due to plant roots as the samples are weathered. The spectral signature interpreted for the highly weathered rock sample showed the presence of Halloysite only.

Spectral measurements of the mudstone samples have signatures mainly of Dolomite and Ankerite. Montmoillonite and Illite signatures are also indicated in all the measured spectra.

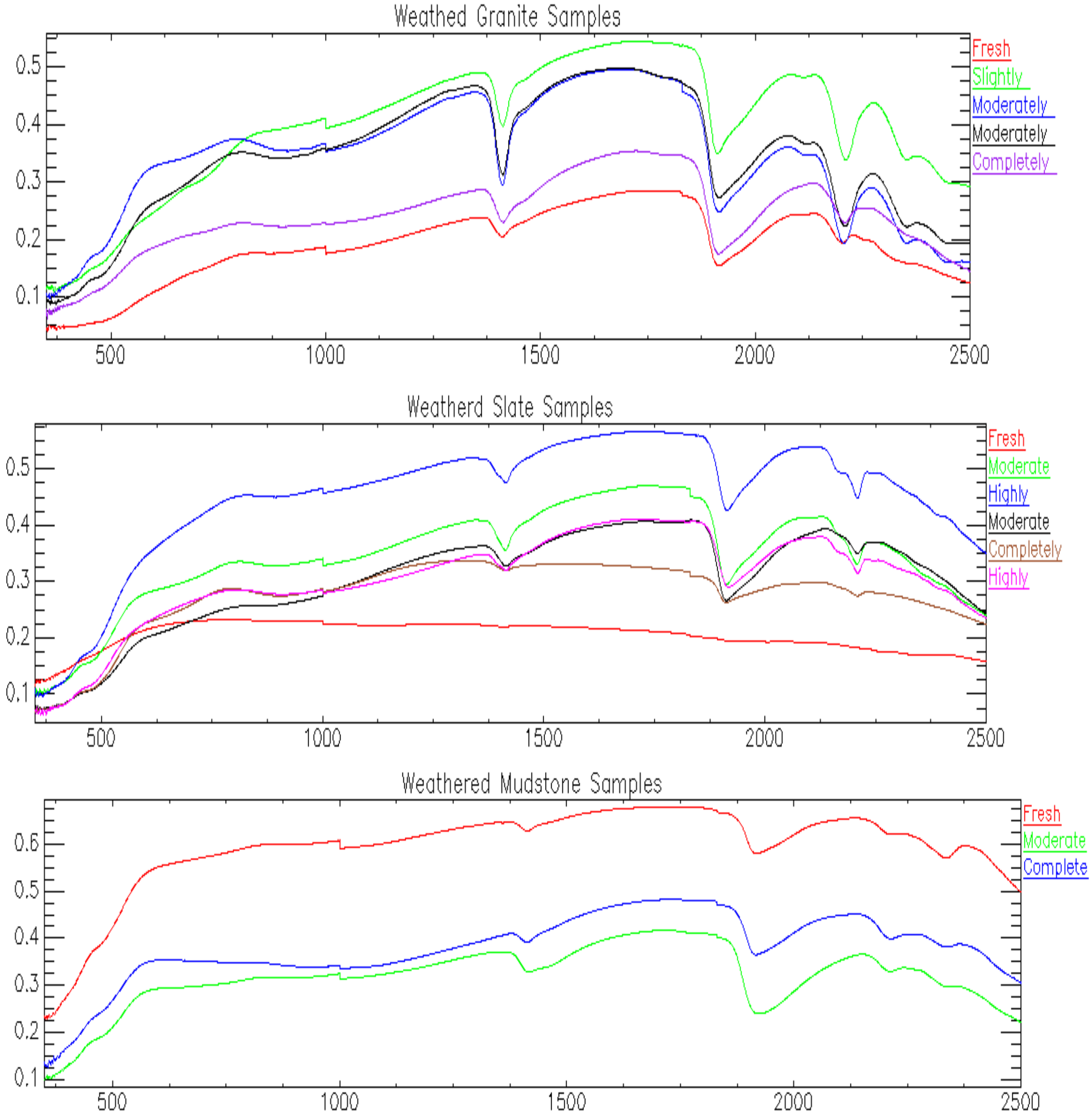


Figure 3-7 VIS/NIR spectral profile of granite, slate and mudstone samples.

3.4.2. The TIR observations

The temperature variations of the intact rock samples with the emissivity of their surface mineralogy as obtained from the spectra measurements were compared. For this task, since the spectral response curve of the camera was not available, the emissivity of the spectral measurements for the whole range of the 8µm to 15µm was used.

For Granites the thermal infrared spectra measurements of fresh, highly weathered, and slightly weathered samples were made. In general the samples have higher emissivity and the common trough of emissivity near the Reststrahlen absorption band between 8µm and 12µm due to the (Si-Al)-O stretching vibration. This is probably associated with presence of minerals like plagioclase feldspar in the fresh samples while its depletion in the weathered spectra duo alteration lead to reduction in the absorption. The trough is noted to shift towards the shorter wavelengths with increasing degree of weathering. The slightly weathered samples have 0.95 emissivity value as the highest most common while in the reststrahlen band the depression goes down to 0.75. One features noted in the granite samples is that the spectra of the sample which has dark colour causing it to have a slightly higher overall emissivity. In all the spectra, a deflection from the smooth curve occurs at the left lower corner of the depression (Figure 3-7, Granite) which is more prominent in the darker sample around 8.6µm. The moderately weathered sample closely matches the spectral feature from the slightly weathered samples with slight increase in overall emissivity. The highly weathered sample shows higher overall emissivity of 0.97.

The spectral measurements of slate samples consisted of fresh, moderately weathered, highly weathered and completely weathered. Similarity in the spectral feature is observed with clear absorption feature in the reststrahlen band. The spectrum on the shorter wavelength side is flat. Wider and shallow absorption feature also occur on the longer wavelength side of the reststrahlen band. In the highly weathered slate samples spectra twin absorption features occur around 9.5µm area and 8.2µm wavelength. The overall emissivity is lower in the weathered slate samples. With increasing degree of weathering the depth of the absorption features decrease and the overall emissivity increases consistently (Figure3-7, Slate).

The spectra feature obtained from the Mudstone intact rock samples show no significant difference among the different weathering degrees. The only discernible difference is the slight increase in the overall emissivity. All spectra show carbonate absorption feature around 6.25µm wavelength. (Figure 3-7, Mudstone)

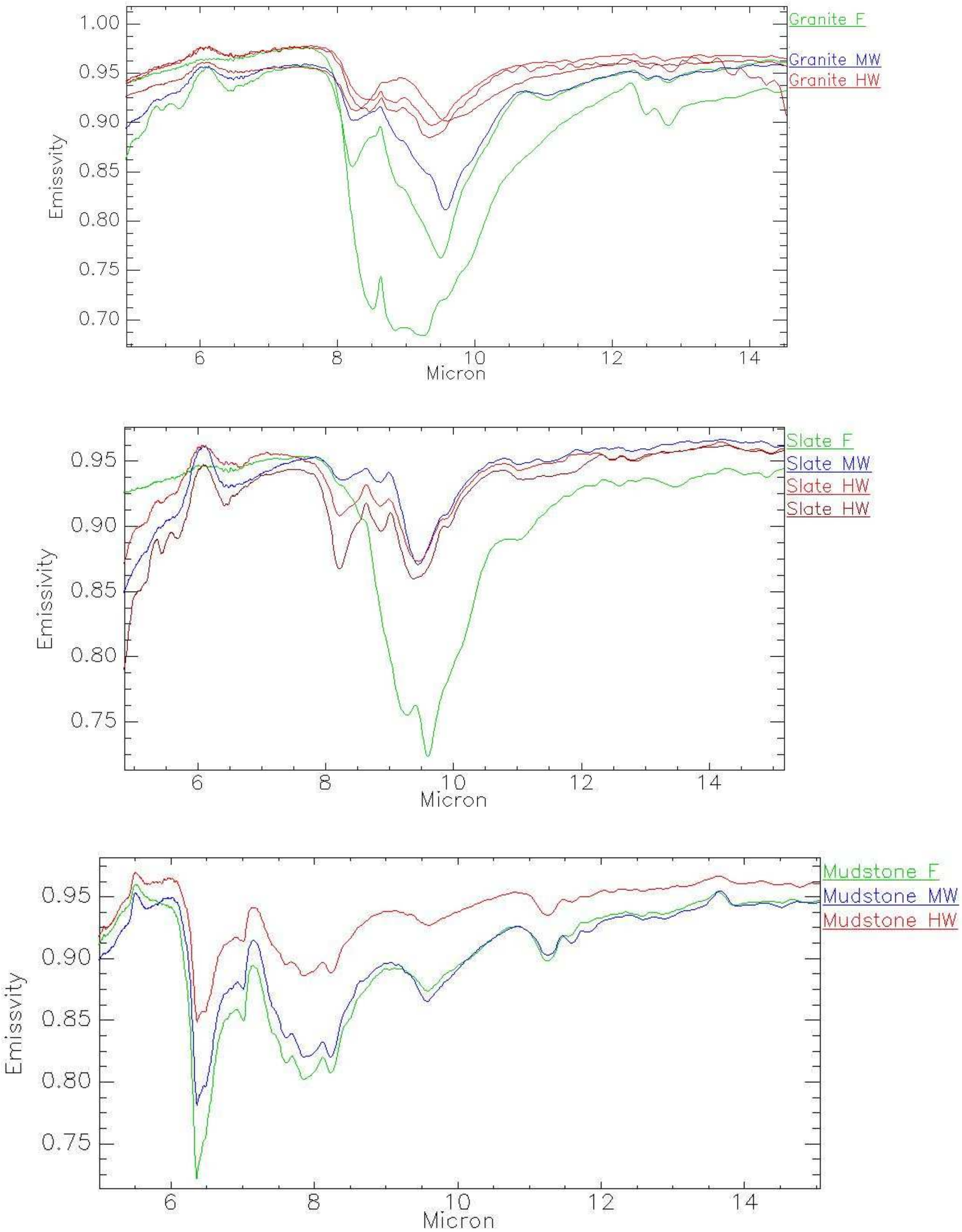


Figure 3-8 TIR spectral profiles of the granite slate and mudstone samples

3.5. Temperature data analysis

3.5.1. Temperature data pre-processing

The live image displays on the computer can be set to maximum of 128 by 128 pixels which can also be saved automatically along with the temperature read outs as snap shots. The temperature read outs are retrieved as comma delimited text file in series of rows representing an instant. Although the live display and saved snapshots are as high as 128 by 128 pixels resolution, the actual resolution of the readout temperature stored is that of the 16 by 16 pixels corresponding the to the sensor matrix on the camera. Hence, a scene that is made up of 16 rows by 16 columns is stored as a single row of 256 temperature values read starting from the top left corner to the 16th value to the right, and continue doing the same, along the same row, for the successive rows of temperature values. This is repeated as many times as the frequency of the images with every row indicating the time elapsed between successive retrievals.

In order to reconstruct the image for analysis the images which came as rows of text file had to be rearranged in to series of 16 by 16 matrices (frames). This has been done using Matlab code which would read throughout the series of lines and load them into 16 by 16 matrices of frames as many as temperature image instants (Annexed). The files are then stored as ASCII files and read into ENVI as an external data by specifying the number of instants (images) expected which is perceived as number of bands in ENVI. This would create stack of images each representing its respective time of acquisition. The images are then stored once again as native data format in ENVI, and used for further analysis.

During the acquisition of the images, interruptions have occurred due to technical issues. Especially the measurements from the slope outcrops have a large proportion of measurement gaps. Hence for the image, to be analysed with change in temperature over time, it has to be compensated for the times the measurements were not taken by offsetting the otherwise sequentially stored vales. This was done in relative way by stretching (distributing) the images frame (individual images) over the range of a day by the corresponding laps of time between measurement instants. This has been explained more in the next section (Data Analysis) as shown in figure 3-7.

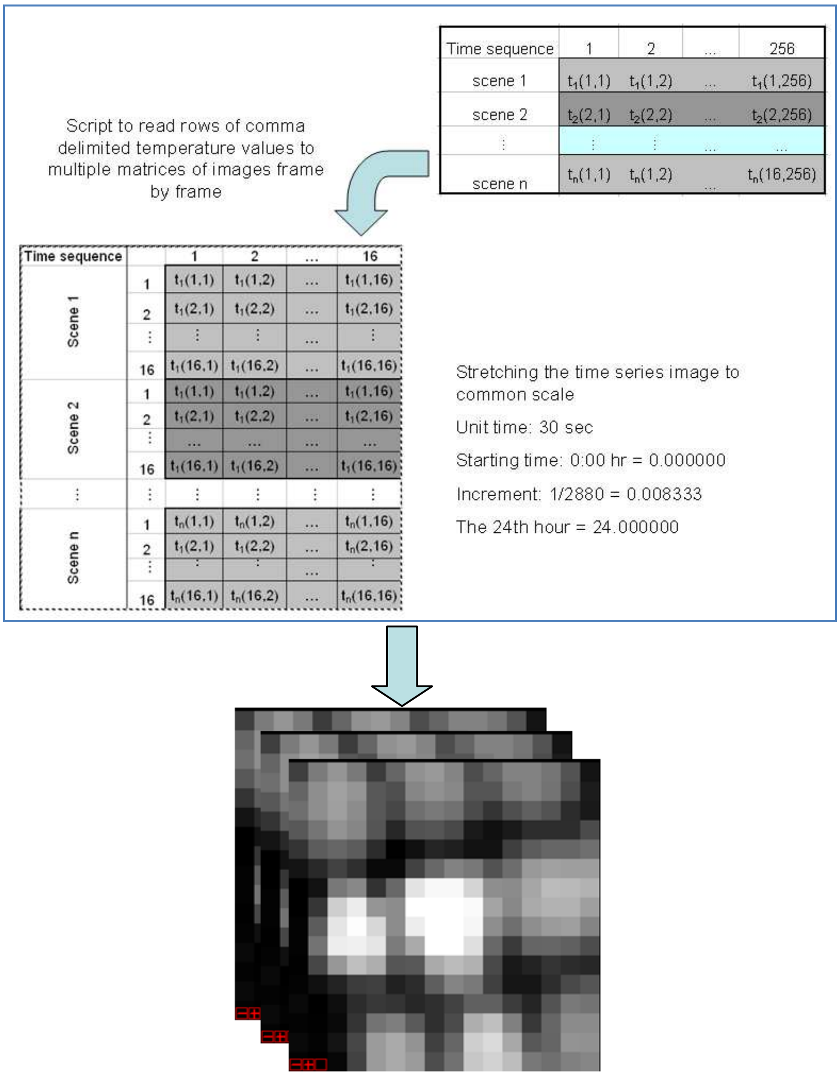


Figure 3-9 A flowchart for followed to reconstruct the time series images from the temperature readout records of the camera.

3.5.2. Data preparation for analysis

As such there is no direct analytical method developed for the analysis of temperature profile as a characteristic of materials property. Most techniques deal with the derivation of the overall mass property or the temperature profile with depth, rather than the surface itself (Mellon et al., 2000; Schieldge J. , 1980). In the light of the limitation on no known existing methods, exploratory parameters were derived from the temperature profiles of the outcrops and samples of varying degrees of weathering. These parameters were then compared for possible systematic variation as per the various states of weathering degree as obtained from field observation.

Before deriving the parameters, the acquired raw temperature profile data were first smoothed out for removing the noise with out lose of information. This would make the extraction of parameters from the profile manageable. A Savitzky-Golay (SavGol) smoothing was applied in such a way that the temperature profile data closely matches the raw data.

Savitzky-Golay approximates the underlying function within a moving window by a polynomial of higher order, typically quadratic or quartic (William H. Press et al., 1993). A polynomial is fit to points inside a moving window of symmetrical span on either side of the data points to find a new value for the central point. This is repeated by moving the window with unit increment for all the other points creating a whole new polynomial fit at every instant. For the data sets at hand the window size was set to 30 points on either side of the central data point, and with third order polynomial to preserve the temporal nuisance in the original raw data. The filtering was done by using the SavGol function available in IDL environment.

In addition to the smoothing, the time reference was changed to linear units for ease of computation and plotting the data. The temperature profiles were taken continuously every 30 seconds over the diurnal range with some gaps mentioned earlier. Hence, a 24 hour window of acquisition time was divided into 30 s units. The new time series run from 0.000000 at mid night (0:00 local time) to 24.000000 at the end of that day with increment of 0.0083333 (equivalent to 30 seconds).

The analysis was first applied on the more controlled data acquired from the continuous temperature measurement on mosaic of samples from varying degree of weathering and lithology. Since measurement was planned in such a way that each sample is represented by at least 4 pixels, sample temperature profiles were taken from the four pixels corresponding to locations of individual samples. These sample profiles were then characterized and analyzed for indices which can be relate to the samples degree of weathering. In the mosaic data sets three rock types with three different states of weathering were represented.

Following the analysis of the sample mosaics comparable indices were applied on the image acquired from the Slate slope outcrop and Granite slope outcrop. This is because the fact that the measurements from the sample mosaic were more complete and spatially controlled than those on the situ measurements. Hence methods which work on the more controlled sample measurements are thought to be applicable to those with limited measurement window, i.e. in the situ measurements. First the analysis of the data from the sample mosaic is presented followed by the two datasets of measurement from the slope outcrops in the following sections.

3.5.3. Analysis of the data

A. Temperature series of intact rock samples mosaic

The relative positions of the reference times for extracting index temperature values and ratios are shown in figure 3-10. Some of the index temperatures considered are obtained at different but relatively equal interval since the samples were hit by the sun at different times and shaded by a light post at different time as well.

As can be inferred from the curve of temperature series the rocks show lowest temperature in early morning as expected and reach maximum around noon. The variations are not only due to the materials properties as there are various external factors that caused varying solar irradiance which contribute to offset the natural heating process. Hence these effects can't be considered in the analysis as they are variable depending on the configuration of targets from which the temperature is acquired.

Several indices were derived from the temperature series which could be used to infer the class of the samples degree of weathering. The indices were obtained by employing the temperature readings at selected common times. The times are selected based on two major considerations. The first one is temperature values that can give indication on the heating process as a function of thermal property changes. The second is based on the inherent characteristics of the temperature curve itself. These time intervals are the lowest morning temperature record (A), maximum temperature record right before direct solar irradiance (B), the temperatures after receiving 5, 30 and 80 minutes of direct solar irradiance (B, C, D) respectively and the day's peak temperature (F). The beginning of the direct solar irradiance is defined by maximum curvature of the temperature series curvature for each measurement independently. The figure shows the relative positions of the considered temperatures in the series (Figure 3-10).

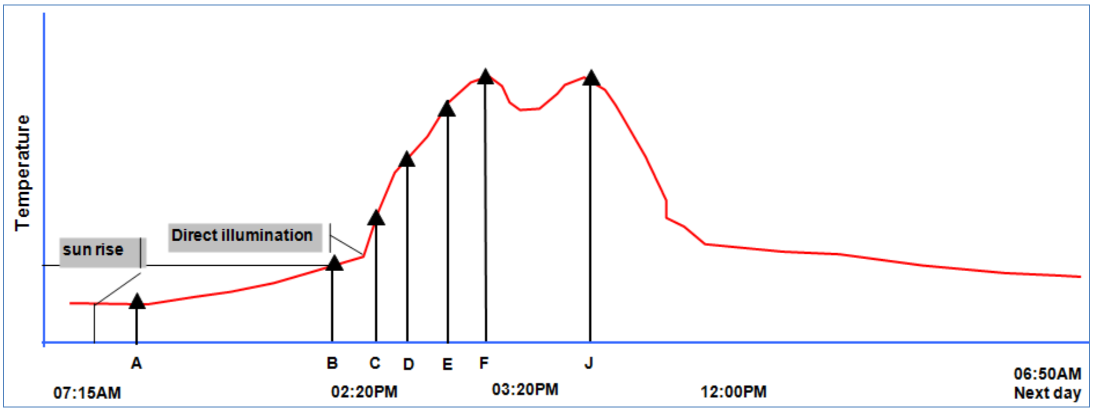


Figure 3-10 Relative position of the times index temperature reading were taken to compare the difference in heating process between samples of different weathering classes. The letters are explained in the text.

The reason for selecting those times for inferring the indices/parameters is to have the rate of temperature increase which is a function of the materials thermal property. Nevertheless the varying rate of heating up observed is different depending on the environmental conditions such as the occurrence and absence of direct solar irradiation, irregularities due to irregularities in orientation of the measured targets. Especially in the later case, the effect is removed by considering the cooling part of the temperature series curve where the materials cooling process is governed only by its thermal property and not by their irregular orientations. Further an attempt was done to enhance the indices by rating some of them.

In the following section the temperature series data sets from each intact rock samples of varying degree of weathering are dealt with by considering indices. The samples are treated separately for each lithologic group with three classes of weathering degree. The indices considered are

- The temperatures at the selected times
- Ratios of the temperatures at common selected times

In each case the times used to readout the temperature for the obtaining the indices were fixed to be same throughout the slate samples except for the maximum temperature occurrence times which differs slightly between the samples temperature profiles. Hence for the earliest minimum temperature record the time was fixed at a common time when the lowest temperature was recorded in the group of the temperature series. Corresponding to this, since the trend was more or less linear, the time of the earliest sample to be hit by the sun directly was set as the morning highest temperature reference point. The next temperature indices used to compare the degree of weathering were the temperature after 5 minute, 30 minute, and 45 minute after the direct irradiance and at time of maximum temperature occurrence for the individual samples. Finally the temperature at the end of the measurement is considered.

In addition to the direct comparison of the temperature gradients ratios of some of the indices were derived to enhance the variability between the different weathered units. The ratio of prior and post direct solar irradiance were gradient was derived to represent the behaviour of the materials in both conditions in one expression.

The part of the temperature profile corresponding to the cooling stage was used to infer the variation in the rate of cooling. Hence comparison was made between the steepness of the temperature series curve in the cooling phase and compared with the rate of cooling of each weathering grade. Nevertheless lack of fitting to any model with least residuals made interpretation difficult and has been left out.

B. Temperature series of the Slate slope rock mass

The measurement at the slope site started before sun rise at 7:00AM. Nevertheless, the measurements were interrupted two times for reasons accounted in the annexed comment logs. An attempt was made to test the comparable indices of temperature values at specific times as those from the samples mosaics on the images.

The lowest temperature was recorded in the morning at the beginning of the measurement about 13.7 °C. Then it starts to heat up with rapid increase in temperature at a rate of about 0.04°C/minute. The major difference noted due to the effect of variability in orientation of aspect is the shape of the temperature series curve. The areas exposed earliest show convex upward in the time series in contrast to the concave upward concave shape of the faces oriented towards the north. The third major discontinuity pane faces north east and shows no deviation from linear increment in the morning measurement until 12:00 AM. This time coincides with the occurrence of the shadow of the parts of the slope blocking the sun at that time, causing it to heat more slowly than the parts of the slope that blocked it.

To characterize the change in temperature over the course of the measurement four (4) time were selected from the temperature series to derive ratios of temperature change between them. These are selected to allow as close temperature indices as the ones from the sample mosaic measurements. Hence, thermal images at four different intervals before noon and were used to inspected patterns resembling the distribution of weathering in the rock mass wit in the scene (Figure 9).

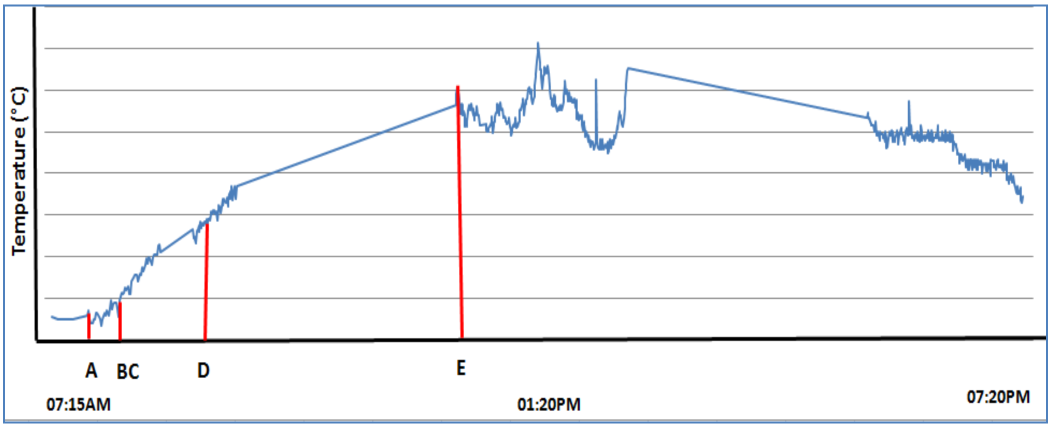


Figure 3-11 Relative position of the times index temperature reading were taken to compare the difference in heating process on the Slate slope rock mass. The letters represent temperature read outs at comparable time to the corresponding letters in the sample mosaic time series.

In addition, temperature series variances over the course of the measurement duration were made for selected regions from weathered and un-weathered parts of the rock mass. Slope faces with similar orientation but different states of weathering were used to sample this time series and the variances in temperature within the regions were compared with each other. This is used to indicate how the spatial correlation of the temperature variation is with a weathering state.

Previous works emphasise the presence of inversion in temperature between weathered and un-weathered rocks in the morning (pre-dawn) temperature and noon temperature. Hence, the weathered rock mass shows higher temperature as compared to the un-weathered one in the morning while the reverse holds in the afternoon. Making use of this notion the following approach was used.

First an appropriate time of the lowest temperature occurrence was chosen for the entire data set. This occurs around 07:50 AM, in Slate rock mass outcrop. Then the highest temperature was also chosen likewise which was at 01:24 PM. The difference between the two gave the daily range of temperature for the data set. On the other and the ratio of the lowest predawn temperature of each pixel in the thermal image to the mean temperature of the entire scene at the same time was computed. Similar ratio was obtained for the scene at a later time around 12:15AM when the slope being measure has reached the first peak. This was chosen rather than the absolute highest temperature of the day because of the complications due to periodic shadowing effect. Taking the ratio obtained for the morning and afternoon scenes, a second ratio was obtained by dividing each with the daily range. The notion followed in this case is that materials which have lower thermal capacity, as would be the case in weathered rock mass, would heat up faster. Such materials also tend to have higher temperature fluctuation. Hence the final ratio would give higher value for weathered rock mass where as it would be lower for less weathered rock mass. The ratios are made consistent by switching the placement of the devisor and dividend in A and B so that higher value are obtained for weathered rock masses in line with the assumption.

$X = (T°_{Morning}) / (T°_{Morning\ mean}) \Rightarrow [A] / (14.45°C)$

Y = ($T°_{Mean\ Noon}$) / ($T°_{Noon}$) => (25.96°C) / [F]

Z = $\Delta T°$ => [F] – [A]

Where, F and A are of temperature images shot at the respective times as the letters in the temperature profile. Finally, images of Z/X and Z/Y in [°C] are produced to infer the degree of weathering.

C. Temperature series of the Granite slope rock mass

The temperature measurement from the granite outcrops in general give no indication of feature s to associate with photographic image. This proved to be a drawback to perform the analysis effectively. The slopes are composed of granitic rock mass which are rather well situated for studying the differential weathering conditions. However, due to technical problems measurement in the area only started later than sun rise at 04:47AM.

The slope is more or less uniform unlike the Slate slope outcrop. The orientation of the slope facing to the north causes the slopes to be irradiated indirectly throughout the day. The thermal image was acquired from a scene covering moderate to highly weathered rock mass sections of the slope. Approximate correlation of the photographic image and the thermal image was made making use of faint linear features that demark the contact between moderately weathered and slightly weathered parts of the rock mass. These appear to be developed from original joint planes up on the progress of weathering sideways.

Close indices of temperature are extracted that could be comparable to the sample mosaic measurements. Hence four reference times were selected at three different intervals before noon and two intervals after noon to read out index temperature values from the temperature series (Figure 3-12). The ratio of temperature values were then computed which are comparable with the first two ratios from the sample mosaic measurements.

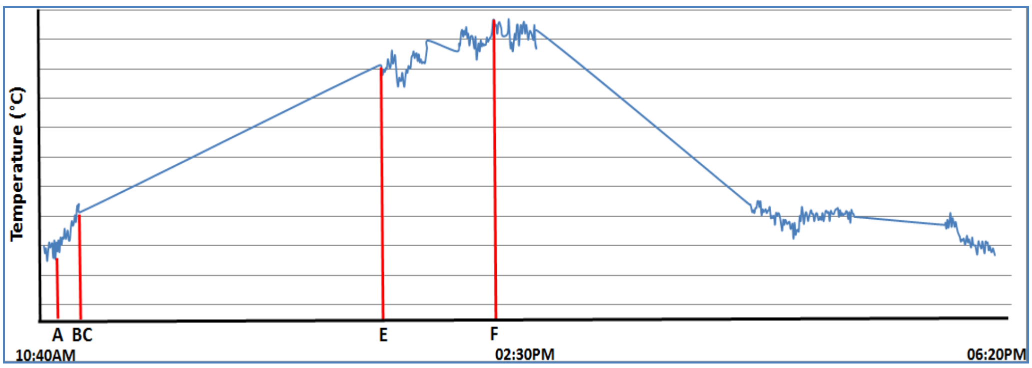


Figure 3-12 Relative position of the times index temperature reading were taken to compare the difference in heating process on the Granite slope rock mass. The letters represent temperature read outs at comparable time to the corresponding letters in the sample mosaic time series.

4. Results

4.1. Temperature series analysis of slate intact rock samples

Following is the results obtained by inferring temperature of the samples at comparable times. Nevertheless the actual time differ slightly as the time of direct exposure and lowest temperature are different in each of the group of the samples.

4.1.1. Temperature indices

The predawn temperature is lower in the highly weathered sample than the fresh and moderate weathered ones (Figure 4-1). This trend persists in the subsequent times of temperature readings. Nevertheless the moderate and fresh samples have the same temperature throughout the series of records. No variation in temperature occurs in the post noon record where all sample have equal temperature.

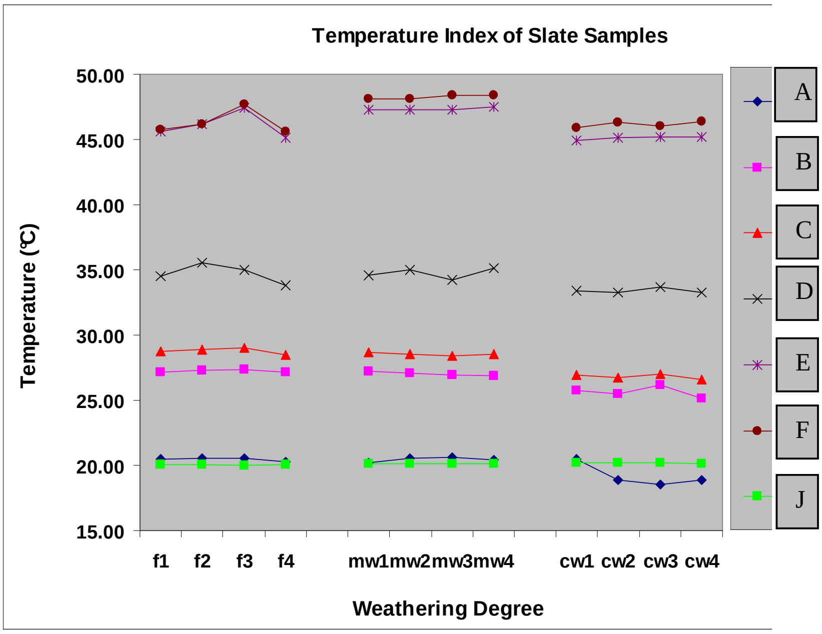


Figure 4-1 Trend of the temperature indices of intact rock samples of Slate. f stands for fresh, mw for moderately weathered, and hw for highly weathered. The accompanying numbers represent the different samples of each class.

In the Granite samples, the lowest morning temperature is significantly lower in the weathered rocks whereas slightly weathered and moderately weathered rocks show no difference at all. This is enhanced further in the temperature of the samples attained after 30 minutes of direct solar irradiance. The pattern persists in the subsequent temperatures attained by the samples. In most cases the moderately weathered samples have the lowest temperature instead of the expected fresh samples (Figure 4-2).

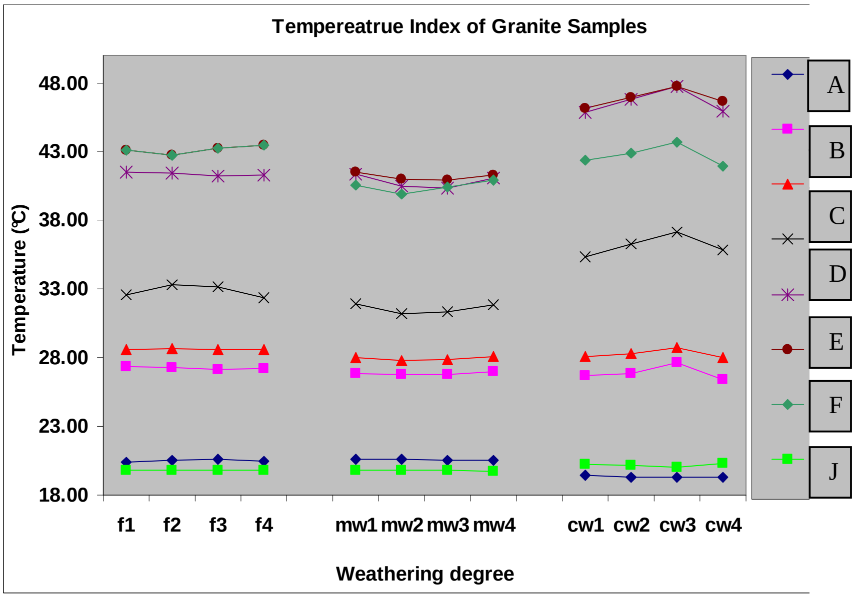


Figure 4-2 Trend of the temperature indices for intact rock samples of granite, from Table 1.5

Among the samples of the Mudstone, highly weathered samples start with the lowest minimum morning temperature among the three weathering classes. The trend persists for the later on records of temperature in all the samples (Figure 4-3). Reversal of the trend starts to take place as the weathered rock starts to peak up temperature faster than the moderate and fresh samples. All the patterns observed in the Mudstone intact rock samples are consistent unlike those of the slate and granite samples.

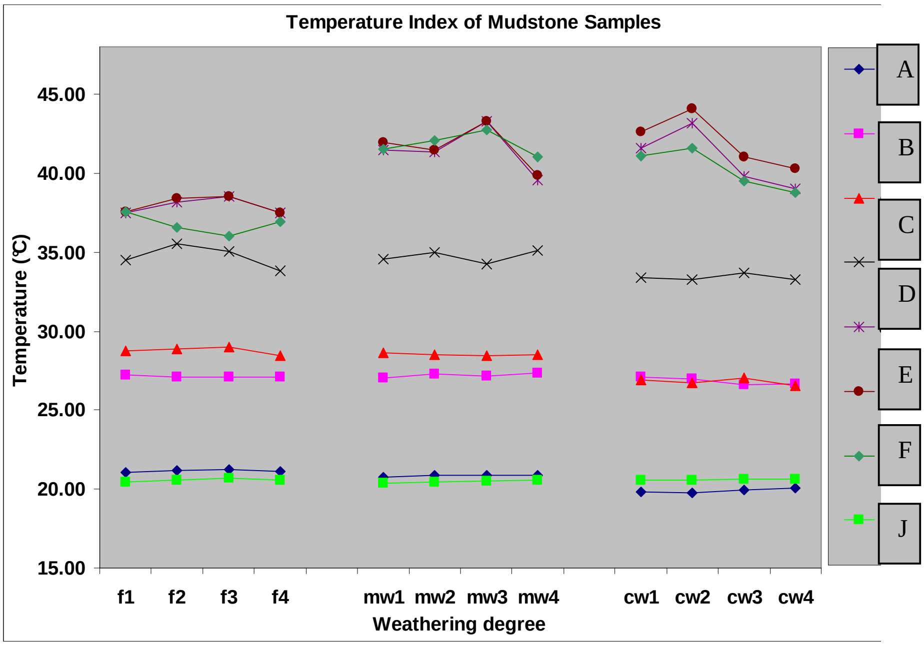


Figure 4-3 of the temperature indices for intact rock samples of Mudstone, from Table 1.7

4.1.2. Ratio of temperature indices

The ratio of the temperature after 80 minutes of direct solar irradiance to that after 5 minute irradiance shows direct relation with the increasing degree of weathering. The same feature occurs in the ratio between the temperature readings between the peak and that after 5 minutes of direct solar irradiance. The last ratio, (B/A) / (D/C), is used to represent the variation in the temperature gradient before and after the direct illumination of the samples by sun. This has been included to utilize the combined temperature gradient in the two heating conditions of direct and indirect solar irradiance, and enhance the differentiation between the different weathered rocks. Nevertheless, no persistent systematic variations are observed in the values.

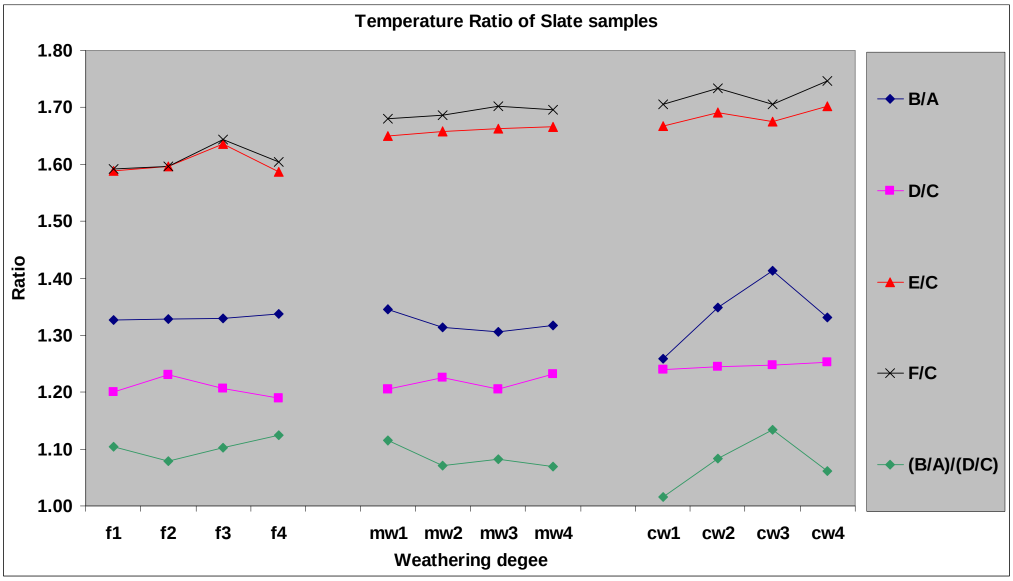


Figure 4-4 Trend of the temperature ratios of intact rock samples of Slate from Table 1.2.

In the ratio of the temperature of the Slate samples after 80 minutes of direct solar irradiance and that of after 5 minute shows a consistently increasing ratio with degree of weathering (Figure 4.4).

On the other hand the ratio of the temperature gradient in the morning to the afternoon, (B/A) / (D/C), relates inversely to the degree of weathering (Figure 4.5).

The situation is reversed in mudstone and almost without any trend in the case of the slate samples.

The earlier trend is further enhanced in the ratio of the temperature indicated in and Figure 1-7. In general the weathered samples show faster rate of heating. The trend in the mudstone samples ratio depicts a clear picture of increasing trend in the entire temperature ratio with degree of weathering (Figure, 4-6).

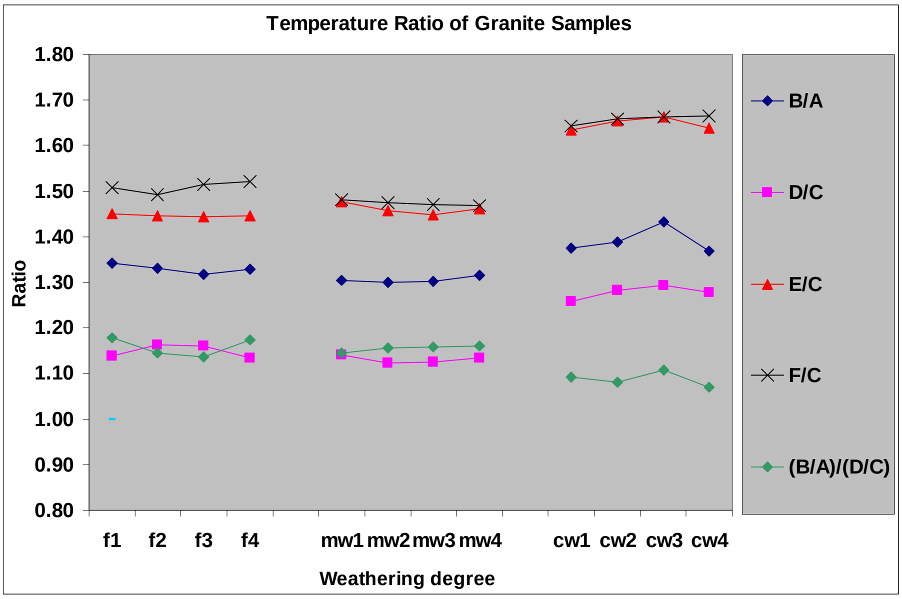


Figure 4-5 Trend of the temperature ratios of intact rock samples of Granite from Table 1.5

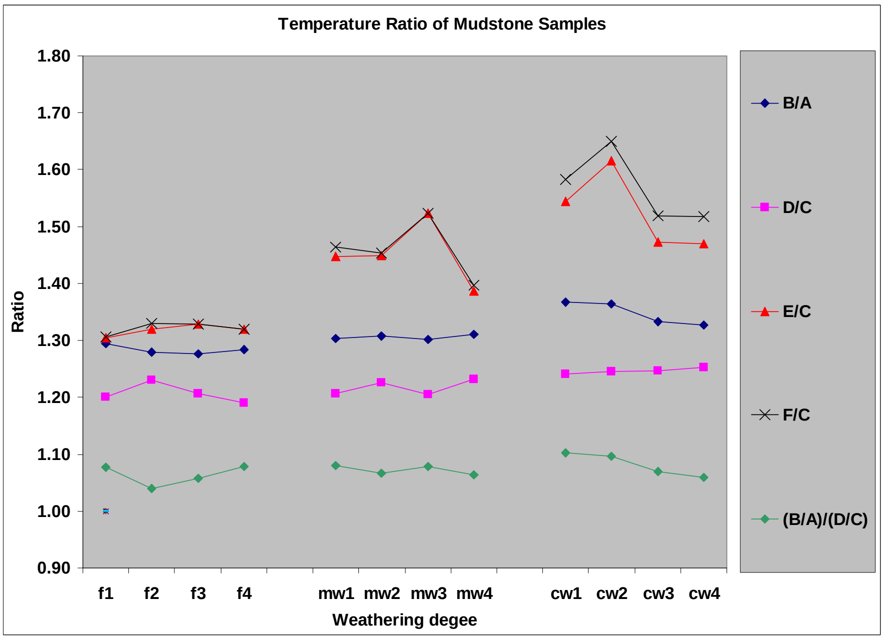


Figure 4-6 Trend of the temperature ratios of intact rock samples of Mudstone from Table 1.8

4.1.3. Parameters from the cooling rate

4.2. Analysis of temperature series from the Slate slope rock mass

A. Temperature indices

The weathered parts of the Slate slope are highlighted, by the index temperature ratio to certain extent. In almost the three index ratio images the middle and lower right area of the image corresponding to the higher degree of weathering gave higher value that appear as brighter region than the areas corresponding to the darker slightly weathered area (Figure 4-7). The times of the temperature shots from which the ratios are derived in this case are comparable with the times of temperature readout used to derive the index in the sample mosaics measurement. Especially, in the D/BC ratio, the overall diagonal alternation of light and dark regions highlights the similar pattern of weaethering degee variation in the photographic picture.

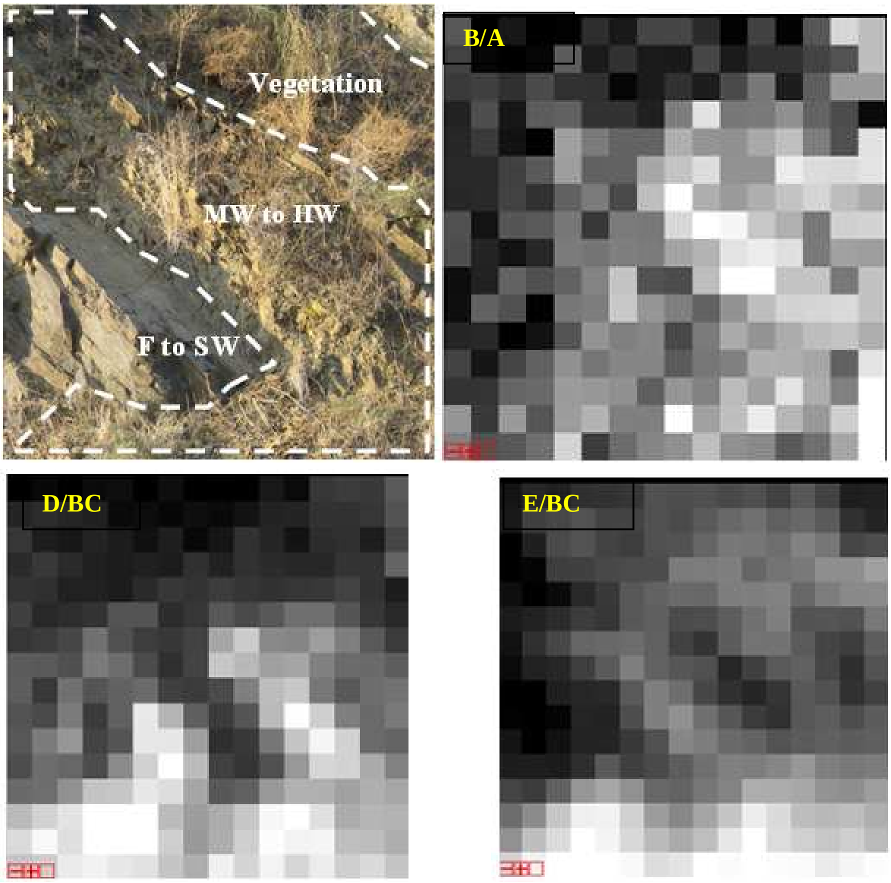


Figure 4-7 Images of temperature ratios B/A, D/BC, and E/BC along with a picture of approximate coverage of the Slate rock mass slope. The weathering degree is designated from field observation where F stands for fresh, SW for slightly weathered, MW for moderately weathered and HW for highly weathered.

B. Inversion in temperature

The results of the parameters used as indicators of temperature inversion between noon and morning temperature of the Slate slope clearly highlighted the boundaries of different weathering classes.

The higher values indicate regions that have apparently higher temperature in the morning and lower in the afternoon when compared within the scene, in relative sense. This could be associated with the high degree of weathering where highly weathered materials appear warmer than the fresh counterparts during the day due to their faster heating. The reverse happens in the morning image where the weathered parts, having less thermal inertia, would cool faster and attain the lowest temperature, and hence the inversion in the relative warmth with the fresh counterparts that sustain the heat for longer time. The coupled higher than scene average values of the two indicator parameters, C/A and C/B, would most probably qualify as very reliable means of determining different weathering zones with higher values representing weathered and lower values indicating un-weathered parts.

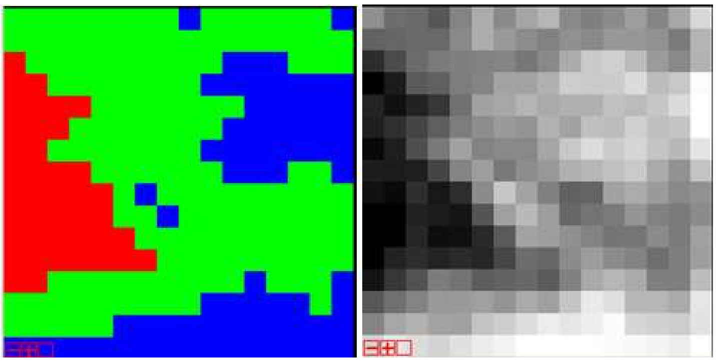


Figure 4-8 equally sliced classes of the *Z/X* parameters for the Slate slope rock mass, as indicator of temperature inversion. The interpretations are consistent higher values indicating higher degree of weathering (color code red = 9.28-12.58, green=12.58-15.89, blue=15.89-19.19 all in °C)

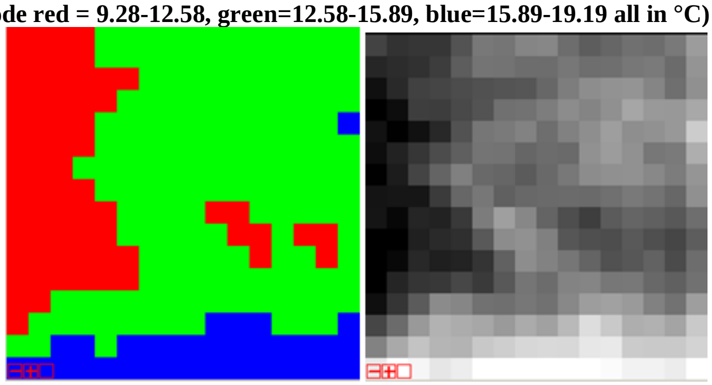


Figure 4-9 equally sliced classes of the *Z/Y* parameters for the Slate slope rock mass, as indicator of temperature inversion (color code red = 10.53-13.06, green=13.06-15.59, blue=15.59-18.11 all in °C)

4.3. Analysis of teh temperature series from the Granite slope rock mass

A. Description

The temperature measurement from the granite outcrops in general give no indication of feature s to associate with photographic image. This proved to be a drawback to perform the analysis effectively. The slopes are composed of granitic rock mass which are rather well situated for studying the differential weathering conditions. However, due to technical problems measurement in the area only started later than sun rise at 04:47AM. The slope is more or less uniform unlike the Slate rock mass outcrop. The orientation of the slope facing to the north causes the slopes to be irradiated indirectly throughout the day. The thermal image was acquired from a scene covering moderate to highly weathered rock mass sections of the slope.

B. Temperature indices

The weathering degree coincides with this trend increasing from the lower right corner of the thermal image scene towards the top left corner (Figure 4-10). Overall temperature range is higher for the weathered part of the rock mass than the slightly weathered ones. In the earliest lower temperature was not available for this slope as the measurements only started at 10:40 AM.

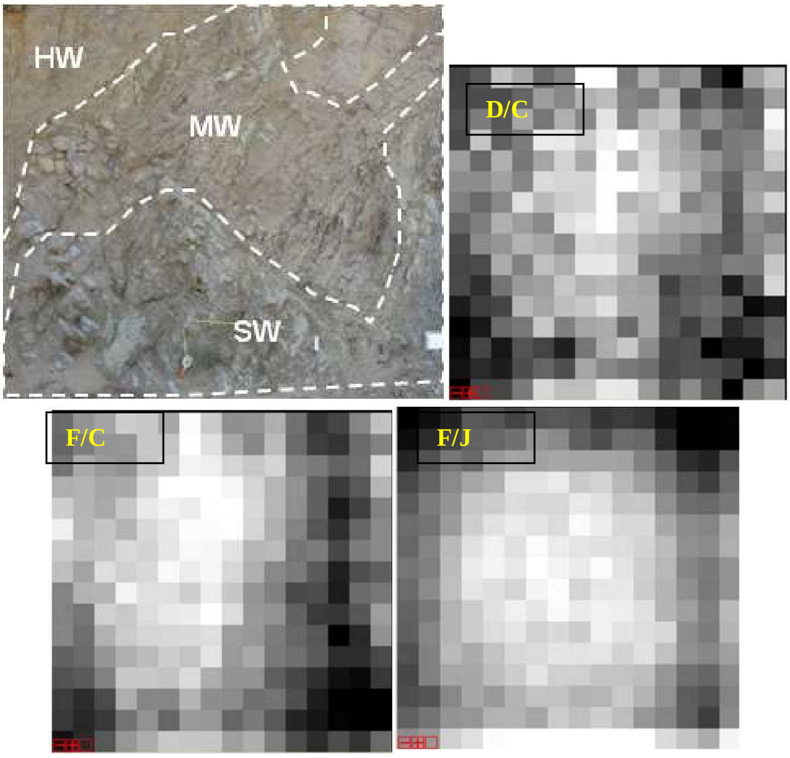


Figure 4-10 Images of temperature ratios D/C, F/C and F/J along with picture of the approximate coverage on the Granite rock mass slope. The weathering degree is designated from field observation where SW stands for slightly weathered, MW for moderately weathered and HW for highly weathered.

C. Temperature Inversion

The results of the parameters used as indicators of temperature inversion between noon and morning temperature of the Slate slope clearly highlighted the boundaries of different weathering classes. Rounded zones signifying the similar patterns of the weathering degree showed in the photographic image (Figure 4-12).

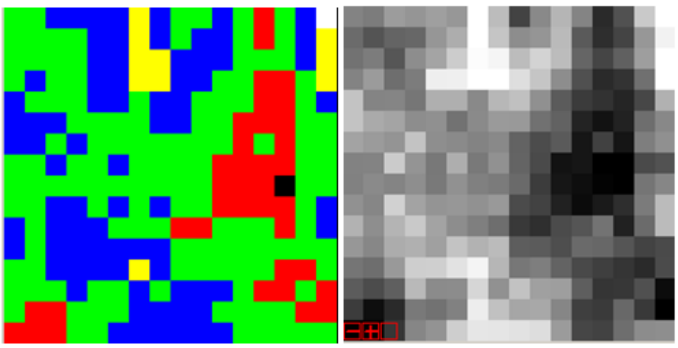


Figure 4-11 equally sliced classes of the *Z/X* parameters for the Granite slope rock mass, as indicator of temperature inversion (color code red = 1.28-1.34, green=1.34-1.4, blue=1.4-1.45, yellow=1.45-1.51 all in °C)

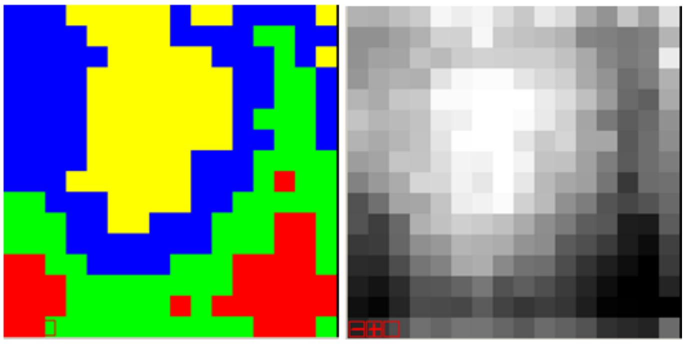


Figure 4-12 equally sliced classes of the *Z/Y* parameters for the Granite slope rock mass, as indicator of temperature inversion (color code red = 1.19-1.28, green=1.28-1.36, blue=1.36-1.45, yellow=1.45-1.54 all in °C)

It is noted that the range of the indicator parameters values are very close in the couple of the outputs while they differ greatly differ between the different lithologic groups as reported in the slice class values in the figures (Figure 11 and 12), the values of the Granite slope are higher by 10's of magnitude than the Slate slope.

5. Discussion

Exhaustive study has been made and is still going on regarding the effect of thermal fluctuation as cause of weathering in rock mass. The aim of this study has been in close proximity but on a reverse process. Whereas the first one deal with effect of temperature variation on rock weathering and/or decay, this study considers the impact weathering has on changing the thermal response of the rock mass and use it to find means of quantifying the degree of weathering.

This has been tested in the context of temperature variations observed on artificially arrange samples and rock mass outcrops over the course of a full day. The daily thermal response of rock samples has been intended to be used as indicator of the different weathering degrees. The results of the observations are discussed in the following section separately for the sample mosaic and the rock mass slope.

5.1. Interpretation of the Sample mosaics temperature indices

The argument followed to differentiate weathered and un-weathered rocks from temperature series measurements is based on the notion that rapid and extreme fluctuation would be dominant in the weathered rock record than the fresh. The selected parameters in the analysis section were hence used to rate this property and compare the above proposition. The temperature series measurements are carried out for only one complete cycle of a day in all the cases. Hence, no information can be obtained on the seasonality of the series. Rather a methodology was adapted to be able to infer information from the characteristics of the single daily trend.

The reason for measurements of the samples mosaic temperature series is for inferring the parameters in a more controlled condition than the natural outcrops of rock mass. In the artificial mosaic of the samples, external factors such as variation towards irradiance and vegetation cover are either avoided or kept to the minimal. This can enhance the interpretation by avoiding the uncertainties in the spatial distribution of the different weathering degrees represented as well.

The orientation has an influence on the heating up trend, even under controlled conditions. Hence, to have a method that is replicable without the effect of the external factors; ratios of the temperatures at certain instants of time are used.

The lowest morning temperature and temperature right before the start of direct irradiation have been used to compare the heating rate in the indirect irradiation condition. The temperature values taken at relatively equal interval after the beginning of the direct irradiation of the samples are used to compare the variation in trend of heating rate under direct illumination. The ratio of the temperature is included in the analysis to minimize those temperature differences arising from variation in illumination condition alone.

5.1.1. Performance of the indices

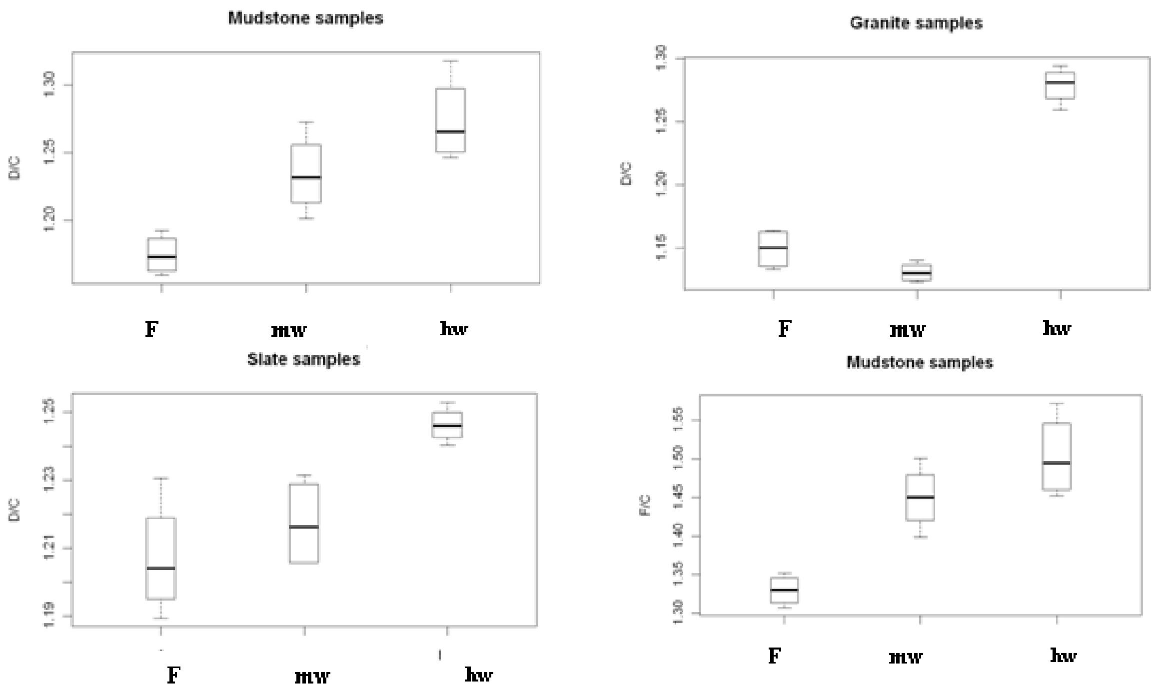
A. Indic temperature

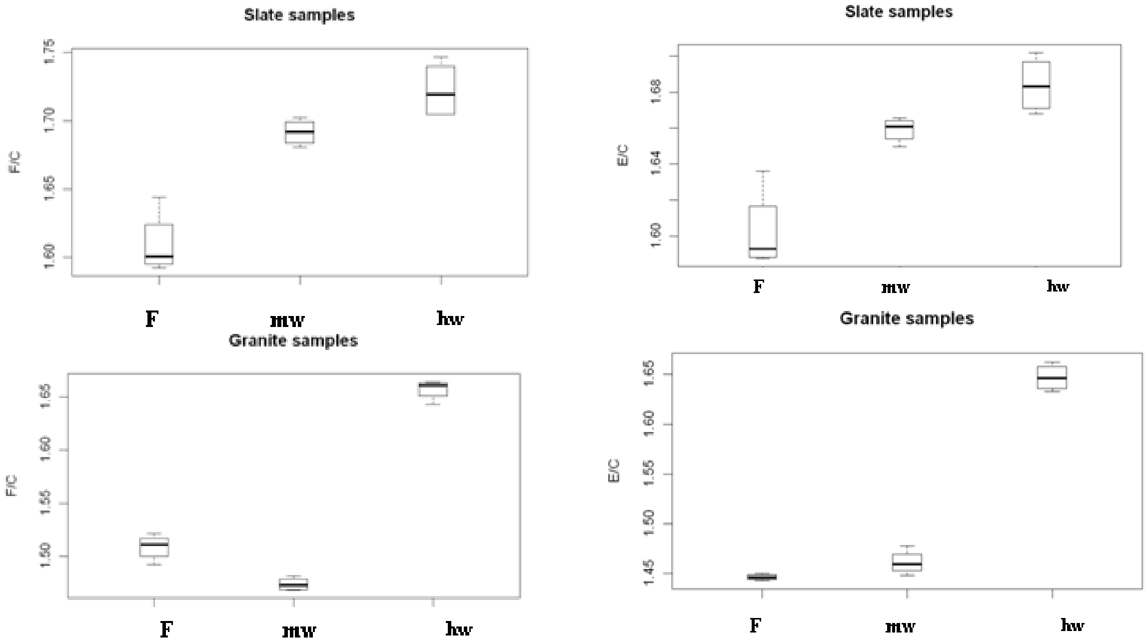
When considered separately, no significant trend is observed between the earliest index temperature values in the different degrees of weathering. The differences appear only in the temperature records after about 30 minutes of direct solar irradiation. The index temperatures of the highly weathered samples are more spread apart than the moderate and fresh ones. This could give a first indication to the difference in thermal response related to the difference in the degrees of weathering. The temperature indices of the completely weathered samples are generally shifted lower which could be due to their lower morning temperature they start with than the other samples. Such irregularities in the observation are to be expected, as the thermal history of the samples would have an effect on the subsequent processes.

B. Ratio

Apparently, the direct use of temperature values is more prone to external factors such as the brightness of the day. This was overcome by using the relative values of the temperature, assuming that the change in temperature is at least unaffected unlike the absolute value.

Some of the ratio of the index temperatures from the intact rocks experiment have reasonably consistent trend with the degree of weathering. This is noted in the ratios E/C, F/C, (Figures 5-1). (B/A) / (D/C). In all ratios the fresh samples showed lower values than the highly weathered ones. This trend is not maintained when the moderately weathered samples of the granite rocks are considered, having values that are higher or lower than of the fresh and the highly weathered samples by value. This is contrary to expectation that it should have a moderate value. These are noted in the ratios B/A, F/C (Figures 5-1), and (B/A)/(D/C).





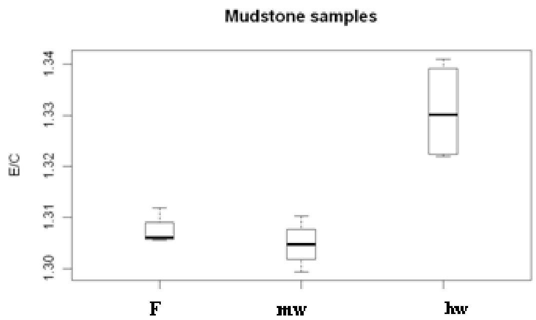


Figure 5-1 The ratio of index temperature of the mosaic samples (B/A, D/C, E/C, and F/C) plotted against the three states of weathering for each lithology; F stands for fresh, MW stands for moderately weathered, and HW stands for highly weathered.

In all the samples, the ratios of highly weathered samples show relatively higher values than their respective values in the moderate and fresh samples. An upward trend is shown by the ratios with increasing degree of weathering except the granite samples where the moderate samples have majority of the ratio lower than both the fresh and highly weathered samples. Considering the first order ratio, i.e., excluding (B/A)/(D/C), the lowest ratio is that of D/C, in all the samples, while the highest is F/C.

5.1.2. Implication of the indices on use for weathering degree

In all the discussions that follow, references to the index temperature are made by symbols for clarity. Hence, the following nomenclature is assigned.

A: the minimum morning temperature

B: the temperature right before the beginning of direct solar irradiance

C: temperature after 5 minutes of direct solar irradiation

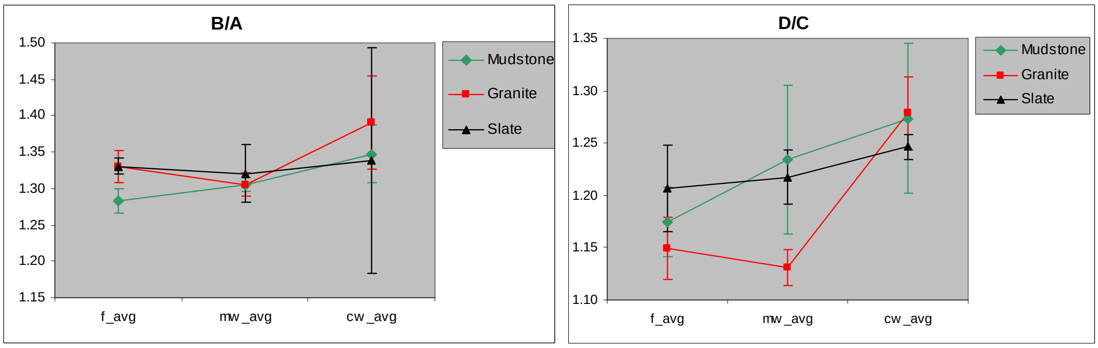
D: temperature after 30 minutes of direct solar irradiation

E: temperature after 80 minutes of direct solar irradiation

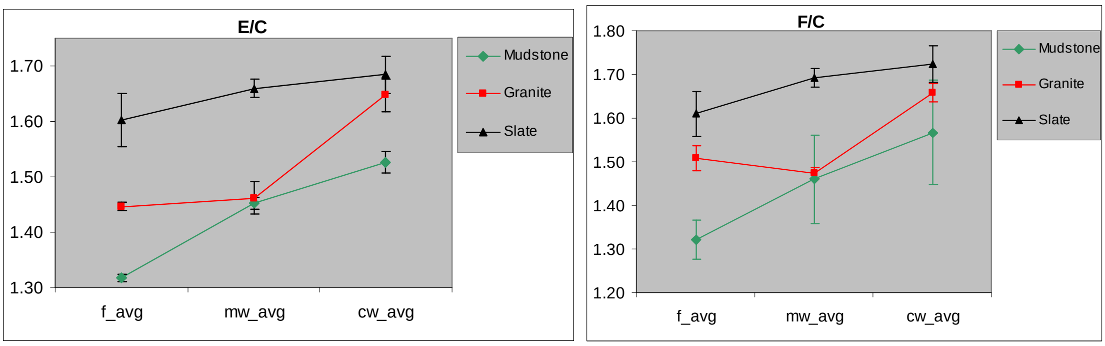
F: measured peak temperature

These references are in line with the schemes followed to address the times in the earlier sections (Section 3.5.3).

An upward trend is noted in the *E/C* and *F/C* ratios with increasing degee of wethering. In the case of the *F/C*, the moderate samples of granite showed slightly lower than the expected intermidiate value between that of the fresh and highly weathered ones. The close similiarity between the moderately weathered and fresh samples is also noted.



5-2 The average ratio of the index temperatures indicated on top averaged for each state of weathering degree in each lithology. The bars correspond to the range of values in each case indicating the degree of overlap in each case.



5-3 The average ratio of the index temperatures indicated on top averaged for each state of weathering degree in each lithology. The bard represent the range of values to indicate the degree of overlap.

The mean values of the *B/A* ratio in the Granite and the Mudstone samples an overall increasing trend is observed. The moderately weathered granite samples on the other hand had the lowest value than the fresh and highly weathered class, which is inconsistent with the expected trend.

In the plots of average values for each of the parameters, the range has been used to infer possible replication of the range of values between the different lithologic classes. The *D/C* parameter although less consistent in the trend throughout the different rock types, has more overlapping values between the different weathering classes of all the lithologic groups (Figure 5-2). If not for the factors affecting the trend of the value with the weathering degree, an easily transportable model of quantifying the weathering degree is suggested by the high degree of overlap between the ranges of values for different weathering classes of the three lithologies tested in this study. The degree of overlap between the values of the *D/C* parameter in similar unit of weathering degree from different lithologic groups is significantly higher than that of the other parameters.

This suggests the possibility of *D/C* scale to be transferable to various situations to quantifying degree of weathering in situation without requiring further information on the type of rock. Nevertheless, the problem of lower variability in values between some of the samples from the same lithologic group with different weathering degree should be overcome before using the parameter.

On the other hand, in the *E/C* and *F/C* parameters, although they have better consistency in their value in distinguishing the degree of weathering with in each of the lithologies, they have almost no overlap in value between the different weathering degrees of the three lithologic rock types (Figure 5-3). Hence, there is less possibility for directly inferring the weathering degree in cases where there is no information on the type of rock. However, the parallel trend in the values suggests a possibility of relative quantification. This indicates that from the difference in the values of *E/C* and *F/C* alone the degree of weathering cannot be estimate, unless selected sites are referred on the outcrop or the sample to calibrate the parameters.

In the case of the parameter *B/A*, the trend is moderately consistent as compared to *F/E*, *E/C*, and *D/C* parameters. It takes into account the long-term temperature change unlike the latter ones that involve short-term temperature gradient. The responses between the different weathering groups when considered separately for each litholgic group have lower differentiation. The degree of overlap between the values of the same weathering unit from different lithologic groups is noted only in the moderate and highly weathered samples (Figure 5-2).

5.1.3. Implications of the VIS/NIR and TIR

The difference in the 0.3- 2.5 µm reflectance spectra was used to infer major variation between the signatures to relate the weathering to mineral alterations that have influence on the thermal behavior. Only certain minerals were identified with the help of the TSG. No major difference in the spectral signatures were observed. Overall reflectance in the weathered samples usually had higher reflectance suggesting a high albedo. Nevertheless this is not consistent in all the cases where some times the highly weatherd samples behave more like the fresh ones while the moderate weathered samples have a rather higher reflectance in most cases.

The average emissivity over the range of 8 to 15 µm shows similar trend where the values are lower for the fresh and the moderately weathered samples. This could be one of the reasons for the relatively similar radiant temperatures of the two weathering classes, especially in the Mudstone samples (Figure 5-2)

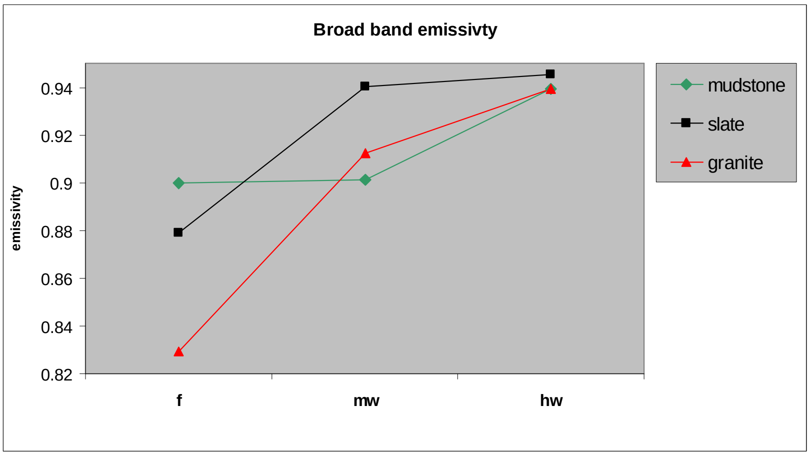


Figure 5-4 average emissivity of the sample spectra over the 8-15 microns wavelength.

5.2. Interpretaion of the slope outcrops temperature indices

Despite the effort made to acquire the data from the same time range as that of the sample mosaics, it was only possible to get certain part of temperature series from the outcrops (for both the Granite and Slate). In addition, the measurements had to be interrupted for some interval in both cases. This part mostly coincided with the temperature series segment that was selected for most of the analysis in the sample mosaics. Hence only limited comparison can be made between the observed index temperatures from the sample mosaics and the slope rock mass outcrops.

Further In the case of the Slate slope, the measurements after noon are heavily affected by shadow overcastting from the slope face irregular features themselves and hence were also left out from the analysis. A possible solution could have been use of digital surface model of the slope to simulate hourly or higher frequency of solar irradiance for a 24 hour cycle and correct the effect of the surface irregularities by matching it with the temperature record from the same location. Although the DSM (Digital Surface Model) was available for the Slate slope the coverage of the temperature image was outside the range of the DEM extent on the slope.

5.2.1. Indices

A. Slate slope

The Slate rock mass slope is a road cut outcrop mainly of meta-sandstone slate rock mass. One of the difficulties in the measurement is the orthogonal blocks of the slope face giving various orientations to the slope face. Three orientations are prominent on the slope faces, which are lighted differently at different times of the day due to their varying aspects. The temperature values sampled from weathered and un-weathered faces of the slope having similar orientation showed significant differences (Figure 5-5). When closely examined the images during the time of near constant temperature in the steps show a more or less uniform darker tone (and hence temperature) than those immediately after the individual cooling steps. Possible cause could be the effect of the orientation of the faces making up the slope.

Comparison of the temperature series with its variance series per selected regions from weathered and un-weathered parts of Slate slope rock mass showed marked variation between the two classes than within. The high frequency variations are short term temperature fluctuations common to many high resolution temperature measurements. The important observation from this curve is the fact that the variability between the weathered and un-weathered rock mass is apparent in the time before and beyond about 09:00AM and 05:00PM respectively, where there is a wider spread in the temperature series variance between them.

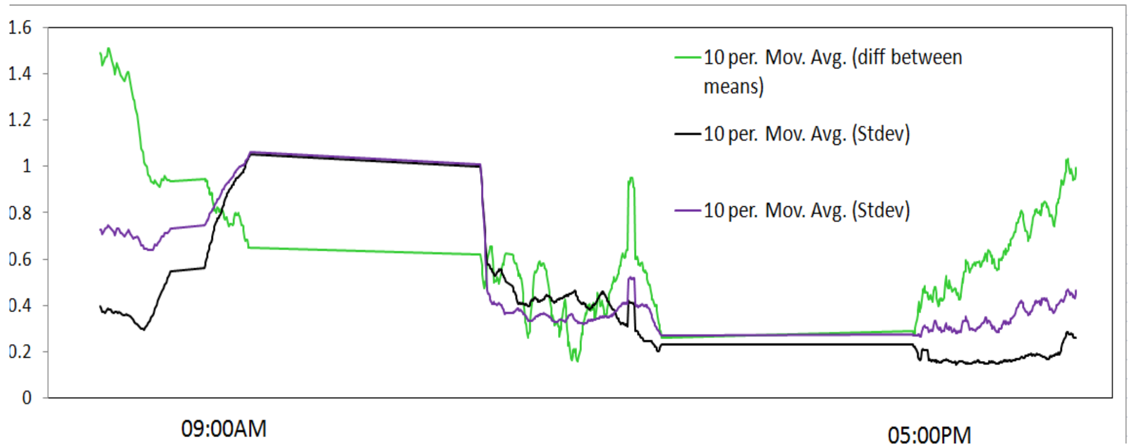


Figure 5-5 sample temperature series and variance of the temperature series per selected regions from weathered and un-weathered parts of Slate slope rock mass.

The indices E/C and D/C showed close resemblance pattern of weathering distribution. This is in line with the observation in the sample mosaic measurement. The relative differences are especially higher in the D/C. The absolute values of the ratio are different from those of the values in the sample mosaic but at least comparable in relative difference between the weathered and un-weathered parts of the slope outcrop.

B. Granite slope

The temperature measurement from the granite outcrops in general give no clear indication of features to associate with photographic image. This proved difficulty in performing the analysis effectively. The slopes are composed of granitic rock mass, which are rather well situated for studying the differential weathering conditions. However, due to technical problems, measurement only started after sunrise at 04:47AM. The slope morphology is uniform unlike the Slate rock mass outcrop. The orientation of the slope facing to the north causes the slopes to be irradiated indirectly throughout the day This can partly explain the lower radiance temperature of the granite slope than the slate slope. The thermal image was acquired from a scene covering moderate to highly weathered rock mass sections of the slope. Hence, the central and top left part of the scene is warmer than the lower right part throughout the measurement, which is from 10:47 AM to 06:30 PM. The weathering degree coincides with this trend increasing from the lower right corner of the thermal image scene towards the top left corner. The effect of core intact rocks in the highly weathered rock mass is evidenced by higher temperature of the intact rocks in the lower temperature background.

Similar argument as the representation of inversion in temperature as the Slate rock mass slope is applied in the Granite slope as well. The result is a good replication of the observed weathering degree distribution.

The D/C and F/C temperature indices ratio show slight resemblance of the weathering pattern distribution from visual inspection. Hence, brighter regions highlighting higher values of ratio correspond with higher degree of weathering. This is in line with the observation from the sample mosaics where the comparable indices show higher value with increasing degree of weathering. Nevertheless the values of ratio are not the same, which is to be expected as the uncertainties and difference in the distance of measurement in the two cases.

5.2.2. Inversion indicator parameter

The indices of inversion in temperature highlighted the weathered and un-weathered sections of the Slate outcrop. The basis for relating the higher index to increased degree of weathering is based on two plausible assumptions. The first is that weathering causes rocks to fluctuate in temperature more in than the un-weathered ones. Secondly, the higher fluctuation leads to lower temperature in the morning and higher temperature at noon.

Based on two assumptions the index can be used to consistently relate with the degree of weathering as shown below.

The three images A, B, C are derived using the simple arithmetic

A = [Image at Morning] / (T° Morning mean) => [Image at Morning] / (14.45°C)

B = (T° Mean Noon) / [Image at Noon] => (25.96°C) / [Image at Noon]

C = ΔT° => [Image at Noon] - [Image at Morning]

The following ratio images would tend to give higher value for higher degree of weathering according to the assumptions made at the beginning. Hence,

C/A, higher => weathered.

C/B, higher => weathered.

Although other changes that could give similar result are unavoidable, at least regions that have higher value in both the derive ratio images (C/A and C/B) have higher probability of representing the weathering degree. The term “high” is applied only in relative manner, referring to range of values in each of the image, which are divided at equal interval.

6. Conclusion and Recommendation

6.1. Conclussion

The results of the analysis show some comparable parameters which can be related to the weathering degree. The inconsistency of the expected trend in some of the cases could be a matter of artefact. It should also be noted that the variation in the temperature measurements are also influenced by the previous heating history of the samples in addition to the state of materials thermal property as the measurements were done only for one cycle.

The results in the direct comparison of the temperature records at the specified times is more consistent in the case of the mudstones samples. This could perhaps be the result of the non complexity of the material composition which is uniform in colour, brightness, and mineralogy. In fact the major difference between the weathering degree is the size

of individual blocks which decreases with higher degree of weathering. On the other hand, the mineralogy, porosity and moisture content variations in the samples are far more complex in the case of the Granite and Slate. These could have a not usually supplementary effect on the thermal property with each other.

There is a close similarity between the thermal property of the samples from the fresh and moderately weathered class in most of the instants. This could be an indication to the lower difference in the thermal property of lower grades of weathered intact rocks. Any little difference left is further masked by art effects external factors making it impossible to infer the difference unless in a very controlled situation. Temperature variation is very sensitive to smaller and even short-lived cast of shadow causing rapid cooling and heating as can be observed in the temperature series of the taken from the intact rock samples experiment.

The ratio of temperature read after 30 minutes, and 80 minutes of direct irradiation, and the peak temperature for the day to that of the temperature read after only 5 minutes of direct irradiation (designated as D/C,E/C, and F/C respectively) gave a more consistent upward trend of values with increasing degree of weathering. Despite the high degree of consistency in values throughout the different lithologic groups, the lack of overlap between the range of values, especially in E/C and F/C, implies limitation of the parameter to cases of more information availability. Nevertheless, the sub parallel trend in the values can be used to relatively evaluate the weathering degree.

The ratio of the temperature read right before the beginning of direct irradiation to that of the minimum temperature recorded for the day, designated as B/A, gave promising result to be used as quantitative evaluating index of degree of weathering. The high degree of overlap between the values in the different lithology have a good potential to use be as a scale that can be transferred in conditions where there is limited information about the rock type.

As observed in the thermal spectral profile, the spectra from the fresh samples showed lower emissivity than the weathered rocks. They tend to have lower absorption of thermal irradiance and consequently lower radiant temperature. This could partly explain the persistent brightest scenes (high temperature) observed in most of the thermal images series in the weathered section of the granite rock mass

6.2. Recommendation

- Measurements should cover more than one cycle to account for heating history, in the case of sample mosaics. This will help to overcome accumulated difference due to earlier thermal history of the samples or the rock mass.
- More controlled experimental setting is crucial to achieve a result that is consistent throughout since the temperatures are very sensitive to slightest variation in incoming radiance. This required concurrent logging of the weather to incorporate the effect of wind direction, cloudiness, and moisture variation.
- The use of thermal camera with accompanying visual image is important if it is not included to reference the observed temperature image with visual interpretation. In addition finding a solution to address the variation with respect to aspect and slope is needed to further the research in controlled manner. Photogrammetric techniques or LiDAR measurements could be applied to model the surface variation which can be used to artificially radiate the slope and obtain variation caused by geometry of the slope.
- Physical parameters and thermal properties should be measured and used to model the heat transfer to fully understand the variation on temperature. As the results from the spectral measurement did not suggest any significant compositional difference, emphasis should be on the determination of some of the physical properties. Especially the issue between moisture content, porosity, and density should be correlated to understand their effect and accordingly design a quantitative means of measuring the difference from the predicted behaviour in the variation of the temperature.

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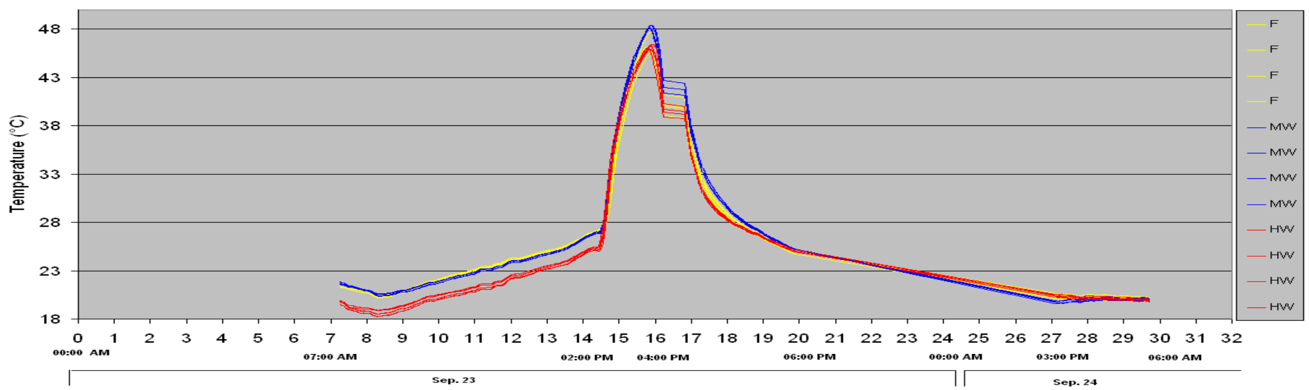
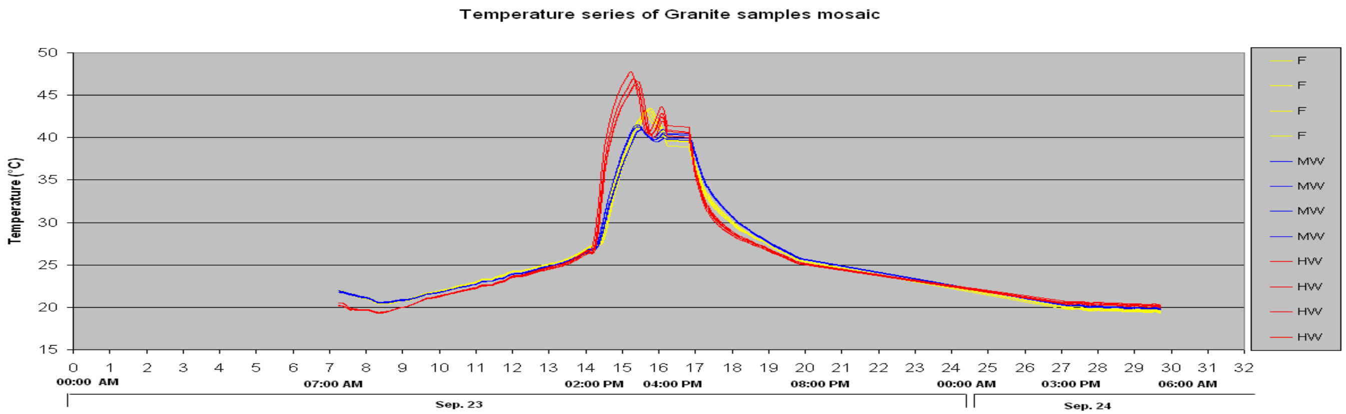
Annex 1

Temperature series curves (F= Fresh, MW=moderately weathered, HW= highly weathered)




Temperature series of Granite samples mosaic
Temperature (°C)
50
45
40
35
30
25
20
15
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
00:00 AM
07:00 AM
02:00 PM
04:00 PM
08:00 PM
00:00 AM
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MW
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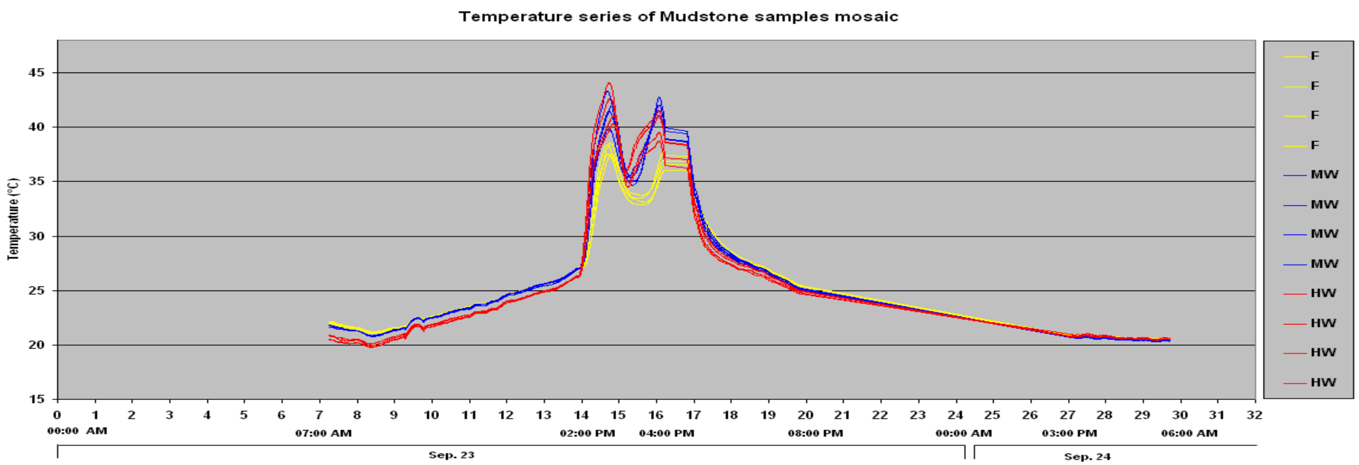
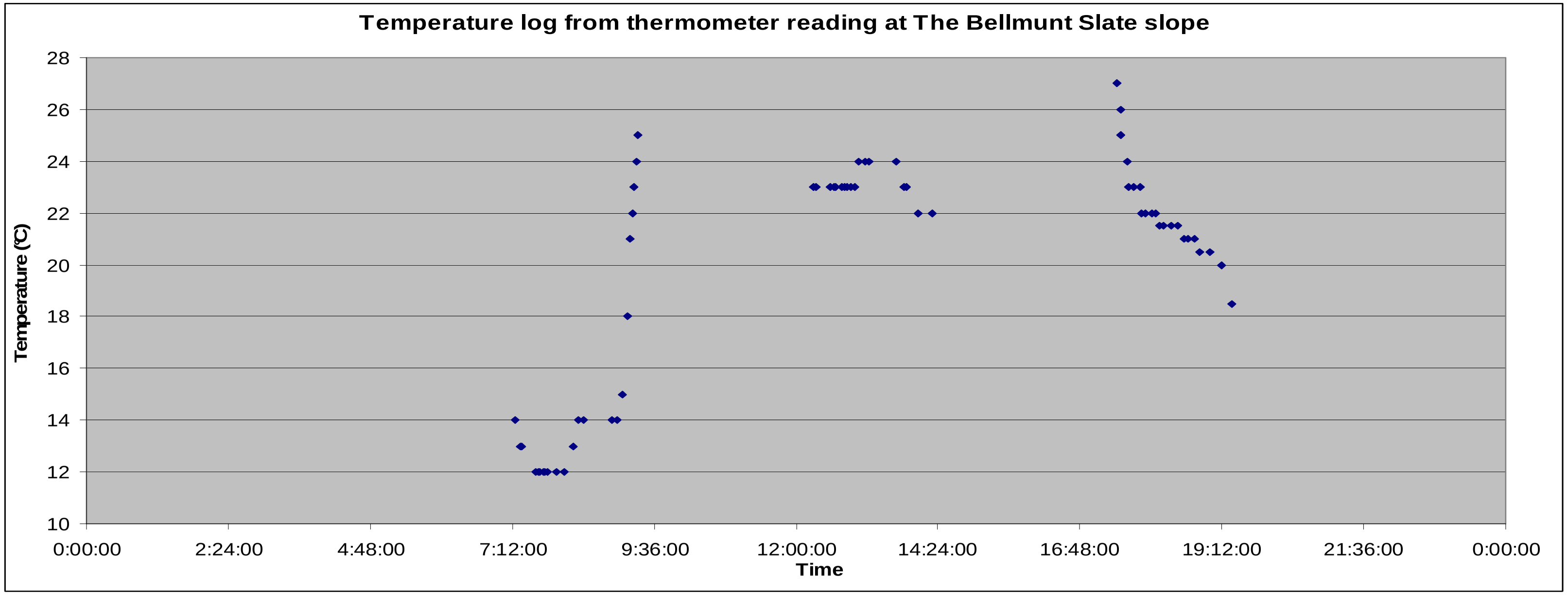
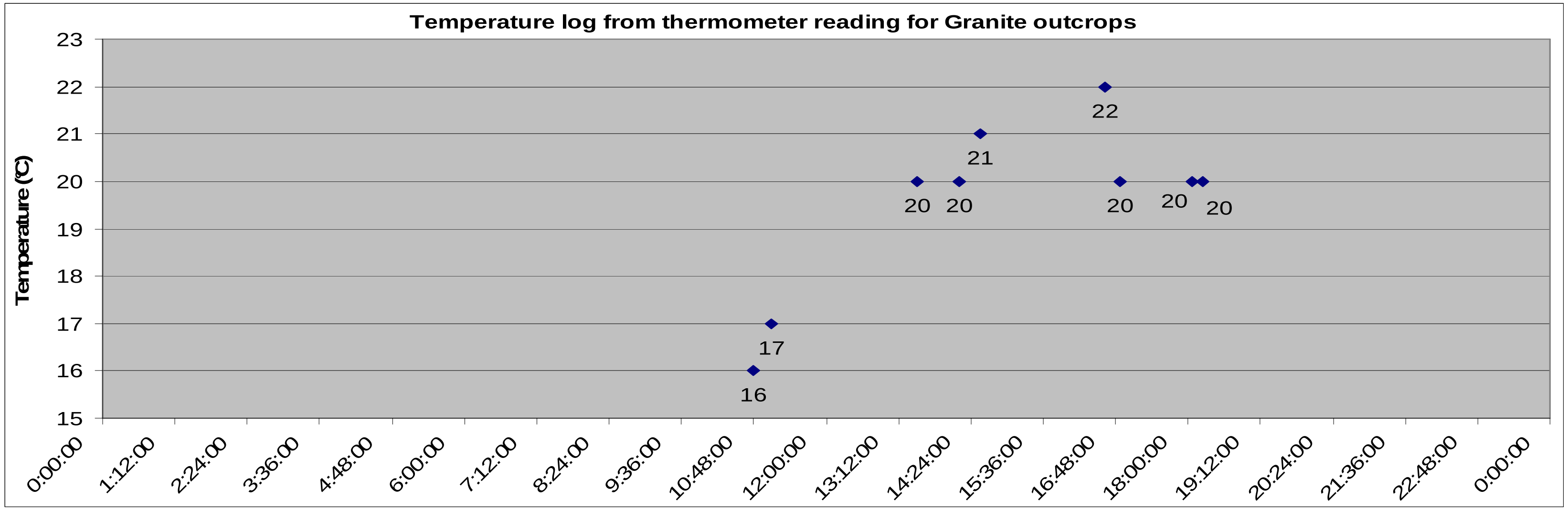
MW
HW
HW
HW
HW


Temperature series of Mudstone samples mosaic
Temperature (°C)
45
40
35
30
25
20
15
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
00:00 AM
07:00 AM
02:00 PM
04:00 PM
08:00 PM
00:00 AM
03:00 PM
06:00 AM
Sep. 23
Sep. 24
F
F
F
F
MW
MW
MW
MW
HW
HW
HW
HW

Annex 2

Temperature logs from thermometer readings.




Temperature log from thermometer reading for Granite outcrops
Temperature (℃)
23
22
21
20
19
18
17
16
15
0:00:00
1:12:00
2:24:00
3:36:00
4:48:00
6:00:00
7:12:00
8:24:00
9:36:00
10:48:00
12:00:00
13:12:00
14:24:00
15:36:00
16:48:00
18:00:00
19:12:00
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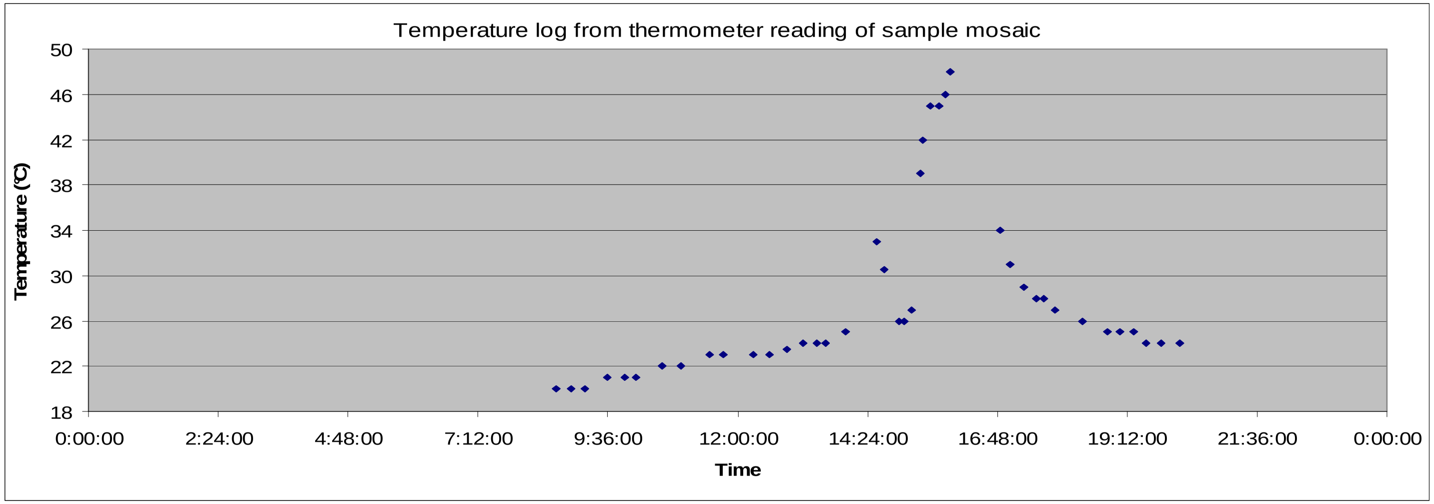
0:00:00
16
17
20
20
21
22
20
20
20



Annex 3

Overall Field Data Summary

	Slope name					
	Belmunt	**Granite**	**Sample 1**	**Sample 2**	**Hostal**	**Sandstone**
Location	Along the road to Belmunt, 5 km NE of Falset	Along the road **4** km north of Flaset	At the Camp	At the Camp	South east of Falset	South East of Faslet
Lithology	Slate	Granite	Granite, Slate, Mudstone mozaic	Granite, Slate, Mudstone mozaic	Mudstone	Sandstone
Inclination	50° to 60 °	60° - 70°	0 °	0°	Vertical	Sub vertical
Aspect	North East	North	Horizontal	Horizontal	East	---
Date of field assessment	September 22, 2009	September 25, 2009	September 23, 2009	September 24 and 25, 2009	September 21 and 24, 2009	none
Date of thermal imaging	September 22, 2009	September 25, 2009	September 23, 2009	September 24 and 25, 2009	September 23 2007	September 21, 2006
Scene coverage	3.8 m X 3.8 m	5 m X 5 m	0.52 m X 0.52 m	0.52 m X 0.52 m	---	Approx. 4.2 mX 4.2 m
Resolution	24.24 cm	33.06 cm	3.31 cm	3.31 cm	---	—
Distance of the camera	11 m	14.7 m	1.5 m	1.5 m	---	---
Data types	Contineous thermal image, Contact temperature log, Samples	Contineous thermal image, Fewer Contact temperature log, Samples	Contineous thermal image, Contact temperature log,	Contineous thermal image, Contact temperature log,	Morning and day thermal image, Samples	Thermal image, Weather condition log
starting time	7:00 AM	10:47 AM	7:14 AM	2:20 PM	morning image	(Morning) 8:45 AM
Ending time	7:22 PM	6:28 PM	2:11 PM	3:12 AM	day image	(After noon) 6:07 PM
Duration	5 hr 53 min	3 hr 35 min	11 hr 35 min	3 hr 50 min		Morning1 hr 25 min After noon 1 hr and 5 min
source of data	Own data	Own data	Own data	Own data	Asrat (2007), Own data	Venus (2006)
Remark	Extended interruption around 10:00 AM and 4:PM	Extended interruption around 12:00 AM and 4:00 AM	Interuption due to Florescent lamp	Interuption due to Florescent lamp	Morning and After noon images	No ground geotechnical assessment of the weathering degree

Annex 4

Field Data of Belmunt slope

Easting	Northing	Sample	Weath. deg.	Description	Colour	Lithology	Comment	Acquisition time	Duration
4557197	315965	1a	F	Shiny, fine grained, discoloured to yellowish brown	Grey to Dark grey	Slate	Sunny	7:00 -7:20	20 min
		1b	MW	Completely discoloured, and dark spots, easily brocken by hand	Reddish brown			7:31 - 8:28	57 min
		1c	HW	Pebble sized core remenants inside disintegrated material	Reddish brown			8:52 - 9:25	33 min
								12:13 - 12:30	17 min
				-				12:34 - 14:22	1 hr 48 min
								17:24 - 19:22	1 hr 58 min
							Total	**7:00 - 19:22**	**5 hr 53 min**

Annex 5Field data on samples mosaic

Location	Weath. eg.	Description	Colour	Lithology	Weather condition	acquisition time	Duration
At the camp	F	Intact rock	white with dark spots	Granite	Sunny	7:14 - 7:17	3 min
	F		dark grey	Slate		7:20 - 7:56	36 min
	F		white	Mudstone		7:58 - 10:20	2 hr 2 min
	MW		yellowish brown	Granite		10:23 - 11:09	46 min
	MW		brownish coating	Slate		11:26 - 15:24	4 hr
	MW		white	Mudstone		15:25 -16:13	48 min
	HW	disintegrated	yellowish brown	Granite		16:49 - 17:17	28 min
	HW		redddish brown	Slate			
	HW		greyish white	Mudstone		17:19 - 20:11	2 hr 52 min
					Total	**7:14 - 20:11**	**11 hr 35 min**

Annex 6

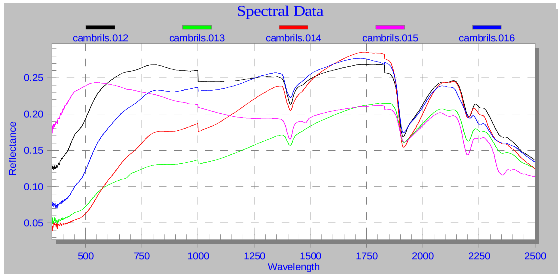
Field data on Granite slope

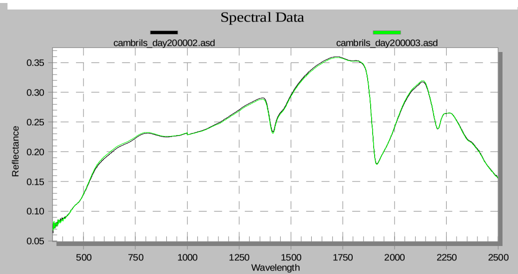
Easting	Northing	Sample	Weath. Deg.	Description	Colour	Lithology	Weather	Acquisition time	Duration
316949	4559485	2a, 2-2c	Highly	Completely disntegrated but intact original rock fabric	Light grey	Granite	No direct exposure to sun		
		2b, 2-2a	Fresh	Hard and dense, discoloration limited to discontinuity surfaces	White with black spots			10:47 - 11:05	18 min
		2c	slightly	Dense, but reduced hardness, discoloration slightly penetrates discontinuity surfaces, no sign of disintegration	Brownish white with black spots			13::30 - 14:16	45 min
		2-2b	Moderately	Significantly reduced strength	Yellowish brown			14:14 - 15:29	1 hr 15 min
								16:29 - 17:21	52 min
								18:03 - 18:28	25 min
							Total	**10:47 - 18:28**	**3 hr 35 min**

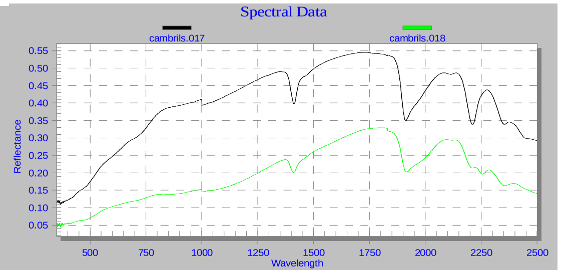
Annex 7

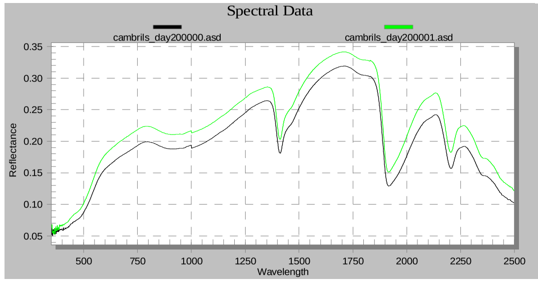
Spectral Plots of VIS/NIR reflectance for samples obtained from various degree of weathering classes and lithology.

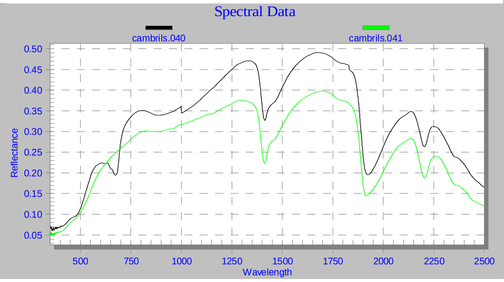
A. Granite samples

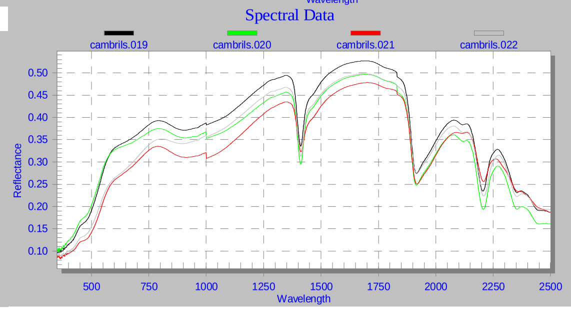




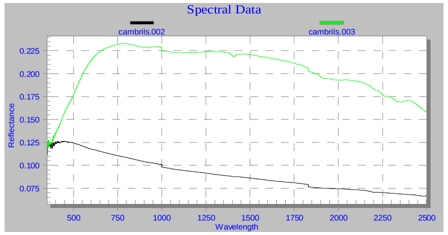


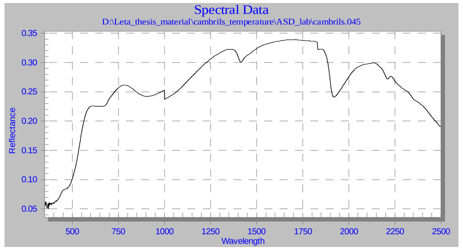


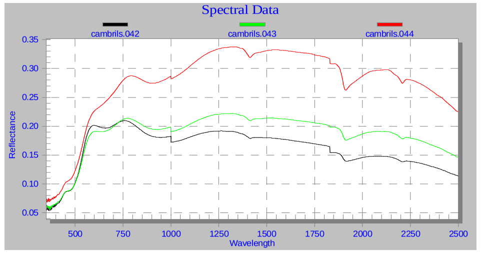


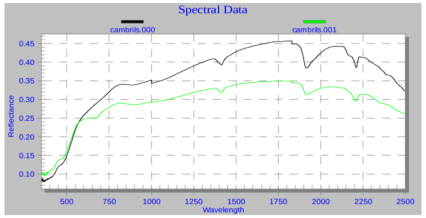


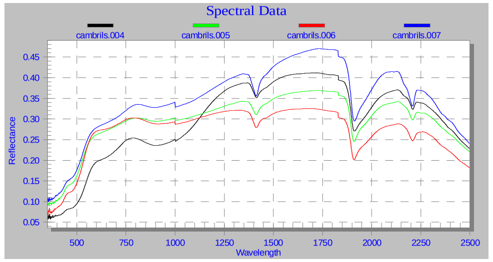
B. Slate samples

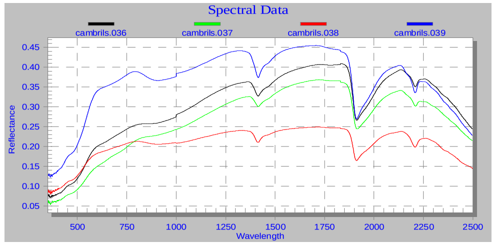


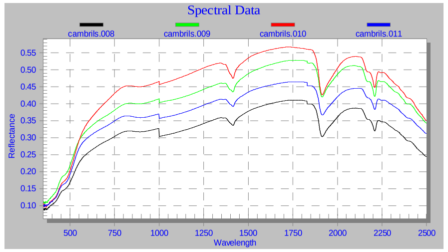


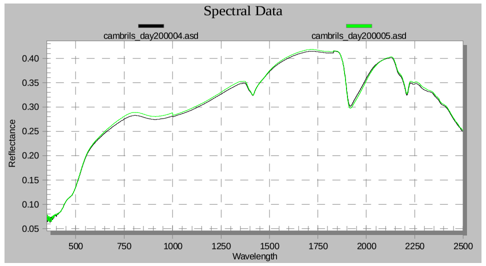




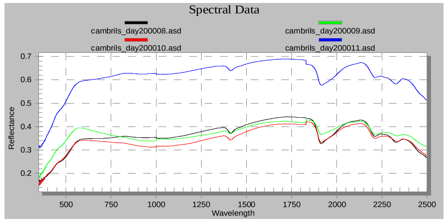


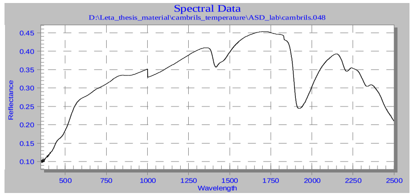


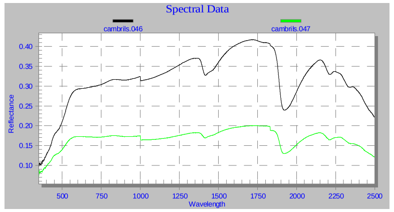


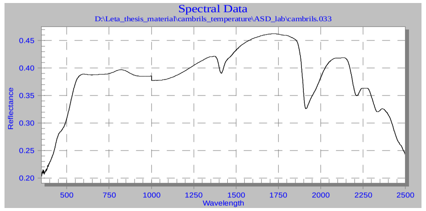


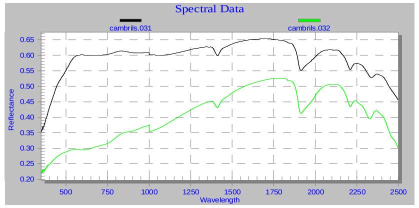
C. Mudstone samples

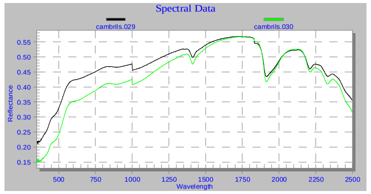


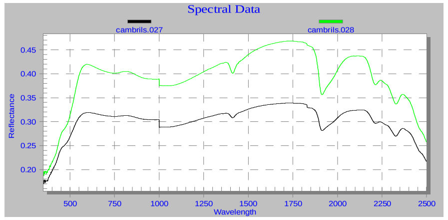


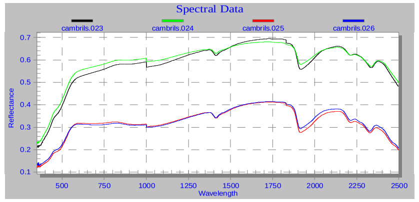


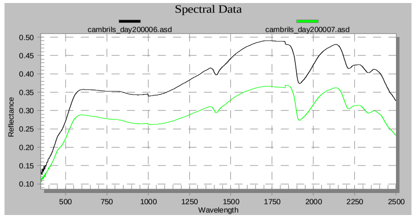












Annex 8

Mat Lab script used for re-sampling the raw *.csv format outputs of temperature readouts from the thermal camera to series of images.

```
function [img, time] = readimage(filelocation,beginFrame,endFrame)
%% use the function like [img,time]=readimage('D:\My Documents\data\thermal\thermal-right2.csv',1,10), and 1,10
means the
%% frame No. of the images you want.

time=[];
fid = fopen(filelocation); %´ò¿ªÒ»¸öÎÄ¼þ£¬Ä¬ÈÏÖ»¶ÁµÄ
fseek(fid, 0, 'bof'); %´Óbegin of file¿ªÊ¼Êý¸Ö¸Õë¹éÁã
fscanf(fid, '%s%c%s',3) % ¿ì½ø¹ýÎÄ¼þÍ·µÄ·Ï»°"Tuesday,6-May,2008,18:03:58"¡£

for i=1:beginFrame-1  %Ìø¹ýbeginlineÖ®Ç°µÄËùÓÐÐÐ£¬¿Õ×ª
    fscanf(fid, '%f,', 1);
    fscanf(fid, '%f,',256);
end
clear ans;

sumFrame=endFrame-beginFrame+1; %Ñ»·N´Î£¬N¾ÍÊÇÐèÒªµÄ¡Êý£¬µÈÓÚendFrame-beginFrame+1
img = zeros(16,16,sumFrame);
```

```
h = waitbar(0,'Reading data...');
for i=1:sumFrame
    time = [[time];fscanf(fid, '%f,', 1)]; % ¶ÁÈ¡Ê±¼ä¼ÇÂ¼
%     fscanf(fid, '%f,', 1);
    [A,count] = fscanf(fid, '%f,',[16,16]); % °Ñ1¸ö×Ö·ûÎªÒ»×é£¬¸³Öµ¸øA[16,16]£¬ÏÈÌîµÚÒ»ÁÐ£¬Ö±µ½ÌîÂú
    try
    img(:,:,i)=A;
    catch
        disp(['woops! it stopped in i=',num2str(i)]);
        disp(lasterr);
        break
    end
    waitbar(i/sumFrame)
end
close(h); %¹Ø±Õwaitbar
fclose(fid); %¹ØÉÏÕâ¸öÎÄ¼þ
```

Annex 9

Comments

!!! Time in 24 hour formats.

!!! Live measurements refer to temperature imaging

September 21, 2009

Activity: Observation of the stratigraphy of the area; visits and sampling at Bellmunt slope, the granite slope and Mudstone slopes.

Note: Total of nine samples recovered, three from each lithology for the Fresh, Moderately and highly weathered states. Mudstone samples show difference in weathering degree resulting in different sizes of boulders with the more weathered finer grains lying on top of larger block sizes.

September 22, 2009

Location: 0°48’25.22”E and 41°08’42.82”N 315965E/4557197N (UTM, WGS-84, Z-31N)

Distance away from slope 11 meters.

6: 57 Start of Live measurement every 5 minute. Temperature from thermometer put on non sun facing side, Min/max, 20°/18°.

7:30 Change of live measurement frequency to 1 minute

7: 42 cars blocking the view.

7:45 sun rise (Local news paper published official sunrise time for the day as 7:38).

9:09 change of the thermometer position to the sun facing side.

12:14 live measurement interval changed to 30 seconds.

12:47 thermometer position changed to sun facing side.

12:50 second set of samples for the unit collected from the site for slight, moderate and completely weathered states.

13:03 thermometer position changed to non sun facing side.

13:41 thermometer position changed to sun facing side.

14:00 slight drizzle foe about 5 to 10 minutes.

14:35 stopped measurement due to power shortage for 3 hours.
17:25 second live measurement set started, position of thermometer on sun facing side.
18:13 thermometer position changed to non sun facing side
19:23 end of live measurement.
Note: *lower variation of the reference central pixel temperature in the live temperature image. Sometimes the weathering of the slated is indistinguishable from infill between the plates.*

September 23, 2009
Activity: measurement of mosaic of samples collected from the three lithological units laid out on the floor under the thermal camera at eh camp. Camera height 1.5 meter, measurement interval of 30 second, number of samples 9 in ordered layout of three states of weathering degree in the three lithologies, sample sizes of 10 cm by 12 cm dimensions, a glass of water included in the scene
7:15 Start of live measurement
14:00 shadow on part of the samples (Mudstone), picture.
14:34 shadow on Slates
14:43 Thermometer temperature reading of the shadow
15:05 – 15:13 shadow on Mudstone
16:30-16:49 interrupted measurement, freezing of computer.
20:10 measurement stopped to avoid interference from florescent lamp for 6 hours
2:25 live measurement continued after the lights were out.
7:00 end of the measurement for the sample mosaics before sunrise.

September 24, 2009
Activities more samples during the morning and live measurement of another sample mosaic in the afternoon.
The rock samples had on average 31°C temperature at the start of the live measurement
14:32 start of live measurement
14:46 Shadow on the top row.
15:05 shadow on top left corner

15:17 interrupted to change battery for the camera

19:54 live measurement stopped due to florescent lighting

0:43 continued live measurement

3:12 End of live measurement.

September 25, 209

Activity: measurement at the Granite slope.

Location: 0°49’4.9”E 41°9’57.77” N (316949mE/4559485mN, WGS-84, UTM Z-31N)

Slope faces to the north, never directly lit by sun. Measured from distance of 14 meters.

9:45 start of live measurement

10:06 stopped to save power

10:47 change of site to be imaged, so more variation of weathering degree could be in the scene.

14:33 stopped live measurement to save battery.

16:30 continuation of live measurement

18:15 end of live measurement