THE EFFECTS OF ASPECT, DIRECTIONAL HEATING AND DEPTH ON BEDROCK TEMPERATURES AND THE POTENTIAL RELATIONSHIP WITH THERMAL FATIGUE WEATHERING

By

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Dedication

In loving memory of...

Marike Kleu (11/12/1988 – 01/03/2020)
Adriana Cornelia Kleu (14/06/2018 – 01/03/2020)

…no doubt in my mind, Squiggle is redesigning heaven's interior, while Adi is blowing baby kisses at the angels.…

Declaration

I, Izak Johannes Breytenbach, hereby declare that the work presented in this thesis is my own unless referenced otherwise. I also declare that this work has not been submitted at any other institute for any degree, examination or other purpose.

22/02/2021

Signed Date

Abstract

Geomorphological weathering processes and their relationship with temperature fluctuations are frequently researched. These research efforts are mostly restricted to surface conditions where soils, loose-lying rocks or rock outcrops are assessed. However, there is a shortcoming in the understanding of the thermal properties in a rock mass, particularly in the upper metres below the surface, as this has not been investigated or researched in any great detail. The research reported here is unique in this regard as it exploited the use of rotary core boreholes in tillite bedrock in the Karoo (Western Cape, South Africa) which were drilled as part of an invasive materials investigation for a proposed new hard rock quarry to supply road stone.

Temperature data were captured on a bedrock ridge hosting tillite outcrop with a strong east to west orientation. The site work was done in two separate phases. The initial phase of research saw data being captured for one year on two aspects (i.e. north and south) at a depth of 0.3 m. This was followed by the second (more detailed) phase, where three aspects were assessed (i.e. north, south and a flat crest), but at depths of 0.3 m, 2.0 m and 6.0 m, totalling nine data acquisition points. The second investigation phase gathered data for seven months. Supplementary weather data were also captured for the site.

Subsequent data analyses revealed that there is much to learn about the thermal behaviour of bedrock in the upper metres below the surface, and that the temperature properties or thermal regimes are not as simple as often assumed. Temperature differences related to aspect are not only surficial, but are transmitted to underlying bedrock, and notable temperature differences were measurable to a depth of at least 6.0 m. Seasonal temperature fluctuations also have a pronounced effect on the rock mass temperatures and it was proven that deeper parts of the bedrock accumulate and dissipate heat at different (i.e. retarded) rates compared with shallower parts of the rock mass, creating suitable thermal conditions to induce thermal fatigue. Thermal properties were also proven to be non-linear. During analyses, the concept of

temperature inversions was proven, whereby one part of the bedrock becomes hotter or cooler relative to another/adjacent part of the bedrock, compared with its earlier temperature state. It was argued that these temperature inversions may exacerbate thermal fatigue. This research proved that aspect (i.e. directional heating) and depth need to be considered when analysing thermal regimes in a rock mass, as these have a distinct influence. The effects which manifest themselves create suitable conditions for thermal fatigue, not only near the surface but also at depth in the bedrock.

Lastly, the effects of meteorological conditions on shallow bedrock temperatures were assessed. Preliminary findings suggest that boundary conditions and meteorological processes may indeed affect shallow bedrock temperatures, but only under certain circumstances and not to the same extent as reported in the literature for conditions researched at the surface. Wind temperature relative to the rock temperature, as well as a combination of wind and rain were found to be the most significant factors.

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1. Introduction

Landscape formation by geomorphological processes is an extremely complex and comprehensive field of study which is continually pursued by researchers. These processes are not limited to earth alone and extend to other celestial bodies as well (e.g. Tesson *et. al.*, 2020; Ravaji *et. al.*, 2019). Weathering processes often forms the focus of ongoing research which, according to Warke (2013, p198) "*…reflects the fact that rock is no longer in a state of balance or equilibrium with prevailing conditions of temperature, pressure, and moisture availability compared with those under which it was formed"*. By obtaining an understanding of geomorphological weathering processes, the hope is that landscape formation will be better understood, seeing as weathering is the precursor to erosion (Pope, 2013) and weakens bedrock (Migoń, 2013). However, achieving such an understanding, particularly in a holistic manner, is a daunting task due to the complex interactions between various weathering processes and other external factors. In addition to the interaction of these processes, changes with time also play a significant role in bedrock erosion and subsequent landscape evolution, as was illustrated by Matsuoka *et. al.* (2006).

Viles (2013) discussed the intricate and complex relationships between weathering (i.e. synergistic weathering processes) and other geomorphological processes, and also emphasised the relationship between the processes of weathering and diagenesis. Of importance is the observation made by Viles (2013, p13) that "*…Although weathering is usually seen to operate on rock surfaces, in soil, within saprolite and at the saprolite-rock boundary, in karst and other environments weathering may occur much lower"*. From the context, it is deduced that the term "lower" is synonymous with "deeper", thereby suggesting that weathering processes may also take place below the surface, as is often the case with karst profiles.

Furthermore, it is virtually impossible to assess geomorphological processes in their entirety in a single human lifetime (Warke, 2013) and variations may occur which influence weathering processes (e.g. climate change) as a result of long term changes (Gutiérrez and Gutiérrez, 2013; Viles, 2013; Hall *et. al.*, 2012). Consequently, it is challenging to consider individual geomorphological processes in isolation, as multiple processes are concurrent under real-world conditions. Weathering is considered a non-linear dynamic system (Viles,

2013; Warke, 2013) and the various components in such a system have complicated interactions with each other (Viles, 2013). Nevertheless, to study a particular process, it becomes necessary to largely disregard concurrent processes which may affect one particular property or process being studied and assess individual process separately.

Research efforts assessing rocks, bedrock or soil materials are extensive and largely focus on surface conditions (e.g. Lamp *et. al.*, 2017; McKay *et. al.*, 2009) or conditions immediately below the surface (e.g. McAllister *et. al.*, 2017; Gunzburger and Merrien-Soukatchoff, 2011). However, depending on publication, the terms "at surface", "near surface", "sub-surface" or "below surface" are generally poorly defined and may conflict depending on each researcher's interpretation or the scale of their investigation. For example, it would be assumed that the term "at surface" would refer to measurements taken on top of an exposed rock or soil surface, typically at ground level; however, in the case of Hall (1999), "surface temperatures" were obtained within (i.e. below) a millimetre of the surface. The definitions for "near surface", "sub-surface" and "below surface" are also not simple, as these terms are not universally defined and may or definitions may not correlate. For example, Gunzburger and Merrien-Soukatchoff (2011) assessed "near-surface" temperatures to depths of up to 50 cm below surface, but also described this as "sub-surface" temperatures; however, these depths may not necessarily be considered "near-surface" by a researcher assessing temperatures on a millimetre scale below surface.

Thermal effects have also been studied to establish the effects on exfoliating rock domes (Collins *et. al.*, 2018) or the processes associated with rock falls (Collins and Stock, 2016). Such research greatly aids our understanding of the geomorphological processes that affect weathering and erosion at, or close to surface level. However, very little geomorphological research has investigated processes occurring in the upper few metres of a rock mass (i.e. below surface level) and as a result, our understanding of geomorphological processes in such a rock mass is somewhat limited. This does not refer to mining or geothermal studies. When considering a holistic approach to assessing weathering processes at the surface, it stands to reason that one should understand the properties of the parent material being scrutinised and therefore it is essential to discern which processes affected the bedrock, and to what extent, before being exposed at surface and subjected to surface weathering processes. As an example, Gómez-Heras *et al*. (2006, p237) emphasised that most insolation weathering models assume "*…breakdown in terms of the vertical temperature distributions obtained*

from a single surface measurement and a limited set of arbitrary depth temperatures....”, highlighting perhaps the biggest limitation or difficulty with assessing a rock mass: the absence of data obtained from within the rock body or bedrock (i.e. with depth). Throughout this study, the term “rock” will be used loosely to refer to the rock mass or bedrock investigated.

Existing research related to weathering processes which assess rock or soil temperatures broadly follow a similar approach and will be discussed more elaborately later. Temperature loggers are installed at some level (at or below the surface) and temperature readings are recorded over certain periods and at variable frequencies to assess weathering (or other) processes. Yet despite extensive research work being undertaken in this regard, virtually all research efforts focus on surface or near-surface conditions. Some relevant examples in this field of research date back nearly a century (e.g. Griggs, 1936; Blackwelder, 1933) and even currently, the field of research is constantly evolving.

Table 1.1 summarises some of the more significant examples related to the research at hand (which will be discussed in subsequent sections), but by no means summarises all relevant research related to weathering or temperature studies. This summary highlights the fact that assessments are, for the most part, limited to the upper 100 mm below the surface, possibly except for Gunzburger and Merrien-Soukatchoff (2011) and Anderson (1998), who assessed properties at depths of up to 50 cm. Many more examples are available in the literature. From the presented summary (Table 1.1), it is apparent that there is a shortcoming in the understanding of conditions or regimes and the related effects in the upper five or even ten metres of a given bedrock profile, particularly as far as temperatures are concerned. The research reported in this thesis made a deliberate effort to determine the thermal behaviour properties, and factors influencing them, in the upper profile of bedrock to a depth of six metres. This approach is unique and similar work has not been investigated or reported in detail previously.

Assessing rock properties at depth, as opposed to at (or near) the surface is simpler in the sense that many factors that influence surface conditions (e.g. meteorological processes, albedo, etc.), or even the interaction between these processes occurring at the surface (e.g. albedo and wind temperature, as discussed by Hall *et. al.*, 2005b), are theoretically largely not at play or have a limited impact.

Table 1.1 Summary of most relevant literature sources considered for the research

Author(s)	Depth Assessed	Assessment	Location	Rock Type
Messenzehl *et. al.* (2018)	10 cm	Rock weathering, rockwall stability and rockfall supply	Swiss Alps	N/A
McAllister *et. al.* (2017)	5 – 100 mm	Stone temperature and moisture variability	Northern Ireland	Sandstone
Pisabarro *et. al.* (2017)	0.1 – 0.2 m	Ground temperatures, landforms and associated processes	Northern Spain	N/A
Lamp *et. al.* (2017)	Surface	Thermal stress weathering and spalling	Antarctica	Dolerite
Eppes *et. al.* (2016)	Boulder surface	Solar-induced thermal stresses and cracking in a boulder	Southern California	Granite
Gunzburger and Merrien-Soukatchoff (2011)	10 - 50 cm	Theoretical modelling of heat exchange through rock surface	France	Gneiss
Smith *et. al.* (2011)	5 – 100 mm	Near-surface temperature cycling	England	Limestone
McKay *et. al.* (2009)	Surface	Rock temperatures and the implications for rock weathering	Atacama/Antarctica	Dolerite
Burnett *et. al.* (2008)	10 cm	Aspect-related influences on slope forms and processes	Colorado plateau	Sandstone/shale
Gómez-Heras *et. al.* (2006)	Prepared surface	Surface temperature differences between minerals	Spain	Granite
Hall *et. al.* (2005a)	Surface	Aspect and biological weathering	China	Granite
Sumner *et. al.* (2004)	Surface	Thermal attributes of rock weathering	Namibia/Drakensberg/Marion Island/Antarctica	Granite-gneiss/basalt/lava block/sandstone
Iñigo and Vicente-Tavera (2002)	10 cm	Thermal gradients in granitic rocks	Spain	Granite
Hall and André (2001)	Surface	Weathering by thermal stress	Antarctica	Granodiorite
Hall (1999)	5 – 40 mm	Thermal stress fatigue	Antarctica/Canada	
Anderson (1998)	0 – 42 cm	Granite bedrock temperatures in alpine setting	Wyoming	Granite
Jenkins and Smith (1990)	Surface	Daytime rock surface temperature variability	Otterburn (sample)	Sandstone
Richter and Simmons (1974)	Prepared surface	Thermal expansion behaviour of igneous rocks	Laboratory	Igneous
Griggs (1936)	Prepares surface	Fatigue in rock failure	Laboratory	Granite

1.1 Motivation for Research

With the majority of current and past geomorphological research efforts (some of which are summarised above) focussing on surface or near-surface conditions, there is strong motivation to assess geomorphological processes and rock properties in the metres below ground level, as this has not been undertaken before. The use of borehole shafts remaining after geotechnical investigations present an ideal opportunity to make such a research effort possible.

The identification of hard rock quarries for the production of high-quality road construction aggregate in South Africa is a service commonly rendered by the engineering geological fraternity based on the COLTO (1998) specification and SAPEM (2013) guidelines. Geotechnical material investigations for hard rock aggregate sources (i.e. quarries) are generally undertaken using rotary core drilling. Once drill core has been retrieved, the remaining borehole shafts present an excellent opportunity to investigate certain physical properties of bedrock at depth, provided such a borehole does not suffer collapse.

For this particular project, investigation boreholes were drilled to a depth of 25 m, but this may vary depending on project requirements. Compared with this, most rock or bedrock property research efforts consider surficial (i.e. geomorphological investigations) or very deep (i.e. mining or geothermal applications) materials, and seeing as these types of investigations have completely different approaches, implications and deliverables, they are seldom directly comparable in a geomorphological context.

1.2 Aim of Research

This research assessed temperatures of an intact rock mass at depths which have not been assessed or reported in research literature before. The ultimate aim of the research was to establish whether there are notable differences in heat build-up/dissipation or temperature fluctuations/oscillations of rock related to its orientation or aspect, and to what extent (if any) the vertical depth in bedrock affects, or is affected by, such variations. This was achieved by studying the thermal properties at different aspects, depths and under varying meteorological

conditions to determine whether these factors could potentially influence geomorphological weathering processes, more specifically, thermal fatigue.

The objectives for this work can be briefly summarised as follows:

- Assess whether the effects of thermal variation (i.e. temperature differences) related to aspect are confined to surface conditions, or transmitted to any notable depth below surface.
- Assess whether, or to what extent, bedrock temperatures are affected by vertical depth and how it responds compared with shallower temperatures over time.
- Determine whether prevailing thermal properties are sufficient to induce thermal events (e.g. thermal shattering, thermal fatigue, etc.).
- Establish whether the effects of meteorological events occurring within boundary condition are transmitted to depth in bedrock.

1.3 Approach to Research

To achieve the aims of the research physical (temperature) readings were measured *in situ*. This was done as it was considered critical to substantiate any findings employing physical field data (Hall and André, 2001), as opposed to observational inferences or laboratory-based extrapolated conclusions (Viles, 2013). A site was selected with a suitably orientated topography where boreholes were positioned in such a manner that data could be obtained from boreholes facing the highest insolation (i.e. north-facing) and lowest insolation (i.e. south-facing). A third site was also monitored which was situated at the horizontal crest of the study site. Supplementary baseline weather data were also captured.

Data collection was done in two phases. Initial data accumulation was used as a trial or proof of concept, followed by more elaborate and purpose-specific data acquisition. The data were processed and analysed to reach research conclusions.

2. Literature Review

2.1 Weathering Processes

Studying individual rock weathering processes in isolation remains a challenge and published research into the subject extends back nearly a century (e.g. Griggs, 1936; Blackwelder, 1933). As it is the precursor of erosion (Pope, 2013), weathering of bedrock is clearly of significance. According to Pope (2013), rock weathering is a critical component of earth science which has not received adequate coverage in the literature.

Warke (2013, p198) defined weathering as "*…the fact that rock is no longer in a state of balance or equilibrium with prevailing conditions of temperature, pressure, and moisture availability compared with those under which it was formed*". Regardless of individual definitions, in essence, it can be concluded that weathering is the result of some disruption to the state of equilibrium at which a material formed, forcing a reaction or change to adapt to newly imposed conditions (Bland and Rolls, 2016). Physical weathering is attributed by Matsukura (2013) to processes including unloading, slaking (due to moisture-related shrinkage and expansion), thermal stress, frost action and salt-crystal growth. Even though numerous definitions of "weathering" are available in the literature, Viles (2013) stated that individual "weathering processes" are generally vaguely defined.

To complicate the matter, numerous other fields of science or engineering have an overlapping interest in weathering, thermal fatigue or thermal stress as they are of direct interest (e.g. mining, metallurgy and the built environment in general). However, as the application and approach used by other industries differ from those used in geomorphology, similar topics are often investigated from completely different perspectives or based on very different assumptions, making the findings generated by these various industries largely incompatible or of limited use to geomorphologists. For example, the work done by Chen *et. al.* (2016) assessed the effect of elastic rock deformation on rock mass temperature and while findings were interesting and valuable in their field of study, they hold little direct significance for geomorphologists. Besides, research approaches amongst geomorphologists also vary and efforts are made to study processes at virtually all scales which are not necessarily directly comparable. Dorn *et. al.* (2013) stated that while fracturing related to

thermal stresses should be present at the nanoscale, no known observations have been made at this level for the study of, amongst others, insolation weathering.

The physical effects of erosion also have an influence on rock materials at depth, as these materials are under considerable internal stress due to the weight of overburden and the overlying rock mass itself. However, as the overburden is removed (i.e. erosion) and the confining pressure is reduced, the rock is allowed to dilate (i.e. expand) and release some of the internal pressure, which promotes the formation of joints (Summerfield, 1991). The relationship between weathering and erosion is, therefore, a complex and dynamic one. The work done by Zhang *et. al.* (2013) concluded that the rate of decay of bedrock decreased as the thickness of overburden increased and that there is a significant relationship between rock decay and daily moisture and temperature fluctuations. However, Hall *et. al.* (2012) stated that jointing in rock could allow weathering to take place at depth because the jointing allows movement of surface oxygen and surface moisture to penetrate the rock mass through said joints. The importance of water penetrating bedrock through cracks or fractures was again emphasised by Hall and Thorn (2014), while Eppes *et. al.* (2016) found that cracks forming in any rock material present or promote the opportunity for other weathering mechanisms to further weather the rock material.

Assessing or studying individual rock weathering processes in isolation remains a challenge (Viles, 2013). While some weathering processes are virtually instant (e.g. thermal shock), others proceed over centuries or even on a geological time scale, making a comprehensive study of such a process impossible in a single human lifetime. Consequently, there appears to have been an emphasis on more rapid weathering processes in research, resulting in fewer assessments and a poorer understanding of slower geomorphological weathering processes. This observation was earlier noted by Hall (1999) who stated that many geomorphological studies have ignored the role of thermal stress fatigue; arguably one of the slowest weathering processes under consideration.

In recent decades, research work into weathering processes has escalated dramatically as concepts have become better understood, leading to more in-depth investigations. Numerous research opportunities have become available on ideal research sites in remote, isolated and extreme locations such as Antarctica and certain desert environments (e.g. the Atacama Desert) in recent decades, and consequently, the effects of thermal fluctuations and

weathering mechanisms have been studied extensively (e.g. Kanamaru *et. al.*, 2018; Hall, 2013; Warke, 2013; Matsuoka, 1995). The majority of recent or current geomorphological weathering studies tend to focus on continuous or repetitive/cyclic processes which are studied in temperate climatic conditions over extended periods, as opposed to short, isolated or extreme events such as forest fires or lightning strikes (Knight and Grab, 2014; Sumner *et. al.*, 2004). These studies typically take into account factors such as rock temperatures, rock moisture, physical rock properties or boundary conditions, relating them to the type, degree and rate of weathering processes encountered (Hall and André, 2001). Less emphasis has been placed on moisture properties (McAllister *et. al.*, 2017), even though this does not mean that other properties are comparatively less significant.

The relationships between various processes (including insolation, aspect, zonality, albedo, etc.) have been related to rock thermal regimes. McAllister *et. al.* (2017) cautioned that research emphasis is often (and likely unjustifiably) placed on temperature extremes and diurnal regimes, while Zhang *et. al.* (2013) found that water or moisture may have a larger influence on weathering processes than temperature. This was likely, at least in part, due to the rock types used in their research, but the authors made a valid point.

Research undertaken by McKay *et. al.* (2009) saw measurement of rock surface temperatures in a hyper-arid environment (i.e. the Atacama Desert) and found that rock temperatures are generally warmer than air temperatures at a given location due to the heating effect resulting from illumination (i.e. solar radiation) to which the rock surface is subjected. Also, it was found that that thermal stresses are largely concentrated at (or very near) the rock surface. This observation was previously noted by Sumner *et. al.* (2004) who found that higher rock temperatures at the surface (caused by insolation) result in steep temperature gradients between a rock's surface and an adjacent air mass. This rock and air interface is defined by Warke (2013) as boundary conditions.

A significant portion of existing and past research efforts focus on retrieving or preparing samples and assessing different properties in an isolated or simulated environment, or on a reduced scale. The latter is cautioned against by Hall and Thorn (2014) as these "unnatural" preparations undoubtedly affect the behaviour of the material tested. For example, Jenkins and Smith (1990) utilised field samples to conduct laboratory simulations and investigate weathering regimes in environments where conditions could be controlled. The aim of their

work was to investigate the impact of only single variables (e.g. temperature). Hall *et. al.* (2012), as well as Hall and Thorn (2014) cautioned against this approach stating that it remains a challenge to scale such assessments to true world landform conditions. This conundrum is perhaps best summarised by Viles (2013, p16) who stated: "*…one key need in investigating weathering synergies is for the scale at which data can be collected to match as near as possible the scale of the question being asked…*". There is, therefore, a strong motivation not to correlate, or attempt to correlate, simulated test results with real-world conditions. This was also argued by Hall (1999) who pointed out that materials tested in situ are confined and will behave differently to unconfined samples tested in a simulated or laboratory environment. Hall and Thorn (2014, p1) stated that "*…results of questionable laboratory experiments have led many geomorphologists to consider terrestrial temperatures to be inadequate to generate thermally induced stresses leading to rock failure…*".

Despite the above, fundamental research by Griggs (1936) used accelerated heating (as high as 110 ºC) and cooling cycles to simulate temperature fluctuation caused by directional heating and cooling under controlled conditions but reported that no notable effects were caused by the directional heating. He ultimately suggested that fatigue failure is likely a more significant failure agent than differential rock mineral expansion. A similar experimental approach was followed by Aires-Barros (1977) while experimenting with thermal fatigue.

Richter and Simmons (1974) researched the effects of thermal expansion in igneous rocks but used an experimental temperature range between 25 ºC and 550 ºC, most of which falls outside real-world temperature conditions and therefore holds limited value for geomorphological research. Nevertheless, they concluded that experimental heating rates should not exceed 2 ºC per minute if cracking (i.e. thermal shock) caused by thermal expansion is to be avoided.

Other authors (i.e. Boelhouwers and Jonsson, 2013) contest the concept of thermal shock in its entirety. Nevertheless, this heating rate figure is often cited in the literature (e.g. Warke, 2013; Sumner *et. al.*, 2004), but citations seldom note that this rate was specified for a sample measuring only 6 mm in diameter at experimental temperatures of up to 250 ºC. Care should, therefore, be taken to make sure that figures are cited or used within the intended context as they may not necessarily apply to real-world conditions. Other limits have also been proposed. For example, Yang *et. al.* (2019) used a heating rate of 5 ºC per minute and a

cooling rate below 5 ºC per minute to avoid thermal shock during their research. Furthermore, it should also be taken into account that different geological rock materials are likely to respond uniquely under similar temperature conditions.

More recent research undertaken by Kim *et. al.* (2020) assessed thermally damaged sandstone. Materials were subjected to temperatures of up to 500 ºC and findings ultimately showed that lower temperature exposure typically results in slower micro-crack development, compared with higher temperature exposure. As before, however, there are practical limitations in relating the experimental temperature range (i.e. between 100 ºC and 550 ºC) used by Kim *et. al.* (2020) to more moderate temperature conditions typically studied in geomorphology. Clearly, the results of laboratory simulated tests should be interpreted with caution and should not be cited out of context; as such high-temperature conditions are not generally representative of real-world natural conditions, except perhaps in the case of instantaneous occurrences (e.g. catastrophic events, fires or lightning strikes). On the whole, these findings may be more relevant to metallurgical studies than geomorphological studies, but still provide fundamental insight.

2.2 Rock Temperatures, Solar Radiation and the Concept of Insolation Weathering

Solar radiation drives the hydrological cycle on earth with some 30 % of the incoming radiation being reflected back to space, but solar radiation is also not uniformly distributed over the earth's surface and is concentrated between latitudes of 40 º north and 40 º south, while polar areas have a solar radiation deficit (Summerfield, 1991). In addition, the influence of aspect (i.e. topographical orientation) is also at play and is considered in this study.

Geomorphological weathering research efforts related to aspect, directional heating or insolation are largely concerned with surface or near-surface conditions, concentrating mainly on soils, stones or rock materials exposed at surface level (e.g. Eppes *et. al.*, 2018; Hall, 2013; Warke, 2013; Eppes *et. al.,* 2010; Jenkins and Smith, 1990) or immediately below surface level (e.g. Messenzehl *et. al.*, 2018; Lamp *et. al.*, 2017; Pisabarro *et. al.,* 2017; Hall, 2013; Hall *et. al.,* 2005a). Some researchers (e.g. Bou Jaoude *et. al.*, 2018; Eppes and Keanini, 2017) have even gone through great lengths to assess fracture mechanics. Aldred *et.*

al. (2016) concluded that while aspect-related thermal stresses do cause orientated or preferential cracking in stones, the resulting cracks may be affected by other weathering mechanisms to a more pronounced extent after they were formed by thermal processes. In addition, Burnett *et. al.* (2008) concluded that influences due to the aspect may not only be related to temperature differences, but also moisture differences and that these factors strongly affect slope and cliff processes.

Hall (1999) argued that insolation itself does not cause weathering, but instead insolation induces breakdown through thermal fatigue from repeated cycles of heating and cooling. The concept has also been challenged by some researchers who argue that insolation weathering models assume rock breakdown based largely on surface measurements and inferences that vertical temperature distribution occurs (Gómez-Heras *et al*., 2006). The same authors also accepted that temperatures decrease at an exponential rate from the surface towards the interior of rock material, with the most rapid temperature decreases occurring in the first (i.e. outer) few centimetres. This was echoed by McKay *et al*. (2009) who concluded that the majority of the thermal stresses experienced by a rock material occur at (or very near) the rock surface.

Of significance, but seldom taken into consideration, is the suggestion by Hall and Thorn (2014) that the most pronounced effects of mechanical failure by thermal weathering occur during cooling, as opposed to heating. If thermal weathering is indeed more pronounced during cooling, it stands to reason that any mass of rock (i.e. loose-lying stones or bedrock) may be susceptible to thermal weathering, provided a thermal gradient occurs due to one part of the body dissipating heat. Work reported by Messenzehl *et. al.* (2018) considered only the upper 20 m of a profile and stated that annual temperature cycles might be negligible below this depth, resulting in constant temperatures; however, the comment was not sustained in the reported work.

The significance of thermal regimes is perhaps best summarised by Hall (1999), who noted that temperature gradients in large rock masses can cause thermal stress because the temperature gradients are not linear. Nevertheless, all discussions on the topic assume that insolation weathering is the result of volume changes related to temperature fluctuations (e.g. Gómez-Heras *et al*., 2006). Building on this, Eppes *et. al.* (2010) found strong evidence that directional solar heating was fundamentally linked to the cause of cracking of desert

pavement rocks and similar work by Moores *et. al.* (2008) confirmed the same. Sub-critical cracking was further researched by Eppes and Keanini (2017) who noted that once a crack has formed in rock, a decreasing amount of external loading is required for such a crack to propagate.

Gómez-Heras *et al*. (2006, p237) emphasised that most insolation weathering models assume "*…breakdown in terms of the vertical temperature distributions obtained from a single surface measurement and a limited set of arbitrary depth temperatures….*", highlighting perhaps the biggest limitation or difficulty with assessing a rock mass: the absence of data obtained from within the mass itself (i.e. with depth). Despite this apparent shortcoming, Gómez-Heras *et al*. (2006) accepted that temperatures decrease exponentially with depth, noting that the most rapid decreases occur within the first few centimetres below the surface, but also mentioned that long term temperature fluctuations penetrated deeper into a rock and have a slower rate of change.

Hall and André (2001) advised that thermal gradients may be present in rock and that rock temperature should be measured at various depths to assess this possibility. Furthermore, Hall (1999) reported that rock temperatures vary with depth and found that temperatures at a depth of 2 cm are as much as 12 ºC lower than those measured at surface. This suggested that heat is not transmitted to notable depths. Iñigo and Vicente-Tavera (2002), as well as McAllister *et. al.* (2017) studied the relationship between depth and thermal effects, but in neither instance was the research done *in situ* and, coincidentally, both efforts only assessed conditions to a depth of 100 mm.

Gunzburger and Merrien-Soukatchoff (2011) studied the heat balance and thermal regime within a rock using temperature data captured at depths of 10 cm, 20 cm, 30 cm, 40 cm and 50 cm and used the data to model the heat exchange mathematically. Of the work done by Gunzburger and Merrien-Soukatchoff (2011), Hall and Thorn (2014) comment that "*…diurnal temperature fluctuations attenuate close to 50 cm depths…*". While the results reported by Gunzburger and Merrien-Soukatchoff (2011) certainly do show marked changes with depth, this statement seems premature without considering measurements taken at even greater depths. The temperature results reported by Gunzburger and Merrien-Soukatchoff (2011) are shown in Figure 2.1

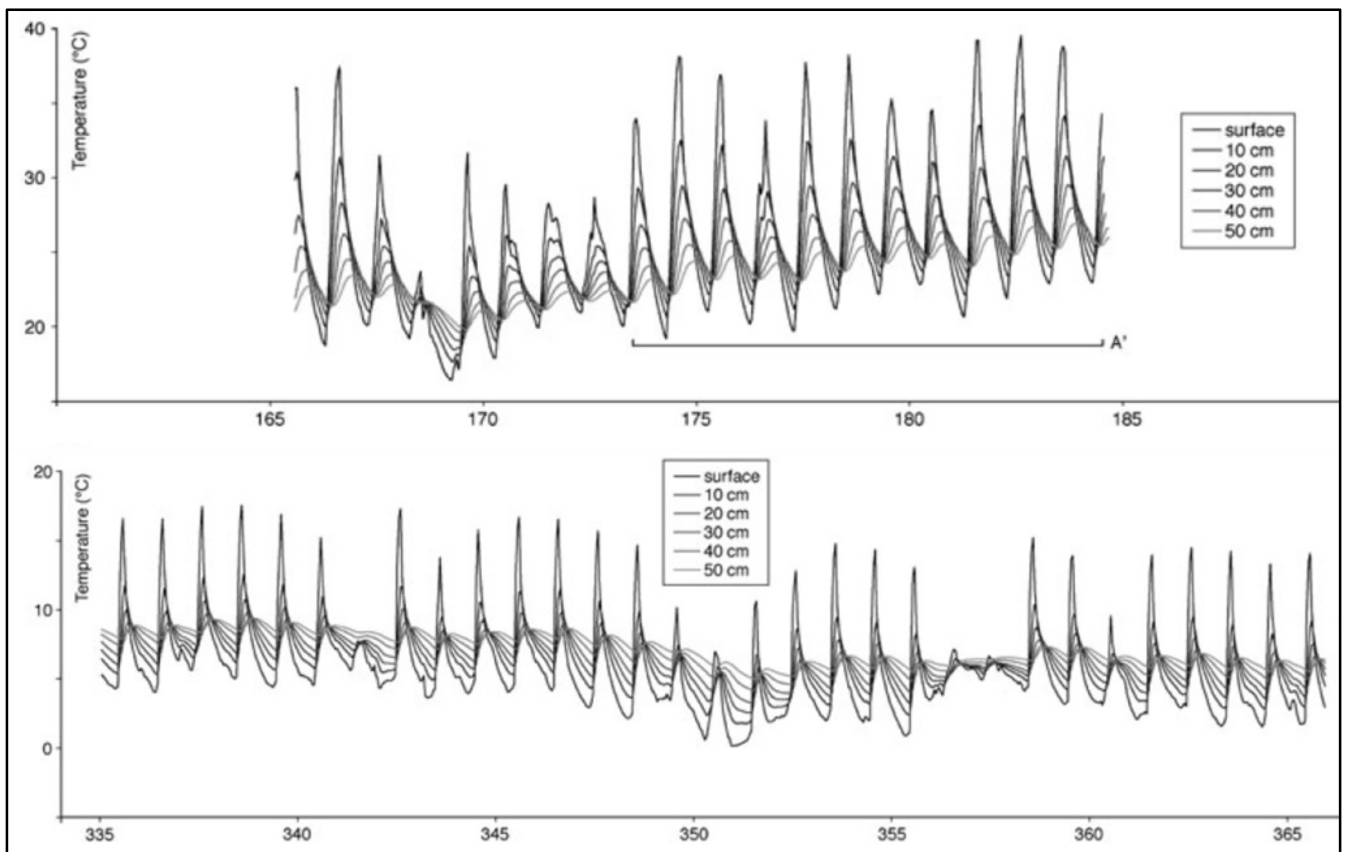

Figure 2.1 Temperature measurements in summer (top) and winter (bottom) at various depths (adapted from Gunzburger and Merrien-Soukatchoff, 2011)

From the figure, it is apparent that temperature oscillations became less peaked as the depth at which measurements were taken increased. Simply stated, temperature oscillations became less pronounced with depth. Nevertheless, the results were strongly synchronous on all accounts, though it is clear that seasonal differences are strong.

Similar work done by Coutard and Francou (1989), and Anderson (1998), recorded bedrock temperatures in an alpine settings, but were specifically focussed on the processes of frost shattering. In addition, long term research by Matsuoka (2008) assessed frost weathering with temperature loggers from surface to depths of 0.4 m. For the most part work undertaken to assess frost shattering, frost weathering or freeze-thaw processes are set in very different climatic environments to that of the current research, but nevertheless, some interesting findings made in these settings should be considered.

In the work reported by Anderson (1998), measurements were taken at surface and at depths of 1 cm, 2 cm, 4 cm, 8 cm, 16 cm, 32 cm and 42 cm and the data were used to model near-surface thermal histories using Fourier's law. Of particular interest is a graphical comparison of the surface temperatures and the deepest measurements (i.e. 42 cm) taken over a one year period given by Anderson (1998), as illustrated in Figure 2.2. From the graph it appears that the temperature changes occur synchronously, with the 42 cm temperatures possibly lagging slightly behind the surface temperatures. Furthermore, it is evident that surface temperatures (i.e. minima and maxima) are much more pronounced or peaked compared with the measurements taken at 42 cm depth.

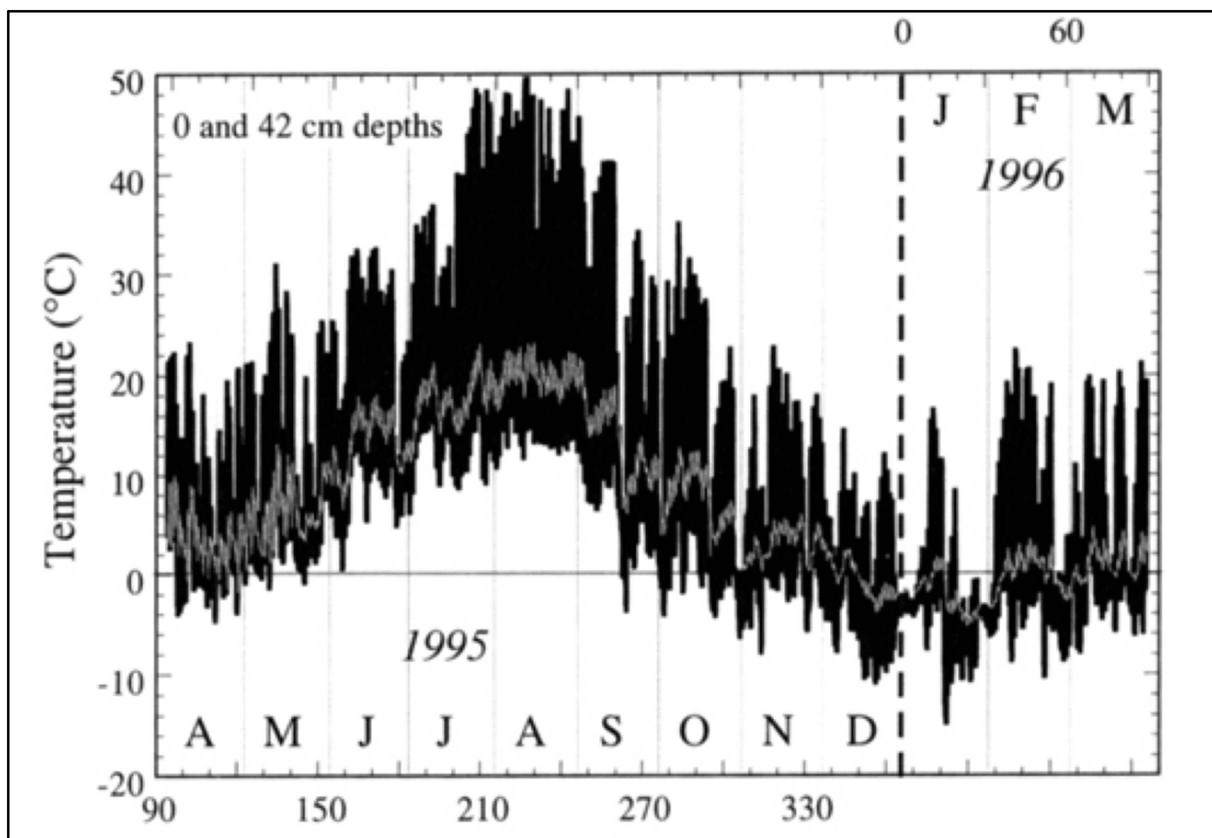

Figure 2.2 Surface temperatures (black line) and temperatures at 42 cm depth (white line) captured in an alpine setting (from Anderson, 1998)

2.3 Factors Affecting Rock Temperature

Rock temperatures very often form the focus of research efforts and attempts are made to establish the link between temperatures and direct (i.e. mechanical) weathering. Though not

strictly relevant, one should not overlook the complex interplay that rock temperatures may have on other weathering processes occurring in tandem (Viles, 2013). Gómez-Heras *et al*. (2006) highlighted that temperature may have a secondary weathering effect and used the influence of temperature on the mechanism of salt crystallisation as an example which, in itself, may also influence weathering but by a distinctly different mechanism. Similarly, it is likely that biological weathering will also be affected when, for example, temperature fluctuations or aspect may influence the rate of faunal or fungal growth on a rock surface (e.g. Hall *et. al.*, 2005a; Waragai, 1998).

Nevertheless, as the emphasis of this research focussed on rock temperatures, it is important to consider factors which have influence in this regard. Contributing factors that affect bedrock or rock surface temperature have also been studied extensively, but as mentioned earlier, challenges arise when considering these factors in isolation. With this taken into consideration, the following properties or factors affecting rock temperatures need to be taken into account:

2.3.1 Rock and Mineral Composition

The effect of rock composition (i.e. mineralogy) was discussed by Gómez-Heras *et al*. (2006), who considered igneous rock materials (i.e. granite) that suffered granular disintegration for their research. The authors proved that various minerals in a rock assemblage have different temperatures under identical conditions and therefore do not react similarly, or expand/contract at the same rate or under identical temperature conditions.

This differential expansion causes strain between minerals due to repeated stress cycles related to heating and cooling, which ultimately cause breakdown by fatigue failure when crystal boundaries inevitably form a weakness in the rock mass. Gómez-Heras *et al*. (2006) ultimately concluded that albedo is the main controlling factor affecting maximum temperatures, with the crystal size of the minerals also being a contributing factor. For this reason, they emphasised that the surface of the stone material investigated cannot be considered a homogeneous medium.

2.3.2 Solar Radiation

Solar radiation, in this instance, forms the key source of heat. The majority of geomorphological research efforts consider only solar radiation as a heat source. Summerfield (1991) mentioned that of the total incoming solar radiation, only a small fraction affects geomorphological processes. A large amount of radiation is reflected back to space by the atmosphere, while some radiation also drives the hydrological cycles in the atmosphere.

2.3.3 Other Factors

Beside the factors discussed above, others have been reported to have an impact on rock temperatures and a few such examples include:

- Forest fires which may cause spalling or shattering (Summerfield, 1991).
- Wind or cloud-cover (Gómez-Heras *et al*., 2006).
- Lightning strikes (Sumner *et. al.*, 2004).
- McKay *et. al.* (2009) found that the delayed rate of heat dissipation has a significant effect. As a result, the time of day was proven to be relevant as a rock material would be warmer than the adjacent air mass in the afternoon and throughout the evening (i.e. slow heat dissipation), but colder than the air mass in the morning (i.e. slow heat build-up).
- Conduction of heat in a rock mass, changes in stress fields and the circulation or movement of ground fluids (Chen *et. al.,* 2016).
- Cloud cover, air temperatures, maritime influences and the time of year (Jenkins and Smith, 1990).
- Geothermal or tectonic processes.

2.4 Thermal Fatigue

Thermal fatigue has come to be accepted as a major contributor or cause of weathering, even as possible source of regolith formation on asteroids (Delbo *et. al.*, 2014), but was

disregarded in literature for a long time (Hall, 2013). Even fairly recent geomorphological works have neglected thermal fatigue as a distinct source of weathering. One example of this is the comprehensive work compiled by Viles (2013), which lists only freeze-thaw as a mechanism of weathering related to temperature cycles (Figure 2.3). Hall (1999) stated that many geomorphological studies do not anticipate the role of thermal stress fatigue and that thermal stress (or thermal stress fatigue) should not be misconstrued as insolation weathering. He further mentioned that the analysis of weathering by thermal fatigue is urgently required.

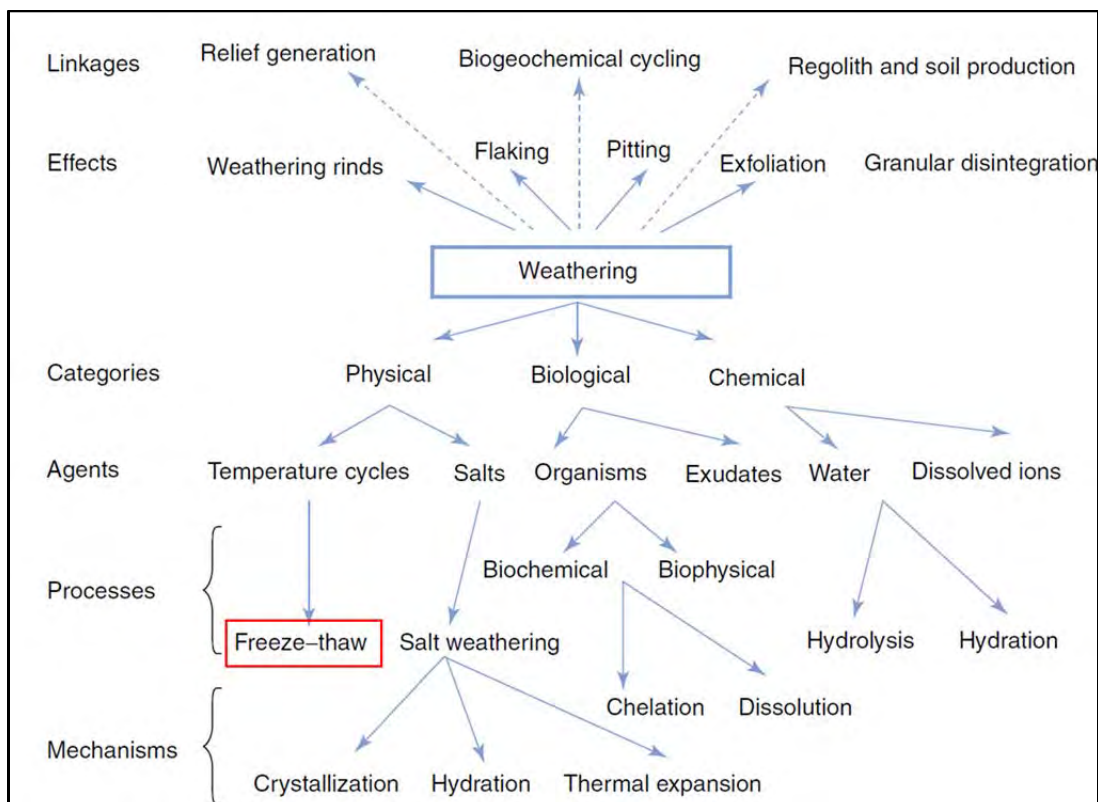

Figure 2.3 Summary of weathering processes (adapted from Viles, 2013)

Gere (2004) simply illustrated fatigue failure by using the example of breaking a paper clip or metal wire by repeatedly bending it back and forth thereby constantly applying and reversing stress in the material. Fatigue was defined as "*the deterioration of a material under repeated cycles of stress and strain, resulting in progressive cracking that eventually produces fracture*" (Gere, 2004 p136). Hall and Thorn (2014, p1) mentioned that "*Thermal fatigue is produced by temperatures that lead to repeated stresses (often far) below normally determined strengths of the material involved*", but they also emphasised that clear

distinction should be made between thermal stress (i.e. thermal shattering) and thermal fatigue as they have different driving forces.

In a more recent example, thermal fatigue in geomorphological processes was illustrated mathematically by Eppes and Keanini (2017), as well as Ravaji *et. al.* (2019). Eppes and Keanini (2017) assessed sub-critical cracking exposed at surface using Paris' Law to conceptualise fatigue crack propagation in rock, using idealised assumptions. It was found that temperature oscillations (i.e. amplitude) and the rate/frequency of temperature oscillations proved to be key considerations. In principle a higher frequency of temperature oscillations (or temperature inversions) occurring in rock will cause more rapid fatigue failure relative to lower oscillation frequency. For the purposes of this research a "rock temperature inversion" is defined as "*A scenario where one part of the rock mass is warmer than an adjacent part of the rock mass at one time, but at a later time the same rock mass is cooler than the adjacent rock mass (and vice versa), resulting in a periodically alternating temperature differential*".

In the scenario where a rock mass is considered, physical fatigue is caused by thermal fatigue, which in itself results from oscillating rock temperatures or temperature inversions and the resulting volume expansion and contraction. In the case of thermal fatigue failure, individual heating or cooling "events" are not significant enough to induce failure; however, the cumulative effect will ultimately induce failure given time. In contrast, thermal shock occurs when a thermal "event" exceeds the capacity of a material to accommodate expansion or contraction timeously (Hall, 1999). Hall and Thorn (2014) suggested that spalling is generally considered a product of fatigue and that failure resulting from thermal fatigue will likely occur along pre-existing points of weakness in the rock.

In the past, physical breakdown or granular disintegration was attributed solely to differential thermal expansion under insolation, when in reality breakdown is attributed to the cumulative effects of repeated differential expansion and contraction of minerals which induces failure due to fatigue (Gómez-Heras *et al*., 2006). Rocks exposed in any natural environment are subjected to a range of cycling temperature cycles (Gómez-Heras *et al*., 2006).

2.5 Effects of Meteorological Conditions

Research of weathering processes at the surface is a complicated and intricate field of study. Hall *et. al.* (2012, p1) stated: "*The Earth's landforms and landscapes (assemblage of landforms) at any moment in time express the integration of the balance between internal (endogenetic) and external (exogenetic) forces influencing that surface, as modulated by both a unique local history and the surface material*". With the abundance of processes that occur resulting from an array of weathering agents or contributing factors, researchers are faced with the challenging task of assessing these agents, factors or processes in isolation, or at least attempting to do so.

The above complex interaction is defined by Warke (2013) as a non-linear dynamical system in which it is difficult to predict individual variables' behaviour due to their complex nature and interactions with other variables. The range of weathering mechanisms involved, themselves, vary as a result of environmental conditions that prevail at a specific location and these spatial attributes often form the focus of research efforts. Properties that have been researched include insolation, aspect, zonality, boundary conditions and albedo to name but a few.

Atmospheric and geomorphological processes are driven and affected by several factors, chief among which is solar radiation. The concept of boundary conditions was defined by Warke (2013, p198) as "*Temperature and humidity conditions in the thin layer of air that passes over and is in immediate contact with rock surfaces*". While the influence of boundary conditions can arguably be better observed when assessing soil materials (e.g. Ewing and Kocurek, 2010), it is often included in other research efforts by inference and may not necessarily be discussed specifically or highlighted. Sumner *et. al.* (2004) mentioned that rapid cooling can be caused by the removal of a heat source or wind blowing on the surface of a rock or rock material, but due to rock materials being comparatively poor conductors of heat, a thermal gradient occurs. Gómez-Heras *et. al.* (2006) stated that rocks exposed in any natural environment will experience a range of temperature cycles and that short term temperature fluctuations may occur due to wind or cloud cover while deeper rock materials will see long term temperature fluctuations at a slower rate of change. However, Hall *et. al.*

(2012) noted that while climatic conditions do affect weathering, it is the properties of the rock material that remain the dominant control.

Research by Eppes *et. al.* (2016) consisted of an in-depth study of solar-induced thermal stresses in a prepared boulder sample placed on a surface. Their findings proved that cracking in the boulder often coincided with storms or other weather events which disturbed or perturbed the rock's surface temperature conditions. Coincidentally, their findings cautioned against the use of a 2 ºC per minute temperature change as a threshold for weathering or thermal shattering.

Variations in rock surface temperatures were related by Jenkins and Smith (1990) to the external factors such as insolation, cloud cover, air temperatures, maritime influences and seasonal cycles. In addition, the same authors identified rock properties such as albedo, thermal conductivity, heat capacity and moisture content to further influence temperatures, along with climatic and meteorological controls.

According to Warke (2013), weathering occurs when rock is no longer in a state of equilibrium compared with when it was formed, due to variations in temperature, pressure and moisture. McKay *et. al.* (2009) stated that "*…rapid thermal variations may be an important source of rock weathering*" while Summerfield (1991) noted that water (or moisture) plays a role in virtually all mechanisms of physical and chemical weathering. Warke (2013) further stated that temperature and available moisture are the two main drivers of weathering in arid areas. The concept of zonality was addressed by Sumner *et. al.* (2004) who found that processes dependant on thermal changes are not necessarily zonal as far as geographic distribution is concerned. From all of these research efforts, it is clear that there is no single property that can be identified as the main cause or mode of weathering and attempting to study processes in isolation is virtually impossible. However, throughout published literature into geomorphological research there is a persistent strong focus on (rock or surface) temperatures and to a lesser extent, moisture conditions.

Gómez-Heras *et. al.* (2006) cited Newton's law of cooling to emphasise that the rate of cooling of a material depends directly on the temperature difference between a body (i.e. the rock) and the ambient conditions (i.e. adjacent air mass). This can also be elaborated and related to Fourier's law if the rate of heat transfer from a material (i.e. rock) to another

medium (i.e. air or other parts of the rock) is considered. Such an exercise would be fundamentally complex when assessing a rock and air interface due to proven variability in virtually all parameters at play. Of importance in this context, is that both physics laws mentioned can be related directly to processes that occur in boundary conditions. Hall *et. al.* (2012) also cited Newton's law of cooling and illustrated that sudden temperature changes can occur in cold environments when solar radiation is reduced or removed (e.g. by cloud cover), thereby causing tensile forces (due to contraction) as a result of thermal strain. In addition, Hall (1999) reported that temperature oscillations can occur in the upper 4 mm of a rock as a result of short spells of wind.

The concept of thermal shock and thermal fatigue has been discussed by multiple researchers and was previously summarised. Warke (2013) stated that sudden decreases in the surface temperature of a high-temperature rock mass will create stress and Gómez-Heras *et. al.* (2006) concluded that repeated cycles of differential expansion between individual minerals may induce breakdown by fatigue failure, also noting that temperatures decrease exponentially with depth, with the most rapid decreases occurring within the first few centimetres below the surface. They further concluded that albedo is the main control for the maximum temperatures a rock material can reach.

Work done by McKay *et. al.* (2009) showed that rock temperatures were warmer than air temperatures in the afternoon and throughout the night, but cooler than air temperatures during the morning, indicating retarded thermal responses relative to the air. Jenkins and Smith (1990) in turn reported delays of between one and one and a half hours between sunrise and the time at which rock temperatures started increasing. In addition, McKay *et. al.* (2009) concluded that mean rock temperatures are higher than mean air temperatures (in a desert setting) since the rocks investigated received continuous illumination. The processes and physical interactions found in boundary conditions are therefore, once more, quite complex.

Jenkins and Smith (1990) concluded in their research that temperature fluctuations with a short duration are surficial and are not transmitted "*…to any great depth*", though no indication was given as to the depth that was referred to. The work of Gunzburger and Merrien-Soukatchoff (2011) sustained this statement to a limited extent. Hall (1999) stated that while the surface and interior of a rock may be cooling in a given scenario, the surface

would cool much faster than the interior of the rock, resulting in a (thermal) stress field between the interior and surface of the rock. He noted that rock temperatures vary with depth and found that a temperature difference of up to 12 ºC may occur between a rock surface and the interior of the rock, some 2 cm deep.

2.6 Literature Review Summary

From existing research literature it is clear that while rock weathering and temperatures have been researched extensively, there is a shortcoming on information specifically related to rock temperatures – particularly of an intact rock mass or bedrock – at depths extending significantly below the surface. Existing research seldom reports on conditions at depth of more than 50 cm below surface. Concepts such as aspect-related temperature fluctuation and thermal fatigue failure have been researched well and have been expanded to include other overlapping factors or fields of study.

What remains to be determined is whether rock temperatures in a rock mass (i.e. bedrock) behave notably differently from other circumstances (i.e. experimental setups) reported in literature, specifically at greater depths which have not been assessed before. In addition, it is yet to be determined whether prevailing conditions at depth could potentially create a suitable setting to induce thermal shattering or fatigue failure. The research at hand aims to address these shortcomings.

3 Methodology

This chapter outlines the approach followed to capture data. In brief, temperature measurements were recorded in iterative phases and consisted of preliminary data capture and follow-up data capture. The differences in equipment and experimental setup are described, along with technical specifications (where relevant) and site selection criteria.

3.1 Borehole Drilling

The motivation for utilising geotechnical borehole shafts for temperature measurements, as opposed to open or exposed rock surfaces (e.g. cliff faces or cave walls), was fairly simple. Measurements taken in a confined and sealed borehole shaft are not directly affected by external influences such as albedo, meteorological processes (i.e. boundary conditions) or fauna/flora, all of which have been proven to affect temperature fluctuations. Essentially measurements were taken inside a confined rock mass (bedrock), with as few external influences as possible. Temperature fluctuations in the air column inside the borehole shaft were not considered representative of the rock mass temperatures, based on the recommendations of Hall and André (2001), and this problem was overcome using contact temperature measurements from thermal probes deployed against the borehole sidewall. This will be discussed in more detail later.

The borehole shafts that were used for research equipment installation consisted entirely of geotechnical rotary core boreholes. As part of a larger investigation, twenty rotary diamond core boreholes were drilled into bedrock across a selected study area to depths specified by project requirements (i.e. approximately 25 m). The boreholes were drilled using an NXC size barrel in the upper 1.50 m, which was then reduced to a smaller TNW size barrel. Near-surface depths were exclusively drilled using NXC sized barrels with an outer diameter of 91.95 mm and an inner diameter of 68.45 mm, yielding drill core with an approximate diameter of 68 mm. The resulting borehole shafts used for the installation of equipment were mostly between 92 mm and 95mm in diameter, yielding only limited space for equipment installation. Several drill rigs were used for this project but the boreholes used here were drilled using either XY44 or YWE D90 drill rigs.

The process of rotary core drilling will not be described in detail here due to the complex and technical nature of the task. Technical information on the process is summarised well by Heinz (1985). It is worth mentioning, however, that the rotary core drilling process continually circulates drilling water and lubricants through the borehole shaft and as a result, moisture conditions in the borehole sidewalls are affected. In general, boreholes drilled into bedrock are mostly left with a small volume of lubricating water at its base after the drill rods and drill bit are withdrawn. In porous or highly fractured bedrock, this water may dissipate or infiltrate into the rock mass and/or its joints; however, in massive or intact bedrock this water often remains behind in the borehole shaft and may dissipate over a very long time by evaporation into air contained in the borehole shaft, or infiltration into the bedrock exposed in the shaft.

Using borehole shafts for this research did have disadvantages and limitation too, however. Apart from the severe practical restrictions associated with spatial confinement, the largest disadvantage of using a borehole shaft is that the actual point used for data capture cannot be inspected directly. This makes it virtually impossible to check that the equipment deployed correctly until data are retrieved or downloaded. In addition, the fact that drilling lubricants were used and drilling water remained at the base of the drill shaft(s), means that humidity or moisture measurements of data are completely compromised and cannot be used for any sensible analyses.

Following the material investigation requirements, all rotary core boreholes were drilled to a maximum depth of approximately 25 m, or the nearest coinciding drill run end depth. Once boreholes were completed, they were sealed or capped using concrete blocks. For this research, the three boreholes used were sealed with a standard concrete block (30 cm × 30 cm), but each borehole had a 160 mm diameter PVC standpipe installed with a tight-locking screw-on cap. This allowed access to the borehole shaft, while simultaneously ensuring that no external factors (e.g. wind, precipitation, surface runoff or insect nesting) would influence the conditions in the borehole shaft. A typically sealed borehole with concrete block and PVC standpipe cap is illustrated in Figure 3.1. The site was investigated as a potential hard rock quarry for the production of road stone and as such, the methods used do not necessarily comply with those recommended for geomorphological research (e.g. Morrison and Lawrie, 2013; Schrott *et. al.*, 2013).

Figure 3.1: Block and standpipe capping used to seal borehole shafts

3.2 Logging Equipment

Numerous methods are available for investigating physical properties related to rock surface weathering and erosion processes (Moses *et. al*., 2014); however, in this instance, an approach on physical, *in situ* contact temperature measurements was considered best. Due to the limited space available in the borehole shafts, an innovative equipment setup was required and logging equipment options were restricted to those which could physically fit into the borehole shafts.

Hall and André (2001) emphasised the importance of assessing rock temperatures in conjunction with rock moisture and rock properties, as well as the importance of recording rock surface or contact temperatures, as opposed to surrogate air temperatures. As it was not possible to measure the rock moisture in the borehole sidewalls (which was also affected by

drilling lubricants), it was decided that air humidity measurements would be used instead as supplementary information and that the essential temperature data would be captured using a thermal probe (i.e. contact pin) deployed against the sidewall of each borehole shaft.

Research into weathering processes is faced by many practical challenges. Chief amongst these is the practical limitations with collecting data at a high-frequency interval (Hall and André, 2001) and the fact that geomorphological processes cannot be comprehensively assessed in a human lifetime (Warke, 2013). Viles (2013) highlighted the need to capture data at a scale (i.e. interval or timespan) to match the process being investigated and clearly, assessing most geomorphological processes to extrapolate long (i.e. geological time) term findings has its limitations. Though different researchers may have individual approaches to similar research to that undertaken here, Hall and André (2001) reported a concise list of considerations to use and recommended that rock temperature, rock moisture and physical rock properties be considered as these influence the type, degree and rate of weathering processes. They also emphasised the importance of taking experimental research measurements on-site or in the field (as opposed to simulated laboratory setups), a topic also discussed by Viles (2013) who cautioned that extrapolation from laboratory test results to field conditions is not always possible. In this instance, field data were captured over two periods, using different logging equipment and can be summarised as follows:

3.2.1 Preliminary Data Acquisition

Initial field data collection was done between 8 April 2018 and 8 April 2019 in line with the recommendation of Hall and André (2001) that a full seasonal cycle (i.e. one year) be used for data acquisition. Of the suitably sized logging equipment options available, the RC-4HA/C miniature temperature and humidity data loggers were selected. These units are generally used in food processing and transport industries. If used with an additional thermal (i.e. contact) probe, the logger has a temperature range of -40 ºC to +85 ºC with an accuracy of ±0.5 ºC and measures temperature in 0.1 ºC increments. Simultaneously, the logger can measure relative humidity between 0 % and 99 %, though accuracy is limited to ±3 % (Elitech, n.d.). The equipment uses a USB interface which enables direct data transfer to processing software (i.e. Elitech).

Data loggers were installed in three boreholes, at three specific depths. Unfortunately, it became apparent during data analyses (to be discussed later) that multiple loggers sustained internal damage (most likely due to sustained high humidity conditions in the borehole shafts) and yielded compromised data. Nevertheless, some data were salvageable and a decision was made to use this data as a trial to establish a proof of concept on which to base further research work.

3.2.2 Follow-up Data Acquisition

Following the preliminary data acquisition, the research was expanded. For the expanded research efforts it was decided to replace the logging equipment used during the initial phase with more robust units. For this reason, Hairuis SSN-22ET and SSN-61 temperature and humidity loggers were used, each with an external thermal temperature probe (i.e. contact pin) to allow contact temperature measurements. When using a thermal (i.e. contact) probe, the logger has a temperature range of -40 ºC to +125 ºC with an accuracy of ±0.5 ºC and measures temperature in 0.1 ºC increments. Critically, if this logger is assembled with a thermal probe, it does not capture air temperature. The equipment also uses a USB interface which enables direct data transfer to Data Logger Graph (version 6.8) software.

3.3 Logging Equipment Installation

The research reported here is fundamentally different from other research efforts in one critical aspect. Where the majority of current or recent research considers surface or near-surface (e.g. 100 mm depth) conditions, the research at hand was concerned with notably greater depths as the aim was to assess the properties of a rock mass and not only surficial conditions or loose-lying stones. With this in mind, equipment was installed as follows:

3.3.1 Preliminary Data Acquisition

The initial data acquisition was undertaken by installing the temperature loggers at depths of 0.3 m, 2.0 m and 8.0 m in each of the three boreholes selected. Of the nine loggers installed,

only three ultimately yielded trustworthy data which could be salvaged. The remaining loggers recorded dubious data which were ultimately discarded from consideration, or the loggers suffered complete failure. Nevertheless, a deployment system was constructed using 20 mm PVC conduits and metal assemblies, where the thermal probe or pin could be retracted during installation using a spring-loaded arrangement and then deployed after installation into the borehole shaft to make contact with the borehole sidewall.

Each logger body was hosted in a PVC electrical switch box. The 20 mm PVC conduit was selected as it can flex and bend to some extent, making installation somewhat easier. These PVC constructions were referred to as logger strings. For each string, the uppermost section was measured and cut taking into account the height of the standpipe and anchoring point (i.e. height above ground level), to ensure that the probes were deployed at the correct intended depth in the borehole shaft relative to ground surface level.

The thermal probe shaft was wrapped in insulation tape to avoid temperature measurements being influenced by the metal deployment assembly. Humidity was measured through open slots in the logger body. All remaining openings or crevices (e.g. USB port, screws, battery port) were also closed using insulation tape to avoid damage to the loggers' internal electronic components. The assembly is illustrated in Figure 3.2, which shows a probe in the deployed state, while Figure 3.3 shows a complete logger string.

The probes used were synchronised using the equipment software (i.e. Elitech) and programmed to capture data at 30-minute intervals. While a high-frequency data (e.g. 30-second intervals) would have been preferred (as recommended by Hall, 1999), the equipment storage capacity and remote location of the site simply did not make this option viable. Data were captured for one seasonal cycle (i.e. one year) as recommended by Hall and André (2001) and were downloaded after six months and again after one year due to limited data storage capacity.

Certain data from the time of data download were discarded as the loggers and borehole moisture were allowed to equilibrate after removal and re-installation of the equipment. This included three days' data after the initial installation of the loggers, and one day's data after the six-month data download.

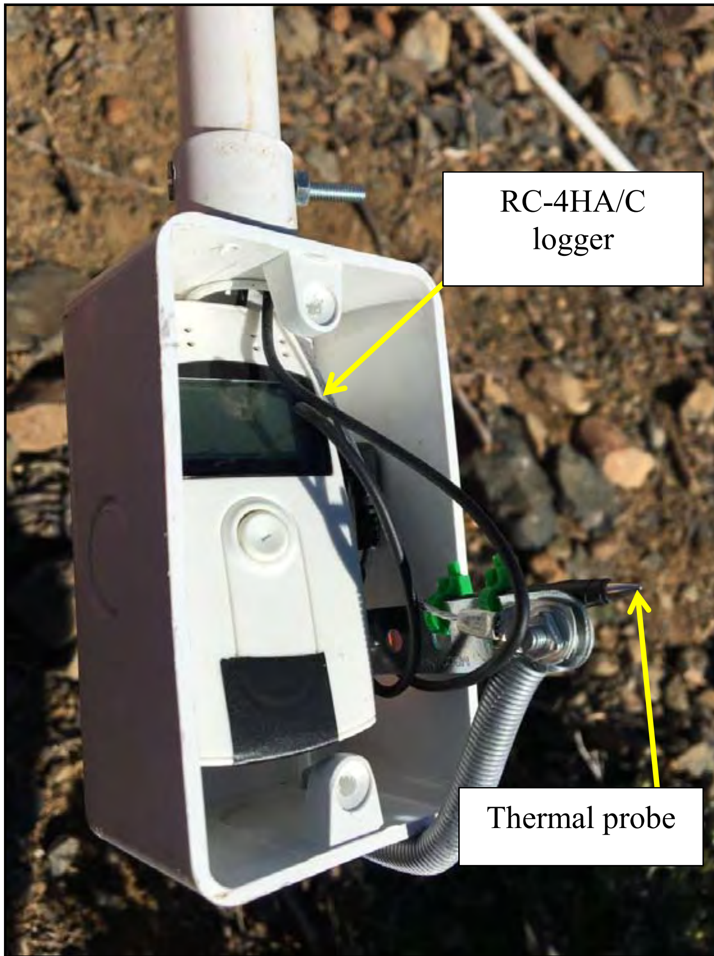

Figure 3.2: Typical probe assembly in a deployed state

Subsequent data analyses showed isolated sudden and short downward temperature fluctuations or spikes. This was ultimately attributed the fact that the temperature logger pins slanted downwards after deployment and it was concluded that this downward orientation resulted in water droplets (i.e. condensation) periodically moving down the probe shaft to the tip of the probe, where it markedly lowered the recorded temperature. This problem was most prominent in autumn and spring, presumably due to more frequent condensation, and was taken into account in further research.

The problem was countered by installing the next batch (i.e. follow-up data) of loggers in such a manner that the probe shaft was orientated at an upward angle, causing any droplets that may form on the shaft to move downward and away from the probe tip. This modification proved successful.

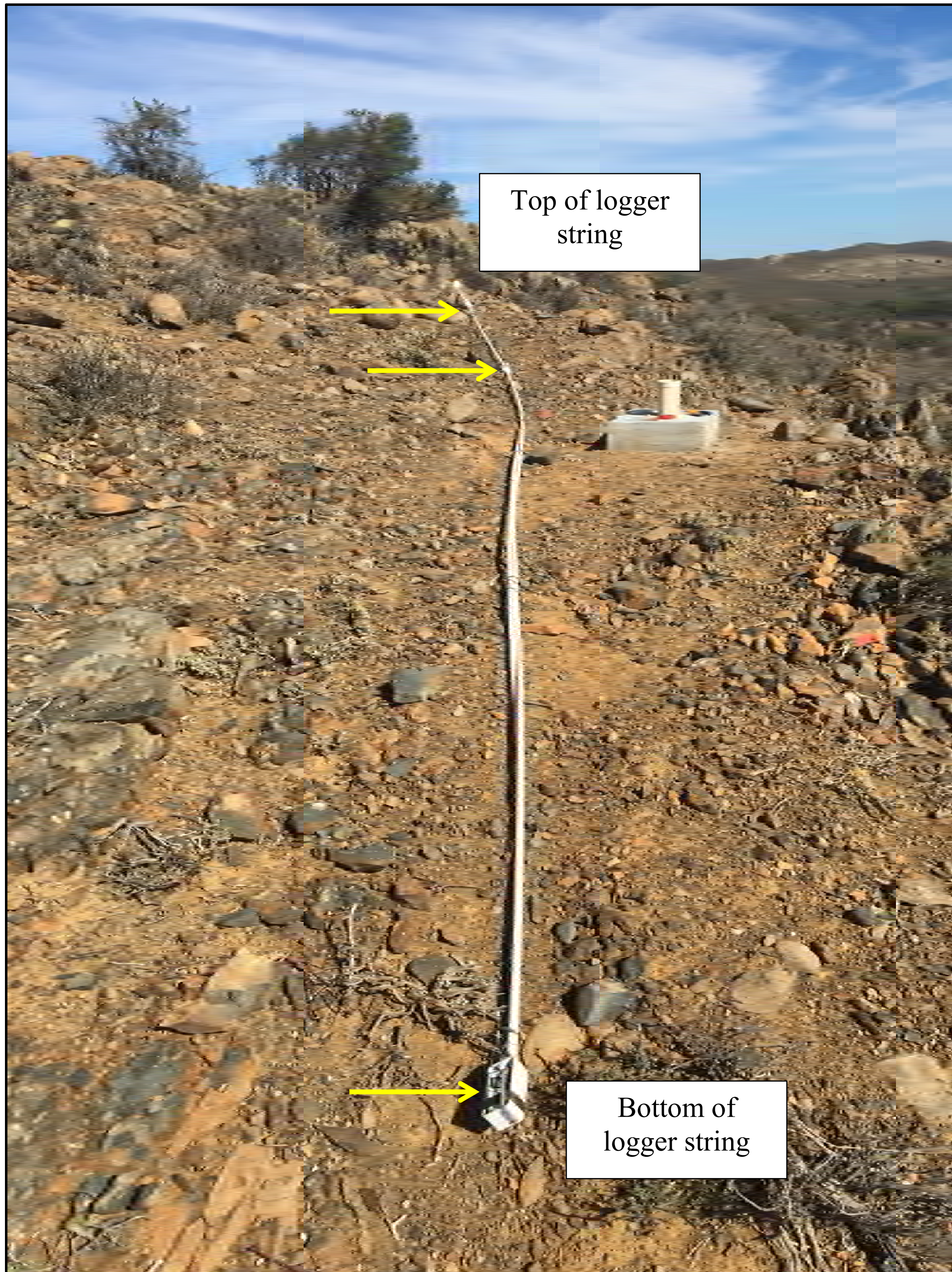

Figure 3.3: Assembled logger string with logger boxes as indicated

3.3.2 Follow-up Data Acquisition

The follow-up research effort not only changed the logging equipment used but also how equipment was installed. To install the temperature loggers at respective depths of 0.3 m, 2.0

m and 6.0 m, logger strings were constructed using 50 mm diameter PVC conduits/pipes, which was considerably more sturdy and robust than the smaller conduits initially used. However, as before, a spring-loaded temperature probe assembly was built which could be retracted during the installation of the logger strings to avoid grating and damage of the temperature probe against the borehole sidewalls during insertion (i.e. lowering the logger string into the borehole shaft). Once a logger string was installed in the borehole, the spring-loaded temperature pins were released and deployed against the borehole sidewalls to record contact temperature measurements.

The spring-loaded deployment assemblies were constructed using various metal components and pivots; however, the temperature probe pins were again wrapped in insulation tape to ensure that they were not affected by the temperature of the metal assemblages. As before, the logger bodies and all slots, openings and crevices of the loggers were also wrapped extensively in insulation tape to ensure that internal electronics were not compromised by moisture or condensation. This resulted in no humidity data being captured. Figure 3.4 shows a typical logger assembly in a deployed state, while Figure 3.5 shows an assembled logger string.

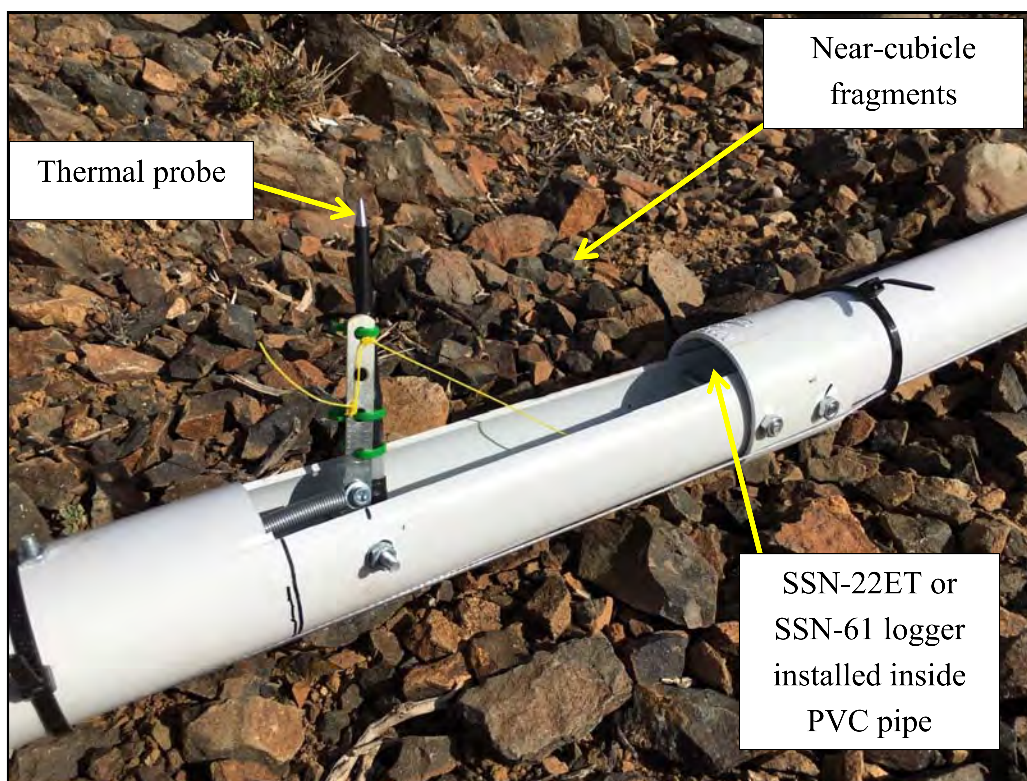

Figure 3.4: Typical probe assembly in a deployed state

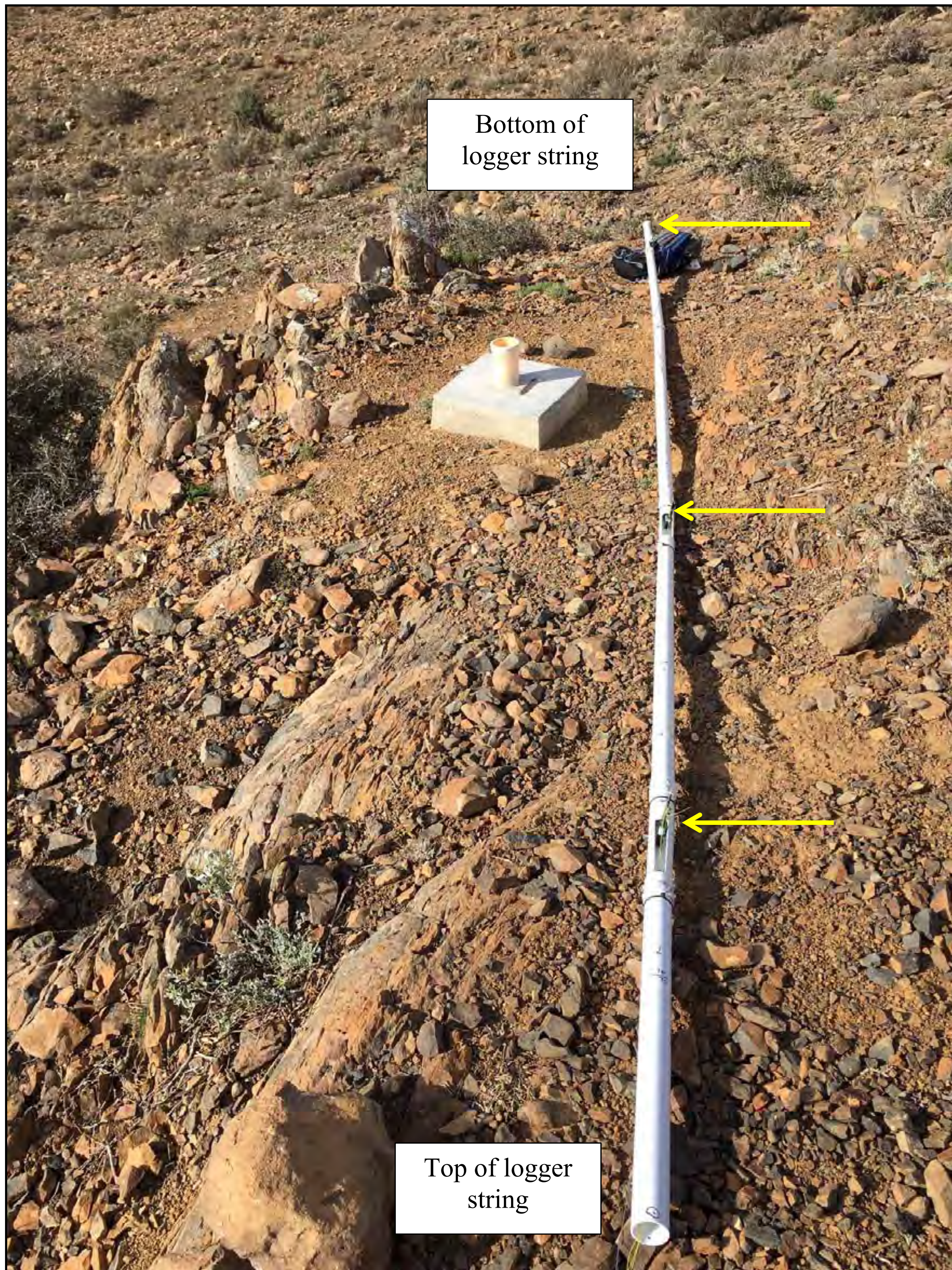

Figure 3.5: Assembled logger string with loggers as indicated

The nine data loggers were synchronised and programmed to record temperature readings at 30-minute intervals, as before. Data were captured for six months from mid-winter (6 June

2019) until mid-summer (12 January 2020). While it would have been ideal to capture data for an entire seasonal cycle (recommended by Hall and André, 2001) site access was restricted and equipment had to be removed in January 2020. Datasets captured during the first 24 hours after installation were disregarded in analyses, as conditions were left to equilibrate in the borehole shafts.

3.3.3 Logger Comparison

In order to determine whether the two sets of data loggers used for the initial and follow-up data recordings were comparable, the data were scrutinised. However, taking into account that the data were captured at different dates or time periods (i.e. years) with no overlapping acquisition period, a sensible analysis is not possible. It was initially anticipated that a selected time period of corresponding data from the preliminary and follow-up data could be used (e.g. a three month period of corresponding dates in 2018 and 2019, respectively), but although both datasets exhibited similar seasonal trends the daily, weekly and even monthly weather conditions were simply too variable to allow a direct statistical analysis.

3.4 Weather Station

Site meteorological conditions were recorded with the aid of a Davis Vantage Vue® weather station, installed 1.00 m above ground level. An additional data logger was installed in the unit to increase data storage capacity. The weather station records parameters including wind (direction and speed), temperature (outside and inside), humidity (outside and inside), wind chill, heat index, dew point, rainfall and air pressure.

The system consists of the external weather station unit (as shown in Figure 3.6) and a separate console unit (containing the data logger) which records data using a wireless connection. The console unit is not designed for outdoor use and as a result, a solution was needed to accommodate the unit as there were no buildings or other infrastructure on the site in which to shelter the console. Subsequently, a hard plastic case was modified to host the console unit.

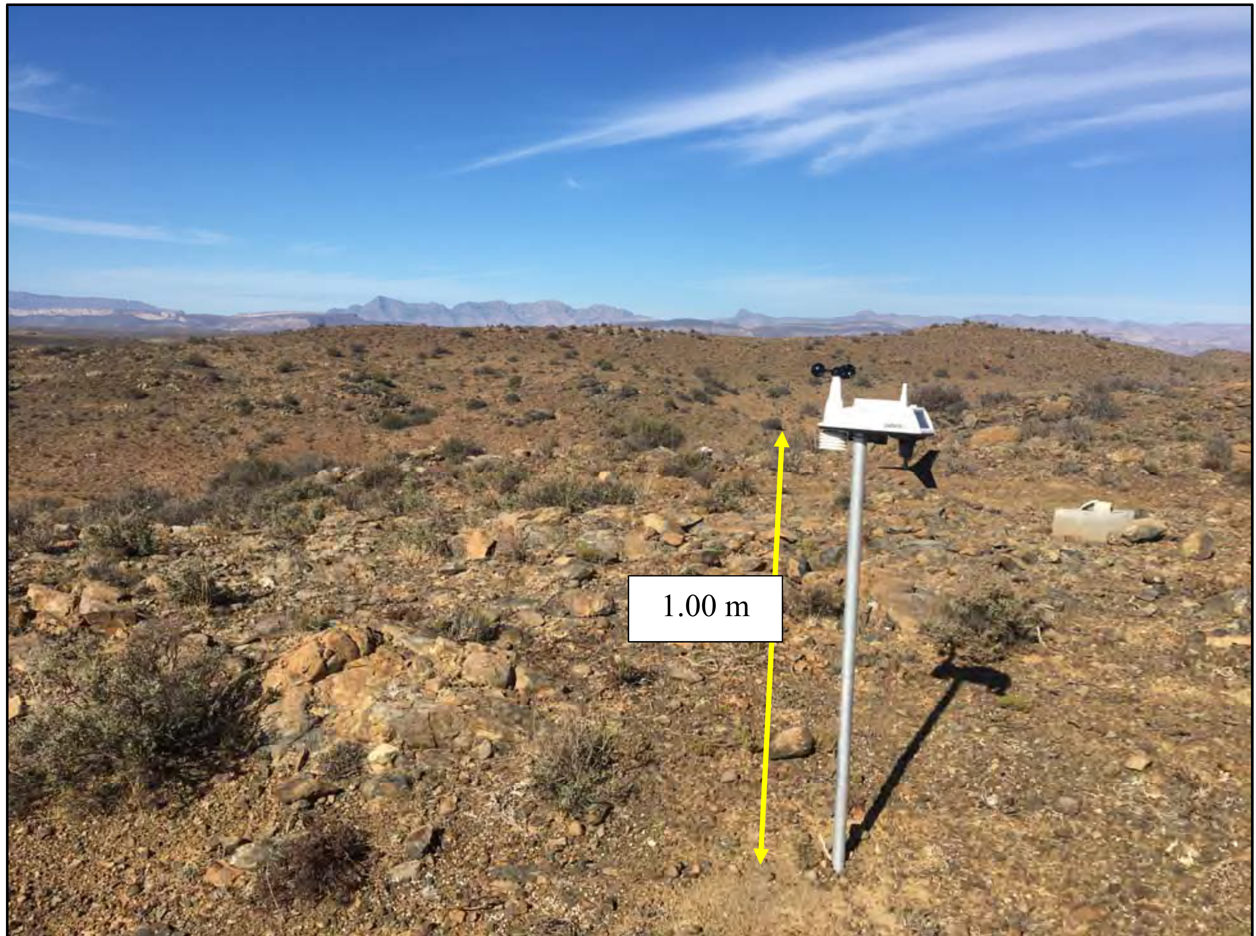

Figure 3.6: Vantage Vue® weather station unit installed at the crest site

Additional ventilation openings were cut into the case and covered with fine netting to avoid insect or critter inhabitation. A typical computer (CPU/USB) fan was also installed on the sidewall of the box to ensure good air circulation (to keep the console within operating temperatures) which was connected to a small solar panel. The plastic container hosting the console was then placed in a cracked boulder near the weather station and the remainder of the joint was stacked with rocks to avoid any critter tampering (refer to Figure 3.7). The solar panel was placed on top of the cracked boulder from where it activated the cooling fan automatically during periods of sunlight (i.e. daytime).

Of the various weather station data accumulated, only the "outdoor" measurements recorded by the weather station unit were considered. "Indoor" data recorded by the unit were taken by the console unit inside the stored container and therefore had very little significance. For this research air temperature, rainfall, wind speed and to a lesser extent wind direction were considered in analyses.

Figure 3.7: Weather station console enclosure

Equipment specifications indicate that the air temperature measurements have an accuracy of 0.5 ºC, while rainfall was measured by an internal tipping cup with a capacity of 0.2 mm. Also, the wind-cup assembly is rated to have an accuracy of 3 km/h, while the wind direction is accurate to 3 º; however, there is a further inherent wind direction inaccuracy associated with installation (i.e. alignment with north). As a result, the wind direction records should be used taking into account these limitations.

Before installation, the weather station and console unit were synchronised (i.e. time, longitude, latitude and elevation) and the unit was programmed to transmit and record data at two-hour intervals. In the case of temperature, the data recorded included the maximum and

minimum temperatures measured during the two hour period, as well as the cumulative rainfall recorded in the same period. Maximum wind speeds were also used. More frequent recordings were not practically feasible due to data storage limitations (and remote location of the site), though it would have been ideal to match the 30-minute intervals used by the rock temperature loggers.

All data recorded were downloaded to Weatherlink 6.0.3 software using a USB interface. From there data were imported into spreadsheets format for further analyses.

3.5 Site Selection

3.5.1 Requirements of a Suitable Site

For a site to be considered for this research, several primary and secondary requirements were identified to qualify its suitability. Primary requirements were considered mandatory while secondary requirements were considered preferred properties. Primary requirements can be summarised as follows:

- *Site Topography:* Site topography was considered the most fundamental requirement during site selection. A site was only considered if it had a pronounced topography which formed a well-defined ridge-like structure and two distinctive, opposing side slopes. A valley or incision type structure would also have been considered (having two opposing slopes facing each other); however, no such sites were considered for the quarry project.
- *Site Orientation:* The second main consideration of a suitable site was its topographical orientation. To achieve the goal of this research the most preferred layout was a strong east to west orientation. This orientation was arguably considered the best to assess the impact of directional insolation and aspect. As an alternative, a north to south orientation was also considered.
- *Bedrock Material:* All profiles used for measurements had to be similar. In this regard, it was a requirement that all sensors be installed to take contact measurements directly from bedrock and not soil material (e.g. surface colluvium or residual horizons). As such, it was apparent that suitable boreholes should host bedrock

material virtually from the surface (i.e. areas of bedrock outcrop with limited surficial or no overburden).

- *Borehole Placement:* The placement of boreholes was considered crucial. One borehole was required on each opposing face of the topographical features (i.e. northern and southern aspect; or eastern and western aspect) for comparative monitoring. A third borehole at the crest of the site was considered an advantage as it could be used as an intermediary assessment point, though this was not considered critical.

Secondary considerations were:

- *Remoteness:* Fairly remote sites were preferred to limit the impact of any activities in its proximity (e.g. ground vibrations, movement on surface etc.).
- *Bedrock Type:* Preference was given to sites which hosted uniform bedrock material types. For this research, a uniform, very fine-grained material was preferred, though not essential. However, as measurements were taken below ground level, the effects of certain parameters (e.g. albedo, meteorological conditions, etc.) are less significant.
- *Shade:* Sites were preferred where no shade was cast on boreholes or their immediate surroundings by features in their immediate vicinity (e.g. vegetation) as this could affect temperature measurements.
- *Hillslope Processes:* Areas with notable soil cover where hillslope processes may affect surface conditions (such as described by Cammeraat, 2013) were avoided. While it is impossible to avoid hillslope processes entirely on the site(s) available for research, it would have been ideal to use such a circumstance.

3.5.2 Sites Considered

Several sites were identified for investigation as part of the strategic projects NRA X.005-010-2013/1F and NRA X.005-020-2013/1F commissioned by SANRAL SOC. These sites were distributed across the Western Cape Province and Northern Cape Province of South Africa. Due to project confidentiality, the exact location of the sites may not be disclosed.

Two potential sites were identified which were considered for this research. The first was situated in the vicinity of Springbok (Northern Cape Province) and consisted of a Mokolian (Namaquan) aged batholithic structure, comprising fine to coarse-grained granite. The site was considered as it formed a ridge with a nearly perfect north to south orientation, thereby satisfying the two primary requirements for site selection. Borehole placement was also considered suitable. However, this site was ultimately disregarded as boreholes on the eastern side of the ridge hosted significant vertical thicknesses of residual granite. This was not considered suitable as it was required that the monitored profile should consist exclusively of bedrock.

The second site – which will be discussed in more detail later – was ultimately utilised for this research project. The site is located in the vicinity of Klaarstroom in the Western Cape Province and hosted a ridge of Permian aged tillite outcrop which was orientated almost perfectly east to west. The site complied with all the primary requirements and was therefore selected and used for this research project. It further satisfied all secondary requirements as well, possibly except for the bedrock type. It was preferred that bedrock should consist of a uniform, very fine-grained material and in this case, the bedrock does not fully comply with this description. While the material did have a very fine-grained matrix, it also included dropstones. Nevertheless, this will be discussed in later sections.

4 Site Description

4.1 Landscape and Climatic Setting

The research site is situated in the arid Karoo area of South Africa in a more moderate climatic environment compared with other research undertaken in desert environments (e.g. Eppes *et. al*, 2010; McKay *et. al.*, 2009; Moores *et. al.*,2008). The general region in which the study area is situated is shown in Figure 4.1.

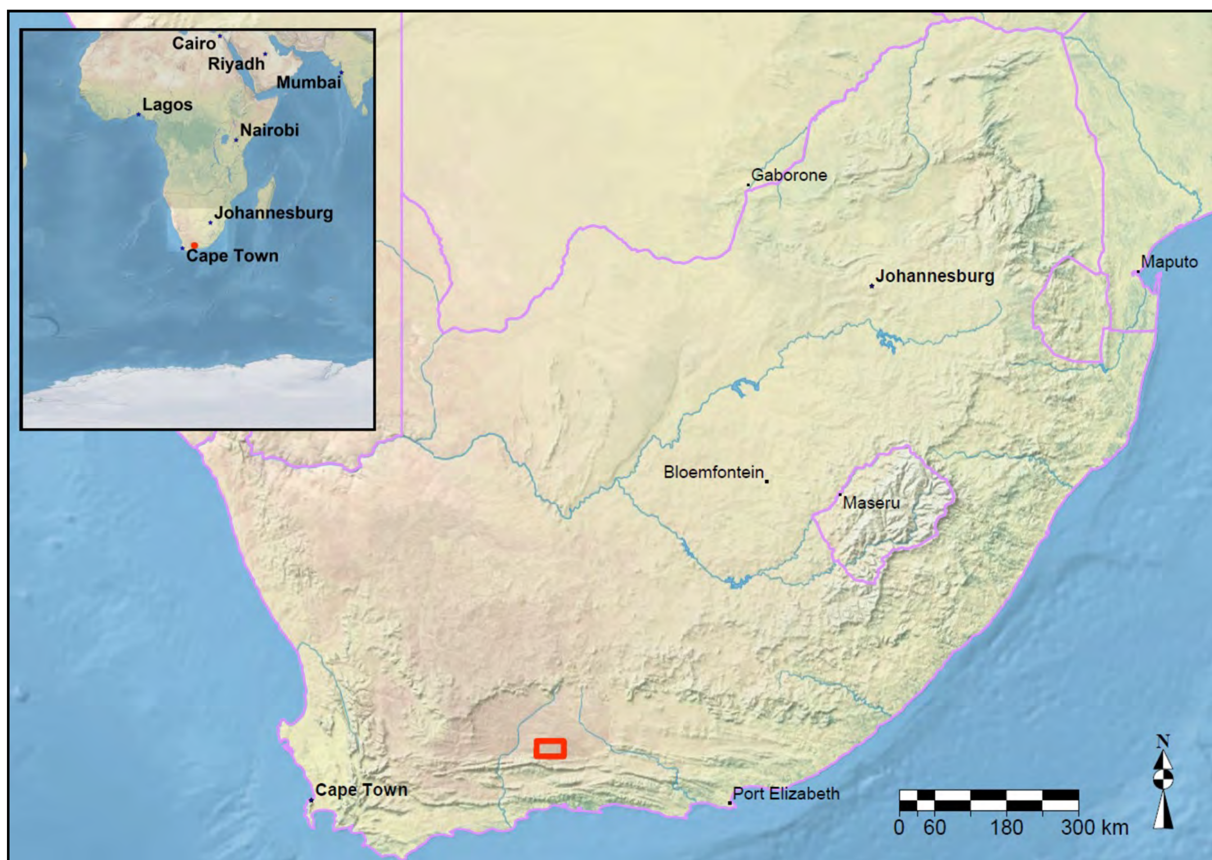

Figure 4.1: Approximate location of research site

The region in which the study area is situated is characterised by typical Karoo-type landscape, with vast open plains and low sedimentary bedrock ridges. The study area itself has topography slightly different to that of the surrounding region due to the protrusion of elongated tillite ridges with an east to west orientation. A relatively thin tillite ridge comprised the specific study site, measuring some 140 m in width (i.e. north to south), with an almost perfectly east to west orientation.

Climatic conditions were summarised by Mucina and Rutherford (2006) and are characterised by low seasonal rainfall, with annual precipitation between 155 mm and 165 mm. Rainfall generally occurs in summer, with mean annual temperatures between 16 ºC and 20 ºC according to Mucina and Rutherford (2006). Summers are typically very hot, while winters are cold, with 26 to 27 frost days per annum. Site meteorological data were captured during the initial part of the research (i.e. 5 April 2018 until 10 April 2019). While similar data were recorded for the second phase of the research, the second stint did not span an entire year. Nevertheless, the annual weather data for the site reported a mean temperature of 16.8 °C, with minimum and maximum temperatures of -1.9 °C and 39.3 °C, respectively. Rainfall during this period totalled 100.2 mm, which is below the average regional rainfall; however, the region was suffering an extended period of drought at the time of the research.

As far as vegetation is concerned, Mucina and Rutherford (2006) indicated that the study area is characterised by the so-called Gamka Karoo type vegetation, which includes an array of vegetation types such as Karoo dwarf shrubs (e.g. *Chrysocoma ciliate, Eriocephalus ericoides*) and low trees (e.g. *Euclea undulata*). It was also reported that drought-resistant grass species occur in dense stands (including *Stipagrostis* and *Aristida*); however, grass species were largely absent at the time of the research due to an extended period of drought experienced in the region. Other endemic vegetation associated with this area includes succulent shrubs (e.g. *Chasmatophyllum stanleyi, Hereroa incruva, Hoodia dregei, Ruschia beaufortensis*), low shrubs (e.g. *Jamesbrittenia tenuifolia*), herbs (e.g. *Manulea karrooica*) and succulent herbs (e.g. *Piaranthus comptus*). Notably, shrubs and low trees appeared to be concentrated in areas of bedrock outcrop along the ridge. Figure 4.2 shows typical site groundcover vegetation, while Figure 4.3 shows an example of clustered shrubs hosted in bedrock joints in an outcrop.

4.2 Site Geology

The drilling investigation undertaken for material investigation purposes revealed that the study area is underlain by dark blue-grey and dark green-grey (i.e. low albedo) Dwyka Group tillite bedrock of the Karoo Supergroup.

Figure 4.2: Typical vegetation groundcover on research site

The Dwyka Group is of Palaeozoic (late Carboniferous to Early Permian) age (Johnson *et. al.,* 2006), and the regional bedrock in the vicinity of the study area is strongly orientated east to west, consisting almost exclusively of sedimentary bedrock materials. Although there are structural geological features (e.g. faults) in the surrounding region, none are indicated in the vicinity of the study area.

The Dwyka Group was summarised by Johnson *et. al.* (2006) and consists of multiple facies. The massive diamictite facies is described as highly compacted diamictite which is clast-rich in the south and clast-poor in the north of the Karoo Basin. Clasts are typically rounded to angular and dropstone may be up to two metres in diameter, while also often being striated. Johnson *et. al.* (2006) interpreted the deposits as lodgement or drop-out deposits which formed under subglacial or subaqueous conditions; however, Herbert and Compton (2007) suggested that meteoric and glacial meltwater were the source of cementing precipitate and not Permian aged seawater, as suggested by some.

Figure 4.3: Shrub growing in cracked bedrock outcrop

Bedrock outcrop on the site sometimes exhibited so-called tombstone or flagstone cleavage (Brink, 1983), a feature which is not particularly pronounced on this site but is common in other parts of the southern and southwestern Karoo. The formation of the tombstone cleavage was researched by Fagareng (2014) and found to be associated with the Cape Fold Belt which induced shortening and deformation during sub-greenschist facies conditions. While the research site used by Fagareng (2014) is located in the Laingsburg area (approximately 150km due west of the study area), it is known (from other quarry site investigations conducted in the Laingsburg area as part of the SANRAL project) that the tillite materials there were very similar to those encountered on the research site under consideration here. In support of this, Fagareng (2014) noted that the tillite materials researched consisted primarily of quartz, feldspar, muscovite and chlorite.

As part of the quarry investigation, five sets of XRD analyses were performed on samples taken from the tillite core, sampled across the larger quarry area. The results of X-ray

diffraction (XRD) and petrography tests are summarised in Table 4.1. The XRD results of five samples comply with the material composition description given by Fagareng (2014), as the major constituents are similar, though microcline content is more substantial than muscovite.

Table 4.1: X-Ray diffraction results of tillite samples

CONSTITUENT (WEIGHT %)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Calcite	1.34	1.21	1.15	0.57	1.33
Chlorite	13.87	13.35	12.66	10.82	12.72
Dolomite	0.91	1.23	1.14	0.85	0.75
Microcline	7.66	8.09	10.33	12.32	11.28
Muscovite	6.74	6.66	6.02	6.53	6.18
Plagioclase	32.55	33.07	33.04	32.45	32.32
Quartz	34.65	33.15	33.66	33.12	33.46
Smectite	2.28	3.23	1.99	3.34	1.97

A photograph of typical drill core recovered from boreholes is illustrated in Figure 4.4 and it shows that roughly the upper one metre of the profile consisted of closely jointed "first brown" tillite, while the remainder of the core consisted of "blue" tillite. Some discolouration is evident on the photograph due to dried drilling lubricant (e.g. 4.90 m). The closely jointed rock mass in the upper metre of the profile was recovered as a blocky or stony material, despite actually constituting bedrock. The targeted bedrock material from this drill core was described based on the guidelines of SAICE (1990), which was used as the profiling standard during the project investigation. Though the complete supplement of information may not be disclosed, the "blue" tillite was generally described as follows:

Dark blue-grey speckled and mottled grey-white, very fine-grained, unweathered, closely to medium jointed, very hard rock: TILLITE. Dropstones are smaller than 15 mm in diameter and mostly smaller than 8 mm in diameter, angular to sub-rounded and mostly consist of quartzite. Joints are undulating, open (2 mm to 5 mm wide) and contain traces of light grey silty sand.

Figure 4.4: Typical tillite drill core recovered from geotechnical borehole

Though a uniform, fine-grained material would have been preferred for this research (e.g. dolerite), the fact that dropstones in the tillite matrix in the project area are of a limited size, and not up to two metres in diameter as described by Johnson *et. al*. (2006), means that the material is still considered acceptable for the intended research applications.

An additional consideration which was relevant to the larger material investigation of this site was the degree of weathering of the tillite discussed by Brink (1983), which divides tillite materials into one of five classes based on the extent of chemical weathering it has sustained. This classification is based largely on visual and tactile observations. In the case of the material investigation, unweathered (W1) or "blue tillite" was the targeted material (at depth) for aggregate production, while near-surface bedrock mostly consisted of slightly weathered (W2) or "first brown" tillite.

Finally, three geological features or material properties of the tillite are considered critical as far as existing or pre-existing jointing, discontinuities or orientated weaknesses are concerned. The implications thereof will be expanded in later discussions. These include:

- *Stress History:* Though the effects of the stress history are not the focus of the research, it should nevertheless be considered (de Vilder *et. al.*, 2019; Viles *et. al.*, 2018). Tillite bedrock at this site has been subjected to regional tectonic deformation associated with the Cape orogeny, which occurred during the late Permian and early Triassic periods, as extensively discussed by Newton *et. al.* (2006). The deformation has resulted in preferentially orientated stress fields in the bedrock which, in turn, influences joint and fracture orientations. This, in fact, was very clear during the material laboratory analyses of the rock material as the rock material had a very clear tendency to break into elongated fragments during crushing.
- *Disintegration:* Tillite bedrock in the southern African environment is known to disintegrate upon exposure to the atmosphere; however, the process constitutes physical breakdown with no chemical alteration (Brink, 1983). The result is the formation of distinctive almost cubicle gravel fragments. A typical example of this can be seen in the background of Figure 3.4.
- *Desiccation Cracks:* Though not commonly observed in the research area, the larger surrounding quarry site contained rare exposures of tillite outcrop where depositional desiccation cracks could be discerned. A typical example is illustrated in Figure 4.5.

Figure 4.5: Depositional desiccation patterns visible in tillite outcrop adjacent to the research area

4.3 Regional Groundwater

Although the study area is situated on a ridge which is elevated above its surroundings, a description of regional groundwater conditions is considered perfunctory information. With this in mind, Vegter (1995) indicated that the probability of successfully drilling for groundwater in the area is more than 60 %. In addition, if groundwater is encountered, the probability is between 30 % and 40 % that the yield of such a borehole would exceed 2 l/s. Vegter (1995) further indicated that groundwater in the area is usually encountered at depths of between 10 m and 20 m, occurring in compact tillite, shale and sandstone bedrock.

In this instance, the study area is situated near a minor non-perennial tributary of the Traka River and hence, it is probable that the local groundwater conditions will be dictated by base flow conditions associated with the tributary flow channel. This was confirmed during the early stage

exploratory drilling investigation, when multiple shallow-water strikes were recorded near the dry tributary bed, some distance away from the research site under consideration.

Nevertheless, though some drilling water and lubricants remained at the base of the three boreholes used during this research, the boreholes are situated at elevations well above adjacent water levels recorded near the tributary channels. As such, no regional groundwater influx occurred in the research boreholes and moisture in the borehole shafts are the result of drilling fluids left behind after drilling.

Lastly, it must also be taken into account that the research was undertaken at a time when the region was experiencing a prolonged and sustained drought and hence groundwater conditions were likely different to those deduced statistically.

4.4 Site Layout

To better illustrate the experimental approach used, a description of the site layout is pivotal. Of the twenty rotary core boreholes drilled for the material investigation, three were specifically selected due to their topographical positions. As the aim of the research is to identify any differences in bedrock temperature due to aspect, one borehole was selected from the northern-facing slope and one from the southern-facing slope of the ridge, while a third borehole, drilled on a flat (i.e. horizontal) crest of the tillite ridge, was also selected as a reference point. Topographical survey data for the material investigation was used to compile an illustration of the study area and is shown in Figure 4.6. The ridge consisted of a summit (i.e. crest site) and two opposing back slopes, as defined by Schaeltz (2013). Figure 4.7 shows a view of the eastern slope and crest of the ridge, taken some distance away.

The ridge itself is steep in places, with the southern face of the ridge being considerably steeper than the northern face. The ridge tapers to the east to form a gentle foot slope. The northern and southern boreholes are not equidistant from the crest borehole and while ground level at the northern-facing borehole was recorded at an elevation of 905.9 m.a.s.l., ground level at the southern-facing borehole has an elevation of 898.1 m.a.s.l. Ground-level at the crest borehole had an elevation of 913.1 m.a.s.l.

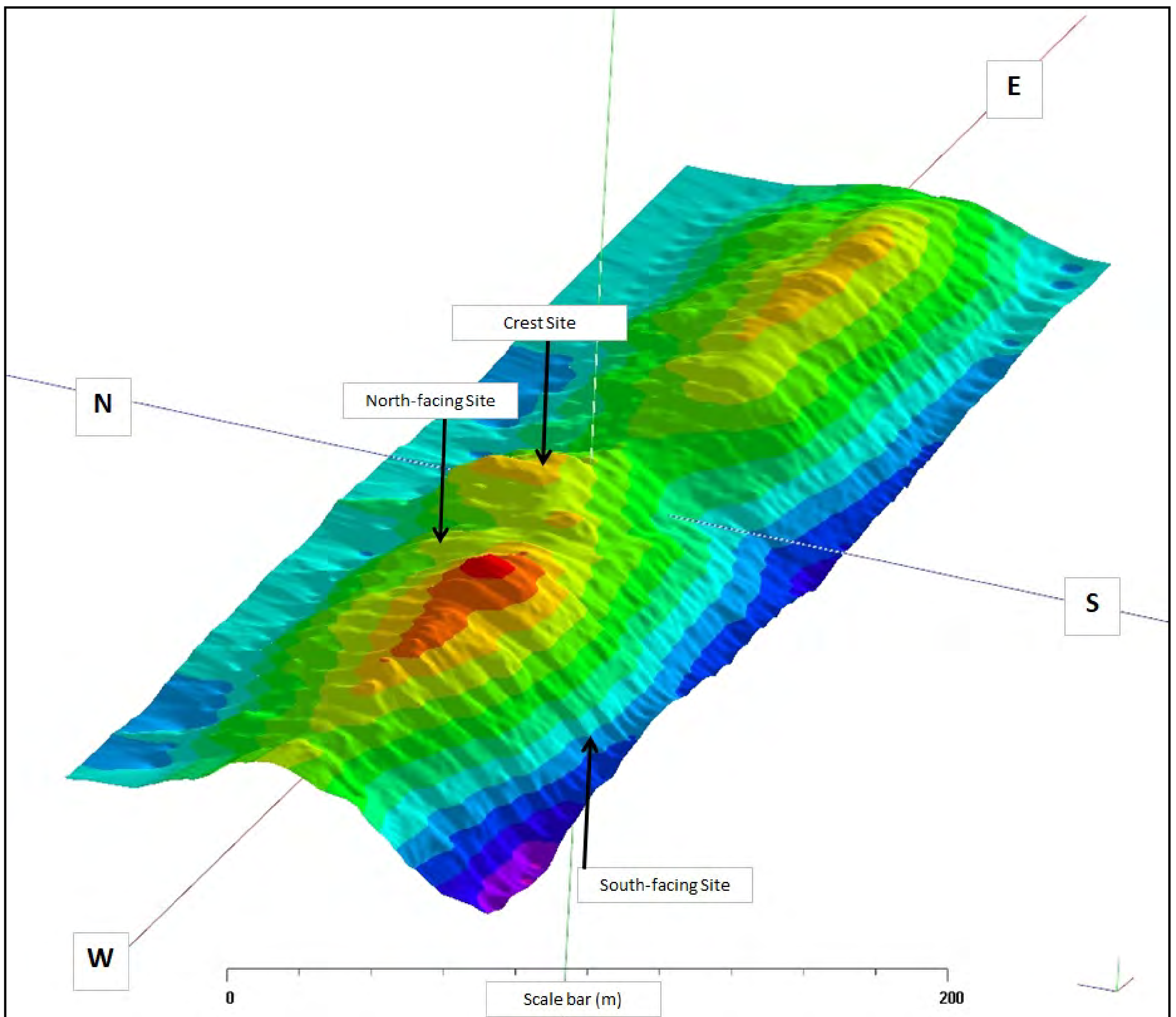

Figure 4.6: Topographical site layout model (2.5 times vertical exaggeration)

Using the topographic survey results, it was calculated that the area immediately surrounding the southern-facing borehole has a gradient of approximately 16 º, while the northern-facing borehole surroundings dip at approximately 9 º. The crest of the ridge is essentially flat or horizontal.

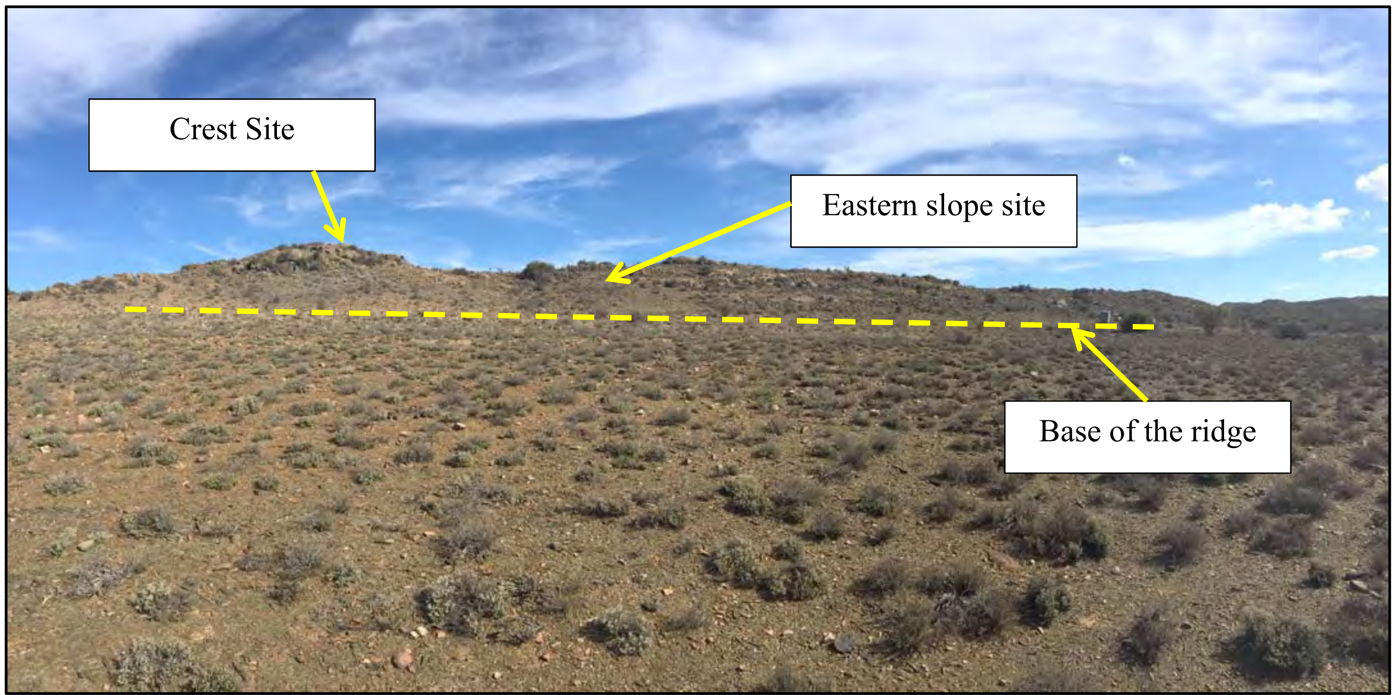

Figure 4.7: Distance view of the study area from the east (western site not visible)

5. Results and Analyses

The site data captured were processed in spreadsheet format and analysed in more detail, which will be discussed in following sections. Nevertheless, the summary below described the datasets accumulated during the trial and the follow-up research. The data includes meteorological measurements (i.e. outside air temperature, wind speed, rainfall and rain), as well as temperature measurements recorded in boreholes.

5.1 Data Acquisition and Grouping

5.1.1 Preliminary Data Acquisition

After discarding the measurement data captured during and shortly after (initial and mid-way) installation of the data loggers, a total of 17 552 data points were captured by each of the three loggers ultimately considered from the trial data. The combined data for the three loggers are illustrated in Figure 5.1, which shows a data plot for the entire duration of the research period.

Data were captured for an entire seasonal cycle (i.e. one year), as recommended by Hall and André (2001). To assess potential differences or relationships between shallow bedrock temperatures at the three site positions (i.e. aspects) selected, data analyses had to be simplified because working with a single large dataset (i.e. one year period) is cumbersome and some peculiarities may be overlooked that occur over shorter periods. As a result, the data were divided into four subsets, with each subset coinciding with a season. The (southern hemisphere) seasonal periods used were summer (1 December – 28 February), autumn (1 March – 31 May), winter (1 June – 31 August) and spring (1 September – 30 November). The data compiled for the autumn period consisted of two batches (i.e. a period in 2018 and a period in 2019) that were merged into a single data set. The descriptive statistics of data captured at 0.3 m on the northern slope, crest and southern slope is summarised in Table 5.1. The descriptive statistics describe the entire year, and was also subdivided to describe each of the four seasons.

Findings of the data analyses will be discussed in more detail in the following sections and data for this part of the research is included electronically (i.e. spreadsheet) in Appendix A.

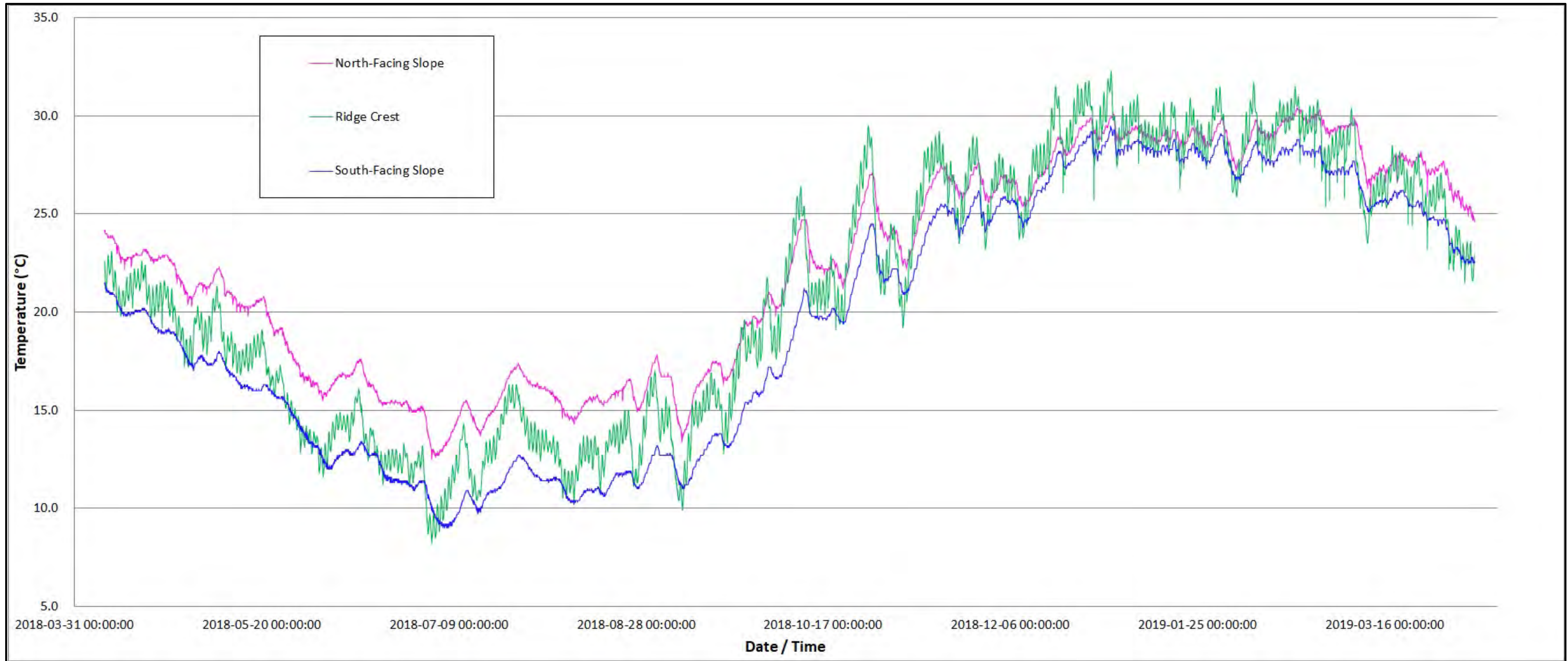

Figure 5.1: Temperature data from northern site, crest site and southern site covering a period of one year

Table 5.1: Descriptive statistics summary of annual and seasonal temperature data for three loggers installed at a depth of 0.3 m on three aspects for trial research

	Mean	**Range**	**Minimum**	**Maximum**	**Data points**
Northern Slope Summer	28.7	5.0	25.4	30.4	4320
Northern Slope Autumn	23.3	13.5	16.4	29.9	4464
Northern Slope Winter	15.5	5.1	12.5	17.6	4416
Northern Slope Spring	21.8	14.2	13.4	27.6	4352
Northern Slope (Year)	22.4	17.9	12.5	30.4	17552
Ridge Crest Summer	28.9	8.6	23.7	32.3	4320
Ridge Crest Autumn	21.9	17.6	12.8	30.4	4464
Ridge Crest Winter	12.9	8.5	8.2	16.7	4416
Ridge Crest Spring	21.1	19.6	9.9	29.5	4352
Ridge Crest (Year)	21.1	24.1	8.2	32.3	17552
Southern Slope Summer	27.7	5.2	24.3	29.5	4320
Southern Slope Autumn	20.9	14.2	13.5	27.7	4464
Southern Slope Winter	11.4	4.9	9.0	13.9	4416
Southern Slope Spring	19.0	15.2	11.0	26.2	4352
Southern Slope (Year)	19.7	20.5	9.0	29.5	17552

5.1.2 Follow-up Data Acquisition

The data captured during the follow-up investigation spanned only approximately seven months (as opposed to a full year for the trial data) due to site access restrictions and consequently, analyses were approached slightly differently. Nevertheless, after discarding the data captured 24 hours after installation, the loggers yielded 10 602 datasets each. It soon became apparent that one logger (i.e. northern slope, 6.0 m depth) suffered failure after capturing only 2809 datasets. As such, the dubious data were discarded and not used in further analyses. Descriptive statistics were derived for each data logger's data and are reflected in Table 5.2.

Table 5.2: Descriptive statistics summary of temperature data from nine loggers for follow-up research

Site (Slope)	North 6.0 m	North 2.0 m	North 0.3 m	Crest 6.0 m	Crest 2.0 m	Crest 0.3 m	South 6.0 m	South 2.0 m	South 0.3 m
Mean	24.1	21.9	21.3	21.7	19.8	19.5	19.1	17.3	17.3
Standard Deviation	0.4	2.4	4.7	0.9	2.9	5.6	0.9	3.1	6.2
Range	1.7	8.2	18.6	3.3	9.7	20.1	3.5	10.1	20.7
Minimum	23.3	18.7	12.0	20.4	16.1	10.6	18.0	13.7	8.7
Maximum	25.0	26.9	30.6	23.7	25.8	30.7	21.5	23.8	29.4
Data Sets	2809	10602	10602	10602	10602	10602	10602	10602	10602

Findings of the data analyses will be discussed in more detail in the following sections while data for this part of the research is included electronically (i.e. spreadsheet) in Appendix B.

5.1.3 Meteorological Data

Meteorological data captured during the two phases of research were processed into spreadsheet form. Data for the 2018 – 2019 period is included in Appendix C, while data for the follow-up research in 2019 – 2020 is included in Appendix D.

5.2 Trial Investigation

5.2.1 Annual Data Correlation

From the onset of analyses, graphical and statistical data indicated significantly greater variation in temperatures of the ridge crest site compared with the northern and southern facing slope sites (refer to Figure 5.1). Though all three data sets appeared to have similar periodic fluctuations, the data from the crest logger were found to be highly erratic compared with the remaining two loggers and were therefore treated with some scepticism. It was ultimately deduced that the temperature probe/pin failed to make contact with the borehole shaft sidewall in this borehole and as a result, this logger measured air temperature and not contact temperature. For this reason, the crest data will be excluded from further discussion and follow-up research made an effort to confirm or disprove this deduction.

The data summary showed that shallow bedrock on the northern slope face has a mean annual temperature of 22.4 ºC, compared with the southern slope which had a mean of 19.7 ºC. The annual data showed that temperature fluctuations were synchronous on a seasonal basis. Unsurprisingly, temperature peaks occurred during the summer, while the lowest temperatures were recorded in winter. Temperature extremes vary more notably during spring and autumn, suggesting that winter and summer temperature variations may be less significant than mentioned by Jenkins and Smith (1990), though this will be discussed later.

The most fundamental observation reflected in the data, however, is that the bedrock temperatures of the north-facing rock are consistently higher than those of the south-facing rock, with no exceptions noted in the data.

5.2.2 Summer Data Correlation

Summer data captured between 1 December 2018 and 28 February 2019 can be seen in Figure 5.2. The data were synchronous between the southern and northern slope faces, with very similar temperature fluctuations being apparent. The southern borehole had a temperature range of 5.2 ºC, compared with 5.0 ºC for the northern borehole, while the southern site also had a mean temperature for this period which was 1.0 ºC lower than that of the northern site.

At the same time, the southern site had a minimum temperature some 1.1 ºC lower than that of the northern site. It can be argued that minimum temperatures on the southern site are marginally more peaked (relative to the northern site), while maximum temperatures on the northern are more peaked compared with the southern site. As expected, the summer period recorded the highest rock temperatures, but the difference in maximum temperatures recorded for the two aspects was only 0.9 ºC.

5.2.3 Autumn Data Correlation

The autumn data captured in Figure 5.3 illustrate only the data recorded between 8 April 2018 and 31 May 2018 and not for the entire autumn period (i.e. 1 March to 31 May). The data supplement from this period (i.e. 1 March to 8 April) were, however, captured in 2019 and added to the data used for analyses even though not reflected in the illustration.

The autumn data showed a significant decrease in rock temperatures on both aspects of the ridge, which is not surprising considering the seasonal change. The graphical data representation suggests that the short term temperature fluctuations are more pronounced compared with the summer data and this was confirmed by the descriptive statistical data. The northern and southern bedrock had data ranges of 13.5 ºC and 14.2 ºC, respectively, nearly three times those recorded in the summer.

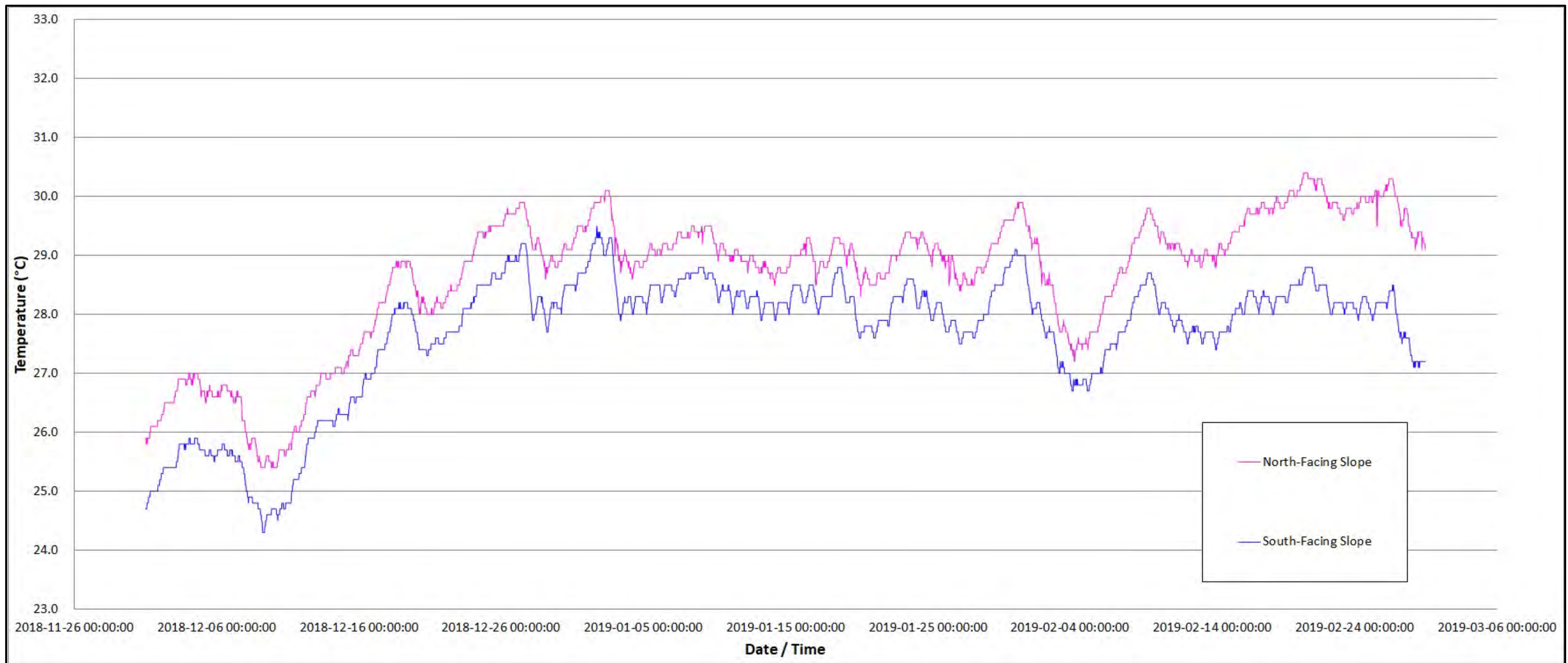

Figure 5.2: Trial research temperature data for summer

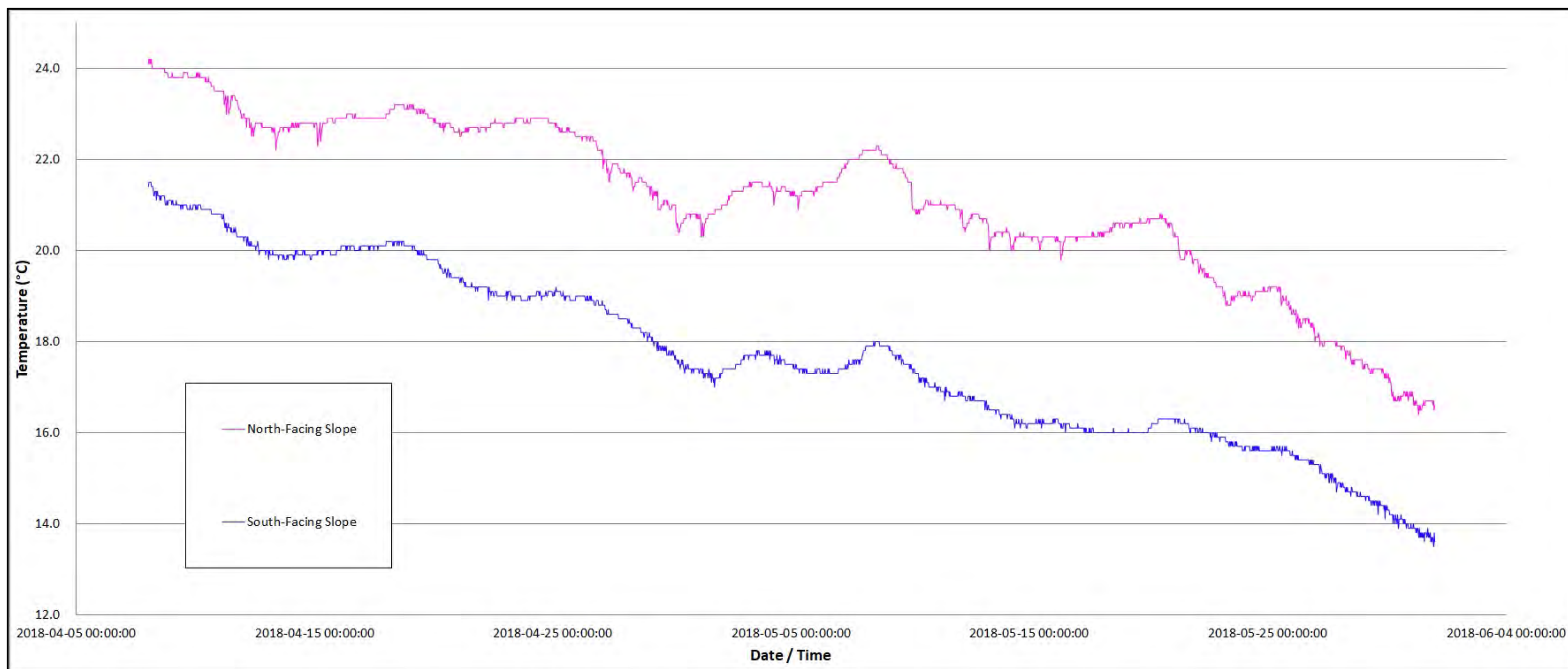

Figure 5.3: Trial research temperature data for autumn

In autumn, temperature differences between the two aspects became notably larger, with a 2.4 ºC difference in mean temperatures between the northern site (i.e. 23.3 º C) and the southern site (i.e. 20.9 º C). The minimum and maximum temperatures were also more peaked (compared with the summer data), with the northern-facing site recording maximum and minimum temperatures of 29.9 ºC and 16.4 ºC, respectively, compared with the southern-facing site's corresponding temperatures of 27.7 ºC and 13.5 ºC.

5.2.4 Winter Data Correlation

Data captured during the winter are illustrated in Figure 5.4 and show the lowest temperatures in the year for both test sites. From the figure, it is apparent that both peaks and troughs in the graph are seemingly more pronounced for the north-facing site than for the south-facing site and that increases and decreases on the southern side are retarded slightly relative to the northern site. This arguably suggests slower or more gradual thermal responses in the rock on the southern site.

Mean values for both sites were the lowest recorded in the entire year, with the southern site significantly recording a mean temperature some 4.1 ºC lower than the northern site. However, similar to the summer data the range in recorded data showed a 5.1 ºC range for the northern site and a 4.9 ºC range for the southern site; hence, the temperature range difference for the two sites was only 0.2 ºC. Maximum temperatures recorded on the northern and southern sites were 17.6 ºC and 13.9 ºC, respectively, with corresponding minimum temperatures of 12.5 ºC and 9.0 ºC. The difference in maximum and minimum temperatures between the two sites was 3.7 ºC and 3.5 ºC, respectively.

5.2.5 Spring Data Correlation

The final dataset – that reflecting spring temperature measurements – is shown in Figure 5.5. This graph illustrates the converse of the autumn data, in that temperatures show a gradual increase as the season moves towards summer. The descriptive statistical data showed that mean temperature in spring were very similar to those recorded in autumn, but marginally lower. The northern and southern sites had mean temperatures of 21.8 ºC and 19.0 ºC; hence there was a 2.8 ºC differential.

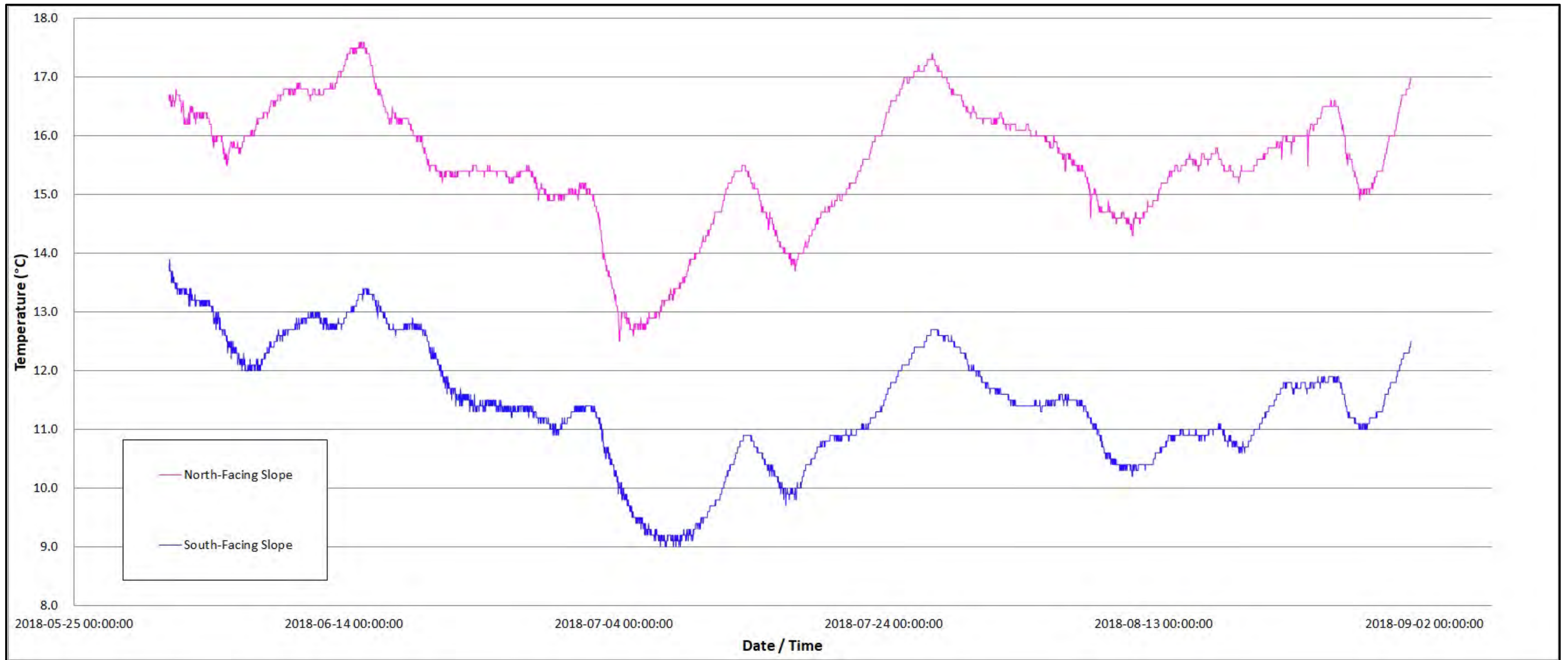

Figure 5.4: Trial research temperature data for winter

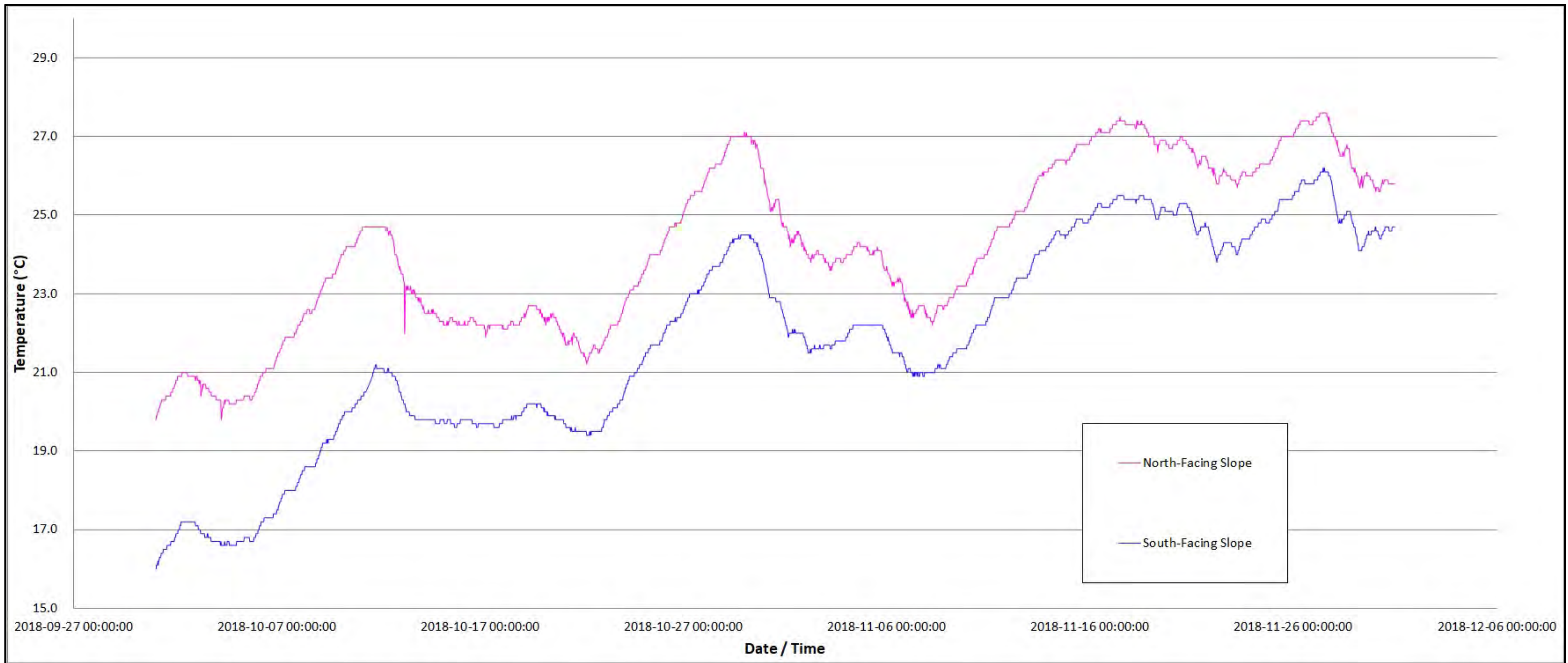

Figure 5.5: Trial research temperature data for spring

The difference between the minimum and maximum temperatures recorded on the two sites was 2.4 ºC and 1.4 ºC, respectively. Critically, however, the data captured during the spring period showed the largest temperature data range recorded during the entire year. The northern site recorded a range of 14.2 ºC, compared with the southern site's temperature range of 15.2 ºC. The graphic representation further suggests that the difference in mean temperatures between the two sites becomes less pronounced as summer draws nearer.

5.3 Follow-up Research

5.3.1 Rock Temperatures at 0.3 m

Findings of the follow-up data were similar to those reported during the trial research. The data summary of near-surface readings (i.e. 0.3 m depth) again confirmed that the northern-facing slopes have the highest mean temperature (i.e. 21.3 ºC), while the south-facing slope has the lowest mean temperature (i.e. 17.3 ºC). Data that were previously lacking but captured during the follow-up research showed that the mean temperature of the crest site is intermediate between the northern and southern slopes and the mean temperature for the crest site was reported as 19.5 ºC.

A similar observation was made when comparing the minimum and maximum temperatures between the three sites. The new data confirmed the observation previously made that the southern-facing slope had the largest temperature range relative to the northern-facing site. The crest site again ranked in the middle of the three sites considered.

A graphic illustration of the two aspects and the crest site is shown in Figure 5.6. From the illustration, it appears that temperature oscillations on the northern-facing slope are notably more peaked compared with the crest and the southern-facing slope. This observation was also previously reported; however, the crest site data did not appear to correlate particularly strongly with the northern or southern sites' data as far as peakedness is concerned. Nevertheless, all three sites appear to have synchronous data temperature fluctuations.

Figure 5.6: Rock temperatures at 0.3 m (follow-up research)

5.3.2 Rock Temperatures at 2.0 m

The graphic illustration of logger data from a depth of 2.0 m is shown in Figure 5.7. The three datasets revealed that the northern-facing slope has the highest mean temperature (i.e. 21.9 ºC), with the crest site being intermediate (i.e. 19.8 ºC) and the southern-facing site having the lowest mean temperature (i.e. 17.3ºC). However, from the graphical illustration, it is clear that the temperature differences between the three sites become smaller as summer approached. The southern-facing slope showed the largest temperature oscillation or range (i.e. 10.1 ºC), compared with the northern-facing slope (i.e. 8.2 ºC) and the crest site (i.e. 9.7 ºC). Critically, though, these temperature ranges are all more than 10 ºC smaller than those recorded by shallow temperature loggers (i.e. 0.3 m). Temperature maxima were highest for the north-facing slope and lowest for the south-facing slope, with the crest site once more being intermediate. The opposite applies to the temperature minima, and the crest was once more proved to be an intermediate site in this regard.

5.3.3 Rock Temperatures at 6.0 m

As previously mentioned, it was apparent that the (6.0 m) temperature logger at the north-facing site suffered failure after approximately two months. Nevertheless, some of the faulty logger's data were salvaged and processed. Figure 5.8 shows temperature plots for the three loggers installed at a depth of 6.0 m.

As noted in the data of shallower loggers, the south-facing slope had a lower mean temperature than the crest site, while the north-facing site data was incomplete. The south-facing site also showed a marginally higher (i.e. 0.2 ºC) temperature range when compared with the crest site, as well as the lowest minimum temperature. The converse was again noted, with the crest site having a higher maximum temperature than the southern-facing site. It can be inferred that the northern-facing site would have recorded the highest maximum temperature and also the highest minimum temperature; however, the incomplete data for the relevant logger leaves this observation to be substantiated.

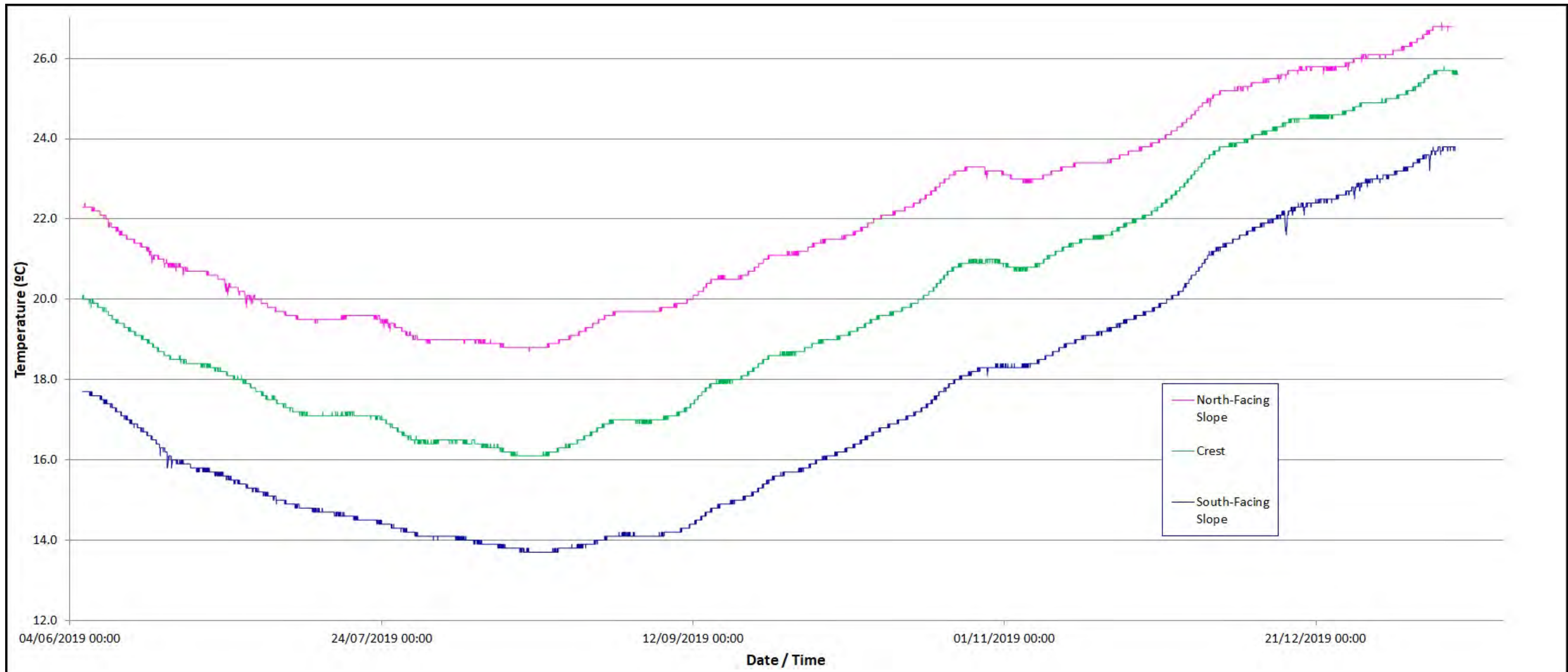

Figure 5.7: Rock temperatures at 2.0 m (follow-up research)

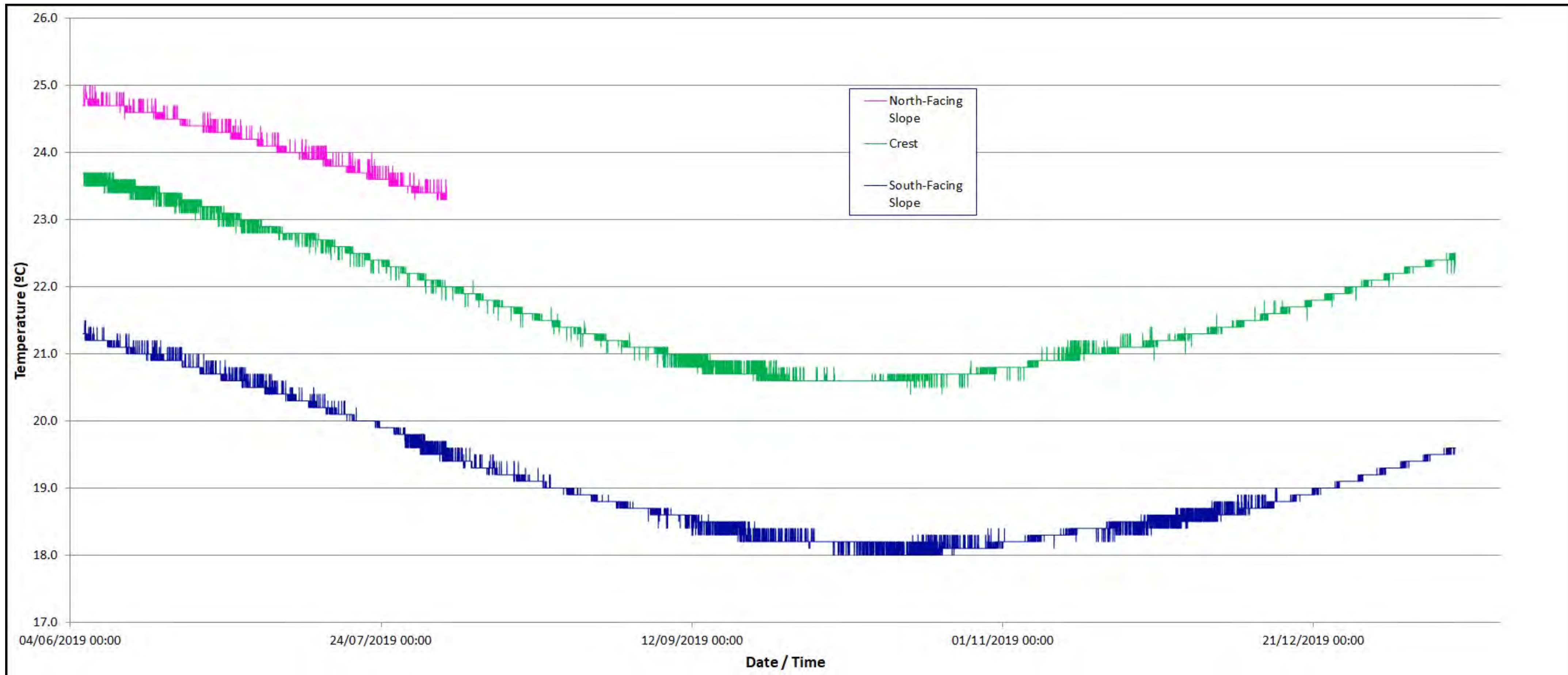

Figure 5.8: Rock temperatures at 6.0 m (follow-up research)

5.3.4 Rock Temperatures on the North-Facing Aspect

Following analyses of data captured at similar depths across three aspects, data were further scrutinised to assess thermal properties at various depths of each aspect. In the absence of a complete dataset for the logger installed at a depth of 6.0 m, the remaining two loggers (2.0 m and 0.3 m) revealed that multiple temperature inversions (i.e. reversals) occur through the course of autumn at different depths as bedrock temperatures oscillate (refer to Figure 5.9).

For this research a "rock temperature inversion" is defined as "*…a scenario where one part of the rock mass is warmer than an adjacent part of the rock mass at one time, but at a later time the same rock mass is cooler than the adjacent rock mass (and vice versa), resulting in a periodically alternating temperature differential*". Simply stated, a temperature inversion occurs when one part of the bedrock becomes hotter or cooler relative to another/adjacent part of the bedrock, compared with its earlier temperature state.

In mid-winter, the rock mass at a depth of 2.0 m maintained a higher temperature than the near-surface (i.e. 0.3 m) bedrock. Though the two temperature ranges alternate (i.e. invert) numerous times in autumn, eventually at (approximately) the start of summer, the shallow rock temperatures exceeded the temperatures at depth and the shallow rock consistently became warmer.

The graph also clearly illustrates that the shallow (i.e. 0.3 m) rock temperatures are more susceptible to rapid temperature oscillations than the deeper (i.e. 2.0 m) rock. Partial data for the logger installed at a depth of 6.0 m suggest that this logger is even less susceptible to rapid temperature oscillations; however this remains to be verified by a complete dataset.

5.3.5 Rock Temperatures at the Crest Site

With a complete data supplement from all three loggers installed at the crest site, the results confirmed the temperature inversion(s) noted in data from the north-facing slope. Furthermore, the crest data (illustrated in Figure 5.10) also showed that the temperature inversions occur between all thee depths in the bedrock.

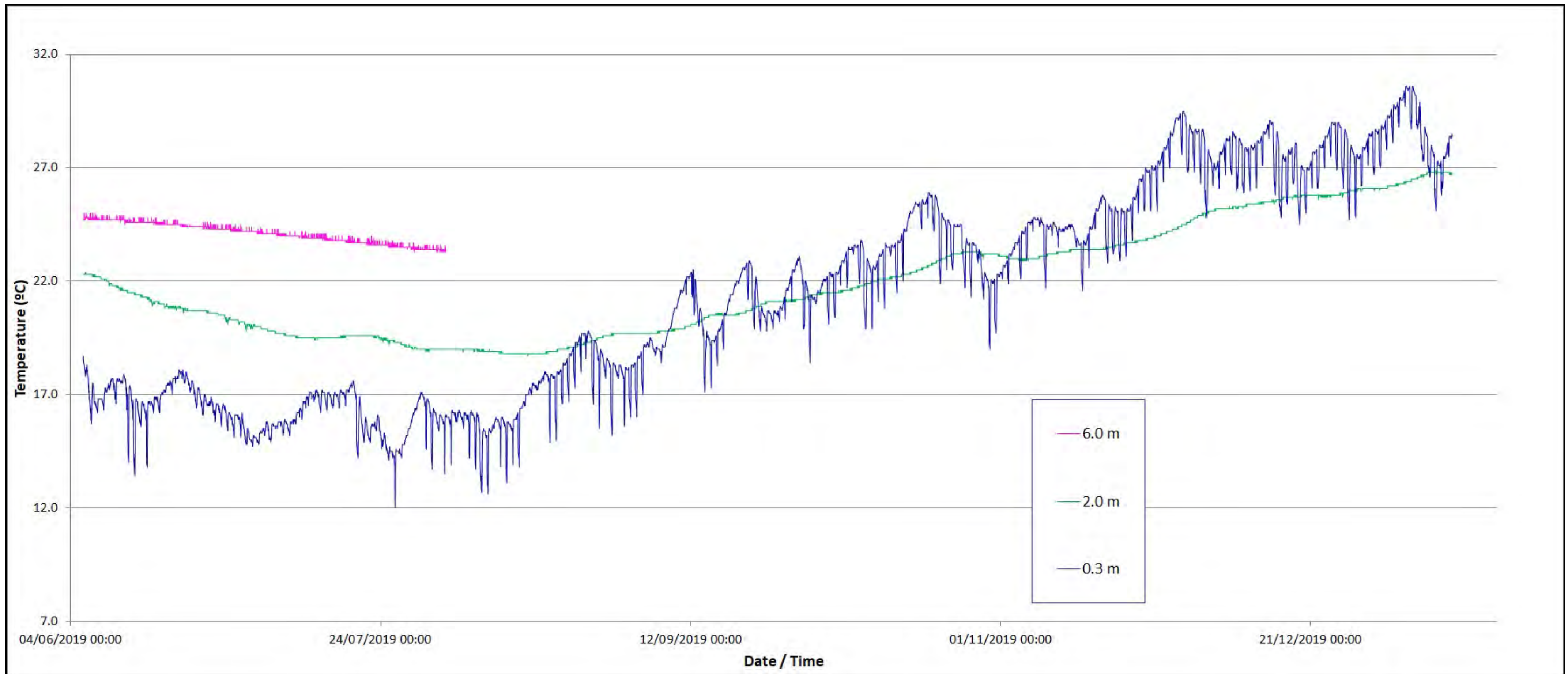

Figure 5.9: All depths, northern site (follow-up research)

Figure 5.10: All depths, crest site (follow-up research)

From mid-winter the deepest part of the rock measured (i.e. 6.0 m) maintained the highest temperatures, with the rock at 2.0 m maintaining intermediate temperatures and the shallow rock (i.e. 0.3 m) recording the lowest temperatures. These temperatures were completely inverted by mid-summer.

However, when considering the susceptibility of rapid temperature oscillations, it is again clear that near-surface temperatures are much more susceptible to rapid fluctuation and that this susceptibility becomes less pronounced with depth. Though this may seem logical, the implication is that some eleven (major) temperature inversions occurred in the rock at depths of 0.3 m and 2.0 m, compared with nine (major) inversions in the rock at 0.3 m and the deeper rock at 6.0 m.

In comparison, only three temperature inversions were observed between the rock at depths of 2.0 m and 6.0 m; hence there is a strong argument to be made that thermal stress fatigue failure is more likely to occur at shallow depths where temperature inversions occur much more frequently and with greater temperature oscillations.

5.3.6 Rock Temperatures at the Southern Aspect

The complete dataset for the southern-facing site revealed similar results to that of the crest site and results are illustrated graphically in Figure 5.11. The rock at a depth of 6.0 m appears to retain heat longer through the winter period and has notably higher temperatures than the rock at 2.0 m and 0.3 m. The rock at 2.0 m is also warmer than the rock at 0.3 m in mid-winter.

Multiple temperature inversions were recorded in the bedrock at various depths throughout spring and by mid-summer, the inversions were complete with the deepest part of the bedrock being the coolest and the shallow part of the bedrock being the warmest. The rock at a depth of 2.0 m stabilised at an intermediate level. This data again illustrates very clearly that the susceptibility to rapid temperature fluctuations decreases significantly with depth in the rock.

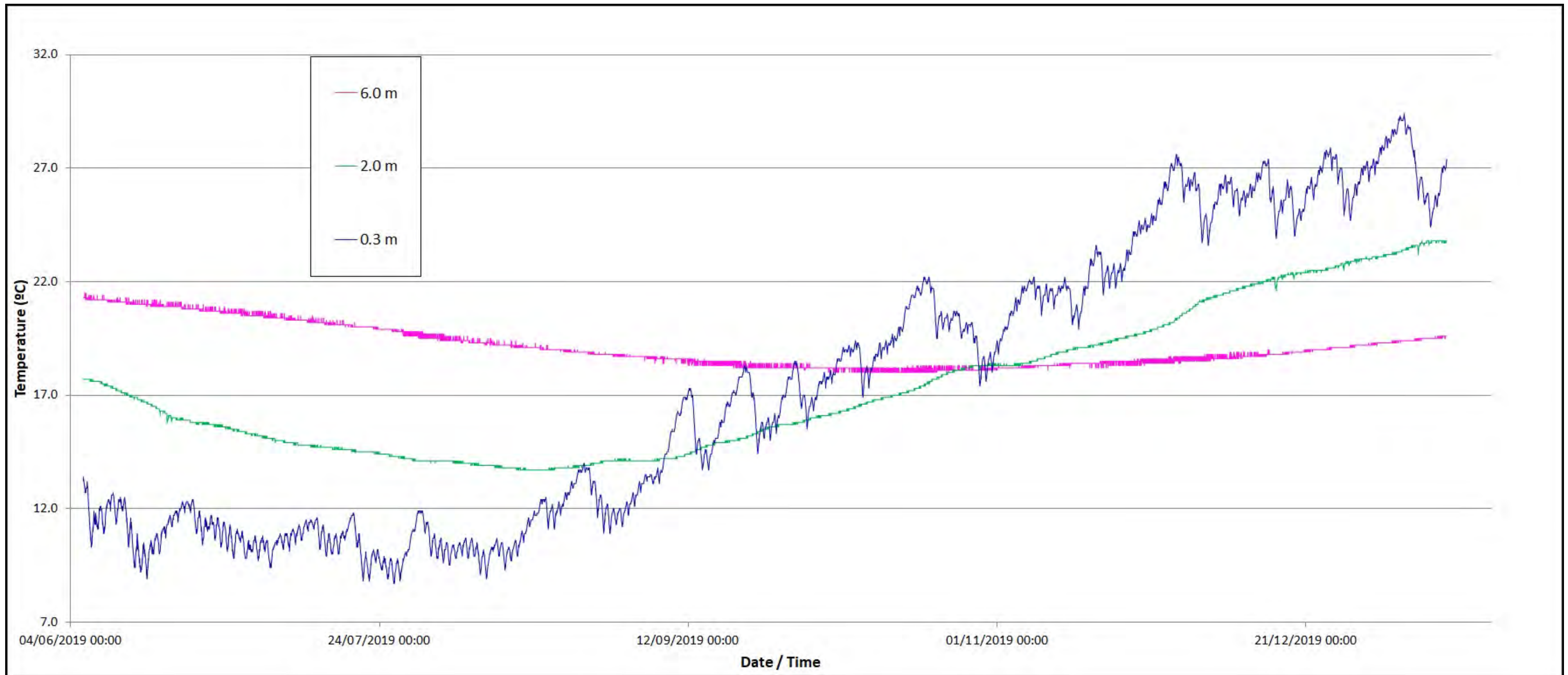

Figure 5.11: All depths, southern site (follow-up research)

5.4 Seasonal Bedrock Temperature Changes and Thermal Fatigue

5.4.1 Concept of Thermal Fatigue

The concept of fatigue was discussed earlier and the discussion will not be repeated here, except for the concluding remarks which the two most fundamental considerations, namely temperature oscillations and the rate/frequency of temperature oscillations. Essentially it was argued that a greater frequency of temperature oscillations (i.e. temperature inversions) occurring in rock will likely cause more rapid fatigue failure compared with a lower oscillation frequency. Also, it was further contended that thermal fatigue failure would be exacerbated by larger temperature oscillations, ranges or fluctuations.

5.4.2 North-facing Site

Temperature measurements of the vertical rock profile on the north-facing site of the rock mass are illustrated in Figure 5.12 (a). To avoid the influence of solar radiation, data were used as measured at midnight, recorded on the sixth day of months between June 2019 and January 2020. The date used was selected arbitrarily. As reported in the previous section, however, this dataset is incomplete due to the failure of the logger installed at a depth of 6.0 m.

Nevertheless, the data recorded at a depth of 0.3 m showed an initial overall temperature decrease between June 2019 and July 2019. Thereafter, temperatures consistently increased until January 2020. In comparison, the rock temperatures recorded at a depth of 2.0 m continued a decreasing trend from June 2019 until August 2019, at least an additional month longer than that recorded at a depth of 0.3 m. From August 2019 until January 2020, the bedrock at 2.0 m also gradually increased in temperature; however, the range of temperature fluctuations is markedly smaller than those recorded at a depth of 0.3 m. As mentioned before, the limited data captured at a depth of 6.0 m is insufficient to make conclusive inferences.

Perhaps the most significant observation that can be made from the data is that there is a time delay between when the rock temperatures begin to (consistently) increase at depths of 0.3 m and 2.0 m. The overall temperature decrease (i.e. heat dissipation) at a depth of 0.3 m ceased between

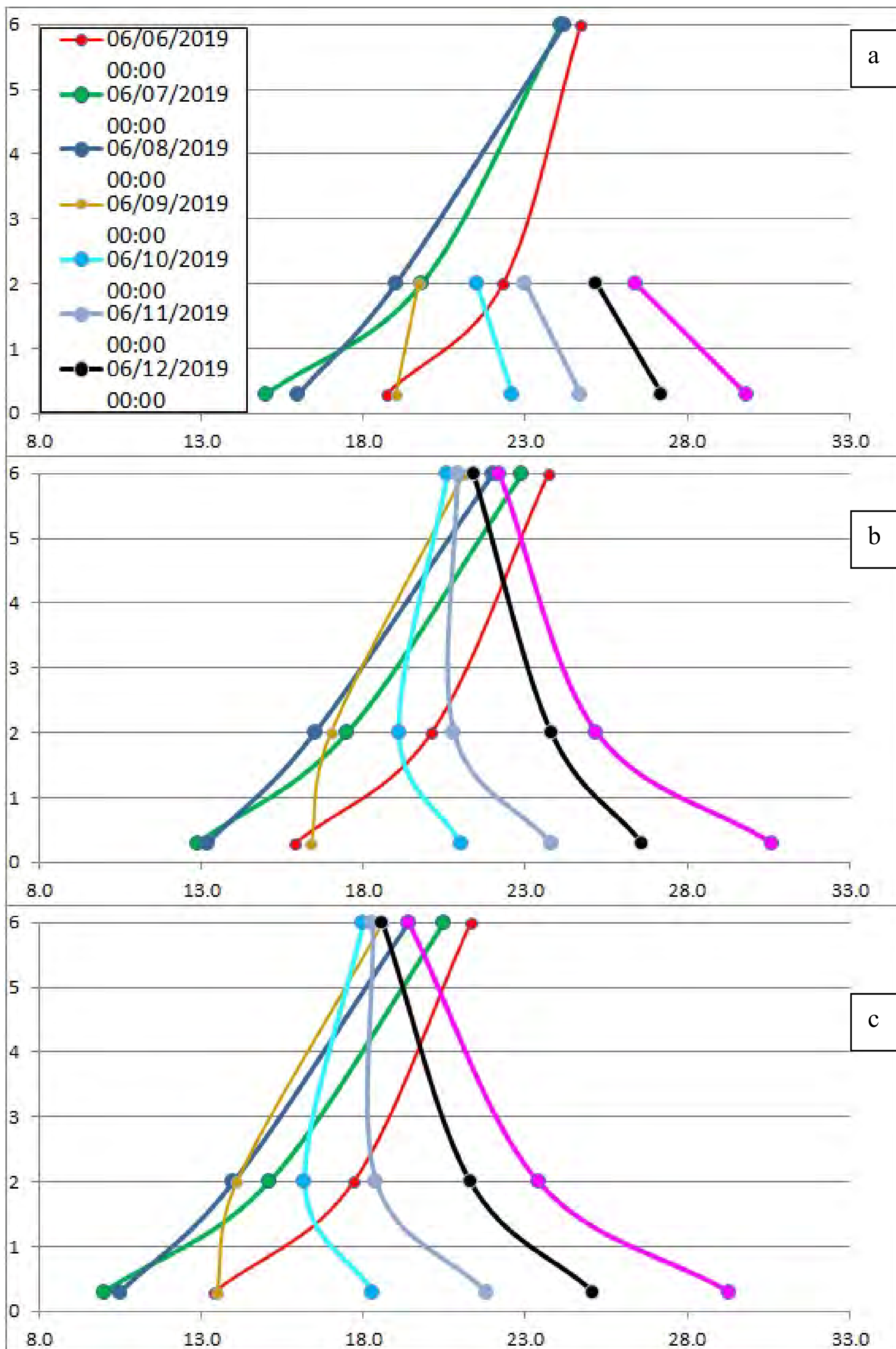

Figure 5.12: A compilation of temperature (° C) profiles (X-axis) with depth (m) (Y-axis) on corresponding days at the a) north-facing site, b) crest and c) south-facing site

July 2019 and August 2019 and was followed by the onset of temperature increase or heat build-up. Comparatively, the rock temperature at a depth of 2.0 m only started increasing between August 2019 and September 2019.

Significantly, this suggests that for approximately one month the bedrock is heating up closer to the surface (i.e. 0.3 m) while it is still dissipating heat at greater depth (i.e. 2.0 m), creating ideal circumstances for thermal stress and related fatigue. This condition is further exacerbated by daily temperature fluctuations, as illustrated in Figure 5.9, which suggest that multiple temperature inversions occur in the rock between depths of 0.3 m and 2.0 m during the seasonal oscillation.

5.4.3 Crest Site

The complete set of data from the crest site confirmed previous observations which reported that temperature fluctuations or oscillations became less pronounced with an increase in depth, as illustrated in Figure 5.12 (b). As with data from the north-facing site, temperatures measured on the crest site at a depth of 0.3 m recorded a seasonal rock temperature decrease from June 2019 until July 2019, and between July 2019 and August 2019 temperatures began to increase. Once again the data suggest that the bedrock temperatures at a depth of 2.0 m only started increasing a month after the rock at a depth of 0.3 m.

More significantly, the data obtained from a depth of 6.0 m showed that at this depth, temperatures only started increasing between October 2019 and November 2019, some two months after increases were recorded at a depth of 2.0 m and some three months after increases were recorded at a depth of 0.3 m. The observations above should be seen in the context of temperature inversions, illustrated in Figure 5.10.

With conditions proven to be suitable to induce thermal fatigue, it stands to reason that parts of the bedrock that experience more frequent temperature inversions combined with seasonal temperature oscillations will see accelerated fatigue failure compared with parts of the bedrock which experiences less frequent temperature inversions. Elaborating on this assumption, it is clear that there are far more temperature inversions depicted between the data of loggers installed at depths of 0.3 m and 2.0 m, than there are between loggers installed at depths between 2.0 m and 6.0 m.

Similar properties were previously discussed and this could arguably imply that the rock will sustain weathering as a result of thermal fatigue more readily closer to the surface than at depth.

5.4.4 South-facing Site

The data captured on the south-facing site had similar properties to those from the other sites, but with some differences. Figure 5.12 (c) shows that the rock temperatures at 0.3 m depth changed from a decreasing trend to an increasing trend between July 2019 and August 2019, while the same change only occurred between August 2019 and September 2019 at a depth of 2.0 m. As with the crest site, the rock at a depth of 6.0 m only started showing an increase in temperatures between October 2019 and November 2019, a significant delay compared with shallower depths.

The summary illustrated in Figure 5.11 again shows that in conjunction with the delayed seasonal thermal changes, multiple temperature inversions occur in the bedrock between depths of 0.3 m and 2.0 m and once more, this is not noted when comparing the results from 2.0 m with the results from 6.0 m. As before, it may again be argued that this could induce thermal fatigue at shallower depths more readily than at depth.

5.4.5 Comparison Between Sites

Figure 5.12 summarises the data ranges from the descriptive statistics which were previously highlighted. From this comparative set of graphs, it can be seen that the southern site has the lowest comparative temperatures, while the northern site has the highest, and that the crest site is seen as intermediate. Graphically it is also clear that for each respective depth where measurements were taken, the southern site had the largest temperature range (or variations), while the northern site had the smallest ranges. The crest site was once again found to be intermediate in this regard. More detailed data could enable three-dimensional thermal modelling of bedrock in future.

To refine dates on which bedrock temperatures cease heat dissipation and commence heat built-up, the data were further scrutinised. While it would have been ideal to mathematically identify a specific date for this change in each case, such a calculation is not practically sensible since

temperatures constantly vary throughout any given day. Instead, the existing data were used as a guide to determine the general period when these seasonal temperature reversals occurred. These date ranges were then used to revisit the original temperature data in more detail in an attempt to derive more accurate dates.

Attempts to estimate an exact date of the seasonal temperature reversals at a depth of 0.3 m proved futile. Figure 5.13 shows the temperatures recorded in the approximate period the change took place. However, the daily variations are such that identifying a single day when the change started on each aspect is simply not possible. At best, a range of days could be identified during which the change occurred and in this case, the date range spanned from 20 July 2019 to 29 July 2019. It could not be discerned from this data whether any of the sites (i.e. northern face, crest or southern face) changed before the remaining sites; however, one would expect rock on the northern site to show an increase first. This was not substantiated by the data.

Data for the loggers installed at a depth of 2.0 m are illustrated in Figure 5.14 and provided a better indication of seasonal change. In this case, the data showed that the north-facing site experienced the seasonal change last (10 September 2019), while the crest site (16 August 2019) and the south-facing site (18 August 2019) changed very nearly at the same time. Because the crest site has proved to be an intermediate site in virtually all other regards, one would have expected the crest site to change before the southern site; however, the margin, in this case, is so small that it could have been determined by other factors.

Last, Figure 5.15 shows the data for loggers installed at a depth of 6.0 m as recorded during the period of seasonal change. No data were available for the north-facing site in this period due to equipment failure, as previously explained. Nevertheless, data showed a more gradual change than encountered at depths of 0.3 m or 2.0 m. Though the turning point is somewhat subjective, estimation suggests that the crest site temperatures reversed from 20 October 2019, where the south-facing site reversed from 13 October 2019.

The dates derived for each of the data sets are summarised in Table 5.3. From the summarised data it can be deduced that thermal fatigue strain associated with seasonal bedrock temperature oscillations are minimal in the upper rock mass (i.e. 0.3 m) and that this part of the rock mass is more intensely influenced by heat generated from radiation at the surface.

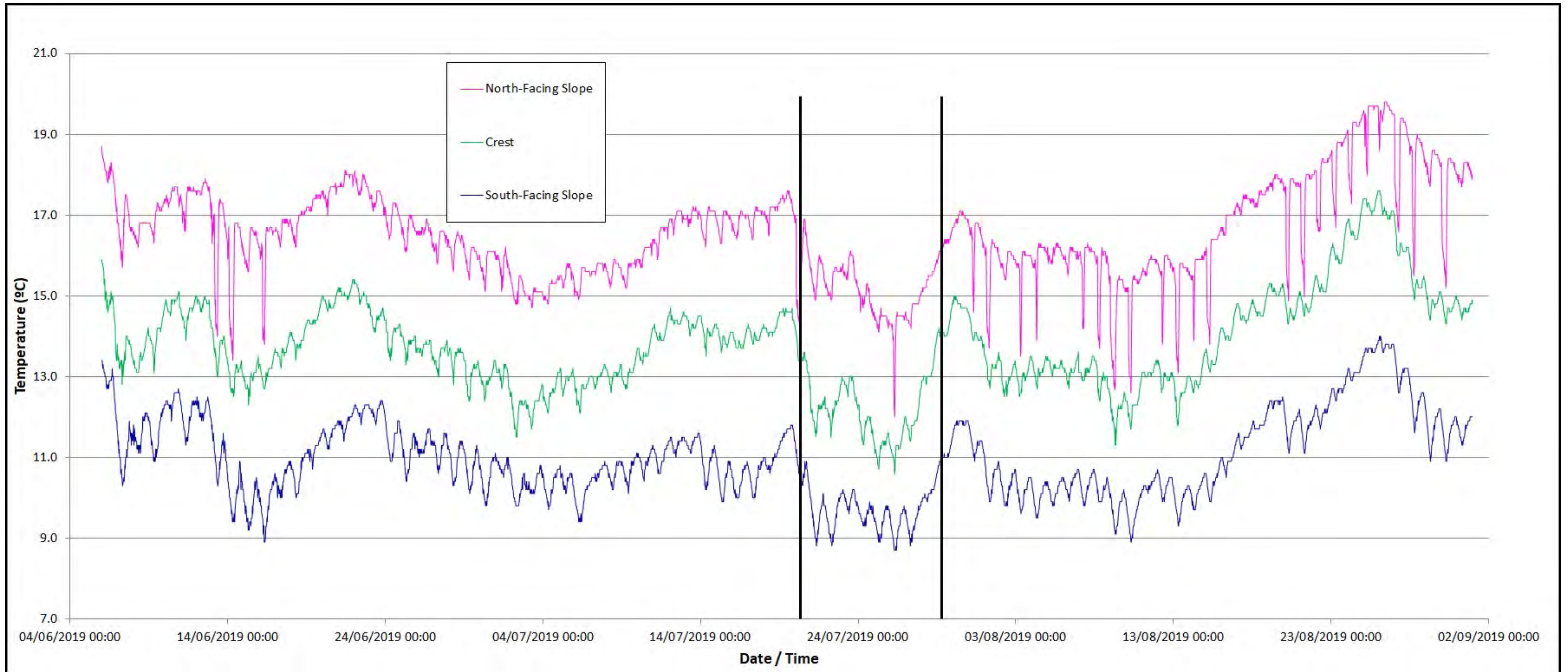

Figure 5.13: Seasonal temperature recorded at a depth of 0.3 m indicating transition period from heat dissipation to heat build-up

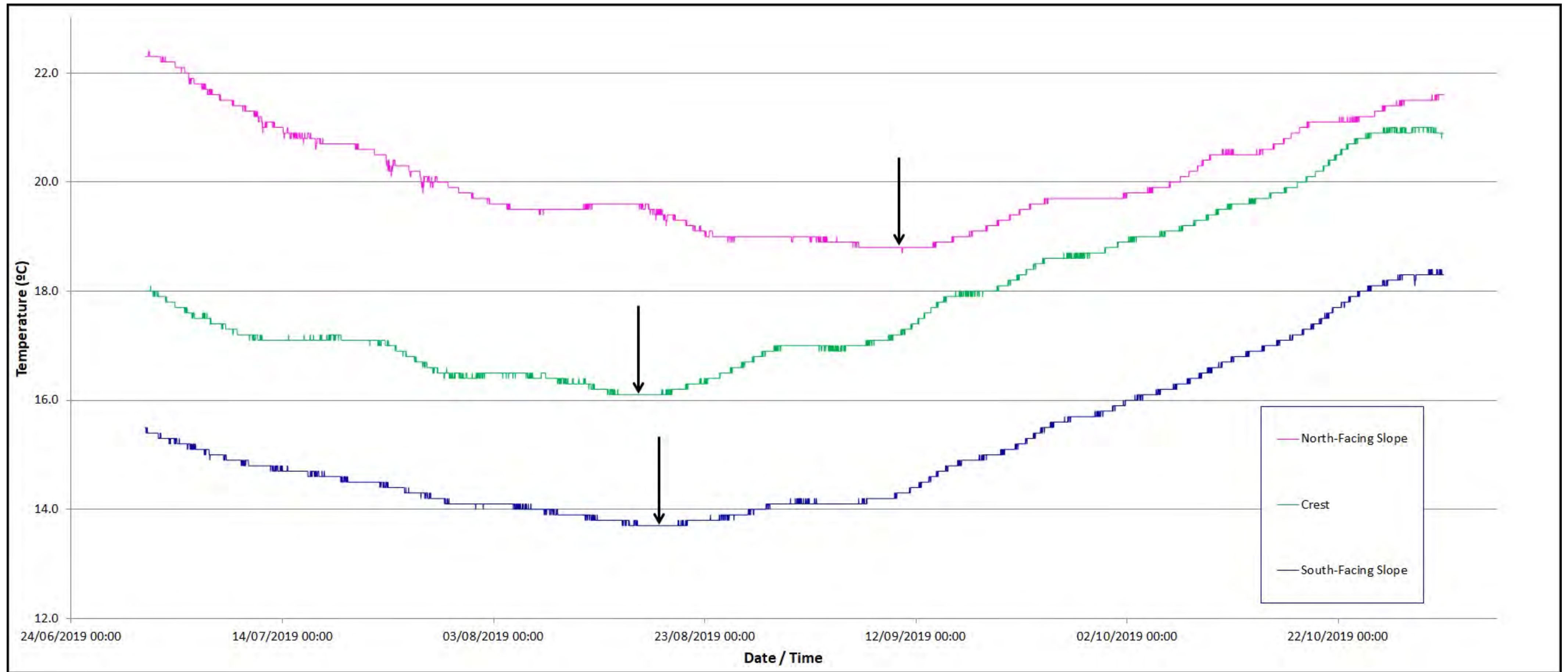

Figure 5.14: Seasonal temperature recorded at a depth of 2.0 m indicating transition from heat dissipation to heat build-up

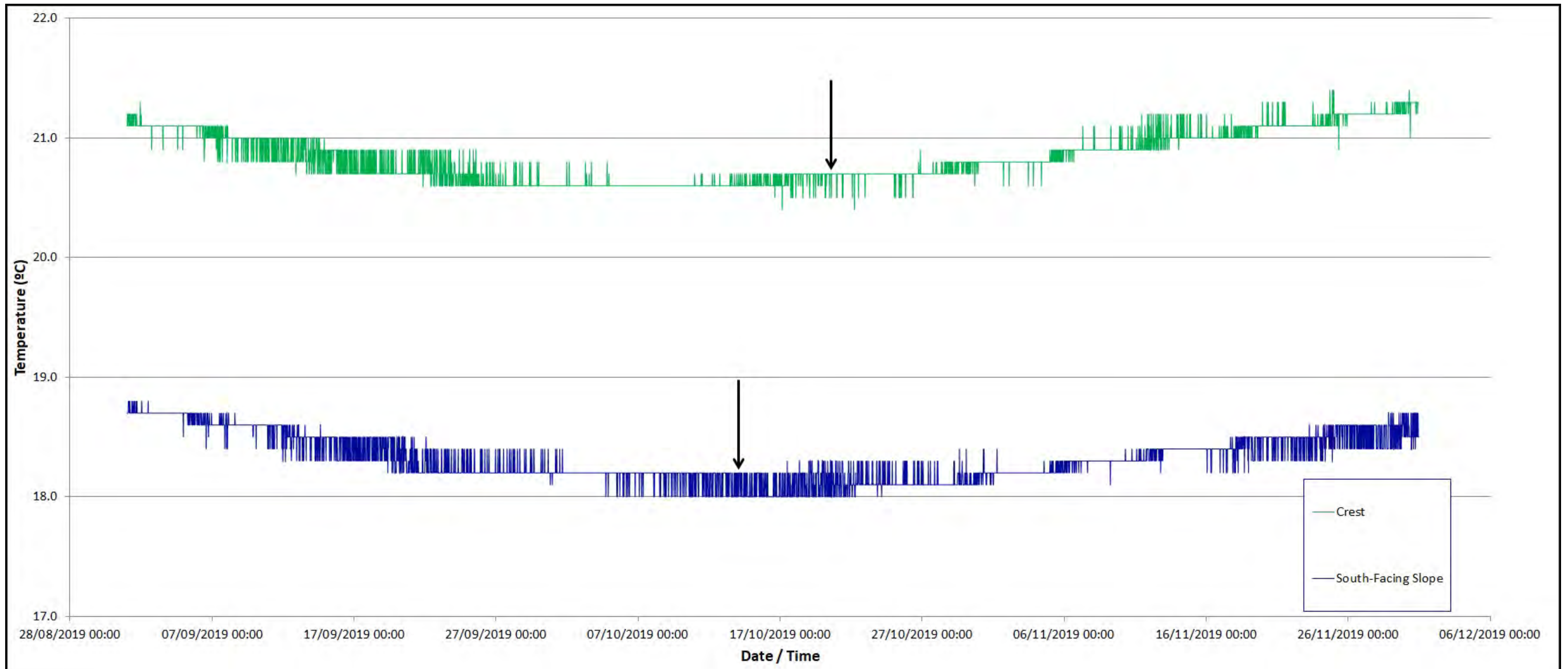

Figure 5.15: Seasonal temperature recorded at a depth of 6.0 m indicating transition from heat dissipation to heat build-up

Table 5.3: Estimated dates of seasonal temperature change

Depth	Northern Site	Crest Site	Southern Site
0.3 m	20 – 29 July		
2.0 m	10 September	16 August	18 August
6.0 m	No data	20 October	13 October

However, at a depth of 2.0 m, seasonal bedrock temperature fluctuations were significantly different (i.e. 25 days) in the onset of temperature reversal (i.e. increase), resulting in a scenario where thermal strain or thermal fatigue could originate at depth. Unfortunately incomplete data for the loggers installed at 6.0 m means that the deduction cannot be inferred for that depth.

5.5 Meteorological Processes and Rock Mass Temperatures

The final component of this research project considered the influence that meteorological conditions may have on bedrock temperatures. While such influences have been proved extensively at surface level (e.g. Eppes *et. al.*, 2016), it has not been determined experimentally whether surface meteorological processes have an influence which is transmitted to any notable depth in a rock profile. Taking into account that contraction due to cooling (as opposed to heating) results in greater tensile stresses (Hall and Thorn, 2014), any significant temperature reductions transmitted to a rock profile may theoretically induce thermal fatigue and subsequent weathering.

To achieve this type of assessment, only rock temperature data measured at the crest site at a depth of 0.3 m were considered in conjunction with weather data. Only the crest site data were considered, as this was the location where the weather station was also installed. By measuring rock contact temperatures at a depth of 0.3 m in a sealed borehole, other effects generally influencing similar research at surface level (e.g. albedo) were largely removed.

Data were scoured manually to identify any anomalous temperature variations which appeared to coincide with meteorological events (e.g. rainfall, high winds, etc.). This allowed the research to determine whether the rock sustained any marked changes in temperature due to meteorological processes that occurred at the surface, in boundary conditions. The bedrock temperature data were

plotted against air temperature, rainfall and wind (speed) to identify events of interest during the research period. The air temperature, rock temperature and rainfall data are illustrated in Figure 5.16, while Figure 5.17 shows wind speed.

5.5.1 Air Temperature and Rock Temperature

Perhaps unsurprisingly, the period of data highlighted in Figure 5.18 showed that air temperatures and rock temperatures oscillate mostly synchronously. However, data showed that there is a delayed response in heat build-up and dissipation in the rock compared with the air temperatures. The relationship observed supports comments made by Warke (2013) and McKay *et. al.* (2009), that a lag or delay between daily air and rock temperature changes were reported. Nevertheless, this period in the data had no rainfall and wind speeds did not exceed 15 km/h (Beaufort Scale Force 3 conditions).

The delays between air temperature and rock temperature changes were variable and in most instances, the delay was between six and twelve hours, depending on the severity of the change in air temperature. These changes were two-fold and occurred both when air temperatures increased and decreased. The inference is not necessarily that a change in air temperature caused a change in bedrock temperature, but instead that the air temperature responds to decreased or increased solar radiation much faster than the rock does at depth (i.e. 0.3 m).

5.5.2 Wind and Rock Mass Temperature

When discussing the effects of wind on the shallow bedrock temperatures, it should not be confused with surface rock temperatures discussed by Sumner *et. al.* (2004), who mentioned that rapid rock cooling can be caused by the removal of a heat source or wind blowing on the surface of a rock. In this case, a relationship between wind and changes in the rock temperature (at a depth of 0.3 m) would infer that temperature changes induced by the wind at the surface are significant enough to cause a thermal gradient which causes heat dissipation from depth to surface. Hall (1999) indicated that temperature changes may occur as deep as 4 mm below the surface in a rock.

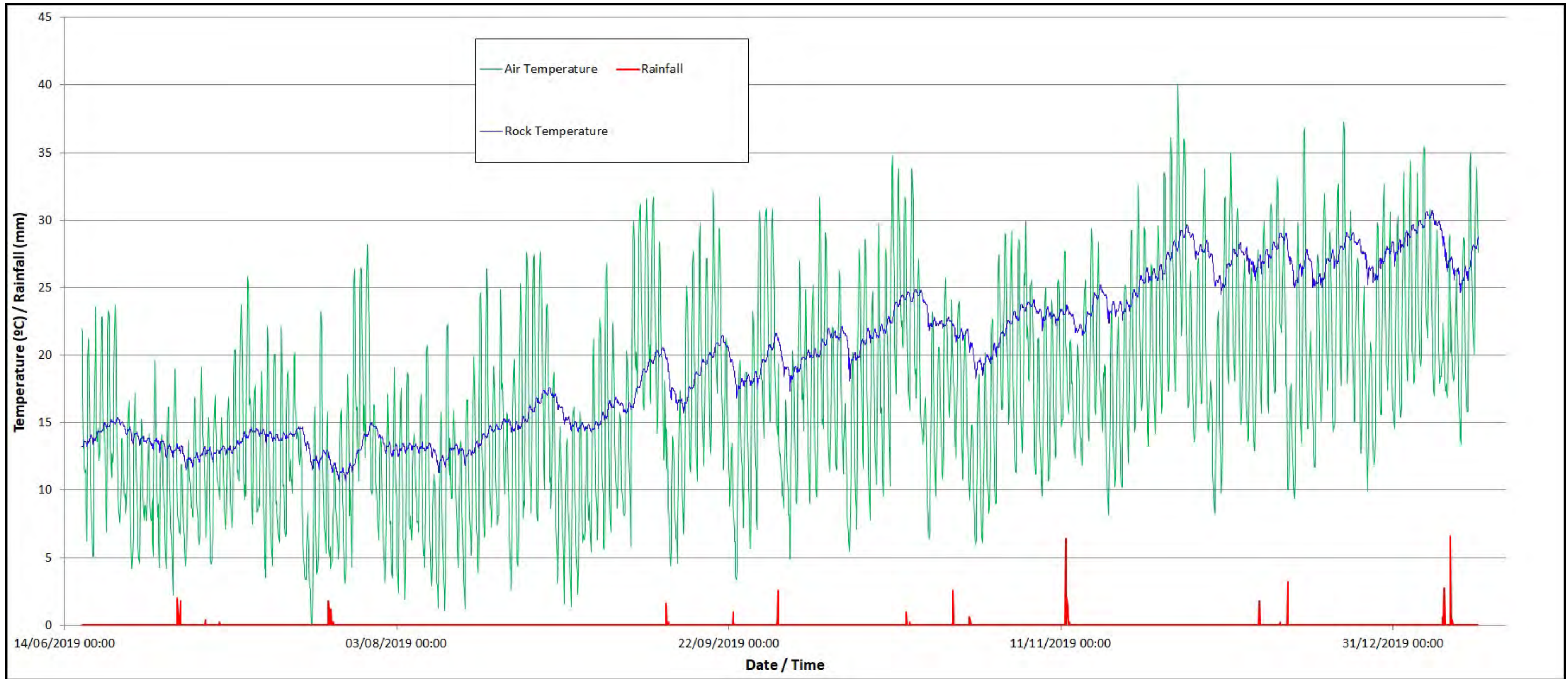

Figure 5.16: Cumulative air temperature, rainfall and rock temperature data for follow-up research period

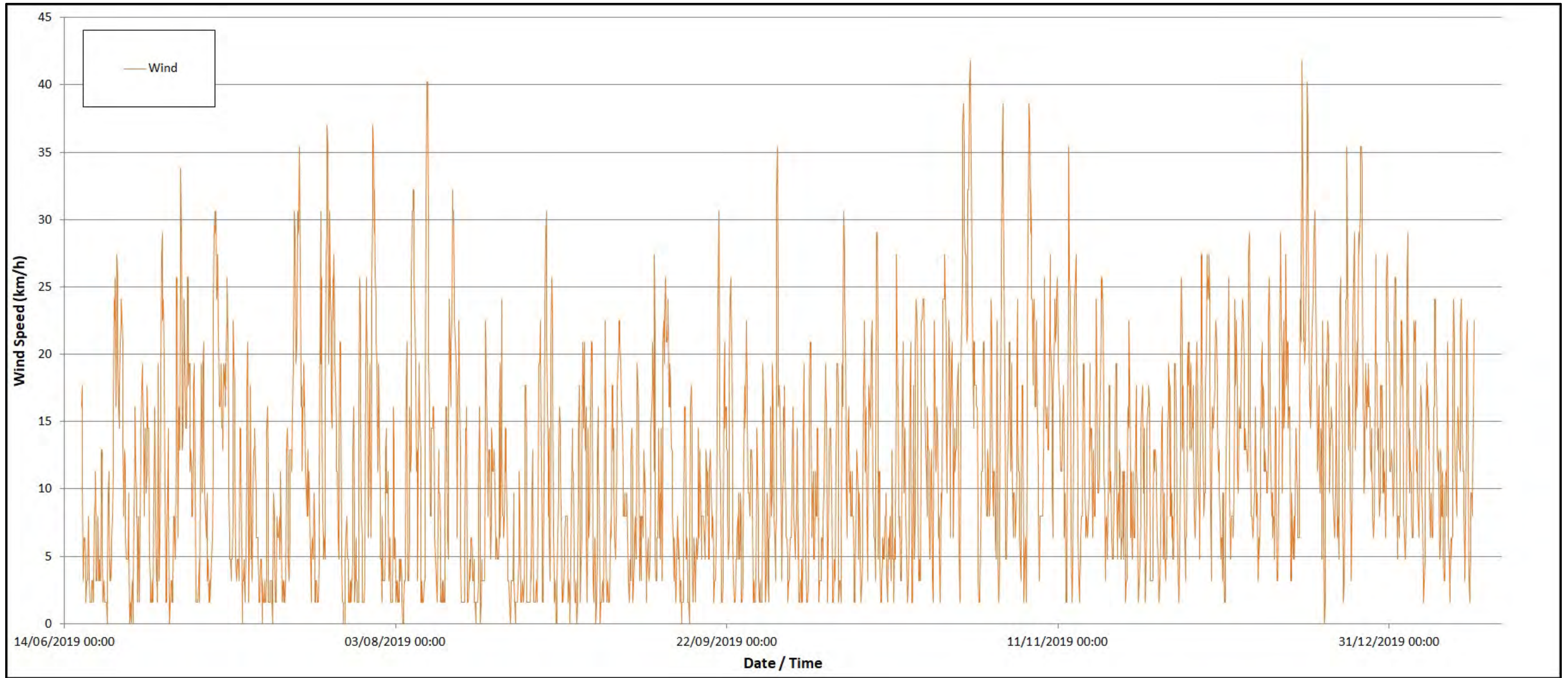

Figure 5.17: Wind speed data for follow-up research period

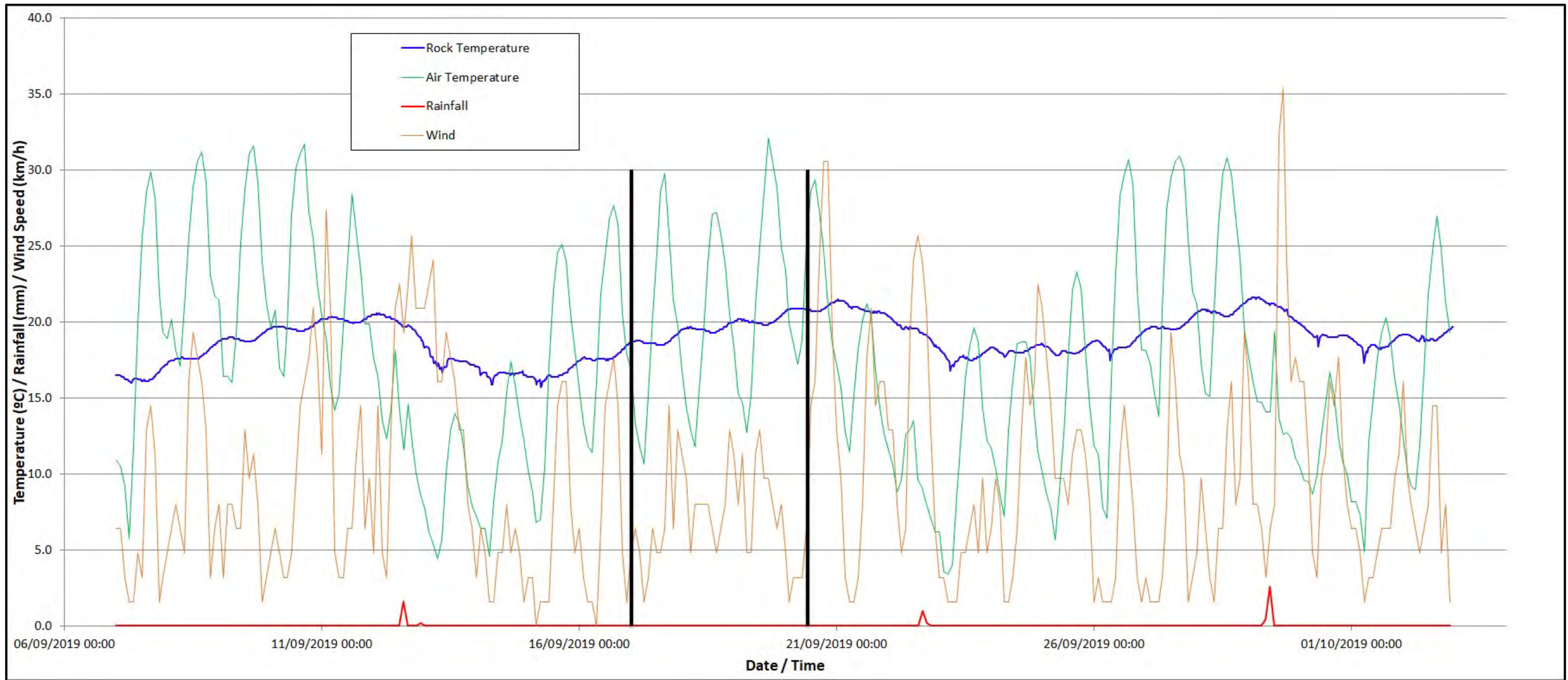

Figure 5.18: Air temperature and bedrock temperatures (0.3 m)

Data were scrutinised to identify periods when no rainfall occurred and daily air temperature oscillations were not out of the ordinary. A three-day period was identified which largely conformed to this requirement and is illustrated in Figure 5.19. In this time window, two periods of significant wind were recorded where wind speeds were between 15 km/h and 40 km/h (i.e. Beaufort Wind Scale Force 3 – 5). The data showed that even the higher end of the wind speeds recorded did not result in a notable change in rock temperature, even when the winds were sustained for six to eight hours. Critically, during peak periods of wind the air temperature was either higher than, roughly the same or slightly cooler than the rock temperature. Bedrock temperatures remained relatively constant (except for daily temperature oscillations) under these conditions, whether notable winds were recorded or not.

However, Figure 5.20 shows the significance and implications of the air temperature. At the first wind peak (point 1) the air temperature is warmer or equal to the rock temperature and no notable temperature changes occurred in the bedrock (other than daily temperature oscillations). However, the second wind peak (point 2) occurred when air temperatures were markedly lower than the rock temperatures and the data show a distinct temperature drop in the rock following the period of peak wind. This suggests that "strong" wind combined with air temperatures significantly lower than that of the rock may, in fact, influence the shallow bedrock temperature.

5.5.3 Rain, Air Temperature and Rock Mass Temperature

While it would have been ideal to assess the influence of rainfall on the rock temperatures with no other atmospheric variables, no instances could be found in the data recorded where rainfall occurred in windless conditions. As such, it was not possible to assess to what extent (if any) the cooling effect of evaporation alone (from the surface) could have. Nevertheless, the effects that were observed can be summarised and explained at the hand of Figure 5.21 and Figure 5.22.

Figure 5.21 illustrates that a significant rainfall event occurred in conjunction with relatively gentle winds. The rock temperatures showed no exceptionally sudden decreases but instead showed a gradual daily decline lagging behind air temperature decreases. This suggests that whatever cooling (associated with evaporation) occurred at the surface with the gentle wind that prevailed had little (if any) effect on the rock temperature.

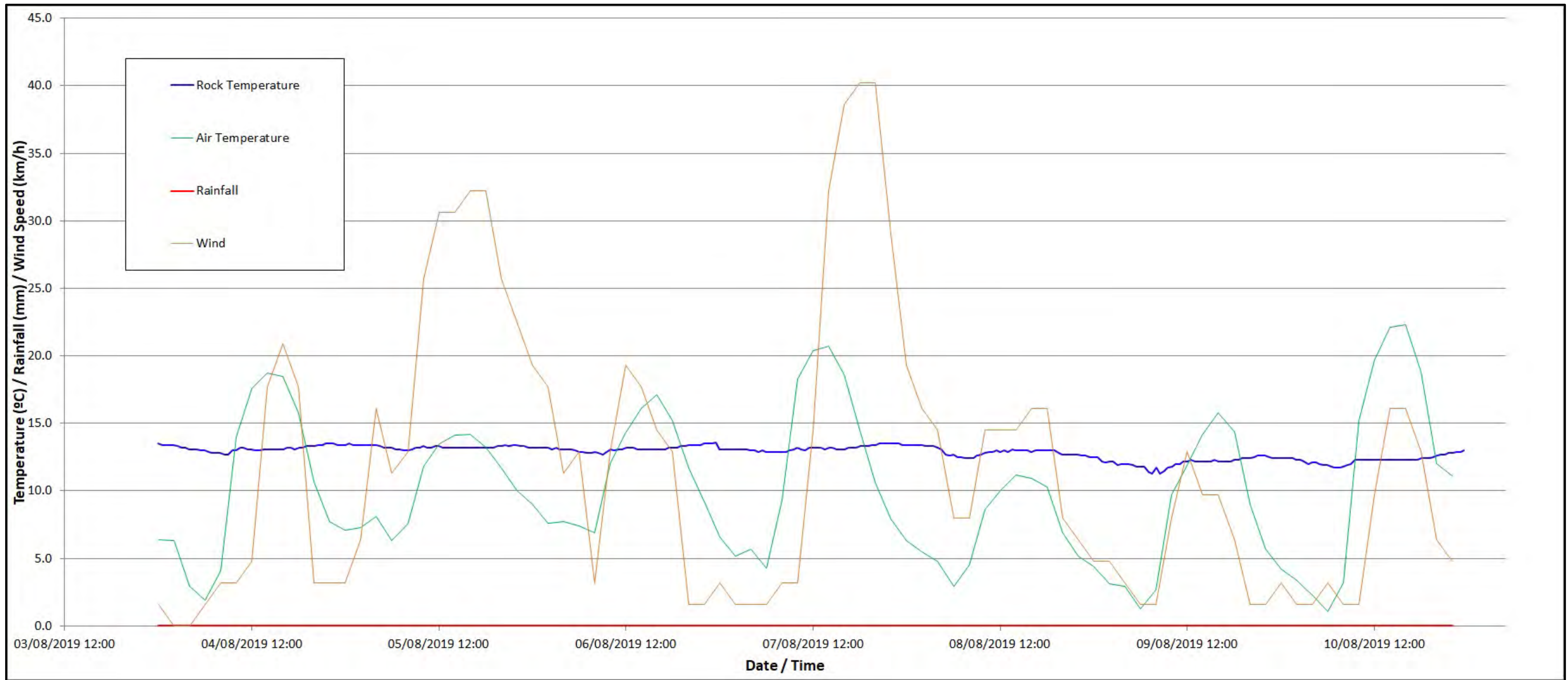

Figure 5.19: Wind speed with moderate air temperatures and bedrock temperatures

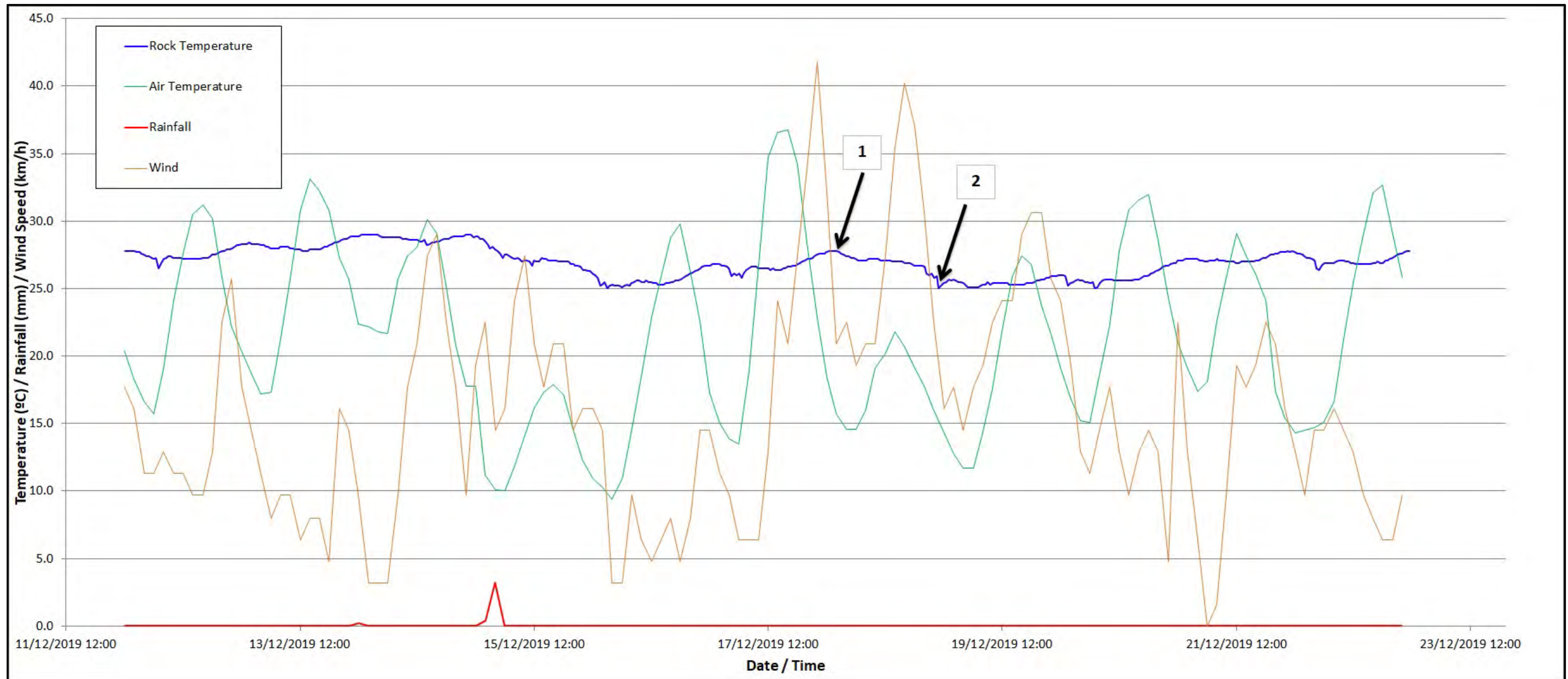

Figure 5.20: Wind speed, air temperatures and bedrock temperatures, where air temperature is equal or warmer than rock temperature (1) and air temperature is cooler than rock temperature (2)

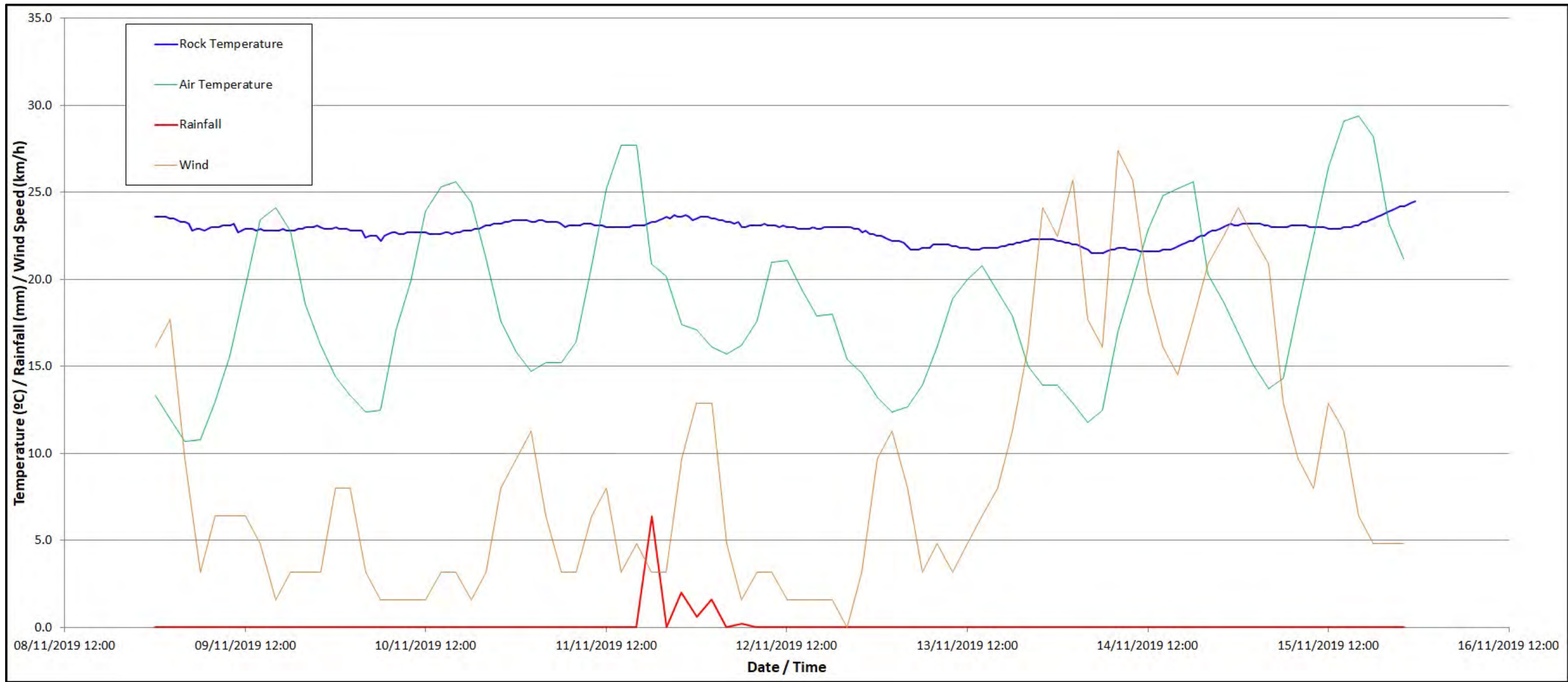

Figure 5.21: Rainfall with limited wind and bedrock temperatures

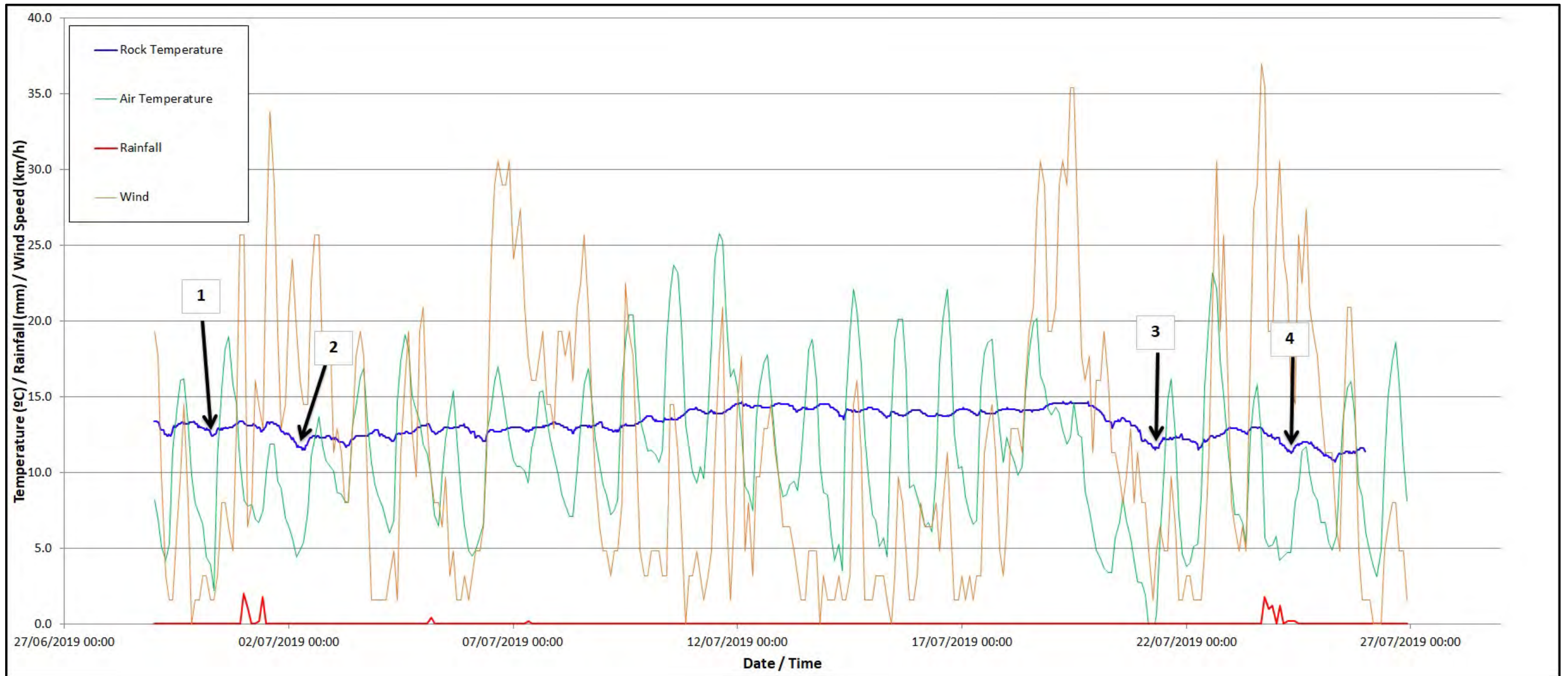

Figure 5.22: Rainfall, wind and rock mass temperatures. 1) Bedrock temperature decrease with air temperature decrease but no wind. 2) Bedrock temperature decrease with no notable decrease in air temperature. 3) Bedrock temperature decrease synchronously with air temperature decrease. 4) Bedrock temperature decrease preceded by wind and rainfall.

In contrast to this, Figure 5.22 shows some interesting temperature fluctuations. Point 1 on the figure shows a typical decrease in rock temperature which occurred shortly after a significant decrease in air temperature, but with no notable wind. Point 2 shows a notably larger drop in rock temperature, even though the air temperature did not decrease as much as was the case at point 1.

Critically, however, rainfall and significant wind occurred in the period leading up to the decrease in the rock temperature (at point 2), suggesting that the combination of the two phenomena cooled the rock near-surface sufficiently by evaporation to result in a temperature decrease at a depth of 0.3 m as heat loss/transfer occurred from depth to surface.

The second example illustrated in Figure 5.22 is similar to the first. At point 3 the rock temperature decreased to 11.6 ºC and the temperature drop occurred synchronously with little wind and an air temperature decrease to below 0 ºC. In comparison, point 4 shows an instance where the rock temperature reduced to 11.3 ºC when the air temperature minimum leading up to this point was only 4.2 ºC. However, the rock temperature reduction at point 4 also was preceded by a rainfall event and notable wind.

This, again, suggests that the combination of rainfall and significant wind can reduce the surface rock temperature (by evaporation energy losses) sufficiently to induce thermal transfer (i.e. cooling) from a depth of 0.3 m.

6. Discussion

6.1 Shallow Rock Temperatures

After salvaging some data from the trial investigation period of the research, the original intent was modified to assess seasonal rock temperatures at a shallow depth (i.e. 0.3 m) on two different aspects for a full seasonal cycle following partial equipment failure. The findings assessed whether there are notable differences in the rock temperatures in slopes facing north and south. While temperature differences related to aspect at the surface is an accepted concept, it has not been concisely proven whether such temperature differences are transmitted to sub-surface strata or bedrock.

Several conclusions were drawn despite the crest site logger seemingly yielding questionable data which was ultimately disregarded from consideration. The high variability of the said logger suggested that it possibly did not make contact with the borehole sidewall and therefore measured more rapidly alternating air temperatures, as opposed to rock surface contact temperature measurements. This in itself supports the recommendation by Hall and André (2001) that air temperatures not be used as a substitute for surface temperature measurements.

Aside from the above impediment, the remaining data from the northern and southern faces of the rock mass appear sound and delivered interesting findings. These two datasets confirmed that there are strong similarities in temperature tendencies/responses for the two aspects; however, throughout the year the south-facing site consistently had marginally lower bedrock temperatures at shallow depth, compared with the north-facing site. This suggests similar thermal properties to those reported by Lamp *et. al*. (2017) in the sense that temperature differences can be discerned based on aspect, except in this case the differences were measured in bedrock.

It therefore appears that micro-climates are indeed created due to different aspect, similar to those highlighted by in literature (e.g. Burnett *et. al.*, 2008). In addition, the consequent temperature changes (in this case) are transmitted to the sub-surface on a larger (even regional) scale, but critically, it also proves that temperature differences due to aspect may affect an underlying rock mass and not only surface temperatures. However, whereas directional heating and aspect have been related to crack propagation in surface rocks (e.g. Eppes *et. al.*, 2010; Moores *et. al.*, 2008),

the data gathered here is not sufficient to deduce whether similar cracking will be experienced by bedrock below the surface.

That being stated, it also appears that rock on the southern site showed slightly more gradual or delayed thermal responses (i.e. changes) which can theoretically be related to less severe insolation ascribed to site aspect. The temperature differential is at its lowest during the summer and at its largest in winter; however, temperature ranges are largest in spring and autumn.

It is worth noting that none of the maximum temperatures recorded at a depth of 0.3 m in the rock remotely approached the 110 ºC maximum temperature used by Griggs (1936) and were also considerably lower than maximum readings recorded by other case studies (e.g. Gómez-Heras *et. al.,* 2006) undertaken under similar circumstances, but at surface level. Therefore, it can be concluded that shallow bedrock conditions are distinct from laboratory experimental setups or research conducted at ground surface level, confirming observations made by Hall (1999) and Hall and Thorn (2014). Nevertheless, this research proves that aspect and directional heating not only affect surface temperatures (as has been proved comprehensively in existing research), but also the underlying bedrock temperatures due to varying amounts of insolation being received and heat being transmitted to underlying bedrock at the different aspects. While differences in minimum and maximum rock temperatures at various aspects are notable, they are perhaps not as extreme as sometimes expected.

The fact that temperature fluctuations follow similar heating and cooling cycle tendencies suggests that temperature differentials between different aspects are synchronous, but also have seasonal range differences. Also, the differences in temperature properties recorded on the two aspects do theoretically create suitable conditions for thermal stress fatigue as a temperature gradient prevails in the rock, but it is unlikely that such fatigue failure will be distinguishable in a single (or even multiple) human lifetime(s). Considering the difference between thermal shattering and thermal fatigue defined by Hall and Thorn (2014), it is unlikely that temperature fluctuations were severe enough to induce thermal shattering. This certainly seems to be the case in the data captured; however, the data were only captured at 30-minute intervals and therefore the possibility (however remote) exists that rapid temperature drops may have occurred, but could simply not be captured due to frequency of data recordings.

Furthermore, the fact that temperature fluctuations are more pronounced during autumn and spring, suggests that these two seasons create the best conditions to induce thermal fatigue failure, despite the absence of extreme temperatures (i.e. minima and maxima) recorded during summer and winter. While the research tendency is often to focus extreme temperatures or conditions (i.e. winter and summer or desert and arctic conditions) to assess thermal weathering mechanisms or fluctuations, the data showed the largest temperature variations occur in more moderate seasons (i.e. spring and autumn), with spring showing the largest variation in bedrock temperatures of the entire seasonal cycle. Therefore, it stands to reason that mechanisms affecting weathering based on temperature fluctuations (in this area in particular) should best be studied in spring (or autumn) and not during the peak seasons (i.e. winter or summer).

Ultimately, the trial study showed that shallow bedrock temperatures are indeed affected by aspect and directional heating, with distinctive seasonal changes.

6.2 Thermal Variations with Rock Depth

With proof presented that temperature fluctuations associated with directional heating and aspect are indeed transmitted to underlying bedrock at shallow depths, the research was expanded to determine whether the rock temperatures are also influenced at greater depths. The elaborated follow-up research therefore studied bedrock temperatures at three depths (i.e. 0.3 m, 2.0 m and 6.0 m) in three boreholes (i.e. north-facing, south-facing and flat crest). Data were recorded from mid-winter until mid-summer and findings are reported in this section.

The elaborated research proved that bedrock temperature properties are significantly variable with depth at any given position and/or aspect. Data showed that bedrock at depth would retain heat longer, resulting in the bedrock (at depth) being notably warmer at mid-winter compared with shallower parts of the rock mass (i.e. 2.0 m and 0.3 m). The opposite would apply if the seasons were reversed. The data further confirmed that shallow bedrock is more susceptible to rapid temperature oscillations than deeper bedrock, resulting in vastly different temperature regimes in the rock mass.

6.3 Thermal Fatigue

6.3.1 Concept of Thermal Fatigue

The concept of thermal stress fatigue was discussed in chapter 2 of this thesis but was perhaps best defined by Hall (1999, p48) as "*…where material is subjected to a series of thermally-induced stress events, each less than that required to cause immediate failure, that, collectively with time, cause the material to fail*". Hall (1999, p48) further stated "*The reality is that that insolation does not 'weather' but rather is, in most instances, the driving force. The actual mechanism of breakdown is thermal stress fatigue resulting from 'warming and cooling' and this could be induced by wind not just sun.*".

The data presented here, however, suggests that thermal stress fatigue may not only be caused by surface conditions (e.g. insolation and wind), but a secondary cause of thermal stress fatigue is the variable rates at which bedrock itself builds, retains or dissipates heat at various rates and depths throughout the seasonal cycle. The latter confirms observations made by Iñigo and Vicente-Tavera (2002). This supports the contention that temperature gradients can cause thermal stresses in large rock masses as temperatures (i.e. thermal gradients) in the rock do not behave linearly, as already discussed. It is worth considering that Hall (1999) also noted temperature inversions during the cooling phase, where the rock temperature at a depth of 2 cm became hotter than the surface temperature, thereby creating a stress field. This essentially mirrors the findings reported here, only on a much smaller scale and only at the surface.

Richter and Simmons (1974) noted that stress created in a rock material is caused by a mismatch of linear expansion at grain boundaries (of a rock material) as a result of differing thermal expansion, effectively linking thermal fatigue failure to physical fatigue failure. Simply stated, individual minerals or particles will expand at different rates at the same temperature, ultimately inducing stresses that result in material failure or breakdown. Critically, such failure is related only to temperature and not to a specific process affecting the temperature (e.g. solar radiation).

The simplified concept of fatigue failure was previously discussed as illustrated by Gere (2004) who used the example of breaking a paper clip or metal wire by repeatedly bending it back and forth, constantly applying and reversing a load. Gere (2004, p136) defined fatigue failure as "*the deterioration of a material under repeated cycles of stress and strain, resulting in progressive*

cracking that eventually produces fracture". In the case of the bedrock under consideration, the physical fatigue is caused by thermal fatigue, which in itself results from oscillating rock temperatures or temperature inversions.

The comparison of a bending a paper clip with fatigue failure given by Gere (2004) was further elaborated to give two examples which apply to the rock properties under consideration. First, larger loads are likely to induce material failure more quickly. This notion was supported by Hall and Thorn (2014) who stated that "*…the larger the stresses, the fewer the thermal cycles needed to cause failure*". If one considers bending a paper clip back and forth only a few millimetres, this will take notably longer to cause the paper clip to fail than when bending the paper clip at the same rate or frequency, but over numerous centimetres. This can be related to thermal fatigue in that larger temperature oscillations are likely to have a more pronounced effect than comparatively smaller temperature oscillations.

Secondly, the rate or frequency at which a paper clip is bent back and forth affects how quickly it will ultimately break. The higher the frequency at which the clip is bent the sooner the material will exceed its inherent strength, causing it to break. As such, it can be deduced that the more frequently temperature oscillations – or temperature inversions – occur in rock, the faster fatigue is likely to cause material failure.

Though the example above is grossly simplified, the findings echo the conclusions of Eppes and Keanini (2017), based on Paris' Law. As previously mentioned, temperature oscillations (i.e. amplitude) and the rate/frequency of temperature oscillations proved to be fundamental. Simply stated, higher frequency of temperature oscillations (or temperature inversions) occurring in rock will cause more rapid fatigue failure relative to lower oscillation frequency.

The two factors mentioned above, namely temperature oscillations and the rate/frequency of temperature oscillations, are considered key. Essentially it is anticipated that a greater frequency of temperature oscillations (i.e. inversions) occurring in a rock mass will likely cause more rapid fatigue failure compared with a lower oscillation frequency. Also, it is further argued that thermal fatigue failure will be exacerbated by comparatively larger temperature oscillations or fluctuations.

6.3.2 Rock Temperatures and Thermal Fatigue

The follow-up research effort proved that bedrock temperature properties are significantly variable with depth at any given position or aspect. Data showed that bedrock at depth would retain heat longer, resulting in the rock (at depth) being notably warmer at mid-winter compared with shallower parts of the rock (i.e. 2.0 m and 0.3 m). The opposite would apply if the seasons were reversed. The data further confirmed that shallow bedrock is more susceptible to rapid temperature oscillations than deeper bedrock, resulting in vastly different temperature regimes in the rock mass assessed.

It is interesting to compare these findings with those reported by Gunzburger and Merrien-Soukatchoff (2011) who proved that there are marked differences in temperature oscillations, even between depths of 10 cm and 50cm. However, despite the differences, their results followed a very similar pattern, though temperature oscillations became markedly less peaked with depth. The results obtained from depths of 0.3 m, 2.0 m and 6.0 m reported here do not merely have different frequency of oscillations, but are inherently completely different as far as seasonal thermal responses are concerned. Temperature oscillations at all three positions became less pronounced with depth and it is expected that at some depth point the rock mass temperature should equilibrate, regardless of aspect. This remains to be proved.

The findings further suggest that thermal fatigue may not necessarily be related only to surface or near-surface conditions that are influenced by insolation, meteorological processes (e.g. wind and rain) and other geomorphological processed. Results showed that thermal inversions occur in bedrock as a result of different rates of heat build-up, retention and dissipation on a seasonal basis. The heat build-up and dissipation are non-linear, echoing statements made by Viles (2013), Warke (2013) and Hall (1999). Also, thermal inversions are similar to thermal fatigue processes encountered at or near-surface (e.g. Hall, 1999; Gunzburger and Merrien-Soukatchoff, 2011), but due to less frequent and arguably smaller temperature oscillations, the effects could be less severe.

With the above taken into consideration, it can be argued that bedrock weathering by thermal fatigue closer to the surface may be far more pronounced than at depth since temperature inversions occur at a much higher frequency and with larger temperature oscillation (i.e. range) than encountered at greater depth.

With preceding sections supporting the influence of seasonal temperature fluctuations mentioned by Iñigo and Vicente-Tavera (2002), data reported here were even further scrutinised to assess whether seasonal changes may also influence thermal properties or fatigue at depth in bedrock, as opposed to surface or near-surface depths only. While previous observations were proven in concept, there is an additional consideration to assess which will also influence thermal fatigue and that is the time delay, if any, between temperature inversions or fluctuations at different depths or positions (i.e. aspects) in rock.

To illustrate the point, if a temperature inversion occurs on a north-facing slope but a similar temperature inversion occurs only at a later stage on a south-facing slope of the same rock, this will result in a thermally strained rock at some point between the two faces, as one face would be building up heat while the other would be dissipating heat. While these temperature variations may be different (i.e. smaller) in magnitude than those often recorded during surface investigations, any thermal gradient potentially induces thermal fatigue and therefore, any notable temperature differences remain significant.

In fact, the range of temperature changes measured in the bedrock at depth is much smaller than those cited in surface studies. Typical temperature changes were in the order of 0.1 ºC or 0.2 ºC between 30-minute measuring intervals, indicating much slower thermal responses or changes compared with surface experiments, where temperature changes may occur almost instantaneously due to other effects (e.g. wind or rain). To illustrate this, Figure 6.1 illustrates a data excerpt which shows the temperature changes (ΔT) which occurred over 30-minute intervals over a four month period. From the figure it is clear that measured changes are relatively small and clearly do not approach the threshold(s) suggested for thermal shock.

It can be concluded that processes occurring at a larger scale should not be disregarded or overlooked, and summarised the following observations from the research:

- Conditions causing thermal fatigue are not restricted only to the surface (or near-surface) and can occur within bedrock at depths of numerous metres.
- Thermal fatigue is not only caused by atmospheric conditions or solar radiation directly but may also be caused by the secondary effect of retarded heat build-up and dissipation in a rock on a seasonal basis.

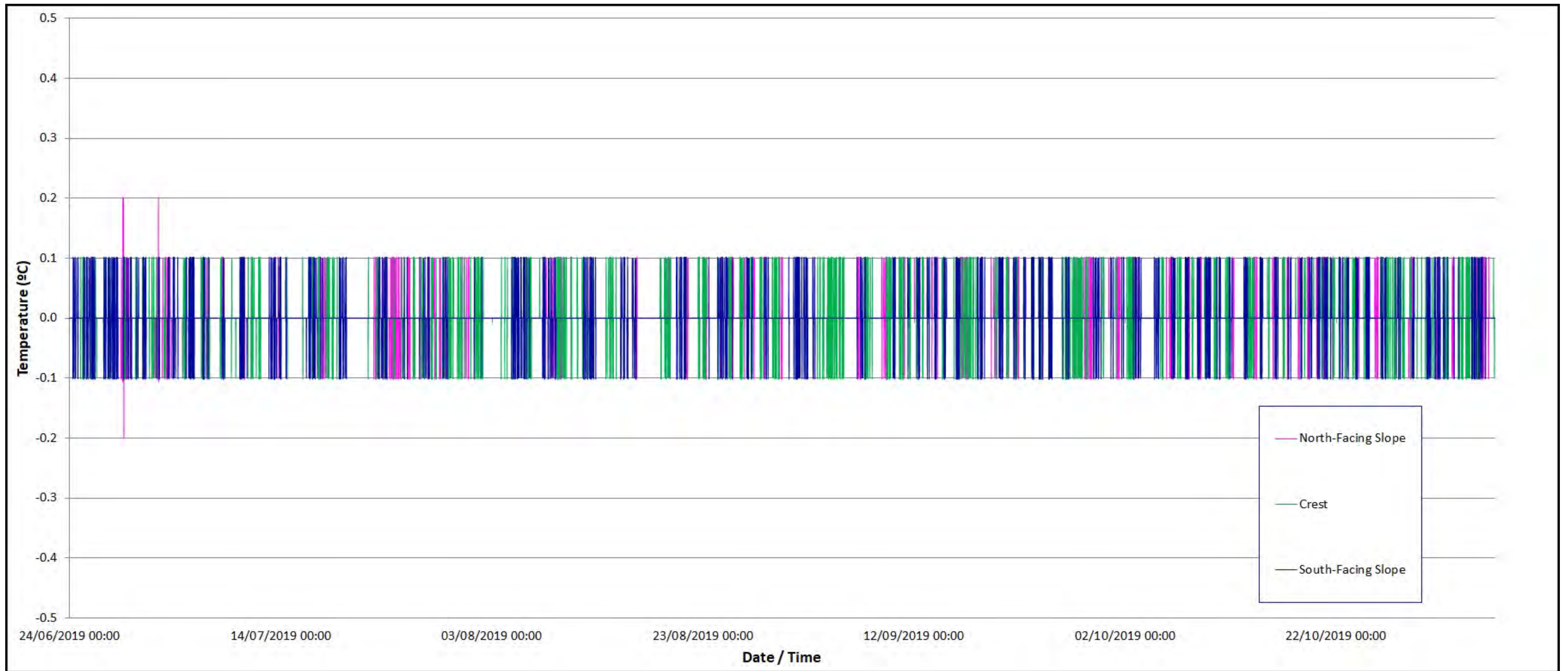

Figure 6.1: 30-minute temperature changes reported over a four month period

- A clear distinction must be made between daily temperature variations within the rock and long term (i.e. seasonal) temperature oscillations when considering thermal fatigue and associated weathering processes, particularly when assessing bedrock conditions. Subdividing data into seasonal datasets proved key as temperature ranges alone are not considered sufficient to identify peculiarities in results. The observation of similar seasonal temperature data ranges was echoed by Sumner and Nel (2006).
- It was proven that seasonal temperature oscillations occur in rock and that these variations occur at different rates as a non-linear function of depth. Simply stated the rock stopped heat dissipation and commenced heat build-up at different times/dates, depending on the depth in the profile.
- Seasonal temperature cycles variations are less pronounced at shallower depths (e.g. 0.3 m) than at greater depths (i.e. 2.0 m or 6.0 m). Near-surface temperatures (i.e. 0.3 m depth) are unsurprisingly influenced to a larger extent by surface conditions (e.g. solar radiation) than the seasonal rock temperature fluctuations.
- Assuming that thermal weathering is indeed most pronounced during cooling/contraction (Hall and Thorn, 2014), temperature differentials at any depth in the bedrock may induce mechanical weathering, assuming that the temperature differentials are sufficiently large to induce contraction of one part of the mass relative to another part of the adjacent mass. Such a mechanism would then likely be seasonal.
- Temperature inversions occur more readily at shallower depths (e.g. between 0.3 m and 2.0 m) than at greater depths (e.g. between 2.0 m and 6.0 m). This suggests that the shallow rock will arguably be subjected to thermal fatigue processes at a far more frequent rate, ultimately causing more rapid fatigue failure compared with the rock at depth.

6.3.3 Site-specific Thermal Fatigue

Despite the fact that data suggest suitable conditions (i.e. temperature oscillations) for thermal fatigue, no direct evidence of fatigue failure or fatigue cracking were observed. This is not to say that such evidence is absent; however, as highlighted earlier in this thesis the bedrock exhibited cracking, jointing and orientated plains of weakness which could be attributed to the geological stress history, typical tillite disintegration or depositional

desiccation cracks/features. It is not possible to prove that any of the existing cracks or discontinuities in the bedrock originated specifically from thermal fatigue instead of any of the other geological factors. As such, inferences to thermal fatigue cracking will be of a theoretical nature only, despite the fact that condition were proven to be suitable to induce such failure.

6.4 Meteorological Processes and Rock Mass Temperatures

Considering the findings of Eppes and Keanini (2017), any surface or near-surface changes encountered due to climatic (or meteorological) conditions may result in mechanical weathering due to sub-critical cracking. It is therefore important to determine whether such potential changes may (or do) occur. Results showed that apart from seasonal temperature oscillations, daily rock temperature fluctuations correspond with air temperatures, though oscillations are not as pronounced and rock temperature fluctuation lag behind air temperatures by six to twelve hours at a shallow depth of 0.3 m.

Perhaps the most significant conclusions reached were related to the relationship between wind and bedrock temperatures. Results suggest that wind alone has little effect on the temperature of rock sheltered from boundary conditions when the air temperature is higher than or equal to that of the rock. However, if the air temperature is significantly lower than the rock and the wind speed is notable, the rock temperature is affected (i.e. decreased). It was not possible to determine whether certain thresholds apply to wind speeds that may influence the rock temperatures.

Results further suggest that rainfall combined with the wind also have effects on the rock temperature. Such conditions would presumably conform to the description of a storm, which Eppes *et. al.* (2016) listed as the most significant event during which most rock cracking occurs. It is anticipated that the effects of evaporation cause the rock at the surface to cool, resulting in heat transfer from deeper in the bedrock to the surface, thereby lowering the rock temperature (i.e. inducing a thermal gradient). The added effect of wind moving over a wet surface further enhances evaporation and lowers the surface temperature more rapidly.

All things considered then, it can be concluded that certain meteorological processes can indeed influence bedrock temperatures at relatively shallow depths (i.e. 0.3 m). However, these effects are less pronounced than those previously proven to occur at surface level or immediately below surface level (e.g. Eppes *et. al.*, 2016; Hall, 1999). It was also concluded that while individual meteorological processes can have an influence, the effects are much more pronounced when such processes interact.

7 Conclusions and Findings

The research reported in this thesis was aimed at assessing the effects of thermal variations related to aspect and to determine whether any such effects are transmitted to notable depth in bedrock. In addition, it was sought to determine whether the prevailing thermal properties in the bedrock could potentially result in conditions suitable to induce thermal fatigue or thermal shattering. Following this, it was investigated whether the effects of meteorological conditions or phenomena which occur at surface or in boundary conditions can be transmitted to an underlying rock mass. Findings and conclusions can be abbreviated as follows:

7.1 Directional Heating and Aspect

While it is an accepted concept that aspect or directional heating results in temperature and other physical differences that may influence weathering or slope processes (e.g. Burnett *et. al.*, 2008; Jenkins and Smith, 1990), and cracking in rocks (e.g. Eppes *et. al.*, 2010), the research presented here proved that such temperature differences also manifest at shallow depths (i.e. 0.3 m) in bedrock due to aspect or directional heating. Temperature differences extended to depths of at least 2.0 m and even 6.0 m.

The temperature differences were not only measurable, but data showed that a southern-facing rock (slope) has less pronounced temperature fluctuation and arguably also reacts in a slightly retarded or delayed fashion compared with a northern-facing rock (slope), which recorded more peaked temperature fluctuations. That being stated, temperature differentials were not necessarily as extreme as sometimes expected and were certainly less obvious than measured at the ground surface.

7.2 Rock Mass Temperature Fluctuations with Depth

With the concept of bedrock temperature differentials related to aspect and directional heating being established, it was further concluded that non-linear rock temperature

fluctuations occur as a function of depth, confirming the comments made by Viles (2013), Warke (2013) and Hall (1999). Findings showed that the assumption that temperatures decrease exponentially with depth (Gómez-Heras *et. al.*, 2006) do not apply to bedrock, as seasonal temperature cycles are also at play in the bedrock. The same authors stated that long term fluctuations penetrate deeper into a rock, but experience slower rates of change. This also rings true for bedrock, as was proved during current research. The observation made by Iñigo and Vicente-Tavera (2002) is of importance, as they noted that in winter, a stone would lose energy while absorbing energy in summer. Considering this from a different perspective, temperatures would be high and decreasing in winter, while being comparatively low and building heat in summer. This tendency was noted in the bedrock assessed, and the effect of seasonal delay became more apparent with depth.

Data showed that temperature fluctuations are more frequent closer to the surface, which seems logical, and that thermal responses in the bedrock become slower and less peaked with depth. This largely confirms the observations reported by Gunzburger and Merrien-Soukatchoff (2011) which showed that even between depths of 10 cm and 50 cm below the surface there is a notable change in the peakedness of temperature oscillations. In addition, bedrock temperatures at a depth of 6.0 m appeared to follow a retarded seasonal cycle as it accumulated and dissipated heat at a much slower rate, whereas the shallow bedrock (i.e. 0.3 m) saw more rapid responses to seasonal changes, but data were not captured at close enough intervals to compile or sensibly model thermal gradients, as recommended by Hall and André (2001). Nevertheless, this generates different thermal regimes in the bedrock as a function of depth. The findings do show, however, that temperature differences with depth are perhaps not as irrelevant or insignificant as sometimes anticipated and that temperature difference may extend well below what was referred to by Jenkins and Smith (1990) as "*any great depth*".

7.3 Temperature Inversions and Thermal Fatigue

The research presented here further sustains the concept of thermal fatigue, supporting arguments from researchers such as Hall (1999), as well as Hall and Thorn (2014). Perhaps the most significant finding made in this research was that the prevailing thermal regimes caused by varying (seasonal) rates of heat build-up and dissipation at various depths create

suitable conditions for weathering by thermal fatigue. Hence, thermal fatigue may not be caused by atmospheric conditions or solar radiation at the surface alone, as is sometimes assumed (e.g. Hall, 1999). The data proved that temperature inversions occur in bedrock and that the number of temperature inversions that occur generally decreases with depth due to slower thermal responses in the rock mass. Also, heat build-up and/or dissipation at various depths in bedrock do not commence or cease at the same time due to varying rates of thermal response.

From the data it was concluded that temperature inversions occur much more readily at shallow depths, thereby creating a suitable condition for thermal fatigue weathering. It is also anticipated that the severity of thermal fatigue will be dictated by the frequency and comparative temperature range of temperature inversions and oscillations experienced. This supports the notion put forward by Hall and Thorn (2014) that larger temperature oscillations are likely to induce thermal fatigue failure sooner. In addition, a second (but likely less prominent) thermal regime change will also occur laterally in a bedrock mass due to the temperature differential associated with aspect. Data accumulated during this research is not considered sufficient to comprehensively assess such conditions in great detail, however.

7.4 Effects of Meteorological Processes on Bedrock

From preliminary findings, it was concluded that the effects of meteorological processes upon bedrock are much less notable compared with changes that occur at surface level. Rock temperature changes recorded at a depth of 0.3 m were rarely related to meteorological events and it, therefore, appears that the influence of such events is less notable when compared with the observations made closer to the surface (e.g. McAllister *et. al.*, 2017; Hall, 1999). Near-surface (i.e. 0.3 m) bedrock temperatures were found to lag between six and twelve hours behind daily air temperature changes.

It was further found that bedrock temperature is only affected by wind if the wind temperature is significantly lower than that of the rock. The most prominent meteorological influence on bedrock temperature was found to be the combination of wind and rainfall, which appears to result in a temperature decrease in the shallow bedrock, conforming to observations related to cracking of rock at the surface described by Eppes *et. al.* (2016), as

well as Eppes and Keanini (2017). It is anticipated that the effect of wind over a wet surface enhances evaporation and consequently lowers the material temperature. This change in temperature is transmitted thermally to the underlying bedrock.

7.5 Practical Conclusions Implications of Research Findings

Several practical conclusions were also made based on the research:

- The data recorded during this research proved that real-world temperature ranges measured *in situ* are far more moderate than some experimental test setups used or assumed in simulated environments. This affirms the comments by Hall (1999) and Hall *et. al.* (2012) that comparing or scaling experimental setups to landscape or real-world conditions is challenging and presents a strong supporting argument for conducting research *in situ* and at a suitable scale (Viles, 2013).
- Temperature fluctuations or variations were proved to be most pronounced in autumn and spring and not in summer or winter, as is often assumed. While maxima and minima occurred in summer and winter, respectively, the findings suggest that these might not be the best seasons to assess temperature fluctuations experimentally. This echoes comments by McAllister *et. al.* (2017) that temperature extremes or diurnal temperature fluctuations often form the emphasis of research and that this may perhaps not be entirely justified.
- Cognisance must be taken of seasonal drift and inconsistent (i.e. non-linear) thermal responses in bedrock.
- By coincidence, recommendations made by Hall and André (2001) that contact temperatures should be used and not air temperatures were found to be justified during the early stages of the research.

7.6 Final Conclusion

The research presented here proved that the thermal regime of a rock profile is perhaps not as simple or uniform as generally anticipated and that further work in this regard is justified. Most importantly, the research approach adopted here presented strong evidence that surface

temperature differences due to aspect and directional heating also prevail in shallow bedrock and that seasonal cycles and temperature fluctuations can be discerned at different aspects and depths. It was ultimately concluded that shallow parts of the rock mass are affected more notably by short-term temperature fluctuations (e.g. daily temperature fluctuations, meteorological conditions, etc.), whereas deeper parts of the rock mass are characterised by retarded seasonal temperature oscillations which take place over longer periods and are much slower to respond to thermal change.

Moreover, the research showed that temperature differentials occur with depth (and laterally) in a bedrock profile and that heat build-up or dissipation does not occur linearly, resulting in pronounced temperature inversions and consequently, thermal strain. The commencement and termination of heat build-up and dissipation also do not coincide chronologically. All of these contributing properties create suitable conditions for thermal fatigue and consequent weathering. The research led to a number of findings, which can be summarised as follows:

- Thermal regimes inducing thermal fatigue are not restricted to the surface (or near-surface) only, but can occur within bedrock at depths of numerous metres.
- Thermal fatigue may be caused by the secondary effect of retarded heat build-up and dissipation on a seasonal basis, and may not necessarily result solely from atmospheric conditions or solar radiation.
- Clear distinction must be made between diurnal temperature variations and long term (i.e. seasonal) temperature oscillations when considering thermal fatigue and associated weathering processes in bedrock.
- Thermal properties in bedrock are not linear or uniform and it was proven that heat build-up and heat dissipation commence at different times, depending on lateral and vertical distribution.
- Temperature oscillations are not of constant amplitude and consequently modelling potential fatigue cracking (e.g. using Paris' Law) for such a scenario would necessitate data correction or modification.
- Temperature inversions occur more readily and frequently at shallower depths than at greater depths. The implication is that shallow bedrock may arguably be subjected to thermal fatigue processes at a far more frequent rate than deeper bedrock, ultimately resulting in more rapid fatigue failure closer to the surface than at depth.

- It was shown that thermal fatigue cracking may theoretically occur in bedrock at depth where suitable thermal changes occur. However, it was not possible to prove that cracking in bedrock on this site resulted exclusively from fatigue failure as other geological controls were also at play.
- Temperature oscillations in bedrock measured much smaller peaks (i.e. 0.1 °C – 0.2 °C) compared with similar observations reported in literature for work undertaken at surface.

8 Recommendations and Further Work

8.1 Equipment Usage and Experimental Setup

The equipment used for this research was specifically developed to exploit available geotechnical boreholes. Unique deployment systems (i.e. logger strings) were constructed using PVC conduits or pipes to deploy temperature loggers with external thermal probes to a specific depth. Critically, the system was temporary and could be retrieved and dismantled upon completion of the site work, which was a condition of the site-use.

The use of boreholes drilled to significant depths for geomorphological research purposes has proved to be very beneficial and it is recommended that a similar approach be considered in future. There are practical limitations to using such a setup, however, and certain modifications or additions would be beneficial (refer to section 8.2).

8.2 Further Work and Experimental Setup Modifications

As the work presented here presented a proof of concept, it would be beneficial to build on the concept and expand the scope of research further. By obtaining more detailed data, a comprehensive thermal regime can be modelled for a rock profile or rock body in three dimensions. However, significantly more detailed data would be required than presented in this thesis. It is anticipated that further work should attempt to obtain data as follows:

- As temperature inversions and oscillations were more abundant at shallower depths, it would be beneficial to obtain data at a higher density (i.e. smaller spacing/intervals) at shallower depths and that the data gathering points should be spaced further apart as depth increases. An attempt must be made to determine at which depth temperature inversions are expected to occur most frequently and assess whether a link can be established between this depth and the depth of the most pronounced weathering in the rock profile.
- Multiple points should be used for data acquisition, as opposed to only three points in each borehole used in this research. The boreholes used for data capture should preferably be spaced equally far apart and these points should cover all possible directional aspects.

- The maximum depth at which data should be recorded is debatable. However, from practical observations and literature, it is considered that a depth of 20 m may be sensible. An attempt should be made to determine whether the entire rock mass's temperature remains constant at this depth, as assumed by Messenzehl *et. al.* (2018). It should also be attempted to determine at what depth (if any) bedrock temperatures on all aspects equilibrate.

Assuming similar research is to be undertaken or repeated, a number of practical modifications can be considered. These include:

- The addition of a surface temperature measurement point to supplement sub-surface data. This was perhaps the biggest short-coming of the research, as far as data accumulation and analyses are concerned.
- If available, a site with a similar gradient on both sides of the ridge would be preferred, as well as the use of borehole shafts drilled perpendicularly to the surface. Using such a setup would allow a more directly comparable set of results.
- Borehole shafts should be pumped dry after drilling in order to remove all remaining drilling lubricants or water at the base of the borehole. Alternatively, the shaft can be air flushed from the base. Even if humidity or moisture measurements are not to be made, the effect of condensation in a borehole with water/moisture at its base adversely affects equipment. The use of a desiccants installed with the equipment may also be considered, but care should be taken to select products which are environmentally sound and will not results in contamination or adverse effects.
- It would be ideal to use a site where bedrock has not been influenced by geological or tectonic deformation. A strongly (topographically) orientated, fine-grained batholithic structure would present an ideal site, provided it is free of abundant exfoliation joints or cracks in the vertical profile.
- Similar research would certainly benefit from using long term data, as opposed to the relatively short periods of data accumulated in this study.

Throughout this thesis emphasis was placed on the recommendation by Hall and André (2001) that surface temperature measurements should be used, as opposed to surrogate air temperature measurements. The data captured in this research presented an ideal opportunity to support this

observation when the logger installed at 0.3 m on the crest site during the initial research did not make contact with the borehole sidewall and therefore measured air temperatures as opposed to rock (i.e. contact) temperatures.

During the research it was found that while the loggers on the northern and southern sites measured contact temperatures, the probe pin on the crest site did not make contact with the borehole sidewall. Figure 8.1 illustrates the marked difference in data recorded, with both the northern and southern sites recording moderate or slower temperature changes, compared with the much more erratic readings at the crest site. Not only was the variation at the crest site much larger, but the data range captured was also notably broader than that of the remaining sites. This observation was confirmed in the follow-up research, where the crest data peaks/oscillations were much more similar to the northern and southern sites.

In addition to this, it is probable that the air temperatures that were measured at the crest site were higher than that of the actual rock mass, because even though this borehole shafts was sealed, a significant portion (roughly 30 cm) of the standpipe protruded above the surface, meaning that the air mass inside the upper borehole shaft was heated. That aside, general convection in the borehole shaft would also influence the air temperatures.

This example gives fairly strong support to the recommendation of Hall and André (2001) not to use air temperature measurements, as they are not, in fact, representative of the rock or rock mass temperature.

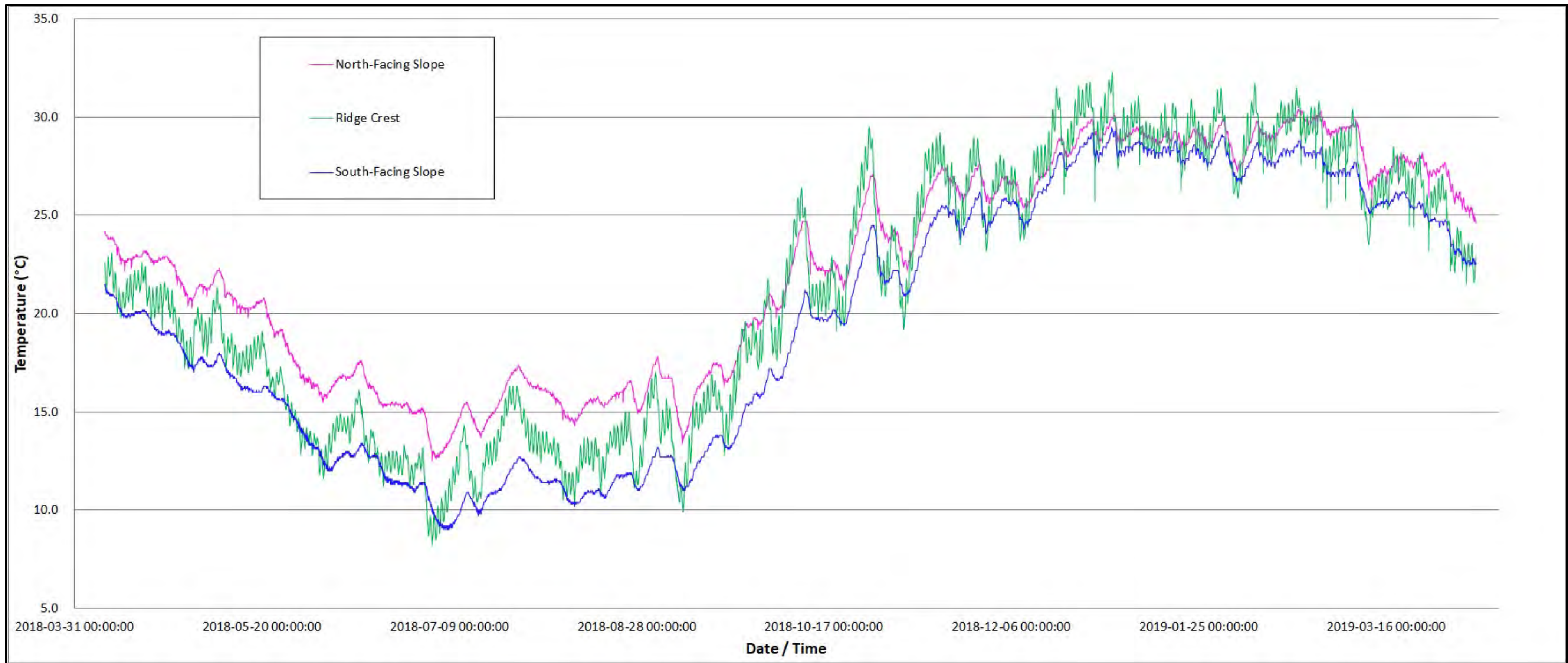

Figure 8.1: Comparison between air temperatures and rock contact temperatures

9. Project Evaluation

This project achieved its goals and intended aims with reasonable success. While the approach used is unique and provided additional insight to our understanding of thermal properties in the upper metres of a rock profile, certain additions to the experimental setup (e.g. surface temperature monitoring) would have been greatly beneficial. Nevertheless, the research has proved, in concept, that bedrock thermal regimes at depth are not as simple as is often assumed. There is significant scope to repeat similar research in different settings with modified experimental setups and additional measuring points.

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