

**Weathering potential of wetting and drying of sandstone and basalt:
a laboratory isolation study**

By

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Abstract

The cyclic wetting and drying of a rock is considered to be one of a number of physical weathering processes that have an effect on the weathering of rock. While the presence of moisture is known to be of critical importance for the activation and enhancement of a number of other known weathering processes, such as cryogenic weathering, salt weathering and slaking it is possible that the mere cyclic application and removal of moisture over time may also have an effect on the physical structure of a rock. The precise nature of the process is not well understood, however.

This document begins by investigating the studies that have previously been undertaken to determine how the wetting and drying weathering process is defined and to ascertain the current state of knowledge regarding this process. After an establishment of background context, a physical experiment is carried out on Clarens Formation sandstone and Marion Island basalt to note the relationship between cyclic wetting and drying and the changing physical properties of the rocks. The rocks were subjected to 105 wetting and drying cycles over a period of 21 weeks. At the beginning of the experiment, physical rock properties were measured by way of the method laid out by Cooke (1979) and again at the end of the experiment. Since the experiment was carried out under static environmental conditions, the

comparison of physical rock properties gives a good indication of how the rocks have altered their structure over the experimental time period.

The results obtained in this experiment show that different rock types will change in different ways when exposed to a common weathering process. The basalt samples experienced no mass loss at, while the sandstones did. The sandstones, which are rocks that are of common lithology and of very similar physical and chemical structure reacted to the wetting and drying weathering process in ways that could not be predicted without experimentation. The data does show a clear causal link between the application of external stimuli and rock property change, however.

Changes in physical rock properties are not always straightforward and linear, but evolve dynamically over time, often yielding results that appear to oppose those intuitively predicted. A number of questions are asked regarding the philosophical approach that is taken to process isolation studies, with emphasis given to the careful consideration of the place that such studies have in the realm of process geomorphology. While process isolation studies may give an excellent indication of what a particular weathering process may be capable of under certain conditions and on certain rock types, they should not be regarded as indicative of what is occurring in the field. Additionally, it has become clear that it is not possible to predict how a specific rock type may respond to a specific weathering process without physical experimentation since the number of variables present in a typical weathering system are simply too vast to easily categorise.

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Chapter 1: Introduction

1.1. Weathering in geomorphic context

It is accepted knowledge that rocks are affected by the external environment in a process known as 'weathering' (Bland and Rolls, 1998, p. ix). Rocks that are in a state of disequilibrium will attempt to alter themselves such that they attain a more stable state. After studying this phenomenon, it has been determined that the alteration of rock structure is caused by a number of different system components that scientists have termed 'processes'. The processes that are responsible for this tendency towards stability are not always well understood, however. The science that is tasked with the study of landforms and the weathering processes that shape them is appropriated termed process geomorphology. Since its inception in the mid- 20th century (Huggett, 2003), geomorphologists have categorised a large number of so-called 'weathering processes' in an attempt to better understand the link between the physical environment and the breakdown of rock. These processes are separated into two overarching categories, physical and chemical. Physical weathering processes are processes that contribute to the physical alteration of a rock's structure without causing any chemical change. If a rock could hypothetically be weathered only by physical weathering processes, its chemical structure would remain static; only the geometry of the rock would change. Chemical weathering processes refer to the presence of chemical reactions which takes place within the rock. The chemical composition and structure of a rock will thus change over time as the process affects the rock.

Modern geomorphic studies have shown that a combination of physical and chemical weathering processes combine to form a system that is responsible for the structural alteration of rock. Early research often did not consider weathering processes in terms of a system.

Rather, most investigations into the various processes that cause rock to weather were generally studied from the point of view of a single process or category of process. When it came to the study of weathering in periglacial and glacial settings, for example, geomorphologists came to believe that they were dominated by mechanical weathering processes as opposed to chemical ones (Darmody *et al.*, 1987; Darmody *et al.*, 2000; Allen *et al.*, 2001; Darmody *et al.*, 2005; Dixon and Thorn, 2005) and that there was one process that dominated the cold climate weathering regimes above all others: that of cryogenic weathering, also known as freeze-thaw weathering (Łoziński, 1909 and Łoziński, 1912, as cited in Darmody *et al.*, 2000; Hall 1997). Freeze-thaw weathering appeared to explain the angular fragmentation of rock often seen in cold climates through 'frost shattering' or 'frost-bursting'. This hypothesis provided what appeared to be an extremely elegant explanation for the landforms that were seen in environments where the ambient air temperature oscillated frequently between positive and negative temperatures (as expressed on the Celsius scale). Unfortunately, since cryogenic weathering appeared to explain landforms in cold climates so well and in so many cases, geomorphologists frequently stopped there, without investigating further to see if any other processes were active. In addition to this, many laboratory experiments that were set up to explore freeze-thaw weathering used moisture regimes that differed considerably from those that one could realistically expect in the field (White, 1976; McGreevy, 1981; Dredge, 1992). In a sense, these early experiments were set up to investigate whether or not freeze-thaw weathering was possible under any circumstances rather than being set up to investigate the viability of the process under standard field conditions. This approach is scientifically flawed, since in laboratory conditions, it is generally possible to prove anything that you want, whether it is feasible or not in standard field conditions. An example of this is given in Sass (2005) for cryogenic weathering, where reference is made to studies (McGreevy, 1981 and Dredge, 1992) that question the validity of making use of conditions that may be generated in the laboratory, but might be unrealistic

under field conditions (the specific examples in this case refer to very high levels of moisture saturation and very low temperatures, both of which are not verified in the field). Ideally, a philosophy of falsificationism should be followed when conducting laboratory conditions in an effort to preserve experimental integrity and keep the data that are obtained from the study relevant and applicable.

In contrast to this early mode of thinking, modern geomorphologists now believe that the results of weathering in one specific location cannot be attributed to the effects of one single dominant process, but rather are the result of an entire system of processes all acting in concert (Pope *et al.*, 1995). The effects of these various processes can be divided into two categories. Each process may have a direct effect on the system, meaning that rock alteration occurs as a direct result of the presence of the process in the system, or it may have a synergistic effect, meaning that the presence of the process enhances the effects of other processes within the system (the processes may be predominantly effective in either of the two categories, or both). Because of the difficulty involved in the study of the synergistic effects of weathering processes, most researchers either study the direct effect of a single process (such as Hall and Hall, 1996) or they attempt to describe the physical and chemical effects of a complete system (such as that of the field study carried out by Kanyaya and Trenhaile (2005)). This provides a good example of the contrast between a reductionist study and a holistic study. It is important to note, however, that the synergistic effects of the various weathering processes are not well understood i.e. we have limited understanding of how the various processes affect one another. It is felt that the links between various processes will be better understood if the processes themselves are better understood. Following a reductionist approach, the purpose of this study is to determine what the wetting and drying weathering process can achieve without interference from other weathering processes.

1.2. *Experimental Philosophies*

For any scientific study, it is important to understand the philosophical framework upon which it is based (Thorn, 1988, p.11). The philosophy of the observer will define the approach that the researcher takes to the study, as well the nature of the aims set and the method by which the aims are accomplished. As stated above, two of the major philosophical approaches to system study are reductionism and holism with both approaches having positive and negative elements. Holism was formally defined by Jan Smuts in his book *Holism and Evolution* as “The tendency in nature to form wholes that are greater than the sum of the parts through creative evolution.” (Smuts, 1926). However, the earliest known exploration of this concept comes from Aristotle’s work *Metaphysics*, in which he makes the statement: “The whole is more than the sum of its parts”. Essentially, Holism boils down to the following basic idea. Even if every part of a complex system could be broken down and studied to the point where every aspect of every component is completely and absolutely understood, the system would still not be fully understood. The important idea that holism brings to the scientific table is that components of a system should not be studied solely in isolation because they all act together and all influence each other (both constructively and destructively) in ways that are often very difficult to understand. Therefore, any complex system should be studied as a whole. There is an entire realm of mathematics known as Complexity (otherwise known as Chaos Theory), devoted specifically to the study of systems in this manner. It is increasingly believed that many geomorphic systems (including process systems) are complex in nature (Phillips, 2003; Phillips, 2006), which in time will lead to the natural marriage between studies of complexity and process geomorphology. Unfortunately, studies of this type require an advanced knowledge of Complexity Theory and other elements of mathematical nonlinear dynamics. For this reason, studies of this nature are largely ignored by most process geomorphologists. In particular, Complexity Theory is beyond the scope of this study, but its importance in future studies of this type is noted.

Field studies are generally holistic due to the fact that, taking place in an external environment as they do, they are mostly not controllable to the degree that is inherent to a laboratory study. Any cause and effect links that are studied are the cause and effect of a system, rather than that of an isolated component. The advantage of such a holistic approach in geomorphology is that studies built on this approach yield precise information regarding what exactly happens in real-life situations, without having to worry about whether or not the laboratory setup accurately reflects the real world. The disadvantage of such an approach is that, because the environment isn't controlled, it is difficult to connect the results that are obtained to specific components of the system. Thus, the studies on their own are largely descriptive and offer little insight into the mechanics of the processes that are being studied.

In contrast to Holism, Reductionism states that any complex system can be understood by breaking it down into ever simpler components, the thorough understanding of which will lead to a complete understanding of the over-arching system. The difference between this idea and that of holism is immediately obvious. The problem with both of these philosophical frameworks is that they are both essentially hypothetical. Holism hints at mysterious elements hidden within the complicated patterns of a complex system that can never be truly understood, while true reductionism requires the impossible task of reducing a complex system into simple components that can be easily studied and recompiled into a whole that makes sense. In contrast to holistic studies of entire weathering systems, reductionism gives rise to studies that try to isolate and quantify the individual processes to the initial exclusion of all else, after which information gleaned will be reinserted into the overall model. This study, as a process isolation investigation, falls into the reductionist category of experimental studies, since it endeavours to isolate and investigate only one weathering process, rather than an entire suite. While holistic studies may yield more accurate

models of weathering process suites than any study conducted from a reductionist point of view (particularly with the introduction of Chaos Theory), it is believed that reductionist studies will help to establish the boundary conditions by which such complex systems can be defined. This is of critical importance, since in chaotic systems, even the smallest misstep in the definition of a boundary condition can have dramatic consequences to the outcome. As an example, consider any climatic system. These systems are difficult to predict accurately because of the incredible number of variables present in them at any given time. Process systems are similar in terms of their complexity. Reductionist studies such as the one presented here can yield insight into what individual processes may realistically achieve; information of critical value in the establishment of any feasible weathering system model. Thus, it can be seen that while this study is modeled closely on the others that have been conducted before it, particularly in terms of methods used, it has been designed with more long-term aims in mind. Its intention is to begin a process that will yield information by which advanced weathering models can eventually be built. This is merely an initial investigation into studies of this type, but it is believed that in the future, they will be of immense value. Therefore, it can be seen that this study has been designed intentionally as a stepping stone for future work, i.e., to be the first step in something greater and long-term.

1.3. Action vs Process: The place of wetting and drying

There are three critical elements that must be considered in all weathering studies, namely the properties of the rock being studied, the thermal conditions and the moisture conditions (Hall, 1997). With the exception of dilatation or pressure release, all currently known weathering processes are believed to either directly require, or are known to be greatly influenced by, the thermal conditions impressed upon the rock by the external environment and/or the presence of moisture within the system. It is inconvenient, therefore, that both change in temperature and change in moisture are believed to be capable of causing

weathering directly themselves, in addition to their indirect roles in other weathering processes (Hall and Hall, 1996; Hall, 1997). For example, the ambient temperature of a specific area is believed to have an effect on the effectiveness of the various chemical processes (Darmody *et al.*, 2000) at work within any given rock, but changes in temperature can also directly cause thermal fatigue and thermal shock (Hall, 1997). Similar concerns arise with change in moisture. Moisture variation is required for salt weathering to take place (Fahey, 1986; Goudie and Parker, 1998; Wüst, 2000; Jagoutz, 2006), but as in the case of thermal changes, the very action of wetting and drying is believed to have a direct weathering effect. These direct and indirect effects have distinct ramifications when considered in the context of an experiment designed from a reductionism philosophical standpoint (as laboratory process studies typically are). To illustrate, consider the salt weathering example. As has already been stated, the salt weathering process often involves changes in moisture levels, both in salt crystallisation and hydration (Goudie and Parker, 1998; Fahey, 1986; Wüst, 2000; Jagoutz, 2006) in order to occur. If the process is recreated in a typical laboratory setting, which generally takes the form of wetting and drying rock samples in a brine solution of known salinity to stimulate salt crystal growth in rock pores, the results will not yield information purely about the weathering potential of the salt weathering process. Rather, the gathered data will reflect the combined effects of salt weathering and that of direct weathering by wetting and drying. The effects of thermal fatigue and chemical weathering will also affect the data from the experiment. Thus, the results of such an experiment will be influenced somewhat, although to what degree, it is currently not known.

It is therefore important to realise that the more complex weathering processes will be built on changes in temperature and changes in moisture, which induce weathering processes in their own right.

1.5 Aims and Objectives

The aim of this study is to investigate the action of wetting and drying as a weathering process under isolated laboratory conditions to determine the nature and intensity of the rock alteration so that its role in a system, made up a variety of weathering processes, may be better understood. To accomplish the stated aim, three objectives must be achieved.

- Objective 1 is to analyse the studies done on the wetting and drying process up to this point so that the current knowledge state can be accurately described.
- Objective 2 is to study the effects of periodic wetting and drying under isolated laboratory conditions, on the physical rock properties of sandstone and basalt.
- Objective 3 is to determine if the current train of thought regarding weathering studies in general, and wetting and drying in particular, need be altered in order for the science of process geomorphology to develop further effectively.

1.6. Project outline

The fulfillment of the above objectives will be laid out in six chapters. Chapter 1 has served to create a brief historical and philosophical framework into which this study can be inserted, so that its place in the wider realm of process geomorphology may be understood. Chapter 2 discusses the theory of wetting and drying as it is currently understood and reviews research conducted to this point. In particular, the wetting and drying weathering process will be defined; a definition that will serve as standard for the rest of this document. Chapter 3 will discuss in detail the laboratory methods that were used. Chapter 4 presents the results of the study, as well as any observations that are relevant. Chapter 5 discusses the results (in chapter 4) in detail, with particular emphasis on contrasts between what was measured and

what was expected. Chapter 6 contains concluding remarks and recommendations pertaining to future research.

Chapter 2: Review of wetting and drying process studies

2.1. Introduction

In this chapter, the wetting and drying weathering process will be examined in detail. First, the mechanics by which the process is believed to function will be investigated by studying various texts on the subject, as well as establishing how the wetting and drying weathering process will be defined in this document. Following this, the research conducted up to this point will be considered and summarised. Once the current level of knowledge has been examined, the direction of future research can be more easily determined and focused.

2.2. The wetting and drying process as it is currently understood

The wetting and drying process has been studied by a several authors, each of which has offered their own unique and valuable insights into the process. This is important because any meaningful study into the process needs to begin with establishing that which is already known or believed to be true. There are two primary schools of thought when it comes to wetting and drying.

2.2.1. Huggett (2003) and Scherer (2006)

Huggett (2003) defines the wetting and drying weathering process in terms of the expansion of hydrated clay minerals present within the rock structure. This is an important hypothesis to consider, primarily because clay minerals must be present within the rock for it to be weathered in this way. It is important to note that while Huggett (2003) defines this process as wetting and drying, many texts refer to this process as slaking and make a distinction between it and the wetting and drying process, which is not believed to require the presence of clay minerals in order to be effective (Yatsu, 1988; Hall and Hall, 1996). The interpretation that Huggett (2003) gives has been included since it highlights the difference of

opinion between researchers on the importance of the presence of clay minerals. In many other texts, rock alteration as a result of clay mineral hydration and expansion is not called wetting and drying, but is rather referred to as slaking.

Scherer (2006) explores the importance of clay mineral hydration and expansion, but does not define this mechanism as wetting and drying. Rather, this paper investigates the importance of the spatial placement of the clay minerals within the rock structure. It is interesting to note that, while Scherer explores a number of different mechanisms by which rock may be weathered, wetting and drying without the presence of clays is not one of them. After studying the literature carefully, it can be noted that a large number of papers subscribe to the idea that clay mineral expansion is the only way by which wetting and drying may damage a rock. In this light, the fact that Huggett (2003) has defined the process in terms of clay mineral expansion becomes understandable. However, as was mentioned above, there are a number of texts that suggest that clay minerals need not be present for the wetting and drying of a rock to cause damage. If these texts are correct, there must be another explanation for the damage caused by wetting and drying. This is not to say that the idea behind slaking is incorrect. Indeed, there is overwhelming evidence that slaking does occur. Rather, it is important to consider the possibility that clay mineral expansion does not tell the complete story; there is more to the process than slaking of clays.

2.2.2. Bland and Rolls (1998)

Bland and Rolls (1998) state that weathering by wetting and drying may occur in rocks that have little or no clay minerals present within them. Instead of considering the role of clay minerals, Bland and Rolls (1998) propose that the observed rock damage comes as a result of the presence of unsatisfied electrostatic bonds found at pre-existing fracture sites within the rock. Water entering into the fracture will become polarised according to the charge on the

edges of the fracture, due to the polar nature of water molecules. Polarised water molecules will then begin to form layers in the fracture in a process known as adsorption. As more water fills the crack, hydraulic pressure begins to build up, which creates strain on the rock. This expansion, if great enough, will cause the rock to undergo plastic deformation, altering the mechanical structure of the rock. When drying, the rock does not return completely to its original form, but rather undergoes a small amount of plastic deformation (Hall and Hall, 1996); an effect known as 'hysteresis'. Thus, both the wetting of the rock and the drying of the rock play a role in the weathering process. It is important to note that, if this hypothesis regarding the wetting and drying process is correct, the effect of the weathering process may not be immediately visible in terms of mass loss. Damage may be visually observed, but the actual extent of material loss may be very small. Thus, it is possible that rocks susceptible to wetting and drying may fail unexpectedly, even if monitored quite closely (eg. Hall and Hall, 1996).

After analysis of the above works, it becomes apparent that there are two distinct processes that can potentially be at work as a result of wetting and drying of a rock. Figure 1 shows the two processes schematically. The defining difference between the two is that for slaking to take place, clay minerals must be present within the rock, whereas for wetting and drying as defined by Bland and Rolls (1998), clay minerals need not be present.

It is critical to note that while there are two distinct weathering processes described here, they both have the same initiating action and the same final product. Rock structure alteration by slaking is not caused directly by the action of wetting and drying but rather by the expansion of hydrating clay minerals within the rock. This makes it a synergistic weathering process, in much the same way that salt weathering (through hydration) would be. What is meant by this is that, in rocks that contain little or no clay, clay mineral expansion (slaking)

cannot be taking place and any rock alteration that occurs as a result of the wetting and drying action must be the result of a process described by Bland and Rolls (1998).

In a rock that does contain clay however, slaking, as defined by Huggett (2003) and Scherer (2006) will be present, but wetting and drying as defined by Bland and Rolls (1998) may be present as well. In short, slaking requires both the presence of clay minerals and the wetting and drying action in order to occur, whereas wetting and drying as defined by Bland and Rolls (1998) only requires the wetting and drying action. For this reason, the wetting and drying weathering process will be defined according to that given by Bland and Rolls (1998) as it is less likely to have synergistic implications.

2.3. Review of articles on wetting and drying

Wetting and drying as an action has been studied by a number of researchers using a variety of methods. Some studies have been conducted in the field in order to gain an understanding of the effects that the action has on different rock types in different environments, while other studies have taken place purely in the laboratory, either simulating the effects of a specific external environment (such as Wells *et al.* 2005) or under isolation to further the understanding of the mechanical effects of the action on various rock types. A third type of study is purely theoretical, modeling the effects of wetting and drying mathematically and comparing results to those seen in field and laboratory conditions.

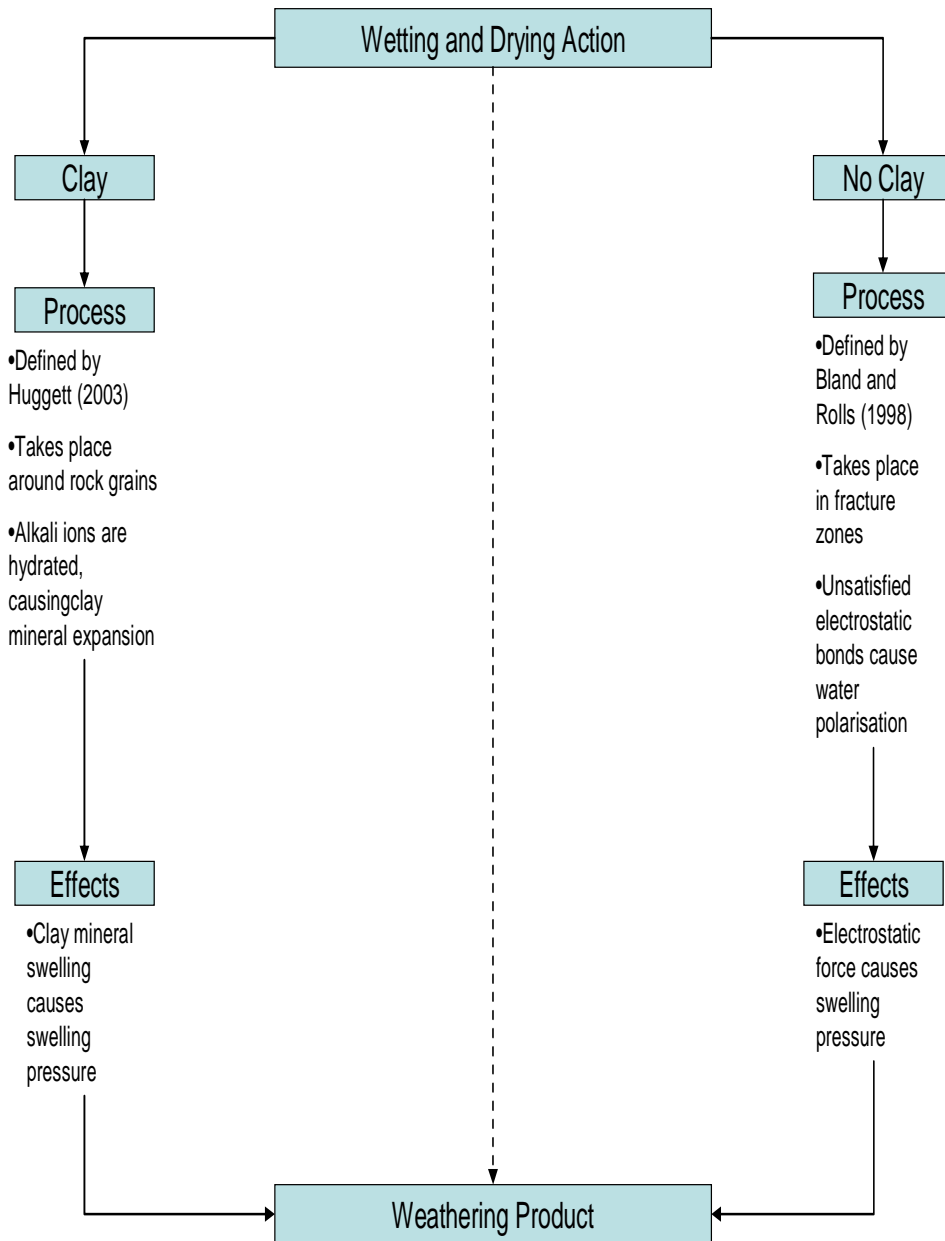


Figure 1. Wetting and drying as explained by Huggett (2003) compared to that of Bland and Rolls (1998)

2.3.1. Laboratory studies

Studies carried out exclusively under laboratory conditions have several advantages, but also have one or two recognised problems. They are useful because they allow for more controlled environmental conditions, which makes for an easier establishment of the links between cause and effect. In addition, laboratory experiments can be tailored to answer specific questions pertinent to the study. This makes such studies ideal for investigating the mechanisms at work within each weathering process. However, the ability to control the experiments can lead to setups that do not reflect scenarios seen in the field. Thus, processes studied in the laboratory may affect samples in a way that they never would be in the field as a result of unrealistic external conditions. Many of the articles published concerning the wetting and drying process are conducted exclusively under laboratory conditions. This is largely due to the difficulties that one encounters in the study of one specific weathering process within the complexities that one finds in any field weathering system, but it is also due to the difficulty that one finds in finding natural conditions where the wetting and drying process is likely to be dominant. Laboratory studies conducted up to this point vary widely, both in terms of the objectives that are set out as well as the methods by which those objectives are achieved. Laboratory studies can initially be grouped into one of two scenarios. First, some laboratory studies try and simulate an existing field environment so as to ascertain the behaviour of certain processes under a specific set of conditions. For example, Wells *et al.* (2005) attempt to simulate an environment that is known to exist in the field to determine what the effect of wetting and drying is likely to be under those conditions. Second, other studies merely keep the external laboratory environment as stable as possible so that specific rock properties may be accurately analysed.

Table 1 provides a listing of studies done in a laboratory setting on the wetting and drying process, with a focus on the nature of the experiments that were conducted and the results that were obtained.

Hall and Hall (1996), Sumner and Loubser (2008) and Gonzalez and Scherer (2006) take place under isolated environmental conditions which, while tightly controlled, do not attempt to emulate any specific field scenarios. These studies are concerned with investigations into the mechanics of wetting and drying, regardless of the conditions under which the process is operating. It could be argued that studies of this type lack context, but understanding the mechanisms of a weathering process is best done in this way in order to minimise the number of changing variables within the experimental system. An ideal experimental setup of this type should have one independent variable (controlled by the researcher) and one dependent variable that is measured against the independent. This allows for determination of the relationship between the two. All other potential variables should be kept as static as possible. While the various studies of this type all have a similar overarching experimental structure, they are all different. Hall and Hall (1996) investigated the relationship between the way in which different rock types received moisture and the measured changes in internal rock structure (as established by changes in mass), while Sumner and Loubser (2008) carried out an experiment in a comparable fashion, but with the objective of determining the relationship between the changes in moisture amplitude and the physical properties of the sample rocks. Gonzalez and Scherer (2006) had the two-fold objective of testing an experimental autonomous wetting and drying system and noting the relationship between the number of wetting and drying cycles experienced by a given rock sample and the measured change in physical dimension over time (i.e. swelling). A further example is showcased by Pardini *et al.* (1996), who investigated the relationship between the



Author	Rock type / Sample shape and dimensions	Experimental procedure	Properties studied	Cycles/Measurements / Cycle duration	Results
Huang <i>et al.</i> , 1995	Shale Cube: 1 inch x 1 inch x 1 inch	Wetting and drying cycles carried out at different temperatures	Maximum swelling pressure and strain	2 Cycles / Wetting by humidity chamber: Wetting continued until no weight change noted; generally around 20 days	Pressure and strain is related to shale moisture susceptibility, testing temperature, initial tempering air humidity
Hall and Hall, 1996	Sandstone/Dolerite: 8cm x 4cm x 3cm	Cyclic wetting and drying, using different methods of submersion	Change in sample dry mass, changes in water holding ability, degree of saturation	145 Cycles / 3 hour wetting; 21 hour drying	Wetting and Drying can have an effect on the degree of rock breakdown without any other weathering processes being present
Pardini <i>et al.</i> , 1996	Smetitic mudrock: 10cm x 18cm x 5 cm	Non-contact laser profiling	Surface microtopography variations and bulk density	3 Cycles / 3 day wetting; 12 day drying	Minimal effect on surface microtopography and bulk density
Botts, 1998	Clay Shales Core: 56 mm diameter	Slake-Durability test	softening within fissures, measurement of slaking under confining pressures, application of critical state model to slaking within clay shales	1 Cycle / Wetting time not given; 0 to 28 day drying	80% reduction in strength possible after 1 wetting and drying cycle



Hachinohe <i>et al.</i> , 1999	Tertiary sandstone/Mudstone Core: Exact dimensions not given	Weathering profiles observed in the field; measurement of rate at which the strength of weathered material decreases with time as determined by needle penetrometer	residual strength ratio	N/A	Weathering rates decrease logarithmically over time rather than monotonically
Gökçeoğlu <i>et al.</i> , 2000	Various marls, Claystone, Sandstone, Ignimbrite (141 samples): 30cm x 30cm x 30cm	Multiple slake durability testing	Mineralogy by XRD, uniaxial compression testing	4 cycles	Durability of clay-bearing rock correlates well with amount of expandable clay mineral in the rock
Nicholson, 2001	Limestone/Chalk: Physical dimensions not specified	Freeze-thaw, wetting and drying, slake durability, salt weathering on different rocks	Effective porosity, mercury intrusion porosimetry, scanning electron microscopy, weight loss, fracture density	40, 80 Cycles / 12 hr wetting; 6 to 10 hr drying	Changes in effective porosity were measured and are likely the result of changes in the degree of moisture saturation of the samples
Cantón <i>et al.</i> , 2001	Consolidated mudstone: 20cm x 10cm x 5cm	Samples wetted and dried for different numbers of cycles and then analysed	micro-morphology, elemental and soluble salt chemistry, total mineralogy	5, 10, 20 / Placed in sandbath until sample surface appeared wet	Increase in porosity; increase in water absorption capacity

Pejon and Zuquette, 2002	French Mudrock Core: 75 mm diameter; 20 to 30 mm length	SEM measured condition of samples before and after free and pressure swelling tests	Grain-size distribution, pore-size distribution, cation exchange capacity, mineralogical composition	11 Cycles / Duration determined by moisture level. Time not given	Significant breakdown of mudrocks, even when rocks had low clay mineral content
Kanyaya and Trenhaile, 2005	Basalt/Sandstone/Argillite Cores and cubes: 2cm x 2cm	Samples wetted and dried using tidal simulators in laboratory environment	Rate of downwearing in the field by MEM	Between 700 and 930 Cycles / Set 1: 11hr wetting; 1hr drying Set 2: 6hr wetting; 6hr drying; Set 3: 1hr wetting; 11hr drying	Downwearing rates decrease with elevation within the inter-tidal zone
Wells <i>et al.</i> , 2005	Quartz chlorite schist Cube: 15mm x 15mm x 15mm	Wetting and drying studied under simulated tropic climate	Fragmentation, moisture content and moisture uptake rate	5000 Cycles / 5 min wetting; 67 min drying	Wetting and Drying can cause changes in rock morphology in quartz chlorite schist
Gonzalez and Scherer, 2006	Portland Brownstone (Sandstone) Plate: 100mm x 22mm x 3.6mm	Wetting and Drying conducted by automation	free-swelling, ratio of wet to dry modulus, sorptivity	Automated / 30 min wetting; 60 minute drying	Gradual increase in swelling over time
Sumner and Loubser, 2008	Sandstone 57mm x 47mm x 23mm	Cyclic wetting and drying, using different moisture amplitudes	porosity, water absorption capacity, saturation coefficient, change in dry mass	52 Cycles / 2 - 6 min wetting; 48 hr drying	Moisture amplitude appears to have limited effect on the degree of weathering that takes place over an intermediate time period

Table 1. Listing of studies undertaken in the last 20 years pertaining to the wetting and drying weathering process as studied in a laboratory environment

action of wetting and drying various rock types and the changes in surface micro-topography as measured by a non-contact profiling laser. This experiment is born out of the idea that wetting and drying caused rock structure alterations on samples, as well as the internal rock structure changes that the other research articles prioritise. Such surface profiling studies help researchers keep in mind that rock alteration does not only occur in one manner and in one location, but rather takes place over a large process spectrum. As an example, Scherer (2006) has noted that clay mineral location within a rock matrix is an important element of slaking, in addition to the clay mineral concentrations within the rock. A comparison of the studies done by Pardini *et al.* (1996) with one of Hall and Hall (1996) show that the same weathering process may have different weathering effects on the surface of a rock when compared to the effects that may be noted on the internal rock structure. One of the reasons for this is the fact that the changing external environmental conditions will have a direct impact on a surface process and a more indirect impact on a sub-surface one.

The physical dimensions of the samples used in the various laboratory experiments vary widely in terms of both size and surface geometry. For example, Wells *et al.* (2005) make use of cubic samples of dimension 15mm x 15mm x 15mm, which contrasts significantly with those used by Gonzalez and Scherer (2006), who made use of plates with dimension 100mm x 22mm x 3.6mm. These differ still further from samples used by Pejon and Zuquette (2002), who made use of cylindrical samples that were 75mm in diameter and 20mm to 30mm in length. All these samples differ both in terms of physical size and surface geometry. Size is important because it introduces an element of scale into the studies. It is difficult to take data gathered by experimentation on samples of a certain size and shape and apply it to samples of a different size and shape, even if the samples are similar in every other manner. This is because differing sample geometries effectively act as different experimental variables within

a system. Sample geometry is important because different geometries mean different rock volume to rock surface area ratios, even in samples of similar mass. As was stated above, wetting and drying may have different effects when active on a rock surface as opposed to when it is active below the rock surface and different geometries will mean different degrees of intensity for effects present on the surface and sub-surface of the rocks. Once again, these differences make the comparison of data between different studies very difficult.

A further difference in method can be seen in the cycle durations used in the various experiment. Wells *et al.* (2005) made use of a wetting period that lasted 5 minutes and drying period of 67 minutes, while Nicholson (2001) wetted samples for 12 hours and dried them for between 6 and 10 hours. Hall and Hall (1996) saturated samples for 3 hours and allowed them to dry for 21 hours. Reasons given for the 24 hour time period are partly of convenience, but also because it does reflect certain possible field scenarios, such as evaporating snow melt or short rainfall events. Hall and Hall (1996) persisted for 5 days, after which the samples were left undisturbed for two days, thus completing a weekly experimental cycle. Other studies do not use time as a measure for the saturation length, but rather use moisture saturation as determined by weight (eg. Pejon and Zuquette, 2002; Huang *et al.*, 1995). When there are so many differences within each experimental method, it is no surprise that results yielded by all of these experiments can differ substantially as well.

2.3.2. *Field studies*

In contrast to laboratory studies, field-based studies are conducted within a naturally existing system and thus should give a more accurate indication of what is really happening at a given time than a laboratory based simulation of a natural environment. As a result, they should serve as an ideal platform for the testing of results obtained in the laboratory. Bretz (1962) states that in geomorphology “field relations are the final court of appeal” (cited in

Phillips, 2003, p.2). Geomorphology involves the study of large, complex field-based systems and the best understanding of these systems can be obtained by studying them directly. Any geomorphology study should thus start and end in the field, or risk losing its relevance. In particular, it is important to understand the weathering systems prevalent in areas that are believed to be heavily influenced by wetting and drying. Table 2 lists studies that investigate the effects of the wetting and drying action on various rock types in various field locations.

Field studies are an important part of any study concerning a weathering process and wetting and drying is no different, despite the difficulties involved in studying it in this manner. A focus has been on intertidal zones that yield known, predictable wetting and drying cycles. Tidal zones are particularly useful due to their remarkable regularity, making measurement of such things as number of wetting and drying cycles very easy. In addition, the wetting and drying patterns seen in such environments are generally fairly easy to replicate under laboratory conditions due to their consistency. For the most part, studies that investigate the effects of wetting and drying in inter-tidal zones involve the placement of automated sensors called traversing micro-erosion meters (or TMEMs), which gather data on the down-wearing of rocks. While the effects measured by TMEMs are certainly dominated by the action of wetting and drying, one could make the argument that the wetting and drying process may not necessarily be exclusively in play. There are many factors, of both a weathering and an erosive nature that are occurring under such conditions. This demonstrates both the positive aspects of any field study as the negative ones. One major benefit of the current state of field inter-tidal studies is their relatively standard nature and a number of studies have been carried out in the same manner in different parts of the world (eg. Porter and Trenhaile, 2007; Trenhaile, 2006, Stephenson and Kirk, 2001).

Author	Rock type	Experimental procedure	Properties studied	Cycles/Measurements	Results
Stephenson and Kirk, 2001	Limestone/Mudstone bedrock	TMEM measuring equipment placed on site	Surface-swelling	24055 measurements	Swelling noted in 17% of all measurements
Duperret <i>et al.</i> , 2005	Chalk	SEM conducted on samples of various moisture levels	UCS, Young's modulus	10 day cycle	Samples subjected to artificially induced weathering experience decrease in strength, but an increase in Young's modulus
Blanco-Chao <i>et al.</i> , 2007	Not specified	Schmidt Hammer readings taken at 109 different field sites	Rock Hardness/Rock strength	N/A	Significant levels of active abrasion occur in the upper regions of inter-tidal zones
Trenhaile, 2006	Basalt/Sandstone/Argillite	MEM measuring equipment placed on site	Expansion and contraction in the field	800 to 1000 tidal cycles	Expansion seen in Argillite and basalt, but not in sandstone
Porter and Trenhaile, 2007	Basalt/Sandstone/Argillite	TMEM measuring equipment placed on site	Expansion and contraction in the field	10 day cycle	Contraction in the elevation zone appears to be caused by alternate wetting and drying

Table 2. Listing of studies undertaken in the last 20 years pertaining to the wetting and drying weathering process as studied in a field environment

Such studies as those noted above produce results are comparable to one another, a distinct advantage over the majority of the current laboratory studies. However, because these experiments take place in the field, it can be argued that the experiment studies the effects of wetting and drying as an action, rather than as a process. This is important to note because the data that are gathered in experiments like this are not reflective of one singular weathering process (such as one might expect to measure in a laboratory), but rather show the effects of an entire system of processes (both erosive and weathering) and there is no way of determining the exact degree to which the wetting and drying process is acting on the samples. Researchers have attempted to address this problem by duplicating field conditions in a laboratory using tidal simulators. These data are then compared to the data gathered in the field to establish the role of the wetting and drying process in tidal scenarios.

2.3.3. Theoretical studies

Finally, some studies are purely theoretical, making use of computational and statistical models to predict what wetting and drying will do to the structure of various rock samples over time. Table 3 lists the computational studies that have been conducted up to this point. Theoretical studies have objectives that do not require field or laboratory components (except for purposes of model verification). A major advantage to a theoretical setup is that data contamination by changing environmental conditions is not a problem because a computational model will have specific environmental parameters as part of the model. This allows concepts to be tested without the concern of data corruption by experimental error. The objective of most studies of this type is to try and enhance the predictive qualities of models currently in existence or to find new ways to accurately model environmental systems.

Author	Rock type	Experimental procedure	Properties studied	Results
Alsaaran and Olyphant, 1998	Hypothetical coarse-grained material	Computer model	Rock-water interactions under fluctuating boundary conditions	Modeled results compare reasonably favourably with measured values
Moosavi <i>et al.</i> , 2006	Mudrock	Time delay neural networks	Statistical analysis	TDNNs show promise in the prediction of cyclic swelling pressures over time
Doostmohammadi <i>et al.</i> , 2007	argillaceous	Computer model	swell-shrink behaviour of rocks under variable water contents	Improved prediction of swelling pressures
Trenhaile, 2008	N/A	Model study		Weathering can play an important, but indirect role in assisting wave quarrying

Table 3. Listing of studies undertaken in the last 20 years pertaining to the wetting and drying weathering process as studied by computational model

2.4. Summary of the current state of knowledge on wetting and drying

After studying the articles that document the current investigations of the wetting and drying weathering process, a number of conclusions can be drawn. First, the laboratory studies generally lack any kind of standardisation. This can be viewed as a positive point because it means that many aspects of the wetting and drying process have been investigated by different people with the result that much data have been gathered. However, it also means that the various studies cannot be easily compared to one another, making it difficult for all the information gathered on the process to be integrated into one cohesive whole. The most likely reason for this is the fact that the majority of studies are conducted in isolation; not isolation in the experimental sense, but rather in the sense of the global pool of knowledge. Individual studies are not generally designed to fit into a larger system of study, but rather are designed to function on their own, as isolated components. A second problem is the element of synergy. It is understood that weathering processes do not generally act in isolation, but rather form part of a larger, more complex system (see Chapter 1). This means that it is not only important to understand how each individual process operates, but also how all the different processes interact with one another to cause the observed effects. This critical element of any system study is extremely difficult to quantify as a result of the two-dimensional nature of most experimental setups.

2.5. Future studies and the role of this dissertation

Research studies should not only consider articles that have been published on the subject at hand in the past, but should begin to consider the role that the current study will play in furthering investigations conducted in the future. This study will investigate the effects of the wetting and drying weathering process on 3 different rock types (one basalt and two sandstones), with a specific focus on how wetting and drying of a rock may affect the physical

properties of a rock over 105 cycles. This study follows the path laid out by the studies carried out before. In particular, it is based on the work by Hall and Hall (1996) and Sumner and Loubser (2008) and seeks to further expand on the results obtained in those studies. The following chapter (Chapter 3) gives a detailed description of the experimental method that was followed in order to obtain the data presented in Chapter 4.

Chapter 3: Methodology

While wetting and drying is the process under consideration here, it is important to realise that other physical (and chemical) weathering processes may be taking place as well and as such it is important to take them into account. In this experimental setup, most processes will be eliminated, and those that cannot will be quantified. For the most part, physical weathering processes can be eliminated relatively easily (with the exception of clay mineral expansion), while chemical weathering processes are more difficult to eliminate and will thus be accounted for mathematically. This will ensure (as far as is possible) that the only rock alteration that is occurring is as a result of wetting and drying (as defined in Chapter 2 of this document).

3.1. Chapter Outline

The following chapter will deal specifically with the experimental method employed in this study to fulfill the aim and objectives stated in Chapter 1. To begin with, the rock samples that were used will be introduced and discussed, with particular focus being given to why they were specifically selected and why they are valuable to the study as a whole. Also, the nature of the sample preparation will be discussed and motivated for, after which the laboratory preparations will be detailed. Following this, the experimental method will be detailed chronologically and explained both in terms of relevance to this specific study and in terms of studies that have been conducted before.

3.2. The Samples used for experimentation

Three different rock types, one igneous and two sedimentary, were used in this experiment. Each rock type enhances the study in a specific way, whether it be as a result of the geographical location from which it was obtained or as a result of its internal structure. The

structure of the rock has primary relevance to the study because structure forms the physical framework that any mechanical process must exist within. The location has secondary relevance in this study, due to its primarily mechanical focus, but it still may yield important information to geomorphic processes beyond the laboratory.

Samples were taken from Marion Island (basalt, set 1) and from the Clarens Formation in the SA Drakensberg (sandstone, sets 2a and 2b). Marion Island is known to have a highly variable moisture environment (Boelhouwers *et al.*, 2003). Obtaining rock samples in large quantities from a location as remote as Marion Island is logistically difficult, so the samples in this experiment have all been cut from one bulk sample, which was brought back from the island. Two bulk samples of sandstone were taken from different locations in the Clarens Formation in the South African Drakensberg, from which the experimental samples were cut. This has been done because of easier access to the locations from which the samples are obtained. Also, the greater diversity of physical rock properties in Clarens Formation sandstone necessitates the collection of samples from two proximate locations. This provides the three “rock types” used for the three sets here.

3.2.1. Fine grained grey basalt from Sub-Antarctic Marion Island

Figure 2 shows one of the experimental samples that were cut from a rock brought back from Tafelberg on the Eastern Succession of Marion Island. Marion Island is one of two islands that make up the Prince Edward Islands group located within the Southern Indian Ocean at co-ordinates 46°54'S, 37°45'E. These two islands (Marion Island in particular) are currently being studied by programs conducted by SANAP (South African National Antarctic Program).

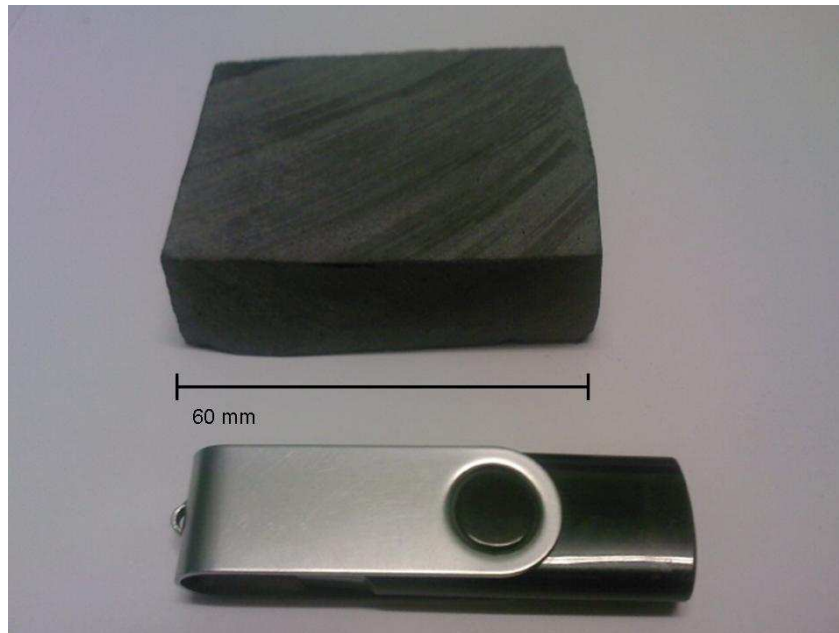


Figure 2. Image of a sample from Set 1 (Marion Island basalt), 60 mm in length

According to Hedding (2007), Marion Island is an important arena for geomorphic research because of the island's close proximity to the Antarctic Polar Convergence Zone, making it a good indicator for any shifts in the Antarctic polar convergence zone location. In addition to this, the Prince Edward Islands group is well-placed for research into periglacial geomorphology (periglacial being defined as a geomorphic regime located in a cold climate that is not predominantly a glacial environment). Turkington *et al.* (2005) state that "weathering is arguably the most crucial and fundamental phenomenon in landscape evolution and topographic development" (p.1). This article claims that the weathering of material is a necessary initial phase for most forms of erosion and landform denudation. For this reason, having a good understanding of the weathering processes active in any given system would lead to an improved understanding of other processes (not weathering related) that are known to shape the area's landforms. Traditionally, cold climates, such as that found on Marion Island are believed to have weathering regimes that are dominated by mechanical weathering

processes as opposed to chemical weathering processes. While modern research is beginning to show that this view may be incomplete, it is still clear that mechanical processes do play a significant role in the rock weathering systems that are found in these areas. However, the exact nature and role of the processes that are in play are not well understood. Since Marion Island has an extremely wet climate, a good understanding of the role played by the wetting and drying weathering process is vital to any investigation of the weathering systems present on the island. Conversely however, Marion Island is made up primarily of volcanic rock, which is dense and hard, as opposed to the softer sandstones and mudstones that the wetting and drying weathering process was traditionally thought to significantly affect. No research of this type has been done on the basaltic rock that makes up much of Marion Island and this study will thus serve as an initial investigation into the effects of wetting and drying on rocks from that area. While the study does not have Marion Island as its primary focus, the data presented here represent a probe into the weathering systems currently in operation there, specifically since Boelhouwers *et al.* (2003) notes that Marion Island has an extremely dynamic environment in terms of moisture fluctuations. This, coupled with the fact that the rock that makes up Marion Island contains little to no clays (Boelhouwers *et al.*, 2003) makes Marion Island basalt an ideal sample to investigate for this study.

The Marion Island basalt used in this experiment has a bulk density of 2741 kg/m³ and an average initial hardness of 737 LD units as measured by Equotip hardness meter. It is made up of 47% SiO₂, 16% Al₂O₃ and 14% Fe₂O₃ (determined by XRF analysis at University of Pretoria), with the remaining 23% being made up of smaller quantities of other minerals.

3.2.2. Sandstone from the Clarens Formation, SA Drakensberg

The two rocks from which Set 2a and Set 2b (examples of which are shown in Figure 3) have been cut have special relevance because they have been taken from the same

lithology upon which famous Bushman Rock Art has been painted at Main Cave in the Drakensberg. In recent years, particular attention has been given to the conservation of this rock art, as it appears to have deteriorated noticeably through weathering (Meiklejohn, 1994; Meiklejohn *et al.*, 2009)

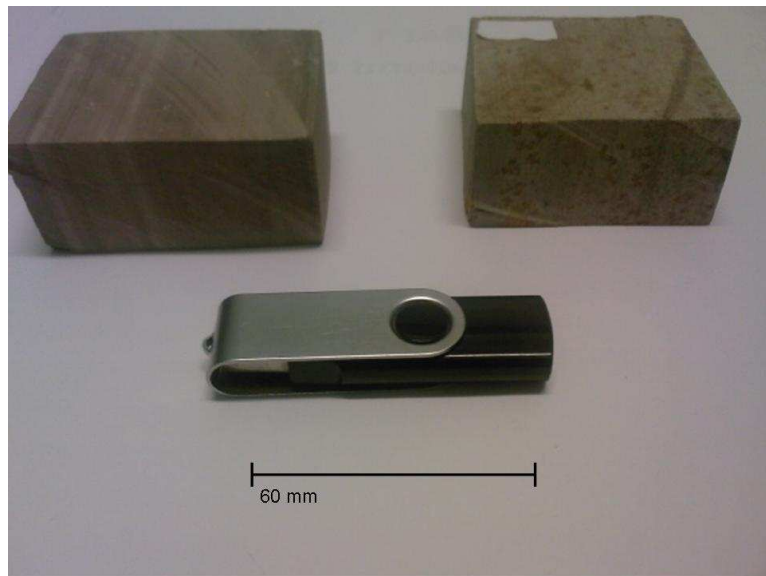


Figure 3. Samples taken from Clarens Formation, Drakensberg, 60 mm in length

Unfortunately, a generally poor understanding of the weathering systems active in the areas containing rock art have resulted in a poor understanding as to how rock art may best be conserved (Loubser, 1991, cited in Meiklejohn, 1994). What is of specific interest to this study is the fact that Meiklejohn (1994) states that not many studies have been made with regards to specific weathering processes known to be active in the Main Cave area. Meiklejohn (1994) states that it is critical that extensive research be carried out regarding the mechanisms that cause rock art to deteriorate. Meiklejohn (1994) carried out studies with regards to changes in moisture at rock art sites and noted that moisture fluctuations do occur, particularly at exposed sites. Since then, studies have been carried out in the field of rock art conservation; indeed studies that pertain directly to an enhanced understanding of the

weathering processes that cause rock art deterioration now exist to a much larger degree than did 15 years ago (as summarised by Sumner *et al.*, 2009), but the processes present are still poorly understood at best. This study, with its specific focus on the role that wetting and drying will play in the decay of the rocks that the Main Cave rock art is painted on will add to the overall understanding of the weathering processes currently in play at this site and can yield additional information that will assist in the conservation of these priceless works of art. The rock sample that makes up Set 2a was taken adjacent to the Main Cave site on an East-facing slope. It is grey in colour and has a bulk density of 2544 kg/m^3 , with an average initial hardness of 623 LD units. It is made up of 70% SiO_2 and 14% Al_2O_3 , with the balance made up by smaller quantities of other minerals. Set 2b was taken from the North-facing slope. As with Set 2a, it has a fine grain, although it is a slightly lighter grey colour. It has a bulk density of 2434 kg/m^3 and an average initial hardness of 648 LD units. The rock is comprised of 78% SiO_2 and 11% Al_2O_3 , as well as smaller amounts of other materials. The comparison of these two rocks is valuable because, although they are taken from the same site and are part of the same rock formation, they have different mineralogies, meaning that the same weathering action may lead to different weathering effects.

3.3. Sample preparation

The samples have been prepared to make them as geometrically uniform as possible, to ensure that the conditions under which the wetting and drying process will be active remain as constant as possible. This will make comparison of the results over the entire experimental set possible. The samples were cut into rectangular blocks with an average dimension of 60mm x 45mm x 25mm. These dimensions have been chosen for purposes of convenience, given the dimensions of the original clasts from which the samples have been cut. Critically, the samples were not polished; they were only cut. Table 4 gives the exact physical dimensions, masses and bulk densities for all the samples used in this experiment.



Number	a-axis (mm)	b-axis (mm)	c-axis (mm)	Initial mass (g)	Bulk density (kg/m ³)
1 1	54.85	43.58	27.00	173.91	2695
1 2	60.75	44.68	20.68	152.34	2715
1 3	59.73	45.90	21.28	162.72	2790
1 4	59.20	42.83	26.13	182.33	2753
1 5	66.08	44.18	25.58	208.48	2793
1 6	61.83	46.88	27.20	215.69	2736
1 7	56.48	42.20	25.58	171.92	2821
1 8	57.98	45.58	22.53	164.53	2764
1 9	61.60	43.83	22.98	165.20	2663
1 10	59.88	43.68	23.20	157.85	2602
1 C1	61.28	43.83	26.98	200.44	2767
1 C2	65.63	45.28	19.03	158.66	2807
1 C3	53.68	46.13	28.93	195.37	2728
2a 1	61.98	44.95	27.98	197.81	2538
2a 2	60.48	41.75	29.65	189.91	2537
2a 3	55.25	43.08	25.40	162.44	2687
2a 4	62.08	46.28	29.50	215.20	2540
2a 5	58.60	43.78	22.80	148.63	2541
2a 6	55.23	45.95	23.88	150.31	2481
2a 7	56.23	45.10	24.35	157.42	2549
2a 8	56.10	45.83	27.65	178.09	2505
2a 9	54.28	44.38	23.68	144.11	2527
2a 10	51.85	46.83	28.63	173.08	2490
2a 11	61.53	46.85	28.50	215.26	2620
2a 12	51.03	44.38	29.45	169.56	2543
2a 13	59.15	42.58	27.70	178.50	2559
2a C1	53.00	49.88	28.75	190.54	2507
2a C2	53.55	50.15	27.15	184.31	2528
2b 1	57.18	50.05	29.28	205.82	2457
2b 2	55.00	51.20	26.78	180.32	2392
2b 3	53.35	49.13	26.60	170.39	2444
2b 4	54.00	49.10	25.00	164.60	2483
2b C1	53.25	50.70	30.10	185.24	2280
2b C2	51.93	50.98	26.53	167.10	2380

Table 4. Physical dimensions of samples used in the experiment

3.4. Laboratory preparation and Environmental Control

As has been mentioned in previous chapters, the two primary governing factors of physical and chemical weathering processes are change in temperature and the presence of moisture. Because the experiment revolves around the study of weathering caused by changes in moisture, it is important that there be no rapid changes in temperature for the duration of the experiment. In particular, it was critical to ensure that the temperature within the laboratory remained as static as possible, since weathering by thermal shock may occur if the temperature varies quickly within a short space of time. To this end, considerable effort was expended in the creation of a stable environment for the experimental setup. The experiment was carried out in a sealed room whose temperature was controlled by an air conditioner. In order to ensure that the temperature was indeed constant, i-button thermal sensors such as those pictured in Figure 4 were placed throughout the room and monitored constantly. To avoid rock damage by handling, the experiment was designed in such a way that samples were handled as little as possible. The samples were placed on porous plastic trays, and wetted by submersion (as done by Hall and Hall, 1996).

Conducting the experiment in this way means that the sample never needs to be touched physically, thus avoiding contamination by salts that are commonly found in human hands. In addition, the samples were only weighed once a week in order to restrict physical damage by handling. At any point in the experiment when the samples needed to be handled directly, latex gloves were worn in order to limit contamination. In order to reduce chemical effects generated from an external source, distilled water maintained at ambient laboratory temperature was used for the duration of the experiment. The cyclic wetting and drying aspect of the experiment was carried out in partial darkness, away from any direct illumination source

in order to reduce sample exposure to thermal and electromagnetic radiation from artificial light sources.



Figure 4. i-Button thermal sensors were used to monitor the atmospheric temperature in the lab to ensure that it remains within the established experimental parameters

3.5. *The Experiment*

The experiment takes elements from an array of different studies, although it is primarily based on the work carried out by Hall and Hall (1996) and Sumner and Loubser (2008). Figure 5 details the general method followed during this experiment. The key points to be taken from Figure 5 are that the physical rock properties and rock hardness were determined at the beginning of the experiment and again at the end and then compared to one another. Chemical analysis was only carried out at the end of the experiment because

chemical analysis requires the destruction of the samples, which obviously makes them useless for purposes of further experimentation.

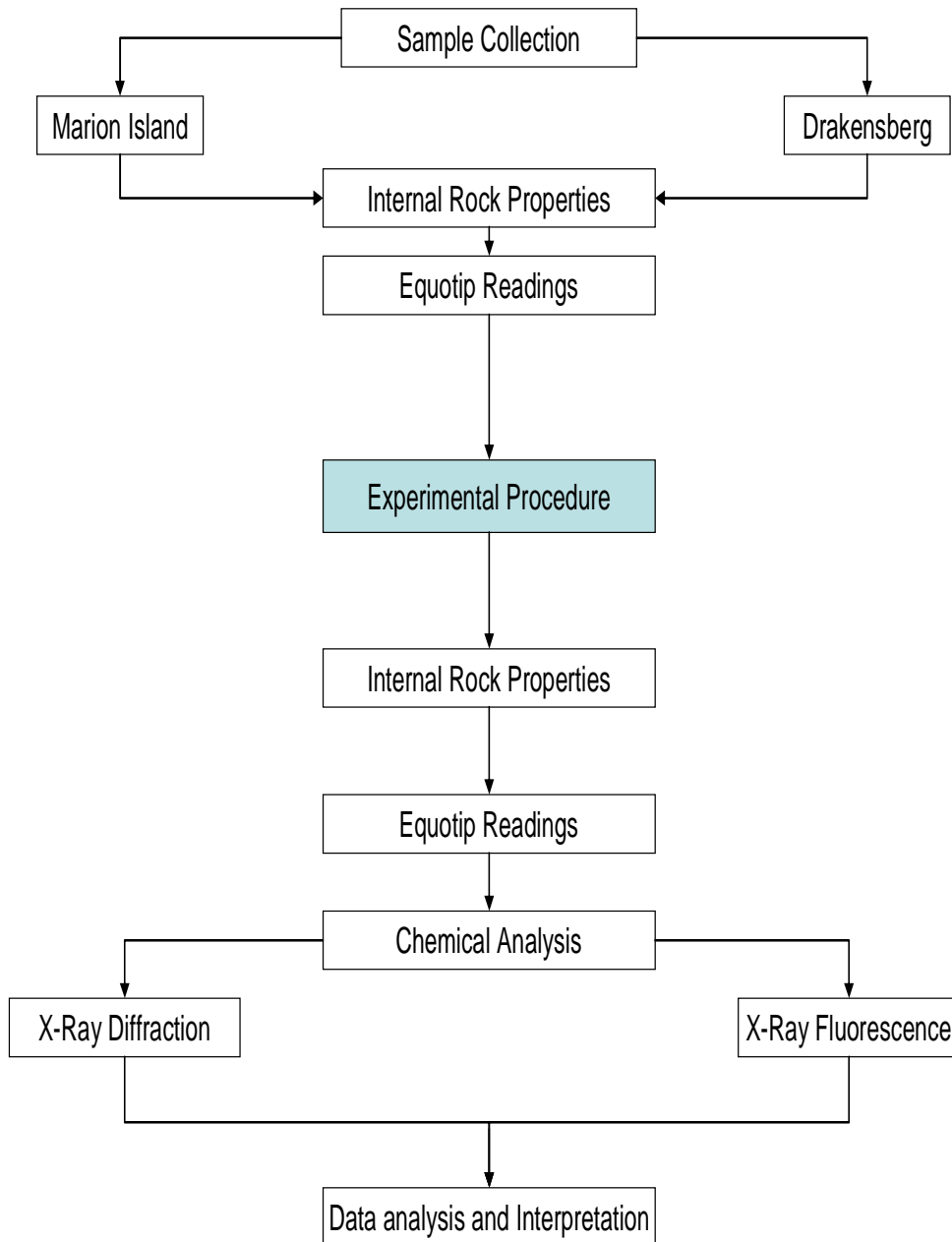


Figure 5. Experimental Procedure

The three sample sets were prepared for experimentation in the manner described in the Section 3.3. of this document. After preparation, the samples were divided in the manner displayed in figure 6, which is further explained in the paragraph that follows it.

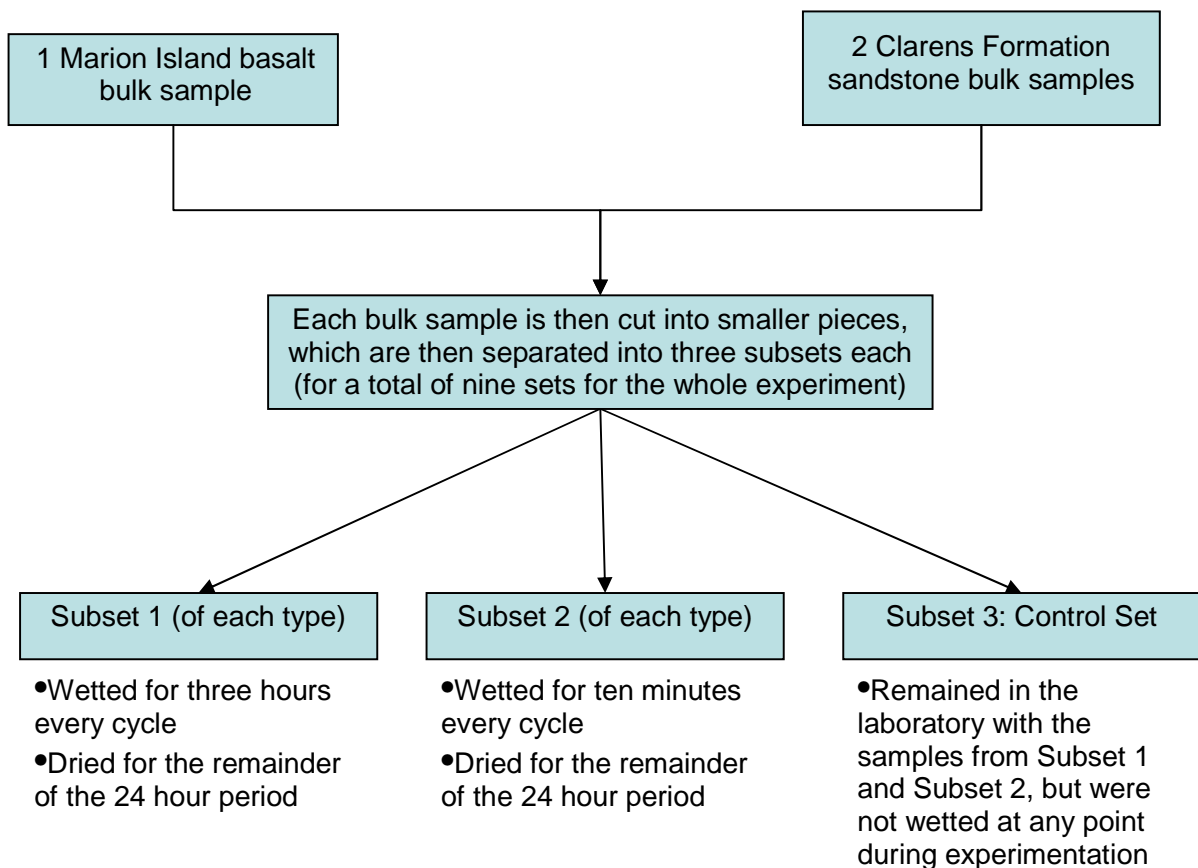


Figure 6. The division of prepared samples prior to the beginning of experimentation

Each rock type was divided into three subsets. The rocks that comprised subset 1 were saturated for three hours and then allowed to dry for the remainder of a 24 hour period. The rocks of subset 2 were only saturated for ten minutes and then allowed to dry for the

remainder of the same 24 hour period. These time periods were used because Sumner and Loubser (2008) compared Clarens Formation sandstone saturated for 2 minutes against Clarens Formation sandstone saturated for 6 minutes and found no significant difference in weathering effects. Thus, in this experiment, the moisture saturation amplitudes were set up to cover a wider range to see if any differences may be evident. The rocks in subset 3 were placed in the same laboratory environment as the rocks from subsets 1 and 2 and underwent all of the same physical rock property testing. The only difference between the rocks that were in subset 3 is that they were not exposed to any form of cyclic wetting and drying. This has been done because there is a possibility that the procedure that has been undertaken to establish the physical rock properties (Cooke, 1979) may be more damaging to the rock samples than the wetting and drying cycles. Even if the damage caused by the investigative process is minimal, it is important to be able to separate the weathering caused by cyclic wetting and drying from the damage caused by the investigative procedures. The inclusion of the samples in subset 3 will allow for the mathematical elimination of the negative effects brought about by the rigours of the physical rock property establishment. Subset 3, therefore, is the control set for this experiment.

Figure 7 shows the method that was followed to simulate the wetting and drying weathering process under laboratory conditions. The experiment was designed around a 7 day experimental cycle that is then repeated for the duration of the experiment. The experiment was conducted over a five month period and consisted of a total of 21 weekly cycles, made up of 105 wetting and drying cycles.

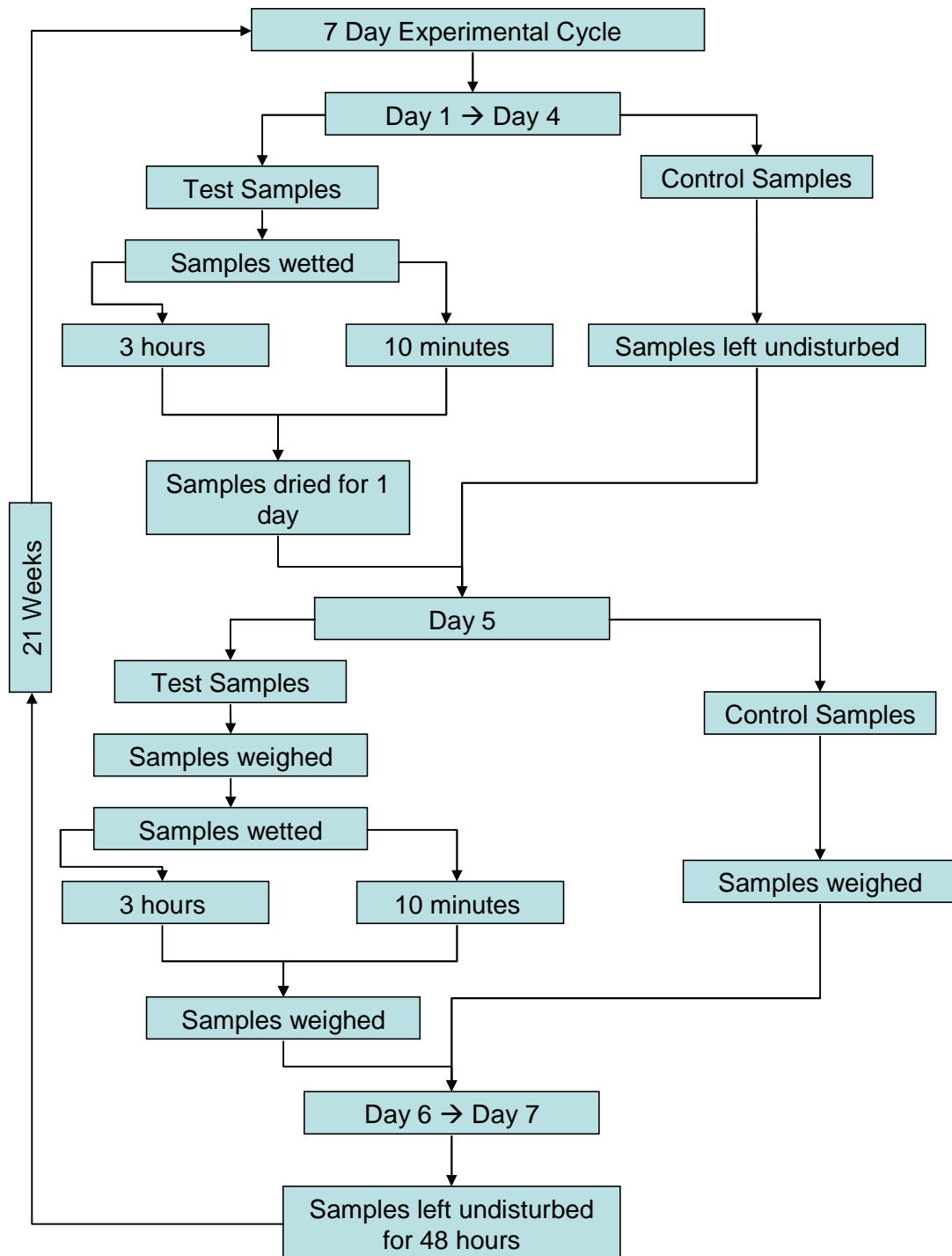


Figure 7. Flowchart detailing the precise method following over a 7 day period to simulate wetting and drying of the rock samples

The precise nature of the experiment that was implemented to simulate wetting and drying is given in Figure 7, but it will also be discussed here in more detail. The method used here is modeled very closely on that used by Hall and Hall (1996), but with some small modifications that have been included to keep the results that are obtained relevant to the study at hand. It also takes elements from the experiment carried out by Sumner and Loubser (2008), which was also based mostly on the work of Hall and Hall (1996). As has already been mentioned, the experiment takes the form of a set procedure laid out over a 7 day period that was then repeated exactly for 21 weeks (105 cycles). The format was as follows:

Day 1:

- The samples from subset 1 were placed on draining trays and completely immersed in a trough of distilled water for a period of three hours, as was done in the experiment by Hall and Hall (1996). At the end of the three hour period, the tray was lifted from the water and the samples were allowed to air dry for the remainder of the day.
- The samples from subset 2 were placed on draining trays and immersed in a trough of distilled water in the same manner as those from subset 1, but for only 10 minutes. At the end of that time, they were lifted from the water and allowed to air dry for the remainder of the day.
- The control samples were left untouched during this time.

Day 2 → Day 4: The procedure followed during Day 1 was repeated exactly for days 2 to 4.

Day 5:

- The samples from subset 1 were carefully weighed. After the mass of each sample in the subset had been measured, the samples were immersed in distilled water for three hours in the same manner as all of the other days. At the end of the three hour period, the samples were lifted from the trough of water and the surfaces of the samples were gently dried by hand with paper toweling to free the samples of excess surface moisture. Following this, they were immediately weighed again.
- The samples from subset 2 were weighed in the same way as the samples from subset 1. They were then immersed in distilled water for 10 minutes, gently surface dried and weighed again.
- The samples from subset 3 were weighed, but not wetted. In this way, a record of the change in the samples as a result of small changes in laboratory conditions was established to further eliminate or compensate for any experimental error.

Day 6 → Day 7: On these days, the samples were allowed to rest undisturbed. No wetting or weighing took place during this time. This is a similar procedure to that followed by Hall and Hall (1996).

The samples were not rotated during the experiment. The upper surface remained pointing upwards during the course of the experiment.

At the end of Day 7, the procedure was repeated again from Day 1 and cycled through 147 days.

3.6: Physical properties of rock samples

Since weathering is defined by the Bland and Rolls (1998) as rock alteration caused by some external environmental source, a clear understanding of the changes in internal rock properties is paramount to understanding the effects of any weathering processes that are taking place. Measurement and computation of the internal rock properties in this experiment was done by the method laid down by Cooke (1979). This method was chosen primarily due to its simplicity and relatively non-destructive nature. Although this method may not be intensely accurate (results being determined in large part by changes in experimental procedure rather than actual rock property differences), it is known to have high degree of precision, which makes it extremely useful for contrast studies such as this one. Since Cooke's method does not require the destruction (or indeed, severe alteration) of the rock sample, as many high precision methods do, the procedure can be carried out at the beginning of the experiment, as well as at the end on the same rock sample sets (as done by Hall and Hall, 1996; Sumner and Loubser, 2008). Unfortunately, due to the fact that Cooke's method requires heating and cooling of the rocks (thus introducing a change in temperature that may cause limited amount of thermal stress) in order to take some of the measurements, it is important to include experimental control samples that do not go through the cyclic wetting and drying part of the experiment. This is done so that any rock weathering that is caused by the establishment of internal rock properties by Cooke's method can be quantified and accounted for mathematically. Because of the potential weathering the rocks could undergo by this method of internal property establishment, it was decided that internal rock properties will only be measured twice, once at the beginning of the experiment and once at the end. However, the saturated and air-dried masses of the samples were measured once every week so that mass changes could be monitored continuously.

3.6.1: Internal rock property establishment

The percentage saturation, micro-porosity, porosity, water absorption capacity and saturation coefficients (Cooke, 1979) of the test samples were determined. For purposes of context, it is important to accurately define each of the above physical properties so that the changes that are noted in the samples can be clearly understood. Part of the apparatus used in this experiment is shown in Figure 8.

The experiment runs as follows:

- The samples were dried for 24 hours 105°C and then weighed (W_0 : dry mass).
- The samples were then saturated in distilled water for 24 hours and weighed again (W_3 : wet mass)
- The samples were then dried again for 24 hours at 105° C, after which they were placed into a desiccator that was evacuated to the maximum extent that the vacuum pump was capable of (atmospheric pressure minus 76 kPa) and left for two hours. The samples were then saturated under vacuum left for a further 16 hours and then weighed (W_2 : complete vacuum saturated mass)
- the samples were then weighed while suspended in distilled water (W_1 : suspension weight).
- The samples were then placed back in a desiccator, which was then evacuated to 'atmospheric pressure minus 65 kPa' (equivalent to the 286 mm Hg specified by Cooke, 1979) and left for a further 24 hours, after which they were weighed again (W_4 : partial vacuum mass)

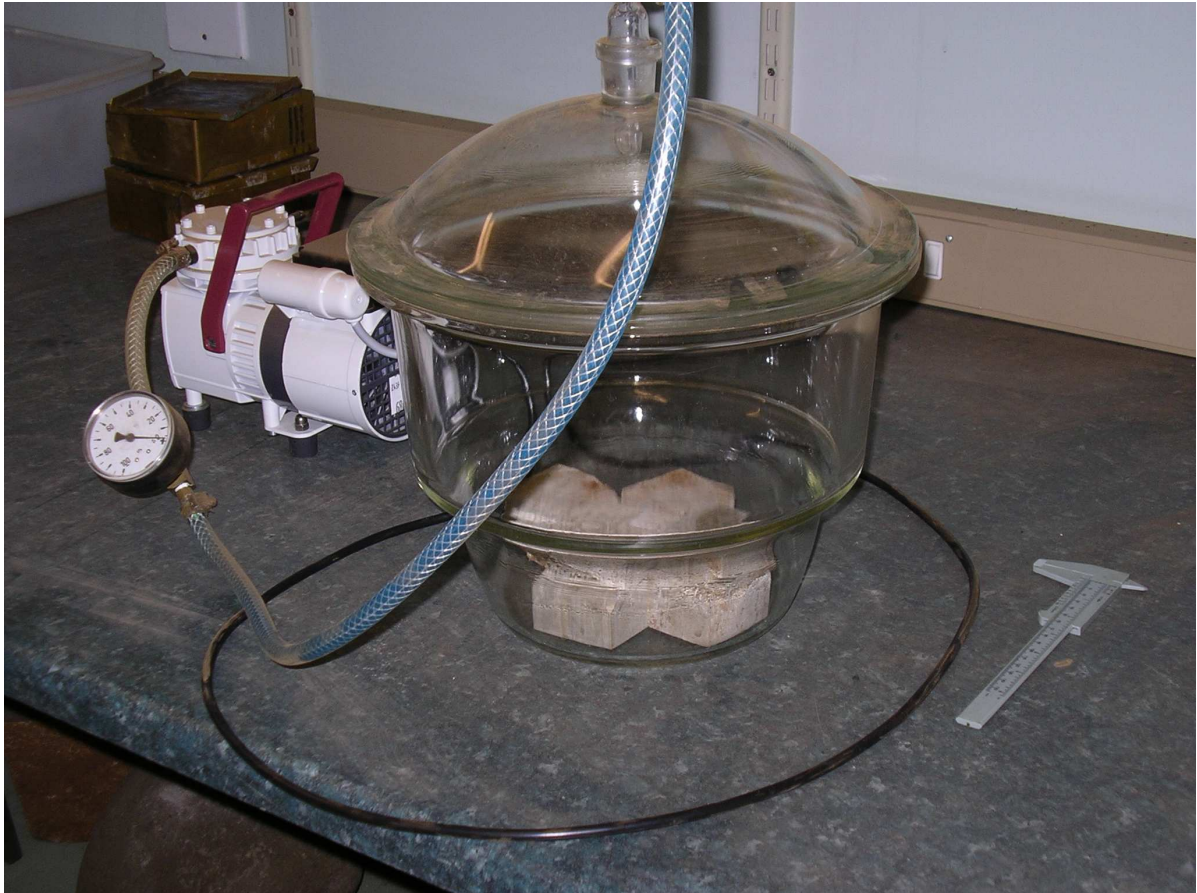


Figure 8. A desiccator and vacuum pump, part of the apparatus used for the establishment of the internal rock properties of the rocks investigated in this study

Percentage saturation: percentage saturation is the ratio of dry mass to wet mass, expressed

as a percentage. The equation is as follows: $\% \text{ Saturation} = \left(\frac{W_0}{W_3} \times 100 \right)$

Porosity: the total volume of pore space in a sample expressed as a percentage of total volume. The equation for porosity is as follows:

$$\text{Porosity} = \left(\frac{W_2 - W_0}{W_2 - W_1} \right) \times 100$$

Micro-porosity: the traditional definition of micro-porosity is the total volume of pore space with a diameter of less than 1 μm , expressed as a percentage of total available pore space. However, in the context of Cooke's experiment micro-porosity requires a different

definition. In this adaptation of the experiment micro-porosity will be defined as "the amount of water retained under negative pore water pressure generated by a vacuum of 'atmospheric pressure minus 76 kPa', expressed as a percentage of available pore space" (adapted from Cooke, 1979, p.354) The equation for micro-porosity is as follows:

$$\text{Micro-porosity} = \left(\frac{W_4 - W_0}{W_2 - W_0} \right) \times 100$$

Water absorption capacity: this is defined as "a measure of the amount of water absorbed in a specific time" (quoted directly from Cooke, 1979 p. 354). The equation is as follows:

$$\text{Water-absorption} = \left(\frac{W_3 - W_0}{W_2 - W_1} \right) \times 100$$

Saturation coefficient: "the amount of water absorbed in 24 hours expressed as a fraction of the volume of available pore space" (quoted directly from Cooke, 1979, p. 354). The equation to saturation coefficient is as follows:

$$\text{Saturation-coefficient} = \left(\frac{W_3 - W_0}{W_2 - W_0} \right)$$

By observing how these values change between the beginning and the end of the experiment, it will be possible to gain an understanding of how the internal rock structure is changing over time. For example, changes in the water absorption capacity and saturation coefficient values will show how the rock's ability to absorb moisture has changed over the experimental period. Porosity, micro-porosity and percentage saturation values will all give indications as to how the rock pore structure has altered over time.

3.6.2: Equotip measurements

The Equotip was developed in 1975 to precisely measure the hardness of artificially manufactured building materials, but it has only recently been considered for use on natural rock. Geomorphologists are beginning to study this tool with considerable interest as it has a much lower force of impact than the Schmidt Hammer, which makes it less destructive to rock samples being tested and more sensitive in the measurement of the strength of a weathered surface (Aoki and Matsukura, 2007). Because of the low impact force the minimum rock size (mass) that an Equotip could measure is much smaller than that of the Schmidt Hammer (25 kg), as noted by Sumner and Nel (2002). Due to the small size of the samples and the precision of the results, the Equotip is an effective indicator of changes in surface hardness of a natural substance over time. Sixteen Equotip readings were taken per sample (eight measurements on each ab-plane in a pattern consistent across all samples in the pattern indicated by figure 9). These measurements were taken on the upward facing plane of the sample, as well as on the downward facing plane.

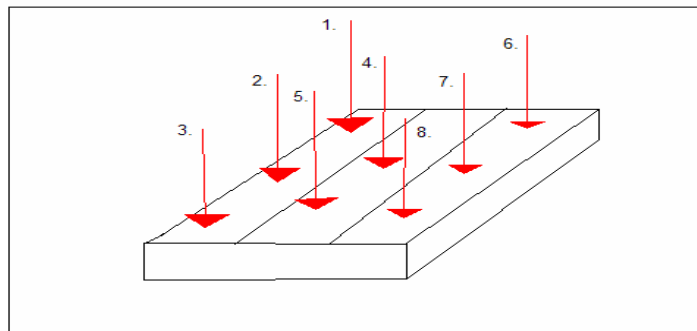


Figure 9. Equotip impact hammer placement on the ab-plane of all samples

It is believed that weathered surfaces will yield lower Equotip hardness readings than unweathered surfaces. Equotip readings were taken at the beginning of the experiment and again at the end. These readings are of particular interest because it gives an indication of

weathering taking place only in the upper few millimeters of the samples. This is important because it will start to show where wetting and drying is effective; at the surface of a rock sample or within the interior. Another interesting idea is the relationship between surface weathering of a sample and the standard deviation of Equotip measurements on that surface. It is believed that a highly deformed surface will be indicated by hardness measurements that are not clustered around the average value. Specifically, a weathered surface should have a higher number of Equotip readings that are unusually low, which will lead to a higher standard deviation. In contrast, a freshly cut sample should be quite smooth by comparison and therefore have a much more clustered Equotip profile.

3.7. Chemical Results

Cuttings from the samples were sent to the XRF division at the University of Pretoria to determine the elemental composition of the samples that were studied. The results obtained from the XRF studies are given in Appendix A. Chemical analysis of moisture leached from the samples was considered, but discarded as it was not known whether the anion and cation analysis of such moisture would be indicative of weathered products caused by chemical weathering, or merely the result of rehydrated salt precipitates being flushed from the rock. Future studies should be considered that address these problems in order to better determine what (if any) chemical weathering is taking place in an experiment such as this one.

X-ray Fluorescence Spectroscopy is a common method for the establishment of elemental composition of a variety of substances. The sample preparation and XRF analysis was carried out at the Stoneman Laboratory at the University of Pretoria. Rocks were placed in a jaw crusher to reduce them to a coarse gravel, after which they were further reduced by means of a tungsten carbide milling vessel. This ensured that the average particle size of the sample did not exceed 75 μm . The samples were then roasted at 1000 $^{\circ}\text{C}$ to determine Loss

of Ignition, after which 1g of sample was added to 6g of $\text{Li}_2\text{B}_4\text{O}_7$ and fused into a glass bead. Major element analysis was carried out on the fused bead using an ARL9400XP+ spectrometer. Some of the sample was also pressed into a powder briquette for trace element analyses. The results (i.e. the elemental composition of the samples used in this experiment) are given in Appendix A.

The data that have been collected by following of the method laid out in Chapter 3 are presented in Chapter 4, along with analysis and observations. The discussion of the data and subsequent analyses are given in Chapter 5.

Chapter 4: Results and Observations

4.1. Introduction

The results and observations chapter is divided into three main sections. Section 4.2 explains the environmental stability precautions taken during the experiment to remove unnecessary physical weathering (particularly weathering relating to thermal change). Sections 4.3. and 4.4. detail the changes in physical rock properties over the duration of the experiment; both internal rock properties and surface characteristics.

4.2. Environmental Control

This section of the results chapter does not yield any information about the wetting and drying weathering process itself. Rather, it exists to demonstrate the relative environmental stability of the experimental setup. It is important to establish this, since a recognised Climate Control Cabinet could not be obtained for this experiment. The following results serve to demonstrate that the environment was as stable as it could be made, within the limitations of equipment and finance. At various times during the experimental timeframe, i-Button thermal sensors were placed adjacent to the samples in the laboratory and checked to ensure that the environment remained as static as possible. The sensors were set to take thermal measurements every minute. This was done to ensure that excessive and rapid air temperature variation did not occur within the laboratory environment, a situation that can lead to weathering by thermal shock. These readings were not taken throughout the experimental period, but considerable amounts of data have been gathered and it shows good temperature consistency during the times that it was measured. Four sensors were used; one sensor placed next to each porous tray upon which the samples rested. The sensors were placed as close to the samples as was possible without interfering with them.

Table 5 clearly shows that the conditions in the laboratory were maintained at a constant average temperature of 18.6 °C. More importantly, the data show that any temperature changes that occur within the laboratory during the experiment occurred at a rate slower than 2°C/min, a rate of fluctuation greater than which could result in thermal shock (Hall and André, 2001). Graphs showing a visual representation of these results are given in Appendix B.

Sensor	Average (°C)	Standard Deviation	Maximum measured temperature change per minute (°C)	Average measured temperature change per minute (°C)
Sensor 1 (n = 12266)	18.46	0.37	1.5	0.09
Sensor 2 (n = 14312)	18.62	0.48	1.5	0.08
Sensor 3 (n = 11647)	18.66	0.46	1.5	0.08
Sensor 4 (n = 11084)	18.8	0.5	1.5	0.09

Table 5. Average laboratory temperature with standard deviation (n = number of readings)

4.3. Physical properties

Quantification of the degree and intensity of the weathering taking place will be done by analysing changes in physical rock properties. By determining internal rock properties of the various samples, it is possible to gain an understanding of the nature of the internal rock structure. Determining how the internal rock structure changes over time also allows the researcher to determine the nature and intensity of the weathering process (in this case, wetting and drying) under investigation. Weekly mass measurements are taken to establish a moisture uptake and moisture release profile. While information regarding the structure of a

rock is not directly revealed by this measurement, it allows for a somewhat continuous monitoring of the experiment and gives some indication as to how the sample changed with time. The primary data by which rock sample change will be determined comes from the study of the change in internal rock properties from the beginning to the end of the experiment. This information could not be obtained on a continuous basis (the reasons for this are outlined in more detail in chapter 3), but the data are far more detailed than the simple mass measurements taken every week. Table 6 shows total mass loss for all samples over the course of the experiment.

Samples Saturated for 3 hours			
Number	Initial mass (g)	Final mass (g)	Mass Difference (g)
1 1	173.63	173.64	0.01
1 2	152.15	152.16	0.01
1 3	162.5	162.53	0.03
1 4	182.1	182.11	0.01
1 5	208.18	208.18	0
2a 1	196.91	196.12	-0.79
2a 2	189.17	188.29	-0.88
2a 3	161.76	161	-0.76
2a 4	214.32	213.45	-0.87
2b 1	204.61	204.25	-0.36
2b 2	179.11	178.83	-0.28

Control Samples			
Number	Initial mass (g)	Final mass (g)	Mass Difference (g)
1 C1	200.14	200.17	0.03
1 C2	158.48	158.5	0.02
1 C3	195.07	195.1	0.03
2a C1	190	189.65	-0.35
2a C2	183.45	183.07	-0.38
2b C1	184.3	184.24	-0.06
2b C2	166.07	166.02	-0.05

Samples Saturated for 10 minutes			
Number	Initial mass (g)	Final mass (g)	Mass Difference (g)
1 6	215.43	215.45	0.02
1 7	171.7	171.72	0.02
1 8	164.36	164.38	0.02
1 9	164.97	164.98	0.01
1 10	157.67	157.67	0
2a 5	147.93	147.42	-0.51
2a 6	149.62	149.04	-0.58
2a 7	156.71	156.16	-0.55
2a 8	177.26	176.63	-0.63
2a 9	143.5	142.97	-0.53
2a 10	172.54	171.85	-0.69
2a 11	214.57	213.67	-0.9
2a 12	168.92	168.22	-0.7
2a 13	177.77	177.05	-0.72
2b 3	169.28	168.99	-0.29
2b 4	163.64	163.37	-0.27

Table 6. Initial and final mass of all individual samples used in the experiment

The samples shown here are those that ended the experimental cycle without fracturing. Two samples (both from Set 2a), fractured into two pieces after 40 wetting cycles and were discarded, since measuring of physical properties would no longer be possible. However, the sample fracturing is significant since this demonstrates that weathering (in terms of mass loss) had taken place. Reasons for this are given in Chapter 5.

4.3.1. Weekly sample mass measurements taken before wetting

Hall and Hall (1996) took mass measurements before and after every wetting session. In contrast, the experiment done here differs from that in that measurements were only taken at the beginning of every 5th wetting session (i.e. at the end of every working week). This, as explained in Chapter 3, was done to reduce the damage of the samples by physical handling as much as possible. However, even with the reduced data resolution that a weekly measurement program will cause, it is still possible to conduct a trend analysis from which much can be learned. Rather than expressing the mass in grams, which would have made comparison between the various sample sets impossible, all measured mass values have been converted to sample moisture saturation, expressed as a percentage. This simple mathematical procedure allows the data to be expressed in a more concise way and makes comparison between different sample sets possible. Conversion from mass to moisture saturation percentage was done using the following equation:

$$\% \text{ Saturation} = \left(\frac{m_x}{w_3} \right) \times 100,$$

where m_x is the measured sample mass for cycle x and w_3 is the complete moisture saturation value of the sample in question under normal atmospheric conditions.

4.3.1.1. Weekly measurements of rock mass for all samples saturated for 3 hours per cycle over the duration of the experimental period

Figure 10 shows an amalgamation of mass measurements taken before each wetting session, which have been converted into moisture saturation percentages. What this graph effectively shows is the amount of moisture that each sample set retains on average over a 24 hour period. Set 2b had the highest recorded dry mass at a value of 33.87%, while Set 1 had the lowest recorded value at 21.51% (as recorded in Table 7). To clarify, this means that the samples that make up Set 2a still retain 33.87% of their maximum possible saturation values after drying for 21 hours, while those in Set 1 retain 21.51% of their maximum possible saturation values after the same period of time; a difference of 12.36%. An interesting observation that can be made about dry masses of all the sample sets is that they appear to share similar peaks and troughs at various points in the experimental cycle. In particular, Set 1 and Set 2a share an almost identical curve across the entire experimental period. It is also noted that Set 1 (Marion Island basalt) has consistently lower dry mass values than either of the samples from the Clarens Formation.

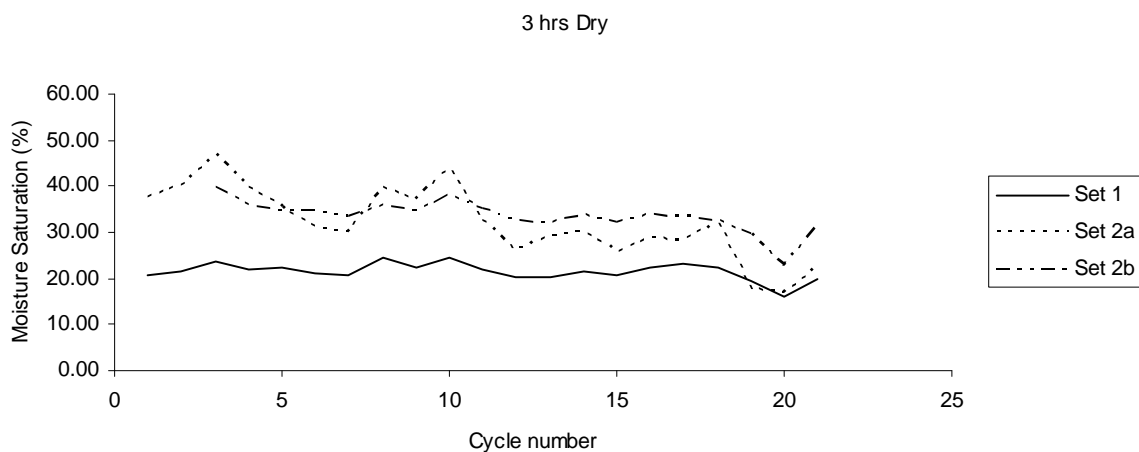


Figure 10. The average rock mass of the 3 hour Sets measured before the samples were wetted

Set number	Average Saturation value	Standard Deviation
1 (n = 5)	21.51	1.91
2a (n = 4)	32.00	7.93
2b (n = 2)	33.87	3.87

Table 7. Average values and Standard Deviation over the entire time frame of the experiment

4.3.1.2. Weekly measurements of rock mass for all samples saturated for 10 minutes per cycle over the duration of the experimental period

As with the samples that were saturated for three hours, Set 2a now has the highest average saturation value (29.03%), while Set 1 has the lowest (18.57%), values which are shown in Table 8. Once again, distinct similarities in the graph curves can be seen across the various sets (Figure 11). Additionally, Set 2a and Set 2b (the Drakensberg sandstones) have both demonstrated a downward trend, while Set 1 (the Marion Island basalt) has shown a neutral trend. A downward trend shows that over time, the samples in that set are retaining less moisture than they were at the beginning of the experimental cycle.

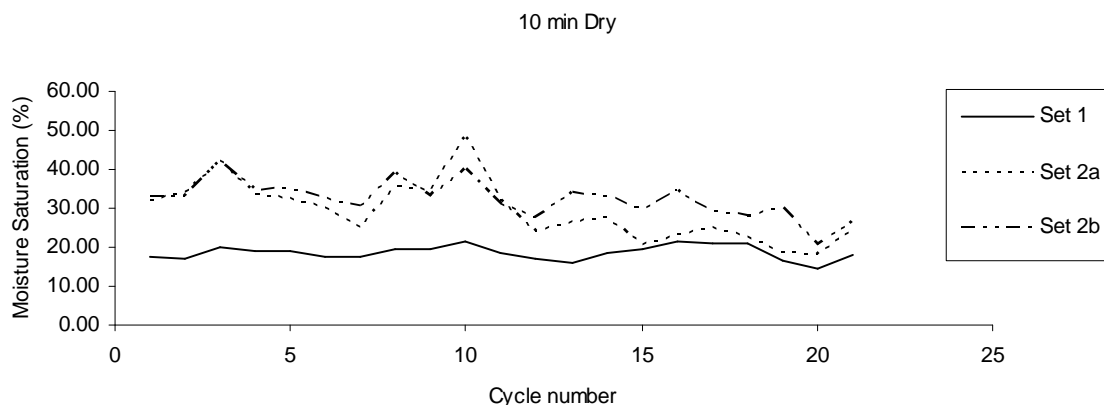


Figure 11. The average rock mass of the 10 minute Sets measured before the samples were wetted

Set number	Average Saturation value	Standard deviation
1 (n = 5)	18.57	1.81
2a (n = 6)	29.03	7.52
2b (n = 2)	32.19	4.83

Table 8. Average values and Standard Deviation over the entire time frame of the experiment

4.3.1.3. Weekly measurements of rock mass for samples that served as a control for the duration of the experimental period

In the control set, Set 2a retains the most moisture, on average, with a value of 16.75%, while Set 1 retains the least moisture, with a value of 12.50% (shown in Table 9). As before, the graph curves bear a marked similarity to one another (Figure 12). Since the control samples were not saturated at any point during the experiment (save when the physical rock properties were being determined), it is believed that the fluctuating moisture saturation values have been caused by changes in ambient moisture levels. It is interesting to note that while the masses before wetting and after wetting are not always consistent over a given time period, the moisture saturation range generally is.

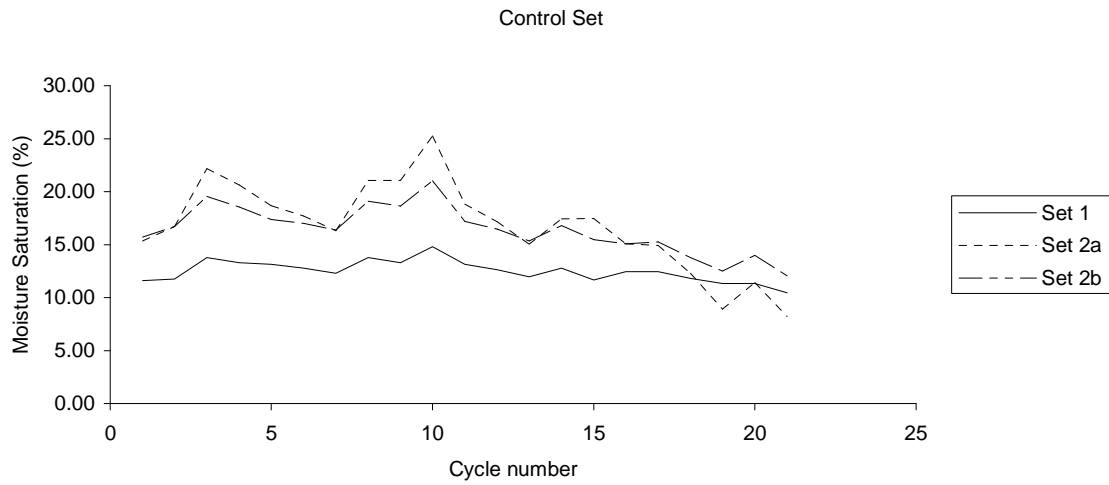


Figure 12. The average rock mass of the Control Sets measured before the samples were wetted

Set number	Average Saturation value	Standard deviation
1 (n = 3)	12.50	1.02
2a (n = 2)	16.75	4.23
2b (n = 2)	16.38	2.26

Table 9. Average values and Standard Deviation over the entire time frame of the experiment

4.3.2. Weekly sample mass measurements taken directly after wetting

As in the case of the dry mass values, the saturated mass values have been converted to moisture saturation values, expressed as a percentage. The equation used here

is $\% \text{ Saturation} = \left(\frac{n_x}{w_3} \right) \times 100$, where n_x refers to the mass of the samples taken after the

wetting period of cycle x and w_3 is once again the full saturated mass the sample can attain under normal atmospheric conditions.

4.3.2.1. Weekly measurements of rock mass for all samples saturated for 3 hours per cycle over the duration of the experimental period

Figure 13 shows an amalgamation of mass measurements taken directly after the wetting cycle and converted into moisture saturation percentage form. This shows the amount of moisture that the samples are taking in in a single wetting cycle. Table 10 shows that sample sets 1 and 2b (Marion Island basalt and one of the Clarens Formation sandstones) have an average saturation value in excess of 90%, while Set 2a (the other Clarens Formation sandstone) saturated to a mere 69.78% over the same period. In addition, the values in Set 2a show marked decrease over the experimental period, while saturation values of the other two sample sets remain more constant. Set 2a attains its maximum saturation value on the third cycle (79.22%) and its minimum saturation value on the 19th (third last) cycle (59.29%). This is a difference of 19.93% under static environmental conditions between the beginning of the experiment and the end. A decreasing value here indicates that the samples are absorbing less moisture during the later cycles than they were at the beginning of the experiment. This will be discussed more fully in chapter 5.

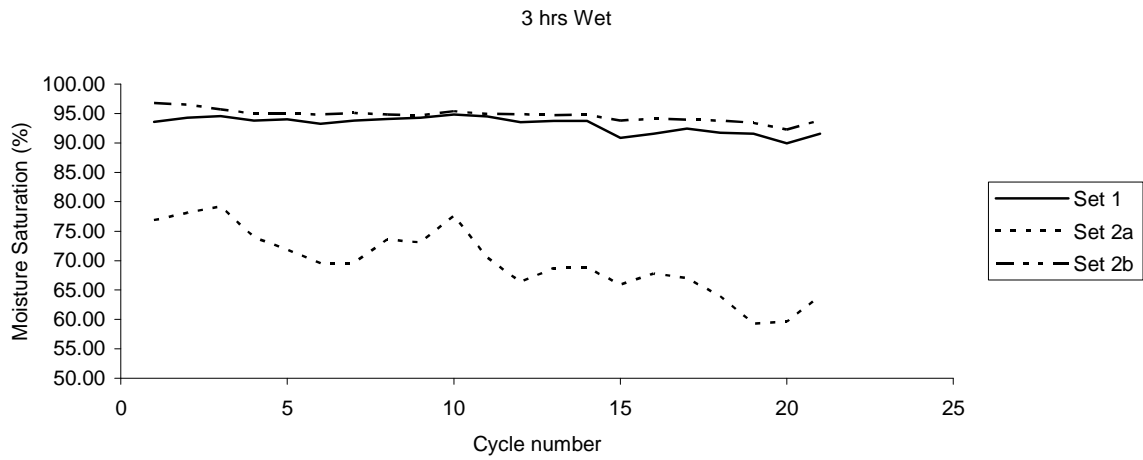


Figure 13. The average rock mass of the 3 hour Sets measured after the samples were wetted

Set number	Average Saturation value	Standard Deviation
1 (n = 5)	93.13	1.39
2a (n = 4)	69.78	5.66
2b (n = 2)	94.68	1.01

Table 10. Average values and Standard Deviation over the entire time frame of the experiment

4.3.2.2. Weekly measurements of rock mass for all samples saturated for 10 minutes per cycle over the duration of the experimental period

Set 2a has the lowest Average Moisture Saturation Value (42.62%) and Set 2b has the highest value (58.43%), as seen in Table 11. The difference between 2a and 2b (15.81%) is significant because the two samples are both sandstones. The results are given graphically in Figure 14.

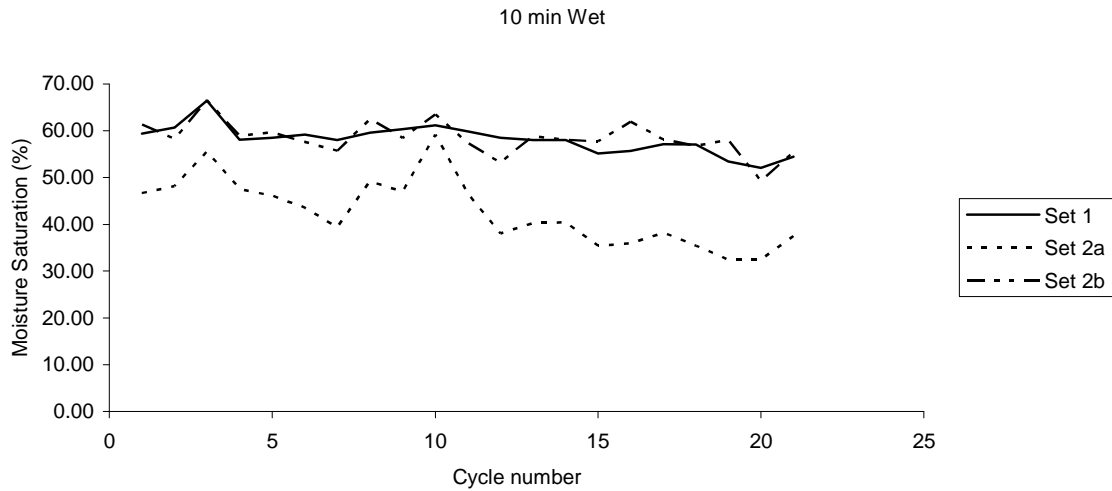


Figure 14. The average rock mass of the 10 minute Sets measured after the samples were wetted

Set number	Average Saturation value	Standard deviation
1 (n = 5)	58.12	3.06
2a (n = 6)	42.62	7.24
2b (n = 2)	58.43	3.62

Table 11. Average values and Standard Deviation over the entire time frame of the experiment

4.3.3. Computed moisture saturation amplitudes of the samples

Sumner and Loubser (2008) studied the effects of different moisture amplitudes on the weathering of Clarens Formation sandstone. There was no detectable difference in the extent of weathering between various moisture amplitudes, even though the entire experiment was conducted on only one type of stone. A version of the experiment is conducted here for all rock types under investigation. Where the study conducted by Sumner and Loubser (2008) studied different weathering effects of four different moisture amplitudes, in this case, only two were used for each set (displayed in Appendix C). However, this study investigates changes

in moisture amplitude across an array of different types of rock, as well as being studied over a greater moisture amplitude range.

4.3.3.1. Moisture saturation amplitudes of samples that were saturated for 3 hours per cycle over the duration of the experimental period

Even though the rock samples were all saturated for exactly the same length of time, the moisture range differs significantly across the set range. Figure 15 and Table 12 indicates that Set 1 has the greatest moisture saturation range (71.62%), while Set 2a has the smallest (37.78%). It should be noted that although the masses measured for the samples before each wetting period fluctuated quite significantly across all sets, but the range has yielded fairly stable trends across all sets. This will be discussed more fully in the Discussion chapter of this document (Chapter 5).

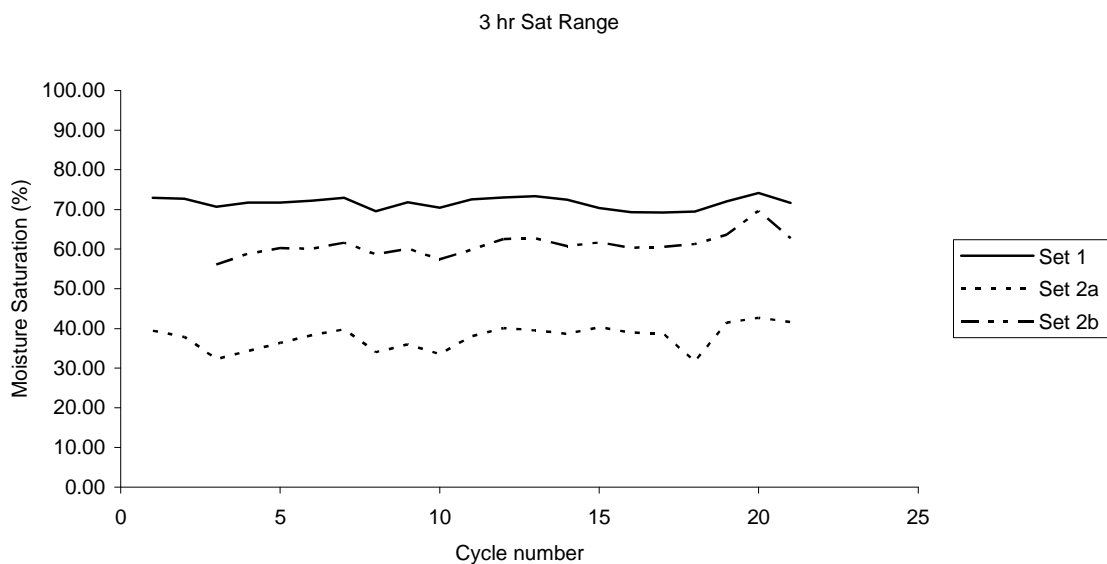


Figure 15. The Moisture Amplitude for the 3 hour Set

Set number	Average Saturation value	Standard deviation
1 (n = 5)	71.62	1.47
2a (n = 4)	37.78	3.12
2b (n = 2)	60.72	3.03

Table 12. Average values and Standard Deviation over the entire time frame of the experiment

4.3.3.2. Moisture saturation amplitudes of samples that were saturated for 10 minutes per cycle over the duration of the experimental period

Set 1 (Marion Island basalt) had the highest range of saturated values (39.55%), while Set 2a (Drakensberg sandstone) had the lowest range of saturated values (14.24%). These values are given in Figure 16 and Table 13. As in the case with the samples that were saturated for 3 hours, the samples saturated for 10 minutes have individual wet and dry masses that fluctuate noticeably, but have a moisture saturation amplitude that is much more stable. This indicates that while the absolute dry masses and saturated masses vary from day to day, the moisture saturation amplitudes themselves do not. Thus, regardless of the initial moisture saturation level, the rock will absorb a constant amount of moisture at a consistent (but not necessarily linear) rate. This holds true for the saturation ranges tested in this experiment, but it is not certain what will occur beyond these ranges. A logarithmic trend has been empirically measured (see Appendix D), which shows that a sample's rate of moisture absorption will slow as it becomes highly saturated. However, for lower saturation levels (such as those measured in this experiment), the absorption rate is close to linear.

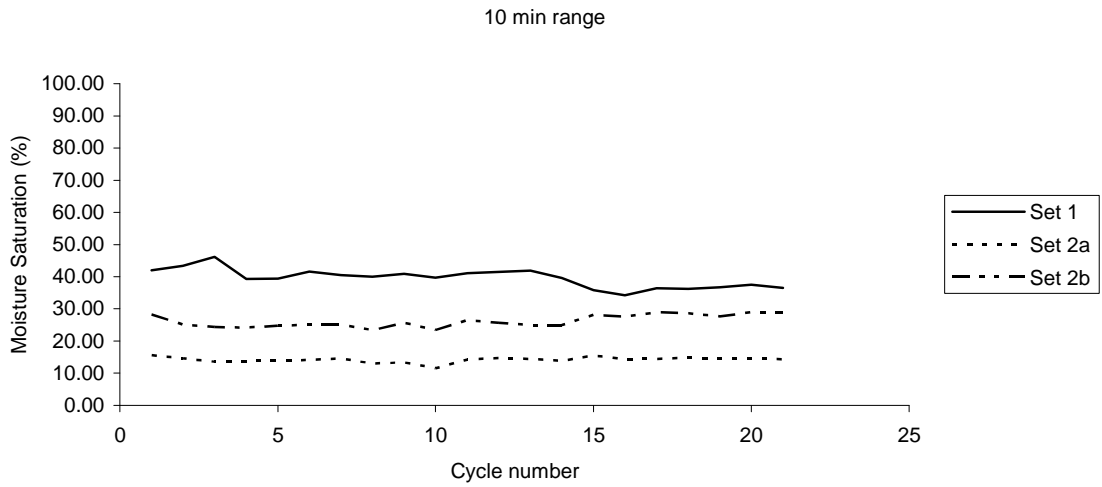


Figure 16. The Moisture Amplitude for the 10 minute Set

Set number	Average Saturation value	Standard deviation
1 (n = 5)	39.55	2.90
2a (n = 6)	14.24	0.87
2b (n = 2)	26.23	1.90

Table 13. Average values and Standard Deviation over the entire time frame of the experiment

4.3.4. Tabular overview measured changes in physical rock properties

This section will catalogue the changes in physical rock properties by contrasting the properties measured at the beginning of the experiment with those measured at the end. The data will be presented via a series of graphs and tables. To begin with, all of the physical rock property changes will be displayed in a set of three tables, divided up by the time each sample set remained saturated. This gives an overview of the data gathered during this section of the study and allows for easy access to all of the data. The data has been organised in this fashion because it allows both for easy comparison of numerical values within each set, as well as comparison between the sets. Each data set will be briefly described and relevant

observations will be made. Once the total data set has been presented, the information will be distilled into smaller sections that will make detailed analysis and observation easier and more understandable. These smaller sections will be represented both in tabular form as well as graphically.

Table 14 to Table 16 detail the changes in physical rock properties detected in the samples that were saturated for every wetting cycle, divided up by length of time the samples spent immersed (3 hours; 10 minutes; Control set). It is important to note that the microporosity values for Set 2a appear to be impossible. Because these variances occur across the whole range of samples in set 2a, it can be inferred that this is because of some form of experimental error incurred during the establishment of the internal rock properties; since the experiment was performed in exactly the same way at the end of the experimental period as at the beginning, any changes that occurred in internal rock structure for Set 2a will still be apparent. Because this is a contrast study, these apparently impossible micro-porosity values have been retained, rather than adopting the more conventional approach of merely stating all excessive micro-porosity values as 100%.



3 Hour Sets					
Set 1	Saturation (%)	Porosity (%)	Water Absorption Capacity (%)	Saturation Coefficient (/1)	Micro-porosity (%)
Initial Values	1.66	4.79	3.01	0.63	92.86
Final Values	1.01	4.48	2.86	0.64	88.56
Difference	0.65	0.30	0.14	-0.01	4.29
Set 2a	Saturation (%)	Porosity (%)	Water Absorption Capacity (%)	Saturation Coefficient (/1)	Micro-porosity (%)
Initial Values	1.70	4.41	4.72	1.07	98.20
Final Values	1.97	5.34	5.00	0.96	102.27
Difference	-0.27	-0.93	-0.29	0.11	-4.07
Set 2b	Saturation (%)	Porosity (%)	Water Absorption Capacity (%)	Saturation Coefficient (/1)	Micro-porosity (%)
Initial Values	3.49	8.70	7.41	0.85	98.02
Final Values	3.07	8.48	7.38	0.87	97.79
Difference	0.42	0.22	0.03	-0.02	0.23

Table 14. Final physical rock properties contrasting to the initial physical rock properties for the samples saturated for 3 hours

10 Minute Sets					
Set 1	Saturation (%)	Porosity (%)	Water Absorption Capacity (%)	Saturation Coefficient (/1)	Micro-porosity (%)
Initial Values	1.67	4.80	2.91	0.61	93.39
Final Values	1.00	4.47	2.83	0.63	90.02
Difference	0.67	0.33	0.08	-0.03	3.37
Set 2a	Saturation (%)	Porosity (%)	Water Absorption Capacity (%)	Saturation Coefficient (/1)	Micro-porosity (%)
Initial Values	1.71	4.44	4.77	1.08	98.42
Final Values	2.08	5.06	5.28	1.05	108.24
Difference	-0.37	-0.62	-0.52	0.02	-9.83
Set 2b	Saturation (%)	Porosity (%)	Water Absorption Capacity (%)	Saturation Coefficient (/1)	Micro-porosity (%)
Initial Values	3.59	8.92	7.45	0.84	98.87
Final Values	3.11	8.61	7.44	0.86	98.07
Difference	0.48	0.31	0.02	-0.03	0.80

Table 15. Final physical rock properties contrasting to the initial physical rock properties for the samples saturated for 10 minutes

Control Sets					
Set 1	Saturation (%)	Porosity (%)	Water Absorption Capacity (%)	Saturation Coefficient (/1)	Micro-porosity (%)
Initial Values	1.75	5.02	3.08	0.61	94.27
Final Values	1.01	4.68	2.86	0.61	91.87
Difference	0.73	0.34	0.23	0.00	2.40
Set 2a	Saturation (%)	Porosity (%)	Water Absorption Capacity (%)	Saturation Coefficient (/1)	Micro-porosity (%)
Initial Values	1.79	4.64	4.88	1.06	108.96
Final Values	1.88	5.04	4.77	0.95	103.59
Difference	-0.09	-0.40	0.11	0.11	5.37
Set 2b	Saturation (%)	Porosity (%)	Water Absorption Capacity (%)	Saturation Coefficient (/1)	Micro-porosity (%)
Initial Values	3.61	8.96	7.50	0.84	97.17
Final Values	3.03	8.49	7.24	0.85	97.09
Difference	0.58	0.48	0.25	-0.02	0.08

Table 16. Final physical rock properties contrasting to the initial physical rock properties for the samples that served as the Control Set for the duration of the experiment

4.3.5. 3 hour saturation compared to 10 minute saturation

Calibrating studies done at the beginning of this experiment (explained further in Appendix D) strongly suggested that there is a logarithmic relationship between the length of time that a sample was submerged and the amount of moisture that it would absorb. Thus, samples saturated for a longer period of time should absorb more moisture than a sample taken from the same type of rock, but saturated for a shorter period of time. To check the validity of this predefined study axiom, the difference in moisture saturation for samples saturated for 3 hours have been compared with the samples saturated for 10 minutes. Since the graph represents a simple difference calculation (10 minute moisture saturation subtracted from 3 hour moisture saturation for every cycle of wetting and drying), if the initial assumption was correct, all lines on the graph should be positive at all times. Figure 18 shows that this is indeed the case. However, Figure 17 indicates that during the drying cycle, the same is only true for Set 1 (Marion Island basalt). Set 2a and Set 2b both have cycles where the samples saturated for 3 hours retained less moisture than the samples saturated for 10 minutes. This suggests that rocks have a natural moisture saturation level under specific environmental conditions below which they are not likely to descend.

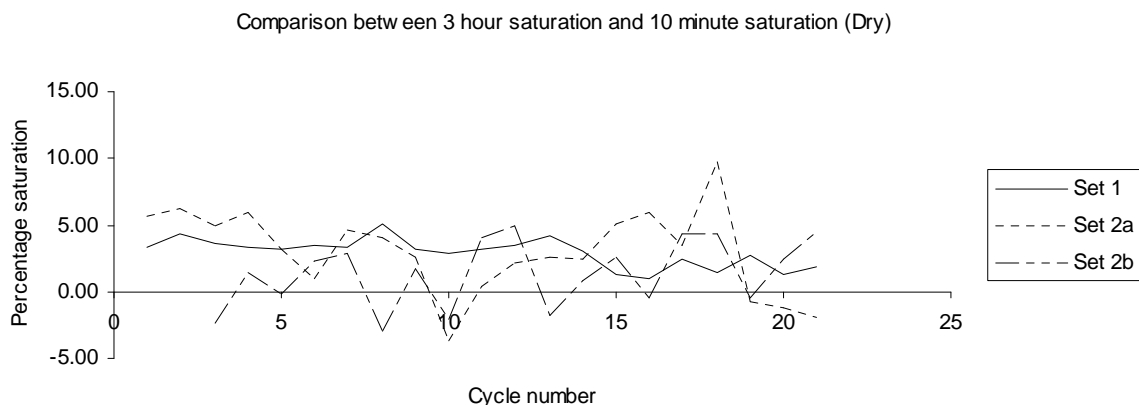


Figure 17. 3 hour set vs 10 minute set dry mass comparison

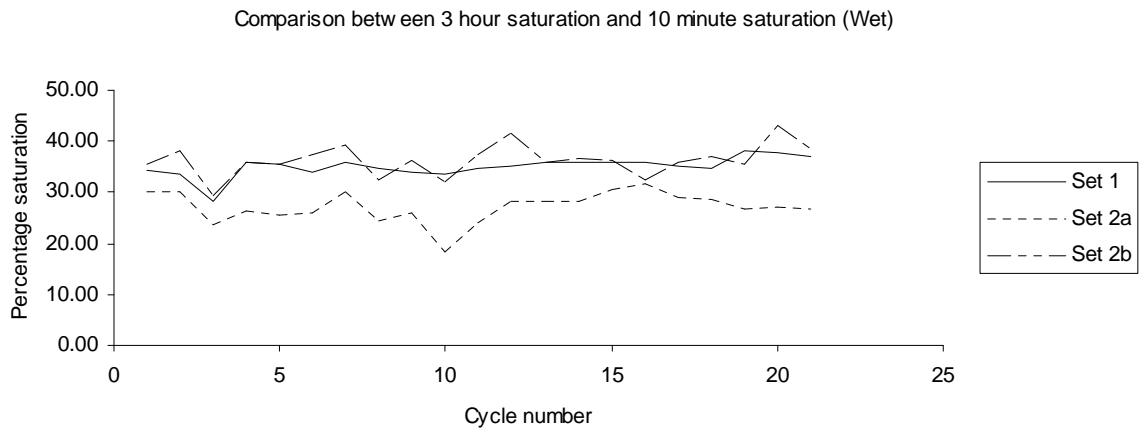


Figure 18. 3 hour set vs 10 minute set saturated mass comparison

4.3.6. Graphical and literal description of results

As mentioned in the previous section, a large tabular representation of results serves to present the data for general inspection, but it is difficult to gather a cohesive understanding of the nuances present in the data from such a depiction, ergo the following section will present the data in a more focus layout that will allow for a better understanding of the intricacies present in the data. The physical rock properties shown in Tables 14 to 16 will be considered in detail, but first it is important to consider the implications of the most basic of the measurements undertaken, namely that of changes in sample mass over the duration of the experiment. The changes in mass will be presented in two ways. First, the changes in dry mass and saturated mass as measured across the various sets will be directly compared to one another. Once this is accomplished, the samples that were tested over the duration of the experiment will be calibrated according to the samples that were used as a control during the experiment. This will show how much the samples that have been subjected to cyclic wetting

and drying over the course of the experiment have changed in relation to samples cut from the same rock that were not subjected to cyclic wetting and drying. It is important that these two graphical representations be considered together, because considering only one or the other does not yield all of the information that the two do together. The values that have been calibrated to the control samples show the difference between the values gained from the test samples and the values gained from the control samples. Because the values do not follow common trends over the various rock types used in the experiment, the original results are important because they serve as a mathematical key that gives relevance to the control calibrated results.

4.3.6.1. Direct changes in dry mass over the course of the experiment as expressed by average change in percentage

Reduction in the mass of a rock over time indicates that the rock is losing material, which suggests that its structure is changing. Specifically, loss of material is an indication that weathering is taking place. In this experiment, all samples showed a decrease in mass with the exception of Set 1 (Marion Island basalt). Since it is most unlikely that exposure of rock to any dynamic weathering process would cause it to gain rather than lose mass, these slight positive values can be attributed to experimental error. Even though the values for Set 1 are positive, they follow the same trends as all of the other samples and are thus still valid results. From Figures 19 and 20, it can be seen that the control sample shows the smallest amount of mass loss over time and the samples saturated for 3 hours showed the greatest amount of mass loss, with the samples saturated for 10 minutes giving intermediate values. This contradicts the paper by Sumner and Loubser (2008), which noted no measurable difference between rocks wetted to different moisture saturation amplitudes. That experiment considered rock saturations over a considerably smaller saturation range, so it is possible the differences in mass loss over the ranges studied were too small to measure in that experiment.

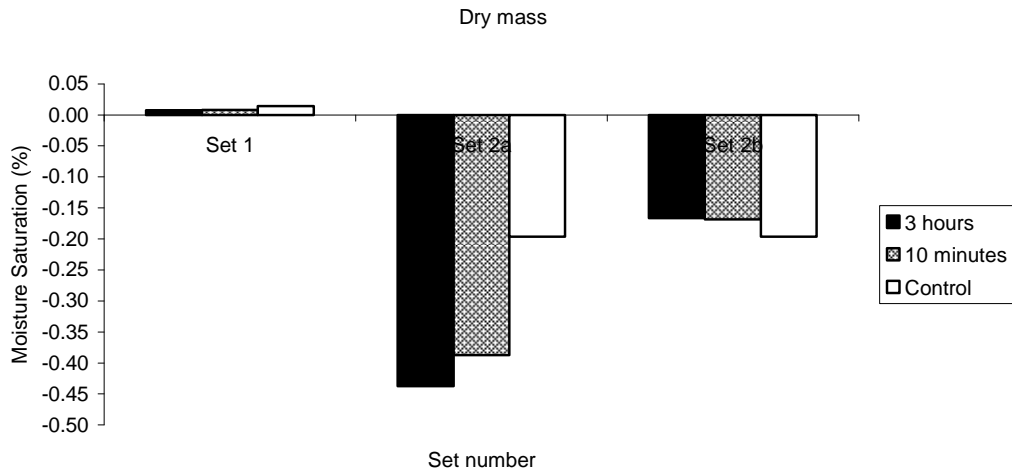


Figure 19. The change in dry mass over the time period of the experiment

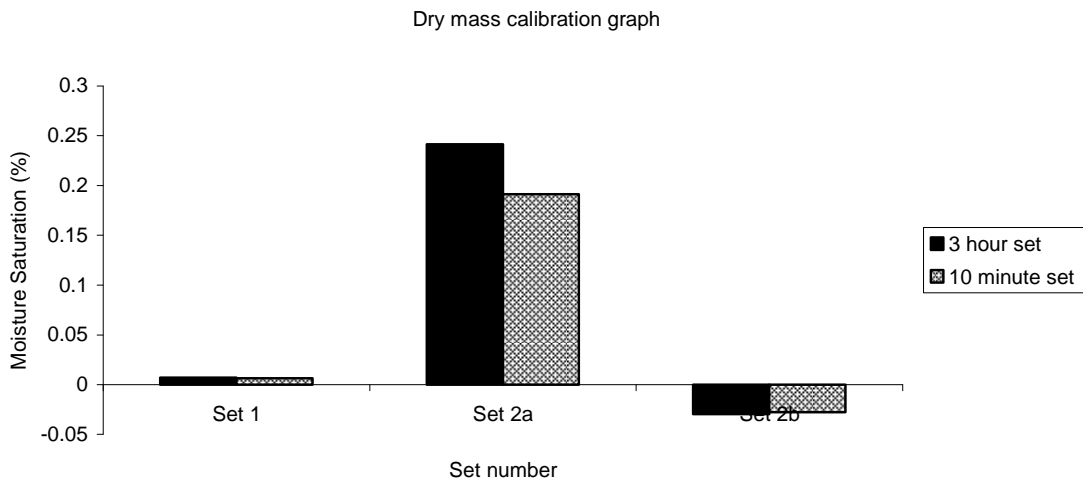


Figure 20. The changes in dry mass as expressed in a percentage and calibrated according to the control sample set

This set immediately serves to illustrate value of control calibration graphs. A cursory examination of the graph data demonstrates a uniform decrease in sample mass over all of the samples used in the experiment. This is expected. Indeed, any increase in mass would be indicative of significant experimental error. However, the data yields additional information when calibrated to the control samples. Most notably, Set 2b (sandstone from the Drakensberg) shows negative values, which in the context of the mathematical method used in this study, indicates that the samples that were wetted and dried cyclically over the duration of the experiment have lost less mass on average than the control samples that are of the same rock type and from the same rock fragment.

4.3.6.2. Direct changes in saturated mass over the course of the experiment as expressed by average change in percentage

All samples showed a considerable reduction in the Saturated Mass values, as shown in Figures 21 and 22. This indicates that all samples are taking in less water over a 24 hour period at the end of the experiment than they were at the beginning over the experiment. Because of the unusually large decrease in the Saturated Mass of the Control samples (possibly reflecting some undetected experimental error), it has become necessary to study the relative differences between the experimental sets and the control sets.

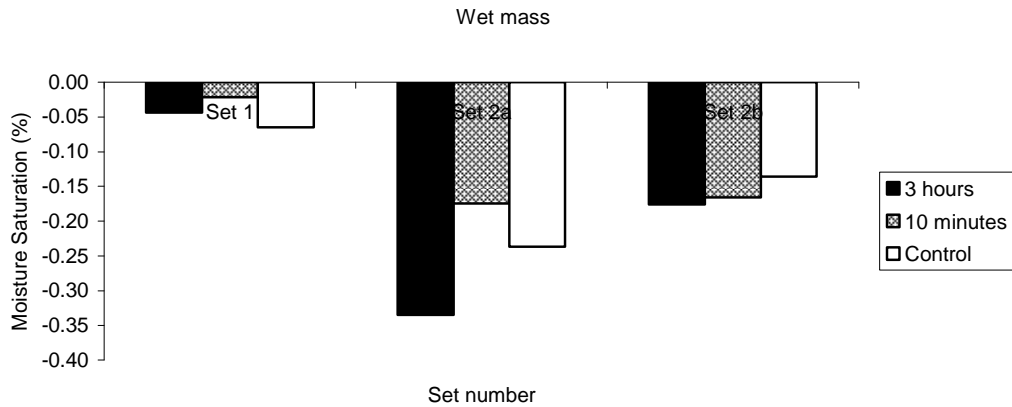


Figure 21. The change in saturated mass over the time frame of the experiment

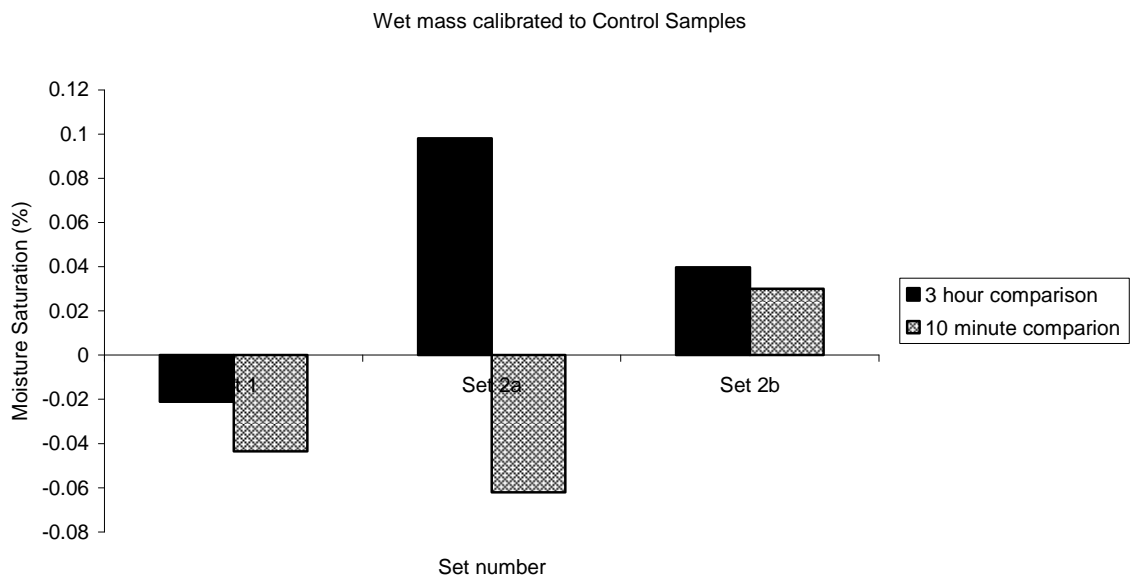


Figure 22. Wet mass calibrated to the Control Sample Set

As in the case of the data depicting the dry masses of the samples, calibrating the saturated masses of the test samples to those of the control samples make apparent certain nuances that are not readily visible from the raw expression of data. Initial investigation of the saturated masses show a measured decrease across the entire sample range, but when the

controls are factored in, it can be seen that the results are more varied than is initially apparent. In the case of this graph, all positive values are indicative of samples that are now able to absorb less moisture on average than the control samples from the same rock type. The most radical anomaly in this set is demonstrated by Set 2a (Fine-grained sandstone from the Drakensberg). The samples saturated for 3 hours are now able to absorb much less moisture than the control samples, while the samples saturated for 10 minutes are now able to absorb more. It is important to note that the samples saturated for 10 minutes can only absorb more moisture than the control samples. They still absorb less moisture at the end of the experiment than they did in the beginning.

4.3.6.3. Direct changes in complete vacuum saturation over the course of the experiment as expressed by average change in percentage

The complete vacuum saturation values show a universal decrease in this experiment, as noted in Figures 23 and 24. To guard against possible experimental error (as in the case of the Saturated Mass values), relative differences will be of major value when studying these results. Complete vacuum saturation values are of interest because it represents the maximum possible moisture saturation that can be achieved with the laboratory equipment available for this experiment.

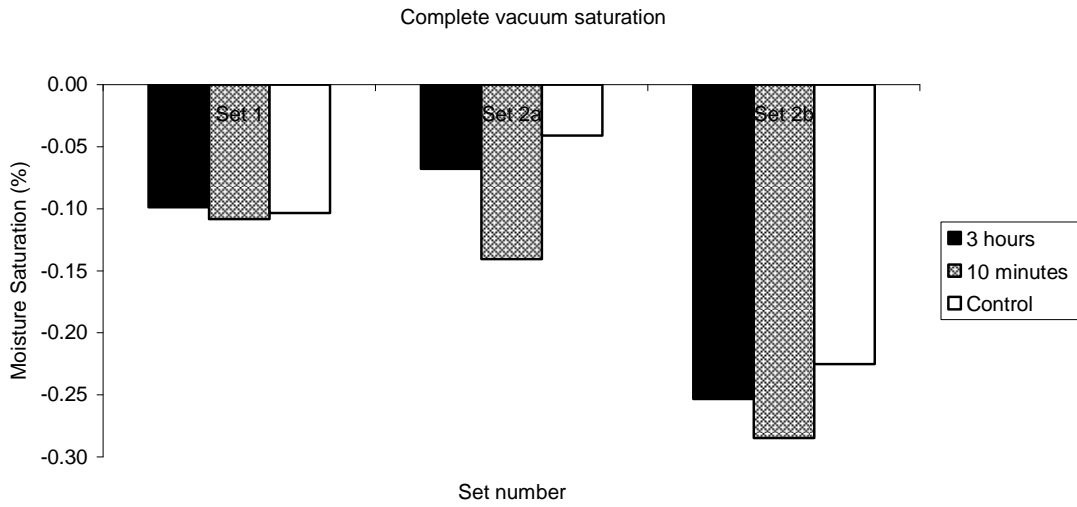


Figure 23. The change in vacuum saturated mass over the time frame of the experiment

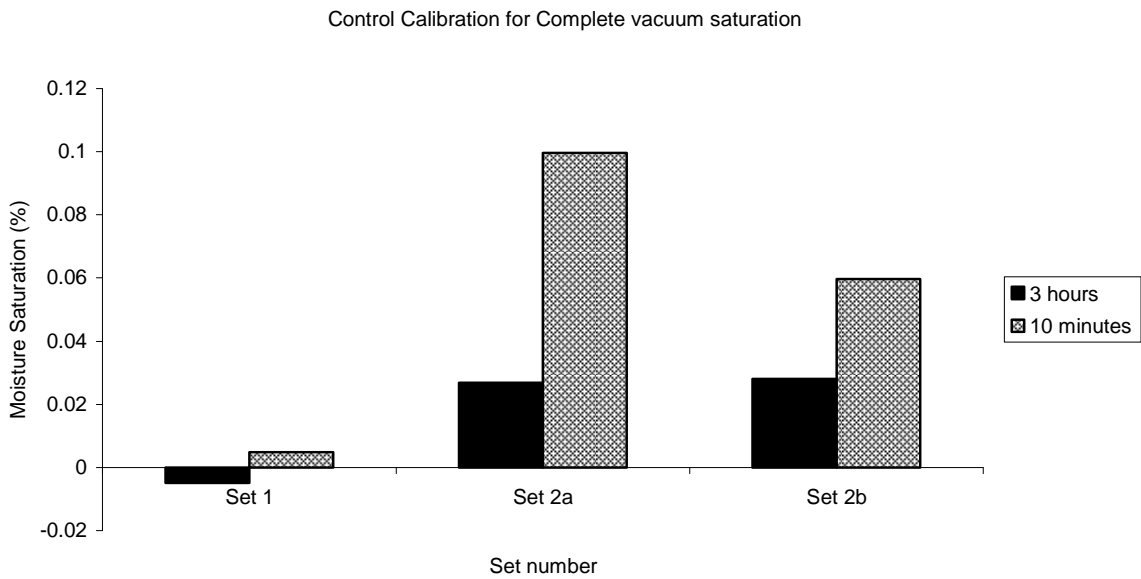


Figure 24. Complete vacuum saturation mass calibrated to the Control Sample Set

Under total vacuum saturation, the samples either demonstrated an increased moisture saturation level or showed very little change. In general, the samples are showing an increased capacity for water absorption when placed in a negative pore-pressure environment. This means that the maximum amount of moisture that the rock samples can absorb has increased from what it was at the beginning of the experiment. This will be more fully discussed in the sections of this document that deal with porosity and micro-porosity.

4.3.6.4. Direct changes in water absorption capacity over the course of the experiment as expressed by average change in percentage

Water absorption capacity has shown a decrease over the entire range of samples with the exception of the test samples in Set 2a, fine-grained Clarens Formation sandstone (shown in Figures 25 and 26). Both of the subsets of Set 2a that were exposed to cyclic wetting and drying have demonstrated an increase in the water absorption capacity.

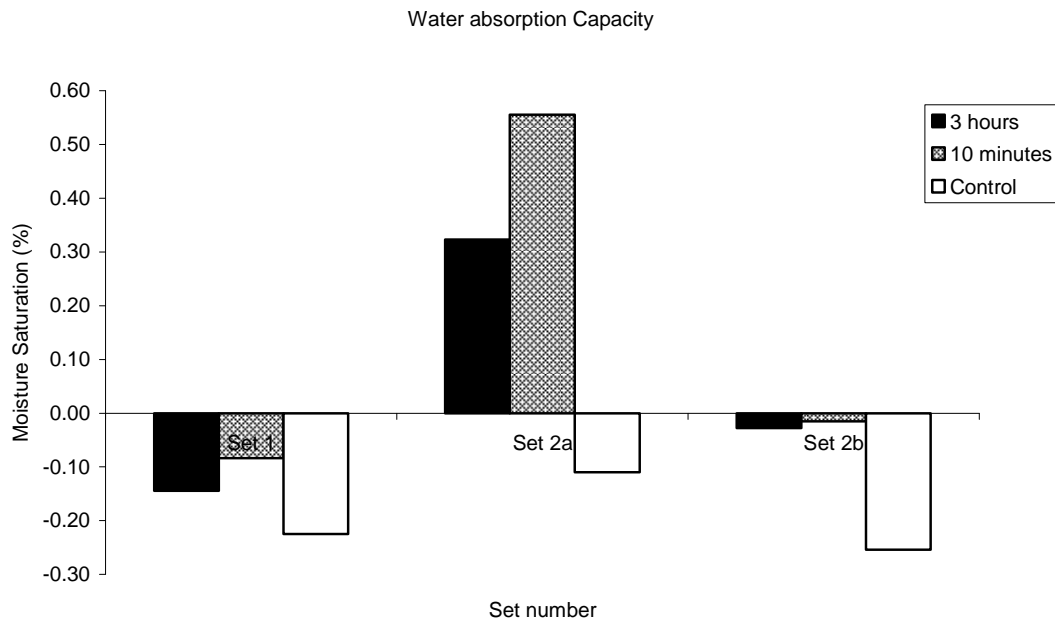


Figure 25. The change in water absorption capacity over the time frame of the experiment

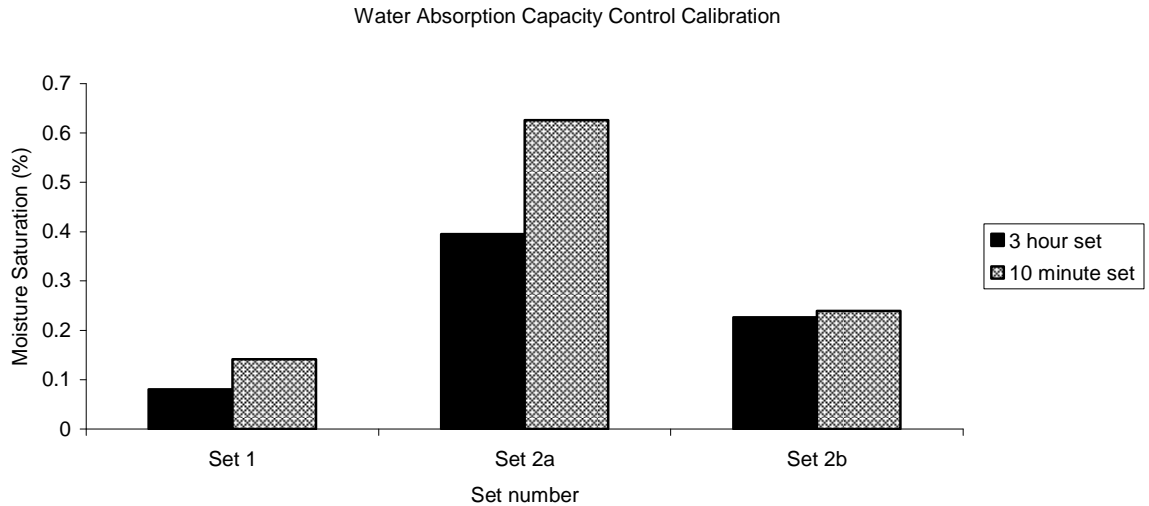


Figure 26. The change in water absorption capacity as calibrated according to the control sample set

Water absorption capacity increased in all test samples when compared to the controls. In Sets 1 and 2b, the water absorption capacity of the samples at the end of the experiment is less than at the beginning of the experiment, but greater than the water absorption capacity of the equivalent control sample. In Set 2a, the water absorption capacity of the control set was smaller than at the beginning of the experiment, as with all of the other sets. However, the water absorption capacity of the test samples were not only greater than the control samples, but also greater than the initial water absorption capacity values obtained for the same samples at the beginning of the experiment. The results obtained for Set 2a are unique in this respect.

4.3.6.5. Direct changes in saturation coefficient over the course of the experiment

Water absorption capacity reveals the amount of moisture that a sample can take up in a set amount of time (in this case, 24 hours). This means that the water absorption capacity of any given sample is effectively an indication of the rate at which a rock sample will absorb water. The results obtained for this rock property show that, alone of all the rocks studied, Set 2a showed a decrease in the rate at which the sample absorbs water. These results are reflected in the readings gathered from the Saturation co-efficient data displayed in Figures 27 and 28 below.

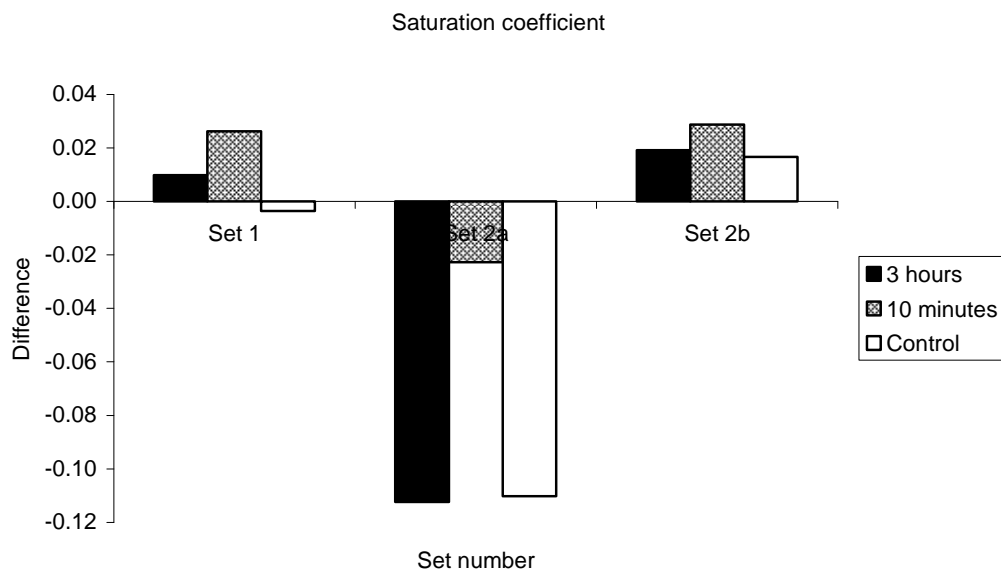


Figure 27. The change in saturation coefficient over the time frame of the experiment

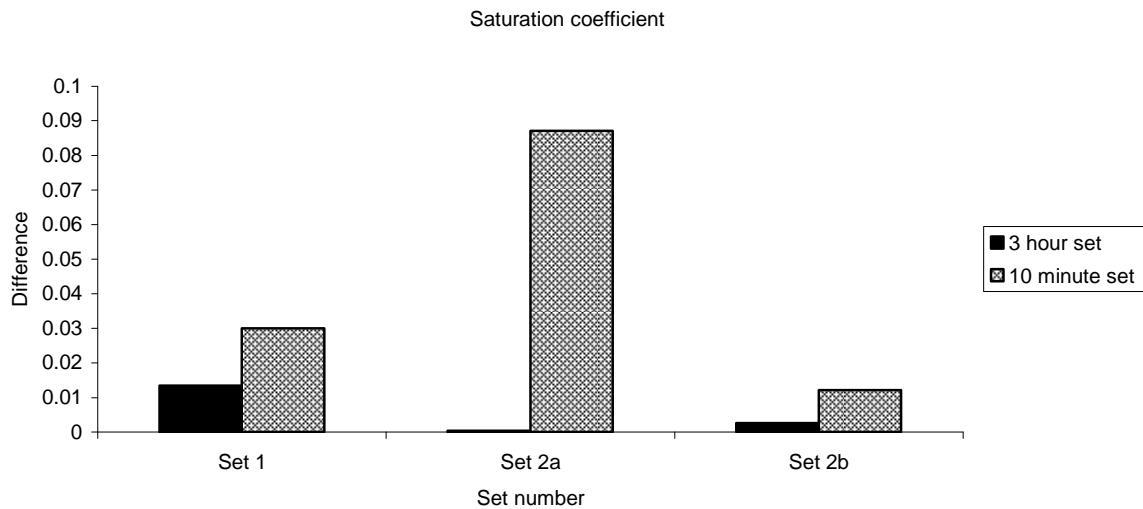


Figure 28. The change in saturation coefficient as calibrated according to the control sample set

4.3.6.6. *Direct changes in porosity over the course of the experiment as expressed by average change in percentage*

With the exception of Set 2a, all the samples have shown a general decrease in overall porosity (Figures 29 and 30). To clarify, this means that there has been a decrease in the volume of pore space within the rock samples when compared to the overall volume of the sample. In general, one expects weathering and internal rock structure change to be reflected by an increase in porosity (as demonstrated by Sumner and Loubser (2008)). This is because weathering product, if it comes from within the rock, rather than from the surface, should cause the pores within the rock to exhibit a general increase in size. However, this is not the only explanation that can be offered for the changes in porosity.

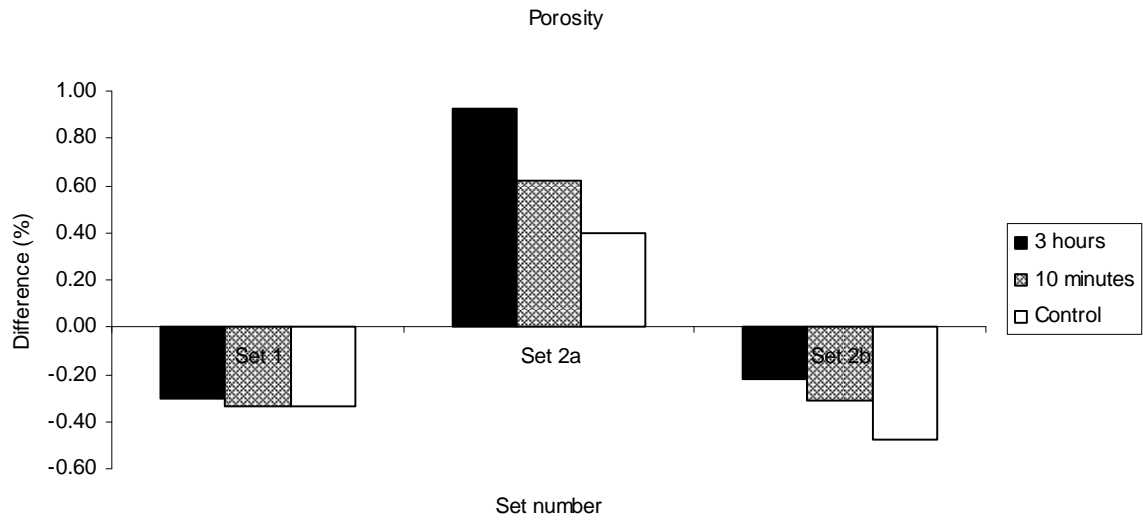


Figure 29. The change in porosity over the time frame of the experiment

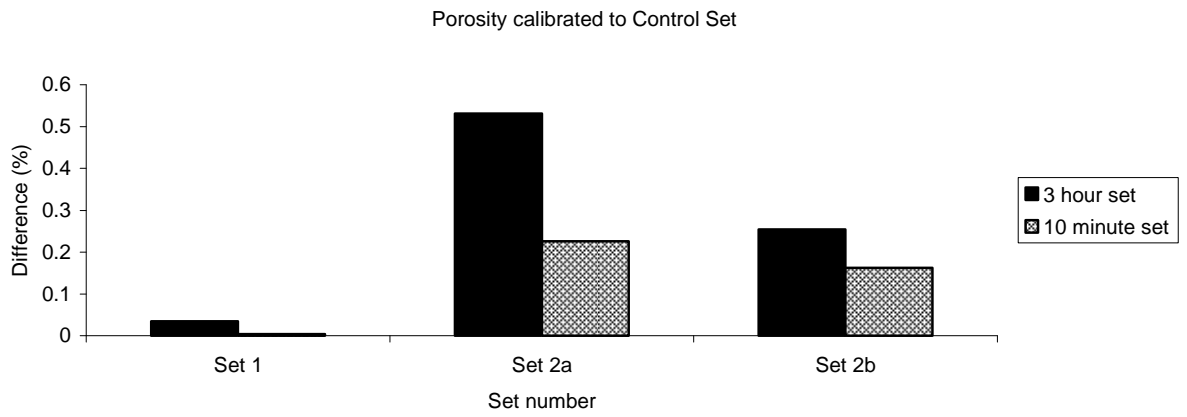


Figure 30. The change in porosity as calibrated according to the control sample set

4.3.6.7. *Direct changes in microporosity over the course of the experiment as expressed by average change in percentage*

The changes in micro-porosity (Figures 31 and 32) noted in the experiment are not consistent across the various rock types. Sets 2a and 2b show no change in micro-porosity of the control samples over the period of experimentation, while Set 1 shows a decrease in the micro-porosity control sample (Figure 31). As in the case of the porosity values, changes in micro-porosity are indicative of changes in the internal pore layout of the rock samples under investigation. While the data are fairly erratic and consequently difficult to analyse as a cohesive whole, it is definitely demonstrative of the fact that the periodic wetting and drying cycles have caused the various rocks to change over time. What is also very clear is that the processes involved are varied, even over rocks that are quite similar. It is quite possible that rocks in one phase of weathering may exhibit an increase in micro-porosity while showing a decrease in another phase.

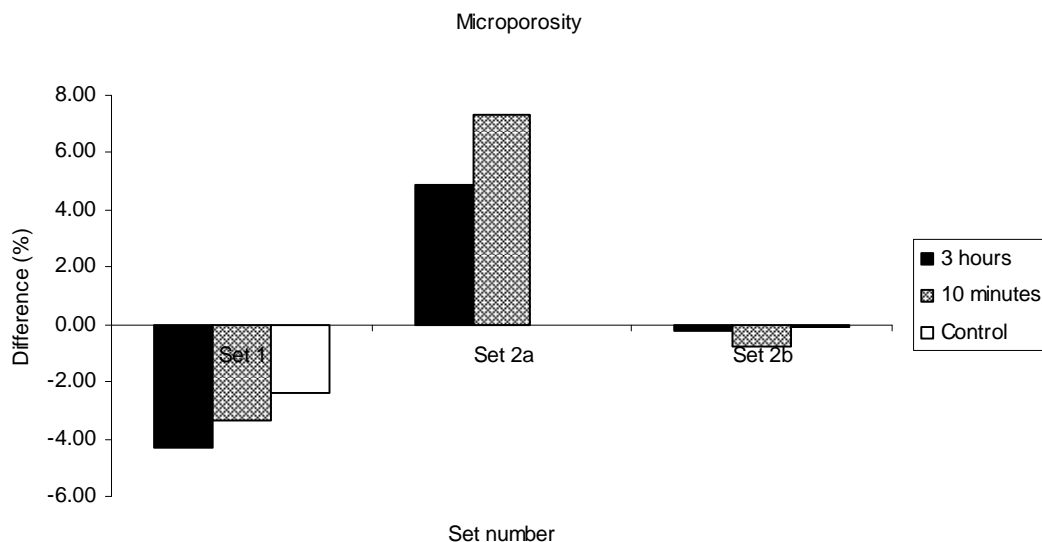


Figure 31. The change in micro-porosity over the time frame of the experiment

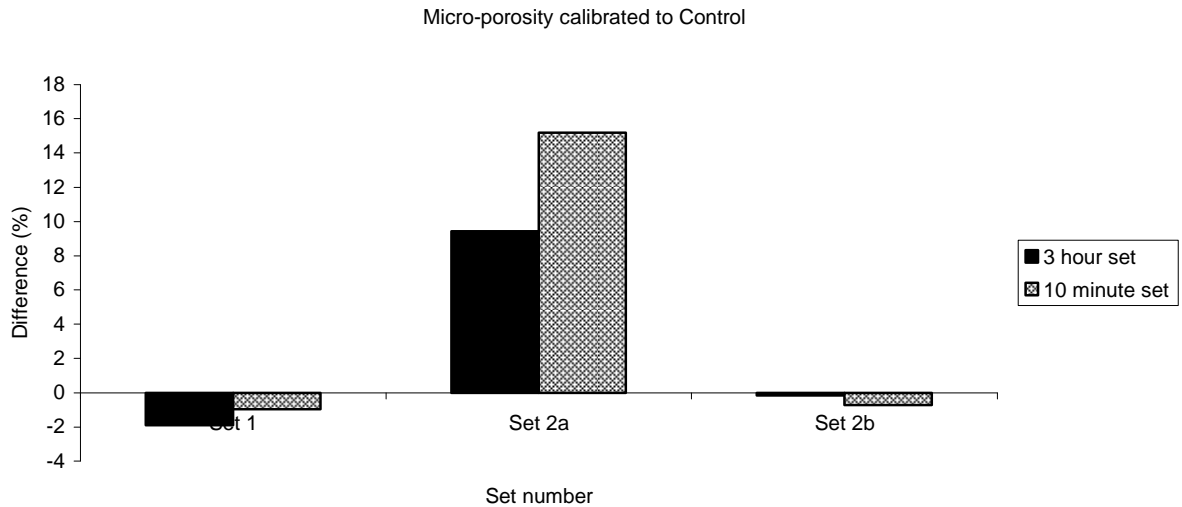


Figure 32. The change in micro-porosity as calibrated according to the control sample set

4.4. Equotip measurements

Side 1 (Figure 33) refers to the surface of the sample that was facing upward during the experimental period and therefore had the most exposure to the micro-climate within the laboratory. Equotip hardness values have behaved very consistently within the various sets, but the set values do not yield consistent values over different rock types. To put it simply, if the LD value of one sample in a set has decreased, then in almost all circumstances, this means that all of the values within a set have decreased. Unfortunately, the expected result (a general decrease across all samples that have undergone cyclic wetting and drying) has occurred in only one of the three samples. Sets 1 and 2b have shown what appears to be an effective increase in hardness when compared to values taken at the beginning of the experimental cycle. Only Set 2a has shown a decrease in measured hardness. In both these cases, the samples that were saturated for 3 hours showed a change in hardness that very closely resembled the changes noted in the control set. The samples that had been saturated for 10 minutes showed a smaller decrease than either of the other two sets. When studying

the samples in the remaining sets (the ones that showed an effective increase in hardness), a similar trend can be seen. In all cases, the LD values for the 3 hour set closely resembles the control set, while both of these sets differ significantly from the 10 minute set.

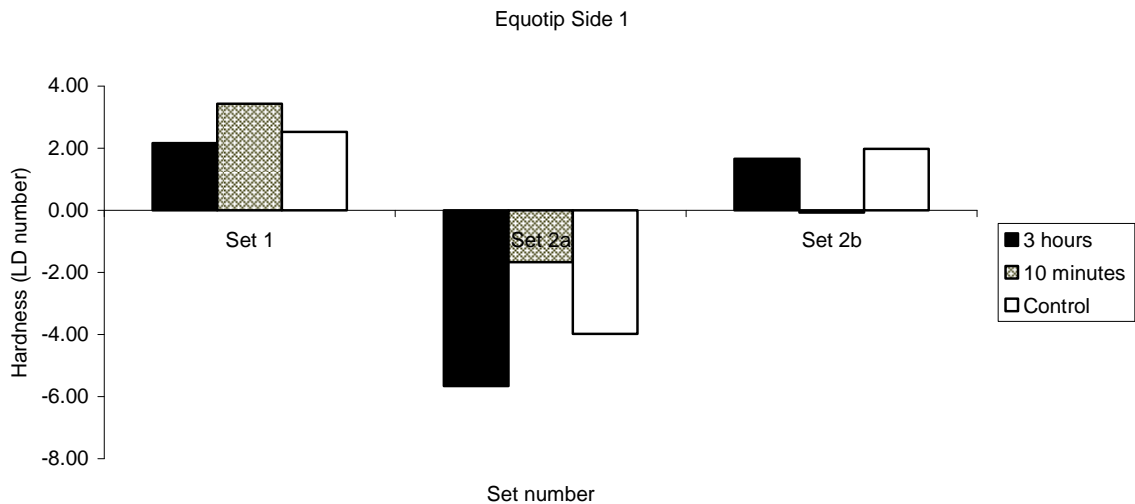


Figure 33. Changes in rock hardness over the duration of the experiment on the upper side of the samples as measured by the Equotip probe

Side 2 (Figure 34) refers to the side of the sample that was facing down during the experimental period and consequently had less exposure to the micro-climate in the laboratory. Equotip values for this side differ quite considerably from the values obtained from the side facing upward. To begin with, they conform more closely to the pattern that one would expect, particularly the samples that were part of the three hour set. The only sample that shows any increase in apparent hardness in the 3 hour category is that of Set 1 (Marion Island basalt). All of the other sets show either no change in hardness, or a decrease in hardness. Set 2a has shown the largest decrease in hardness, with a smaller decrease being seen in Set 2b. All others have indicated an apparent increase in hardness. Of greater value is the consideration of the degree to which the samples changed over time. Other than Set 1

(extremely hard Marion Island basalt), the remaining sets (both of the Clarens Formation sandstones) show the largest decrease in hardness in samples saturated for 3 hours, followed by those saturated for 10 minutes, followed by the control samples. A possible reason for the results seen for Set 1 is that the surface topography of the samples has more of an effect on the Equotip readings than the actual material hardness does. For Set 1, this is likely because the rock is so hard that the surface does not change due to wetting and drying enough to be detectable. This will be discussed more fully in Chapter 5.

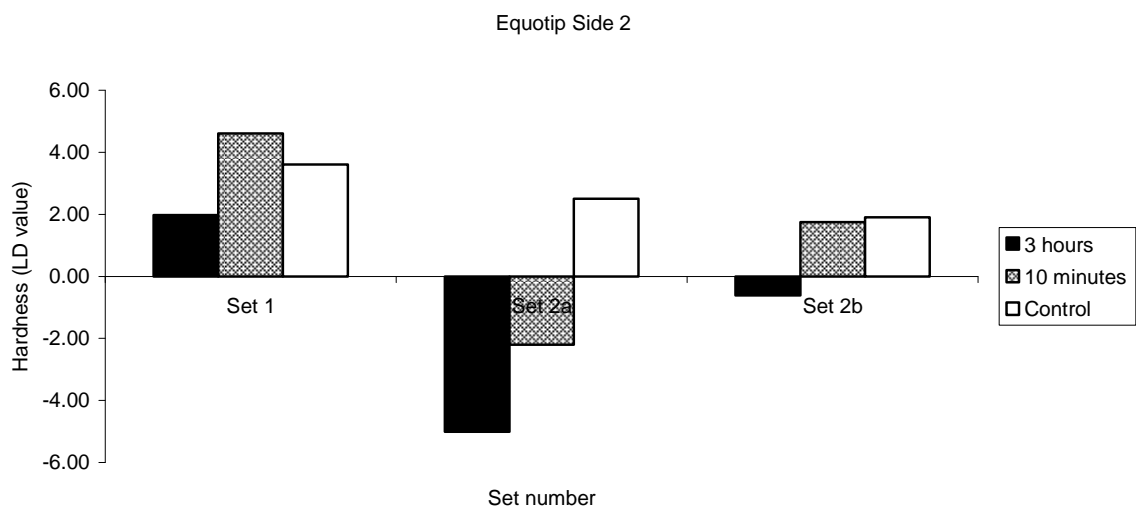


Figure 34. Changes in rock hardness over the duration of the experiment on the lower side of the samples as measured by the Equotip probe

The data that are displayed here show that even the study of one weathering process can lead to a large number of questions (which will be addressed in Chapter 5). There is still much for researchers to learn about the interactions between external stimuli and rock properties. Without a doubt, weathering processes are truly part of systems that are wondrously complex.

Chapter 5: Discussion

The goals of this chapter are as follows. First, to collate all of the data presented in the Results Chapter (Ch. 4 of this document) and discuss what they mean. Notable trends will be discussed, as will notable anomalies in the data. Second, the results and the discussion of results will be compared to previous studies of a similar type and any statistical anomalies will be investigated and explained. Additionally, the potential philosophical implications of this study will be discussed.

5.1. Physical results

The physical results that were obtained from this experiment were unexpected in that they differ from the results obtained in previous studies. Those differences will now be detailed. This section will consider changes in the physical properties of the rock over time as determined by the method laid out by Cooke (1979), as well as the results obtained by the Equotip.

As has been discussed in Chapter 3, the mass measurements taken throughout the course of the experiment were obtained in a different fashion to those measured in previous experiments of this nature. This is because it has been assumed throughout this study that the weathering effects of cyclically wetting and drying various rock samples is likely to be very small. Indeed, when the rocks samples that were wetted were compared to the rocks that served as controls, this assumption has definitely been validated. This will be discussed in more detail later in the chapter. What is pertinent here is the fact that while other studies of this type (Hall and Hall, 1996; Sumner and Loubser, 2008) have taken mass measurements after every cycle, this study takes measurements every five cycles to reduce the damage that the rocks may sustain as a result of excessive handling. A second critical difference between

this study and that of Hall and Hall (1996) is that Hall and Hall (1996) heat-dried the samples completely and saturated them at regular intervals during the experiment. In this experiment, that has not been done and instead follows the method laid out by Sumner and Loubser (2008) in order to reduce rock damage that could be caused by thermal fatigue or thermal shock. For that reason, the results obtained in the experiment are more directly comparable to that of Sumner and Loubser (2008), rather than that of Hall and Hall (1996). In this study, as in the case of Sumner and Loubser (2008), it can be seen that over a number of wetting and drying cycles, the moisture fluctuation range is very stable. While the measured dry masses and saturated masses may change significantly from one week to the next, the range of fluctuation is fairly consistent.

Because weathering is a dynamic process (Bland and Rolls, 1998), it causes the internal characteristics of the rocks to change over time and this can be measured. Research that considers the effects of specific weathering processes on various different rock types always looks at the changes in rock structure that can be observed over time. The different properties that can be measured are numerous and varied, ranging from measurement of the changes in sample surface topography (Pardini *et al.*, 1995) to changes in internal rock structure (Hall and Hall, 1996; Sumner and Loubser, 2008; Nicholson, 2001; Pejon and Zuquette, 2002). This is because if there are no measurable changes in physical properties, it calls into doubt the claim that a dynamic process is present and affecting the samples. Hall and Hall (1996) and Sumner and Loubser (2008) have determined the physical rock properties in a very similar way to this study and, as such, these studies are the most directly comparable. However, data obtained by different means is still of value and will be used for comparative purposes where applicable.

Set 1 (Marion Island basalt), has shown a very slight increase in mass across all of the samples studied. This is possibly due to experimental error. This however shows that the basalt samples lost little (if any mass) during the experiment. Sets 2a and 2b lost mass over the course of the experiment, but not in the manner that was anticipated. Of particular interest is the mass loss measured in Set 2b (sandstone from Clarens Formation, South African Drakensberg). While all samples of Set 2b have indicated that mass has been lost, the control sample set has lost more mass than the either of the test sample sets. There are two possible explanations for this scenario. First, the small difference measured between the test samples and the control samples are the result of some undetected experimental error, meaning that the test samples and control samples have effectively lost equivalent amounts of material. This would imply that the cyclic wetting and drying of the test samples has not had any significant effect on the loss of material experienced by these samples and that the major cause of rock damage in this set is as the result of the method used to establish the physical rock properties. Second, the measured difference is not the result of experimental error. This implies that wetting and drying the samples has somehow had a small inhibiting effect on the rate of material loss in this particular sample set. Both of these possibilities have implications that need to be explored further. To begin with, one must consider the possibility that the methods that are used to establish rock properties may have effects on the samples that are significant enough to mask results pertaining to the weathering process that is actually being studied, due to the fact that the weathering process may have an intrinsically low intensity. Any experiment that requires the heating, cooling, wetting or drying of a sample for purposes for establishing physical properties will likely have this effect present in some measure. Effects like this may be regulated by the careful use of control samples, as in the case of this experiment.

The dry masses and saturated masses both demonstrated a general downward trend over the experimental period. To clarify, the samples were taking up less moisture per wetting cycle towards the end of the experimental cycle, but were also retaining less moisture every wetting cycle. This implies that the rate of moisture absorption was becoming slower as the experiment progressed. However, the overall moisture saturation range remained relatively constant, meaning that the rate at which moisture moved out of the rock during the drying phase had remained more or less constant. This idea is supported by the fact that, since the dry mass moisture levels were matched by decreasing wet mass values, the moisture saturation range remained constant over the duration of the experiment. This phenomenon was noted for all samples that were part of this experiment (Marion Island basalt and both of the Clarens Formation sandstones).

Over the course of the experiment, the amount of moisture that the samples could absorb decreased. There are two reasons for this. First, the samples were losing mass (as determined by the comparison of initial dry mass values with the final ones) and it is possible that the apparent reduction in saturated mass is merely a reflection of the loss in actual sample mass. Second, there exists the possibility that pore channels have been closed off as a result of precipitate movement taking place within the samples themselves. This will be discussed further later in this chapter.

Moisture saturation amplitude was studied by Sumner and Loubser (2008) using sandstone taken from the Clarens formation and it was concluded that, over the time scale of that experiment and the moisture saturation range that was tested, the change in moisture saturation has no measurable effect on the degree of weathering that takes place. This study has, in part, been set up to emulate the earlier experiment by Sumner and Loubser (2008) to see if this remains true for larger differences in moisture amplitude, as well as for a larger

number of wetting and drying cycles. Also, this study tests the effects of changes in moisture amplitude in three different rock types, as opposed to only one. When displayed graphically, it can be seen that samples that were saturated for 10 minutes have a generally lower moisture saturation amplitude than samples of the same rock type that were saturated for 3 hours. However, there does not appear to be a direct and consistent link between the moisture saturation amplitude and changes in physical rock properties. Thus, these data are in agreement with that of Sumner and Loubser (2008), indicating that larger moisture saturation amplitudes do not appear to be a critical factor in the determination of the intensity of rock weathering that a sample experiences as a result of wetting and drying.

Cooke (1979) defines water absorption capacity as the amount of moisture absorbed in a certain amount of time. Sumner and Loubser (2008) determined that, with Clarens formation sandstone, the water absorption capacity decreases as a result of wetting and drying. Results obtained in this study also show a decrease in water absorption capacity with the exception of the test samples in set 2a (fine-grained Drakensberg sandstone). A decrease in water absorption capacity is indicative of a decrease in the rate at which the rocks under investigation may take in moisture under static conditions. The increase in water absorption capacity seen in Set 2a correlates with the significant increases in porosity noted for this same set, while the decreases in water absorption capacity for the other sets likewise correlates to the apparent decreases in porosity noted in those sets. This will be discussed more fully in the section of this chapter that deals with porosity and micro-porosity.

Saturation coefficient is defined by Cooke (1979) as “the amount of water absorbed in 24 hours expressed as a fraction of the volume of available pore space”. As with the water absorption capacity, Sumner and Loubser (2008) measured an average decrease in the amount of moisture that can be absorbed over a 24 hour period. In this experiment the

saturation coefficient, which was measured in exactly the same way as that conducted by Sumner and Loubser (2008), does not respond consistently for all samples. The experimental samples of Set 1 and all samples in Set 2b showed an increase in measured saturation coefficient, but the control sample of Set 1 and all samples in Set 2a showed a decrease. A particularly strange anomaly in the data is to be found upon closer inspection of Set 2a. The samples of Set 2a (one of the two Drakensberg sandstones studied) showed a large decrease in measured saturation coefficient for the subset of samples that were submerged for 3 hours, which is comparable to that of the earlier study. However, while the control set showed a similar decrease in measured saturation coefficient, the measured saturation coefficient for samples saturated for only 10 minutes, while still a net decrease, is much smaller than that saturated for 3 hours. While there is a possibility of experimental error in a setup such as this, the control samples are in place to compensate for such an eventuality. After calibrating the data to fit the control sample set (effectively using the control set as the new axis against which all data are compared), it can be seen that the samples that were saturated for 10 minutes have higher saturation coefficient values, not just for Set 2a, but also for Set 1 and Set 2b. This indicates that moisture saturation amplitude (i.e. the length of time that the rock sample is submerged in any given wetting cycle) does have an effect on the rocks ability to absorb water over an intermediate time-scale, but not in the manner that one might expect. It makes intuitive sense to assume that, as one increases the amount of time that a sample spends saturated, physical rock properties would change accordingly in a more or less linear fashion, but the data clearly show that this assumption is false. One would expect that if saturating a rock sample for 3 hours caused virtually no change in saturation coefficient in relation to the control set, that the same would be true of a rock sample that had been saturated for a shorter period of time, but this is not the case. There is no direct linear trend discernable between the moisture saturation amplitude and the saturation coefficient. The reasons for this are not apparent from the data at hand; thus, further study is required.

Studying the changes of porosity and micro-porosity over time gives an indication of how the structure of a rock is changing. As has been mentioned in previous chapters, porosity in this experiment is defined as the available pore space in a rock sample, expressed as a percentage of the total rock volume, while micro-porosity is the percentage of pore space within a rock sample that is made up of micro-pores (theoretically, pores with a diameter of less than 1 micron, but in reality rather determined by the equipment available for the experiment). Porosity and micro-porosity make the most sense when considered together, so these two physical rock properties will be considered in tandem, rather than separately. Initial qualitative investigation of the data show that, while the samples did not behave completely consistently across the set range, certain trends can still be noted. To begin with, only Set 2a has shown an increase in porosity. There are two possible explanations for the apparent decreases in porosity exhibited by Sets 1 and 2b. The first explanation is that the method by which the porosity is obtained does not give a true indication of porosity. This is possible since the method relies on saturating all available pores with water. It has been shown in the past (Rautureau, 1991) that over time, salts that exist naturally within the rock may move into aqueous solution as the water moves through the pore network within the rock. These ionised salts may then be either leached out of the rock entirely or re-deposited elsewhere within the rock structure. This redistribution of salts may close off sections of the rock pore network that were previously open, effectively 'clogging' the channels through which the water was once able to flow. In addition to the clogging of available pore channels, accretion and concentration of salts is also believed to lead to structural weaknesses within the rock, particularly at the interface between the zone of ionization and the zone of precipitation, which can lead to fracturing. During the experiment, a number of samples did indeed fracture very neatly (the first occurring after 8 weeks or 40 wetting and drying cycles) and this is one possible explanation for this.

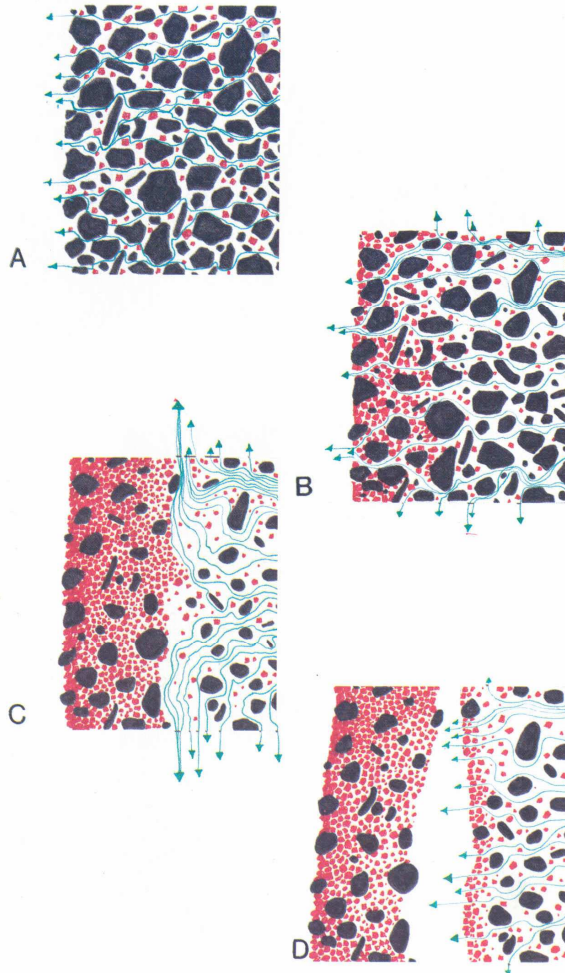


Figure 35. Salt precipitate redistribution and pore blocking (after Rautureau, 1991)

The following image, taken from Rautureau (1991), gives a diagrammatic explanation for the process explained above. This process, a form of subsurface weathering, is brought about as a result of asymmetrical precipitate distribution, due to moisture flowing through the rock consistently over a period of time. Since this is exactly the scenario that has been brought about in this experiment, this is put forward as a potential explanation for both the fracturing of three of the samples over time and (as evidenced by depictions C and D), the apparent reduction in porosity over time. Depictions C and D also clearly show the interface both the zones of ionisation and precipitation as a line of weakness within the rock.

The other explanation for an apparent decrease in porosity is simply that of experimental error, which as before, is compensated for by the presence of control samples against which the experimental samples can be compared. If we consider the data that has been calibrated with the control samples, it can be seen that in every case, the samples that have been saturated for 3 hours have the largest change in porosity and the control samples have the smallest values, with the samples that have been saturated for 10 minutes occupying

the intermediate position. This is very much in line with what was expected, showing that moisture saturation amplitude can be related to porosity.

In the case of micro-porosity, as with porosity, Sets 1 and 2b have shown a decrease while Set 2a has shown an increase. However, other than that, the changes in micro-porosity show little discernable trends. For Sets 2a and 2b (the Drakensberg sandstone), the control samples showed no change in micro-porosity, but Set 2a indicated a significant increase in the number of micro-pores present, while Set 2b showed a small decrease. Set 1 (Marion Island basalt) has demonstrated a decrease in micro-porosity across the board. These results must be considered in light of the porosity values, since as was stated above, the micro-porosity is represented as a percentage of actual porosity. A decrease in micro-porosity, as seen in the data for Set 1, indicates that a smaller percentage of the pore space at the end of the experiment is made up of micro-pores than was the case at the beginning. This means that some of the micro-pores have increased in size to the point where, in terms of the experimental setup, they are no longer perceived as micro-pores, but rather as macro-pores. This is indicative of changes in the rock structure and therefore, of weathering. If this line of thought is to be pursued, it makes the results obtained for Set 2a, namely an increase in the number of micro-pores, anomalous. However, when considered along with the porosity values computed for Set 2a, it becomes possible to make sense of this result. Set 2a was the only set to demonstrate significant increases in porosity. Set 2a thus is very susceptible to weathering (meaning here that the rock structure alters a large amount as a result of relatively small external stimuli) and the increase in micro-porosity could be as a result of new micro-pores being formed in the rock structure.

5.2. Equotip hardness values

In recent years, consideration has been given to the relationship between the reduction of rock strength over time and the degree of weathering taking place (Aoki and Matsukura, 2007). According to Aoki and Matsukura (2007), very hard rocks are generally very resistant to erosion, but once they become somewhat weathered, their ability to resist erosion becomes reduced. Thus, monitoring the rate of decrease in rock strength can be a valuable indicator in evaluating the degree to which weathering is taking place, particularly on the surface of the rock. In this experiment, the upper side and the lower side of the rock samples were evaluated separately because they were exposed to slightly different conditions. The upper side was directly exposed to the air in the room while the under sides were less exposed. The results obtained for the base of the samples are different to those measured on the upper sides in almost all cases, leading to the conclusion that the manner in which a rock is exposed to a water weathering process is an important factor in determining the degree of weathering. This means that the intensity of the weathering action does not relate directly to the weathering products that one finds as a result. Directional aspect of the rock is thus also extremely important. If, as stated by (Aoki and Matsukura, 2007), there is a link between the degree of weathering taking place and a reduction of rock strength, *a priori* logic would suggest that rock samples subjected to eight months of continuous cyclic wetting and drying would have reduced rock strength, which would have been seen in the experiment as a reduction in rock hardness. Interestingly enough, the results obtained in this experiment do not always reflect this. There were initial concerns regarding the use of the Equotip because its extreme sensitivity means that slight pitting in the surface of the sample being measured can result in a reading that is lower than would otherwise be expected. The impact of this was reduced by increasing the number of readings taken on each sample, thus making the anomalies less statistically significant. The anomalies were not eliminated because the pitting that likely causes them is one of the things that causes an apparent reduction in rock

hardness and is also an indication of weathering. Thus, enough readings were taken to ensure that the final results were biased in the direction of the true average hardness rather than that of the anomalous readings. For example, to calculate the average hardness of the upper side of the samples in set 1 of the 3 hour category, 48 Equotip measurements in total were taken on the samples at the beginning of the experiment and again at the end, with the same number of measurements being conducted on the underside of the same samples. The readings within each set correlated closely with each other, but did not correlate well with other sets. What is most interesting is the fact that a large number of samples appear to have an increased hardness. Only Set 2a, which is known to have experienced the greatest degree of weathering over the course of the experiment, behaved in the way that was expected. Enough readings were taken for it to be conclusively stated that the apparent increase in rock hardness is not a result of experimental error, but rather genuinely reflects the changes that are occurring on the surface of the samples. For example, if one considers the upper side of all the sets, only set 2a has shown an apparent decrease in rock hardness, while sets 1 and 2b have shown an apparent increase in rock hardness over the experimental time period. With the exception of set 1, all samples have shown a decrease in mass. Those increases that have been noted are extremely small and could be attributed to experimental error. It is accepted that rock mass loss is an indication of weathering (Matsukura *et al.*, 2001), so it can be concluded that all of the rock samples are now more weathered than they were at the beginning of the study, but sets 1 and 2b have apparently harder surfaces relative to that which they had at the beginning of the study. There are two possible reasons why this may be occurring. Either the sample surface actually is harder than it was before, or it is smoother. A smoother surface would mean that the sensor would strike fewer pits, which generally give a lower hardness measurement. If this is the case, the average hardness value would appear to be higher, even if this is not actually the case. It is not known why some of the rocks investigated in this study would appear to be harder than they were when they started. One

possibility is that the original test samples were only cut and not polished. There is a possibility that irregularities in the surface that resulted from the cutting process were enough to distort the surface of the sample to the point where differences that came as a result of weathering were masked. Further study is required.

The physical data shows consistency within individual sample sets, but varies wildly when the different rock types are compared to one another. Since the experiment was run on the different sets at the same time and in the same way on every occasion, it becomes apparent that the unique elements of an individual rock may have more of an effect on the way that weathering processes will affect it than the known universal laws that govern all weathering processes. This theory has been brought forward by Phillips (2006), who suggests that environmental systems may be of such great complexity that even relatively small local variances may be significant enough to yield results that appear to be in opposition to the results that universal laws would require. If this is the case, universal laws will tell us what can happen; a good understanding of the local conditions will tell us what is going to happen.

5.3. Study site context

Studies conducted over the last number of years have shown that Bushman Rock Art has degraded since the time it was first observed (Meiklejohn *et al.*, 2009). It is believed that this is largely attributable to significant degrees of rock weathering, both on the surface of rock upon which the rock art is painted and below the surface (Hoerlé *et al.*, 2007). Since Bushman rock art is a priceless, irreplaceable resource, considerable attention has been given in attempting to conserve it. However, as will be discussed in more detail below, the intricacies of the weathering systems that are at work in these areas are not always well understood. For example, it is believed that the presence of moisture at these sites plays a significant role in the weathering and degradation of rock art (Meiklejohn *et al.*, 2009), particularly since many

rock art sites are in areas that are characterised by high summer rainfall (Hoerle, 2006), but exactly how this occurs is not well-understood. This makes an effective conservation scheme difficult to implement, because the catalytic and inhibitive qualities of the various components of the weathering system need to be clearly described to ensure that conservation methods do not, inadvertently, have the opposite of the intended effect. The intention of this study has been to determine the effects of moisture on Drakensberg sandstone of the type that rock art is typically found upon. It has been seen that both of the rocks used of this type in the experiment have been significantly affected by their exposure to moisture, but to different degrees. Set 2a was particularly seriously affected, but Set 2b was also affected to some degree. Some of the samples in Set 2a actually fractured after repeated cyclic exposure to wetting. This falls in line with the studies done by Meiklejohn *et al.* (2009), who also concluded that rock moisture (among other things) was an important element of rock weathering in rock art rich areas. It is important to observe that significant differences have been noted for rock samples that were taken from study sites that were very close to one another.

The weathering regime active on Marion Island is one that requires significant study. As has been mentioned before, current trends in process geomorphology suggest that the three major important factors influencing a weathering system are changes in temperature, changes in moisture and the properties of the rock. The beginning of understanding any weathering system is to study how the two extrinsic forces (change in rock temperature and change in rock moisture) influence the intrinsic one (properties of the rock). This statement is the result of an expansion of the definition of weathering given by Bland and Rolls (1998), who stated that weathering is the alteration of rocks in a state of disequilibrium into a more stable state as a result of externally applied forces. This study has attempted to investigate the effects of moisture on rock properties of Marion Island basalt (more colloquially known as 'grey lava') while keeping changes in temperature to a minimum. The intention here is to

create a scenario under which reductionist study will be possible, namely that of the three starting variables (moisture, temperature and rock properties), one will remain constant (change in temperature), one will be externally controlled (change in moisture) and the third one will be observed (rock properties). At the end of the study, it can be said that Marion Island basalt appears to be highly resistant to exposure to moisture. Small grey clasts of lava were predicted by Sumner (2004) to have a clast longevity of 1000 years, so the resistance to weathering under laboratory settings is not unexpected.

5.4. Questions regarding experimental procedures in weathering studies and the evolution of geomorphic thought

The unusual aspect of some of the physical results found in this study lead to a number of questions that need to be asked about the current methods that are employed in the study of process geomorphology in general, and weathering systems in particular. Many of these questions arise from the fact that weathering systems now appear to be rather more complicated than they were initially assumed to be. In fact, the evolution of weathering process studies can be mapped by observing the increasing complexity of the systems. While it is clear that the systems themselves are not changing in terms of their complexity (they are very complex and always have been), our evolving understanding of them is becoming more complex. An example of this is that of cold-climate weathering (already cited earlier in this text). In the early 20th century, cold climate weathering was believed to be dominated by cryogenic weathering, with the result that many of the studies carried out in cold-climates had this axiomatic statement at their core. The idea of a dominant weathering process existing within a particular weathering system is a convenient one, because it greatly simplifies the study of such a system. One needs only to concentrate on that one dominant process, while giving others around it peripheral attention. However, comparative analysis of very different weathering regimes lead to the hypothesis that the various weathering processes should be

treated more equally, leading scientists to perform studies that were specifically designed to challenge the preconceptions of the previous paradigm (eg. Dixon and Thorn, 2005; Hall, 2007). This is a good thing, because it is by challenging preconceived ideas that a specific scientific discipline moves forward. However, even the more equal treatment of individual weathering processes may not be the last word in weathering studies. Careful study of the weathering studies up to this point leads to other questions that need to be asked. Some of these questions will be put forward here and elaborated upon.

The first question is “Are we approaching weathering systems analysis in the correct way and if not, how should we be approaching it?” This initial broad question paves the way for many of the questions that will follow and stems directly from the data obtained from this study. In this study, relatively standard experimental and analytical techniques have been used and yet the results are difficult to interpret and explain. If there is an ambiguous relationship between the experimental method used in the study and the results that were obtained, this suggests that the method needs to be examined carefully and that leads to the following, more detailed questions:

“Does a pure reductionist or a pure holistic approach to science work?” A pure reductionist approach to science has significant appeal to scientists, because it makes the experimental procedures relatively simple and perhaps more importantly, quantifiable. However, a basic reductionist study gives no insight into how the various components of a system relate to one another. A holistic study in its most basic form, requires only the study of the cause and effect of an entire system. Such a black box model is simple to study, but yields little information about the individual components within the system, i.e. the mechanics of the system. Neither study gives any insights into synergy (although holism as a philosophy definitely implies that it exists). This leads to the third and fourth questions:

“Can synergy ever be ignored?” and “Can a system’s synergistic effects ever overpower the measurable effects of individual system components?” The implication of this line of thought is that, if the synergy between two different system components leads to an effect that is larger than that which one or both of those components can generate on its own, but yet is similar in terms of its manifestation, then what, really, is one measuring? Unfortunately, if the synergistic effects of a given system are not quantified (or, as in many cases, not quantifiable), then it becomes impossible to determine what proportion of the data is attributable to core components of the system and what proportion is the result of synergistic interactions. These questions, by their very existence, lead to a corollary: “What is the relevance of an isolation study?” In light of the above questions that relate to synergy, this question becomes highly relevant. In particular, it is worth asking: “Is a process isolation study even possible and what is its place?”, given that, even in a highly controlled laboratory environment, it may be impossible to eliminate or account for all weathering effects that are peripheral to the one that the researcher is investigating. A partial answer to this question may be that process isolation studies should not be used to determine what a given weathering process may do, but rather to determine what the weathering process is capable of under ideal conditions. If one can determine the maximum possible effects of a particular component of a weathering system, if one then measures effects that are beyond that limit, one knows that other weathering processes are in play as well.

The next question is “How does one compartmentalise a system that is, in reality, an analogue system? Are the components of a system merely a subjective construct made for the sake of easy modeling?” Albert Einstein once said: “As far as the laws of mathematics refer to reality, they are not certain and as far as they are certain, they do not refer to reality.” In this study, it has been very difficult to decide what weathering by wetting and drying actually

means, for two reasons. First, as was discussed in Chapter 2, different researchers define wetting and drying in different ways. This makes determining the exact effects of the process difficult. Second, because wetting and drying as an action acts as a catalyst for so many other weathering processes, it is very difficult to tell which experimentally measured results are as the result of the wetting and drying process (as it has eventually been defined) and which measured results stem from other weathering processes that occur purely because the very act of exposing the samples to moisture can initiate other weathering processes.

The final question to be asked here is “What is the philosophical framework of a typical weathering study and is it the best possible philosophical framework that can be applied in these circumstances?” For any experimental study, it is of critical importance that the underlying philosophical framework and its limitations be well understood. If they are not, the potential limitations of the study itself may not be correctly understood, undermining its value in the overall contribution to science.

5.5. Philosophical implications

In the opening chapter of this dissertation, a section was given over purely to the philosophical importance of any scientific study. In particular, reductionism and holism were put forward as two frameworks within which a scientific study may be conducted. Holism, which is characterised by the statement “the whole is greater than the sum of its parts”, indicates that a system needs to be studied completely in order to be truly understood, whereas reductionism attempts to understand a system by breaking it down into its components (which are often arbitrarily assigned based on the preferences of the person conducting the study). After reviewing the data gathered in this study, it has become clear that something that is of critical importance in any system study is the concept introduced by holism known as synergy. After studying the data in detail, it has become clear that no

singular physical or chemical component can be isolated as the singular cause of wetting and drying. Indeed, it is most likely the result of a large array of interlocking weathering processes, some of which are understood and some of which are not. As was indicated in Chapter 2 of this document (the literature review), there are a wide variety of opinions on, not only what the wetting and drying process can do, but also of what it actually is. The application of moisture to a weathering system has so many catalytic effects on other weathering processes that it becomes difficult to track what exactly the mere application of moisture actually accomplishes. Because the interactions between the wetting and drying of a rock sample and the ensuing weathering processes are so complex, it might be better to merely treat wetting and drying of rock as mere action, rather than as a process on its own. I say this because the merely application of water to any sample has such complex ramifications that lumping them all together under one heading seems unwise. It may be better speak of the wetting and drying action and the processes that it may lead to, rather than to speak of wetting and drying as a process. In short, it is extremely difficult to track the one effect that wetting and drying alone is responsible for (if indeed it even exists) and it might be more efficacious to generate a better understanding of other weathering types first, with particular focus on the effects that wetting and drying has on them. Once these have been clearly understood, it may be possible to begin to study wetting and drying as a process, but at the moment, it is just too difficult to eliminate all of the weathering effects that are affected by the application of moisture and to quantify those effects. Any further study should take the form of a synergistic study, by which it is meant that the relationships between the various processes need to be more carefully explored. This implies a more holistic approach, although it must remain quantitative. Methods need to be developed that will give an accurate, understandable indication of how different weathering processes relate to one another.

Chapter 6: Conclusion

The concluding chapter of this document serves to sum up the critical elements of the chapters that have come before, to consider how the aims and objectives of the study have been fulfilled and to make some suggestions regarding the direction that future research should take.

6.1. Accomplishment of aims and objectives

In the investigation of studies that have been carried out to this point, it was determined that each study of the wetting and drying weathering process focused on a different element of the process. While this has yielded a large amount of valuable information regarding the wetting and drying weathering process, it does make comparison of data between studies impossible in anything other than a qualitative sense. While researchers should be encouraged to study as wide an array of things as possible, it is recommended that studies occasionally be carried out with the sole purpose of building specifically on work that has been done before. While studies of this type will not widen our knowledge, they will most certainly deepen it.

The physical experimental aspect of this study sought to investigate the wetting and drying weathering process with specific focus on how the physical properties of igneous and sedimentary rocks would change over time as they were exposed to the process. This has been done, but has yielded results that were not as neat as might have been hoped. However, this has only served to highlight the magnificent complexity of the weathering systems that process geomorphology considers and shows that the processes by no means behave linearly or predictably. Each individual rock type must be investigated against each individual process to determine how these two things relate to each other.

The unusual results obtained in the study have lead to the asking of a number of questions concerning the manner in which process studies are currently carried out. Suggestions are made that the current investigative methods need to be carefully assessed to better understand exactly what it is that they are telling us.

6.2. Physical rock properties

The manner in which Set 1 (Marion Island basalt) and Sets 2a and 2b (Drakensberg sandstones) have responded to cyclic wetting and drying are markedly different from one another. Even more intriguing is the fact that physical rock property changes measured for Set 2a are notably different to those of Set 2b, even though they are both Clarens Formation sandstones and were collected within close proximity of each other and were selected because of their relative similarities to one another. Marion Island basalt is volcanic rock and thus, forms very differently to Clarens Formation sandstone, which is sedimentary rock. The structural differences that result from these different formation processes mean that the different reactions to wetting and drying are not unexpected. While the changes that have been measured for all samples are not easy to interpret, the changes are indicative of rock structure alteration. Thus, according to the definition of weathering laid out by Bland and Rolls (1998), weathering has indeed taken place. What is still unclear is the exact relationship between the wetting and drying of the rocks and the rock alteration. The action of moisture flowing through a rock is known to have a number of effects on the intensity of the weathering processes that are taking place and is of critical importance if processes such as salt weathering and cryogenic weathering are to even take place. In effect, the question becomes, what is the wetting and drying weathering process and what are its effects?

In the definition of any weathering process, what becomes of critical importance is the avoidance of overlaps in definition. Slaking, which refers specifically to the hydration and

swelling of clay minerals within a rock sample, relies on the exact same action as does wetting and drying as defined by Bland and Rolls (1998) and Yatsu (1988), but the mechanics of the processes may be different. If wetting and drying is believed to cause rock weathering in rock samples that contain little or no clay minerals (as Bland and Rolls, 1998 and Yatsu, 1988 would suggest it can), it cannot be classed in the same category as slaking. In the same way, no part of the definition of wetting and drying can overlap with that of salt weathering, which relies on the growth of salt crystals to exert physical force on a rock. What becomes difficult in the study of these weathering processes is their similarities, particularly with respect to the way that the effects are induced in a laboratory setting.

6.3. Future study opportunities

Process isolation studies like this one are of critical importance in furthering the understanding of process geomorphology in general and weathering systems in particular, but it is of the utmost importance that these studies be taken in context. In particular, the researcher must understand the precise nature of the data that have been acquired. While process isolation studies give considerable insights into the manner in which a process may affect a certain type of rock, it does not yield any information in terms of the interacting effects that the weathering processes have on each other. Specific studies should be designed to study this. On a more basic note, a way should be found to accurately quantify chemical weathering effects in studies of this type in order to gauge their effects on the results. Additionally, studies should be carried out on the Equotip hardness tester that compares results that it yields on rock that has been cut and polished against rock that has only been cut. This will give an indication as to the sensitivity of the Equotip when it is used on natural stone, rather than the building materials that it was originally designed for.

At the conclusion of this study, it can without fear be said that the Earth in general, and weathering process systems in particular, are a wealth of complexity and wonderment; something that we as humans can merely hope to truly understand. Rather, we have no choice but to stand back in awe and acknowledge that the world will forever have its secrets, but that it is our privilege as scientists to seek them out.

References

- Allen, C.E., Darmody, R.G., Thorn, C.E., Dixon, J.C. and Schlyter, P., 2001. Clay mineralogy, chemical weathering and landscape evolution in Arctic-Alpine Sweden. *Geoderma*: 277-294.
- Alsaaran, N. and Olyphant, G.A., 1998. A model for simulating rock-water interactions in a weathering profile subjected to frequent alternations of wetting and drying. *Catena*: 225-243.
- Aoki, H. and Matsukura, Y., 2007. A new technique for non-destructive field measurement of rock-surface strength: an application of the Equotip hardness tester to weathering studies. *Earth Surface Processes and Landforms*, 32: 1759-1769.
- Aydin, A. and Basu, A., 2005. The Schmidt hammer in rock material characterization. *Engineering Geology*, 81: 1-14.
- Benavente, D., del Cura, M.A.G., Bernabeu, A. and Ordonez, S., 2001. Quantification of salt weathering in porous stones using an experimental continuous partial immersion method. *Engineering Geology*, 59: 313-325.
- Blanco-Chao, R., Perez-Alberti, A., Trenhaile, A.S., Costa-Casais, M. and Valcarcel-Diaz, M., 2007. Shore platform abrasion in a para-periglacial environment, Galicia, northwestern Spain. *Geomorphology*, 83(1/2): 136-151.

- Bland, W. and Rolls, D., 1998. *Weathering: An introduction to the scientific principles*. Arnold, London.
- Boelhouwers, J., Holness, S. and Sumner, P., 2003. The maritime Subantarctic: a distinct periglacial environment. *Geomorphology*, 52: 39-55.
- Botts, M.E., 1998. *Effects of Slaking on the Strength of Clay Shales: A Critical State Approach*, 2nd International Symposium on the Geotechnics of Hard Soils/Soft Rocks, Naples, Italy.
- Brattli, B. and Broch, E., 1996. Stability problems in water tunnels caused by expandable minerals. Swelling pressure measurements and mineralogical analysis. *Engineering Geology*, 39: 151-169.
- Bretz, J.H., 1962. Dynamic equilibrium and the Ozark land forms. *American Journal of Science*, 260: 427-438.
- Canton, Y., Sole-Benet, A., Queralt, I. and Pini, R., 2001. Weathering of a gypsum-calcareous mudstone under semi-arid environment at Tabernas, SE Spain: laboratory and field-based experimental approaches. *Catena*, 44: 111-132.
- Cetin, H., Laman, M. and Ertunc, A., 2000. Settlement and slaking problems in the world's fourth largest rock-fill dam, the Ataturk Dam in Turkey. *Engineering Geology*, 56: 225-242.

Cooke, R.U., 1979. Laboratory simulation of salt weathering processes in arid environments.

Earth Surface Processes. 4: 347-359.

Darmody, R.G., Thorn, C.E. and Rissing, J.M., 1987. Chemical Weathering of Fine Debris from a Series of Holocene Moraines: Storbreen, Jotunheimen, Southern Norway.

Geografiska Annaler. Series A, Physical Geography, 69(3/4): 405-413.

Darmody, R.G. and Thorn, C.E., 1997. Elevation, Age, Soil Development, and Chemical

Weathering at Storbreen, Jotunheimen, Norway. Geografiska Annaler. Series A,

Physical Geography, 79(4): 215-222.

Darmody, R.G., Thorn, C.E., Harder, R.L., Schlyter, P. and Dixon, J.C., 2000. Weathering

implications of water chemistry in an arctic-alpine environment, northern Sweden.

Geomorphology, 34: 89-100.

Darmody, R.G., Thorn, C.E. and Allen, C.E., 2005. Chemical weathering and boulder mantles,

Karkevagge, Swedish Lapland. Geomorphology, 67: 159-170.

Dhakal, G., Yoneda, T., Kato, M. and Kaneko, K., 2002. Slake durability and mineralogical

properties of some pyroclastic and sedimentary rocks. Engineering Geology, 65: 31-

45.

Dixon, J.C. and Thorn, C.E., 2005. Chemical weathering and landscape development in mid-

latitude alpine environments. Geomorphology, 67: 127-145.

- Doostmohammadi, R., Moosavi, M. and Araabi, B.N., 2008. A model for determining the cyclic swell-shrink behaviour of argillaceous rock. *Applied Clay Science*, 42(1-2): 81-89.
- Dredge, L.A., 1992. Breakup of Limestone Bedrock by Frost Shattering and Chemical Weathering, Eastern Canadian Arctic. *Arctic and Alpine Research*, 24(4): 314-323.
- Duperret, A., Taibi, S., Mortimore, R.N. and Daigneault, M., 2005. Effect of groundwater and sea weathering cycles on the strength of chalk rock from unstable coastal cliffs of NW France. *Engineering Geology*, 78: 321-343.
- Fahey, B.D., 1986. A Comparative Laboratory Study of Salt Crystallisation and Salt Hydration as Potential Weathering Agents in Deserts. *Geografiska Annaler. Series A, Physical Geography*, 68(1/2): 107-111.
- Franklin, J.A. and Chandra, R., 1972. The Slake-Durability Test. *International Journal of Rock Mechanics, Mineral Sciences and Geomechanics*, 9: 325-341.
- Gökçeoğlu, C., Ulusay, R. and Sonmez, H., 2000. Factors affecting the durability of selected weak and clay-bearing rocks from Turkey, with particular emphasis on the influence of the number of drying and wetting cycles. *Engineering Geology*, 57: 215-237.
- Gonzalez, I.J. and Scherer, G., 2006. Evaluating the potential damage to stones from wetting and drying cycles. In: M.S. Konsta-Gdoutos (Editor), *Measuring, Monitoring and Modeling Concrete Properties*. Springer, Dordrecht, pp. 685-693.

Gordon, S.J. and Dorn, R.I., 2005. In situ weathering rind erosion. *Geomorphology*, 67: 97-113.

Goudie, A.S., Viles, H.A. and Parker, A.G., 1997. Monitoring of rapid salt weathering in the central Namib Desert using limestone blocks. *Journal of Arid Environments*, 37: 581-598.

Goudie, A.S. and Parker, A.G., 1998. Experimental simulation of rapid rock block disintegration by sodium chloride in a foggy coastal desert. *Journal of Arid Environments*, 40: 347-355.

Guidi, P.V., Pini, R., Regues, D. and Gallart, F., 1996. Structure and porosity of smectitic mudrocks as affected by experimental wetting-drying cycles and freezing-thawing cycles. *Catena*, 27: 149-165.

Gupta, V. and Ahmed, I., 2007. The effect of pH of water and mineralogical properties on the slake durability (degradability) of different rocks from the Lesser Himalaya, India. *Engineering Geology*, 95: 79-87.

Hachinohe, S., Hiraki, N. and Suzuki, T., 1999. Rates of weathering and temporal changes in strength of bedrock of marine terraces in Boso Peninsula, Japan. *Engineering Geology*, 55: 29-43.

Hall, K., 1991. Rock Moisture Data from the Juneau Icefield (Alaska) and Its Significance for Mechanical Weathering Studies. *Permafrost and Periglacial Processes*, 2: 321-330.

Hall, K. and Hall, A., 1996. Weathering by Wetting and Drying: Some Experimental Results.

Earth Surface Processes and Landforms, 21: 365-376.

Hall, K., 1997. Rock Temperatures and Implications for Cold Region Weathering. I: New Data

from Viking Valley, Alexander Island, Antarctica. Permafrost and Periglacial

Processes, 8: 69-90.

Hall, K., 1999. The role of thermal stress fatigue in the breakdown of rock in cold regions.

Geomorphology, 31: 47-63.

Hall, K. and Andre, M.-F., 2001. New insights into rock weathering from high-frequency rock

temperature data: an Antarctic study of weathering by thermal stress. Geomorphology,

41: 23-35.

Hall, K., 2007. Evidence for freeze-thaw events and their implications for rock weathering in

Northern Canada: II. The temperature at which water freezes in rock. Earth Surface

Processes and Landforms, 32: 249-259.

Hall, K., Meiklejohn, K.I. and Arocena, J., 2007. The thermal responses of rock art pigments:

Implications for rock art weathering in southern Africa. Geomorphology, 91: 132-145.

Hedding, D.W., 2007. Geomorphology and geomorphological responses to climate change in

the interior of sub-Antarctic Marion Island. Unpublished Masters Dissertation,

University of Pretoria, Pretoria.

- Hoerle, S., 2006. Rock temperatures as an indicator of weathering processes affecting rock art. *Earth Surface Processes and Landforms*, 31: 383-389.
- Huang, S.L., Speck, R.C. and Wang, Z., 1995. The Temperature Effect on Swelling of Shales Under Cyclic Wetting and Drying. *International Journal of Rock Mechanics, Mineral Sciences and Geomechanics*, 32(3): 227-236.
- Huggett, R.J., 2003. *Fundamentals of geomorphology*. Routledge, London.
- Jagoutz, E., 2006. Salt-induced rock fragmentation on Mars: The role of salt in the weathering of Martian rocks. *Advances in Space Research*, 38(4): 696-700.
- Kanyaya, J.I. and Trenhaile, A.S., 2005. Tidal wetting and drying on shore platforms: An experimental assessment. *Geomorphology*, 70: 129-146.
- Loubser, J.H.N., 1991. The conservation of rock paintings in Australia and its applicability to South Africa. *Navorsing van die Nasionale Museum Bloemfontein*, 7: 113-143.
- Łoziński, W., 1909. Über die mechanische Verwitterung de sandsteine im gemässigten Klima: *Bulletin International de L'Académie des Sciences de Cracovie class des Sciences Mathematique et Naturelles* 1: 1–25.
- Łoziński, W., 1912. Die periglazie Fazies der mechanischen Verwitterung. *Comptes rendus*. In: *XI Congrès Internationale Geologie, Stockholm, 1910*. pp. 1039–1053.

- Matsukura, Y. and Tanaka, Y., 2000. Effect of rock hardness and moisture content on tafoni weathering in the granite of mount doeg-sung, Korea. *Geografiska Annaler. Series A, Physical Geography*, 82(1): 59-67.
- Matsukura, Y., Hirose, T. and Oguchi, C.T., 2001. Rates of chemical weathering of porous rhyolites: 5-year measurements using the weight loss method. *Catena*, 43: 341-347.
- McGreevy, JP, 1981. Some perspectives on frost shattering. *Progress in Physical Geography*, 5(1): 56-75.
- McGreevy, J.P. and Whalley, W.B., 1985. Rock Moisture Content and Frost Weathering under Natural and Experimental Conditions: A Comparative Discussion. *Arctic and Alpine Research*, 17(3): 337-346.
- Meiklejohn, K.I., 1994. Aspects of the weathering of the Clarens Formation in the KwaZulu/Natal Drakensberg: Implications for the preservation of indigenous rock art. Unpublished PhD thesis, University of Natal, Pietermaritzburg.
- Meiklejohn, K.I., Hall, K. and Davis, J.K., 2009. Weathering of rock art at two sites in the KwaZulu-Natal Drakensberg, southern Africa. *Journal of Archaeological Science*, 36: 973-979.
- Meulenkamp, F. and Grima, M.A., 1999. Application of neural networks for the prediction of the unconfined compressive strength (UCS) from Equotip hardness. *Rock Mechanics and Mining Sciences*, 36: 29-39.

- Moosavi, M., Yazdanpanah, M.J. and Doostmohammadi, R., 2006. Modeling the cyclic swelling pressure of mudrock using artificial neural networks. *Engineering Geology*, 87(3-4): 178-194.
- Nicholson, D.T., 2001. Pore properties as indicators of breakdown mechanisms in experimentally weathered limestones. *Earth Surface Processes and Landforms*, 26: 819-838.
- Nicholson, D.T., 2008. Rock control on microweathering of bedrock surfaces in a periglacial environment. *Geomorphology*, 101: 655-665.
- Pardini, G., Pini, R., Barbini, R., Regüés, D., Plana, F. and Gallart, F., 1995. Laser elevation measurements of a smectite-rich mudrock following freeze-thawing and wet-drying cycles. *Soil Technology*, 8: 161-175.
- Pardini, G., Vigna Guidi, G., Pini, R., Regüés, D. and Gallart, F., 1996. Structure and porosity of smectitic mudrocks as affected by experimental wetting-drying cycles and freezing-thawing cycles. *Catena*, 27(3/4): 149-165.
- Pejon, O.J. and Zuquette, L.V., 2002. Analysis of cyclic swelling of mudrocks. *Engineering Geology*, 67: 97-108.
- Phillips, J.D., 2003. Sources of nonlinearity and complexity in geomorphic systems. *Progress in Physical Geography*, 27(1): 1-23.

- Phillips, J.D., 2006. Evolutionary geomorphology: thresholds and nonlinearity in landform response to environmental change. *Hydrology and Earth System Sciences*, 10: 731-742.
- Pope, G.A., Dorn, R.I. and Dixon, J.C., 1995. A New Conceptual Model for Understanding Geographical Variations in Weathering. *Annals of the Association of American Geographers*, 85(1): 38-64.
- Porter, N.J. and Trenhaile, A.S., 2007. Short-term rock surface expansion and contraction in the intertidal zone. *Earth Surface Processes and Landforms*, 32: 1379-1397.
- Rautureau M. (Editor), 1991. *Tendre Comme la Pierre. Monuments en Tuffeau, Guide Pour la Restauration et l'Entretien*. Université d'Orléans, Orléans.
- Sass, O., 2005. Rock moisture measurements: techniques, results, and implications for weathering. *Earth Surface Processes and Landforms*, 30: 359-374.
- Scherer, G., 2006. Internal stress and cracking in stone and masonry. In: M.S. Konstantinos (Editor), *Measuring, Monitoring and Modeling Concrete Properties*. Springer, Dordrecht.
- Smith, B.J., Warke, P.A., McGreevy, J.P. and Kane, H.L., 2005. Salt-weathering simulations under hot desert conditions: agents of enlightenment or perpetuators of preconceptions? *Geomorphology*, 67: 211-227.
- Smuts, J.C., 1926. *Holism and Evolution*. McMillan, New York.

Sparks, B.W., 1986. *Geomorphology*. Longman, London and New York, 561 pp.

Stephenson, W.J. and Kirk, R.M., 2001. Surface swelling of coastal bedrock on inter-tidal shore platforms, Kaikoura Peninsula, South Island, New Zealand. *Geomorphology*, 41: 5-21.

Sumner, P. and Nel, W., 2002. The effect of rock moisture on Schmidt hammer rebound: Tests on rock samples from Marion Island and South Africa. *Earth Surface Processes and Landforms*, 27: 1137-1142.

Sumner, P., 2004. Rock weathering rates on subantarctic Marion Island. *Arctic, Antarctic and Alpine Research*, 36(1): 123-127.

Sumner, P. and Loubser, M., 2008. Experimental sandstone weathering using different wetting and drying moisture amplitudes. *Earth Surface Processes and Landforms*, 33: 985-990.

Sumner, P., Hall, K., van Rooy, J.L., and Meiklejohn, K.I., 2009. Rock weathering on the eastern mountains of southern Africa: Review and insights from case studies. *Journal of African Earth Sciences*, 55: 236-244.

Swantesson, J., 1985. Experimental weathering studies of Swedish rocks. *Geografiska Annaler. Series A, Physical Geography*, 67(1/2): 115-118.

Thorn, C.E., 1988. Introduction to Theoretical Geomorphology. Unwin Hyman, Boston, 247 pp.

Trenhaile, A.S., 2006. Tidal wetting and drying on shore platforms: An experimental study of surface expansion and contraction. *Geomorphology*, 76: 316-331.

Trenhaile, A.S., 2008. Modeling the role of weathering in shore platform development. *Geomorphology*, 94: 24-39.

Tu, X.B., Jian, B., Wang, S.J., Bian, H.Y., Wang, J. and Li, S.G., 2005. Swelling behaviour induced by alteration in granite and its implications on underground excavation. *Tunnelling and Underground Space Technology*, 20: 378-389.

Turkington, A.V., Phillips, J.D. and Campbell, S.W., 2005. Weathering and landscape evolution. *Geomorphology*, 67: 1-6.

Wells, T., Binning, P. and Willgoose, G., 2005. The role of moisture cycling in the weathering of a quartz chlorite schist in a tropical environment: findings of a laboratory simulation. *Earth Surface Processes and Landforms*, 30: 413-428.

White, S., 1976. Is frost action only hydration shattering? A review. *Arctic and Alpine Research*, 8(1): 1-6.

Wüst, R.A.J., 2000. The origin of soluble salts in rocks of the Thebes Mountains, Egypt: The damage potential to ancient Egyptian wall art. *Journal of Archaeological Science*, 27: 1161-1172.

Yatsu, E., 1988. The Nature of Weathering: An Introduction. Sozosha, Tokyo.

Zhang, C.-L., Rothfuchs, T., Su, K. and Hoteit, N., 2007. Experimental study of the thermo-hydro-mechanical behaviour of indurated clays. Physics and Chemistry of the Earth, 32: 957-965.



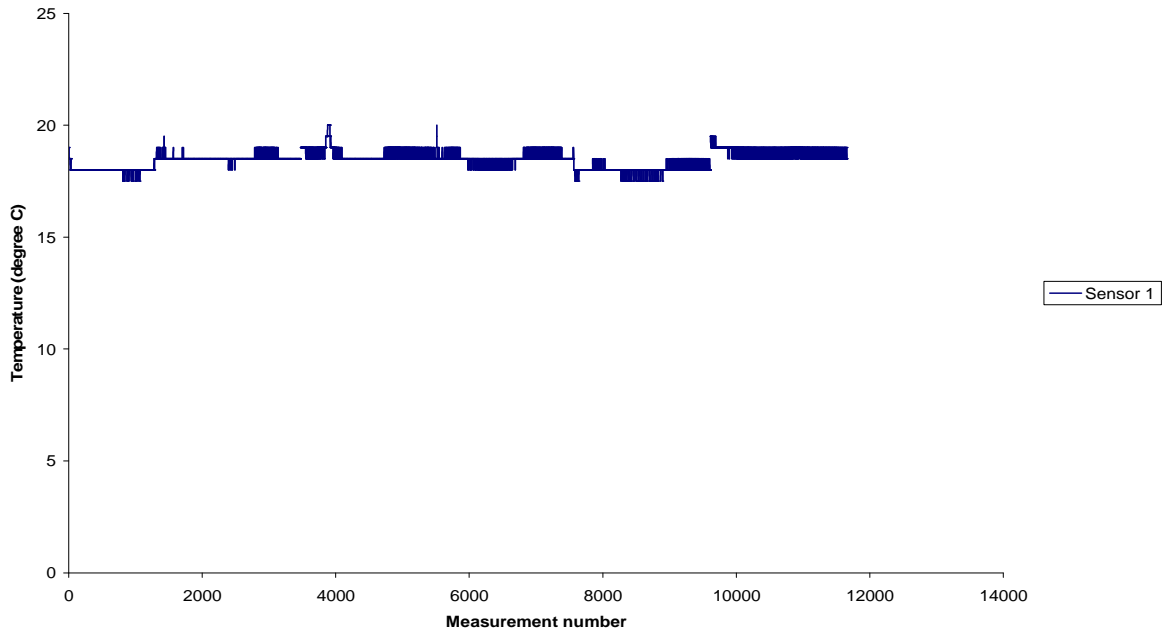
Appendix A: Chemical analysis

%	GSNcert	GSN	SET 1	SET 2a	SET 2b
SiO ₂	65.80	66.22	47.36	69.77	77.73
TiO ₂	0.68	0.67	3.71	0.70	0.51
Al ₂ O ₃	14.67	15.23	16.08	14.08	10.56
Fe ₂ O ₃	3.75	3.77	14.00	4.63	2.52
MnO	0.06	0.06	0.20	0.07	0.05
MgO	2.30	2.25	4.82	1.31	0.90
CaO	2.50	2.67	8.23	0.47	0.15
Na ₂ O	3.77	3.78	3.76	2.96	3.12
K ₂ O	4.63	4.61	1.43	3.72	2.85
P ₂ O ₅	0.28	0.28	0.59	0.00	0.06
Cr ₂ O ₃	0.01	0.01	0.00	0.02	0.01
NiO	0.00	0.02	0.00	0.04	0.01
V ₂ O ₅	0.01	0.01	0.04	0.00	0.01
ZrO ₂	0.03	0.02	0.03	0.04	0.06
LOI	1.32	1.29	-0.85	1.97	1.32
TOTAL	99.82	100.88	99.41	99.78	99.87

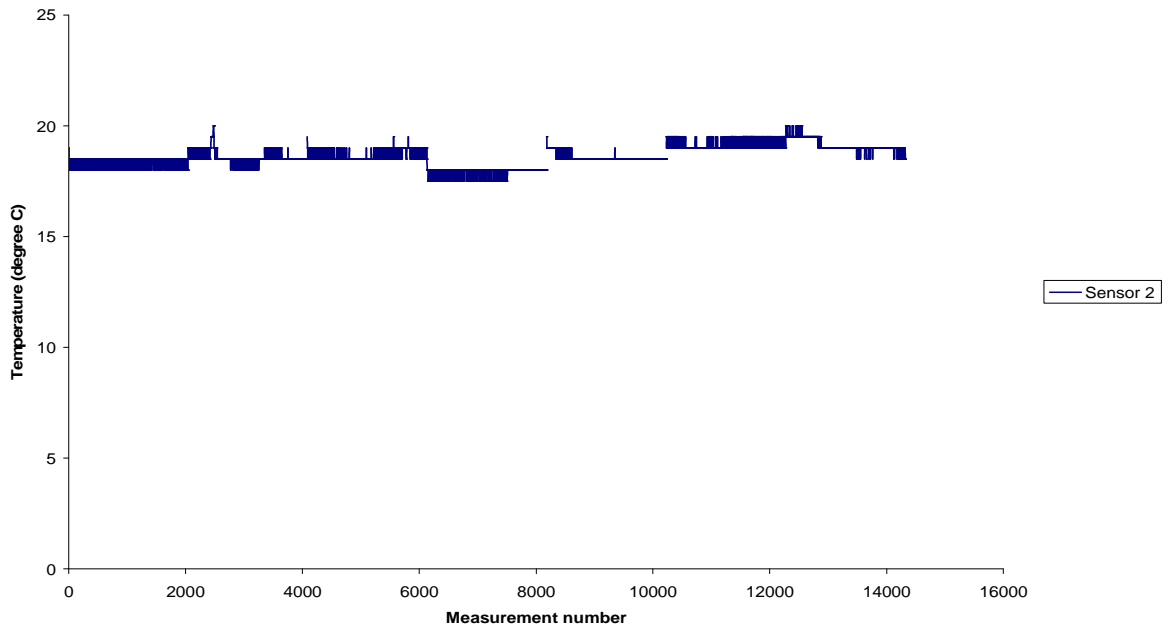
ppm	GSNcert	GSN	SET 1	SET 2a	SET 2b
As	1.6	3	4	6	3
Cu	20	41	23	20	12
Ga	22	18	22	16	11
Mo	1.2	1	8	1	1
Nb	21	21	45	20	13
Ni	34	37	6	21	14
Pb	53	55	8	17	17
Rb	185	186	33	96	85
Sr	570	583	761	166	136
Th	42	48	15	4	4
U	8	10	14	3	3
W*	450	536	139	109	192
Y	19	8	39	26	19
Zn	48	48	105	68	54
Zr	235	212	300	284	393
Cl*	450	706	137	1527	518
Co	65	69	49	25	33
Cr	55	47	7	32	23
F*	1050	2342	1536	1207	1223
S*	140	422	16	176	35
Sc	7	7	18	11	8
V	65	56	222	54	35
Cs	5	9	9	9	9
Ba	1400	1436	325	930	1060
La	75	85	4	30	33
Ce	135	145	83	73	56

Appendix B: Graphic representation of temperature data obtained from i-Button thermal sensors

Sensor 1

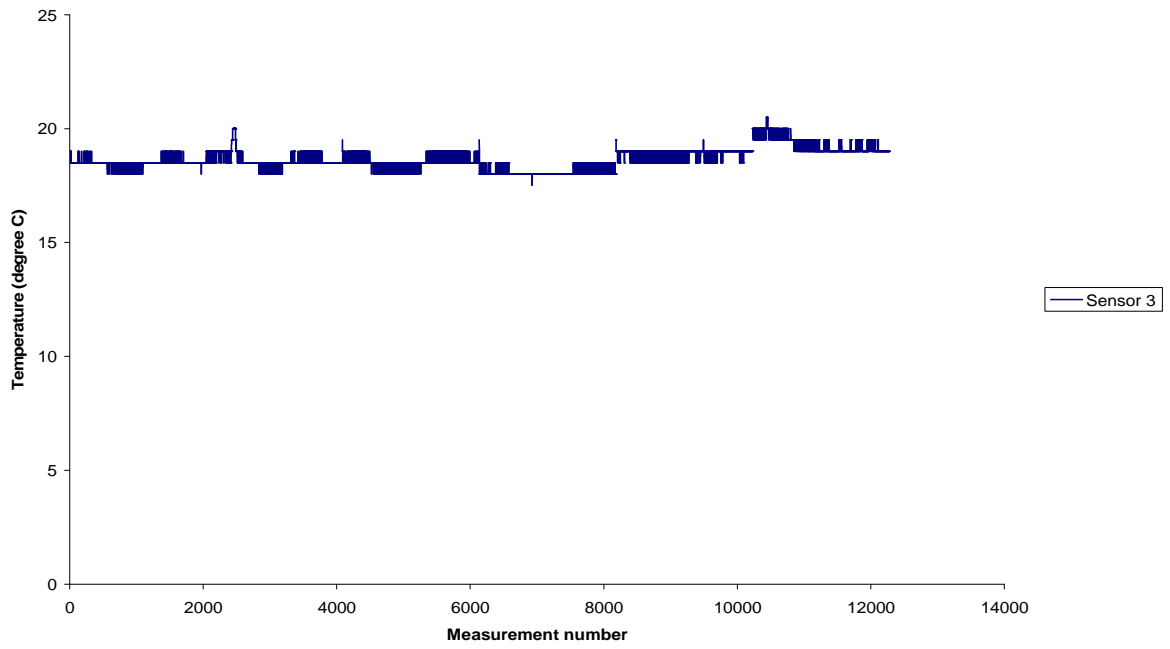


Sensor 2

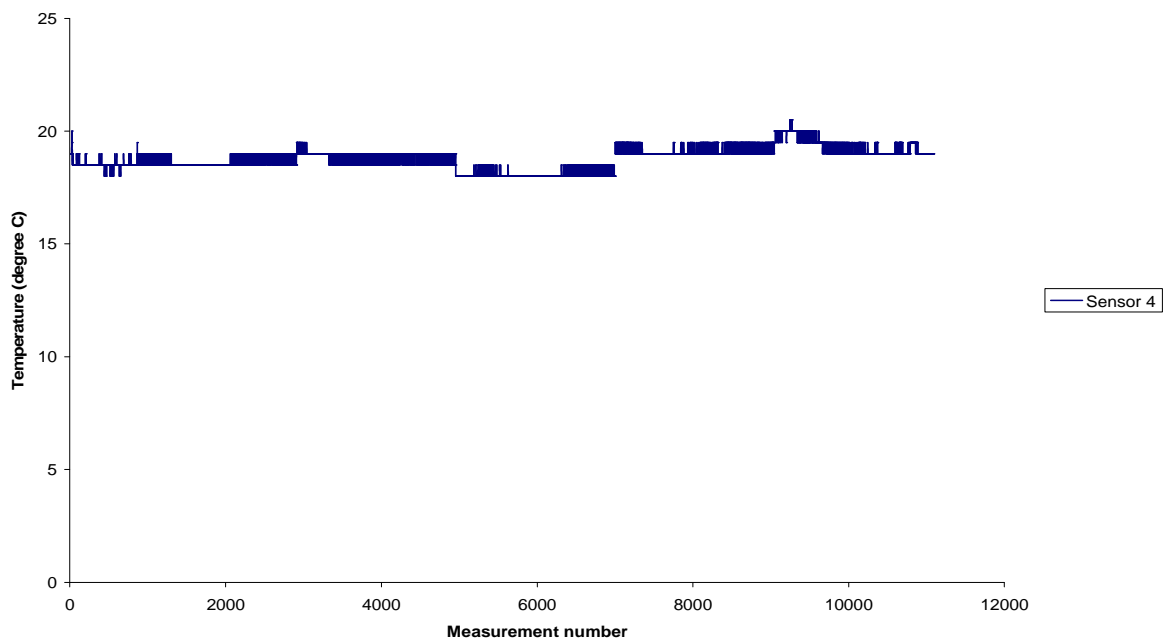




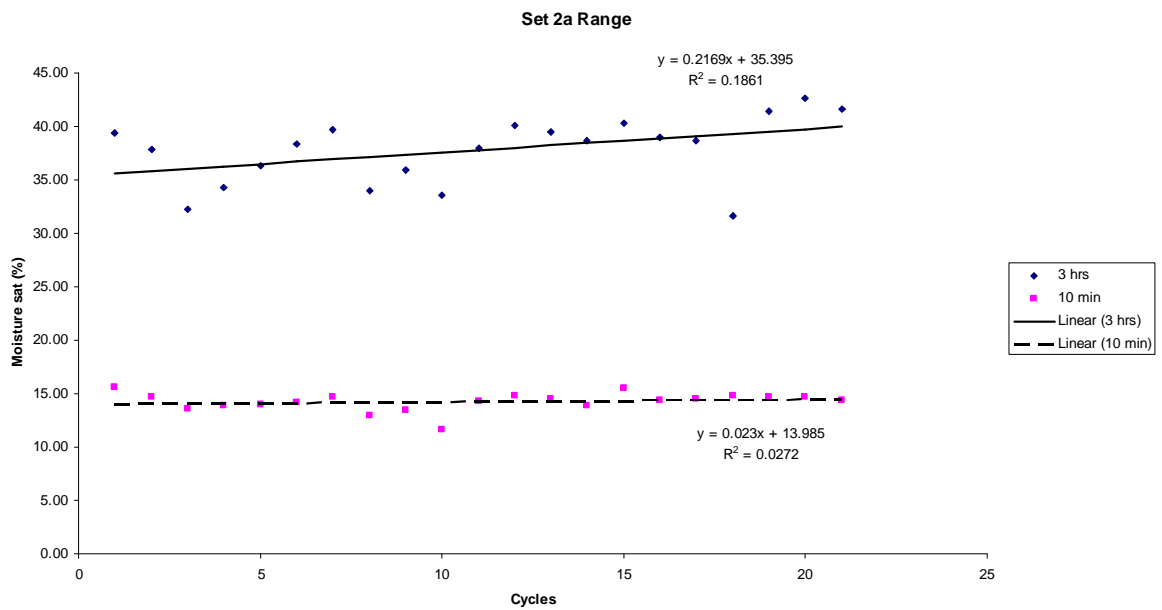
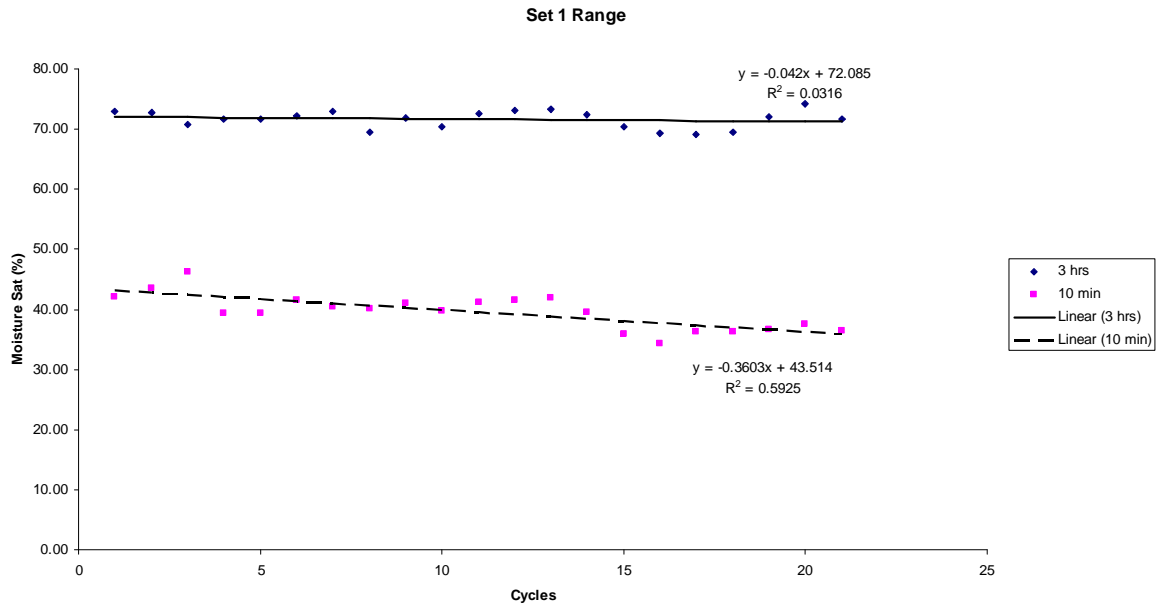
Sensor 3

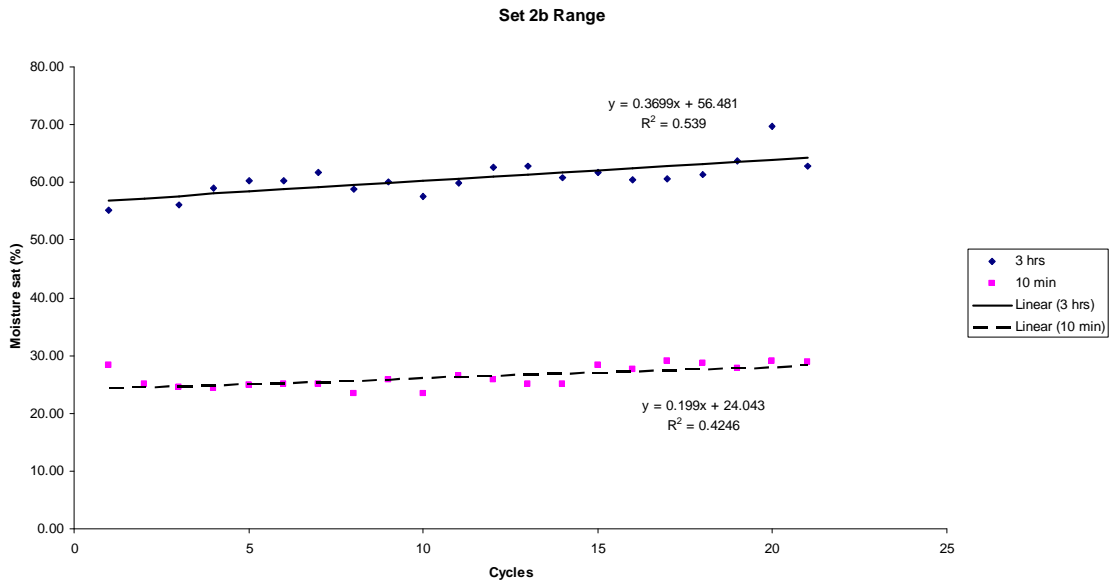


Sensor 4



Appendix C: Comparison of Saturation Amplitude (3 hour sat vs 10 min sat)





Appendix D: Model of moisture absorption rates prior to experiment start

The samples were saturated for one hour, with measurements taken at 2 minutes, 4 minutes, 6 minutes, 10 minutes, 20 minutes, 30 minutes and 60 minutes. The points were plotted in Microsoft Excel and a curve was fitted to the points. It was determined that the samples do not absorb moisture at a linear rate, meaning that the percentage moisture saturation is not directly proportional to time. Instead, it was found that a logarithmic curve fits the data best for all samples used in this experiment, meaning that the percentage moisture saturation is inversely proportional to the rate at which the sample takes up moisture. The higher percentage moisture saturation, the lower the rate at which it takes up moisture. The model's ability to extrapolate accurately was tested by saturating the samples beyond the saturation range from which it was derived. The model was constructed using measurements taken up to 1 hour, so the model was tested for samples of the same type that had been saturated for 3 hours. It was found that in the case of Marion Island basalt (Sample 1), the model over-predicted by 3.3%, while in the case of the two Drakensberg sandstone samples, the model under-predicted by 15.3% for Sample 2a and 12.6% for Sample 2b. The model correlates very closely with the data for the first hour, meaning that the rate at which the samples absorb moisture changes in the period between hour 1 and hour 3 for the sandstone samples. More specifically, the rate at which the samples absorb moisture decreases more rapidly than the model anticipated, leading to a percentage moisture saturation that was correspondingly low. The empirically determined equations are as follows:

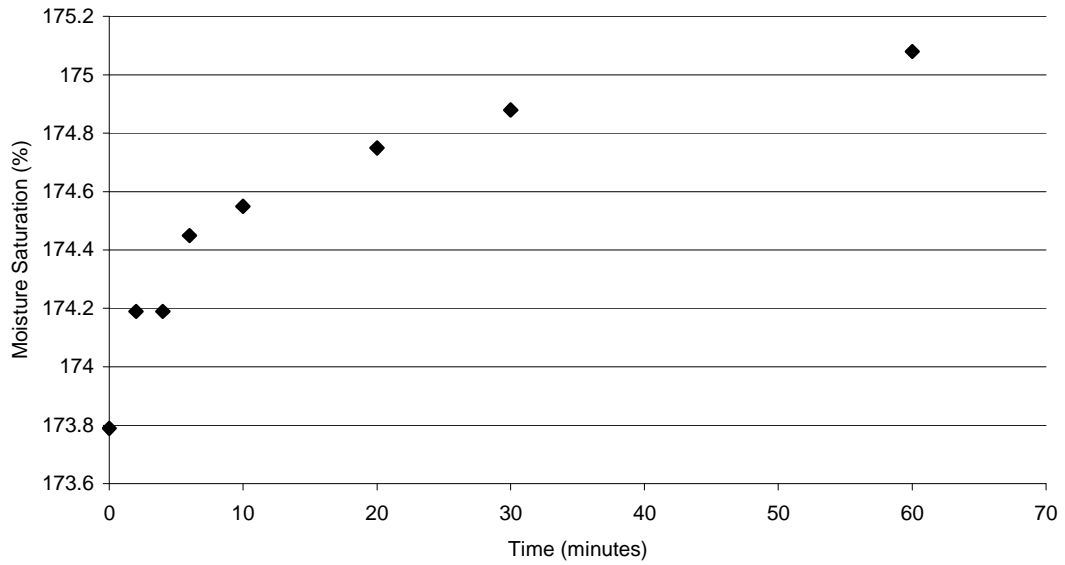
$$\text{Set 1: } S = 15.367Ln(t) + 11.834$$

$$\text{Set 2a: } S = 6.867Ln(t) + 9.387$$

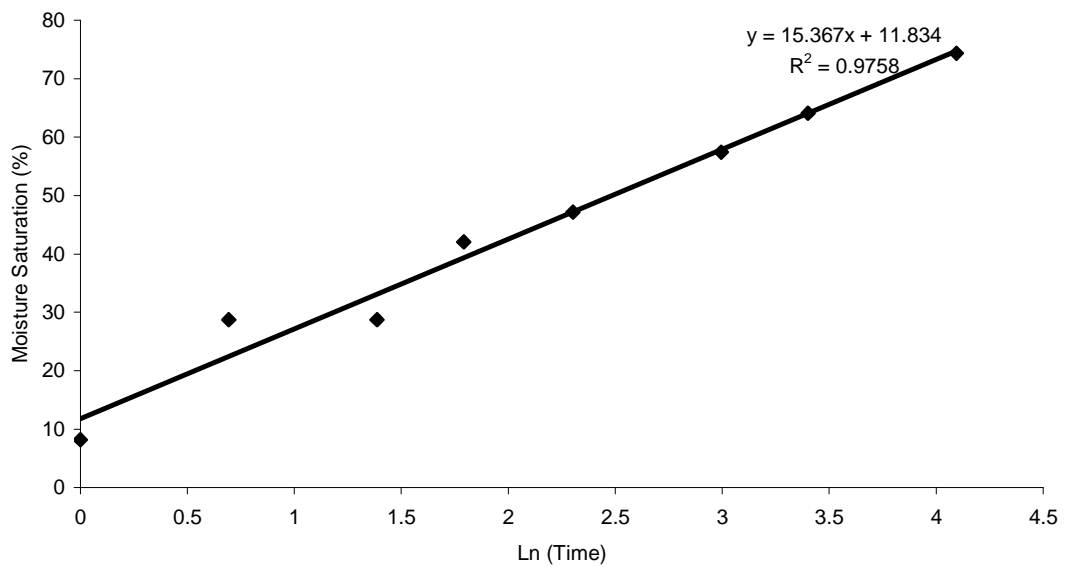
$$\text{Set 2b: } S = 12.325Ln(t) + 13.857$$

Where S = Percentage Moisture Saturation and t = Time in minutes.

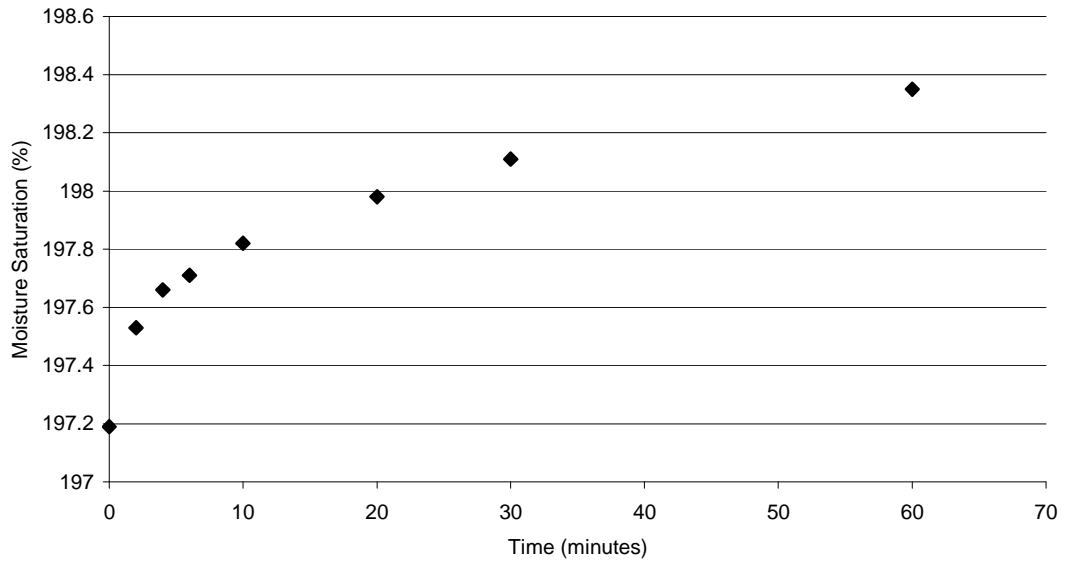
Set 1: Moisture saturation percentage vs Time



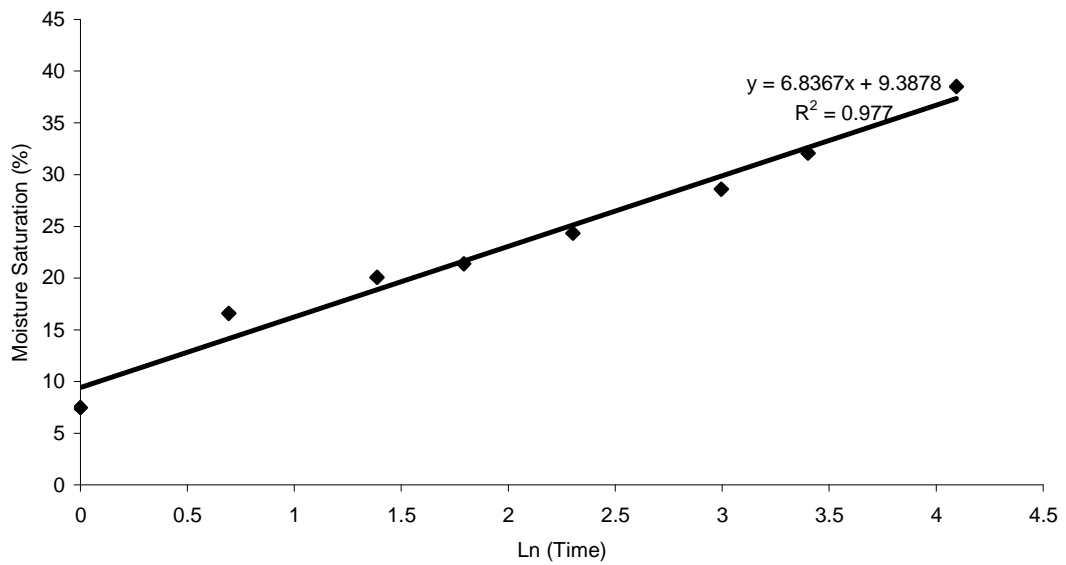
Set 1: Moisture saturation percentage vs Ln of time



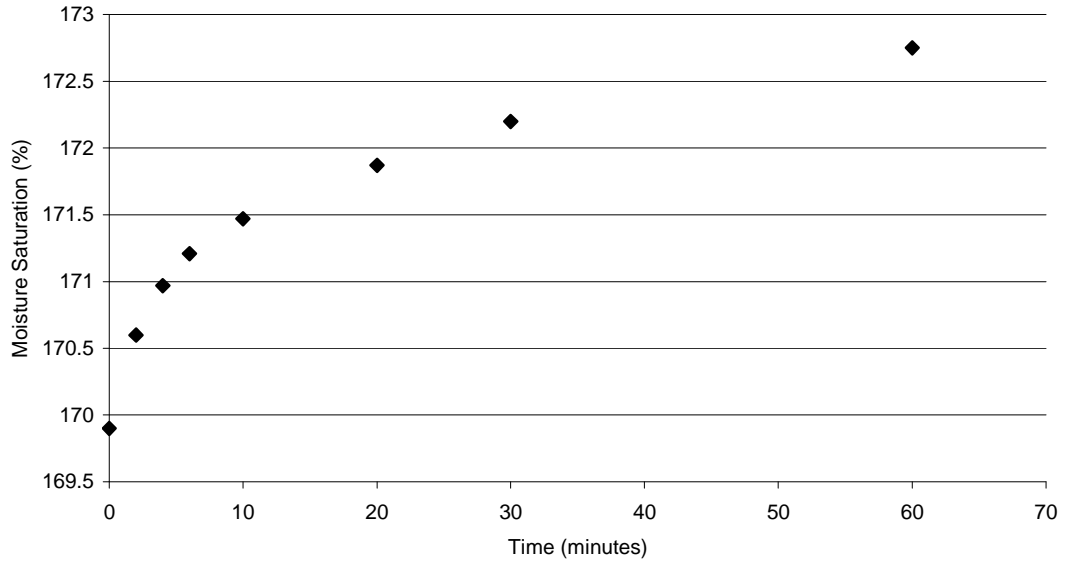
Set 2a: Moisture saturation percentage vs Time



Set 2a: Moisture saturation percentage vs Ln of time



Set 2b: Moisture saturation percentage vs Time (minutes)



Set 2b: Moisture saturation percentage vs Ln of time

