Rock weathering and ultrasonic pulse velocity: an analysis using South African cemeteries as time-series laboratories

By

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Rock weathering and ultrasonic pulse velocity: an analysis using South African cemeteries as time-series laboratories

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Abstract

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The study of rock weathering poses unique challenges due to the operation of weathering processes on small spatial and large temporal scales. Many, although not all, studies that focus on a specific weathering process tend to confine themselves to regional climates in which the processes are expected to function most efficiently; for example, thermal weathering studies tend to take place predominantly in arid or polar regions and many chemical weathering studies are in tropical regions. The aim of this study is to develop and assess an experimental measurement technique for the quantification of weathering in different regions. This technique, which makes use of state of the art ultrasonic technology, can potentially be used to quantify weathering rates in a manner that allows results to be compared for different environmental or climatic regions. Ultrasonic Pulse Velocity (UPV) measurements were recorded in six cemeteries at different locations across South Africa using a variety of field measurement protocols and apparatus configurations. The results show that rock weathering can be assessed in this way, but the weathering signal is extremely small. This method thus requires a high degree of measurement precision from the field operator when data are being gathered. Overall, the results show that climate does exert a general influence on the weathering regime of a specific region, but that the rock properties of any specific tombstone can cause weathering to occur very differently to what may be regarded as typical for a region. The specific weathering regime for a given area is,

therefore, not determined by either climatic forcings or rock properties, but rather is the result of tension between these two elements, the nature of which will be unique to each regional environment.

DECLARATION OF ORIGINALITY

UNIVERSITY OF PRETORIA

I, Michael John Loubser, declare that this thesis, which I hereby submit for the degree Doctor of Philosophy (Geography) at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

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Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

1.1. Studies in rock weathering

Rock weathering refers to the *in situ* disintegration and decomposition of a rock as a response to a disequilibrium with its surroundings. While there are an array of different definitions and consequent theoretical constructs (for example, Yatsu, 1988; Summerfield 1991; Bland & Rolls, 1998), a common point of agreement is the definition of individual weathering processes in terms of climatic variables such as temperature, moisture, change in temperature and change in moisture. This has led many rock weathering studies to be tied to regions where the study under investigation is believed to be most efficient, such as arid regions for thermal weathering processes (McFadden et al., 2005; Gunzburger & Merrien-Soukatchoff, 2011), areas with high levels of moisture availability for chemical weathering studies (White et al., 1998; Oliva et al., 1999; Li et al., 2022) and polar and alpine regions for freeze-thaw weathering (Deprez et al., 2020). However, rock properties, which serve as a control for many weathering processes may have a greater effect on weathering than is generally considered. Hall et al. (2012), for example, suggest that attempting to connect specific weathering processes to distinct climatic regimes may be an exercise in futility, since very few weathering processes have a one-to-one relationship between process and climatic spectrum (i.e., the relationship between a particular climate and a particular weathering process is seldom guaranteed). The relationship between climate and weathering may not be as definitive as most researchers intuitively believe, with rock properties possibly playing a larger than anticipated role in the spectrum of weathering processes operating in any given area.

Understanding the relative roles of climate and rock properties and the relationship between them and weathering should be a fundamental goal for researchers in this field, since they lie at the centre of the conceptual models upon which the science of weathering is based. However, actually taking steps to assess these roles has been a difficult task. With the exception of a relatively small number of articles (for example, Pope et al., 1995; Hall et al., 2012; Dorn et al., 2013), the topic remains largely undiscussed. The reasons for this are both philosophical and practical and will be briefly outlined in the following pages.

1.2. Logical difficulties in separating rock properties and climate drivers

While it is generally accepted that weathering processes operate in suites (i.e. several processes operating in parallel to generate a singular weathering outcome), studies that consider a specific weathering process will typically treat that particular process as being ‘dominant’ in the environment within which it is being investigated, and this may either be explicitly stated or implicitly implied. For example, studies that investigate freeze-thaw weathering will typically assume that the majority of observed weathering forms are due to that particular process, with any other processes playing only a minor role.

As has been pointed out by Hall (1995) concerning freeze-thaw weathering in particular, there is very little evidence to suggest that this particular weathering spectrum is true, beyond the fact that it appears intuitively obvious. In fact, there is some doubt over whether freeze-thaw as a weathering process is effective at all, and it is very possible that the other weathering processes in the spectrum, heretofore regarded as being of either negligible, or at least secondary importance, may be driving weathering rather than freeze-thaw.

It is important to note that the key piece of information to take from this is not that one perspective is right and the other is wrong, but rather that we have no effective way to determine which of them (if either) is correct. Since it is difficult to determine the precise nature of the weathering spectrum for any given scenario, weathering studies are often framed in terms of weathering actions, rather than weathering processes, a distinction which is considered below.

1.3. Weathering action vs weathering process

A weathering action is a systemic imbalance that is known to potentially produce one or more weathering processes under the right conditions, although it may not always be clear which ones. Weathering actions include heating and cooling, wetting and drying and freezing and thawing. None of these actions necessarily cause weathering to occur, but under the right conditions they may. For example, the wetting and drying action can drive salt weathering, cryogenic weathering or slaking, or a combination of all three. Many weathering studies do not explicitly study the effects of a weathering *process*, as defined in this fashion, but rather that of a weathering *action*. Studies that do attempt to study specific weathering processes often do so under isolated conditions, either in a controlled laboratory environment (Remy et al., 1994; Hall & Hall, 1996; Sumner & Loubser, 2008; Loubser, 2013)

, or in a specific climatological location believed to favour that process, as discussed above. These studies are valuable in generating data about rock weathering under specific conditions, but the data are not always usable in a more general sense. It would be risky to assume that the conclusions drawn in studies such as these are transferrable to scenarios that consider different conditions. The important point here is that the relationship between climatic drivers, weathering actions and weathering processes is fundamentally complex, and many studies do not directly engage with it. Ultimately though, most geomorphological studies implicitly assume that this relationship is in place, and more importantly, that it will behave consistently in a general sense (i.e. different weathering regimes will give rise to other weathering processes). If, this were not the case, it becomes necessary to expand the discussion to include rock properties as well.

1.4. Climatic drivers vs rock property controls

Hall et al. (2012) propose that most climates would be sufficient to drive most weathering processes, with the specific regional climate driving the relative contributions of each. They noted, however, that it would be extremely difficult, if not impossible, to determine what these relative contributions might be.

There is thus a question as to the appropriate focus for contemporary weathering theory. Classical theory places the focus on climatic drivers and categorizes many processes in terms of the driving forces required to initiate them (Yatsu, 1988; Bland & Rolls, 1998). The alternate approach put forward by Hall et al. (2012) places the focus more firmly on rock properties as the central focus of the model.

Unfortunately, there has been little headway in selecting one or the other of these two approaches in the decade since Hall et al. (2012) was published, mostly because of the difficulties described above, along with the highly varied nature of field locations, which contrive to ensure that each individual field location is unique (Phillips, 2007). In essence, it is difficult to precisely quantify the effects that the external environment has on rock weathering, because every unique environment has unique rocks, with their own histories and physio-chemical structures, which makes each subsequent climate/rock interaction unique. Rock weathering spectrums are, therefore, generally incomparable across regions, especially if they are far apart.

However, while it is likely impossible to identify specific weathering processes operating in different regions, a meaningful assessment of weathering rates on similar rock types in dissimilar locations could yield valuable information into the relationship between rock properties and climate for rock weathering. In essence a study of this nature would take the following form:

1) Assume two identical rocks have been exposed for the same amount of time to two different environmental conditions in different locations.
2) Assume that the rate of weathering can be accurately assessed at any moment.
3) If the two rocks weather identically, then rock properties are the sole limiting factor and external environmental conditions play no role in how the rocks weather.
4) If the two rocks weather differently, then external environmental conditions play a role in how the rocks weather, if only in intensity.

While the required conditions of such an experiment could not be reasonably met under normal field conditions, a scenario in which they are at least partially met would still yield useful information regarding the relative roles of climate and rock properties. An experiment of this nature is proposed in the section below.

1.5. Necessary conditions to study the relative effects of climatic forcings and rock property controls.

The ideal conditions and requirements that would need to exist for a regional study of this nature would be as follows:

1) Access to a study method and experimental apparatus sensitive enough to find a relatively small weathering signal, with very carefully determined delimitations.
2) Multiple regions of study with differing climates, but common rock types.
3) Rocks that have been exposed to their region’s climate for a known amount of time.

While these conditions (in particular the second and third ones) can never perfectly exist under field conditions, it is possible to find a reasonable approximation of such a scenario, namely that of cemeteries. In South Africa, one of the most common stones used for graves is gabbro, much of which has been extracted from quarries near the towns of Brits and Rustenberg in the North-West Province of South Africa. Gabbro tombstones from this region can be found in cemeteries all across South Africa since approximately 1910 and are still commonly used today (they were observed in nearly all of the contemporary cemeteries surveyed for this study). This means that there are stones of the same type and quarried in the same region, but that have been exposed to different climates for a temporal period of greater than 100 years. Additionally, the period of time that each stone has been exposed to the climate of its region can be closely estimated from the date of death on the tombstones' inscription. It is not possible to know the degree to which each stone has been maintained, but it is reasonable to assume that the stones have been managed more or less consistently by the management personnel of each cemetery, with minor additional changes made by mourners caring for individual stones (cleaning and removal of biological material), but observational evidences suggests that very few tombstones will receive this kind of treatment for longer than one generation (for purposes of this study, a generation is defined as no longer than 25 years).

A more pressing concern for a study such as is proposed here is how weathering should be measured. Gabbro stone is a popular choice for tombstones because it is highly resistant to weathering and a hundred years is not a long time from a weathering perspective. It is, therefore, necessary to make use of equipment that is non-destructive (due to the culturally sensitive nature of the stone), but sensitive enough to detect a very weak weathering signal. Unfortunately, many high precision measurement techniques require the destruction of the sample under investigation, while purely non-destructive techniques provide less information on the material under investigation. Studies on tombstones have typically been purely observational, or comprised primarily of physical measurements to this date, some of which are only viable on certain types of stone, such as the lead lettering index technique, which is most effective when applied to limestone and marble stones. However, ultrasonic pulse velocity measurements have been used as a proxy for intact rock strength in a several studies as early as 1988 (Hall, 1988), although a small number of studies have employed this technique on tombstones to date (for example, Siegesmund et al., 2010; Akoglu et al. 2020). It is possible that this technique could have the required precision and sensitivity to detect a weathering signal in gabbro stone, although this possibility would need to be carefully assessed.

1.6. Challenges in equipment precision and accuracy

Rock weathering takes place at a very small spatial scale and a large temporal scale. This makes the direct observation of rock weathering difficult. However, technological developments have allowed rock weathering to be assessed in more sophisticated ways. This can range from Scanning Electron Microscopy Assessments (Viles, 1987) and mercury porosimetry (Tuğrul, 2004) to high-frequency thermal logging (Hall & André, 2001; McKay et al., 2009; Molaro & Mckay, 2010) and rock hardness measurement techniques (Viles et al., 2011; Mol & Viles, 2012; Wilhelm et al., 2016).

If the sampled stone is of cultural significance, there is the added complication of using a purely non-destructive measurement system. This disqualifies techniques that require the stone to be either damaged or destroyed, such as for mercury porosimetry and Scanning Electron Microscopy, and limits the study to the use of purely non-destructive measurement techniques, which are limited in terms of their capacity to provide information on the precise nature of the structure of the rock under investigation. For example, rock temperature measurements, rock mass loss and rock hardness measurements, which are used frequently in weathering studies as non-destructive assessment tools, provide no direct information on the rock structure changes, but rather offer weathering information purely by proxy. Proxy variables do not assess rock weathering directly, but rather measure a separate variable that is believed to have a consistent correlation to rock weathering.

This means that the data generated by the measurement technique must be correlated to the unobserved variable separately for each study, or else design the experiment to rely purely on relative assessment. In the case of natural stone such as gabbro, relative assessment is the preferred option because of the stone’s variable nature, as opposed to a building material such as concrete which is likely to have generally more consistent composition.

1.7. Aim and Objectives

The aim of this study is to develop and assess an experimental measurement technique that would allow for the quantification of weathering rates in a manner that allowed them to be compared for different regions.

To achieve this aim, the following objectives must be met:

Objective 1: To develop and test the experimental method under laboratory conditions to determine the equipment limitations and delimitations

Objective 2: To test the method under field conditions and adapt as necessary

Objective 3: To deploy method to compare weathering rates in regions with different climates

1.7. Thesis structure

This thesis will be structured in the following manner:

Chapter 2: Literature Review

Chapter 3: General Methods and Study Site Description

Chapter 4: Objective 1 - Equipment limitations and delimitations

Chapter 5: Objective 2 - Cemeteries as time series laboratories

Chapter 6: Objective 3 – An investigation of rock decay across South African climatic regions

Chapter 7: General Discussion and Conclusion

Chapter 2: Literature review

2.1. The Classical Conceptual Model for Rock Weathering

The classical conceptual model upon which the theory of rock weathering is based has at its core the relationship between weathering processes and regional climate (see definitions listed below). Specifically, climatic forcings such as change in temperature and change in moisture will induce an imbalance in the system that is a rock, and that system will attempt to shift itself back into equilibrium. This relationship between climate, weathering processes and rock properties is, therefore, a central part of any weathering study.

In order to demonstrate this, it is instructive to look at some rock weathering definitions that have been drawn from fundamental texts:

The alteration of rocks or minerals in situ, *at or near the surface of the earth and under the conditions that prevail there.*

Yatsu (1988), page 2

Weathering can be defined as the adjustment of the chemical, mineralogical and physical properties of rocks in response to environmental conditions prevailing at the Earth's surface.

(Summerfield, 1991), page 129

The alteration by chemical, mechanical, and biological processes of rocks and minerals, at or near the Earth's surface, in response to environmental conditions.

Bland and Rolls (1998), page ix

Weathering is the breakdown of rocks by mechanical disintegration and chemical decomposition. Many rocks form under high temperatures and pressures deep in the Earth's crust. When exposed to the lower temperatures and pressures at the Earth's surface and brought into contact with air, water and organisms, they start to decay.

(Huggett, 2011), page 137

These four definitions span almost 25 years of weathering research and have not changed substantially since the 1980s. While they range in complexity and precision of language depending on the needs of the specific publication or textbook, all retain a link between external climatic forcings and rock properties. The processes can be divided into physical processes, in which the weathering product is chemically identical to the starting material and chemical processes, which involve a chemical change. Examples of physical processes are freeze-thaw (or cryogenic) weathering, salt weathering, thermal fatigue and thermal shock. Examples of chemical processes are solution, carbonation, oxidation and clay mineral hydration (although this last process has a physical component). For purposes of this study, biological elements will be treated as either chemical or physical weathering processes with a biological component, although that component can be either catalytic or inhibitive (Hall et al., 2012). Traditionally, these weathering processes have been framed in terms of climatic forcings.

Weathering processes under the classical weathering model should, therefore, be most effective within specific temperature and moisture ranges. Following this line of reasoning to its natural conclusion led to the categorisation of specific parts of the world with respect to anticipated dominant weathering processes. A clear understanding of this link is, therefore, key to any weathering study. Beyond these definitions, there is a question of where the focus should be placed in terms of climatic forcings or rock property reactions.

A review of classical weathering texts demonstrates a focus on climatic forcings, with some exceptions. This climatic approach formed part of a general climatically driven approach towards geomorphology which was termed ‘climatic geomorphology’. This approach was formalised by Peltier (1950), who developed a conceptual diagram that categorised likely weathering patterns as a function of mean annual rainfall and temperatures (Figure 1). This ultimately in an entrenched belief by researchers that different weathering processes would be dominant in areas with differing climate.

The relationship between weathering and climate can be seen in Yatsu (1988), with freeze-thaw weathering, salt weathering and the thermal processes (thermal fatigue and thermal shock) all being displayed as having specific locations where they are believed to function with greater efficacy. However, the swelling of clay minerals is shown as having a more profound connection to rock properties, rather than being linked to a specific climatic regime. As with Yatsu (1988), Bland and Rolls (1998) connect location and weathering efficacy with at least some physical weathering processes (in particular cryogenic weathering, thermal shock, thermal fatigue and salt weathering).

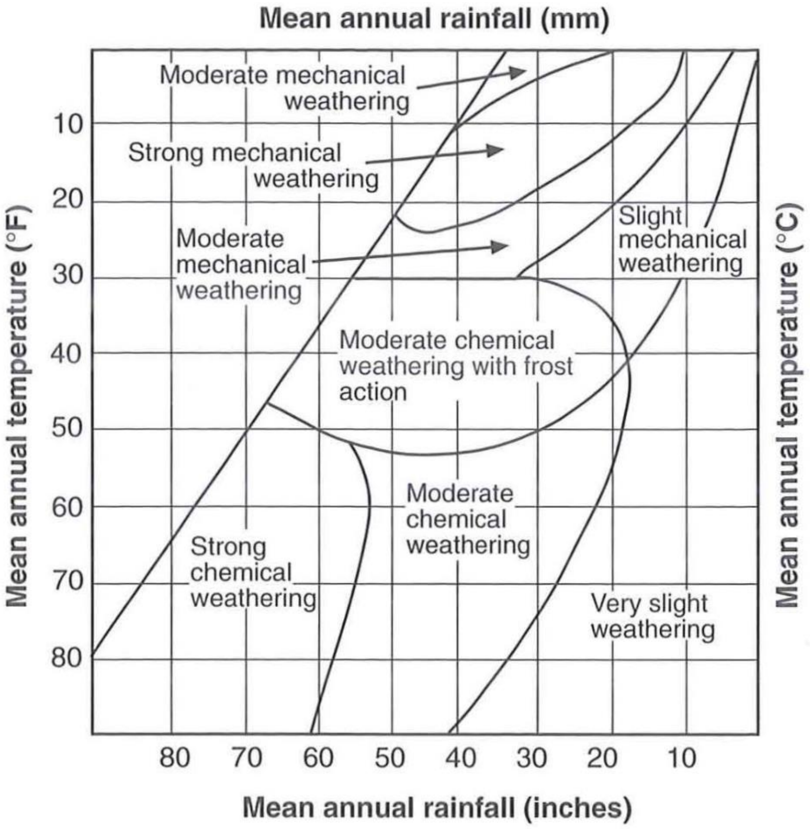


Figure 1. Schematic showing the anticipated chemical and physical weathering regimes as a function of mean annual rainfall and temperature as determined by Peltier (1950). Reproduced from Fitzsimons (2001), page 247.

Carroll (1970) also highlights the role of climate in weathering, specifically referring to the prevalence of physical weathering in cold environments and chemical weathering in tropical environments. This text goes so far as to state that pure physical weathering would only occur in either arid or extremely cold environments. The notion that physical processes dominate in cold climates has stayed in the consciousness of geomorphologists since this original text, with Dorn and Krinsley (2019) labelling it as a conventionally held belief as little as three years ago (as of the time of writing). Similarly, McAllister et al. (2017) have noted that stone temperature studies have generally been confined to either arid or high alpine locations.

In the classical weathering model, climate is deemed to be the dominant element in determining the nature and intensity of weathering that would take place in any given scenario. An early example of this philosophy is that of Peltier (1950), who developed nine morphogenetic regions, each with associated climatic ranges and expected geomorphological processes, although the author did admit that this initial conceptual model was qualitative and fairly speculative. A later study, specific to South Africa, divided the country into a number of climatic realms, designed to indicate what types of weathering would likely occur in a specific area, given typical climatic conditions (Weinert, 1965). This conceptual approach to weathering has implicitly informed many studies that have been conducted in subsequent years, specifically with respect to where the studies are conducted. This is because a climatic focus lends itself to the assumption that different weathering processes will dominate in different climates.

Seminal texts on weathering (Yatsu, 1988; Bland & Rolls, 1998) address most weathering processes as a function of climatic elements. Specifically, the classic weathering model contains four main inputs: absolute temperature (T), absolute moisture (M), change in temperature ($\triangle T$) and change in moisture ($\triangle M$). The majority of weathering processes are defined in terms of these variables, but the relationship between the climatic drivers and the weathering processes are complex (Figure 2).

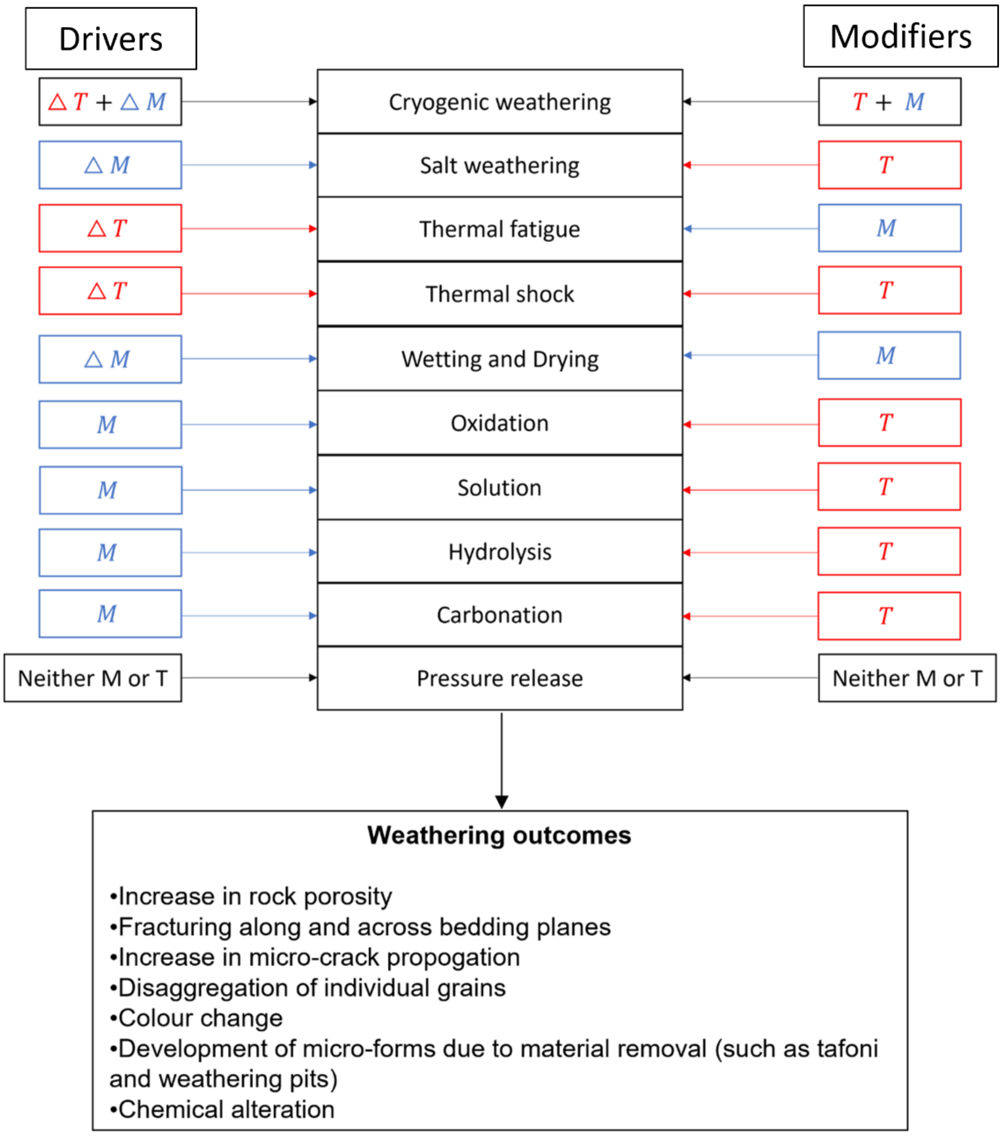


Figure 2. The relationship between climatic drivers and weathering processes, along with potential weathering outcomes (depiction of weathering model adapted from Yatsu (1988) and Bland and Rolls (1998), along with some personal insights from the thesis author)

The schematic shown in Figure 2 should be interpreted as follows. Drivers, shown in the left column, are external stimuli that are regarded as necessary to ensure that a specific process will be operational. Modifiers, shown in the right column, are external stimuli that are known to influence the rate at which a weathering process will operate. While the modifiers are not strictly speaking necessary, they nevertheless can significantly affect how an individual weathering process may function. This conceptual model is very serviceable as a tool for understanding weathering, but it has some notable shortcomings that become apparent when it is applied to field studies. To begin with, while many of the weathering processes have what could be termed a 'primary climatic driver' (for example, thermal shock requires a rapid change in temperature to function effectively), most weathering processes are also influenced by other climatic elements. For example, the absolute temperature under which a chemical weathering process like oxidation takes place will affect the rapidity at which the chemical reaction takes place. As a result, changes in either temperature or moisture will affect both the presence/absence of weathering processes and how effective each one will be.

One exception to the climatically dominated weathering processes is that of pressure or release, or dilatation. This particular weathering process has no direct relationship to climate, but rather refers to a rock's physical structure changing as a result of the removal of compressive stress, usually to due erosion of surface material or deglaciation (Bland & Rolls, 1998). While this process is mentioned in most textbooks about either geomorphology in general (Huggett, 2011) or weathering in particular (Yatsu, 1988; Bland & Rolls, 1998), there are few contemporary studies on this process. There are some studies that research dilatation effects, but they investigate it within the context of rock structure change as a function of either wetting and drying (Weiss et al., 2004) or freeze-thaw effects (Thomachot-Schneider et al., 2018). The bulk of modern research on this topic is related to the impacts of glacial unloading on rock structure (Ballantyne & Stone, 2004; Ballantyne, 2008; Cossart et al., 2008), but studies such as Vidal Romanı and Twidale (1999) have indicated that rock structure can also change over time because of overburden removal from erosion. They also state that quarried rocks may experience unloading after being removed from their parent material.

Dilatation aside, climatic drivers are connected with all other known weathering processes, which can all lead to an array of weathering outputs (different chemical and physical changes in the rock), all of which must be viewed simultaneously and a single point in time (the moment the researcher observes the rock itself). This means that it is often impossible to link a specific process to a particular set of climatic conditions, purely because a common set of climatic conditions can be conducive to an array of different weathering processes, and different combinations of weathering processes will lead to an almost infinite number of potential weathering forms.

Determining how a rock's structure is changing as a result of specific processes is also fraught with difficulty. Chemical weathering processes often have a clear macroscopic indicator that they are taking place, such as a red or brown colour being an indicator for iron oxidation (Oguchi, 2001). Physical weathering processes, on the other hand, occur without any chemical change taking place in the rock, but rather are the breaking of bonds at a molecular level (Eppes, 2022) and typically manifest as a propagation of cracks and dislocations within the rock (Hall and Thorn, 2014), decrease in uniaxial compressive strength (Momemi et al., 2016) or small changes to the rock's surface geometry (López-Arce et al., 2010). Both of these manifestations are low frequency, long duration and are extremely difficult to measure directly. Researchers are, therefore, frequently required to make assessments indirectly, through the means of proxy variables, some of which (specifically rock temperature, rock hardness and ultrasonic pulse velocity) will be discussed later in this thesis.

The ultimate effect of this relationship between climate, process and form makes the use of the classical model difficult under normal field conditions. In particular, since most processes do not have a unique process → weathering form relationship, it is not possible to use this model diagnostically. Viles (2013) discussed this concept in detail and demonstrated that weathering forms develop as a function of complex relationships between different weathering processes. Furthermore, they explain that external environmental variables can affect the specific type and rate of weathering in a given location. An example of this issue is that of tafoni, which has stubbornly refused simple classification (Turkington & Phillips, 2004). More modern studies have demonstrated the azonal nature of tafoni but have still not been able to determine the exact nature of their formation (French & Gugliemin, 2021). In other words, the climate-based weathering model cannot be reasonably used to work out what weathering processes are present in any specific system without making some irreducible assumptions. If specific processes cannot be identified from the nature of the observed weathering forms, and multiple processes might be efficacious under similar climatic conditions, it can be argued that the climate → process relationship is not a well-founded assumption. This is extremely difficult to check, however, because weathering regimes in different locations are subject to so many different local variances (both in terms of local environmental conditions and rock types) that they are essentially incomparable. To that end, an alternative approach to weathering, which has a greater focus on the role of rock properties as a control, should be considered.

2.3. A focus on rock properties and suggestions towards azonality: an alternative approach

Since 1990, researchers have begun to challenge the traditional approach to rock weathering. There are two initial points of contention that were identified. First, there was some debate about the dominance of the freeze-thaw weathering process in cold climates. For example, Hall (1995) stated that freeze-thaw weathering had been given an unreasonable amount of focus when it came to cold climates, at the expense of many other processes. Similar assertions were made by other authors working in periglacial environments, with André (2009) highlighting the literary focus of freeze-thaw weathering as a dominating element, and Thorn (2004) suggesting that the wide-spread belief in the efficacy of freeze-thaw weathering had led to a degree of complacency when it came to the study of other possible processes. This may have transpired due to a widespread deployment of a logical fallacy known as 'affirming the consequent' (a philosophical discussion of which can be found in Bowles, 1996), in which an experiment will presuppose the presence of a weathering process, and then attempt to quantify its effects, rather than posing an open question as to which processes are functioning in any given environment. The primary issue raised by these researchers is philosophically subtle, and not so simple as "freeze-thaw does not occur in cold climates". Rather, they were concerned that studies were ascribing the presence of many cold climate weathering forms to the freeze-thaw weathering process while having very little direct evidence that this was occurring. This preoccupation with a single process promotes the idea that processes can operate in isolation to one another, rather that operating as a suite (Hall, 2013). Ultimately, if this series of assumptions is incorrect, it means that the relationship between climate and weathering process is tenuous at best. It would in fact be equally valid to argue that freeze-thaw does not occur in cold climates on the basis of available data.

At roughly the same time that the freeze-thaw weathering argue was being scrutinised, studies began to demonstrate that chemical weathering processes could function perfectly well in cold climates and were not limited to warmer regions as previously believed (Darmody & Thorn, 1997; Allen et al., 2001; Thorn et al., 2001; Darmody et al., 2005). Reciprocally, it has been argued that freeze-thaw weathering may not be confined to traditionally 'cold' environments, but may function equally well in traditionally arid or even temperate climates (Hall, 2013).

The presence of the above articles within the body of literature highlights two major concerns that need to be addressed with respect to the classical weathering model. First, it may not be possible to identify a dominant weathering process in a given area and ascribe its presence to specific climatic variables. Second, many weathering processes are likely to be ubiquitous, functioning well under many different climatic regimes, whether they are expected to or not.

A step away from the process isolation paradigm was taken by Pope et al. (1995), who recommended that weathering in any given area be described by a combination of different variables ranging from surface characteristic and biotic elements to spatial scale. This concept was introduced as a specific counterpoint to traditional climatic theory, since they (Pope et al.) believed that weathering would vary significantly on a microscale and that the mesoscale issues like regional climate were, therefore, less relevant than previously thought.

The logical shortcomings in classic weathering studies were not the only potential issue. While climates in different locations differ considerably from one another, this is not always true of typical rock temperatures. Sumner et al. (2004) compared rock temperatures from four different environments that were climatically diverse from one another. Specifically, they looked at rock temperature data from Namibia, Antarctica, Marion Island and the Drakensberg in South Africa. They noted that, while the absolute maximum and minimum temperatures differed greatly from one another, the temperature ranges were comparable. This implies that, while actual temperature readings may differ from location to location, changes in temperature may be similar, which means that weathering processes such as thermal fatigue and thermal shock has an equal probability of occurring in each location, in spite of the large differences in temperature between the four. This prompted the authors to speculate that thermal weathering processes may be azonal, able to occur under a variety of climatic conditions, and not being linked meaningfully to location at all.

Many of these various concerns were ultimately summarised by Hall et al. (2012), who pointed out several shortcomings in the current weathering conceptual model. To begin with, they highlight the poorly formed links between process and ultimate form, particularly in the case of physical weathering. They argued that very few physical weathering processes have unique, identifiable macro-forms. In fact, Hall and Thorn (2014) suggest that only thermal shock, of all the currently accepted physical forms, may lead to a unique, observable ultimate outcomes, and even this fact is largely conjecture, and was a statement made in opposition to an article by Boelhouwers and Jonsson (2013), who argued that thermal shock as a weathering process may not exist under natural terrestrial conditions at all.

In a nutshell, the problem of weathering process identification comes from the fact that field-based weathering studies involve the investigation of several interlocking processes that all work synergistically to create a compound outcome that that can only be observed at a single point in time and cannot be meaningfully connected to climate at all. Dorn et al. (2013)

in fact state rather bluntly that they believe this perspective to be wrong. The ultimate conclusion of all of this is that it is difficult (or even impossible) to determine the relative intensity of the various weathering processes operating in a specific area, or even which processes are operating at all. This inability to meaningfully connect climate, process and form potentially limits the usefulness of the classic weathering model, at least in terms of identifying weathering processes that are active in a particular system. Hall et al. (2012) have made several suggestions as to how this problem might be addressed. To begin with, they recommend a re-focusing of the current weathering model from climatic variables to rock properties. Following that, they propose a shift to a simplified conceptual model that seeks to link energy transfer and form, stepping largely away from attempts to categorise the presence of specific processes within a field-based system. This is not because they advocate that the processes do not exist in the form discussed in more traditional models, but because they acknowledge our current inability to differentiate between them. While they do not discuss what an experiment under this conceptual formation might look like, such a study would essentially involve a comparison of energy transfer levels in an environment to the structural change of a rock in that environment, without any speculation as to the processes that were present.

The conflicting views of climate vs rock property dominated paradigms introduce many questions, but a useful starting point might be: “Can the relative roles of climate and rock properties be meaningfully measured?” If the answer is no, then the entire argument is essentially moot, since there would be no way to decide which model to select when moving forward with the development of weathering theory. If, however, the dominance of one or the other could be established, it would go a long way to providing some direction for weathering studies as a whole.

Unfortunately, this is much easier said than done. The conceptual and logical reasons for this have been extensively discussed in the preceding paragraphs, but there are more practical and methodological constrains as well, and these are the subject of the following sections of this thesis.

2.4. Experimental challenges in weathering studies and the necessity of rock weathering proxies

The processes involved in the study of weathering are difficult to study, largely because of problems related to scale. Specifically, rock weathering processes take place on a microscopic spatial scale (although this may manifest in a macroscale form that can be visually observed or measured in some other way), and over a large temporal scale (Pope et al., 1995). Frings and Buss (2019) highlight the challenge of spatial and temporal scales as one of the key challenges to be addressed in studies moving forward.

The manner in which geomorphologists carry out research projects is thus a valuable line of interrogation, particularly with respect to overcoming some of the innate obstacles present in rock weathering studies. Since rock weathering is ultimately focused on quantifying the relationship between climate and rock properties, it is useful to assess the challenges that are involved in this line of research, as well as how geomorphologists have overcome these challenges.

Some questions that can be asked about the nature of weathering studies are as follows:

- What experimental methods have been used to study physical weathering?
- What attempts have been made to quantify the link between regional climate and weathering?
- Do studies typically rely on proxy measurements only, or are they measured directly as well?
- Are studies regionally specific or trans-regional?
- Do studies make significant efforts to interrogate pre-existing theory, or do they merely use it as a baseline?

In light of the contextualisation discussed in the preceding paragraphs, an important question arises: how are researchers dealing with the incomplete understanding of the link between climate and rock weathering? Are they attempting to quantify the relationship between climate and weathering process type and is the theoretical understanding of weathering developing in any substantial way? To explore this issue, it is necessary to review how current weathering studies integrate climate into their methodological frameworks.

This has been done by reviewing existing weathering studies and assessing how rock weathering and climate are typically assessed. For simplicity and structure, the reviewed articles have been divided according to the measured variable that each study used. This has the added benefit of placing a restriction of the number of articles to be reviewed. The studies that are reviewed are predominantly field based, but some lab-based studies have been included if they are deemed instructive to the topic under discussion. Field weathering studies usually involve the use of a proxy, since the accurate determination of rock structure decay under field conditions is challenging. The specific proxies under review are rock temperature, rock hardness, and ultrasonic pulse velocity. Articles from the last 40 years have been selected for review. This time period has been chosen because the majority of studies from 1980 onwards are predominantly quantitative in design and allow for easier comparison. The specific requirement was that the study either have a field component, or be a lab-based simulation of a field environment. A list of the considered articles can be found in Table 1 and Appendices 1 and 2.

Many of the weathering proxies that are reviewed here are indirect. For purposes of this thesis, a *direct* weathering measurement is defined as being a technique that directly assesses the alteration of a rock as a result of the studied weathering process, while an *indirect* measurement is one where rock weathering is inferred from a secondary variable.

2.4.1. Indirect measurements: rock temperature

Rock temperature has been studied extensively within the context of weathering, and has been used primarily in polar and arid environments to infer the existence of either the presence of thermal processes (Eppes & Griffing, 2010; Eppes et al. 2020), or freeze-thaw weathering (Hall, 1997). In both cases, there are difficulties to be found from an assessment perspective. Thermal processes (particularly thermal fatigue) can be difficult to identify, while there is some debate in the literature as to the efficacy of thermal shock. Hall and Thorn (2014) posited that thermal shock may be the only physical weathering process to leave a unique visual signature (polygonal fracture patterns characterised by the fact that they cut through bedding plans in sedimentary rock), while Boelhouwers and Jonsson (2013) query whether or not thermal shock can occur under field conditions at all. This debate is partly because laboratory experiments and field measurements are often difficult to correlate. In spite of this, there are a relatively large number of studies dedicated to the measurement of rock temperature as a proxy for rock weathering. However, only around 13 of the 31 reviewed studies into rock temperature assess any variable other than temperature itself.

It should also be noted that there are very few published confirmation studies, in which experiments published in peer reviewed journals have been repeated in order to confirm the results. This can be most easily observed by looking at the experimental designs of the various studies. Almost no scientists involved in gathering data on the subject make use of precisely the same spectrum of equipment and measurement techniques. Indeed, even the same scientist is unlikely to use exactly the same methodology as that which they have used before (a table of articles demonstrating this point can be found in Appendix 1). In case the of a laboratory study, the location given in the table is the location from which the samples were acquired for study.

The measurement of rock temperature in the field can be used by geomorphologists in at least three different ways. First, the rock temperatures present in the field can be correlated to direct measurements of things for a particular rock, in order to attempt to connect external stimulus (in this case the rock temperature) to a structural change in the rock indicative of weathering. For example, Eppes and Griffing (2010) compared rock temperatures measured over eight months to Scanning Electron Microscopy images of marbles in California, while Gómez-Heras et al. (2008) made use of optical petrography of thin sections of rock material as a point of comparison.

Second, rock temperatures can be used to infer the presence of thermal weathering processes like that of thermal fatigue and thermal shock, without necessarily measuring their physical effects directly. Vasile and Vespremeanu-Stroe (2017), for example, make use of rock temperature and rock hardness as proxies, and compare them to a morphometric analysis that is interpreted through the lens of pre-existing literature on the subject. This does not by any means invalidate the findings. However, it does highlight the reliance of such studies on the validity of previously conducted studies. Similarly, McKay et al. (2009) carried out an in depth analysis of a rock temperature dataset with very high temporal resolution (1 measurement / s). However, their analysis was entirely dependent on findings from earlier studies as to what those results might mean. As in the case of Vasile and Vespremeanu-Stroe (2017), this does not mean that the results are incorrect, or in spurious in any other way. Rather, it simply means that the validity of this article’s findings is dependent on fact that the previous studies’ findings are also valid.

Many of the existing studies on thermal weathering take place in either arid environments or areas that are believed to be susceptible to freeze-thaw. This locational bias was observed by Jenkins & Smith (1990), who stated that, even within an arid context, there was a tendency of researchers to seek out the most aggressive thermal regimes they could find, and then claim them as generally representative of desertic environments. In more contemporary times, it can be seen that this trend has continued, with McAllister et al. (2017) noting that many studies of this type favour ‘extreme’ environments, rather than more moderate ones.

Of the various temperature based studies assessed for this thesis, 26 out of 32 of them are confined to a single region. Studies with multiple sites will confine them to a single climatic type, or have a series of sites in close proximity to one another.

2.4.2. Indirect measurements: rock hardness

The Schmidt Hammer is an industrial device that was originally developed for use in civil engineering in 1954 for testing concrete compressive strength and uniformity. However, the tool has subsequently been repurposed as a convenient, cost-effective device for approximating intact rock strength and relative rock weathering intensity (a review of its use in geomorphological studies can be found in Goudie, 2006). More recently, the Equotip has been introduced, which measures the same parameter as the Schmidt Hammer, but with a greater degree of sensitivity and lower impact force. The low impact force particularly makes the Equotip more suited to assessing the degree of weathering on cultural stone such as monuments and tombstones, which might otherwise be damaged by the heavy impact of the Schmidt Hammer. A review of this apparatus, along with the Schmidt Hammer, can be found in Viles et al. (2011). There have been a large number of studies devoted to this concept and a selection of them are listed in Appendix 2.

Rock hardness has been used as a proxy for rock mass strength and rock weathering (Viles et al., 2011). It is favoured because rock hardness can be easily and relatively cheaply determined in the field by way of a Schmidt Hammer (Goudie, 2006) or an Equotip (Aoki & Matsukura, 2007).

While both of these pieces of apparatus were originally designed to be used on building materials such as concrete, they have been repurposed as geomorphic tools, although Viles (2016) make mention of the fact that extensive use of the Schmidt Hammer has led to the development of a bespoke tool known as the RockSchmidt, for use on stone specifically. Most publications make use of the standard pieces of apparatus, however, and these, as in the case of rock temperature, are proxies for various rock properties, as opposed to direct measurements. Empirical relationships have been demonstrated between rock hardness and uniaxial compressive strength (Wang et al. 2016), as well as rock weathering itself (albeit usually from a relative perspective) (Wilhelm et al. 2016a).

Unfortunately, there are innate drawbacks to the use of the Schmidt Hammer, due mostly to the impact force that the hammer exerts on a sample. This is unavoidable, since the theory behind the functioning of the apparatus revolves specifically around the level of deformation that the hammer causes to an impacted sample.

The Schmidt Hammer, having been in use by geomorphologists since the 1960s (Goudie, 2006), has a long history of use in the field, and more importantly, a well-documented assessment of some of its limitations. In particular, the device is shown to be susceptible to errors as a result of sample moisture content (Sumner & Nel, 2002), rock surface texture (Williams & Robinson, 1983), and sample size (Sumner & Nel, 2002). Interestingly, Goudie (2006) indicate that the device is not particularly susceptible to interference by operator variance. This is likely due to the simple nature of its design and limited vectors of use. To quote the old adage, “there are relatively few moving parts”, meaning that there are relatively few lines of variance that can be explored from a usage perspective. This may not be true with more complex devices like the Equotip.

Of key importance in the use of any proxy measurement is an experimental, empirical comparison with the direct variable. An example of this is that of Pauzi et al. (2011), who investigated the relationship between rock hardness measurements as determined by Schmidt Hammer and microcrack lengths in limestone.

The risks of using a proxy such as rock hardness for rock weathering intensity are well-established for the Schmidt Hammer, and as such, there are an array of different analytical techniques designed to compensate for any shortcomings. To begin with, rock hardness readings are prone to error if not taken under very specific conditions. For example, rocks that are partially saturated in water can return different readings to ones that are dry (Sumner & Nel, 2002). Additional, surface roughness, surface gradient and even the altitude at which the sample is measured may all cause measurable changes in instrument readings. In order to attempt to compensate for these delimitations, there are a number of different ways that the data can be addressed after acquisition. Some researchers will merely average all obtained values together (Nesje et al., 1994), while others will only use the highest reading, or an average of the five highest readings (Evans et al., 1999).

2.7. Contextualisation of research studies within the greater theoretical framework

While research studies can be divided into any number of categories, two broad ones would be theory vs application. Specifically, does a research study endeavour to contribute to our understanding of theory, or does the study apply the existing theory to a practical example to learn something about the world? Since determining the answer to this question has an innate degree of subjectivity, it is important to have some criteria by which to judge an article’s standing with respect to this question. In the case of this thesis, if an article made a specific effort to challenge an existing theoretical belief or construct, it was deemed to be contributing to our overall theoretical knowledge of weathering. If the article merely made use of the existing theory to interpret the results, or made no mention of the role of theory in either developing the experimental technique or in interpreting the results, it was deemed to be an application of existing theory. This is an important question in weathering studies, because it allows them to be classified as being of general relevance or specific relevance. To elaborate, studies of specific relevance are studies that make use of currently existing theory, but apply it to a specific environment, weathering process, or location. Examples of this would be Gruber et al. (2004), who studied rock temperatures in the French Alps or Al-Omari et al. (2013), who studied the effects of freeze-thaw weathering on the Castle of Chambord, in France. An example of a study of general relevance would be Hall et al. (2012), who critique the current understanding of rock weathering.

2.8. The axiomatic nature of the link between weathering and climate

The investigation of the link between climate and weathering processes may be more difficult than it would initially appear. While this link is implicit in many weathering studies, it may not be explicitly stated. In particular, the assumption that specific climatic conditions would cause certain weathering processes to be dominant can be interrogated. More particularly, a geomorphologists' unconscious belief in this principle can be interrogated by testing to see if there is a correlation between specific weathering processes and the location in which their field measurements are carried out. Similar interrogations can be made with laboratory experiments if the researchers have attempted to simulate specific climatic conditions. To assess this, a selection of articles were checked to see if the researchers made mention of the belief that a dominant weathering process was operating in the region where the experiment was being carried out, or if instead, weathering was not categorised at all. More generally, the location, experimental measurement technique and weathering process (if mentioned by the article) were recorded in order to determine potential links between these three things.

2.9. The quantification of a link between weathering intensity and regional climate

A question that must be asked in light of the above review is: Are there studies that specifically attempt to target the relationship between climate and identification of specific weathering processes? If there are not (and there are arguments to be made that it is impossible), then are there studies that specifically investigate the intensity of weathering processes with respect to regional climate? It is important to study this link because, if it is not, the weathering studies risk being relevant only to the very specific locations and situations under which the information was gathered in the first place. The literature has been reviewed to identify articles that specifically attempt to study weathering intensity as a function of regional climate. Very few articles attempt to study either weathering kind or weathering intensity as they relate to regional climatic variables.

Studies that are focused specifically on weathering are frequently dedicated to the understanding of either a single weathering process or a small subset of processes (Hall and Hall, 1996; Sumner and Loubser, 2008 Eppes et al. 2016; to cite some examples). This constraint will typically enforce location restrictions on the study, since a common weathering type is assumed to require a common climate. Thus, even studies that do make use multiple study sites frequently favour similar climatic conditions.

A review of contemporary weathering studies has shown that the majority of modern studies either study weathering at a single site, a small number of sites that are relatively close together, or sites that share common characteristics in terms of contemporary and paleoclimates. Studies are most likely designed in this way because of scientists' innate desire to comply with the principle of *ceteris paribus*, that is "all other things being equal". This refers to the implicit assumption in any bivariate study that, outside of the independent and dependent variables under investigation, all other variables are unchanged over the time and space upon which the investigation takes place.

The importance of this principle in bivariate studies is paradoxically impossible to achieve under field conditions, as discussed by Phillips (2007), who pointed out that true static conditions are impossible outside of stringent laboratory conditions. The chaotic nature of any field environment will ensure that there is always an element of local variance that will likely either cloud or completely obscure the general signal that is being sought by the researcher. It is likely that many weathering scientists, understanding this implicitly, design their experiments and field research methodologies to limit this effect as much as possible.

The majority of weathering studies under field conditions nevertheless attempt to adhere to this principle has closely as possible. A review of the literature (tabulated in Table 1 and Appendices 1 and 2) has shown that almost all weathering studies that attempt to connect climate to rock weathering either take place at a single location, have multiple sites that are all fairly close together, or if they do have multiple dispersed sites, typically focus on a single climate type (such as *polar* or *arid*). One notable exception is that of Sumner et al. (2004), who compared rock temperatures across four different, regionally distinct sites. However, it should be noted that even this study was not originally intended as such, but was rather the result of an amalgamation of several earlier research projects that were not expected to be connected in any way. It was only after the authors noticed the similarities that they started to consider the possibilities of azonality.

2.10. The possibilities for regional climate studies

In order to attempt to assess the link between regional climate and rock weathering under field conditions, it is necessary to try and find a scenario that allows for *ceteris paribus* to be applied as far as is possible under field conditions (although I acknowledge that it will never truly be possible).

In South Africa, tombstones across the entire country are frequently constructed from gabbro stone, which is quarried primarily from Brits, in the North West Province of South Africa. This means that stones of common origin can be found throughout the country in cemeteries that experience an array of different climatic regimes. South Africa has remarkably diverse climate for such a small country, making this setting ideal for a study such as this.

The amount of time that each stone has been weathered under the climate to which it has been exposed can be determined by the date of death on the stone, allowing cemeteries to be used as time series laboratories. This could then be compared to the weathering rates of the stones in a number of different locations, each experiencing different climatic forcings. This would potentially allow for the effects of different climates on weathering intensity to be measured.

There are several difficulties that must be addressed, most of which stem from tombstones' status as culturally important stone. Geomorphologists that are studying cultural stone are further limited in terms of the experimental techniques to which they have access, since the importance of non-destructive measurement techniques is even more critical here. As a result, researchers are often confined to research techniques that are even coarser than usual, although newer experimental techniques are allowing for the circumvention of some these issues. In the case of tombstone research, for example, experimental techniques such as the lead lettering index (Cooke, 1995; Inkpen & Jackson, 2000; Mooers et al., 2017) and visual indices such as that developed by Thornbush (2012) are non-destructive observational techniques that can be used on the stones without risking damage to them. However, there are innate limitations to studies like this. The lead lettering index requires tombstones which have lead letters as part of the inscription, which is typical of limestone tombstones commonly found in Britain. The inscription will initially sit flush against the tombstone, which will then erode away. The inscription will be left as a positive feature, and a measurement of the height difference between the inscription and the surrounding stone gives an indication as to the rate of tombstone decay. However, this is only effective with stones that make use of the lead lettering technique, which is almost unheard of in a South African context, and requires stone that will erode fairly quickly, like limestone. This technique is unusable in countries where tombstones are more typically etched (such as in South Africa), or with tombstones that are more resistance to weathering and erosive processes (South Africa, for example, favours tombstones such as gabbro and granite, which do not weather as rapidly as limestone). Visual indices, such as that developed by Thornbush (2012), are highly site-specific and cannot be used outside of the region in which they were developed. These more passive measurement techniques limit what can be learned from culturally important stone, due largely to coarser data resolution and very specific requirements in terms of site location and stone type.

Gabbro stone is unfortunately unsuited to many of the typical tombstone assessment techniques embraced in Europe, but ultrasonic pulse velocities allow for a new approach to be developed for the assessment of tombstone degradation.

The proposed method, therefore, would be to use ultrasonic pulse velocity measurements measured as a function of weathering time (the amount of time a particular stone has spent in a particular cemetery) to establish a relative weathering rates for cemeteries at several locations across South Africa in order to determine if a relationship between regional climate and rock weathering intensity can be reasonably quantified.

2.11. Cultural stone weathering measurement techniques

Geomorphological principles can be directly applied to the weathering of cultural stone, as discussed by Pope et al. (2002), although its study presents some unique challenges due to the cultural sensitivity of the material. Specifically, the need to respect and preserve cultural stone means that non-destructive measurement techniques need to be employed almost without exception.

Geomorphological studies of cultural stone are usually concerned with the intensity of weathering on the artefact under investigation, so it is common to connect it with surrounding micro-climatic conditions (Feddema & Meierding, 1987; Gizzi et al., 2016; Michette et al., 2022). The purpose of these studies is to quantify the specific effects of the local micro-climatic elements on a specific cultural system with a view to preserving it. There is no primary expectation for the study beyond a preservation solution for the artefact being investigated. Studies like this make use of pre-existing weathering theory for important context, but do not either interrogate or add to the theory. This is not a failing, since theoretical construction and evolution are not their purpose, but it is a common trait of many cultural stone studies. This point is discussed further below both in terms of cultural stone structures and tombstones. Tombstones specifically are discussed separately since they are the subject of this thesis.

2.11.1. Cultural stone structures

Cultural stone structures are frequently of interest to geomorphologists as objects of applied theory. Specifically, geomorphological theory is applicable in terms of developing methods for the preservation of cultural stone. A detailed review of the use of geomorphology with respect to cultural stone can be found in Pope et al. (2002), but specific articles relevant to this study will be reviewed here.

The mechanisms that can affect cultural stone are as complex as any other weathering system, and the available array of studies reflect this. Freezing and thawing is a weathering process that has received considerable attention (Al-Omari et al., 2012, 2014; Freire-Lista et al., 2015), but other processes such as salt weathering (Yan et al., 2022) and thermal weathering (Waragai, 2023) have also been investigated. More complex studies, such as that of Dorn et al. (2017), looked specifically at the effects of weathering rinds, which can cause significant damage to stone buildings and monuments if not properly treated.

On a global scale, cultural stone has been studied extensively, with the United Kingdom and continental Europe particularly being valuable sources of study. In South Africa, cultural stone has been studied less extensively, since the relative youth of South Africa means fewer monuments to study. However, a uniquely South African complementary field is the study of San rock art and its preservation (Hall et al., 2007; Hall, 2009; Meiklejohn et al., 2009).

André and Phalip (2010) pointed out the value of using stone monuments as, in their words, ‘natural laboratories’, showing that such studies can not only make use of pre-existing theory to develop preservation mechanisms, but can also contribute to the development of weathering theory in turn.

New non-destructive assessment methods are in high demand since an accurate assessment of levels of rock decay is imperative when designing preservation measures. Damas Mollá et al. (2022), for example, have developed a detailed indexing system that allows for an array of qualitative and quantitative elements to be combined into a single unified matrix. A similar technique was deployed by Gizzi et al. (2016) who used a 'questionnaire' of sorts to qualitatively assess many visually observable weathering forms.

It should be noted that, under specific circumstances, a limited degree of destructive testing is permissible, such as in the case of André et al. (2008), who combined qualitative geomorphological observations and non-destructive lasergrammetry studies with Scanning Electron Microscopy measurements of stone fragments that had become separated from the monument that they were studying (in this case, the Ta Keo Temple in Angkor, Cambodia). However, these destructive studies are often not possible at all, leaving researchers with purely non-destructive options. Ultrasonic pulse velocity measurements provide a useful avenue of inspection for natural, culturally important stone since measurements can be taken quickly and with a reasonable degree of precision. This technology has been in use in studies since the early 1950s and is well suited to a weathering study that is centred around material that is not allowed to be damaged.

2.11.2. Tombstone studies

A subcategory of cultural stone study is that the investigation of tombstone degradation. This has been a particular field of interest in continental Europe and the United Kingdom where there are a many cemeteries that have tombstones that are of the order of several centuries old. Due to their age and cultural significance, the tombstones cannot be physically sampled or damaged in any way, which necessitates the use of more passive study techniques. In spite of this limitation, tombstones have been used as natural laboratories to yield information on other factors that may influence rock weathering. For example, Inkpen & Jackson (2000) studied tombstone weathering as a function of location in the United Kingdom, and discovered that tombstones at inland cemeteries appeared to weather less than similar tombstones at coastal locations. Inkpen (2013) demonstrated that it was possible to reconstruct past SO_2 concentrations in Oxford and Swansea in the UK using tombstone decay rates, and Mooers et al. (2017) discerned a complex relationship between tombstone decay, land use and air pollution by studying marble tombstones at a variety of locations throughout the United Kingdom. Studies such as these show that cemeteries and the tombstones can yield valuable information that goes above the pure preservation of the stones themselves, despite the limitations posed on any study due to the cultural sensitivity of the sites. However, the unique nature of tombstones allows for them to be assessed in ways that are not available to more traditional monuments. Unfortunately, some of these methods, while useful in continental Europe and the United Kingdom, do not translate well into a South African context. A brief summary of two of the major methods follows here, along with an explanation as to why they are not usable in South African cemeteries.

The lead lettering index is an assessment technique that makes use of different weathering rates between the tombstone material (usually marble or limestone) and the inscription material (lead). The lead inscription should decay at a slower rate than the limestone or marble tombstone, which over time will present as a positive feature. By measuring the height difference of inscriptions against their natural stone hosts, it is possible to estimate the degree of tombstone micro-erosion (Inkpen & Jackson, 2000; Mooers et al., 2017). This method has been very successful in cemeteries with predominantly marble or limestone graves, where lead-based inscriptions are very common. However, in South Africa, lead lettering is less common than in Europe, and it is more common for tombstones to have their inscriptions etched, which makes them negative features to begin with. Since the etchings cannot be assumed to be consistent from one tombstone to the next, this method is unreliable for stones of this nature. Also, South African tombstones are frequently of gabbro construction, which is highly resistant to downwearing, which would mean that differences over a decadal timescale (all that is available in a South African context), are so small as to be negligible.

Equotip rock hardness measurements were used by Wilhelm et al. (2016b) as a proxy for weathering on limestone graves on the Isle of Portland in the United Kingdom. They correlated rock weathering against time and showed a non-linear relationship between these two variables, which suggested that rock weathering behaviour was not constant over time. This method has been tested on South African gabbro tombstones as part of the preparation for this thesis, and it was shown that rock hardness values do not correlate well with time for these stones, most likely because of their afore-mentioned resistance to weathering, as well as the short weathering time scale, which is seldom longer than 100 years.

2.12. Ultrasonic pulse velocity measurements as a proxy for rock strength

Ultrasonic pulse velocity (UPV) is a newer proxy than some many of those previously discussed, but its use as a way of assessing material integrity is well documented (Hall, 1988; Babacan & Gelisli, 2015; Akoglu et al., 2020) and has also been used in studies that relate specifically to rock weathering. An early example of this is that of Hall (1988), who used UPV measurements to assess the results of a laboratory-based freeze-thaw experiment. More contemporary studies have also been carried out, such as Mahmutoğlu (2017), who related thermal weathering effects to UPV, and Khodabandeh and Rozgonyi-Boissinot (2022), who studied the effects of salt weathering on UPV results under laboratory conditions. The key benefit of UPV is that it is a material assessment technique that is both quantitative and non-destructive, which makes it ideal as a measurement tool for both building materials and culturally important stone. Table 1 offers an overview of key UPV studies globally.

2.12.1. Origins of UPV studies in Earth Science

The use of sound waves as a measurement mechanism has been employed in engineering and Earth Science fields since before 1960. For example, Closemann (1953) studied the relationship between the velocity of sound waves and the temperature of a single potassium chrome alum crystal. An early South African example is that of Lutsch (1959), who made use of reflecting ultrasonic waves as a means to locate and quantify fracture zones in South African deep level mines. Throughout the 1960s and 1970s, ultrasonics studies became more numerous, particularly in the fields of geology, geophysics and engineering. It was particularly popular in fields where it was important to be able to assess the structural integrity and intact strength of materials without needing to physically sample the material. For example, Gladwin and Stagey (1974) made use of the technology to assess the effects of thermal fluctuations on the integrity of the rock surrounding an underground power station, while Gregory and Podio (1970) developed technology to use ultrasonic velocities as a way of studying the elastic behaviour of sandstone and limestone rock samples extracted from oil bearing strata several kilometres below the Earth’s surface.

Author	Year	Title	Journal	Rock type	Field / Lab	Proxy	Direct measurement? (Y/N)	High precision (Sample destroyed/ altered in test)	Interrogates / develops existing theory)	Knowledge producer or consumer	Location	Number of sites	Climate type	Link between climate and process (fundamental assumption in project design)	Cultural stone / Building stone / Natural Stone
Akoglu, K.G., Kotoula, E., Simon, S.	2020	Combined use of ultrasonic pulse velocity (UPV) testing and digital technologies: A model for long-term condition monitoring memorials in historic Grove Street Cemetery, New Haven	Journal of Cultural Heritage	Marble	Field	Ultrasonic pulse velocity	No	No	No	Consumer	New Haven, Connecticut	1	Not discussed	No	Cultural stone
Babacan, A.E., Gelisli, K.	2015	Ultrasonic investigations of marble columns of historical structures built in two different periods	Carbonites and Evaporites	Marble	Field	Ultrasonic pulse velocity	No	No	No	Consumer	Easterb Black Sea Region, Turkey	1 region	Not discussed	No	Cultural stone
El Boudani, M., Wilkie-Chancellier, N., Martinez, L., Hébert, R., Rolland, O., Forst, S., Vergès-Belmin, V., Serfaty, S.	2015	Marble Characterization by ultrasonic methods	Procedia Earth and Planetary Science	Marble	Lab	Ultrasonic pulse velocity, water absorption	Yes, drill resistance test	No	No	Consumer	Laboratory (Versailles, France simulated)	1	Temperate oceanic	Yes	Cultural stone

Grossi, D., Del Lama, E.A.	2015	Ultrasound technique to assess the physical conditions of the Monument to Ramos de Azevedo, city of São Paulo, Brazil	Geosciences	Itaquera Granite	Field	Ultrasonic pulse velocity	No	No	No	Consumer	Sa Paulo, Brazil	1	Not discussed	No	Cultural stone
Kahraman, S.	2002	The effects of fracture roughness on P-wave velocity	Engineering Geology	Granite, Marble, Travertine	Lab	Ultrasonic pulse velocity	Yes, artificial fracture generation	Yes	No	Consumer	Laboratory	1	N/A	No	Natural stone
Pamplona, M., Simon, S.	2012	Long-term condition survey by ultrasonic velocity testing of outdoor marble sculptures	12th International Congress on the Deterioration and Conservation of Stone, Columbia University, New York	Marble	Field	Ultrasonic pulse velocity	No	No	No	Consumer	Berlin, Germany	1	Not discussed	No	Cultural stone
Perez Ema, N., Alvarez de Buergo, M., Bustamante, R.	2013	Integrated studies for the evaluation of conservation treatments on building materials from archeological sites. Application to the case of Meridia (Spain)	International Journal of Conservation Science	Various	Field	Ultrasonic pulse velocity, Spectrophotometer	Yes, roughness-meter	No	No	Consumer	N/A (Review article)	N/A	Not discussed	No	Cultural stone

Ruedrich, J., Knell, C., Enseleit, J., Rieffel, Y., Siegesmund, S.	2013	Stability assessment of marble statuaries of the Schlossbrücke (Berlin, Germany) based on rock strength measurements and ultrasonic wave velocities	Environmental Earth Sciences	Marble	Field	Ultrasonic pulse velocity	Yes, microfabric analysis	Yes	No	Consumer	Berlin, Germany	1	Not discussed	No	Cultural stone
Sakcali, A., Yavuz, H., Sahin S.	2016	Quality assessment of natural stone blocks by an ultrasonic method	Bulletin of Engineering Geology and the Environment	Different types of carbonate sedimentary stones	Lab	Ultrasonic pulse velocity	No	No	No	Consumer	Laboratory	1	Not discussed	No	Natural stone
Siegesmund, S., Ruedrich, J., Weiss, T.	2010	Jewish cemetery in Hamburg Altona (Germany): State of marble deterioration and provenance	6th International Symposium on the Conservation of Monuments in the Mediterranean Basin	Marble	Field	Ultrasonic Pulse Velocity, Stable Carbon and Oxygen isotopes	No	No	No	Consumer	Hamburg, Germany	1	Not discussed	No	Cultural stone
Turgut, P., Kucuk, O.F.	2006	Comparative Relationships of Direct, Indirect, and Semi-Direct Ultrasonic Pulse Velocity Measurements in Concrete	Acoustic Methods	Concrete	Lab	Ultrasonic pulse velocity	No	No	No	Consumer	Laboratory	1	Not discussed	No	Building material

Salvatici, T., Calandra, S., Centauro, I., Pecchioni, E., Intrieri, E., Garzonio, C.A.	2020	Monitoring and Evaluation of Sandstone Decay Adopting Non-Destructive Techniques: On-Site Application on Building Stones	Heritage	Sandstone	Both	Ultrasonic pulse velocity	Yes, mineralogical, petrographical, chemical and physical analyses	No			Florence, Italy	1	Not discussed	No	Building material
Mahmutoğlu, Y.	2017	Prediction of weathering by thermal degradation of a coarse-grained marble using ultrasonic pulse velocity	Environmental Earth Sciences	Marble	Lab	Ultrasonic pulse velocity	No	No			Laboratory	1	Not discussed, but heating/cooling and freezing/thawing were simulated	Yes	Cultural stone
Ahmad, A.	2020	Investigation of Marble Deterioration and Development of a Classification System for Condition Assessment using Non-destructive Ultrasonic Technique	Mediterranean Archaeology and Archaeometry	Marble	Lab	Ultrasonic pulse velocity	No	No			Laboratory	1	Not discussed, but heating/cooling simulated		

Table 1. Selection of articles that make use of Ultrasonic Pulse Velocity measurements as a proxy for rock decay or rock structural integrity in natural stone

A major area of application for ultrasonic pulse velocity measurement techniques was in that of building material assessment. Jones (1956) made use of UPV to assess the rate of cement hardening, whose study was based on the simple premise that pulse velocity values would increase as the material hardened, although this early study did not attempt to assess the structural integrity of the final product. Later, however, the same author discussed the relationship between pulse velocity and concrete strength (Jones, 1963), but admitted that the relationship was not well defined, mostly because of physical differences between different batches of concrete, which requires UPV measurements to be calibrated against the strength of the specific concrete batch under review. This study highlights an implicit challenge present in the use of any proxy variable, which relates specifically to the nature of its relationship to the unobserved variable (in this case, the strength of the concrete). If the relationship between the proxy variable and the unobserved variable is not consistent across different stone or rock types, then analysis will generally need to be calibrated to a specific type and then used for that type only. Another example of this is that of Spencer and Shattock (1962) who explored the use of UPV on the materials used to construct roads.

From the articles discussed above, it can be seen that the inception of ultrasonic pulse velocity technology was driven primarily due to a desire to find a way to assess the integrity of building materials and rock that were either a part of, or adjacent to, industrial facilities or other artificial constructs, very often to improve safety. However, once the value of the technology was proven, it began to be employed for a wider range of uses, not all of which related directly to material science and its application to industry.

An early example of the use of UPV in a more traditionally academic setting is that of Manghnani and Woollard (1965), who made use of UPV to measure the elastic properties of basalts found in Hawaii to assist in developing their understanding of seismic-wave measurements of material in the Earth's upper mantle and crust. This work was followed up by Christensen (1966), who looked at ultrasonic pulse velocity values across various fine-grained igneous rocks and noted that rocks with high average atomic weight and low density tended to return lower velocities. Studies like these, while primarily reflective of a geophysical use of the technology, are nevertheless a more traditionally academic application of UPV, as opposed to many of the more applied studies that typically used it in the 1960s.

Academic and applied studies that made use of ultrasonic pulse velocity theory continued through the 1970s and 1980s, although studies remained largely within the domain of geophysics, engineering and material science, with geomorphology adopting the technology later. Hall (1988) is an early example of a geomorphological study that made use of UPV, in which changes in ultrasonic pulse velocity were assessed as a function of the freezing and thawing of water in quartz-michaschist blocks under laboratory conditions.

More recently, UPV has been widely exploited in material science, geophysics and geomorphology. The following paragraphs document the progress that has been made with this technology since the year 2000. This date has been chosen because it is a convenient date by which to bound this literature review, but also because research articles that are older than 20 years would have, by necessity, made use of more primitive technology. This is not to say that the older studies are irrelevant or incorrect, but their findings are less likely to be consistent with those of more recent studies, purely due to differences in equipment. If necessary, articles from the 1990s will be referred to if they are deemed especially relevant, but the majority of reviewed articles are not older than 25 years.

The following sections will document the contemporary use of ultrasonic pulse velocity technology in various fields, divided into studies that were primarily laboratory-based, and those that were primarily field-based. Not all the articles have an explicitly geomorphic focus, but all of them are either of direct interest to geomorphologists or are relevant to the central aim of this thesis.

2.12.2. Laboratory studies

Many studies are purely lab-based and mostly involve either rock property characterisation (Boudani et al., 2015; Vasanelli et al., 2015), or compare ultrasonic pulse velocity measurements to known weathering processes like freeze-thaw weathering (Remy et al., 1994), wetting and drying (Fereidooni & Khajevand, 2019) or thermal shock (Yavuz et al., 2006). Other studies take a methodological approach, investigating the effects of relative transducer placement on data generation (Turgut & Kucuk, 2006), or the relationship between ultrasonic pulse velocity values and other related variables like rock hardness (Gomez-Heras et al., 2020). Ultrasonic pulse velocity studies that are laboratory-based can, therefore, be generally divided into two main categories. First, there are extensive efforts that have been made to connect UPV values to particular physical material properties, with the objective of establishing empirical relationships between the UPV proxy and unobserved variables such as intact rock strength for a variety of natural and artificial materials. This is so that UPV values measured in the field for particular materials can be related to the relative state of the material. As in the case of early UPV studies, the ultimate goal of many such studies is to allow UPV to be used to quickly determine whether or not a given material (usually in a building or other artificial structure) is structurally safe. This focus on safety in building materials has meant that the bulk of UPV studies are focused on specific, common materials such as concrete (Jones, 1956, 1963; Turgut & Kucuk, 2006), limestone (Vasanelli et al., 2015; Khodabandeh & Rozgonyi-Boissinot, 2022) and marble (Sassoni & Franzoni, 2014; Boudani et al., 2015; Mahmutoğlu, 2017; Ahmad, 2020).

2.12.3. Field studies

Field-based studies, on the other hand, are almost exclusively concerned with the study of culturally important stone, and almost always from the perspective of ultimate preservation. This makes sense, since this is in line with the original design mandate of the apparatus. Curiously, the majority of studies that make use of ultrasonics as a proxy for rock degradation do not approach the study from a weathering perspective. Rather, most of the studies, being predominantly published in journals in fields of geology or material science, focus purely on the rock breakdown aspect, without considering the likely effects of climate, which is considered to be the primary driving force behind most weathering processes (as discussed in Chapter 1).

As in the case of the laboratory-based studies, there are not very many rock types represented in field-based ultrasonic studies. The majority favour either limestone (Remy et al., 1994; Vasanelli et al., 2015; Fereidooni & Khajevand, 2019), granite (Fort et al., 2013; Gimenez & Del Lama, 2014; Grossi & Del Lama, 2015; Freire-Lista et al., 2016) or marble (Siegesmund et al., 2010; Ruedrich et al., 2013; Babacan & Gelisli, 2015; Boudani et al., 2015; Akoglu et al., 2020). There are virtually no studies involving the study of gabbro or basalt, apart from Loubser (2022) and the very early studies of Hawaiian basalts (Manghnani & Woollard, 1965). There are limited studies involving sandstone, and those always as a part of larger studies involving other rock types (Mustafa et al., 2016).

2.12.4. Use of Ultrasonic pulse velocity studies to assess culturally important stone

Ultrasonic pulse velocity measurements have been used frequently in American and continental European studies to assess culturally important stone, both under laboratory and field conditions. The relationship between laboratory and field studies is important for work like this since UPV values will be different for different rock types and UPV indices have not been established for all relevant rock types and environmental conditions. Ruedrich et al. (2013), for example, noted that the porosity and moisture content of a specific rock could alter the measured UPV values. They noted, however, that, with marbles stones of comparable porosity and moisture content, UPV values would decrease as weathering increased, as a result of crack growth within the material. This is a generally accepted relationship between UPV and weathering, and is corroborated by studies like Ahmad (2020), who observed a decrease in UPV values for marble stones that had been exposed to extremely high levels of thermal weathering, which they attributed to an increase in rock porosity driven by generation of micro-cracks. Khodabandeh and Rozgonyi-Boissinot (2022) came to a similar conclusion in their study on the effects of salt weathering on the UPV measured UPV values for limestone building materials, in which they also attributed decreasing UPV values to an increase in micro-crack propagation over the duration of the experiment. Siegesmund et al. (2010) studied marble tombstones in Hamburg and measured UPV as a function of water absorption and damage class, an index determined via visual inspection. While they did not correlate UPV with age, they did conclude that UPV was an acceptable method to use for determining the degree of decay in Carrara marble tombstones.

2.13. Operator and equipment bias

The intention of this thesis is to use ultrasonic pulse velocity measurement techniques as a proxy for rock weathering. However, the resistant nature of gabbro stone and the short weathering age of the tombstones, coupled with the innate unpredictability of any field-based experiment, means that the expected weathering signal is likely to be minor, which could lead to the occlusion of relevant data by experimental error. This is, therefore, an issue of reproducibility, which is under-explored in the Earth Sciences, but is beginning to gain attention on a broader scientific scale. Baker (2016) reported that, in a survey conducted by *Nature*, out of over 1500 scientists, over 70% of them had tried and failed to replicate the results from another study. The survey also noted that only 20% of participants had ever been contacted by another researcher that had failed to replicate their results. Fanelli (2018), also drawing from *Nature*'s survey, indicated that between 40 and 70% of respondents believed that publication pressures could lead to either selective or fraudulent publication of data, although this information is admittedly speculative and difficult to verify (although it seems intuitively likely).

While publication pressures are potentially contributing somewhat to the generation of irreproducible data, other studies have begun to demonstrate that some scientific studies are not reproducible in the first place. Sayre and Riegelman (2018) document a project that had researchers attempt to replicate the results of 100 psychology experiments, with only a 36% success rate. The human-centric focus of these experiments means that they are not directly applicable to physical science experiments and low reproducibility is perhaps to be expected due to the fickle nature of their human subjects. However, any field scientist knows that field experimentation often takes place in conditions that can be as inconsistent as any human.

One notable recent article that pertains directly to this topic in geomorphology is that of Church et al. (2020), who studied reproducibility through the lens of a basic fluvial geomorphological experiment. In this study, the authors categorised experimental repeatability into three components; repetition, replication and reproduction. Ultimately, they concluded that to move a science forward, experimental reproduction must at the very least by possible. In the context of the article, reproduction would refer to the generation of experimental results under different conditions that, while not necessarily directly comparable, must conform to a common theoretical structure. In layperson's terms, would the different sets of data lead to common conclusions, given the same theoretical framework?

The two primary sources of potential errors arise from equipment bias and operator bias. Earth Scientists should be well aware of the dangers of both of these biases and know to guard against them, but there are few Earth Science studies that deal specifically with the quantitative study of these issues and the potential effects on generated data and the specific effects are not often tracked. Rather, it appears that biases are typically believed to have been mitigated by the use of proper experimental techniques. This implies that bias is generally considered something that should be guarded against, rather than actively tracked. Repeatability is frequently a part of engineering rock and soil studies (Hurisso et al., 2018; Feng et al., 2019; Zhao et al., 2021), but appears to be under-studied in geomorphology.

Since the intention of this thesis is to track ultrasonic pulse velocity patterns across different regions with different external variables, it is critical that the reproducibility of this experimental method be confirmed to lie within reasonable limits, both used deployed by a single operator and with multiple operators. A detailed exploration of reproducibility in this study will provide context for the data itself, as well as possible insights into future field studies in the Earth Sciences. Reproducibility studies will, therefore, be carried out both under laboratory and field conditions.

Chapter 3: Study area and methodological approach

3.1. Introduction

The method by which ultrasonic pulse velocity (hereafter referred to as UPV) can be compared to rock weathering rate required several steps of refinement before it could appropriately be used under field conditions. These preparatory steps took place under both laboratory and field conditions in order to limit experimental error as much as possible, since the weathering signals that are to be sought are likely to be small and prone to interference from external influences. It is, therefore, important that the experimental method be as sound as possible, to prevent the occlusion of relevant data.

Gabbro stone was used for this study as it is common in cemeteries throughout South Africa and is primarily extracted from quarries within a 100km belt that runs from Rustenburg to Pretoria (Roux, 1998). It is known as Rustenburg Grey and appears to be a popular choice for tombstones because of its resilient nature. Therefore, there are many tombstones in a lot of cemeteries that contain stones with a common point of origin, but that have been exposed to a wide array of different climatic conditions.

Ironically, the resilience of gabbro, which makes it popular as a tombstone, is an undesirable trait for a study such as this, since rock degradation is the variable under investigation. Gabbro is hard and fine-grained, which suggests that weathering traits like microcrack propagation may be slow to initiate and develop. It is thus likely that gabbro would return a potentially weaker signal than other common tombstone rock types like marble or sandstone. Unfortunately, marbles and sandstones, which would be preferable as samples are rarely used as tombstones anymore. As a result, sandstones and marble tombstones cover a short temporal range, and lie almost exclusively towards the older end of the temporal spectrum. Gabbro has the largest temporal range of any rock type at most cemeteries, is widely found throughout South Africa, and is quarried from a small number of locations that are all fairly close to one another. It is, therefore, the only viable option as a rock type in a study like this, in spite of its innate resilience.

There are many potential advantages to making use of cemeteries in this way, but there are many potential drawbacks as well, chief of which is the value ascribed to tombstones from a cultural perspective. The stones exist as memorials, and therefore, cannot be directly sampled, which has generally restricted the weathering studies to visual observations and basic physical measurements, such as dimension measurements and lead lettering assessments (Cooke et al., 1995; Inkpen & Jackson, 2000; Inkpen, 2013). However, in more recent times, non-destructive proxies such as rock hardness (Wilhelm et al., 2016b) and ultrasonics (Siegesmund et al., 2010; Loubser, 2022) have allowed for the introduction of new metrics through which weathering can be assessed. This has not been trialed extensively on tombstones, but the concept has been used before (Siegesmund et al., 2010). The overall aim of this project is, therefore, to assess the viability of an ultrasonic proxy-based experimental methodology to determine the relationship between regional climate and rock decay.

The proposed method is to measure the ultrasonic pulse velocity of gabbro tombstones at a variety of South African cemeteries that have been specifically chosen due to climatic differences.

3.2. Study sites selection criteria

Sites were selected to cover three different South African regions with different climatic regimes. In each region, one to two cemeteries were selected for study.

For the study to meet the stated objectives, the cemeteries needed to comply with specific criteria.

1) Temporal range: An older cemetery has a larger temporal range than a newer one, which is important since changes in UPV values were expected to manifest slowly, and would be prone to interference from external factors. In the case of South Africa, the maximum temporal range that could be established for this study was approximately 100 years, depending on the site. From a weathering perspective, this is a short period of time, which made it all the more important to use cemeteries that cover this range whenever possible.
2) Large number of gabbro tombstones: Gabbro tombstones are primarily quarried in or near Brits or Rustenberg, in the North West Province of South Africa, but are used in many cemeteries throughout South Africa. However, the number of gabbro stones in any given cemetery is roughly related to the distance of the cemetery from the stone quarries. Gabbro stone is very common in most cemeteries in Gauteng province, which lies adjacent to the North West Province, but cemeteries in Kwa-Zulu Natal and the Western Cape have lower numbers of gabbro stones, particularly prior to 1970. This is most likely due to the expense of transporting large amounts of very heavy foundation stone from its source.

Over twenty cemeteries were surveyed throughout South Africa, but the majority of them did not meet the required criteria for the study. Others had to be disregarded for logistical or safety reasons. Ultimately the following restrictions were observed during the reconnaissance phase of this project:

1) Gabbro tombstones older than 1970 are more numerous in cemeteries that lie in large cities, or in towns that are close to large cities.
2) Cemeteries in smaller towns commonly have large numbers of gabbro tombstones newer than 1970, but prior to that are mostly a mix of marble, sandstone and slate tombstones. This results in a situation in which none of the available stone types span the entire age of the cemetery.
3) Ideal sites for this study are, therefore, medium to large cemeteries situated in big cities, with occasional secondary sites sometimes available in small settlements near to a big city (although these sites typically provide smaller datasets, due to a smaller number of tombstones)

Of the twenty sites surveyed in the study, only five were found to be viable, all of which were either in or near to large cities (Pretoria, Cape Town and Durban).

3.3. Regional study sites across South Africa

Ultrasonic measurements were taken at two cemeteries in Cape Town, one in Simon’s Town, one in Howick and one in Durban. In addition, many of the gravestones at Cullinan Main Cemetery were measured using a more intensive measurement technique. Cullinan Main Cemetery lies 40 km away from the centre of Pretoria, which is in the Gauteng Province of South Africa with a sub-tropical climate. The cemeteries in Cape Town and Simon’s Town lie at the extreme southern tip of South Africa and have predominantly winter rainfall, while Durban and Howick are on the eastern coast of South Africa and experience a more tropical climate (Figure 3). These sites were specifically selected because of their differing climatic spectrums in order to determine whether there is an measureable link between rock weathering intensity and climate or not.

As a general rule, gabbro stone comprised a large percentage of tombstones at all of the selected sites, with each site also containing smaller numbers of tombstones constructed from marble, sandstone and granite. However, marbles and sandstones were only used extensively at all of the observed sites for the oldest tombstones, and granites are more numerous for newer stones. Gabbro tombstones were present in each site for the largest temporal range of each stone type.

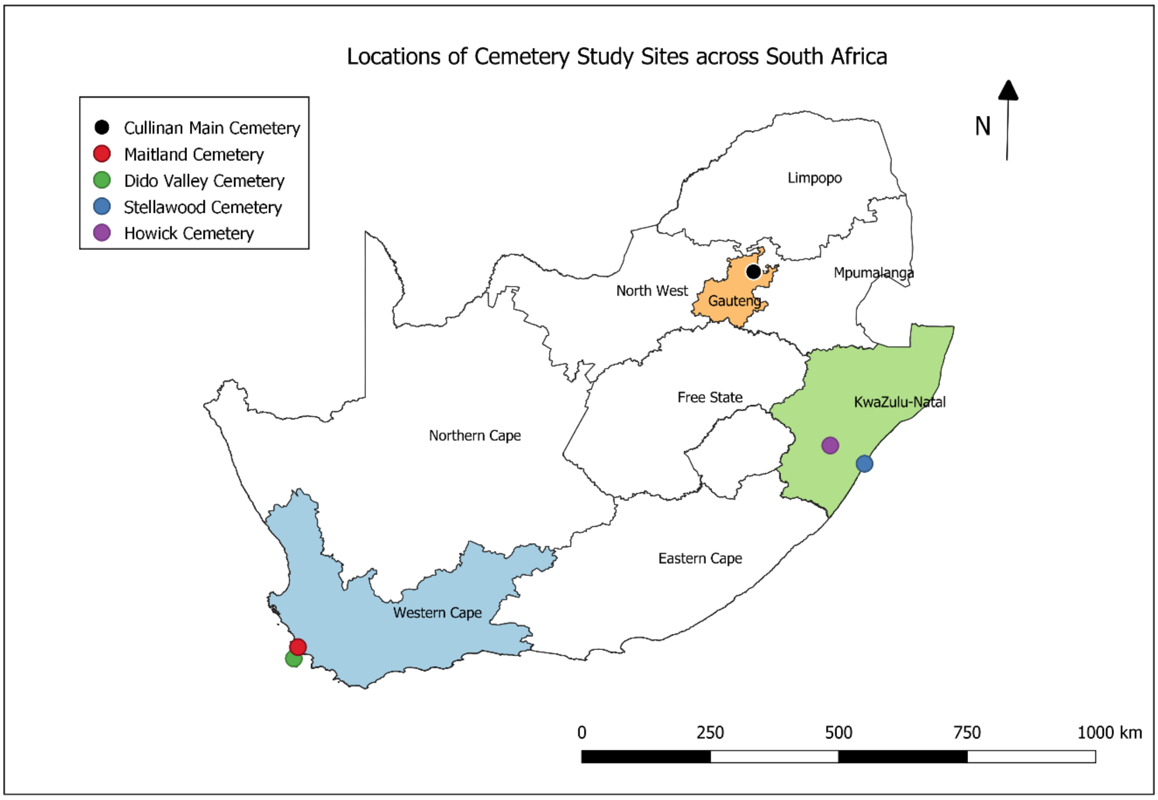


Figure 3. The three regions in which measurements were taken for the regional climatic study

3.3.1. Location of the Western Cape study sites

The Koppen-Geiger Climatic Classification system defines Cape Town’s climate as ‘Warm-summer Mediterranean’, with much of their rainfall occurring in the winter months. Figure 4 shows a modelled average monthly temperature and rainfall diagram which clearly indicates the winter rainfall nature of Cape Town.

Cape Town has a front driven winter rainfall climate with mean monthly maximum temperatures of up to 27° C and mean monthly minimum temperatures of 6.5° C. Summer precipitation averages 16mm per month, but this rises to up to 94mm per month in winter (SAWS).

Three cemeteries were studied in the Western Cape region. The primary site was Maitland Cemetery, which lies within the city boundaries of the city of Cape Town. A second site at Dido Valley in Simon's Town was also assessed. The two cemeteries are only 30 km apart, but have different microclimate settings and surroundings. A third site (Plumstead Cemetery) was also surveyed, but data gathered from that site served only to assist in the development of the field measurement techniques developed for Objective 3 of this thesis. This is addressed in Section 5.7.)

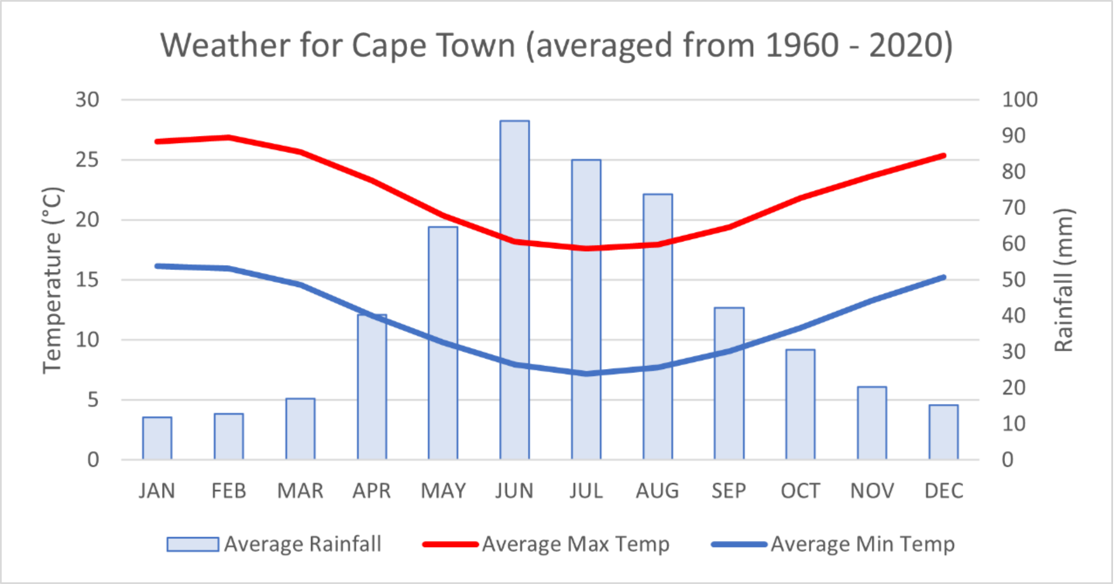


Figure 4. Average monthly temperature and precipitation for Cape Town, generated from data provided by the South African Weather Service (SAWS)

Maitland Cemetery is a large facility situated near Pinelands in Cape Town (Figure 5). The surrounding area is predominantly residential, although there are commercial facilities and office buildings in the area as well. It contains tombstones ranging from the late 1800s to the present day, although the oldest tombstone that was appropriate for ultrasonic assessment was from 1919. This still gives a temporal range of 100 years to work with, and all of the stones could be drawn from within 1 kilometre of one another, with no notable topographical elements lying between them. All tombstones older than 1919 were not constructed from gabbro, but rather materials such as marble and sandstone. While these stone types would have been viable to assess for this study, marble and sandstone graves fell out of use as tombstones circa 1935, with most more contemporary stones being of either gabbro or granite construction. This leads to a temporal maximum range of 40 years for sandstone and marble tombstones, which was deemed unsuitable for this study.

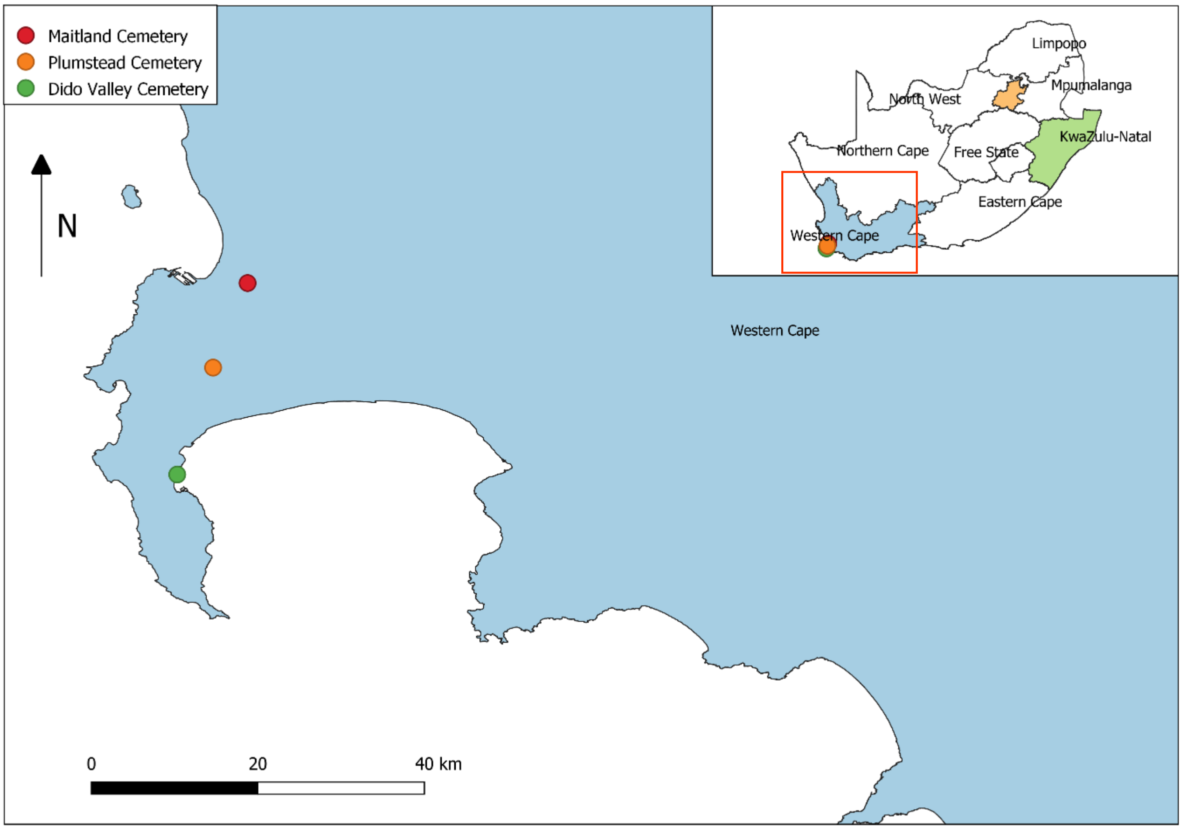


Figure 5. Map showing the location of Maitland Cemetery and Plumstead Cemetery in Cape Town and Dido Valley Cemetery in Simon's Town

There is no easily identifiable pattern in terms of the age of the tombstones and their relative locations in the cemetery. However, anecdotally, there seems to be a larger percentage of newer tombstones in the eastern section of the cemetery, and the very oldest stones lie near the centre of the cemetery, near an old chapel that is no longer in use (Figure 6). Maitland Cemetery has an areal extent of 1300 m^2 and lies within a heavily populated area of downtown Cape Town. Large sections of the Eastern side of the cemetery have tree cover, with the cover becoming sparser towards the West (Figure 7).

Figure 6. The oldest stones in the Maitland Cemetery. These stones are typically inappropriate for this study, either due to shape or stone type

Figure 7. Areal extent and tree cover for Maitland Cemetery in 2022. The red lines show the boundaries of the cemetery (image credit, Google Earth, 2022)

In 1944, the Eastern section of the cemetery had considerable tree cover (Figure 8), much as it does in 2022, while the Western section had less tree cover than it does in 2022. However, not many measurements were taken from the Western section as that portion of the cemetery is still active and it was largely avoided during the study so as not to disturb mourners tending to newer gravesites. These aerial photographs are the oldest ones available from the NGI portal, so the tree cover prior to 1944 cannot be assessed.

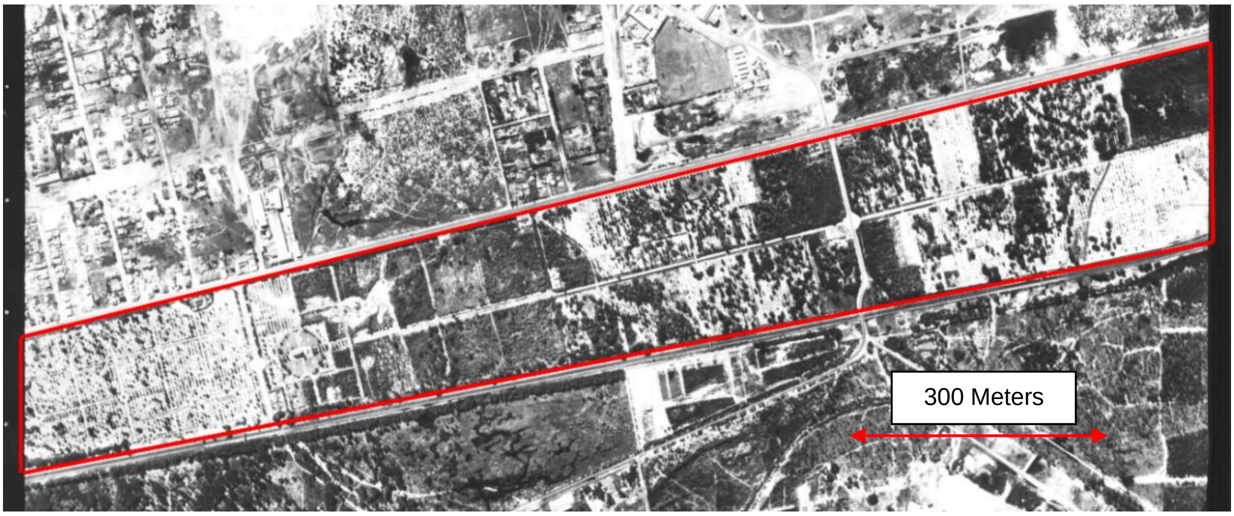


Figure 8. An aerial photograph showing the areal extent and tree cover of Maitland Cemetery in 1944. The red line shows the boundaries of the cemetery. (image credit, Chief Directorate National Geospatial Information, http://www.cdngiportal.co.za/CDNGIPortal)

As can be seen in Figure 9, topography of Maitland Cemetery is generally flat, with dappled shade covering many of the stones. While there are areas of the cemetery with fewer trees than depicted, most tombstones will experience an environment like that in the image, and nearly all tombstones will experience tree shade at some point in the day.

Figure 9. Tombstones and typical tree cover at Maitland Cemetery, Cape Town in the year 2021

Simon’s Town is a South African town near Cape Town that largely exists to service Simon’s Town naval base. There is a naval cemetery that contains tombstones as old as from the late 1800s, but unfortunately they are all constructed from either sandstone or marble, which makes the cemetery unsuitable for this study. As an alternative, Dido Valley Cemetery, which lies on the main road leading into Simon’s Town, has a small number of suitable gabbro tombstones and an acceptable temporal range (90 years).

Dido Valley Cemetery also falls into the ‘Warm-summer Mediterranean’ classification, according to Koppen-Geiger, but lies 70 meters from the seafront and is directly exposed to winds coming off of the sea. Dido Valley, therefore, falls into the same climatic classification as Maitland Cemetery, but the tombstones will experience different microclimatic conditions. In particular, consistent exposure to salt and moisture laden wind blowing in from the sea may contribute to how the stones degrade, due to the proximity of the cemetery to the ocean (Figure 10).

Figure 10. Areal extent and tree cover for Dido Valley Cemetery in 2022. The red line shows the boundary of the cemetery (image credit, Google Earth, 2022)

The tombstones in the cemetery have almost no tree cover at all. While there are a small number of trees in or near the cemetery, none of them are tall enough or placed appropriately to cast shade on any of the tombstones (Figure 11).

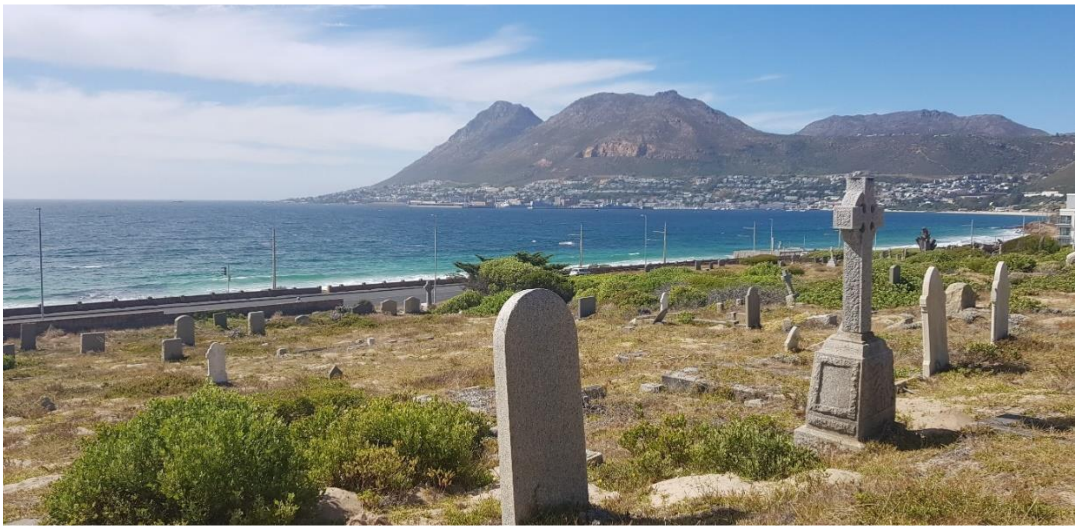


Figure 11. Tombstones in Dido Valley Cemetery, Simon's Town. Note in particular the lack of tree cover and proximity to the ocean, suggesting that these tombstones are likely to be constantly exposed to salt-laden wind

Figure 12 shows Dido Valley in 1945. There is actually more tree cover in the cemetery in 1945 than in 2022, but most of the tombstones will most likely still have been exposed to direct sun most of the time in addition to the salt and wind described earlier.

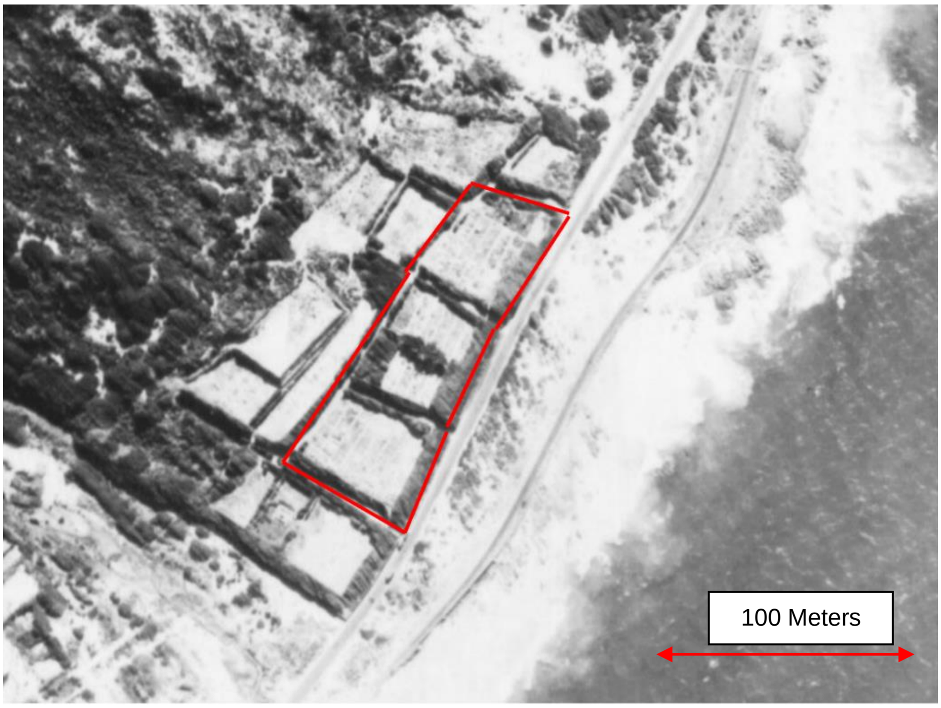


Figure 12. Areal extent and tree cover of Dido Valley Cemetery in 1945 (image credit, Chief Directorate National Geospatial Information, http://www.cdngiportal.co.za/CDNGIPortal)

Plumstead Cemetery in Cape Town and Seaforth Naval Cemetery were also considered for this study and some measurements were taken at each site, but they ultimately proved unsuitable and their overall contribution to the study was minimal. Some of those data are considered later in this thesis though because they offered valuable insights into the refinement of the eventual experimental method discussed in Chapter 6.

3.3.2. Study sites in Kwa-Zulu Natal

Two sites were considered in the Kwa-Zulu Natal region. The primary site was Stellawood Cemetery in downtown Durban and the auxiliary site was Howick Cemetery, located in the small town of Howick (Figure 13). The two cemeteries are 85 km apart, with Stellawood lying on the coast and Howick Cemetery lying approximately 90 km inland. This leads to slightly different climates in spite of their close proximity to one another.

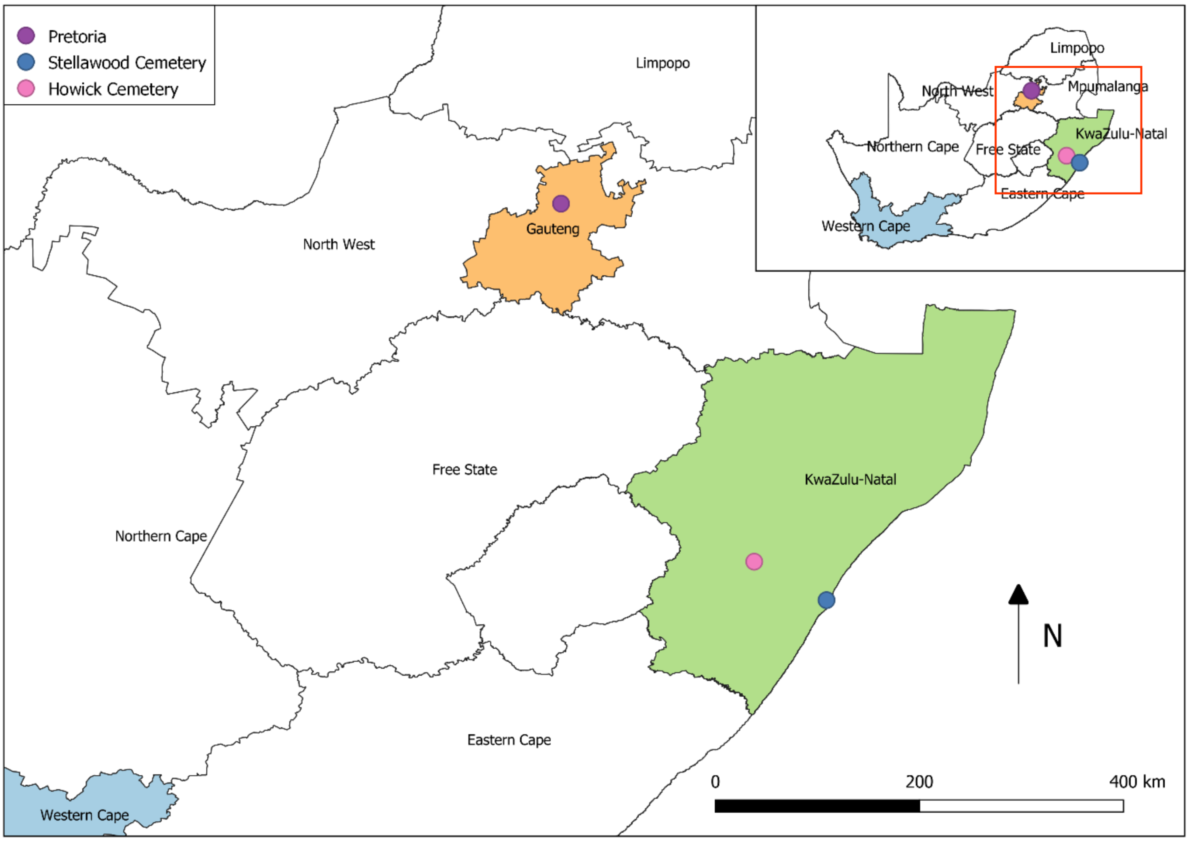


Figure 13. Location of Stellawood Cemetery, Durban and Howick Cemetery, Howick

Stellawood Cemetery is a large, topographically varied cemetery with a large number of tombstones that cover a similar temporal range to Maitland Cemetery in Cape Town. The regional climate is classified as ‘Humid subtropical’ (Conradie, 2012), with rainfall occurring mainly during the summer months, but with the possibility of rain being present through the year (Figure 14). The city has a maximum mean monthly temperature of 29° C in the summer months and a minimum mean monthly temperature of 9° C in winter. Durban has an average monthly rainfall of 83mm, but can drop as low as 10mm in the winter months (SAWS).

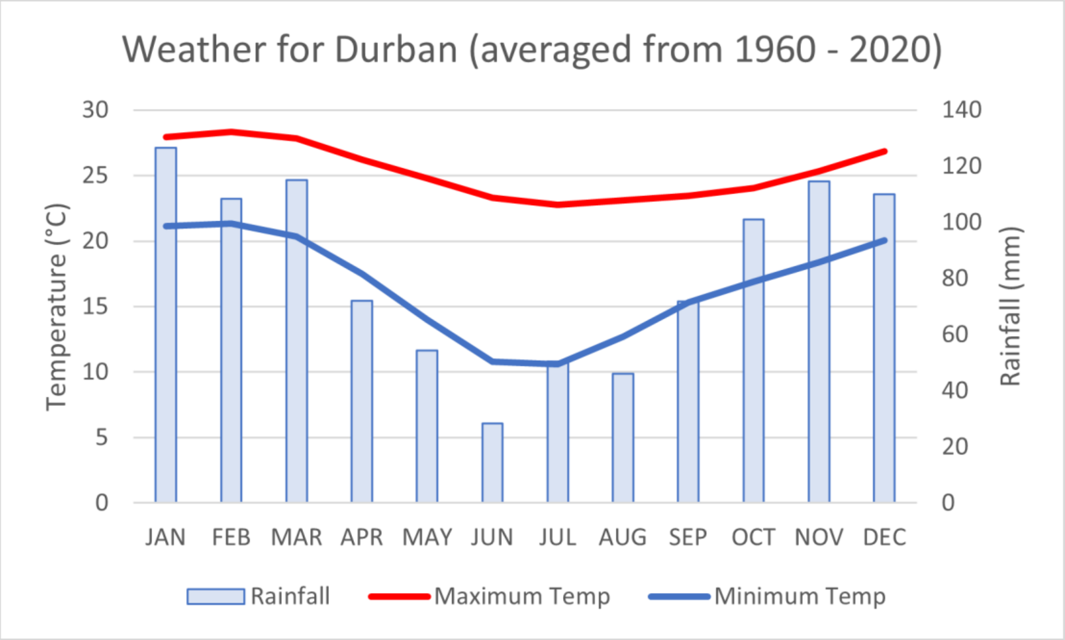


Figure 14. Average monthly temperature and precipitation for Durban, generated from data provided by the South African Weather Service (SAWS)

Stellawood Cemetery covers an areal extent of 440 m^2, with trees scattered over much of the grounds (Figure 15), creating dappled shade cover over parts of the Northern, Central and Southern areas, although sections of the cemetery also contain tombstones that do not experience any shade at all.

Figure 15. Areal extent and tree cover of Stellawood Cemetery in 2022 (image credit, Google Earth, 2022)

Photographs from circa 1940 were difficult to obtain so the tree cover from that time cannot be assessed in the same manner as for the cemeteries in the Western Cape. However, an image from 1968 shows that while the northern and central areas of the cemetery had tree cover, the western area was considerably sparser and the southernmost area was home to a stand of trees that was subsequently cleared in later years (Figure 16).

Figure 16. Areal extent and tree cover of Stellawood Cemetery in 1968 (image credit, Chief Directorate National Geospatial Information, http://www.cdngiportal.co.za/CDNGIPortal)

Figure 17 shows the exposed nature of many of the tombstones at Stellawood Cemetery, and the view of the lopsided nature of palm trees show that the cemetery can experience considerable wind (which was personally experienced during the data collection at this site). It is also the most topographically varied of all the sites, and the tombstones do not have a common facing aspect. It is likely that the stones are placed facing the internal roads of the site, which follow the contours of the terrain, rather than a structured grid pattern.

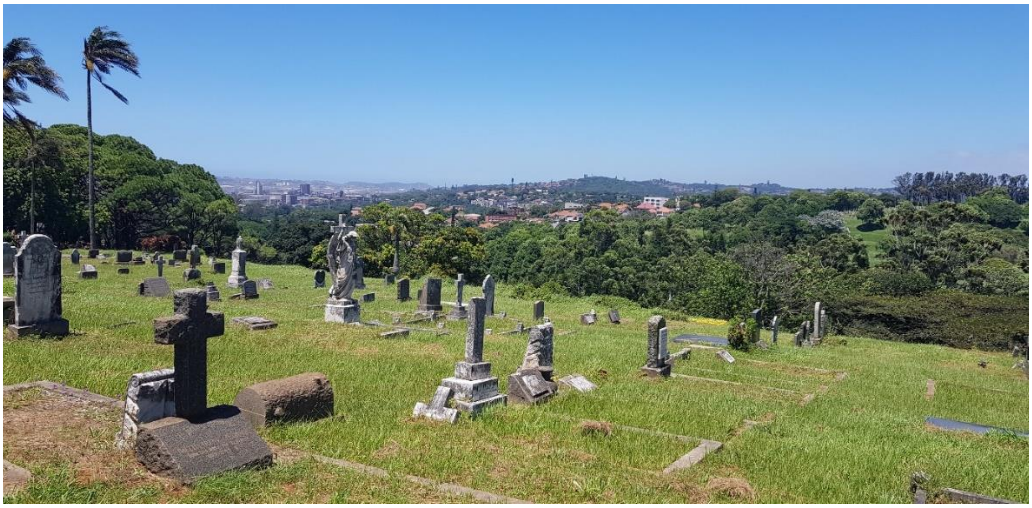


Figure 17. Tombstones in Stellawood Cemetery. Note the exposed nature of the tombstones in the foreground and the tree cover in the background, which casts shade over the tombstones that lie under the trees

Tombstones at Stellawood Cemetery displayed higher levels of lichen cover than was observed at other sites in this study, mostly likely because of Durban's high average humidity and warm temperatures (Figure 18).

Figure 18. Partial lichen cover on a tombstone at Stellawood Cemetery.

Stellawood Cemetery also contains a section devoted exclusively to fallen soldiers (mostly from World War 2), which is independently overseen by the Commonwealth Wargraves Commission (Figure 19).

Figure 19. Tombstones under the care of Commonwealth Wargraves Commission. Note their exposed position. All of the Wargraves are located in the same part of the cemetery and are constructed of gabbro.

These stones were all placed within a short time of one another, since most of the soldiers perished in the same conflict, and the culture of standardisation common to most military organisations has ensured that the stones all have the same physical dimensions and are all constructed from gabbro stone. These stones, therefore, serve as a useful control set for this study. Since the tombstone construction and micro-climate exposure of these stones are essentially equivalent for all of them, any differences measured in the stones should be as a result of pre-existing differences in physical rock properties.

3.3.3. Study site in Gauteng

The primary study site for this study, and the site where the initial method was trialed and assessed was at Cullinan Main Cemetery, 40 km outside of Pretoria near the town of Culllinan (Figure 20).

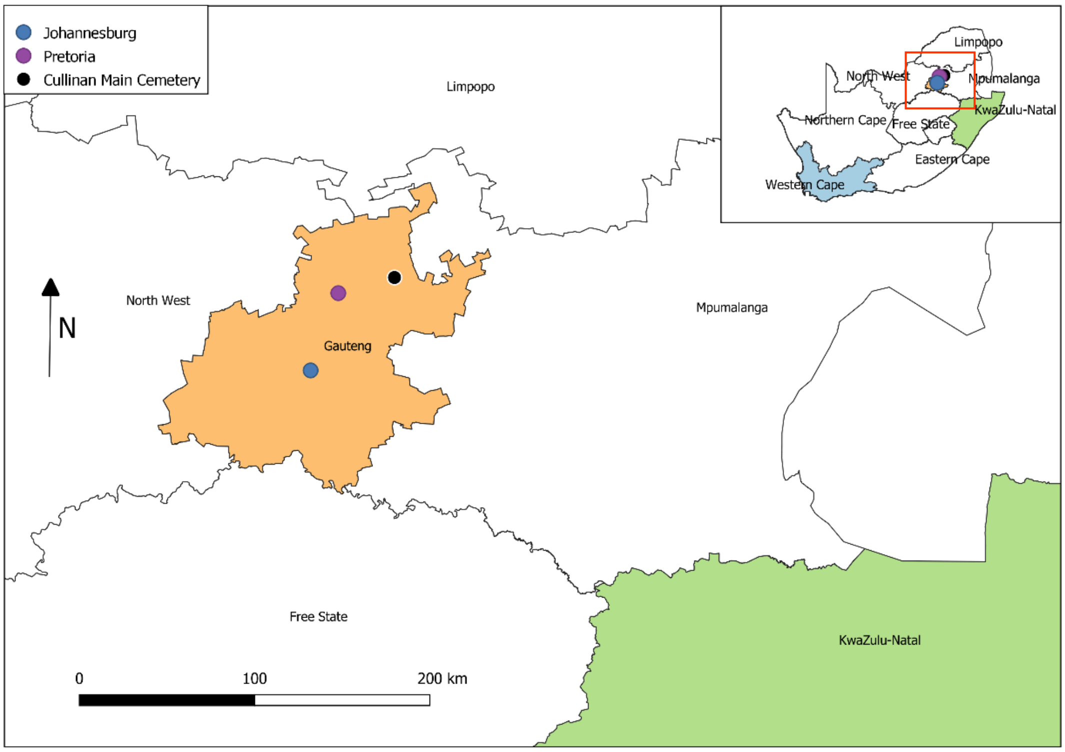


Figure 20.Google Earth Image showing the location of Cullinan Main Cemetery, 40 km from the centre of Pretoria

According to the Koppen Classification system, Cullinan's climate is designated as Cwb (Conradie, 2012), which is described as "Warm temperate, Winter dry, warm summer" (Figure 21).

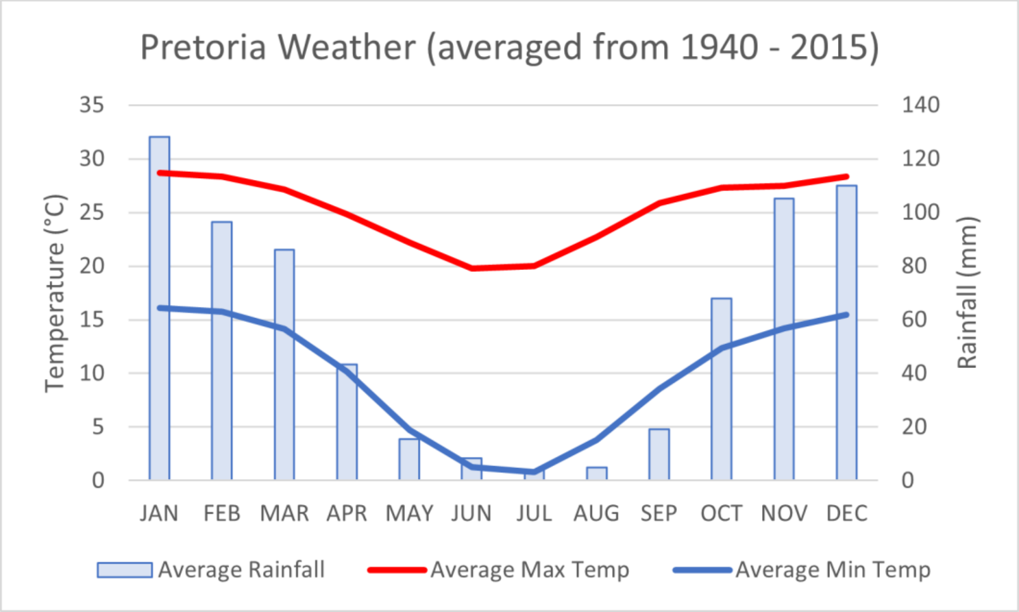


Figure 21. Average monthly temperature and precipitation for Pretoria, generated from data provided by the South African Weather Service (SAWS)

The cemetery has an areal extent of 75 m^2 with a stand of trees placed in the centre (Figure 22). The oldest tombstones are found within the stand of trees (indicated on the photograph by the blue box), while the younger tombstones lie closer to the road (indicated by the yellow box), but all of the tombstones experience both sun and shadow at different times of the day. This appears similar to the shade profile present in 1940, as determined from the earliest available aerial photographs (Figure 23).

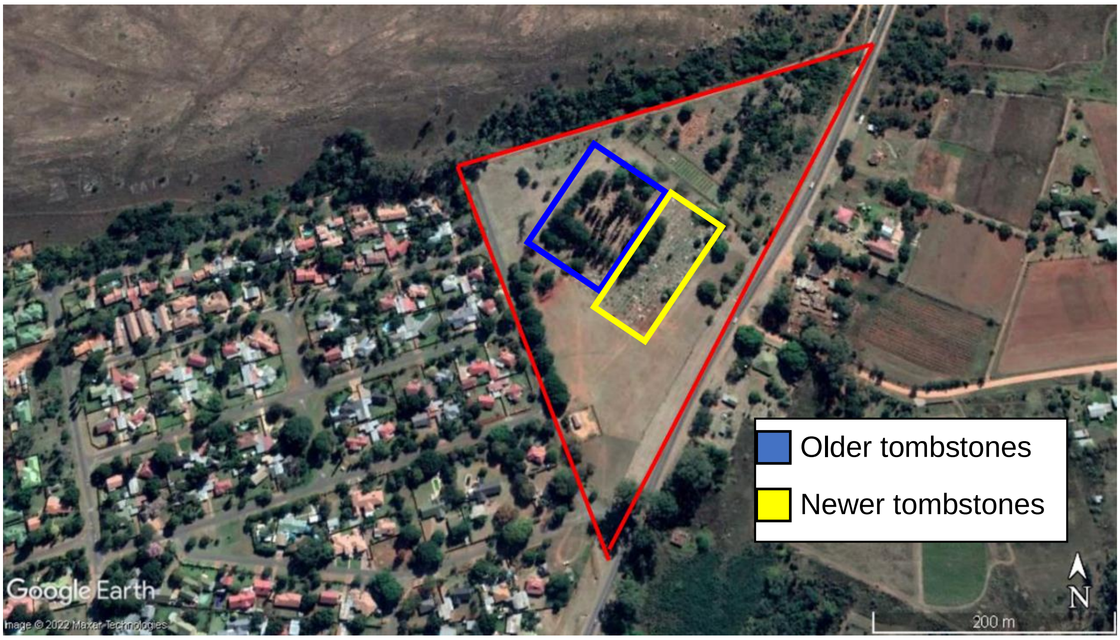


Figure 22. Areal extent and tree cover of Cullinan Main Cemetery in 2022 (image credit, Google Earth)

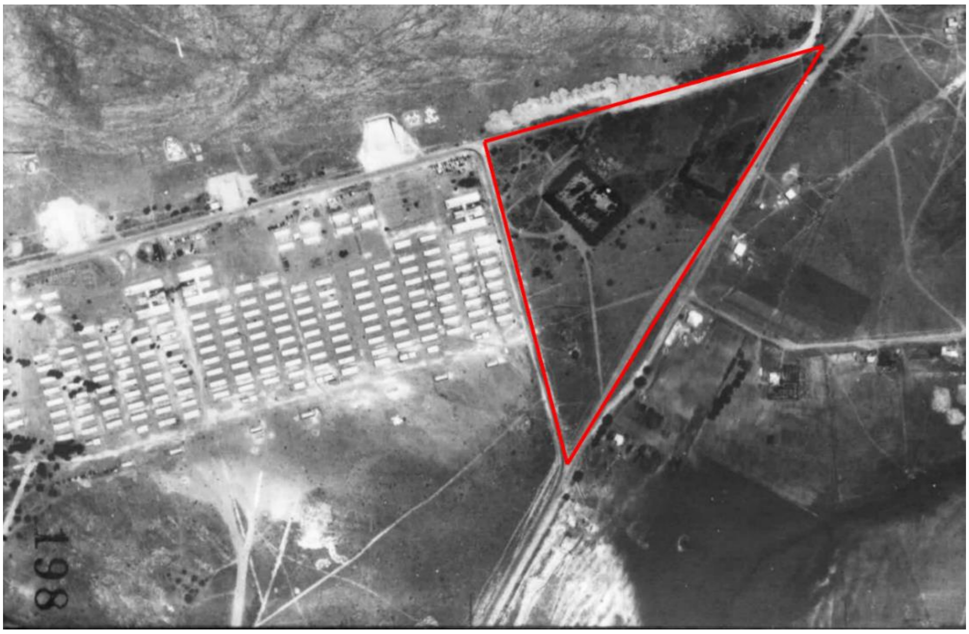


Figure 23. Cullinan Main Cemetery areal extent and tree cover in 1940 (image credit, Chief Directorate National Geospatial Information, http://www.cdngiportal.co.za/CDNGIPortal)

A comparison of Figures 22 and 23 shows that some increased tree cover on the borders of the cemetery in 2022, with a small number of trees being added on the border of the wargrave site to the north of the main site. The central stand of trees that provides most of the shade to the tombstones has been in place since at least 1940.

The tombstones are of varied designs, but many are constructed from gabbro (Figure 24). Many of the older stones have badly faded inscriptions, although most of them are still legible.

Figure 24. Gabbro tombstones and general setting at Cullinan Main Cemetery

All of the cemeteries selected for study are exposed to different regional climates or, in the case of Dido Valley, have a unique climatic aspect that makes it distinct from the others. All of the cemeteries contain gabbro tombstones with similar designs that were laid out over a reasonable temporal range. If climate plays a significant role in the intensity of weathering observed for a particular stone, the cemeteries in each area should display noticeably different weathering trends, as determined by the relationship between ultrasonic pulse velocity and time *in situ*.

The use of these various proxies can also be a potential disadvantage, since both rock hardness and ultrasonic pulse velocity measurements are not direct assessments of rock weathering, but have rather been observed empirically to be connected with weathering (Goudie, 2006; Siegesmund et al., 2010; Viles et al., 2011; Ruedrich et al., 2013). Specifically, the change in ultrasonic pulse for natural stone is regarded as being indicative of a change in weathering intensity, even if the actual weathering intensity is never directly observed. It is important to scrutinise data generated through these methods carefully, particularly since the equipment that is used for generated these data are often used slightly outside of their design parameters.

In order to assess the delimitations of equipment for ultrasonic pulse velocity studies, it was necessary to scrutinise the intended experimental methodology and identify potential avenues of error that could cause problems in data generation, and quantify the effects.

The total method for the project was divided into three primary sections. First, the boundaries of operation for the equipment were established under laboratory conditions, and baseline readings for unweathered gabbro established. Second, the field experimental method was developed and tested at Cullinan Main Cemetery. Finally, on the basis of the Cullinan results, the field experimental method was refined and tested at four cemeteries across South Africa.

3.4. Objective 1 – Laboratory experimental design

3.4.1. Ultrasonic Pulse Velocity Theory

It is an established physical principle that sound waves travel through different mediums at different rates. The mechanics of this process are complex, but the key concept is that sound waves are made up of vibrations that are transmitted through a particular medium at an atomic level. The more rarefied the material is, the longer it takes for the sound wave to travel through the material. Rock that is more weathered will have an array of microcracks present in its structure that will not be there in an unweathered sample of the same type. An ultrasonic pulse traveling through a weathered rock sample will consequently return an ultrasonic pulse at a slower velocity than the equivalent unweathered sample as a result of the increased number of voids that the wave would need to travel through from the transmitter to the receiver (Ruedrich et al. 2013). This measurement technique was originally designed to assess the structural soundness of construction materials (Lutsch, 1999; Spencer & Shattock, 1962), but has been adapted by geomorphologists as an assessment tool for weathering (Hall, 1988; Babacan & Gelisli, 2015; Akoglu et al. 2020). As with all proxies, there are a number of things that can influence the recorded value. The presence of water, for example, could *increase* velocity of the pulse as it passed through, leading to an artificially inflated value (Siegesmund et al. 2010). The fact that the pulse does not travel in a straight line, but rather in the ripple-like motion typically associated with waves means that the pulse can possibly refract in unusual ways when passing through the boundary between two mediums of different densities. This can alter the net measured pulse velocity in ways that are difficult to predict. Nevertheless, ultrasonic measurements have become a standard measurement technique for rock strength assessment, and has been adapted from its initial purpose (assessing the strength and durability of concrete), to being used as a tool for natural stone, particularly in the case of culturally important stone that cannot be damaged. Ultrasonic measurement in geomorphology has proven particularly popular in studies that involve stone that is culturally important, such as monuments or tombstones in cemeteries, since it is non-destructive, but can still yield useful quantitative data.

3.4.2. Experimental apparatus – PUNDIT PL 200

The PUNDIT PL 200 is a state of the art ultrasonic pulse velocity device that was originally designed to allow an operator to make a rapid, quantitative assessment of the structural integrity of building materials such as concrete. However, geomorphologists have considered the possibilities of ultrasonic pulse velocity as a proxy for rock degradation since 1988 (Hall, 1988). Recently, the technology has been exploited more fully, particularly on culturally important stone because of its non-destructive measurement properties (Siegesmund et al., 2010; Ruedrich et al., 2013; Akoglu et al., 2020).

The PUNDIT PL-200 comes as standard with a 54kHz broad headed ultrasonic transducer (the contact surface has a diameter of 49mm), but a narrow headed 54 kHz transducer 3.5 mm diameter) is also available which is designed specifically for use with rough surfaces. In both cases, the transducers may not be closer to one another than 69 mm, so all measurements in this study were taken with the transducers at least 80 mm apart, which is the minimum thickness observed for the majority of the tombstones, most of which were thicker than this.

The ultrasonic couplant is only necessary for the standard transducer in this study, but both transducers were tested with and without couplant in order to observe how they performed in a variety of scenarios (a gabbro sample block with couplant stains can be seen in Figure 25). The PUNDIT PL-200 operating manual does not specify what the ultrasonic couplant is comprised of, but its primary purpose is to ensure a solid contact between the standard broad headed transducers and the sample that is being assessed. A primary point of concern with respect to the ultrasonic couplant is that it stains the sample surface.

Figure 25. Gabbro sample block with stains from ultrasonic couplant. In the background is a bottle of ultrasonic couplant and the rough surface transducers in their polystyrene protective blocks

3.4.3. Experimental limitations and delimitations

Gabbro stone has not been studied extensively in geomorphology from a weathering perspective and there is no information as to the data that it would yield from ultrasonic pulse velocity testing. Additionally, field testing of natural stone will introduce a degree of error due to uncontrollable external field variables that are a normal aspect of any field based study. It is, therefore, necessary to test the various possible sensor configurations under standardised laboratory conditions, and to quantify the error that may be introduced into the data due to irregular field conditions. It is also necessary to determine the effects of operator bias, both from an intra-operator and inter-operator perspective. Intra-operator bias must be quantified to ensure that measurements with the device can be carried out precisely and repeatably, while inter-operator bias must be quantified to assess the validity of using multiple operators across regions that may be spatially distant from one another. These determinations have value not only for this study (although they are crucial for its success), but also for future studies that intend to make use of either this experimental field measurement technique or an adaptation of it. The required laboratory testing will comprise quantification of the following:

1) The type of transducer to be used in the field study

The PUNDIT PL-200 comes as standard with a 54 kHz transducer pair, each with a wide base, designed to fit standard smooth built surfaces via the application of an ultrasonic couplant. However, a 54 kHz rough surface transducer can also be purchased at an additional expense, which has a smaller contact area and does not require the application of ultrasonic couplant. Some geomorphology studies make mention of a 54 kHz transducer, but do not discuss the equipment in greater detail, which makes it likely that the standard transducers are being employed (Binal, 2009; Babacan & Gelisli, 2015; Bahadır et al., 2022). Gimenez & Del Lama (2014), in contrast, did make use of rough surface transducers in their study, but did not find the results that they provided useful, and therefore, focused their study on results provided by standard 54 kHz and high frequency 150 kHz transducers. It is, therefore, important to determine which transducer pairs are best for the experiments carried out in this thesis; the standard 54 kHz pair or the rough surface pair.

2) The effects of ultrasonic couplant on measured results

Ultrasonic couplant is a specified requirement for the use of the standard ultrasonic transducers, but laboratory testing in the course of this study has shown that it can stain rock samples, which makes it inappropriate for use on cultural stone, which cannot be damaged as a result of any experimental measurements. It is, therefore, important to compare results that are obtained when using couplant against results that are obtained without it, to determine if standard transducers can provide useful results without using couplant, or not.

3) The effects of misaligned transducers under field conditions

The irregular shape and size of many tombstones makes precise measurement in the field difficult, and it is reasonable to assume that there will be a certain degree of experimental error. Laboratory experiments to quantify likely field errors are valuable in allowing the researcher to determine when results have the possibility of being driven by experimental error, and when they are reflective of actual changes in rock properties in the field.

4) The effects of intra-operator bias

The weathering signal that this field technique is intended to assess is likely to be small, which means that any systemic experimental error has the potential to occlude it. It is, therefore, necessary to determine how repeatable the measurements are and ensure that results can be replicated to a reasonable degree of precision.

5) The effects of inter-operator bias

The multi-region nature of a study like this makes it desirable to have the option of using multiple operators conducting studies at an array of cemeteries. To assess the viability of this option, it is important to determine how operator skill and experience can affect the measurements that are obtained. This is an understudied aspect of the Earth Sciences in general, and geomorphological studies in particular. This is because geomorphological studies frequently study processes that exhibit small change over long periods of time, and even small degrees of operator error could obscure the changes that are under observation. Quantification of this effect is thus a necessary component in the development of any experimental study that is reliant on the accurate measurement of small variances. In this thesis, all field measurements that were not part of the operator comparison study were carried out by the author, but future studies on a regional scale may require the use of additional personnel.

3.4.4. Statistical tests

The transducer and couplant tests, as well as the inter-operator and intra-operator measurements, will be visually represented by a series of box and whisker plots, but the datasets will be assessed by means of a Kruskal-Wallis statistical test, with any necessary pos hoc testing making use of the Dunn test, with applied Bonferroni correction. The Kruskal-Wallis test is a non-parametric alternative to the standard ANOVA (analysis of variance) test. It is used to assess whether or not a series of independent datasets are all part of the same statistical population. It was selected for this study because the datasets are not assumed to have a normal distribution, which is a requirement for the ANOVA test. In the case where the Kruskal-Wallis test reveals that one or more of the datasets are not part of the same statistical population as the majority of the others, a Dunn post hoc test will be carried out to determine which how many set pairs are different from one another. The Dunn test is the most common post hoc test for the Kruskal-Wallis test and is also non-parametric in nature. Use of non-parametric tests like the Kruskal-Wallis test correlation test were considered by Wilhelm et al. (2016) to be superior to tests like ANOVA for data expected to be non-normal. In their case, they made use of the Kruskal-Wallis test to assess differences in rock hardness data obtained from two different types of Equotip probe.

The experiment that assessed the effects of transducer misalignment were represented with line graphs and assessed with linear regression analysis.

3.5. Objective 2 – Preliminary field application

Once the preliminary delimitations of the equipment and experimental design are established, it is necessary to further develop the technique under field conditions and test its general soundness. This was done by gathering tombstone measurements at one cemetery in South Africa and assessing the outcome. The cemetery selected for this study was Cullinan Main Cemetery. It contains a large number of gabbro tombstones, ranging in exposure time from 1920 to 2022.

3.5.1. Tombstone descriptions and sample selection

The cemetery has been in existence since approximately 1906, with tombstones being constructed initially out of either sandstone or marble. Observations made in the various cemeteries showed that gabbro stones appeared at first in small numbers, beginning in 1912, and became progressively more popular in the following decades. By 1940, marble and sandstone tombstones had been phased out almost entirely and been replaced almost exclusively with gabbro (sometimes referred to commercially as *black granite*), although there are a small number of traditional granite tombstones as well.

Gabbro was selected as the stone of choice for this study for several reasons. It is the most common stone type in the cemetery by a large margin and covers the most extensive temporal range (over 100 years). Sandstone and marble tombstones are only present in the cemetery circa 1910 – 1940, which is too small a temporal range to be useful in this study. Slate and traditional granite stones are present in very small numbers, and therefore, do not constitute a viable dataset. Also, gabbro tombstones typically of square, symmetrical construction, which is ideal for obtaining measurements with the PUNDIT PL-200 using the direct transmission method.

A limitation of gabbro as a stone type is that it is very robust and likely resistant to weathering. While there is no readily available laboratory-based data on South African gabbro weathering rates, observations at the cemeteries showed that gabbro tombstones from 1920 often had more legible inscriptions than did sandstone or marble. It is this property that makes it popular as tombstone, but it also means that the weathering signal that the PUNDIT PL-200 is attempting to detect is likely to be small. While it is possible that this is not the case, it was deemed prudent to design the experimental procedure under the assumption that gabbro weathering rates would be low and the resulting UPV differences would be as well. Another consideration is that there was a change in tombstone design that occurred around 1950. After 1950, most gabbro tombstones were polished on the front and rear of the stones. Prior to 1950, most gabbro tombstones had a polished, smooth front face, but the rear face was left rough and unpolished. This was most likely because the innate hardness of gabbro would make it difficult to shape. This change in the nature of the surface can potentially interfere with the contact that the ultrasonic transducers could make with the older stones, particularly in the case of the standard wide head transducers.

To assess the potential effects of this difference in tombstone design, the initial field measurements were carried out with both the wide head standard transducer and the exponential transducer to quantify the potential effects of tombstone roughness on the results.

For the initial study, 34 gabbro tombstones were selected, ranging in date of placement from 1912 (110 years ago) to 2009 (10 years ago). This was expected to be sufficient to test the proof of concept.

3.5.2. Tombstone measurement technique

Each tombstone was measured five times with each transducer pair. Four measurements were taken near to the corners of each tombstone and one measurement was taken in the centre. The width of each tombstone (i.e. the distance between the front face and the rear face) was measured with a set of vernier calipers. One transducer was then placed on the front face of the tombstone, and the other on the rear. An ultrasonic pulse was then transmitted between the two and the time it took recorded. The time, in conjunction with the measured distance between the transducers was used to calculate the velocity of each ultrasonic pulse.

3.5.3. Statistical and mathematical analysis

Four of the 34 tombstones were measured more intensively to determine the heterogeneity of the measurements. Each of the four was measured in a grid pattern for a total of between 40 and 72 measurements, depending on the size of the tombstone and categorised according to 500m/s velocity bins.

The average value of each tombstone was graphed as a function the of date of death and a linear regression derived for the resulting curve. The correlation between the date of death and the average pulse velocity for each stone was assessed via the Spearman rank correlation test. This was used instead of the more robust Pearson test because the anticipated nature of the data was not expected to conform to the normalised distribution required by Pearson. This correlation was carried out both the standard and exponential transducers. The work carried out for this segment of Objective 2 is presented in Chapter 5 of this document and was also published in the South African Geographical Journal (Loubser, 2022).

3.5.4. Operator bias under field conditions

To assess the effects of operator bias under field conditions, the experiment carried out at Cullinan Cemetery was performed again with two different operators. The operators were trained by the researcher that carried out the original set of measurements (the author of this thesis). The same tombstones were measured as in the original study, using the same set of transducers and under weathering conditions that were as similar as could be managed. This was to quantify the effects of operator skill on the generated result, to determine the effects of multiple operators that contribute to a single dataset.

3.6. Objective 3 – Regional scale study

From the information gathered from Objective 2, the experimental methodology was modified and deployed at cemeteries in different regions across South Africa.

3.6.1. Site selection and field measurement techniques

Four cemeteries were assessed at different locations across South Africa. Two of them (Maitland Cemetery in Cape Town and Stellawood in Durban), will make up most of the discussion, since they are large cemeteries that provided many suitable tombstones for measurement. Two additional cemeteries (Dido Valley in Simon’s Town and Howick Cemetery in Howick) were much smaller cemeteries with fewer measurable tombstones and will be treated as auxiliary datasets. At Stellawood Cemetery, military wargraves fall under the custodianship of the Commonwealth War Graves Commission. These stones have the benefit of similar design and similar age, especially since the bulk of the stones represent soldiers who served to between 1940 and 1950. As such, they serve as a useful in-field control group, having all been placed in the cemetery within a short span of time.

For each cemetery, a modified field measurement technique was employed. The results obtained from Objectives 1 and 2 showed that the standard 54 kHz transducers were unsuited for this type of study and were, therefore, discarded entirely in favour of the rough surface transducers. Also, the number of measurements per tombstone was increased from 5 to between 25 and 50, depending on the size of the tombstone in question. A single operator (the author) carried out all assessments at each cemetery. As before, the direct transmission method was employed to take the measurements, with the only change being a marked increase in the number of readings per stone.

3.6.2. Statistical analytical techniques

As in Objective 2, average tombstone UPV was compared to tombstone age, but minimum tombstone age was also considered. This is because Objective 2 showed that weathering is heterogenous across most tombstones, and the minimum value measured across an entire tombstone is more likely to correlate to the point of maximum weathering. Both average tombstone UPV and minimum tombstone UPV were correlated against tombstone exposure time (referred to in this document as tombstone ‘age’ at the date of measurement), and linear regression analysis conducted. In addition to the linear regression study, basic spatial analysis was carried out for specific tombstones to assess the heterogeneity of generated UPV values for certain tombstones. This information, along with the linear regression was assessed within the context of the various regional climates to which each set of stones had been exposed.

Chapter 4: An assessment of experimental reproducibility for ultrasonic pulse velocity measurements under laboratory conditions

4.1. Introduction

Ultrasonic pulse velocity measurements are expected to generate small weathering signals that could be easily occluded by external variables like experimental error. It is, therefore, necessary to ensure that measurements on gabbro stones are repeatable. It is also important to identify ways experimental error could be introduced and to quantify the likely effects. This will allow for appropriate margins of error to be determined for data generated by the subsequent field experiments. Experiments were set up to test for three levels of reproducibility, as categorised by Church et al. (2020), which are repetition, replication and reproduction, which reflect experimental reproducibility with decreasing levels of rigour. Repetition, in the case of their experiment, refers to an assessment of the precision of data for an investigation carried out multiple times, but with the same operator, apparatus and experimental design. Replication refers to the generation of data using the same experimental techniques and equivalent equipment, but under different circumstances, such as the experiment being run with different operators. Finally, reproduction refers to the generation of data under different circumstances and conditions, but while exploring the same ultimate research question. In the case of *repetition* and *replication*, it is necessary for experimental results to be directly comparable across all experimental runs, within a reasonable margin of error. For an experimental *reproduction*, however, it was regarded as being sufficient for data to be comparable in terms of the general theoretical conclusions that could be drawn from them, even if they were not directly comparable.

An array of experiments were carried out under laboratory and field conditions to determine the effects of experimental configuration and experimental execution on the generated data, as well as the effects of different operators. This information was necessary groundwork for the field experiments carried out in this thesis, but also offered valuable insights into the replicability of experiments carried out in the Earth Sciences in general, particularly in studies that involve the measurement of weak signals that are carried out by more than one researcher.

4.2. Laboratory methodology

The apparatus used in this study is the Proceq PUNDIT PL-200 Ultrasonic Pulse Velocity device, which was originally developed for as a non-destructive method for determining the structural integrity of concrete (Figure 26).

Figure 26. PUNDIT PL-200 ultrasonic pulse velocity apparatus with attached rough surface transducers, pictured next to a gabbro sample stone, alongside detached 54kHz standard transducers

The device can take measurements with the transducers being placed in three different configurations, depending on the nature of what is being assessed. The direct transmission method involves placing the two transducers on opposite sides of the material that is being measured and transmitting a pulse directly between them (Figure 27a). The direct transmission nature of this technique makes it ideal for freestanding stones such as tombstones, and also yields the strongest signal for the receiving transducer to detect. The indirect and semi-direct transmission methods (Figure 27b and c) yield much lower signal returns and are typically used on buildings where the direct transmission method is not viable. Therefore, they will not be considered in this study. All ultrasonic pulse velocity measurements published in this document can be assumed to have been obtained by the direct transmission method.

When using the direct transmission method, the device measures the time it takes for a pulse to travel from the transmitting transducer to the receiving one. The operator inputs the distance between the two transducers and the device calculates the velocity of the pulse using the equation $v = \frac{s}{t}$, where s is the distance between the two transducers and t is the time taken for the pulse to move between them.

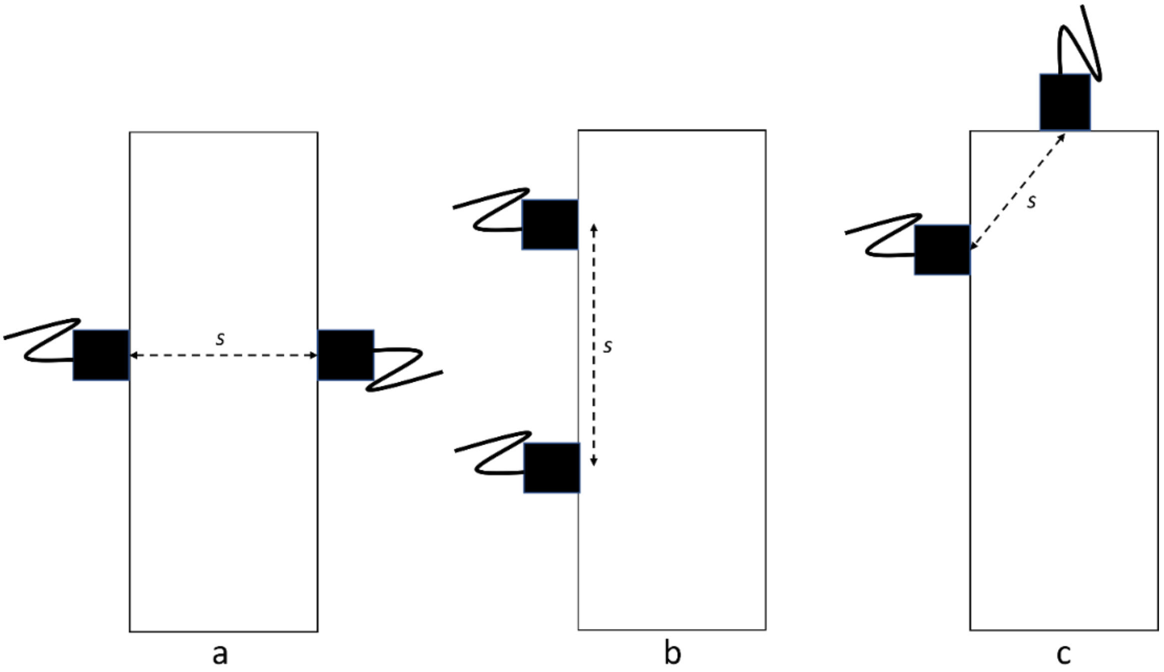


Figure 27. A side view schematic of the three different transducer placement methods: a. Direct transmission b. Indirect transmission c. Semi-direct transmission

The UPV apparatus was tested extensively under laboratory conditions to determine the limitations and boundaries of operation when used on natural stone; in this case, gabbro. This is necessary because the UPV equipment's use as a proxy for rock weathering lies outside of its design mandate. Specifically, the following needed to be tested to establish their effects on generated data:

- Transducer type
- Transducer placement
- Presence and absence of ultrasonic couplant
- Operator skill

The above elements were assessed under laboratory conditions using gabbro stones obtained from a quarry near Brits in the North-West Province of South Africa and is of the same stone type as the tombstones that were analysed in this thesis.

4.2.1. Transducer type

The device comes as standard with 54 kHz transceivers (Figure 28a), which are designed for use with fairly smooth building material and have a surface contact diameter of 49 mm. The device can also be purchased with an option 54 kHz Exponential transducer (Figure 28b), which has a surface contact diameter of 3.5mm and is specifically designed for rougher surfaces.

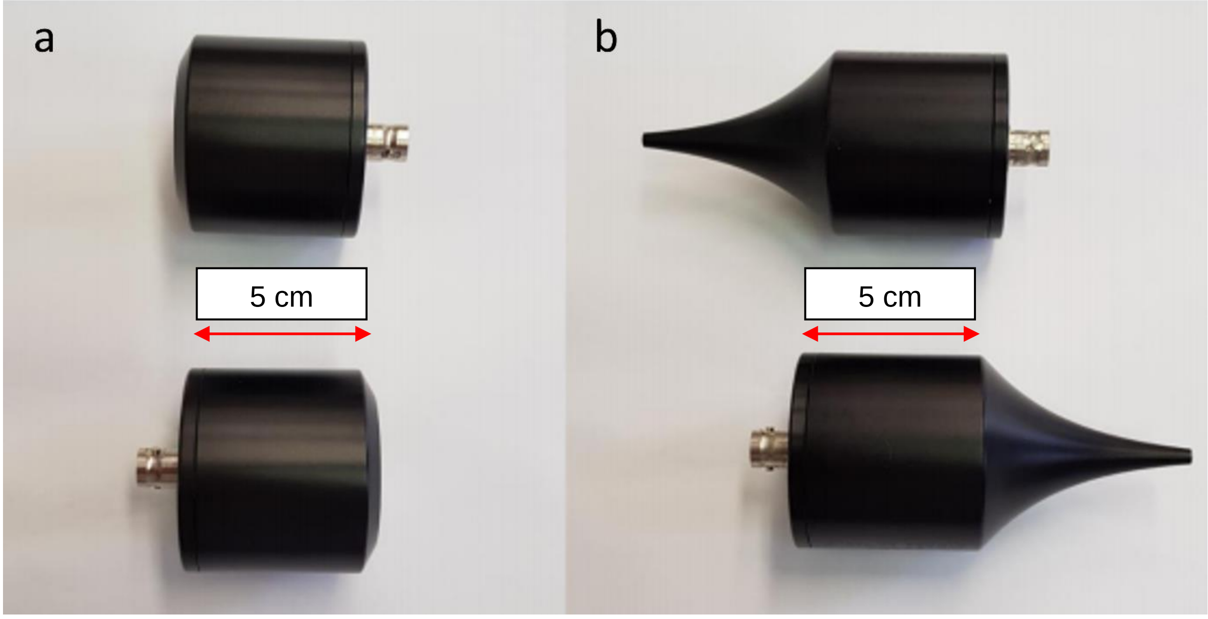


Figure 28. The two transducer types considered in this study. 2a Standard 54 kHz transducer. 2b. 54 kHz Exponential transducer

Since tombstones may vary in terms of their surface roughness, it was important to compare the results of the standard transducer to those of the exponential transducer to determine if data from the two different transducer types could be integrated into a single dataset. If this is possible, then the most appropriate transducer can be used for each sample tombstone, depending on its specific surface characteristics. However, if integration of the two sets is not possible, then a single transducer type would need to be selected for the entire study, even if this meant using a less optimal transducer for specific stones.

The gabbro used in this experiment was of consistent width, and considerably longer than it was wide. As a result, it was possible to take multiple direct transmission measurements across the entire length of the stone with a consistent distance of 49 mm between the transducers each time (Figure 29).

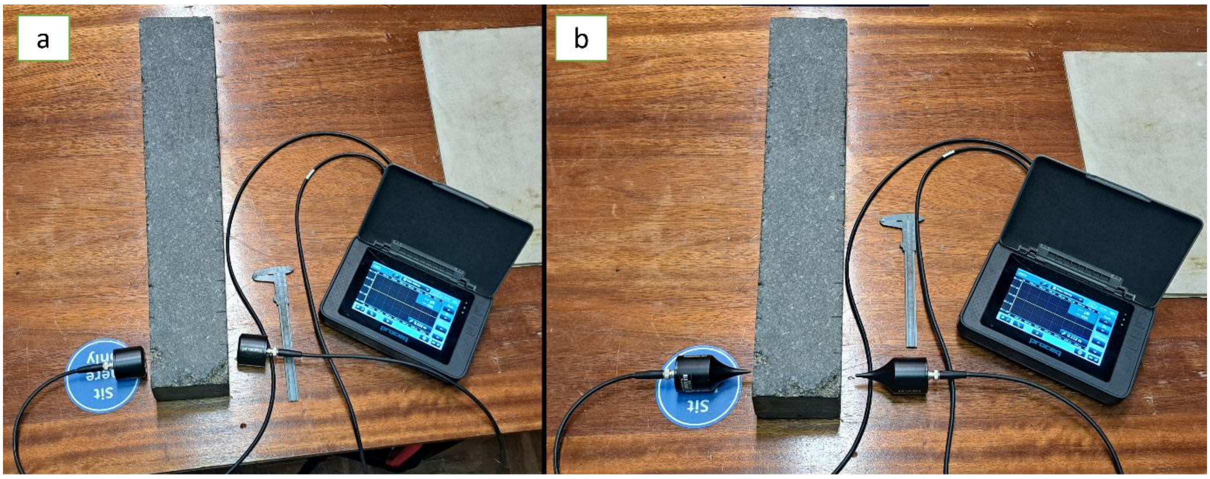


Figure 29. UPV repeatability experiment with calipers for scale. a) illustrates the standard transducers b) illustrates EXP transducers

Measurements were taken across the length of the gabbro sample in the manner shown in Figure 30. The experiment was carried out three times with the 54 kHz transducer set and then three times with the 54 kHz Exponential transducer set and the results compared to one another. The results were represented visually using a box and whisker plot and assessed for variance between experimental runs by means of a Kruskal-Wallis test. In the case of statistically significant differences, a post hoc Dunn test was carried out to determine which sets were responsible for the significant differences determined by the Kruskal-Wallis test.

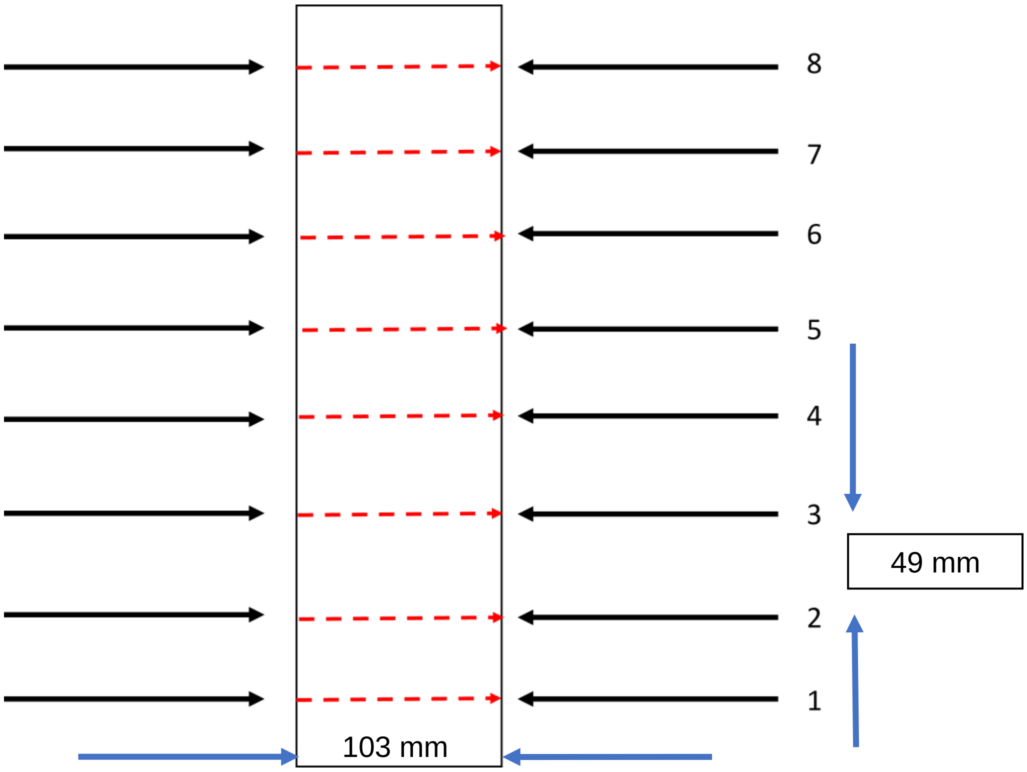


Figure 30. Top view of the experimental method for comparison of transducer types. 1st reading was taken at position 1 and the final reading at position 8

4.2.2. Transducer placement

Measurements taken in the field are often prone to errors that a generated due to less-than-ideal environmental conditions. Specifically, the transducers are designed to be placed directly opposite one another when making use of the direct transmission measurement technique, but this might not be possible when measuring stone that has naturally existing surface irregularities. It is, therefore, necessary to quantify the error that enters the data in the case that the transducers become misaligned when taken measurements in the field. Specifically, it is necessary to quantify the degree of acceptable transducer misalignment, and to ensure that the generated error is consistent when assessed as a function of the degree of misalignment. To assess this, a direct transmission experiment was set up under laboratory conditions and a transducer off-set experiment was carried out. To begin with, an offcut of gabbro was acquired, and an ultrasonic transducer set up in position 1 (Figure 31). The second transducer was placed directly opposite it in the standard configuration and a reading was taken. The transducer was then offset in increments of 49 mm (twice the radius of a standard 54kHz transducer for the PUNDIT PL-200). This was carried out for both the standard 54kHz transducer and the 54 kHz exponential transducer that has specifically been designed for use on rougher surfaces. Once the effects of the offset were determined, the experiment was carried out again with offsets of 10 mm to assess the effects of a smaller degree of error, more representative of the level of experimental error that a careful operator could expect under field conditions.

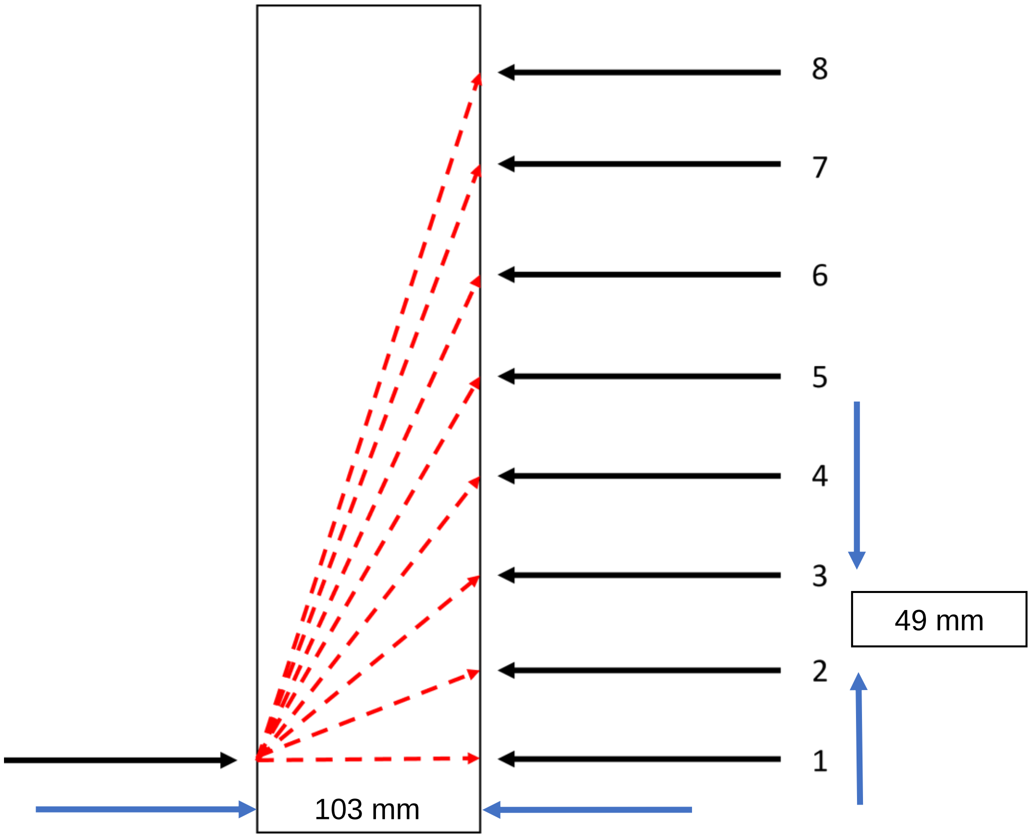


Figure 31. Top-down schematic of measurement method for quantification of effects of data due to transducer misalignment. Two transducers were initially aligned at point 1. One transducer then remained in place and the second transducer was moved from position 1 to 8

The distance between the two transducers was left at the setting provided by the operator for the first measurement, which is when the transducers are properly aligned. The change in measured pulse velocity can then be mapped as a function of transducer misalignment. This is to simulate a field scenario where the objects being measured are asymmetrical or three-dimensionally complex, which may create a scenario in which the transducers may not be aligned directly with one another.

Next, the true distance between the transducers was calculated using a Pythagorean calculation and used to recalculate the measured pulse velocity. This was then compared to the ideal velocity, which was measured when the transducers were correctly aligned. In this way, it was possible to confirm if the change in measured pulse velocity was purely because the misaligned transducers are now further away from one another, or if the misalignment itself contributed to the error. If the recalculated pulse velocity value is close to the control value, then the error is caused primarily by the fact that the distance that is input into the device by the operator is incorrect. If the mathematical correction is not close to the control value, then the transducer misalignment may be causing the ultrasonic pulses to move unpredictably through the gabbro medium. The difference between the actual values and the corrected values gives some insights into the intensity of this effect. If the effect cannot be reliably quantified to the point where it can be corrected for mathematically, it becomes necessary to make use of field samples that are as symmetrical as possible so that the transducers can be correctly aligned.

4.2.3. Presence and absence of ultrasonic couplant

Ultrasonic pulse measurement techniques normally require an ultrasonic couplant smeared on the transducers to ensure good contact with the surface of the sample. In the case of this study, however, tombstones are the primary source of data, and their status as culturally significant artefacts means that they cannot be damaged in any way. The use of ultrasonic couplant has been shown to stain the surface of rocks to which it has been applied and it is, therefore, necessary to take measurements in this case without it. It is thus necessary to quantify the increase in error and change in baseline measurements when ultrasonic couplant is not used.

4.2.4. Operator skill

Since it was anticipated that the weathering signal being sought in the ultimate field experiments was likely to be small, the need for precise, repeatable measurements was essential. To that end ten students from the University of Pretoria were enlisted to carry out the same version of the measurement technique described for the single operator. Following this, a single operator was trained in the use of the equipment, who then carried out the same experiment ten times in a row. The experiment was carried out with both the standard and exponential transducers, and with and without ultrasonic couplant. The range of measurements was then compared for the multiple operators who were not skilled in the use of the equipment, as well as for a single operator, skilled in the use of the equipment, carrying out the experiment multiple times. This part of the study was conducted during the Covid lockdown and the student could not access the university laboratory. To that end, the equipment and a gabbro sample was transported to the student's residence. The original gabbro sample was too heavy to be easily moved, so a smaller piece was used for this part of the study. However, it was sourced at the same quarry as the original and had a very similar overall shape and surface roughness. Since this part of the study is an investigation of the equipment more than the material, this was regarded as an acceptable substitution.

4.3. Effects of different transducer types on UPV results

Measurements were taken on a typical piece of gabbro stone from a quarry in Brits, a town in the North West Province of South Africa. The measurements were taken in the same manner as the initial aligned transducer tests (as in the schematic displayed in Figure 30), with both standard and exponential transducers. Each experimental run was carried out ten times, both without and with ultrasonic couplant. While it would not be possible to use the couplant on culturally important stone such as tombstones, it serves as an important point of comparison since the standard transducers are designed to be used in conjunction with couplant, and it is necessary to quantify the effects of not using it against an idealised baseline. For the sake of completeness and experimental symmetry, the experiment was carried out with the rough surface transducers as well, even though they do not require its use.

4.3.1. Results from experimental runs without ultrasonic couplant

The use of tombstones precludes the use of ultrasonic couplant in this study because there was a concern that application of the couplant could potentially damage them. Therefore, it was necessary to determine if precise, consistent results could be achieved without it. The experiment described above was, therefore, initially run without ultrasonic couplant with both standard and exponential transducers. In each case each experiment was run ten times consecutively. The data are presented as a box and whisker plot showing the results obtained across all ten experimental runs. Each graph for this section has a normalised y-axis, with a minimum value of 500 m/s and a maximum value of 5500 m/s, as all measured values for these sets fell within this range. The experiment was carried out in the manner presented in Figure 30, in which the transducers are aligned correctly with one another. The standard transducers produced the results shown in Figure 32.

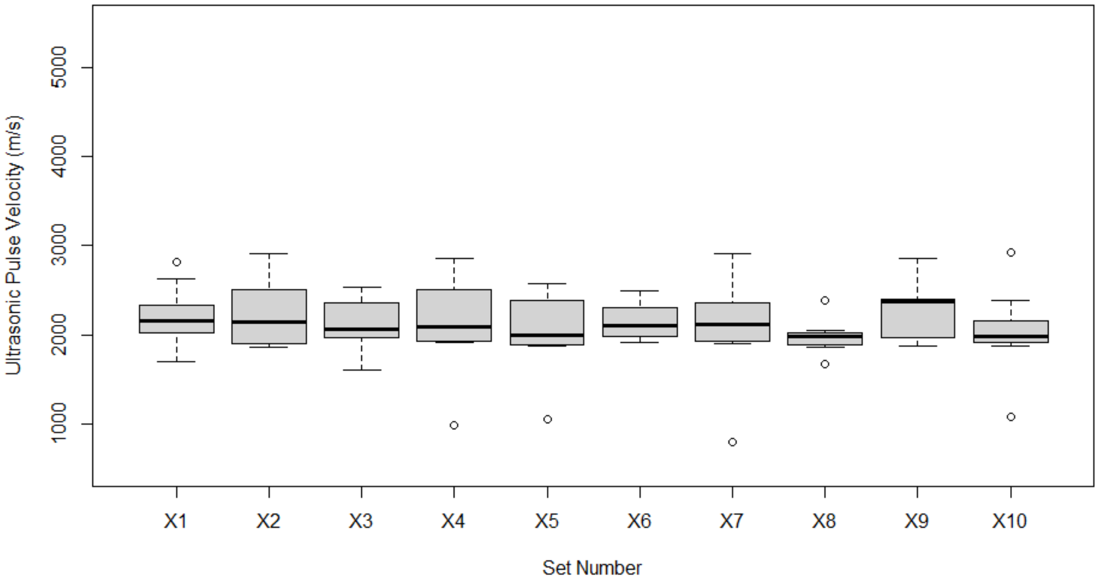


Figure 32. Ten experimental runs (X1 – X10) showing ultrasonic pulse velocity with standard transducers without ultrasonic couplant (n = 10 experimental measurements per run)

After running the experiment with the standard transducers, the investigation was repeated with the rough surface transducers, also without ultrasonic couplant. The experiment was carried out ten times in a row and the results are displayed in Figure 33.

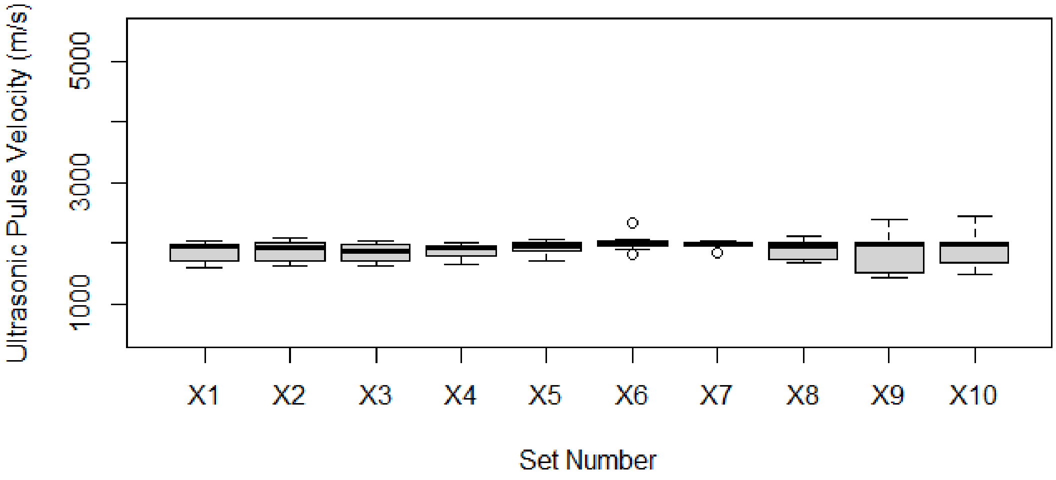


Figure 33. Ten experimental runs (X1 – X10) ultrasonic pulse velocity with exponential transducers without ultrasonic couplant (n = 10 experimental measurement per run)

The average pulse velocity over the entire set was 1991 ± 177 m/s. This value is 183 m/s higher than when couplant was used and lies just outside one standard deviation from the norm.

4.3.2. Results from experimental runs with ultrasonic couplant

The laboratory experiment was also run with an application of standard ultrasonic couplant as a control, representing the method of use that is most ideal for this piece of equipment (Figure 34).

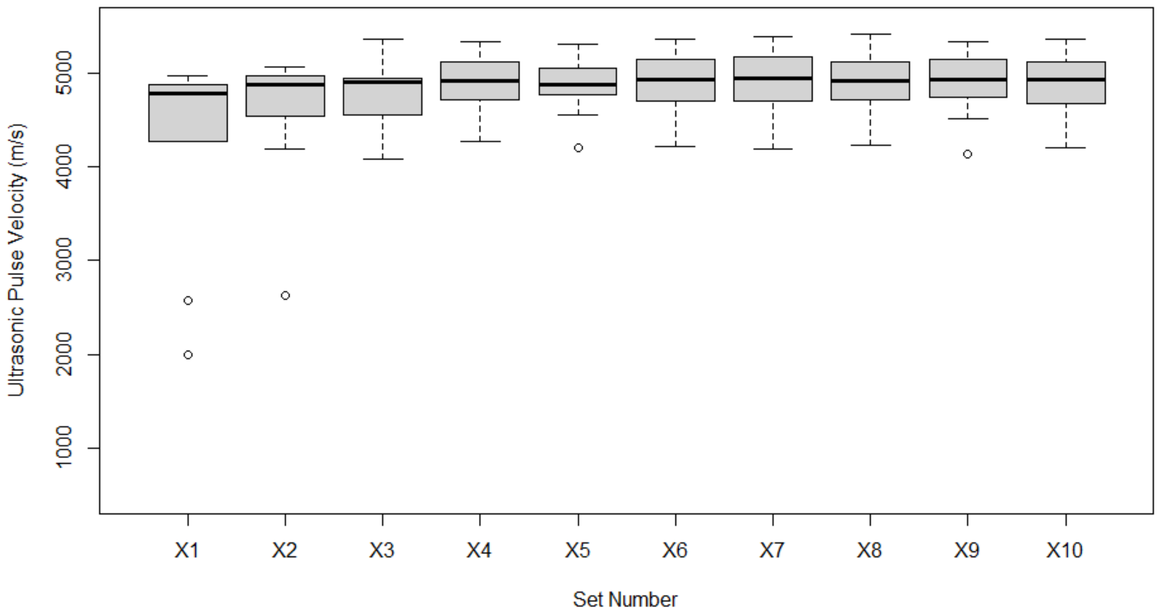


Figure 34. Ten experimental runs (X1 – X10) ultrasonic pulse velocity with standard transducers and ultrasonic couplant (n = 10 measurements per experimental run)

The total dataset produced an average pulse velocity value of 4788 ± 529 m/s over all ten experimental runs, 2673 m/s more than without ultrasonic couplant. The first two sets contain some outliers, but these anomalies do not appear in later sets, suggesting that operator skill improved with repeated use. However, the standard deviation is over 100 m/s more than the set without the couplant, showing that the results are more clustered in general without the ultrasonic couplant, although with more outliers in the dataset.

The experiment was repeated with the exponential transducers in exactly the same manner, again ten times in a row (Figure 35). The y-axis of this graph has been set to the same range as the graph in Figure 34 to allow for easy visual comparison.

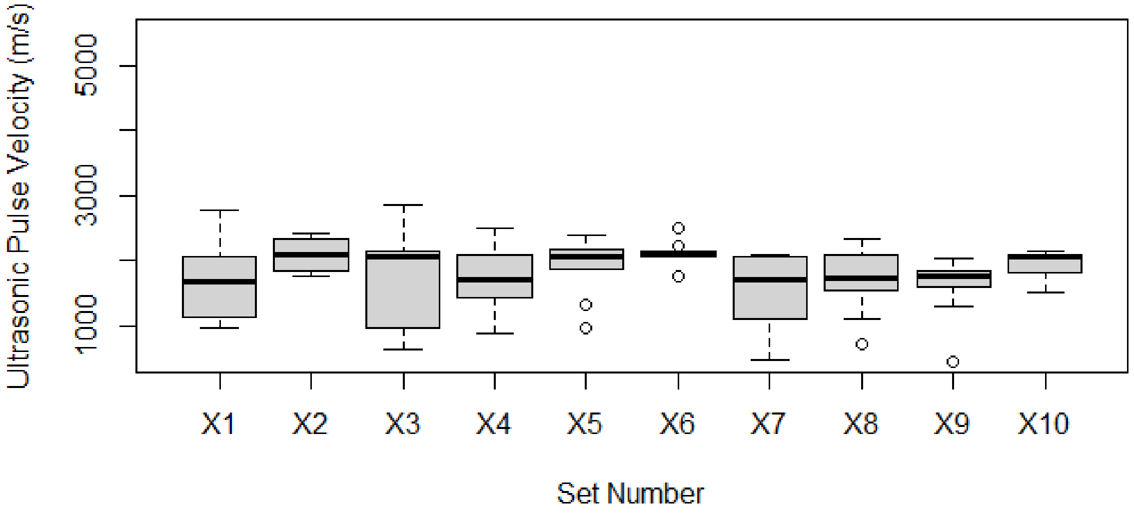


Figure 35. Ten experimental runs (X1 – X10) ultrasonic pulse velocity with exponential transducers and ultrasonic couplant (n = 10 experimental measurements per run)

The total dataset for the exponential transducers produced an average pulse velocity value of 1808 ± 492 m/s, which is 183 m/s higher than without the couplant. The standard deviation of the exponential transducer is less than that of the standard transducer, but comparable, which shows that, over the entire spectrum of the two datasets (n = 100 in both cases), both transducers produce results that have a similar variance around the mean. Under ideal conditions, therefore, both transducers are similarly precise. However, the average value for exponential transducers is 2980 m/s less than that of the standard transducer. This means that, even under ideal conditions, it is not possible to conflate results obtained from standard transducers with results obtained from the exponential transducers.

A Kruskal-Wallis test was carried out for each experimental run and the results are displayed in Table 2, along with a summary of all of the results to this point.

Transducers with Ultrasonic Couplant				
Statistics	**Standard**		**Exponential**	
Mean	4788 m/s		1808 m/s	
Standard Deviation	529 m/s		492 m/s	
Kruskal-Wallis	**X^2**	**p value**	**X^2**	**p value**
	7.4092	0.595	18.875*	0.026
Transducers without Couplant				
Statistics	**Standard**		**Exponential**	
Mean	2115 m/s		1991 m/s	
Standard Deviation	431 m/s		177 m/s	
Kruskal-Wallis	**X^2**	**p value**	**X^2**	**p value**
	5.8873	0.751	7.6643	0.5683

Table 2. Descriptive statistics and results of Kruskal-Wallis test for two types of transducer, both with and without ultrasonic couplant, with a single operator making repeat measurements

These datasets have 9 degrees of freedom, which translates to a χ^2_{crit} value of 16.919 for α = 0.05. Simply put, if $\chi^2 < \chi^2_{crit}$, then we accept the null hypothesis for this test, which is that all run data subsets (in this case, the number of experimental runs in each dataset) are part of the same statistical population. In the case of the above four datasets, only the exponential transducer experiment with ultrasonic couplant (marked with *) shows $\chi^2 > \chi^2_{crit}$ (18.875 > 16.919), meaning that one or more data subsets in that experiment are different from the others. The other three experimental runs all showed all runs in each experiment as being of the same statistical population, meaning that experiments in these configurations have a generally high degree of reproducibility.

4.4. Effects of transducer placement on UPV results

The transducer alignment experimental method is explained in Section 4.2.2. of this document, with one transducer being kept still and the second transducer being moved the equivalent of one standard transducer diameter (49mm) per reading. The experiment was carried out ten times in a row, with both standard and exponential transducers, and both with and without ultrasonic couplant. In each case, the distance between the two transducers (which must be manually input by the operator) was not reset. This was to simulate a field scenario in which the transducers were misaligned, but the field operator was not aware of this. These misaligned results were then corrected using a Pythagorean calculation (Figure

36) and graphed along the measured results and the ideal result, which is determined by the average of the ten measurements taken when the two transducers were perfectly aligned (i.e. the distance between them was *x* in Figure 36).

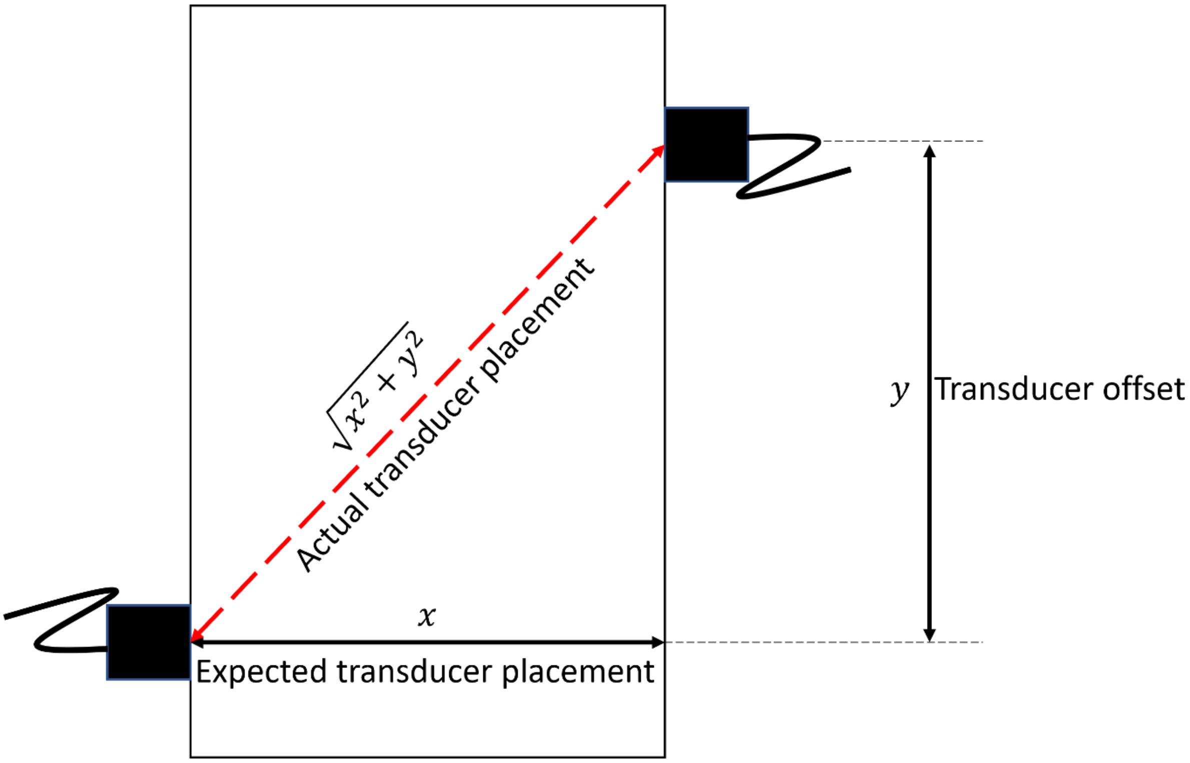


Figure 36. Schematic documenting the mathematical correction to generate the actual velocity of the ultrasonic pulse for an offset geometry

The results of the ten runs were grouped according to transducer location and then averaged, and the results expressed as a line graph. The ideal scenario, where the transducers were properly aligned, lies at position 1 on the *x*-axis, and become more misaligned as they move along the axis, with the transducers being in the greatest degree of misalignment at position ten. In position 2, the transducers are 49 mm out of alignment (hereafter referred to as 1 Unit). In position 10, the transducers were misaligned by 441 mm (9 Units).

4.4.1. Transducer misalignment with ultrasonic couplant

The results obtained from the experimental run with the standard transducer and ultrasonic couplant are show in Figure 37. As expected, the measured (uncorrected values), shown by the dashed lines, are lower than the ideal value, since the transducers are further apart from one another than the value that has been entered in the PUNDIT.

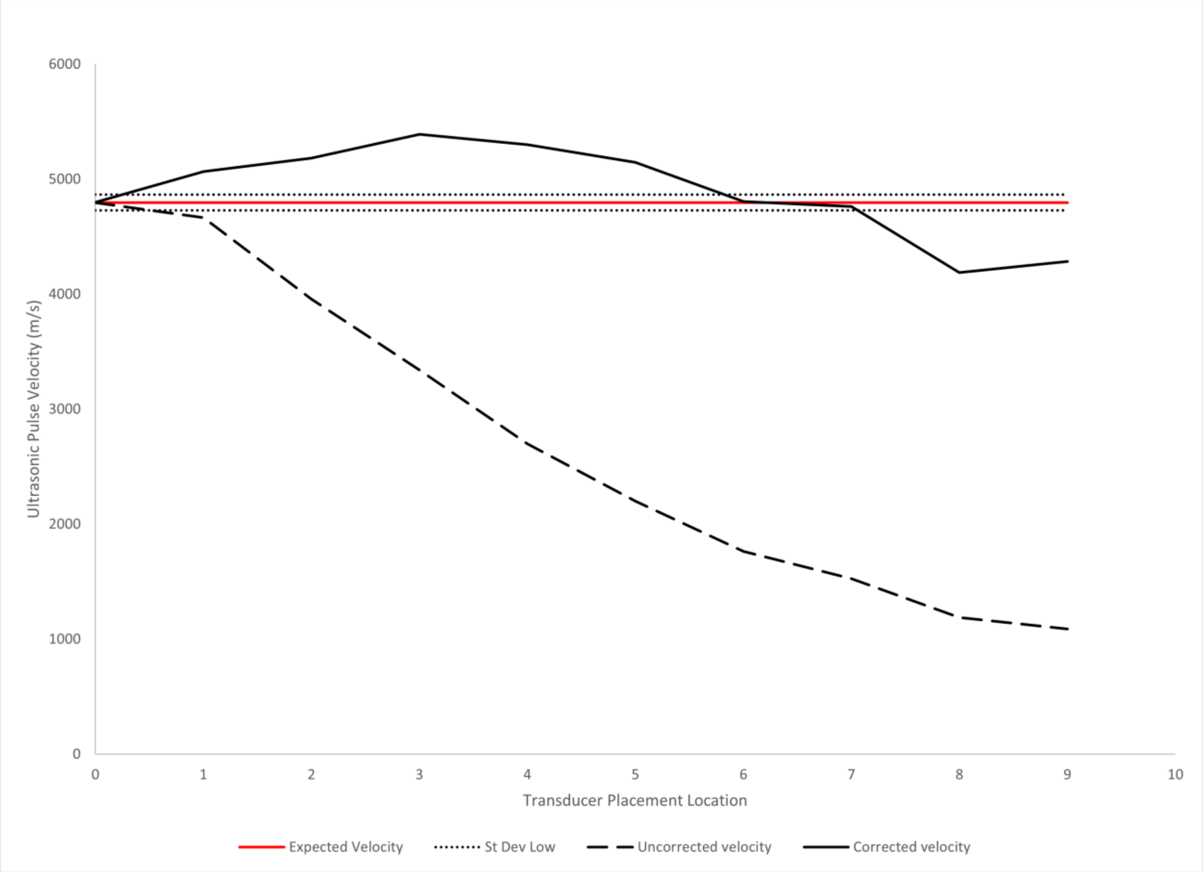


Figure 37. Line graph of ultrasonic pulse velocity for standard transducer with ultrasonic couplant which shows the uncorrected velocity (dashed line), corrected velocity (solid black line) and expected velocity (solid red line)

The applied mathematical correction does not bring the measurement back in line, but rather appears to over correct for transducer positions 2 to 7, and then under corrects for 9 and 10. When transducers are out of alignment by 1 Unit (49 mm), the measured results deviate from the expected value by 400 m/s, and after 2 Units by 840 m/s, with the discrepancies getting worse from there, with the worst result being 3707 m/s lower than the expected value (9 Units out of alignment). The corrected results are closer to the expected value, with a maximum deviation reduced to 609m/s.

Figure 38 shows the results of the same experiment, but for the exponential transducers. In this experiment, the error induced by the transducer misalignment results in values that are lower than the expected value, which is in line with what was anticipated. The uncorrected measurements range from 405m/s lower than expected when 1 Unit out of alignment to 1990 m/s lower at 9 Units out of alignment. The mathematical correction improves these values to 219 m/s and 908 m/s respectively. Even the corrected values for this set report results that are below expected, which suggests a degree of possible signal attenuation as the misalignment of the transducers becomes more pronounced. This will be discussed in more detail in section 4.6. of this chapter.

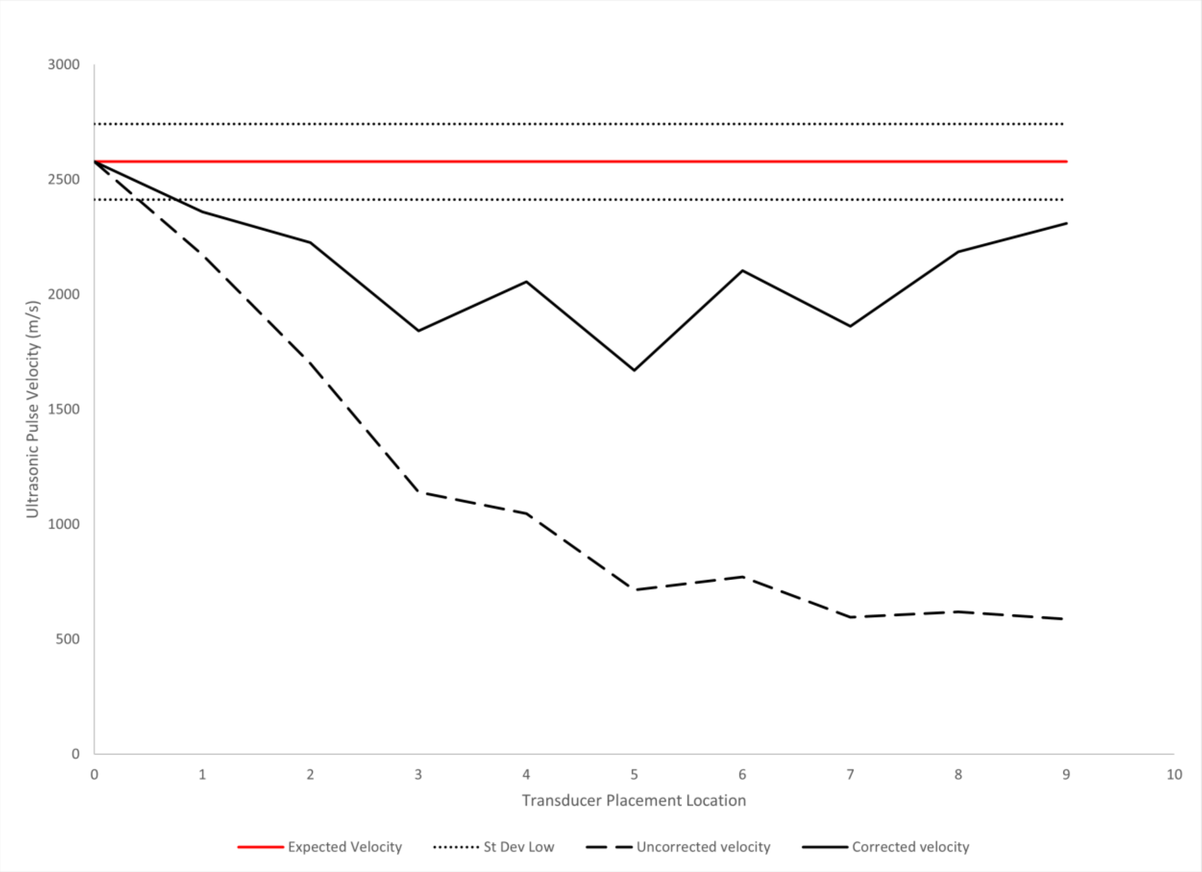


Figure 38. Line graph of ultrasonic pulse velocity for exponential transducer with ultrasonic couplant which shows the uncorrected velocity (dashed line), corrected velocity (solid black line) and expected velocity (solid red line)

4.4.2. Transducer misalignment without ultrasonic couplant

The transducer placement experiment was carried out without ultrasonic couplant in the same manner as the experiment with the couplant. Once again, it was carried out ten times and the results were represented using a line graph. The standard transducers without ultrasonic couplant yielded data that is displayed Figure 39. As in the case of the experiment that made use of ultrasonic couplant, the measured values were lower than the expected value and the mathematical correction yielded results that were improved as compared to the measured values, but still lower than the expected value. Specifically, the minimum deviation from the expected values were 320 m/s at 1 Unit of misalignment and 1944 m/s at 8 Units. The mathematical correction improves these values to 140 m/s and 760 m/s respectively, once again suggesting that some signal attenuation taking place as a result of the misalignment.

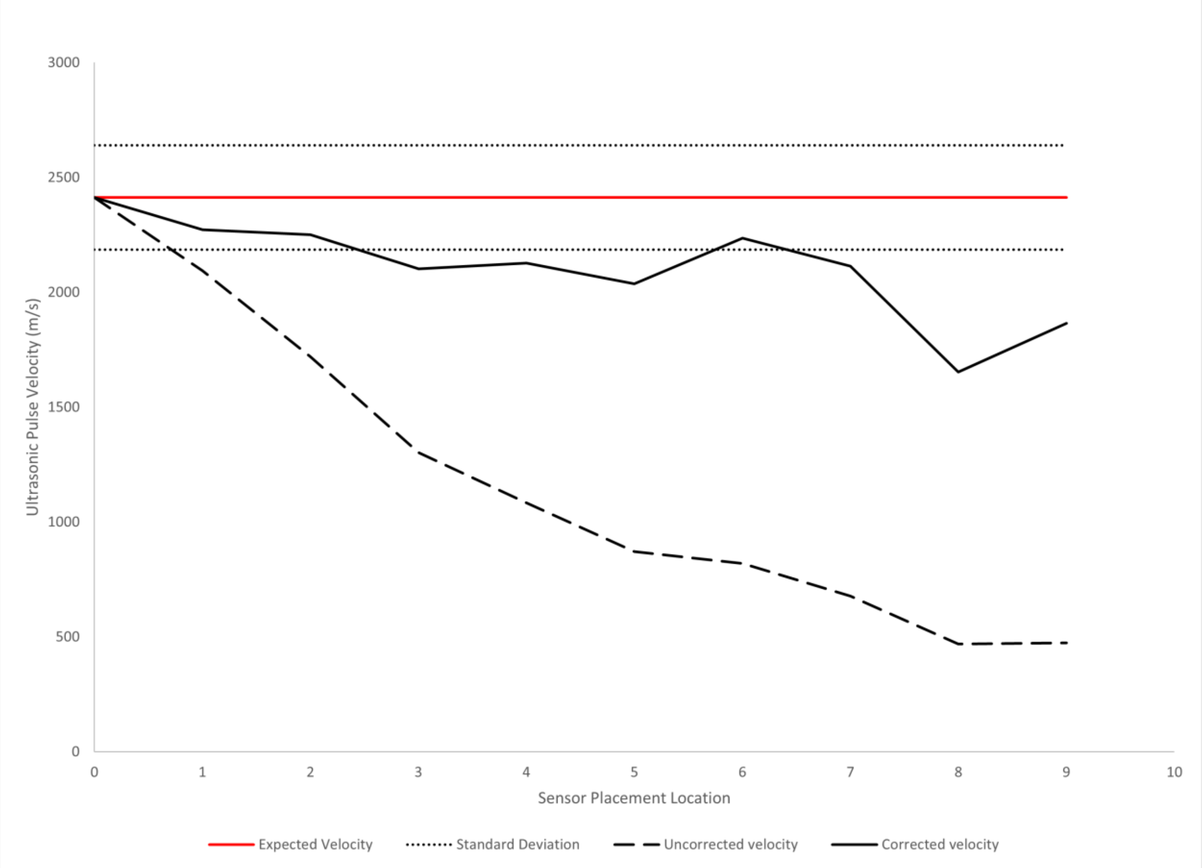


Figure 39. Line graph of ultrasonic pulse velocity for standard transducer without ultrasonic couplant which shows the uncorrected velocity (dashed line), corrected velocity (solid black line) and expected velocity (solid red line)

Figure 40 shows the results of the experiment run with the exponential transducers and without ultrasonic couplant. When the transducers are Unit 1 out of alignment, the measured results are 199 m/s less than expected, increasing to 561 m/s when the misalignment increases to 2 Units and 1551 m/s at 9 Units. The mathematical correction improves these results to 32 m/s, 68 m/s and 511 m/s. The exponential transducers without couplant experienced the least deviation from the expected values of all the datasets. The mathematical correction was also the most successful in normalising the measured values to the expected values. Additionally, these data do not display the under correction that occurred with all the other datasets, with the exception of standard transducer with ultrasonic couplant. This is unexpected for this dataset, but possible reasons for this will be presented in the Discussion section of this document.

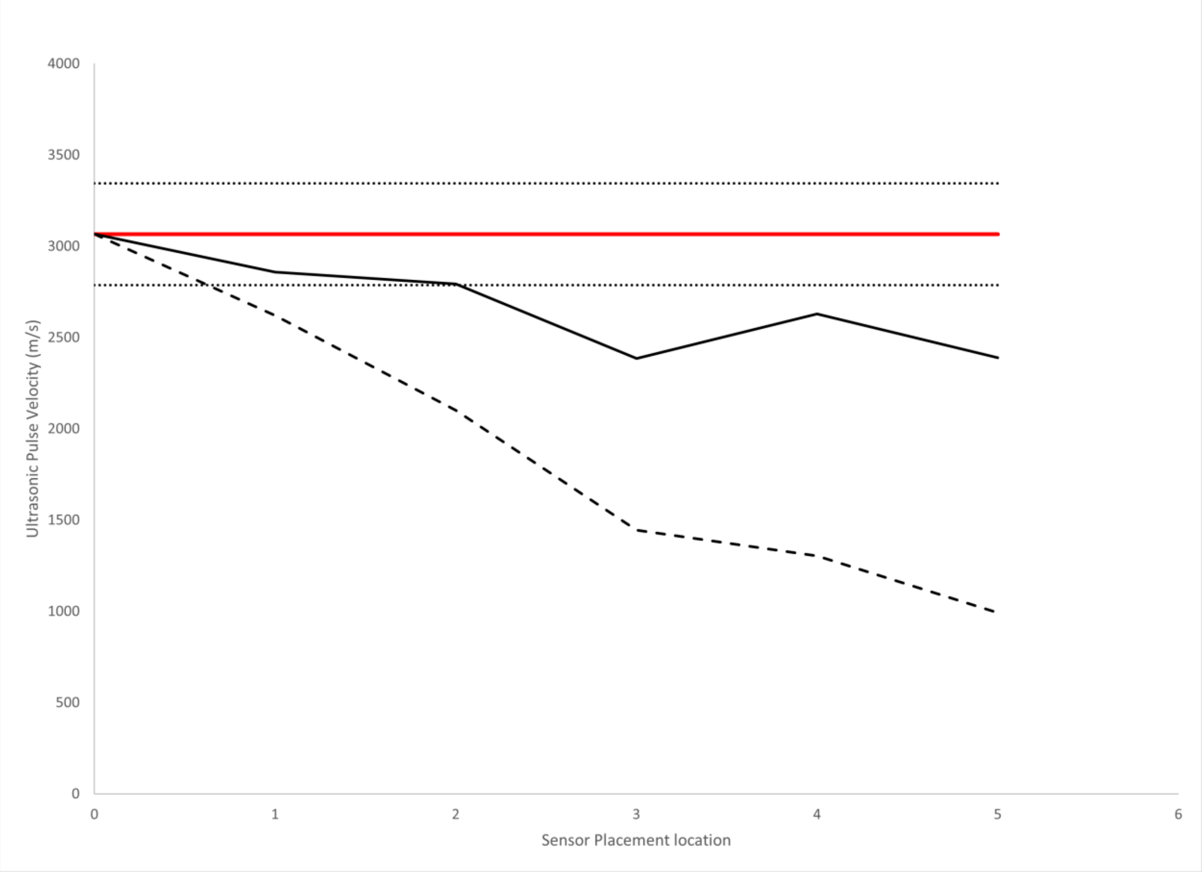


Figure 40. Line graph of ultrasonic pulse velocity for exponential transducer without ultrasonic couplant which shows the uncorrected velocity (dashed line), corrected velocity (solid black line) and expected velocity (solid red line)

4.4.3. High-resolution spatial study

After establishing the effects of transducer misalignment on a decimeter scale, the experiment was carried out again on a smaller scale to determine what the likely error would be under field conditions when the equipment was used by an experienced operator (Figure

41). The exponential transducers were offset by 10 mm for each measurement up to a maximum misalignment of 90 mm. The experiment was carried out ten times and the results averaged. The results show that the error that occurs due to transducer misalignment introduces a consistent, repeatable reduction in UPV of 10 m/s per millimeter of misalignment over a homogenous unweathered sample.

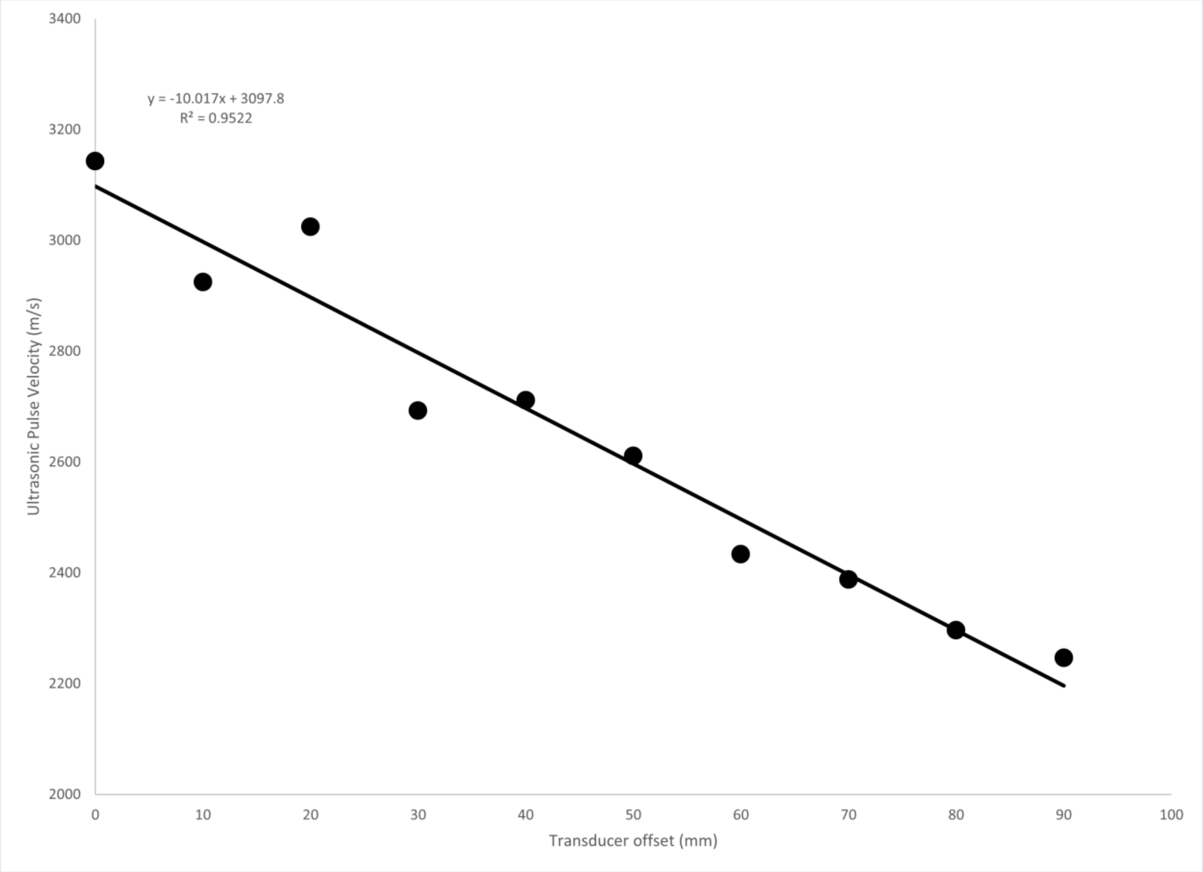


Figure 41. Scatter plot and linear regression showing reduction of measured pulse velocity as a function of transducer misalignment

4.5. Effects of operator skill on UPV results

Regional weathering studies will most likely involve the use of multiple personnel that are not in direct communication with one another. In addition, equipment like the PUNDIT PL-200 is highly sensitive and may be prone to interference by external factors. It is, therefore, important to quantify the precision of the apparatus by assessing the repeatability of measurements taken with the device under different conditions. An initial study was conducted under laboratory conditions with ten different operators in order to quantify operator bias under ideal conditions. Ten different experimental runs were then carried out by the same operator to quantify experimental repeatability. Finally, three operators trialed the time series analytical procedure in the field at Cullinan Main Cemetery in Pretoria to assess the effects of operator bias under conditions that were not ideal, but closely resembled the experimental methodology of the eventual cemetery study. For this experiment, the primary researcher (Operator A) personally instructed the second and third operators in the use of the experimental apparatus.

4.5.1. Laboratory study with multiple operators

Ten operators were given instructions at a level of detail similar to what would have been provided in a peer-reviewed academic article and were then permitted to carry out the experiment under observation, but while receiving relatively minimal supervision. The operators were asked to take eight measurements on a cut piece of gabbro stone with both the standard and exponential transducers. Each operator completed the experiment with each transducer twice, once with ultrasonic couplant and once without it. Finally, a single operator skilled in the use of the apparatus completed the experiment ten times with the standard and exponential transducer, both with and without ultrasonic couplant.

4.5.1.1. Multiple operators with standard transducers

The use of a standard transducer with normal ultrasonic couplant provides repeatable results (Figure 42). This was expected, since this setup represents the simplest use of the equipment under the most ideal of conditions.

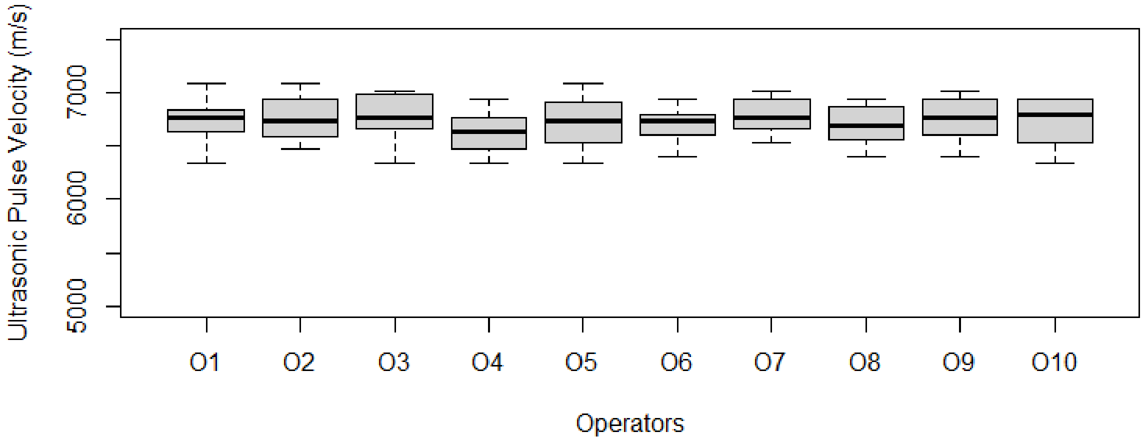


Figure 42. Operator variance across ten different operators with standard transducers and ultrasonic couplant

The omission of ultrasonic couplant immediately introduces a degree of variance into the system that is not present in the case of ultrasonic couplant (Figure 43). As an example, there is almost no overlap between the results obtained by Operator 3 and the results obtained by Operators 9 and 10. Operators 2 and 5 have unusually large data ranges when compared to the others, which was most likely caused by the transducer not being seated against the stone correctly, which is something that the use of couplant would have helped to mitigate.

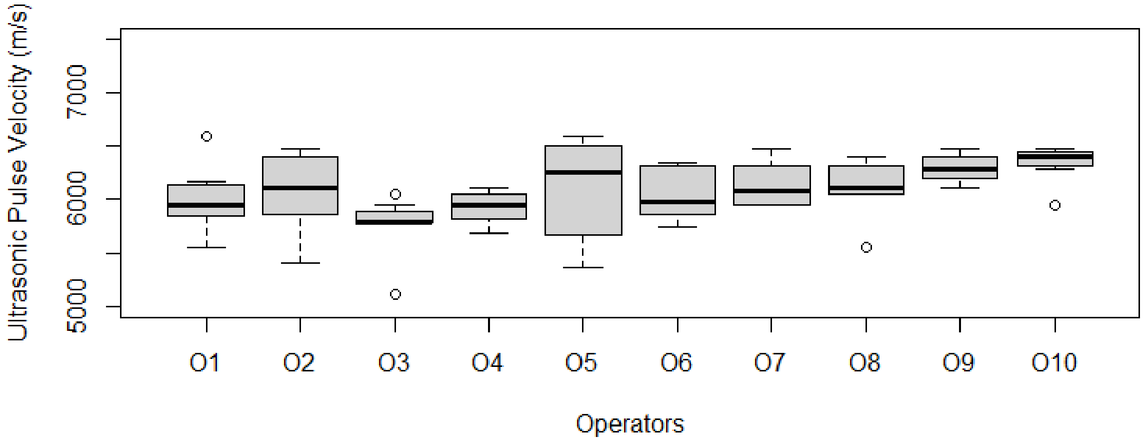


Figure 43. Operator variance across ten different operators with standard transducers and without ultrasonic couplant

4.5.2.1. Multiple Operators with exponential transducers

The rough surface transducers are more varied than in the case of the standard transducers, which is to be expected (Figure 44). The apparatus utilises a much smaller surface area than the standard set for contact with the rock surface, which adds an element of complexity to its use.

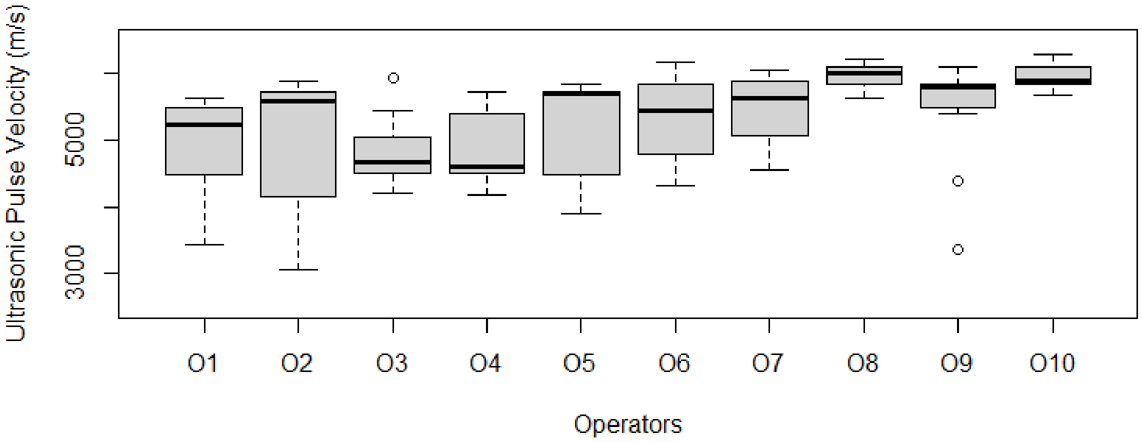


Figure 44. Operator variance across ten different operators with exponential transducers and ultrasonic couplant

Omitting the use of couplant does not lead to the same erratic variance as in the case of the standard transducers (Figure 45). This is unanticipated, since in the case of the standard transducers, the variance was more pronounced in the experimental sets that did not use ultrasonic couplant.

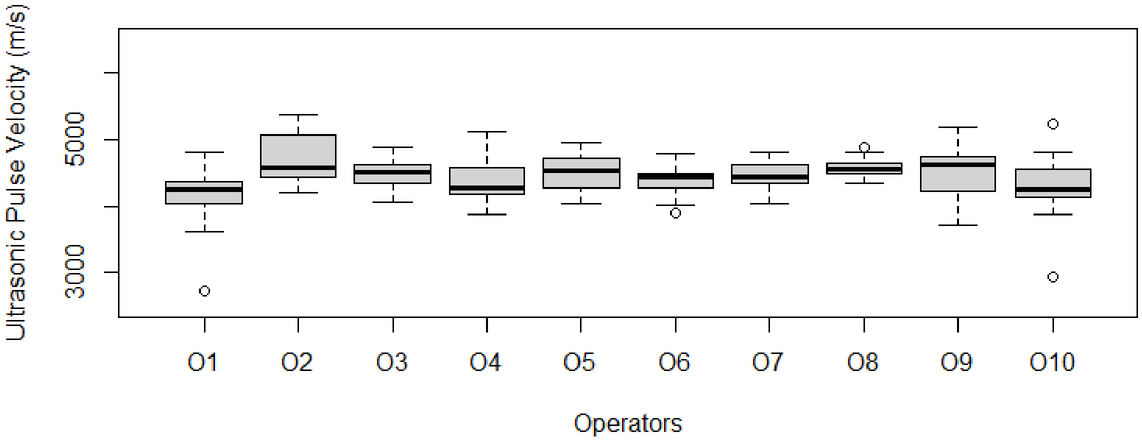


Figure 45. Operator variance across ten different operators with exponential transducers and without ultrasonic couplant

The descriptive statistics and results of a Kruskal-Wallis test for the Multiple Operator assessment are displayed in Table 3. As before, the χ^2_{crit} value for this dataset is 16.919. Only the standard transducers with ultrasonic couplant were able to yield consistent experimental results for all operators, with all other transducer/couplant combinations having one or more operators whose results did not align with the others.

Transducers with Ultrasonic Couplant				
Statistics	**Standard**		**Exponential**	
Mean	6733 m/s		5338 m/s	
Standard Deviation	213 m/s		544 m/s	
Kruskal-Wallis	**X^2**	**p value**	**X^2**	**p value**
	3.8692	0.920	78.31*	<0.001
Transducers without Couplant				
Statistics	**Standard**		**Exponential**	
Mean	6082 m/s		4447 m/s	
Standard Deviation	261 m/s		309 m/s	
Kruskal-Wallis	**X^2**	**p value**	**X^2**	**p value**
	23.846*	0.0046	28.987*	<0.001

Table 3. Descriptive statistics and results of Kruskal-Wallis test for two types of transducer, both with and without ultrasonic couplant, with ten different operators making the measurements

4.5.2. Laboratory study with a single operator

As a final test, the single operator test was carried out again, but this time with a different operator than before.

4.5.2.2. Standard transducers

A single operator with normal ultrasonic couplant is capable of generating consistent, repeatable data under ideal circumstances with a standard 54 kHz transducer set (Figure 46).

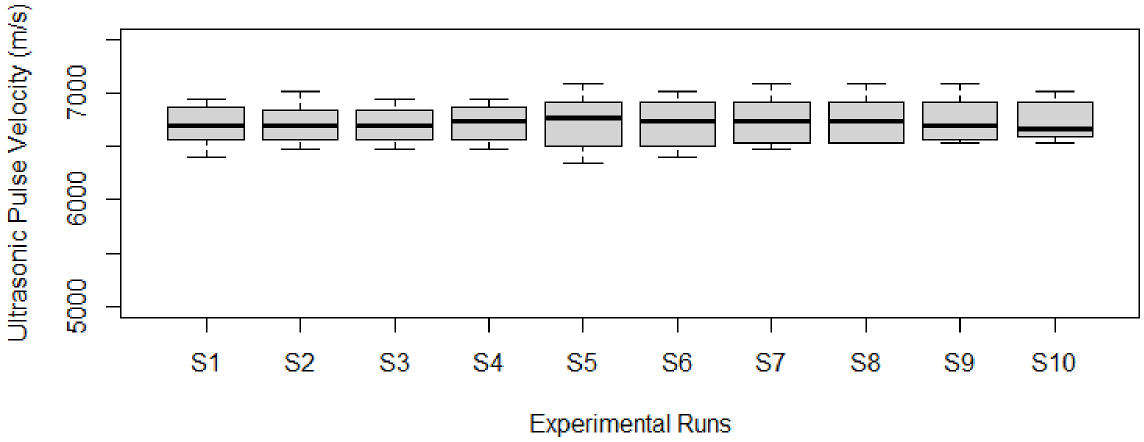


Figure 46. Single Operator with standard transducer and ultrasonic couplant across ten experimental runs

A single operator can produce repeatable results with the standard transducer, even without the use of couplant (Figure 47). The results are more varied than when couplant is used and there are more outliers, but the data ranges overlap well, which indicates that operator bias can be limited by making use of a single, well-trained operator, rather than ten different people.

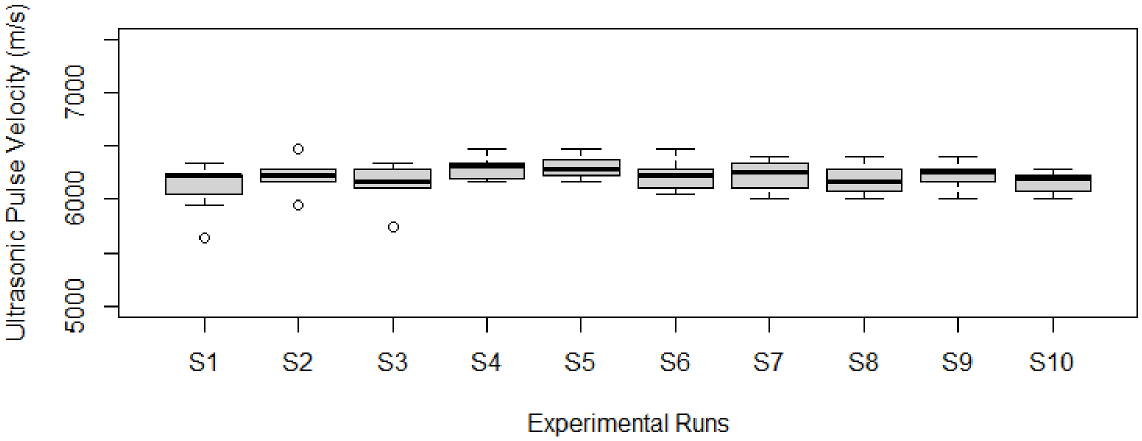


Figure 47. Single Operator with standard transducer and without couplant across ten experimental runs

Rough surface transducers do not yield results that are compatible with standard transducers. Due to their shape, they are also likely to be more prone to operator bias than the standard ones. It is important that the potential for this bias be well quantified for regional experiments where multiple operators will be involved.

4.5.2.3. Exponential transducers

The variance for a single operator with ultrasonic couplant is low with the exponential transducer (Figure 48), which suggests that a skilled operator would be able to carry out experiments repeatedly with precision. There are also no outliers in runs S6 to S10, which suggests that an operator's skill with the apparatus will increase with each subsequent run.

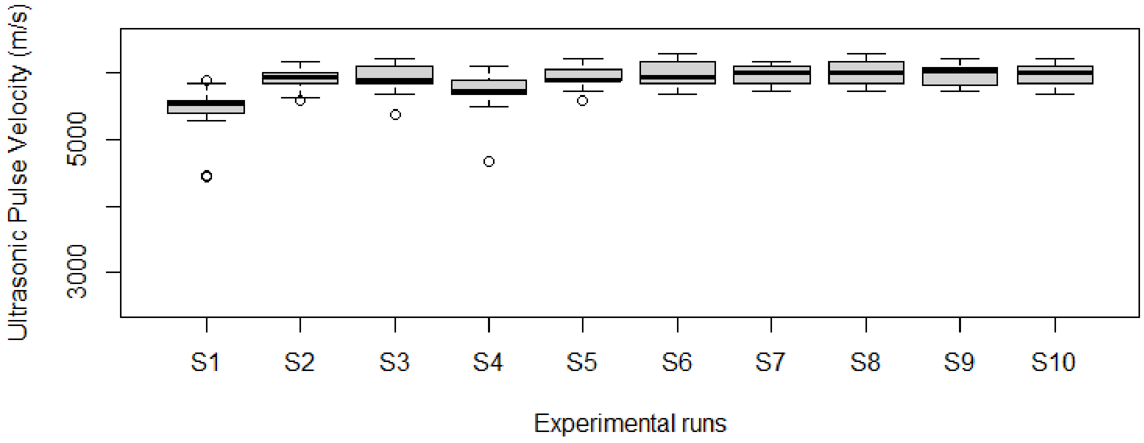


Figure 48. Single Operator with exponential transducer and standard couplant across ten experimental runs

A single operator conducting the same experiment without ultrasonic couplant shows greater variance than when using the couplant (Figure 49), but results are still consistent for eight out of ten runs (the two exceptions being runs 7 and 8).

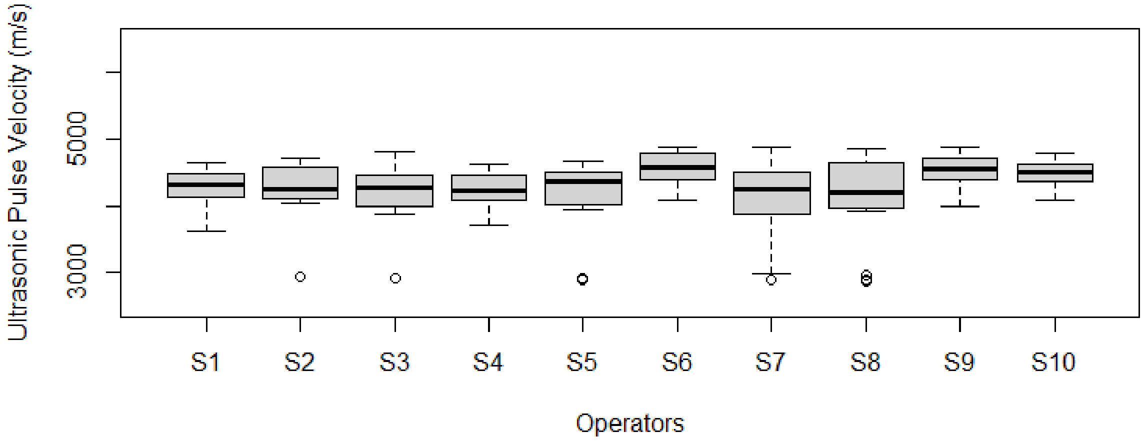


Figure 49. Single Operator with exponential transducer and without standard couplant across ten experimental runs

The descriptive statistics for the second single operator are displayed in Table 4, along with the results of a Kruskal-Wallis test. The χ^2_{crit} value for this dataset is 16.919. In this case, the χ^2 value for both standard transducer setups are less than 16.919, indicating good repeatability across the ten experimental runs. However, both subsets that made use of the exponential transducers have one or more subsets that differ from the others.

Transducers with Ultrasonic Couplant				
Statistics	**Standard**		**Exponential**	
Mean	6727 m/s		5892 m/s	
Standard Deviation	205 m/s		217 m/s	
Kruskal-Wallis	**X^2**	**p value**	**X^2**	**p value**
	0.4448	1	42.964	<0.001
Transducers without Couplant				
Statistics	**Standard**		**Exponential**	
Mean	6212 m/s		4297 m/s	
Standard Deviation	142 m/s		391 m/s	
Kruskal-Wallis	**X^2**	**p value**	**X^2**	**p value**
	10.517	0.3102	25.808	0.002

Table 4. Descriptive statistics and results of Kruskal-Wallis test for two types of transducer, both with and without ultrasonic couplant, with a single operator making repeat measurements

4.6. Discussion

The PUNDIT PL-200 was tested extensively under laboratory conditions to assess its functionality when deployed outside of its design mandate. Two different types of transducer were tested, both with and without ultrasonic couplant. Also, the effects of transducer misalignment were quantified for all of the above transducer and couplant combinations and checked against a mathematical correction and ideal values for the experiment. Finally, the effects of operator skill were quantified by comparing the results acquired by multiple operators carrying out the experiment once against a single experienced operator carrying out the experiment multiple times. The data show that concerns about the effects of operator skill and experimental design are valid, but can be controlled. Key findings can be summed up as follows:

- Results obtained from different transducer types are not directly comparable and cannot be analysed as part of a common dataset.

- Ultrasonic couplant improves the precision of results in experimental runs that made use of the standard ultrasonic transducers, but reduced precision for the exponential transducers.
- Errors that are derived from transducer misalignment are predictable for up to 10 cm of transducer displacement, but become increasingly unpredictable as misalignment becomes more pronounced.
- Repeated experiments by a single skilled operator showed that data was consistent for all scenarios except when the ultrasonic couplant was used in conjunction with the exponential transducers.
- Repeated experiments by single operator with a lower level of skill only generated directly comparable datasets for the standard transducers, while there were statistically significant differences between some of the datasets produced by the exponential transducers.
- Replicated experiments by multiple operators are comparable with using the standard transducers with ultrasonic couplant.
- Replicated experiments by multiple operators produced comparable results only when the standard transducers were used with ultrasonic couplant.

The comparison of the two transducers shows that, when ultrasonic couplant was used, the standard and exponential transducers produced very different datasets, meaning that results from the standard set cannot be conflated with results from the exponential set. However, in the case of the study when ultrasonic couplant was not used, the results from the standard transducers are much closer to those of the exponential transducers. Nevertheless, the results obtained from the experiment involving the ultrasonic couplant show that there are definitely factors that can cause the results obtained from the two transducer types to vary widely from one another. The typical variance found in any normal field environment would suggest that it is safer to adopt a single transducer type for any given field operation, rather than selecting different transducers for different samples as deemed appropriate under field conditions. This has likely occurred due to the difficulties of coating the exponential transducers' contact evenly due to its small size (the contact surface of the exponential transducers has a diameter of only 3.5 mm, as compared to 49 mm for the standard transducers). Varying thicknesses of ultrasonic couplant may affect the pulse velocity value that is returned. This variable is not present in the experiment where ultrasonic couplant was not applied, which will contributed to the more stable results found in that dataset. In the case of the exponential transducers, a skilled operator can compensate for the lack of ultrasonic couplant with careful seating of the transducer against the sample for each measurement. These data show that the exponential transducer is the preferred sensor for natural stone and that precise repeatable results can still be acquired without ultrasonic couplant, as long as the operator is skilled and careful.

The difficulty of assessing natural stone under field conditions means that a degree of experimental error is expected, and it is, therefore, necessary to quantify the degree to which this will occur. The most likely culprit for experimental error lies in the incorrect placement of the transducers when measuring samples with inconvenient physical dimensions. The transducer misalignment experiment documented in section 4.4 was designed to quantify the level of expected experimental error derived from inadvertent, but incorrect transducer placement. The experiment was carried out for the same combinations of transducer setup and couplant application as before.

Therefore, if two transducers placed under field conditions are misaligned by less than 10 cm, the expected measurement error for gabbro stone will be less than 600 m/s (assuming an additional 10% margin for error). When taking field measurements, it is, therefore, not advisable to consider differences in measured pulse velocities of less than 600 m/s as being meaningful. Differences greater than 600 m/s as measured on the same tombstone can thus be considered to represent a genuine difference in the physical properties of a specific tombstone, assuming that all measurements come from sensor placements that are misaligned by 10 cm or less.

Since future applications of this method may need to consider the use of multiple field operators, it is necessary to quantify the effects that multiple operators may have on the datasets. The results of a Kruskal-Wallis test show that only the standard transducer setup with standard ultrasonic couplant allowed all ten operators to produce comparable results. In all other experimental test runs, one or more of the measured data subsets differed from the others. The exponential transducers with ultrasonic couplant performed particularly poorly, with a post-hoc statistical analysis (Dunn test with Bonferroni correction) showing that multiple subsets failed to pair with any of the others.

These data show that using multiple operators can have a potentially detrimental effect on the measured data and will increase the degree of error into the dataset that would otherwise not be present.

The introduction of multiple operators introduces an undesirable level of error into the dataset, but the intended application of this apparatus on a regional scale may necessitate the use of additional personnel. To that end, a second trained operator conducted experiments on a sample with both standard and exponential transducers. For clarity, Operator 1 is the author of this thesis and Operator 2 was a junior postgraduate student trained in the use of the apparatus. The chief difference between the two operators was, therefore, the level of experience that each had with the equipment.

Operator 2 achieved consistent measurements over ten experimental runs for the standard couplant, both with and without ultrasonic couplant. However, in the case of the exponential transducers, the results of a Kruskal-Wallis test showed that one or more data subsets differed from the others in both cases. A post hoc test (Dunn test with applied Bonferroni correction) on the dataset involving exponential transducers without couplant showed that only a single pairing (Data Subsets S4 and S6) failed to correlate to one another. This is attributable to experimental error and is relatively minor when compared to the errors present in the case of multiple operators. The increase in error when compared to the results obtained by Operator 1 is as a result of differences in skill level in terms of operating the ultrasonic equipment. Operator 1 took the experimental measurements present in this document after years of work with the apparatus under both field and laboratory conditions. Operator 2, while carefully trained, had only a few months of experience. However, Operator 2 still produced better, more repeatable results than Multiple Operators did, and therefore, it may be possible to employ additional personnel to aid in contributing to experiments of this nature. However, it must be noted that the degree of error present in the ultimate dataset will be directly proportional to the number of operators participating, and inversely proportional to the relative skill level of the operators. More operators will mean more error, and less skilled operators will also mean more error. Ultimately, the ideal scenario is for a single, skilled operator to conduct all measurements in the study. However, should this not be possible, it is viable to have a small number of well-trained personnel contribute to the greater dataset without excessively compromising it. There are not many articles that discuss the effects of operator bias in the Earth Sciences, but one example is that of Daniels and McCusker (2010), who assessed the potential effects of operator bias in a stream substrate categorisation technique. This article, along with a subsequent rebuttal by Bunte et al. (2011) represents one of relatively few discussions on this topic. The experiment carried out in this thesis have similarities to that discussed by Daniels and McCusker (2010) and Bunte et al. (2011) in that experimental repeatability was assessed in both cases, but the stream substrate method does rely on operator expertise to make appropriate stream substrate selections when sampling, the effects of which were at the core of their study. In the case of this thesis, the experimental techniques rely less on the judgement of the operator in question. In spite of the above, experiments that made use of multiple operators did not yield comparable results. This outcome suggests that operator skill and experience, along with basic differences in experimental approach, can lead to statistically significant differences in experimental results, even with consistent experimental protocols. These data align with the wider narrative explored by Baker (2016), who also suggested a lack of scientific replicability in science as a whole.

The experiments carried out in this chapter have shown that, without proper care, experimental reproducibility is not guaranteed for UPV experiments involving gabbro stone. There is also a more general point to be made about the general reproducibility of experimental measurements in the field sciences. Church et al. (2020) argued that there is a greater need for studies in geomorphology that emphasis experimental repeatability and reproducibility. The experiments carried out in this chapter support Church et al's assertion, since data replicability was affected by various equipment and operator related factors.

4.7 Conclusion

The results of the laboratory experiments have shown that, when carrying out field experiments with ultrasonic pulse velocity equipment, experimental error can be minimised by ensuring that field measurement protocols comply with the following strictures:

- Use only one type of ultrasonic transducer
- Experimenters should use exponential (rough surface) transducers when studying culturally important stone because they do not require the use of ultrasonic couplant
- In cases where multiple operators are required, the standard broad-headed transducers used in conjunction with ultrasonic couplant will provide the best results.
- The exponential transducer is more susceptible to operator error than the standard transducer and experiments that use this apparatus with multiple operators are likely to have a high degree of experimental error. Field experiments that make use of this experimental setup should, therefore, constrain themselves to the use of a single, skilled operator whenever possible.
- If the exponential transducer must be used with multiple operators, then as few operators as possible should be deployed, and they should be as experienced as possible.

While these laboratory experiments offered important insights into the experimental design for using UPV apparatus on natural, culturally important stone, operator bias was also checked in the field. These data are documented in Chapter 5.

Chapter 5: Cemeteries as time series laboratories

Once the limitations and delimitations of the equipment had been established under laboratory conditions, the concept needed to be tested in the field. Specifically, the key assumption in this experimental technique is that, as a tombstone weathers *in situ* in a cemetery, its physical degradation over time will correlate to measured ultrasonic pulse velocity (UPV). To test this assertion, 34 tombstones were measured using the PUNDIT PL-200 and the average UPV for each tombstone compared to the time that the tombstone had been in the cemetery, as derived from the inscribed date of death.

(Sections 5.1 to 5.5 of this document were published in the South African Geographical Journal in 2022 and have reproduced verbatim here. Sections 5.6. onwards documents an extension of the original study that was conducted to refine the final high resolution measurement technique that was deployed in Chapter 6)

5.1. Introduction

Rock weathering is a fundamental element of geomorphology, alongside erosion and deposition (Turkington & Paradise, 2005), but there are considerable gaps in our understanding, due in large part to fact that it is notoriously difficult to study properly. The chief reason for this is the long period of time necessary for the results of a weathering process to become physically observable. An example of an attempt to quantify igneous rock weathering rates can be found in Sumner (2004). A potential answer to this problem lies in the study of gravestones, since the stones of a particular cemetery are placed in close proximity to one another, but over a wide time period, while often sharing similar lithologies.

Cemeteries can, therefore, be used as field laboratories for the purpose of studying how a specific rock type might degrade over time as a result of exposure to a given set of environmental conditions. Using grave sites as field laboratories is not a new concept. There are an array of studies that make use of gravestones as a way of assessing the effects that air pollution is having on cultural stones (Inkpen, 2013; Mooers et al., 2017) or the relationship between weathering rates of gravestones and their specific locations in the world (Inkpen & Jackson, 2000). A specific example of a study that looked at the relationship between time and rock weathering was that of Wilhelm et al. (2016b), who studied how rock hardness values in Portland limestone tombstones changed with exposure time. They demonstrated that rock hardness values decreased for older gravestones, implying that they had weathered more extensively. A study of gravestones would also serve the secondary purpose of offering potential insights into the improvement of conservation measures put in place to limit their natural deterioration, which is an important preservative aspect of geomorphology (Pope et al., 2002).

Unfortunately, gravestones, because of their status as culturally significant artefacts, are difficult to study because no form of destructive testing may generally be imposed upon them (Pope et al., 2002). As a result, many tombstone weathering studies have been constrained to either subjective observations or basic physical measurements (Inkpen & Jackson, 2000; Williams & Robinson, 2000). Inkpen & Jackson (2000), for example, made use of height differences in inscription lettering on marble gravestones to assess weathering rates at different urban and rural locations in southern Britain. The lead lettering of the inscription on marble tombstones is assumed to sit initially flush with the surface of the marble. As the marble stone weathers, the lead lettering will gradually manifest as a positive feature on the stone which can be measured. They noted a general statistically significant relationship between lettering height and age of the stone, suggesting that older gravestones had weathered more extensively than newer ones. This particular measurement technique is only usable on gravestones that make use of lead lettering (typical on marble stones). This method is simple and non-invasive, and is still used in more contemporary studies (Mooers et al., 2017; Inkpen et al., 2017). It cannot, however, be used on stones that have been more traditionally etched, such as is common in the gabbro tombstones of South Africa. Bauer et al. (2002) made use of a straightforward legibility study, which simply assessed the number of tombstones in a given cemetery that had readable dates of death. This too is often undesirable in South African cemeteries, since many of the stones are under 100 years old and the etchings on these stones have often not degenerated to a point of illegibility.

Contemporary technological advances have opened the door to non-destructive testing methods that offer insights into the structure of stone not possible before now. However, the use of new equipment introduces new experimental techniques and it is important that the delimitations of the equipment be well understood. Ultrasonic testing has been used for some time to assess the strength of concrete and other building materials, as well as more exotic materials, such as the ceramic linings found in iron and steelmaking facilities (Damhof et al., 2009). In general, a damaged or significantly altered piece of material will return a lower pulse velocity than one that is in pristine condition (Ruedrich et al., 2013). Geomorphologists and heritage scientists have begun to use ultrasonics for the study of cultural stone, due to its non-destructive nature and ease of use. For example, Pamplona et al. (2012) have used the technique as a diagnostic tool for assessing decay in marble sculptures in Germany. Ruedrich et al. (2013) have likewise made use of ultrasonic techniques to assess statuaries in Germany and Gimenez & Del Lama (2014) have performed similar studies on a monument in Brazil. More recently, Akoglu et al. (2020) have made use of ultrasonic pulse velocity testing to monitor the condition of memorials in Connecticut, North America. Cultural stone has even been compared directly to its quarry stone equivalent using this method (Fort et al., 2013).

While there are studies that have made use of ultrasonic devices for the study of gravestones (for example, Siegesmund et al. (2010) made a study of ornamented marble gravestones in Germany), there is a considerable lack of ultrasonic data on gravestones generally, and no data at all within a South African context. This is of particular interest because gabbro stone is highly resistant to macro-scale, physically observable weathering, and does not yield useful information when studied using techniques developed for the softer stones more commonly used in Britain (and elsewhere). However, the ultrasonic pulse velocity measurement technique would only be useful if it is sensitive enough to detect changes in gabbro stone as a result of weathering that has taken place over a short to intermediate period of time (one hundred years or less).

The aim of this study was to test the viability of assessing the weathering intensity of gabbro stones via the ultrasonic pulse velocity measurement technique in Cullinan Main Cemetery. This is because gabbro is highly resistant to weathering, and it is important to establish whether or not a measurable difference in pulse velocity can be detected over a relatively short degradation period (tombstones in Cullinan can reach a maximum time in place of 117 years, with most being considerably ‘younger’ than that, because the town was only established in 1903). In this study, the term ‘inscription age’ is used to describe the amount of time the gravestone has spent *in situ* at the cemetery, as determined by the date of death on the inscription of the stone.

A high spatial resolution scan was conducted on four gabbro tombstones of differing ages to observe homogeneity of weathering throughout the stone. Two of the stones had been in place for 50 years (both stones circa 1970), while two additional stones at been in the cemetery for 100 years (both stones circa 1920). This was done in order to determine whether or not a tombstone could reasonably be described by a single, average ultrasonic pulse velocity value.

If ultrasonic pulse velocity is a viable proxy for rock weathering, then there should be a measurable decrease in pulse velocity when compared to the time that a stone has spent in place. Unfortunately, there is currently no weathering index that exists for gabbro stones, but indices that do exist for other stone types, such as marble (Sisov et al., 1999, cited in Pamplona et al. 2012) indicate a general decrease in pulse velocity as weathering becomes more intense. Here, the relationship between ultrasonic pulse velocity and the weathering period was quantified to see if it provides results for gabbro stone that are in line with what is observed for other rock types.

Ultrasonic pulse velocity studies were originally developed for relatively standardised material like concrete and building stone. As such, the equipment may generate unusual results if it is used considerably outside of its design specifications. Additionally, different studies may not have access to common equipment, and it is important to understand the delimitations of various equipment types. Therefore, two different transducer packages were used on each of the tombstones and compared.

5.2. Study Area and Methods

Measurements were taken at Cullinan Main Cemetery, which lies just under 40 km from central Pretoria (Figure 50) in Gauteng Province, South Africa. Pretoria is an inland environment at an altitude of 1300 meters and has an average annual temperature of 17.8 °C and average precipitation of 697 mm. Cullinan Main Cemetery was selected because it lies slightly outside of Pretoria in an area that has low levels of industrial sites, which will minimise weathering to the tombstones caused by pollution. In addition, Cullinan Main Cemetery contains gabbro tombstones that were placed *in situ* prior to 1930, which offers a large temporal range, important for this kind of study.

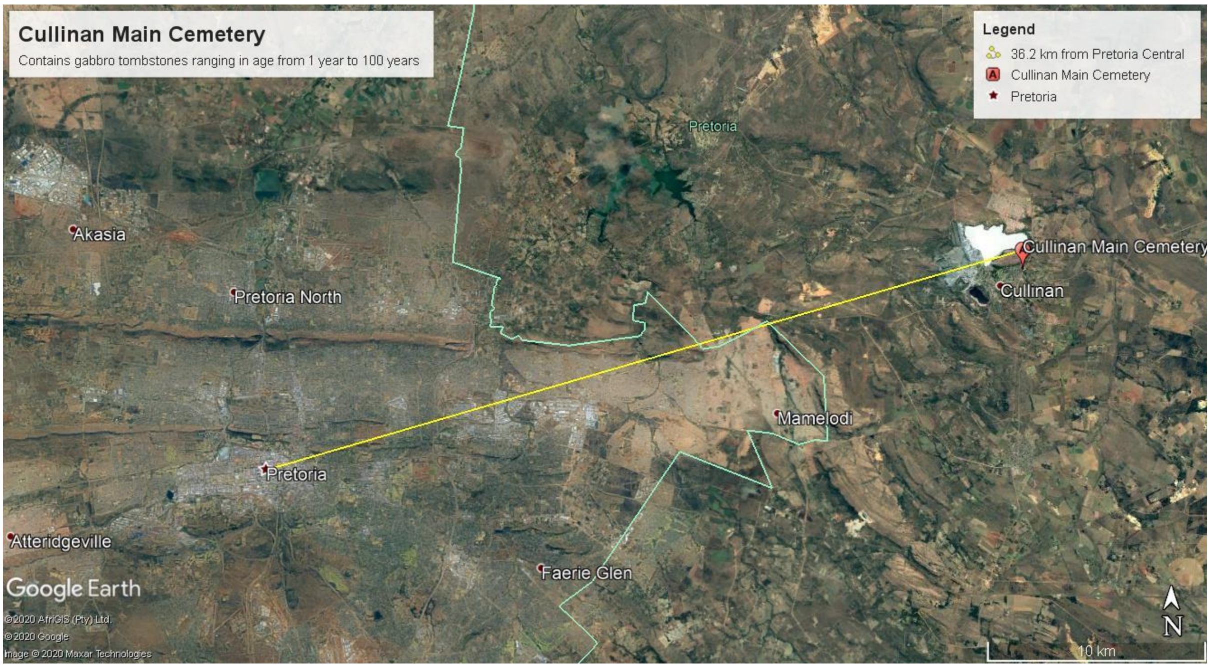


Figure 50. Google Earth Image of Cullinan Main Cemetery Location, relative to the centre of Pretoria.

5.2.1. Ultrasonics

Ultrasonic testing is well-known as a means of establishing the level of degradation of cultural stone, as it is easy to use and completely non-destructive. In general, ultrasonic waves propagate through a solid medium more rapidly than through a more rarefied substance like a gas. As a result, a rock sample that contains a large number of micro-cracks and voids will have ultrasonic waves move more slowly through it than for a more cohesive sample of the same lithology and overall structure. Thus, lower pulse velocities are seen to be indicative of rocks that have sustained a greater degree of sub-surface weathering or alteration (Babacan & Gelisli, 2015).

Sub-surface weathering was assessed by a PUNDIT PL-200 ultrasonic device with both standard 54 kHz transducers (the default sensors for this piece of equipment) and 54 kHz exponential transducers, which are specifically designed for use on rough surfaces. The reason for this is that the 54 kHz transducers are the default option for the PL-200 and as such are the transducers that most studies using this equipment are likely to deploy. The 54 kHz exponential transducers are specifically designed with a much smaller contact area than the standard set and are intended for use on rough surfaces. These transducers are similar in design to those used by Pamplona et al. (2012), who made use of ultrasonic pulse velocity to assess the degradation of exposed marble sculptures in Germany. The possibility of data corruption is expected to be lower, due to the improved contact on rough surfaces. However, due to the fact that tombstones (and cultural stone in general) lie slightly outside of the design delimitations for most ultrasonic equipment, it is important to assess the consistency of the results being produced.

5.2.2. Spatial high resolution scan

The homogeneity of the weathering taking place across the individual stones needs to be quantified. This is to verify the assumption that each tombstone can be classed according to a single, average value. Four tombstones were selected for high resolution spatial scans in order to determine the likely weathering variance. Ultrasonic measurements were taken in a grid pattern, with each measurement being 10 cm apart in both the x and y axes, with all measurements remaining a minimum of 10 cm away from any edges. The number of measurements for each tombstones is, therefore, dependant on the size of the tombstone itself. Two tombstones from circa 1920 were selected, and two from circa 1970.

These ages were chosen because it accounts for a change in tombstone design that took place at some point between 1940 and 1960. Specifically, newer tombstones almost always have all aspects ground smooth (Figure 51a), whereas older gabbro tombstones only have their front faces polished flat, leaving the rear and lateral aspects relatively rough (as can be seen in Figure 51b). This is most likely due to difficulties in working gabbro stone, largely overcome in modern times as a result of improved machinery. The values obtained in the high resolution study were categorised according to their pulse velocities, being divided into 500m/s classes. This was done because, while there is no ultrasonic pulse velocity index for gabbro stone, indices that do exist (for example, marble, as in the case of Sisov et al., 1999), often classify pulse velocity values in 1000m/s increments. Measurements that are, therefore, 500m/s apart would either be classed as having the same degree of weathering intensity as one another, or possibly differing from one another by only one class.

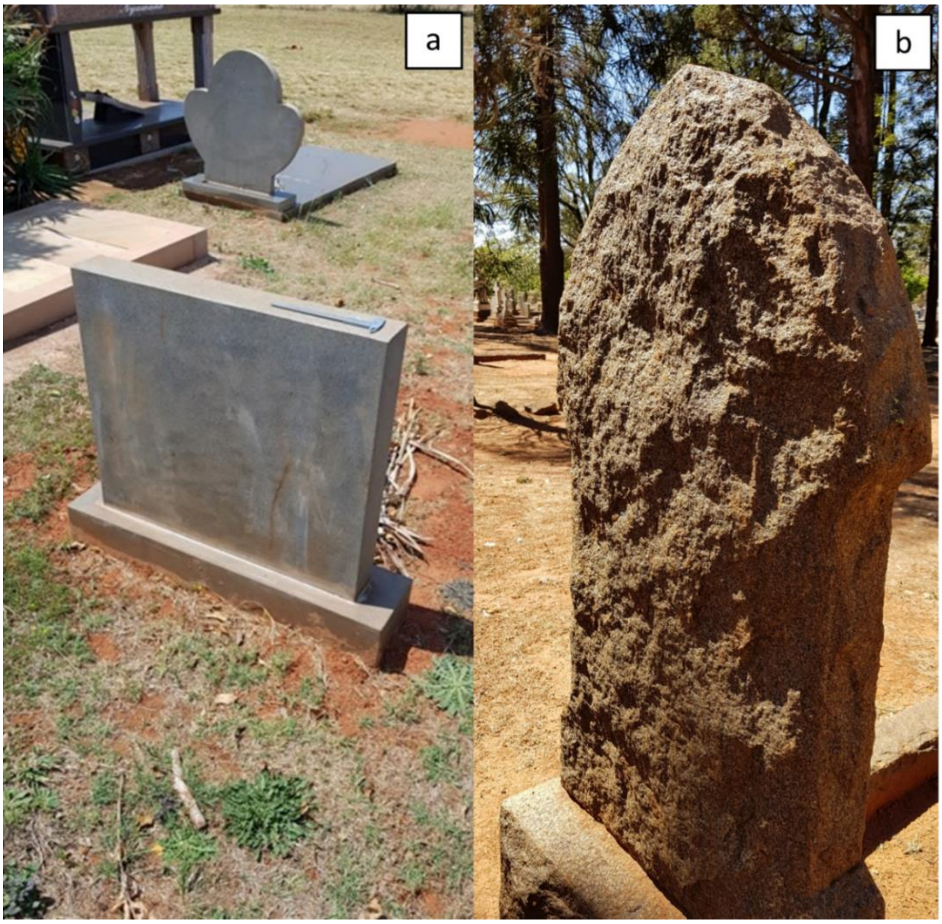


Figure 51 a. Newer gabbro tombstones have their side and rear aspects ground smooth, in addition to the front. b. Older gabbro tombstones have rough side and rear aspects.

5.2.3. Time series analysis

Thirty-four gravestones were selected across as wide a temporal range as possible, as determined by the time of death marked on the stone.

One transducer was placed on the front face of the gravestone and the other directly opposite it on the rear face. By noting the distance between the two transducers, the velocity of an ultrasonic pulse can be calculated (Figure 52a). Five measurements were taken on each tombstone (one measurement at each corner of the stone and one in the centre). The five generated ultrasound values were then averaged to produce a single ultrasound value for each tombstone (Figure 52b).

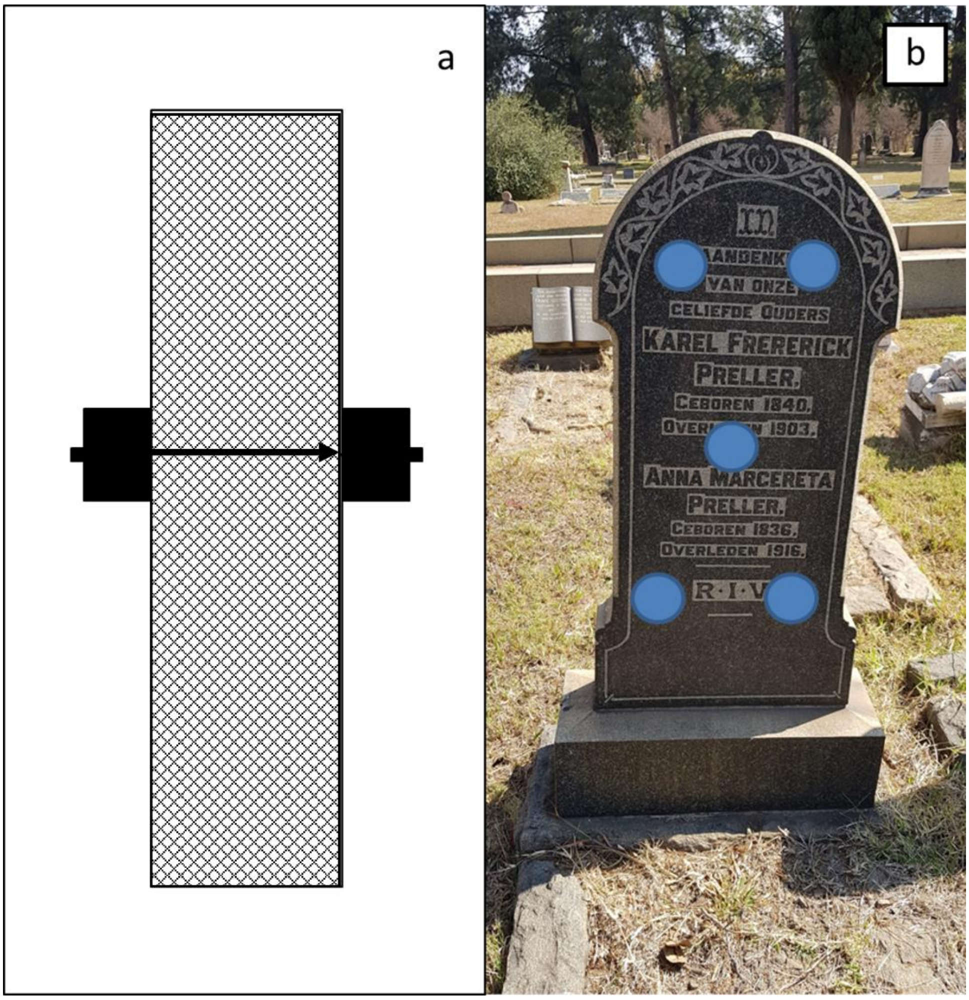


Figure 52a. Sensor placement for direct transmission measurement b. Measurement geometry for tombstone measurement

It should be noted that data gathered from ultrasonic testing are susceptible to manipulation from moisture fluctuations with the stone (Sumner & Nel, 2002; Ruedrich et al., 2013). In order to compensate for this, field measurements were carried out on sunny days when moisture in the stones was likely to be a minimum.

The relationship between pulse velocity and age and was assessed via the Spearman ranked correlation coefficient. This was because the Spearman test is non-parametric and does not require a linear relationship between the variables, which a mathematical assessment of the data shows is not present in all of these data sets.

Typically, the intensity of rock decay for a given stone would be categorised by means of a damage class table, derived from artificial rock degradation studies, as in Sizov et al. (1999), cited by Pamplona et al. (2012). In this case, no such table exists, since gabbro stone has not been studied extensively in a South African context. However, since a key assumption of the ultrasonic pulse velocity measurement technique is that increased weathering will reflect as a general decrease in pulse velocity, proof of the concept will be established if a positive relationship can be observed between ultrasonic pulse velocity and the inscription date on the tombstones (i.e. the longer the stone has been in the cemetery, the more time it has had to weather and the lower the resulting pulse velocity should be.)

5.2.4. Transducer variance

All 34 tombstones were assessed twice, with two different transducer types, with measurements taken at approximately the same point for each. This was to quantify the effects of differing experimental setups on the generation of data. The first transducer was a PUNDIT 54 kHz broad-headed transducer (Figure 53a). This is the standard transducer that comes with a PUNDIT PL-200 device. The second transducer was a 54 kHz narrow-headed transducer, which has been specifically designed for use on rough surfaces (Figure 53b). Such a design would be preferred for some of the older tombstones in South African cemeteries, due to their rough side and rear aspects. However, it is important to compare the measurements generated by the two transducer sets in order to determine whether or not it is possible to create a composite data set containing measurements from both transducer types. If this is the case, it would allow for the swopping out of transducers during an experimental run, adapting for changes in tombstone roughness on the fly.

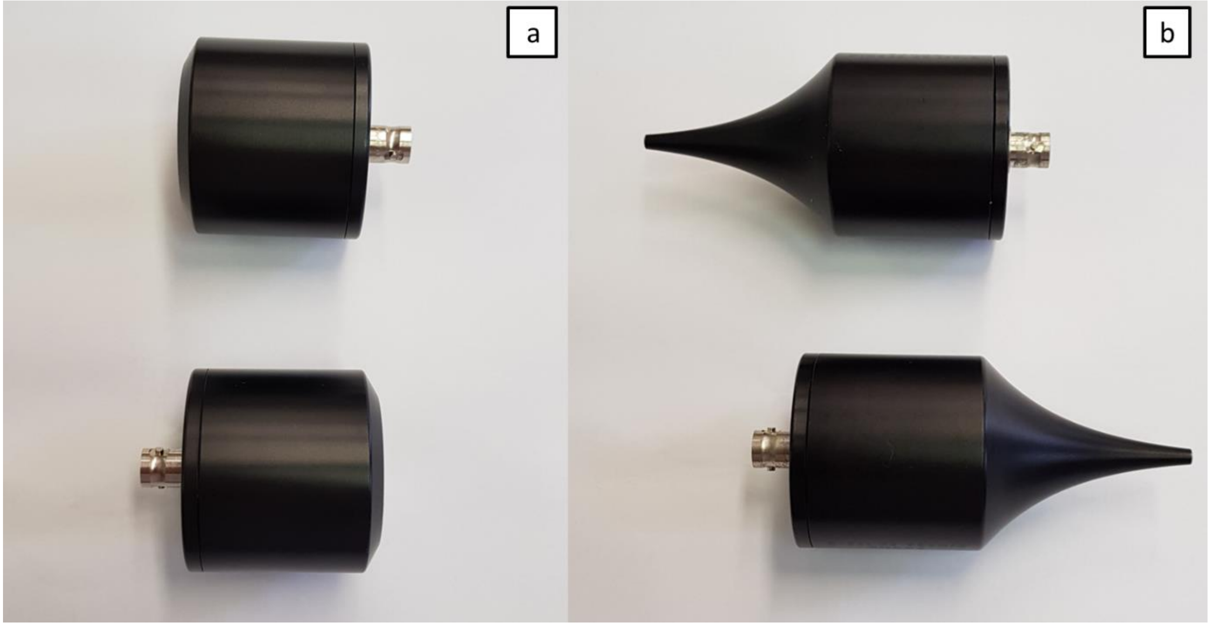


Figure 53a. Image of standard transducer b. Image of rough surface transducer

5.3. Results

There are three major divisions to be presented in terms of results. First, the results of the high intensity area scan will be presented, followed by time series analysis. Finally, results obtained from the two different transducers will be compared.

5.3.1. High resolution Area Scan

The results of the area scan can be observed in Table 5. Four tombstones were studied intensively using the rough surface transducer package. Tombstones 1 and 3 were of an older design (of the type displayed in Figure 51b) and Tombstones 2 and 4 were of a newer design (Figure 51a). While it can be seen that there are some outliers in the data sets, the majority of the data points for each lie within approximately 500 m/s of the average value for the entire stone. For Tombstone 2, 80.5% of the values lie within 500 m/s of the mean, with the other three tombstones having between 88% and 90% of their values lying within this range.

	Tombstone 1 (n=40)	Tombstone 2 (n=72)	Tombstone 3 (n=50)	Tombstone 4 (n=64)
>3500 m/s	4	5	4	1
3000 - 3500 m/s	30	49	30	38
2500 - 3000 m/s	6	9	14	18
2000 - 2500 m/s	0	0	1	3
1500 - 2000 m/s	0	1	0	0
1000 - 1500 m/s	0	4	1	3
<1000 m/s	0	4	0	1
Average UPV (m/s)	3244	2881	3096	2864
Standard Deviation	253	739	438	567

Table 5. High resolution area pulse velocity categorisation for four tombstones in Cullinan Main Cemetery

This definitely suggests tombstones are not weathering completely homogeneously. However, the majority of the measurements lie fairly close to the average value, which suggests that using a single average value to describe a tombstone is reasonable.

5.3.2. Time series analysis

The standard transducer package demonstrates a noticeable positive relationship between pulse velocity and age of tombstones (Figure 54), with the maximum value (5747.4 m/s) being measured on a tombstone set in place circa 2004 and the minimum value (1192 m/s) on a stone present in the cemetery since 1925, giving a total data range of 4555.4 m/s. This correlation between inscription age and measured pulse velocity is statistically significant (Spearman rho correlation of 0.71 at $p<0.01$). This markedly slower velocity for the older stones suggests that there is a larger void/matrix ratio in the rock, the rarefied nature of which will slow the pulse down (Babacan & Gelisli, 2015). This is most likely the result of micro-cracking that has occurred over the years as a result of climatic influences (weathering). While there are undoubtedly some obvious outliers in the data set, the overall trend in the data is clear.

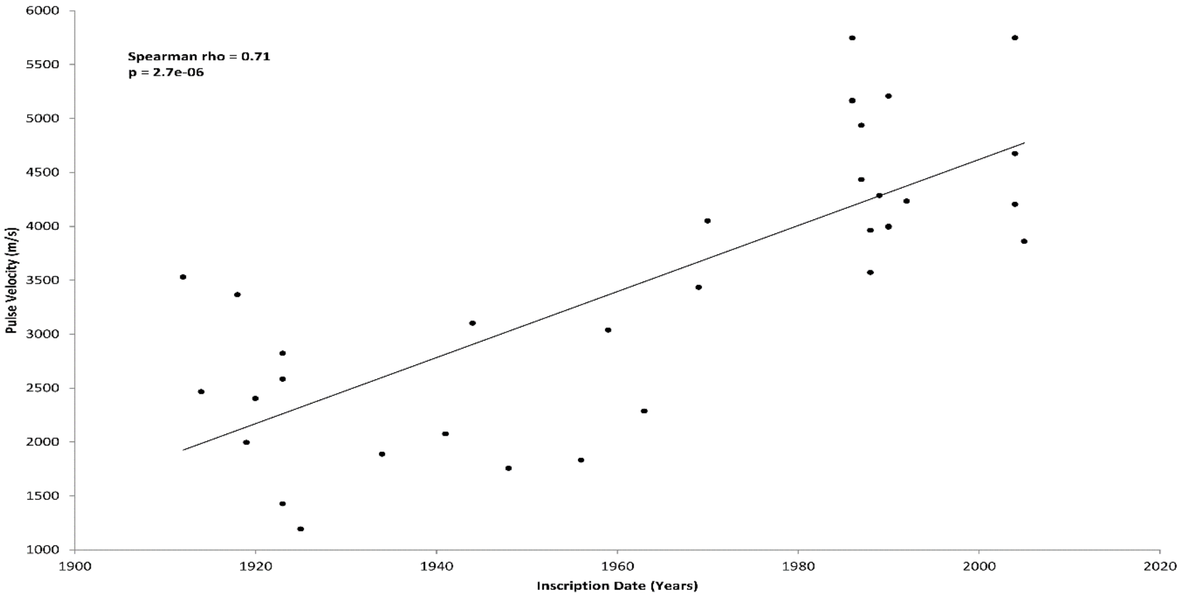


Figure 54. Comparison between Ultrasonic Pulse Velocity and inscription age of tombstone for standard 54 Khz transducer

The rough surface transducers also demonstrate a positive relationship between pulse velocity and age (Figure 55), but the relationship, while still statistically significant (Spearman rho correlation of 0.53 at p<0.01), is overall weaker than that of the standard transducers. The values also cover a smaller range, with the maximum pulse velocity (4065 m/s) in a stone put in place circa 1992, and the minimum (2182 m/s) circa 1920, which gives a total data range of 1883 m/s.

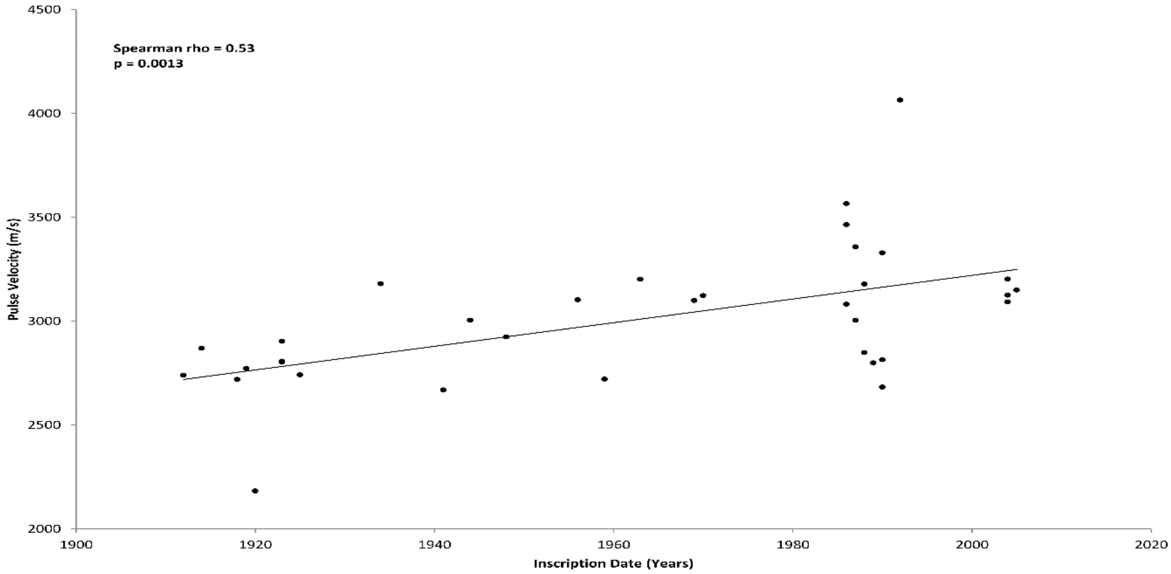


Figure 55. Comparison between Ultrasonic Pulse Velocity and inscription age of tombstone for rough surface transducer

As one would expect, the measurements for the standard transducers and the rough surface transducers have a statistically significant correlation (Spearman rho of 0.5 at p<0.01), as indicated in Figure 54.

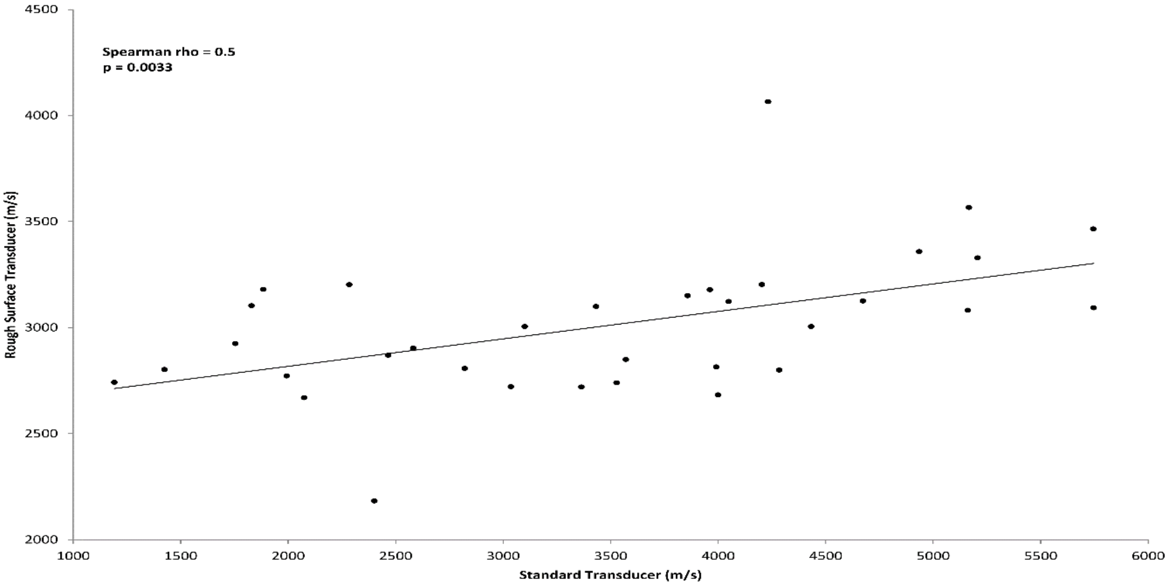


Figure 56. Comparison between standard transducer velocities and rough surface transducer velocities

The data sets generated by the different transducer packages appear to present data on differing scales and cannot, therefore, be combined to form a larger, composite data set. However, they both show the same general trend of weathering and scientists using either only the standard transducers or only the rough surface transducers would most likely draw similar conclusions about the weathering regime present at Cullinan, although the standard transducers show a steeper linear trend than the rough surface transducers, which may lead researchers to intuit a more aggressive weathering regime.

The statistical results can be summarised in the following manner (Table 6):

Label	**Spearman Rho**	**p-value**	**Max (m/s)**	**Min (m/s)**	**Range (m/s)**
Standard transducer --> Inscription age	0.71	<0.01	5747.4	1192	4555.4
Rough surface transducer --> Inscription age	0.53	<0.01	4065	2182	1883
Standard transducer --> Rough surface transducer	0.5	<0.01	N/A	N/A	N/A

Table 6. Summary of Statistical results, showing comparisons between Standard transducer velocity and inscription age, Rough surface transducer velocity and inscription age, and Standard transducer velocity and Rough surface transducer velocity.

5.4. Discussion

The high resolution area scan has shown that the majority of readings for the tombstones lie within a 1000 m/s total range of the average pulse velocity measurement. However, there is enough variance here to suggest that weathering homogeneity should always be assessed as an intrinsic part of any ultrasonic pulse velocity study. The time series analysis presented here is only viable when weathering is fairly homogenous across the entire stone.

The datasets produced by the two different transducers have produced broadly the same results for the Cullinan Cemetery, but there are obvious differences. In particular, the dataset obtained by use of the rough surface transducers fall over a smaller range and have a weaker (although still statistically significant) relationship with the inscription age on the stones. This may merely be a result of the manner in which the transducers measure the pulses, but there is a possibility that there is a physical reason for the differences in the datasets. Specifically, there appears to have been a shift in the nature of tombstone design over the years that may play a role in the way that data is received by the two sensor suites. In spite of this, the two datasets relate well to one another and are, therefore, indicative of a change in micro-cracking within the tombstones over the period of time that they have been exposed to climatic elements. This aligns with Babacan & Gelisli (2015), who anticipate a lower ultrasonic pulse velocity for more weathered stone, and it is certainly expected that gravestones that have been exposed for a longer period of time to climatic influences would be more weathered. The patterns observed in this study also relate well to those observed by (Inkpen & Jackson (2000). Specifically, they observed that the relationship between lead lettering depth and inscription date are approximately linear, which is also observed in this study between pulse velocity and inscription date. Wilhelm et al. (2016b) also noted a general positive relationship between inscription age and rock hardness, as measured by an Equotip rock hardness device. This reinforces the concept that both ultrasonic pulse velocity and rock hardness are valid proxies for rock weathering.

Despite the limitations of this preliminary study, it does demonstrate that the equipment is sensitive enough to detect changes in gabbro stone over a one hundred year time span. The relationship between weathering age and ultrasonic pulse velocity could be improved by application of a combination of a polyethylene sheet and ultrasonic contact sealant, but even without these improvements, there is still an observable, statistically significant relationship between ultrasonic pulse velocity and the ‘weathering age’ of the tombstones.

The standard and rough surface transducers offer statistically comparable results, although they cannot be treated as part of the same datasets. However, the rough surface transducers indicate a weaker statistical relationship than the standard, broad-headed transducers. This may be because the broad-headed transducers make contact with a greater surface area than the rough surface transducers, which could give a more reasonable indication of the degree of weathering taking place, especially if, as is common with natural stone, weathering is not occurring homogenously. The rough surface transducers also do not yield data that is directly comparable to the standard ones. Therefore, it is crucial that a single set of transducers be selected for an entire experimental run.

5.5. Preliminary field conclusion

There is a statistically significant positive relationship between ultrasonic pulse velocity and inscription age for measurements taken both with the standard set of transducers and with the specialised rough surface ones. This means that the older the tombstone is (i.e. the longer it has remained *in situ* in the cemetery), the lower the pulse velocity value that it is likely to return. It is, therefore, possible to assess relative rock weathering intensity as a function of ultrasonic pulse velocity.

Weathering studies on gravestones to this date have primarily focused on visual observation and physical measurements (Inkpen & Jackson, 2000), due in large part to their status as cultural artefacts. Ultrasonic measurements offer a more quantitative and less subjective measurement technique that can potentially offer great insight into rock weathering generally and gravestones specifically, even for particularly weathering resistant rock like gabbro.

While ultrasonic measurements have potentially profound uses in the field of geomorphology, it is important that the limitations of the equipment be well understood, and experimental protocols be put in place in order to ensure that data collected with this technique are as free from corruption as possible. For example, future studies should consider the addition of elements such as polyethylene covering and contact sealant in order to limit the production of experimental noise. This would be especially helpful in cemeteries that have extraneous environmental variables that could introduce added uncertainty into the datasets. Under these conditions, it would be crucial to limit the introduction of experimental noise wherever possible, in order to avoid obscuring a potentially quite subtle data signal. This would likely improve the accuracy of the ultrasonic pulse velocity measurements considerably and allow for the technique to be used in environments more prone to interference from external environmental elements. It is also critical that a single set of transducers be used throughout any given study, since different transducer configurations have been shown to return results that are not directly comparable. More globally, future work should consider the development of protocols that would lead to congruity in datasets gathered in different studies in different parts of the world. This would allow for the generation of composite datasets and open up opportunities for the creation of ultrasonic datasets that encompass a host of different locations, both locally and globally.

(The article published in the South African Geographical Journal ends here. However, subsequent field measurement exercises showed that the initial method, while promising, required further development to improve its effectiveness. The remaining sections of this chapter are a documentation of this development process).

5.6. Field based operator bias studies

The initial experiment showed that there is a correlation between UPV and tombstone age for both the standard and exponential transducers, but this is for a single operator carrying out an experiment in a single cemetery. To gather further data on the efficacy of the experimental technique, the experiment was carried out again with two additional operators and their results compared to the original study. This was done both to assess the repeatability of the initial experiment and to quantify the effects of operator bias on field measurements. Operator bias measurements were shown to be a factor in reducing experimental repeatability under controlled conditions (see Chapter 4), and it was expected that this effect would be exacerbated under field conditions because of their innately uncontrolled nature. If this experimental technique were to prove viable for region weathering studies, future iterations of the idea may require multiple operators. It is necessary to assess the effects that this could potentially have on the gathered data.

Two postgraduate students were taken into the field and extensively briefed on the experimental technique deployed by Loubser (2022). They measured the same set of 34 tombstones with both the standard and exponential transducers. As before, each tombstone was measured five times and the results averaged across each stone. As before, ultrasonic couplant was not used so as not to stain the tombstones during the experiment.

Figure 57a shows a visual comparison of the results obtained by Operator A (the author of this dissertation) and Operators B and C when using the standard transducer. The R and p values on each graph represent the results of a Spearman Rank test. For 34 samples and p

< 0.01, R must be greater than 0.439 to show a significant monotonic correlation between the date of death and UPV. In the case of all three operators, the use of the standard transducer produced a statistically significant relationship between date of death and UPV, although the differences in measurements over specific tombstones varied from operator to operator.

In the case of the exponential transducers (Figure 57b), only the dataset obtained by Operator A showed a significant relationship between date of death and UPV, although the datasets of Operators B and C did still show the monotonically increasing pattern that was present in the dataset of Operator A.

When studying operator bias, it is necessary to establish parameters that determine the point at which the bias has negatively affected the experiment. While the datasets can be quantitatively compared to one another, a simpler, qualitative metric by which bias can be judged is to ask the question: “In the case in which the different operators conduct the same experiment with the same equipment and under the same conditions, would they draw the same conclusions from the generated data?” If yes, this would conform to the criteria of reproducibility, as defined by Church et al. (2020) In the case of the standard transducers, it is likely that they would, but there are methodological concerns about the use of these transducers. The exponential transducers are more suitable for use under field conditions on cultural stone, but are more prone to operator bias than the standard ones.

This suggests that, in the case of the exponential transducers, it is not advisable to have multiple operators take measurements that will ultimately form part of a common dataset. These findings align with the laboratory based operator bias study (Chapter 4), which showed that the exponential transducers produced datasets with large amounts of variance when using multiple operators, but a much smaller variance for a single operator carrying out the study multiple times.

The nature of these data also show that UPV measurements under field conditions may be prone to confirmation bias. This phenomenon, while understudied in the Earth Sciences, is well known in Medical and Pharmaceutical fields and involves the selection and publication of data on the basis of positive correlation of variables, rather than on the potential validity of the conclusions. The results displayed in Figure 57a (the standard transducer) show stronger statistical relationships between tombstone age and UPV than the results displayed Figure 57b (the exponential transducer). All of the operators in Figure 57a show a statistically significant relationship, while in Figure 57b, only Operator A, the most experienced operator, showed a statistically significant relationship.

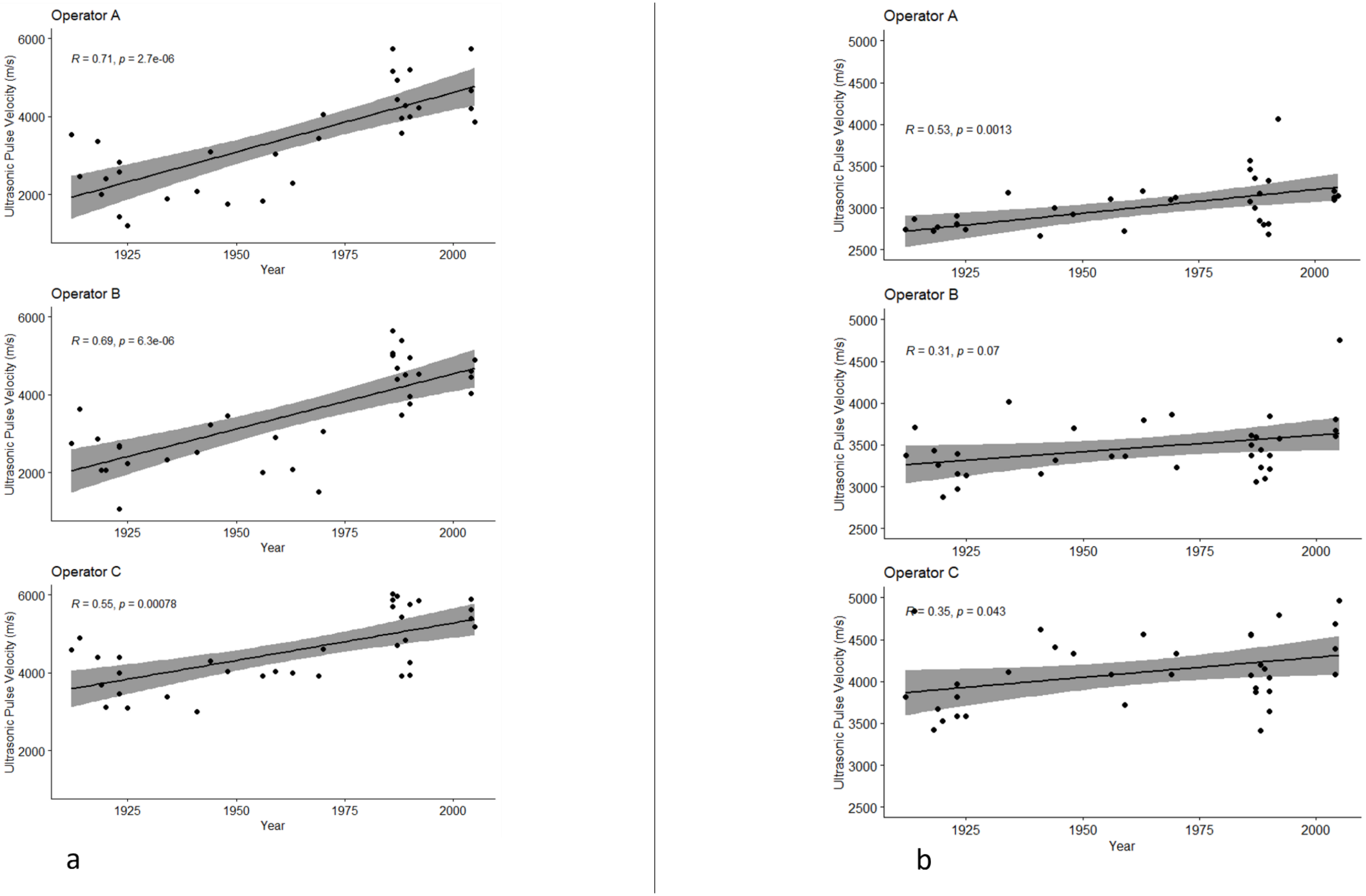


Figure 57. Linear regression showing the relationship between Ultrasonic Pulse Velocity and tombstone age measured by three operators for both standard transducers (59a) and exponential transducers (59b) for three different operators

It would, therefore, be tempting to disregard the exponential results and publish only those obtained from the standard transducer. However, after detailed scrutiny of the experimental method, it is possible to draw the unusual conclusion that an experimental error has resulted in an increase in correlation strength for standard transducers.

Specifically, gabbro tombstones older than approximately 50 years frequently have a well-polished, smooth front aspect, but the back and side aspects are rougher, whereas new tombstones are equally smooth across all aspects. This is a design choice on the part of the tombstone manufacturers, rather than as a result of natural weathering. A standard transducer cannot make clean contact with a rough stone surface, which will introduce errors in the data. Specifically, the poor contact will result in a lower recorded value than expected, since part of the ultrasonic pulse must now travel through the resulting air gap between the transducer and the tombstone, which slows the pulse down (Figure 58).

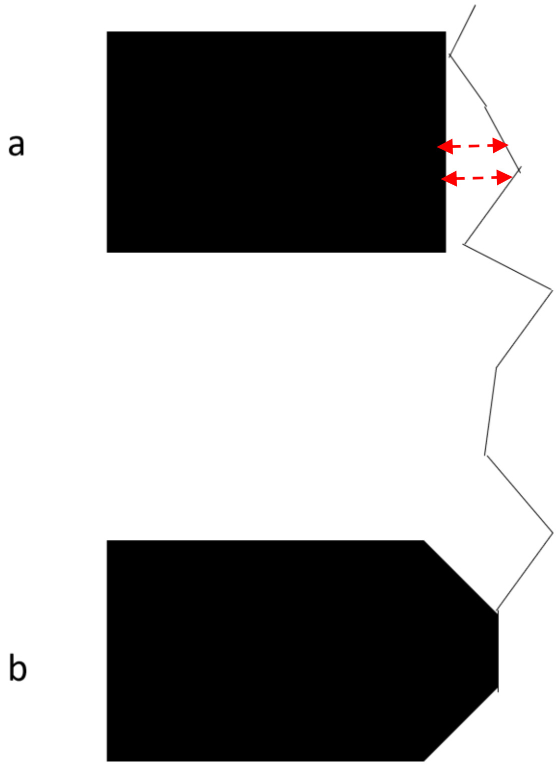


Figure 58. Contact surface of standard transducer (60a) vs exponential transducer (60b)

This means that, for this experimental configuration, a lower UPV value correlates more accurately with tombstone surface roughness than with weathering. This is an example of a flaw in experimental design leading to the achievement of the expected outcome.

This particular issue is likely not unique to this particular field experiment, but may well affect many field studies, particularly if the researcher is not specifically looking for it.

5.7. Modifications of the field experimental technique for wider regional study

The initial field experiment demonstrated that the intended technique was viable for the wider regional study with some modifications. Specifically, all measurements were taken by a single operator, which means that local personnel would not contribute to the generation of the dataset. Also, the standard transducer set was disregarded entirely in favour of the exponential transducer set. The exponential transducers, while more difficult to use and producing generally less desirable data, nevertheless were better suited to providing data in which the dominant signal generated by UPV is rock weathering.

Unfortunately, initial deployment of the experimental method to other cemeteries produced results that were less encouraging than those that were initial observed at Cullinan Main Cemetery. The experimental method was deployed at Stellawood Cemetery in Durban, KwaZulu Natal, as well as Maitland Cemetery and Plumstead Cemetery in Cape Town, and Dido Valley Cemetery and Seaforth Naval Cemetery in Simon’s Town. A brief summary of these data can be found in Appendix 3 of this document, but none of them showed a statistically significant relationship between UPV and tombstone age, as determined by the date of death inscription. There was one exception to this, which was that of Plumstead Cemetery in Cape Town, which yielded the trend displayed in Figure 59 for 31 gabbro tombstones.

This dataset shows a statistically significant relationship between tombstone age and UPV ($p<0.05$), but it is weaker than that of the Cullinan Main Cemetery. However, it was the strongest of all of the cemeteries measured in the larger regional study. The reasons for this poor methodological performance are not initially clear. After a review of the data, three possible reasons emerged for the poor statistical relationships between UPV and tombstone age for the various cemeteries across South Africa. First, UPV might not be a good indicator of rock weathering intensity in gabbro stone. It is unlikely that this is the case, given the wealth of literature that exists that demonstrate this relationship for other stone types (Siegesmund et al., 2010; Ruedrich et al., 2013; Babacan & Gelisli, 2015; Boudani et al., 2015). Second, local environmental variables unique to each site might have been obscuring the data in a manner not present at Cullinan Main Cemetery.

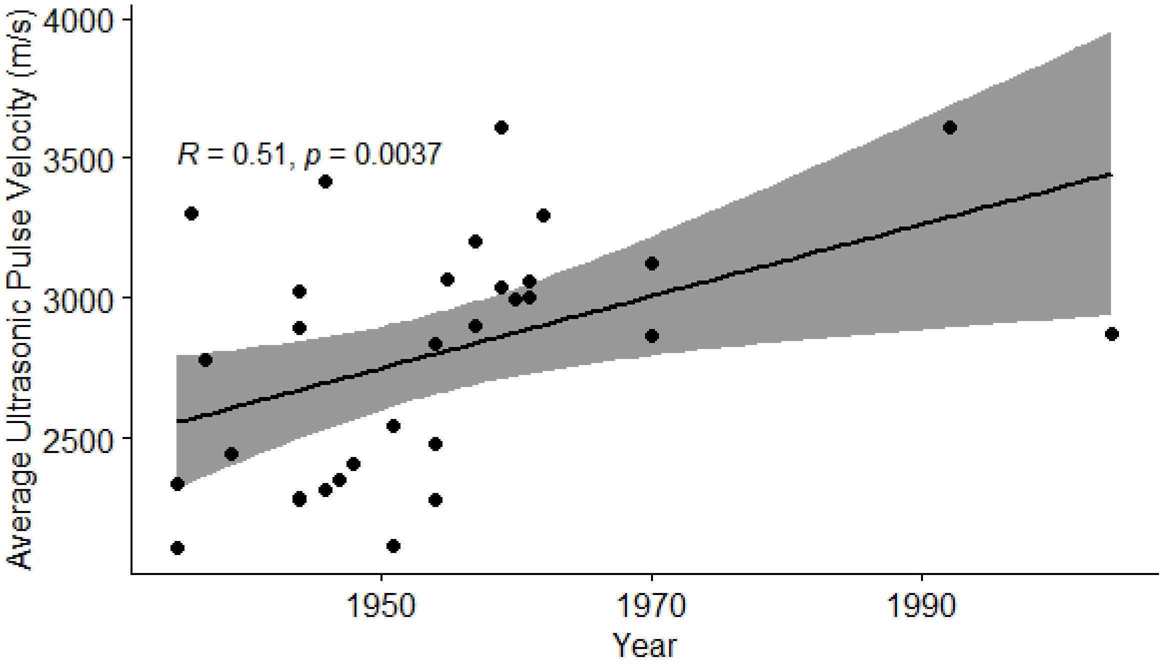


Figure 59. Relationship between tombstone age and Average Pulse velocity for gabbro tombstones in Plumstead Cemetery, Cape Town

This was a potentially anticipated outcome and aligned with the views of Phillips (2007), who made a strong case for local variance interfering with the measurement of global laws for many geomorphological studies. Finally, it was possible that there was a flaw in the initial experimental methodology, and that improving the experimental design could lead to an improvement in the generated data. In particular, it was necessary to test the assumption that weathering would occur homogenously across the surface of each tombstone and that five measurements would, therefore, be sufficient to describe them. In order to determine if there was a problem with the experimental design, the method was modified and redeployed at selected cemeteries.

This method and its results are documented in Chapter 6.

Chapter 6: Ultrasonic pulse velocities as a proxy for rock weathering: a study of South African gabbro tombstones

6.1. Introduction

The results displayed in Chapter 5 show that, while there is a detectable weathering signal at some cemeteries, this signal is not present everywhere. After reviewing the generated data, it became clear that some of the generated data may have been compromised by an implicit assumption in the initial experimental design. Specifically, the decision to classify each tombstone as a function of the average of five tombstones carries with it the assumption that weathering is fairly homogenous across the surface of each stone. This seemed a reasonable assumption at the time, since each tombstone would experience very limited changes in microclimatic exposure across the area of their surfaces. However, if weathering profiles across the surface of a single tombstone were highly variable due to preexisting areas of weakness, these differences would not necessarily be observable with only five measurements. This is conceptually simple (if time consuming) to test, by increasing the number of samples taken for each tombstone and conducting more rigorous analysis.

The new research questions can, therefore, be summed up as follows:

- Does an increase in number of measurements per tombstone improve the statistical relationships between UPV and ‘age’ in the datasets?
- Is weathering across the surface of a tombstone homogenous?
- Are trends observable for small datasets (i.e. if the cemetery is small and the number of available appropriate tombstones is limited)?
- Is it possible to determine a relationship between regional climate and rock weathering?

6.2. Materials and Methods

Following completion of the preliminary study at Cullinan Cemetery, the method was refined and the study expanded to four cemeteries (two in the Western Cape and two in Kwa-Zulu Natal).

6.2.1. Field measurement procedure

The study at Cullinan assumed that weathering would take place homogenously across the surface of each tombstone. However, the results of that study (published in Chapter 5 of this document) indicated enough variance in terms of UPV per stone to suggest that this was not a reasonable assumption. The method was, therefore, modified to allow any heterogeneity present on the part of measured UPV readings to be quantified. In this study, each tombstone was assessed either 49 times or 25 times, depending on the specific tombstone's size. Larger tombstones were measured in a 7 by 7 grid at intervals that ensured that the entire surface of the stone would be covered (Figure 60a). Smaller tombstones were measured in a 5 x 5 grid (Figure 60b). The method was adapted into this format because results from Objective 2 suggested that pulse velocity measurements (and by implication rock weathering intensity) are not homogenous across an entire tombstone, which was an implicit assumption of the initial method. The larger number of measurements taken for each stone allows for the quantification of tombstone heterogeneity and will give a clearer indication of how weathering is distributed across a particular stone. The distance between each measurement point varied from tombstone to tombstone, depending on its size, but in general each point was approximately 10 cm apart, both vertically and horizontally.

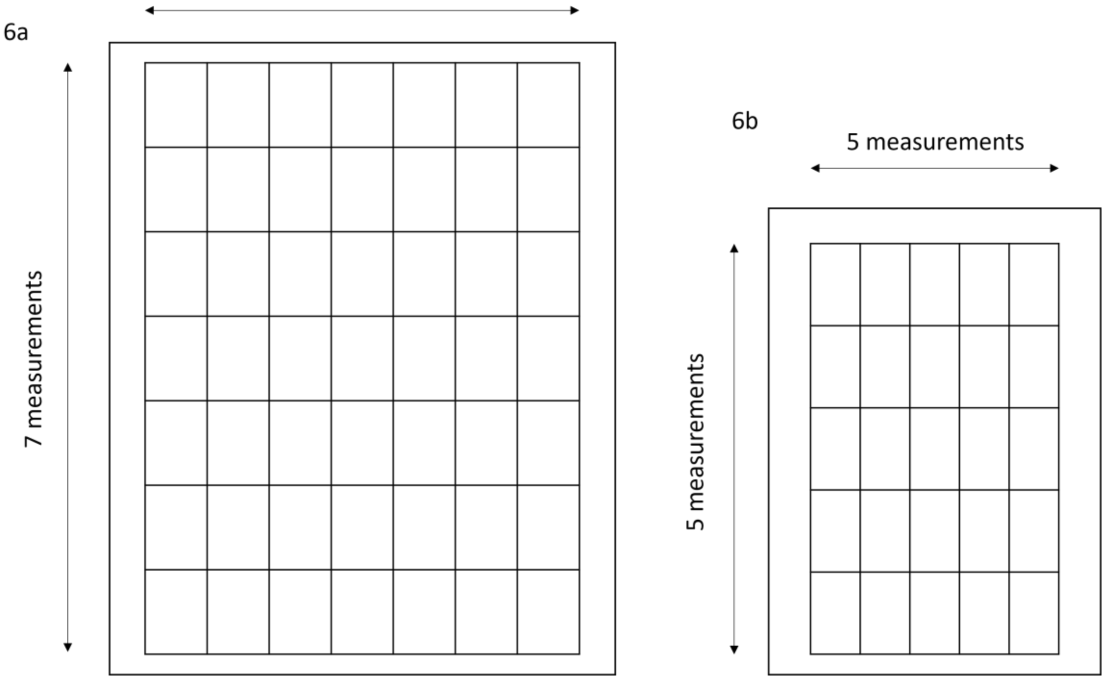


Figure 60. Spatial distribution of UPV measurements across large and small tombstones for high resolution field study method

The number of tombstones measured at each site is listed in Table 7:

Cemetery	Region	Number of tombstones sampled
Maitland Cemetery	Western Cape	32
Dido Valley Cemetery	Western Cape	8
Stellawood Cemetery	KwaZulu Natal	48
Stellawood Cemetery Wargraves	KwaZulu Natal	20
Howick Cemetery	KwaZulu Natal	10

Table 7. Number of tombstones measured in each cemetery for high-resolution UPV study

Howick and Dido Valley Cemeteries are both small, which limits the number of viable samples. Maitland Cemetery and Stellawood Cemetery are larger, which has resulted in larger sample sizes.

6.2.2. Statistical analysis

The total number of values taken for each tombstone were averaged to obtain a single value for tombstone, and these values were graphed against the tombstones' total exposure time, as determined by the date of death. This replicated the procedure followed in Objective 2. However, to account for any possible heterogeneity in terms of the measurements taken across each tombstone's surface, the *lowest* value for each stone was also graphed against the total exposure time. The reasoning was that weathering may not be taking place evenly across the entire surface of the tombstones, but rather been confined to specific locations determined by pre-existing points of weakness. If this were true, then the expected correlation between exposure time and ultrasonic pulse velocity might only be discernable at these points. These minimum values were also graphed against the exposure time. Both average and minimum value datasets were correlated to exposure time via the Spearman Rank correlation test.

A spatial auto-correlation analysis was also carried out for selected tombstones of various ages. This was done on individual tombstones to assess measured ultrasonic pulse velocities as a function of their spatial distribution. The statistical tool selected for this was the semi-variogram, which is designed to describe the variability of a series of measurements as a function of the space that they occupy and the relative distance between them (Curren, 1998). As such, it was used in this study to assess the relationship between UPV values across the surface of a tombstone via the following equation.

$$\gamma(h) = \frac{1}{2[n(h)]}\sum_{n(h)}(z_i - z_j)^2$$

This equation shows a relationship between the square of the difference between *z* values (in this case UPV) and the distance apart from one another (*h*). In general, for a system in which z values are spatially auto-correlated, γ will be low for low values of *h*, and will increase as *h* increases until it reaches a plateau (or sill). If γ remains consistent for increasing *h* values, this shows that UPV is not sensitive to changes in *h* and that UPV values are homogenous across a tombstone's surface. Results from this test were assessed according to a series of conceptual models laid out by Gauci et al. (2022), who used semivariograms to assess erosion rates on shore platforms. In the original publication, six models were proposed to describe the relationship between erosion and space, based on the line shape produced by the semivariogram analysis. For this study, only a subset of the original six were observed, which are listed in Figure 61.

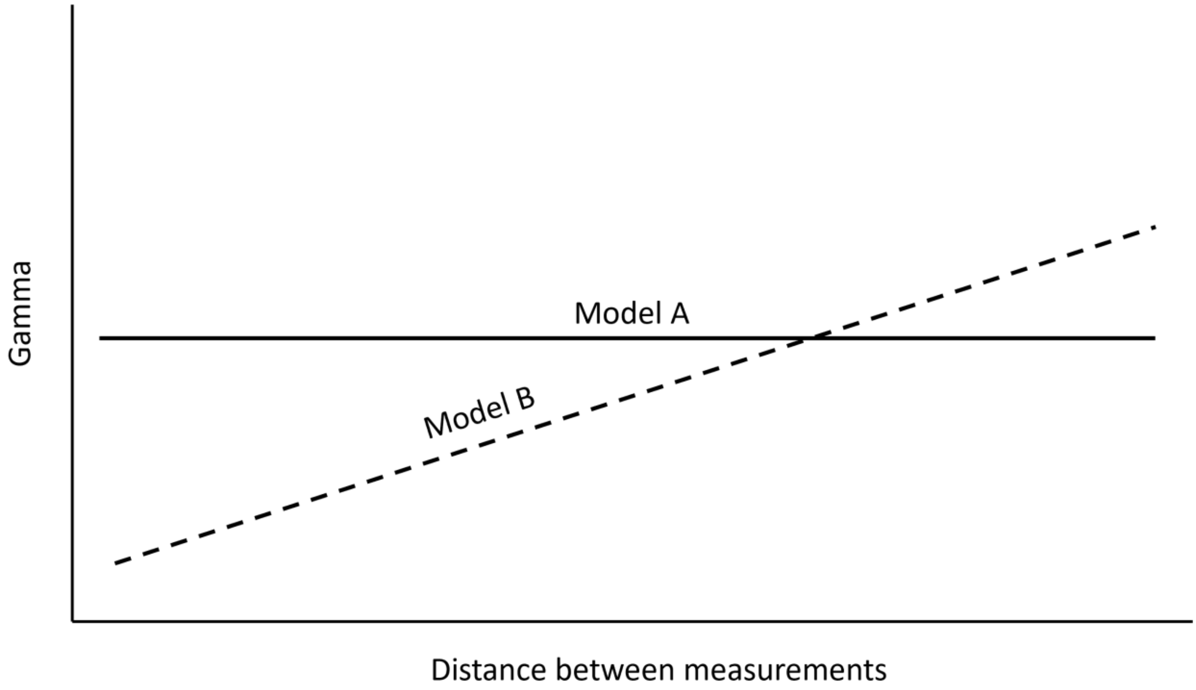


Figure 61. Line graph showing a subset of the semivariogram conceptual models described by Gauci et al. (2022)

According to Gauci et al. (2022), Model A is indicative of a system in which the measured variable (in this case UPV) does not change as the distance between points increases. This means that UPV is consistent across the entire surface and the weathering is, therefore, inferred to be consistent as well. Model B is a system in which UPV changes as distance between measured points increases. This would represent a system in which UPV is more varied across a tombstone's surface and that the overall weathering pattern is heterogenous. Model C, which is not represented on the graphic, would be a case in which there was no pattern and a trend could, therefore, not be determined. All semivariograms displayed in the section below will have the same y-axis range for a given cemetery to make visual comparison between them easier.

6.3. Results

Results for the various cemeteries each yield their own temporal and spatial UPV distributions, but these patterns do not appear to be consistent with one another. The results for each region will be presented separately.

6.3.1. Maitland Cemetery

This cemetery is 3 km away from the ocean at its closest point, but is protected from ocean winds by several large buildings. This means, that while the cemetery experiences a distinct maritime climate, it is not directly affected by wind coming the Atlantic Ocean. 34 tombstones were sampled from the cemetery, with dates of death ranging from 1919 to 2009.

6.3.1.1. Maitland Cemetery spatial analysis

R studio was used to interpolate values to create contour maps from the raw data in increments of 600m/s. Only a selection of the area scans are displayed here, but the images for all of the measured tombstones at Maitland Cemetery can be found in Appendix 4. Figure 62 shows an area scan of two of the newer stones (2008 and 2009) and differences in the spatial distribution of the ultrasonic pulse velocities can be observed. Colours tending towards blue represent faster ultrasonic pulse velocities, while colours tending towards red are slower.

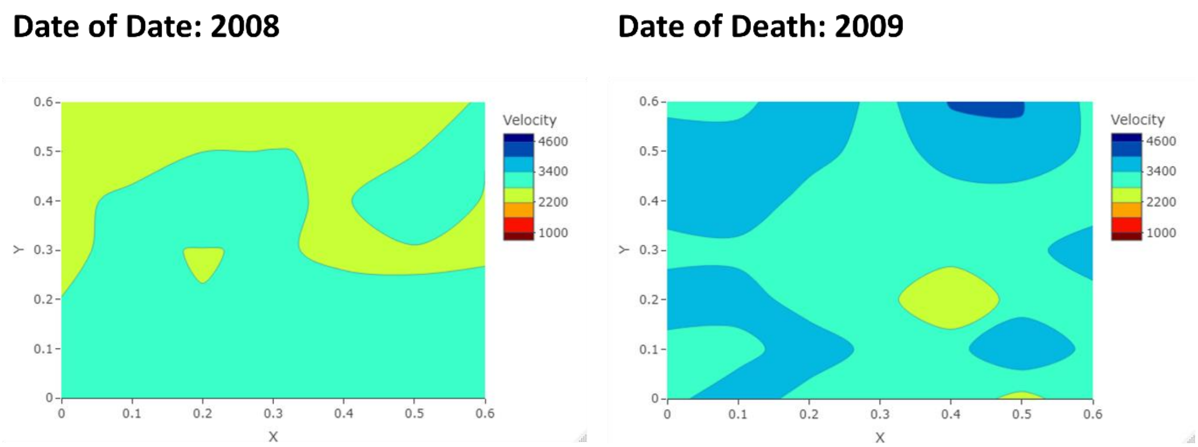


Figure 62. Ultrasonic pulse velocities of two tombstones aged from 2008 and 2009, Maitland Cemetery

While the two diagrams appear visually distinctive, a semivariogram shows that the relative variance of UPV values across their respective surfaces do not change substantially as a function of distance (Figure 63). This corresponds with Model A in Figure 61, and indicates that UPV distribution across the surface of the tombstones has a high degree of homogeneity, and that weathering is, therefore, consistent across the entire surface.

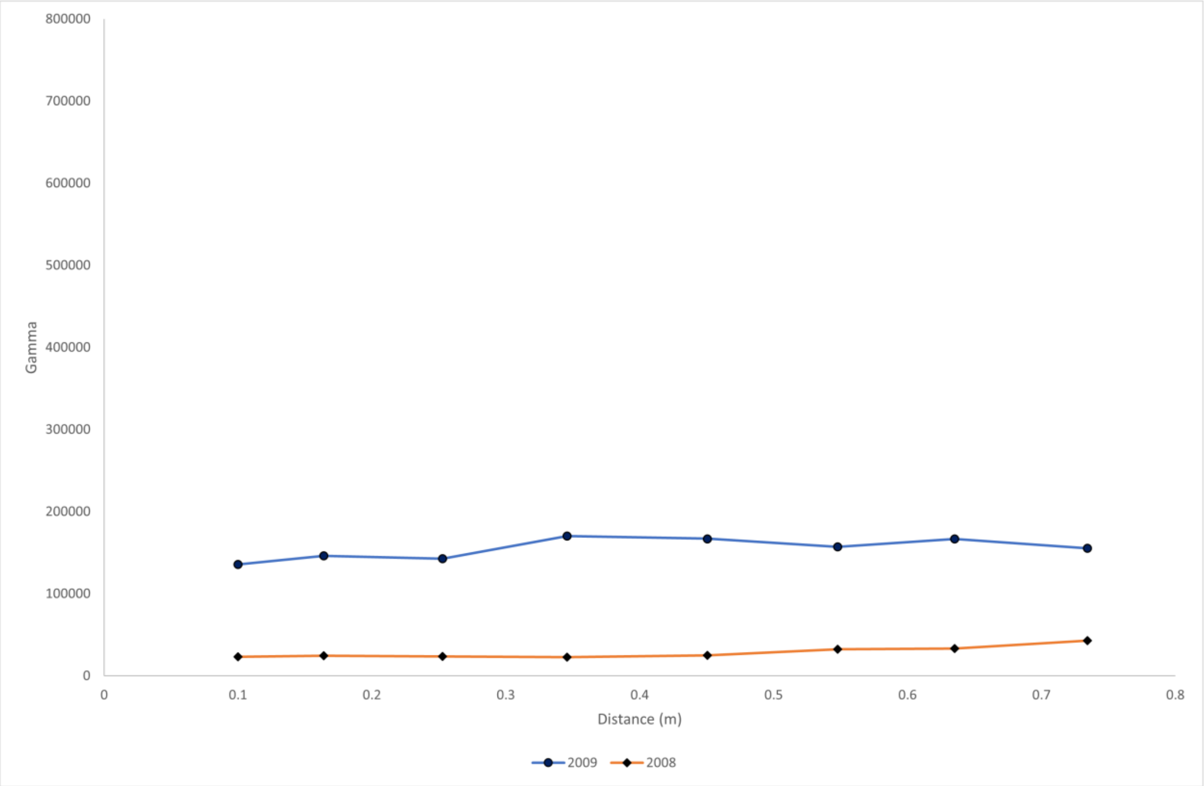
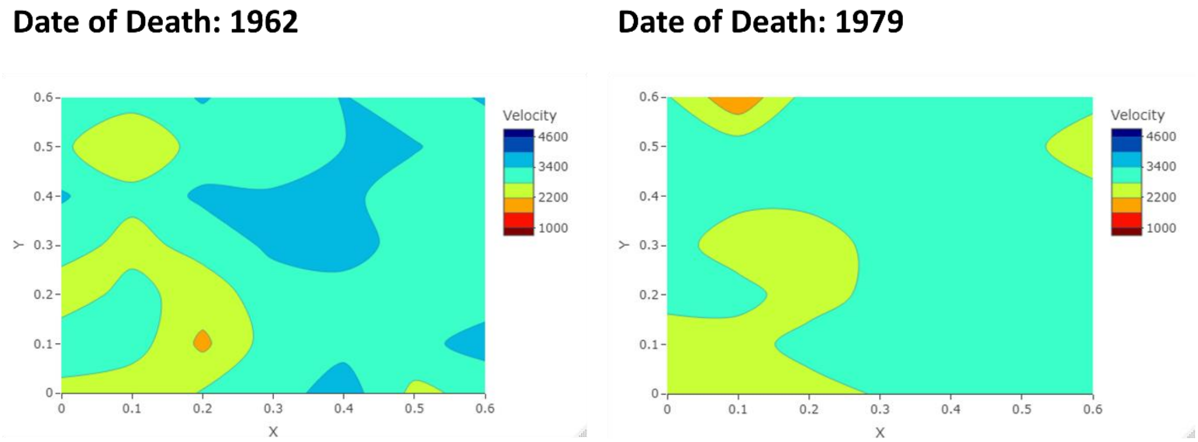


Figure 63. Semivariogram representing the relationship between gamma and distance values for two tombstones circa 2008 - 2009

This pattern changes only slightly for stones that have been in the cemetery more recently than 1960. (Figure 64). However, lower pulse velocities are recorded at a greater number of locations across the surface of the stones than before.



Date of Death: 1962

Date of Death: 1979

Figure 64. ultrasonic pulse velocities of two tombstones aged from 1962 and 1979, Maitland Cemetery

Semivariogram analysis confirm the visual assessment of the UPV distribution (Figure 65). The gamma values show a slight monotonic increase with respect to distance, which supports the assertion that the UPV values are more heterogenous than those observed for the tombstones from 2008 and 2009, although the difference at this stage is still small.

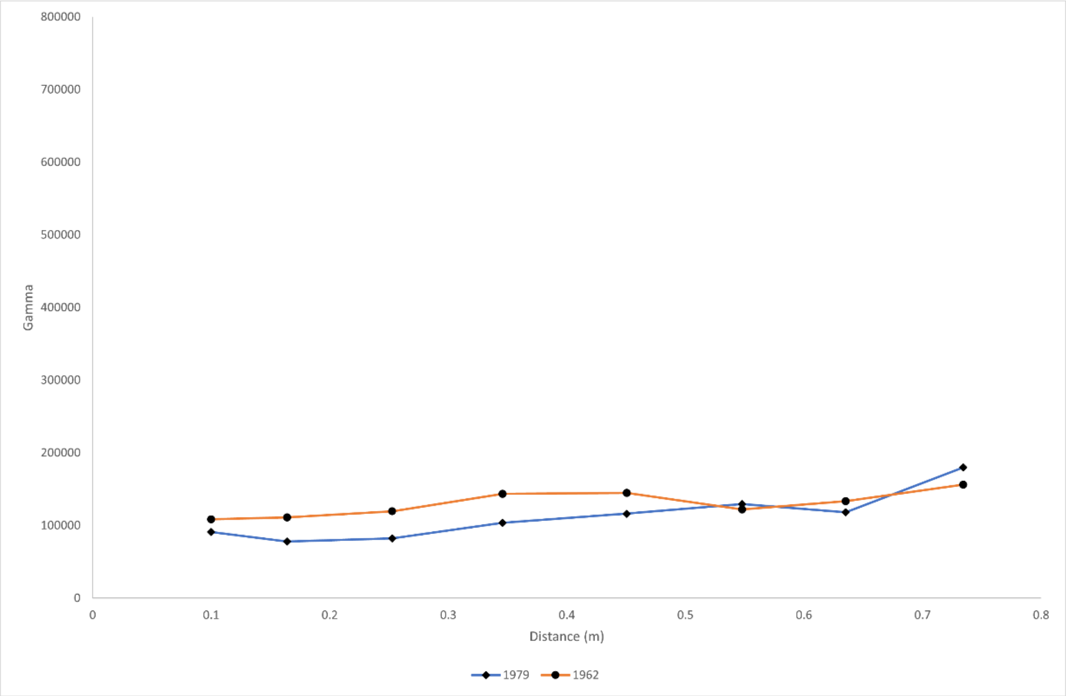


Figure 65. Semivariogram representing the relationship between gamma and distance values for two tombstones (ages 1962 and 1979)

Overall, the weathering pattern across the tombstones has remained consistence and generally homogenous. In general, most tombstones from this cemetery newer than 1962 produce semivariograms that conform to Model A.

Once the stones have been present at the cemetery for approximately 50 years, the lower pulse velocity values begin to appear over a larger percentage of the tombstones surface, suggesting that weathering most likely begins at pre-existing points of weakness in the tombstone, spreading out from there in a front as the surface area of the sphere of weakness increases.

After 70 years of exposure, areas of low pulse velocity have become widespread, suggesting that the weathering front has spread over a greater portion of the stone (Figure 66).

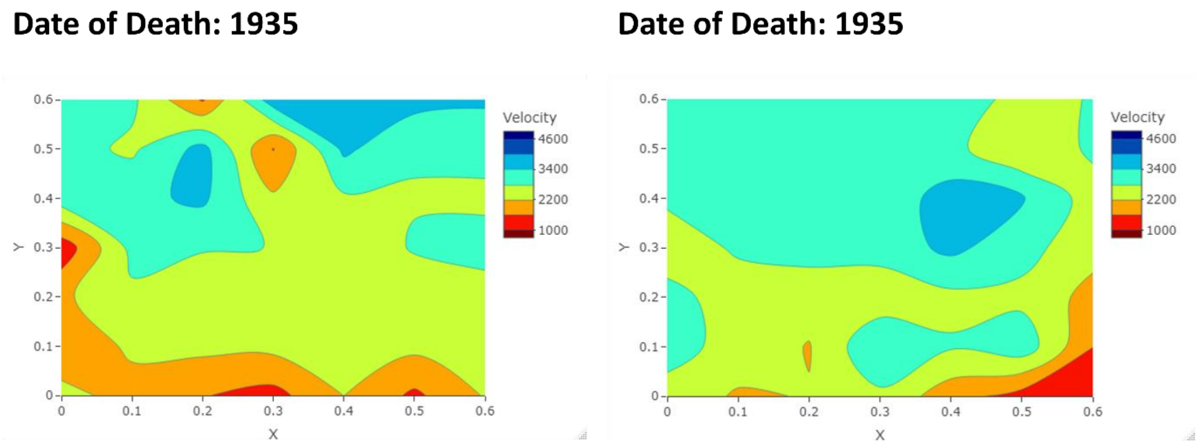


Figure 66. Ultrasonic pulse velocities of two tombstones placed in 1935, Maitland Cemetery

Semivariogram analysis also shows a considerable difference in pattern when compared to newer stones (Figure 67). These two tombstones conform to Model B rather than Model A, which shows that UPV changes as the distance between measured points changes. UPV is, therefore, more variable over these surfaces and weathering is consequently more varied as well.

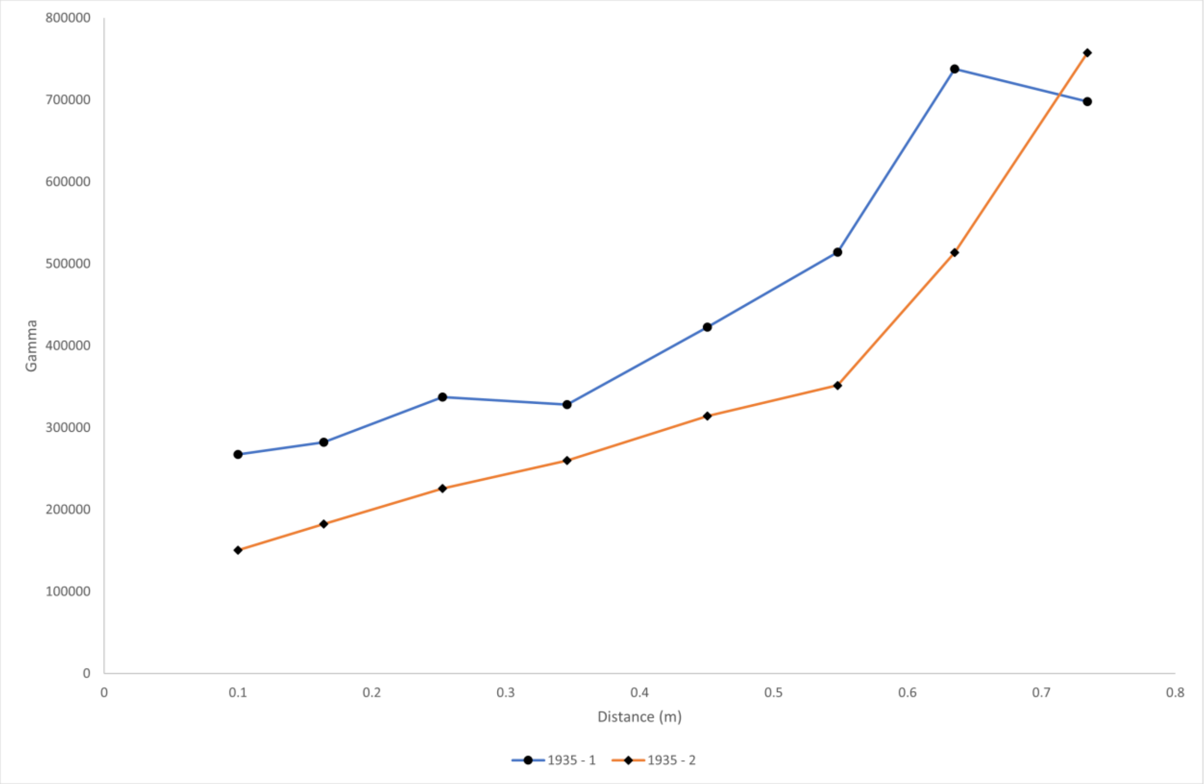


Figure 67. Semivariogram representing the relationship between gamma and distance values for two tombstones (age 1935)

6.3.1.2. Maitland Cemetery time series analysis

Initial time series analysis was carried out according to the method laid out by Loubser (2022), in which the average pulse velocity for each stone was graphed against the time it had been present in the cemetery (as derived from the date of death), hereafter referred to as the tombstone’s ‘Age’.

While Loubser (2022) demonstrated a statistically significant correlation between Age and UPV for the Cullinan Main Cemetery, Maitland Cemetery does not yield the same results (Figure 68).

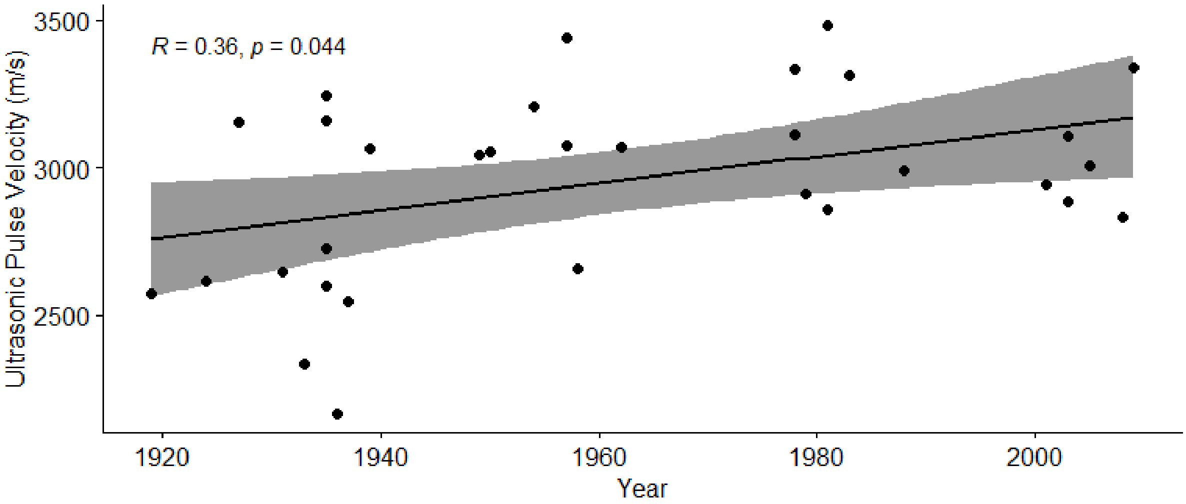


Figure 68. Linear regression relationship between Age (Year) and average UPV, with Spearman Rank correlation coefficient, for Maitland Cemetery, Cape Town (n = 32)

While there is an apparent positive correlation between Age and UPV, the relationship is not statistically significant (R = 0.36). However, the area scans and semivariograms of the tombstones shown above have demonstrated that weathering is not homogenous across the surface of the stones. To account for this weathering heterogeneity, *minimum* pulse velocity for each stone was graphed against age (Figure 69).

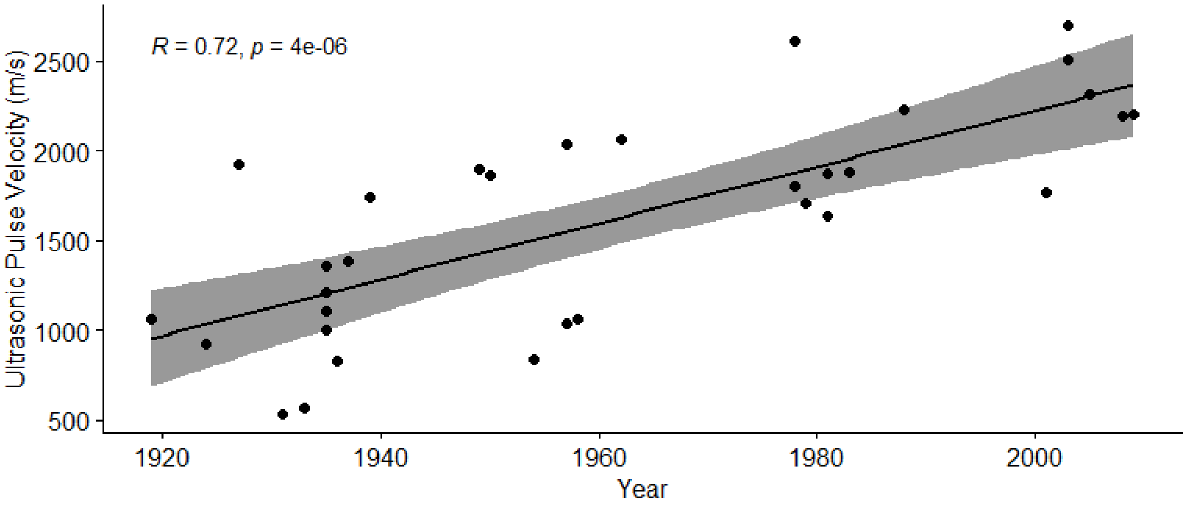


Figure 69. Linear regression relationship between Age (Year) and minimum UPV, with Spearman Rank correlation, for Maitland Cemetery, Cape Town (n = 32)

The resulting data yield a statistically significant correlation between Age and UPV (at $p < 0.005$), which shows positive relationship between the exposure time of the tombstones and the minimum UPV values.

6.3.1.3. Variation of ultrasonic pulse velocities for old and new tombstones

There is a considerable degree of variation in the spatial distribution of the ultrasonic pulse velocities across the entire range of tombstones assessed at Maitland Cemetery. However, it is possible to assess the spatial heterogeneity as a function of time by categorising the tombstones into three age brackets and then comparing the average ultrasonic pulse velocity distributions relative to one another (Figure 70). Stones that range in age from 2009 to 1949 have pulse velocity measurements of between 2667 m/s and 3500m/s that cover on average 70% of each tombstone, with 15% of measurements above 3500 m/s and the remainder below 2667 m/s. However, stones that are older than 1939 show 45% of measurements lying between 2667 m/s and 3500 m/s and just under 40% of measurements lying between 1833 m/s and 2667 m/s. The older tombstones thus have a much higher percentage of measurements at lower values than the newer ones. Notably for the older stones, over half of all measurements are above 2667 m/s and nearly 10% of all measurements taken from older tombstones are above 3500m/s. UPV measurements, therefore, do not decrease uniformly with tombstone age. Instead, on average, over 55% of measured ultrasonic values remain within the velocity range that was observed for the newer tombstones.

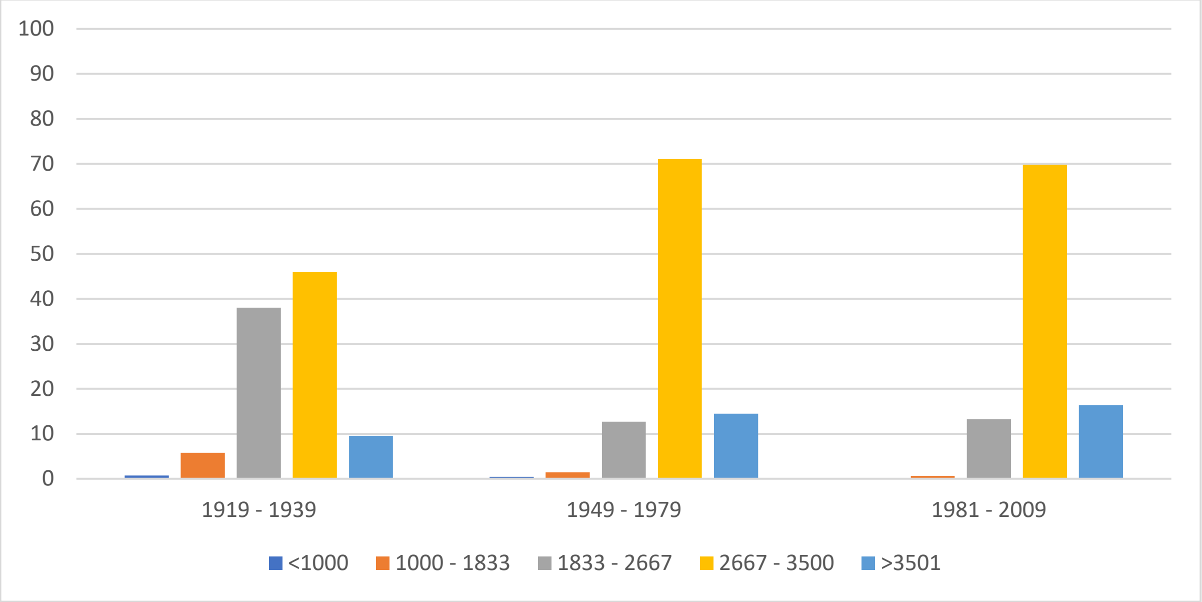


Figure 70. Ultrasonic pulse velocity coverage of tombstones as a function of age, divided into 30 year increments

6.3.2. Dido Valley Cemetery

Dido Valley Cemetery is only 70 metres away from the ocean, with tombstones being heavily exposed to onshore sea breezes from the Atlantic Ocean. The tombstones in this cemetery appear visually to be highly weathered, even for stones that have been in the cemetery for less than 50 years. The sample size for this cemetery is small (n = 8), due to the small size of the cemetery, but useful information can still be extracted. As in the case of the Maitland dataset, a selection of the scans is displayed here, with the remainder shown in Appendix 5.

6.3.2.1. Dido Valley Cemetery spatial visualisation

The newer tombstones demonstrate similar spatial patterns to those observed in Maitland Cemetery, with newer stones being reasonably homogenous in terms of their UPV values (Figure 71). The unusually low values in the corners of the 2020 stone may have occurred due to edge effects, as this stone was smaller than average, with the transducers placed closer to the edge of the stone than would typically be desirable. Despite this, the remaining values are mostly above 4000 m/s, with a few values being lower. The 2015 tombstone shows values consistently above 6000 m/s. It is the only stone in the entire study to have values this high, but the stone was also visually pristine and polished on all sides, unlike most of the other stones in this cemetery, so this stone may not be representative of the cemetery as a whole.

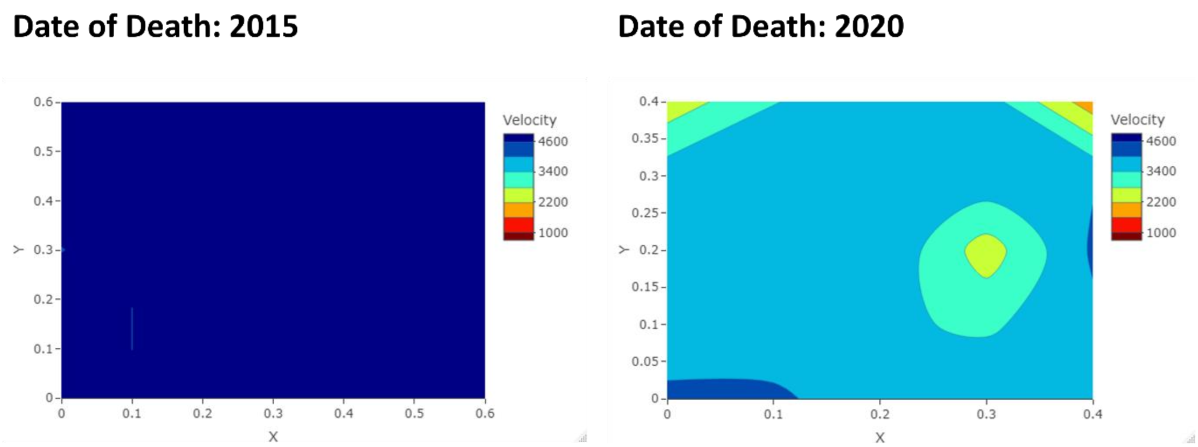


Figure 71. Ultrasonic pulse velocities of two tombstones placed in 2015 and 2020, Dido Valley Cemetery

As with Maitland Cemetery, stones that have been in the cemetery for 90 years display lower pulse velocity values than newer stones (Figure 72), although the lower values cover a greater percentage of the tombstones than stones of an equivalent age in Maitland.

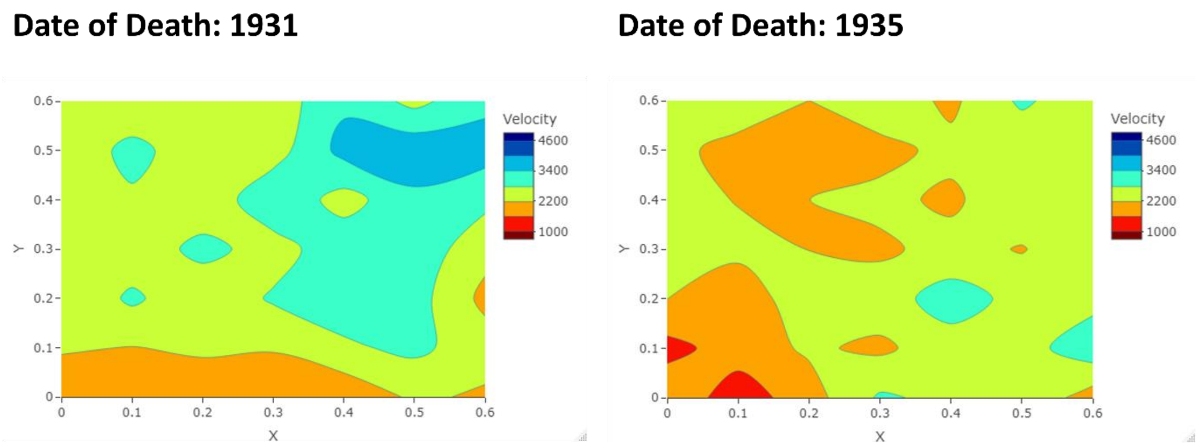


Figure 72. Ultrasonic pulse velocities of two tombstones placed in 1931 and 1935, Dido Valley Cemetery

The patterns observed in Dido Valley show a visually similar pattern to those of Maitland, although the stones appear have a greater degree of spatial homogeneity by comparison.

6.3.2.2. Dido Valley Spatial Analysis

The Dido Valley dataset contains only eight tombstones due to its small size, but there are some conclusions that can still be drawn. A Spearman rank corelation test does not show a statistically significant relationship between UPV and tombstone age, but there is still a relationship between the two variables in which UPV generally increases monotonically with respect to tombstone age. (Figure 73). The relationship between minimum UPV value and tombstone age (Figure 74), shows an even weaker correlation between the two variables. This is different to that observed for the Maitland Cemetery dataset.

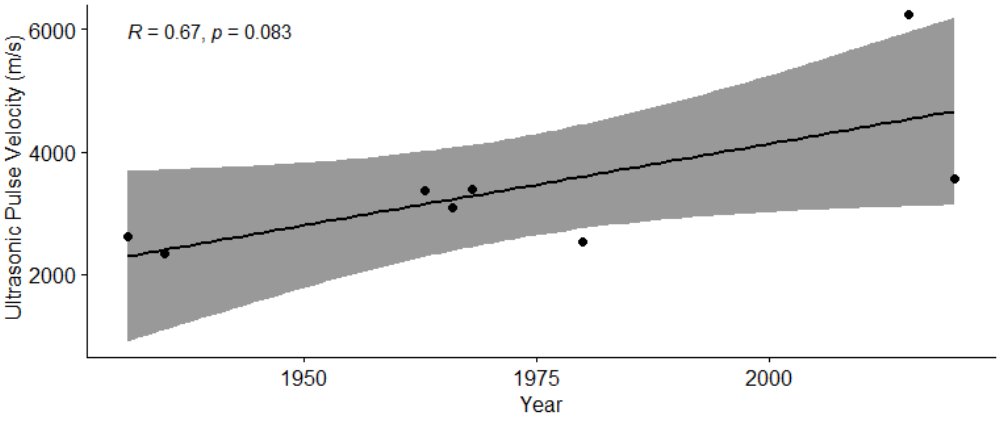


Figure 73. Linear regression relationship between tombstone age (Year) and average UPV, with Spearman Rank correlation, for Dido Valley Cemetery, Simon's Town (n = 8)

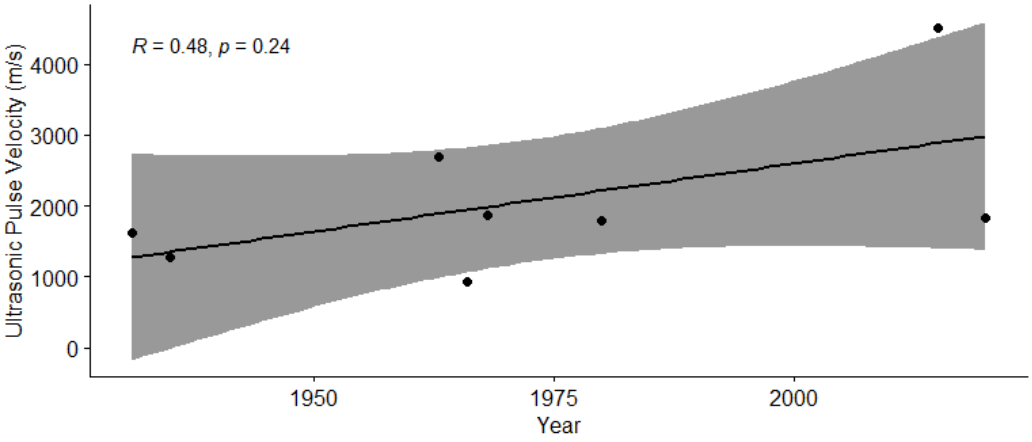


Figure 74. Linear regression relationship between tombstone age (Year) and minimum UPV, with Spearman Rank correlation, for Dido Valley Cemetery, Simon's Town (n = 8)

6.3.3. Stellawood Cemetery

Stellawood Cemetery lies 6km away from the nearest ocean, within the boundaries of the city of Durban itself. The cemetery lies within a topographic depression, with tombstones spaced along the bottom and sides. Forty-eight standard gabbro tombstones were assessed, as well as 20 wargraves under the care of the Commonwealth Wargraves commission. A selection of the Stellawood Cemetery tombstones will be presented in the next section of this document, but the remainder of the measured tombstones are displayed in Appendix 6 of this thesis.

6.3.3.1. Stellawood Cemetery spatial analysis

The two newest stones that were sampled were placed in 2020 (Figure 75). UPV values typically lie between 2667 and 3500 m/s, although there are some variances, both above and below this range.

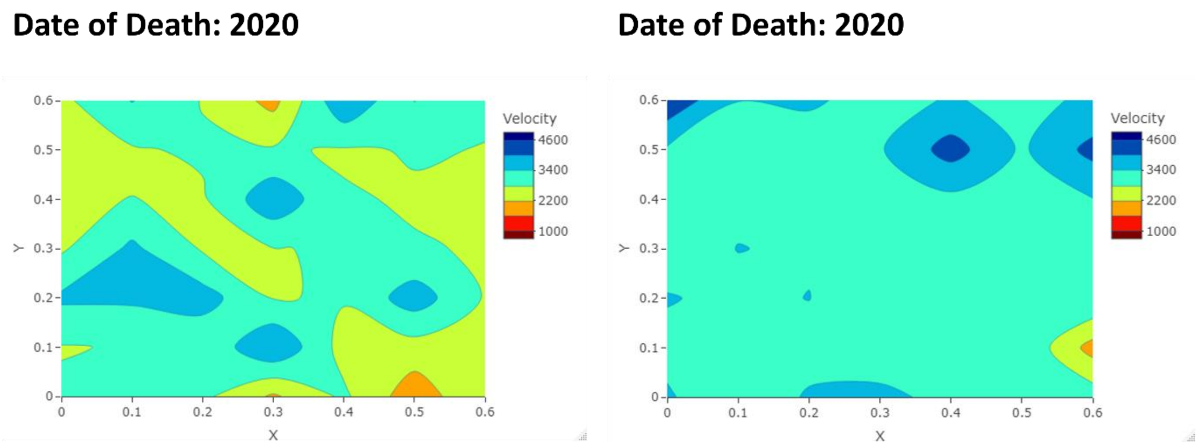


Figure 75. Ultrasonic pulse velocities of two tombstones placed in 2020, Stellawood Cemetery

An analysis of the semivariogram for these tombstones (Figure 76) shows a more variable pattern than those observed at Maitland Cemetery. One of the tombstones showed an increase in UPV values as measurement distance increased (Model B), while the other showed little change (Model A). Both tombstones were placed circa 2020, which was only two years before they were measured. Therefore, differences in the semivariograms have occurred because of differences in the starting conditions of the tombstones (i.e. the rock properties) rather than because of differential weathering. This indicates that tombstones that are visually similar and comprise of the same rock type may still yield different UPV values across their surfaces. This difference in initial rock conditions may have dramatic consequences on the weathering that takes place and will likely result in different weathering profiles for tombstones that have otherwise experienced the same climatic regime.

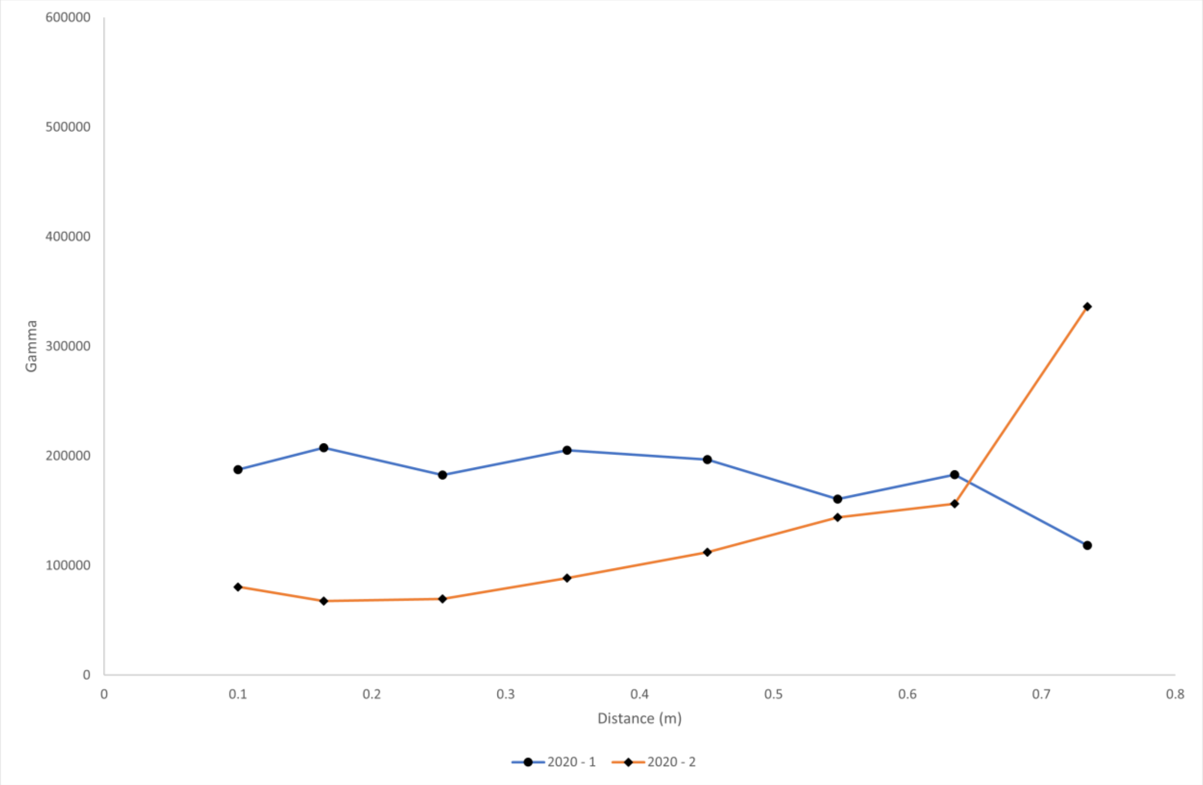


Figure 76. Semivariogram representing the relationship between gamma and distance values for two tombstones (age 2020)

Figure 77 shows the UPV spectrums of two tombstones placed in the cemetery circa 2002. These stones have returned higher UPV values on average than the newer ones and also show a higher degree of homogeneity, as seen from the semivariogram shown in Figure 78, in which both stones comply more closely with Model A than Model B. The data appear to show that these stones have weathered very little. This would be possible if these tombstones were had few points of preexisting weakness when they were initial placed in the cemetery.

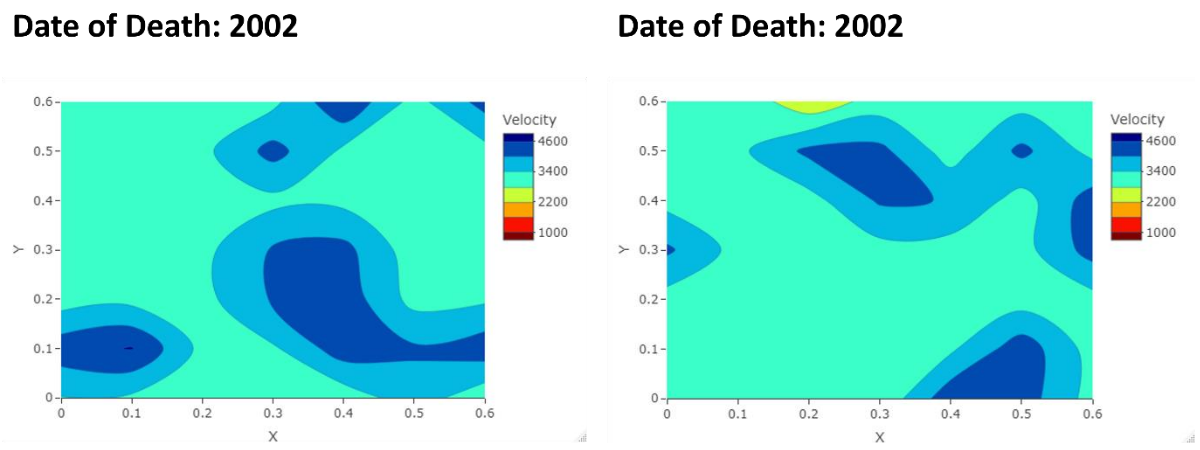


Figure 77.Ultrasonic pulse velocities of two tombstones placed in 2002, Stellawood Cemetery

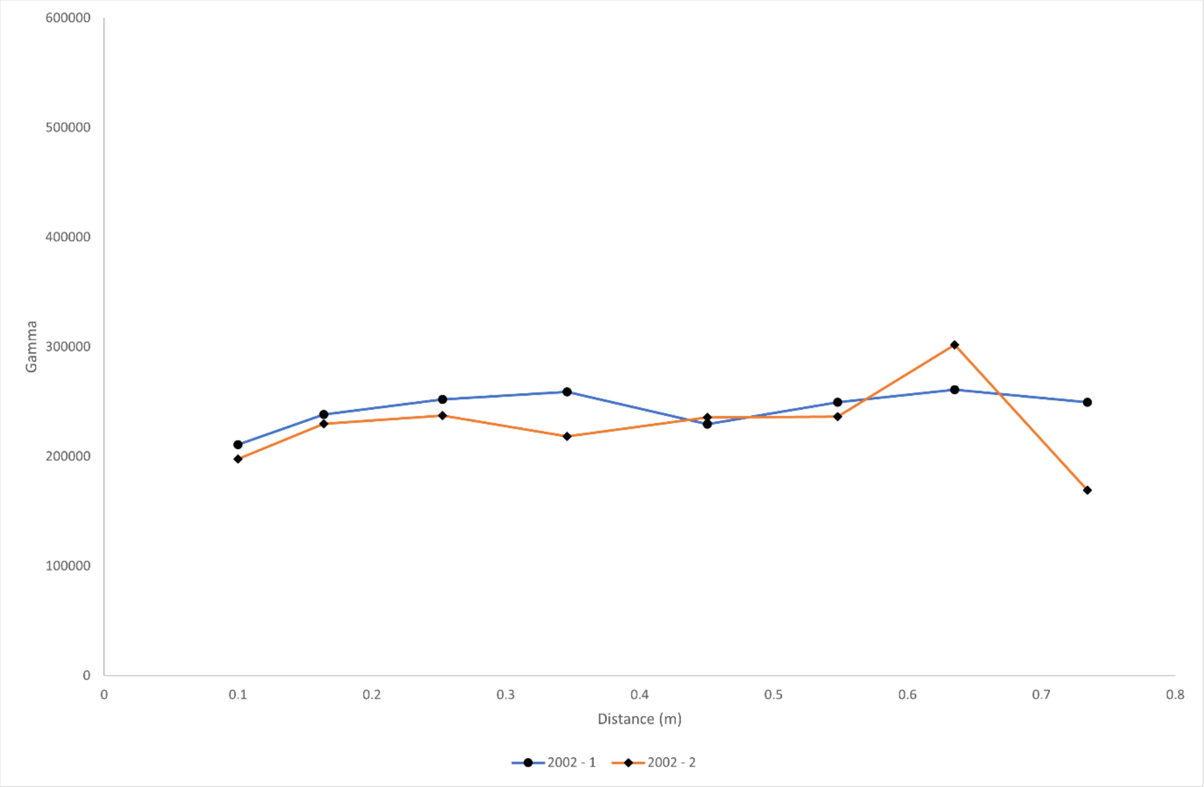


Figure 78. Semivariogram representing the relationship between gamma and distance values for two tombstones (age 2002)

Tombstones that have sat *in situ* for approximately 60 years also show relatively little change when compared to new stones, although there are once again signs of a degree of spatial heterogeneity (Figure 79). This appears to indicate that the stones have changed little in that time.

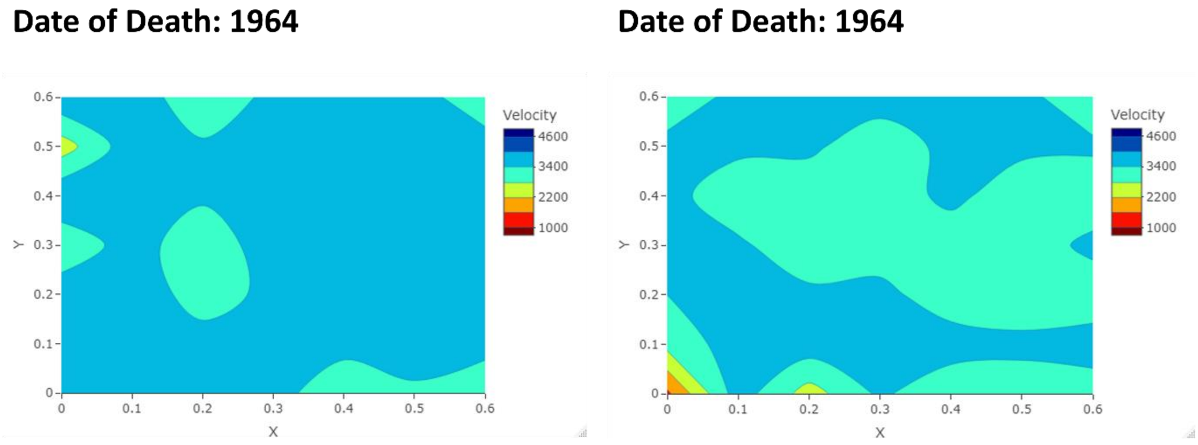


Figure 79. Ultrasonic pulse velocities of two tombstones placed in 1964, Stellawood Cemetery

The semivariograms for these two tombstones yield additional insights into the distribution of UPV values across their respective faces (Figure 80). First, both of the tombstones show monotonically increasing gamma values as distance increases, but that for one of them, UPV values diverge more radically than for the other. This suggests that the stones are both weathering, but not in the same way.

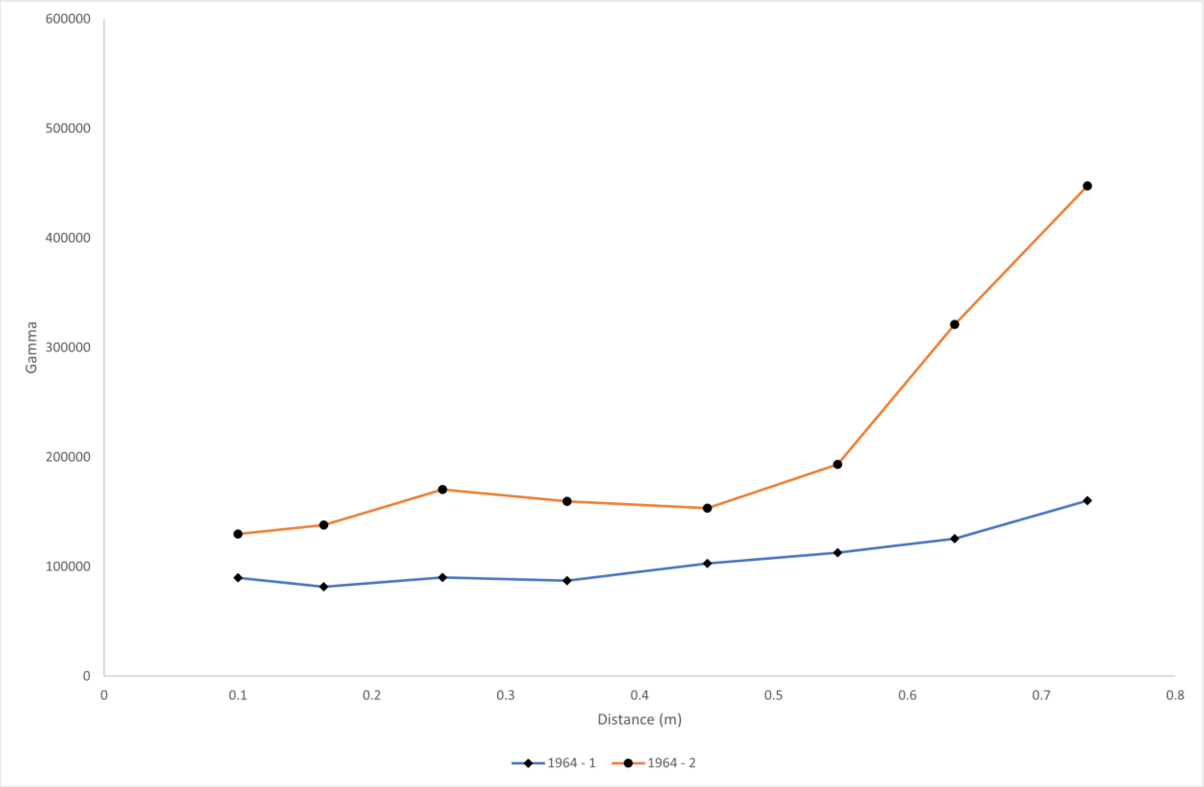
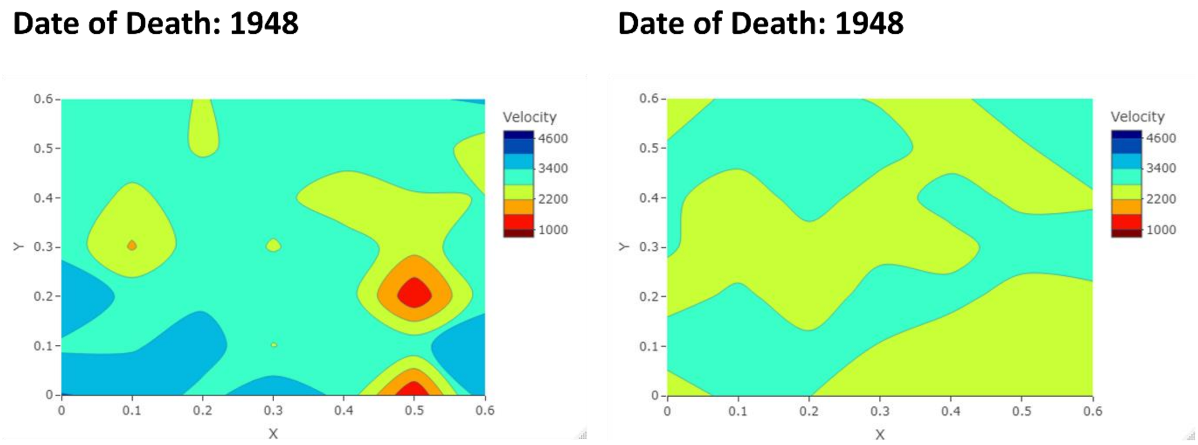


Figure 80. Semivariogram representing the relationship between gamma and distance values for two tombstones (age 1964)

After approximately 75 years, changes in the distribution of UPV pulse velocity measurements begin to become evident (Figure 81). Specifically, very high UPV values are less prevalent, and lower values begin to manifest themselves at certain points on the stones (although not necessarily equally from one stone to the next).



Date of Death: 1948

Date of Death: 1948

Figure 81. Ultrasonic pulse velocities of two tombstones placed in 1948, Stellawood Cemetery

As with the tombstones from 1964, the semivariograms for the tombstones from 1948 both show monotonically increasing trends (Model B), but with different patterns (Figure 82). This again suggests that the tombstones are weathering, but not in the same way.

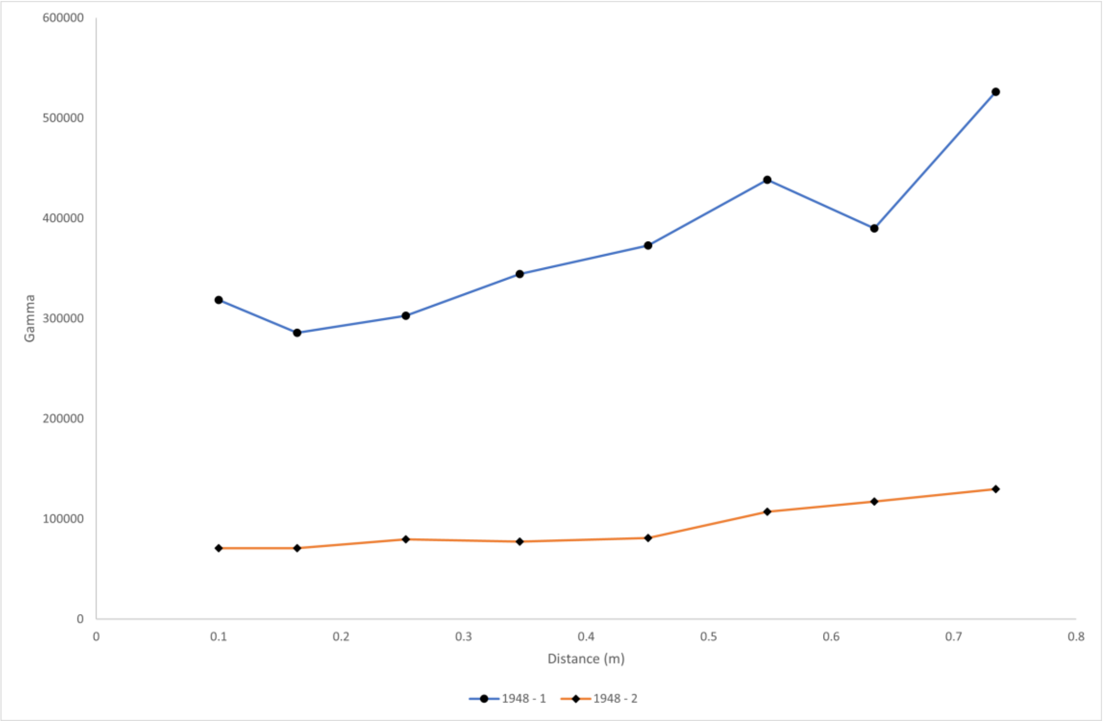


Figure 82. Semivariogram representing the relationship between gamma and distance values for two tombstones (age 1948)

The UPV values of stones that have been in the cemetery for between 80 and 100 years (Figure 83). are not very different to those that have been *in situ* for 60 years. The changes in UPV measurements at Stellawood Cemetery are, therefore, not as profound as those found, for example, in Maitland Cemetery, Cape Town.

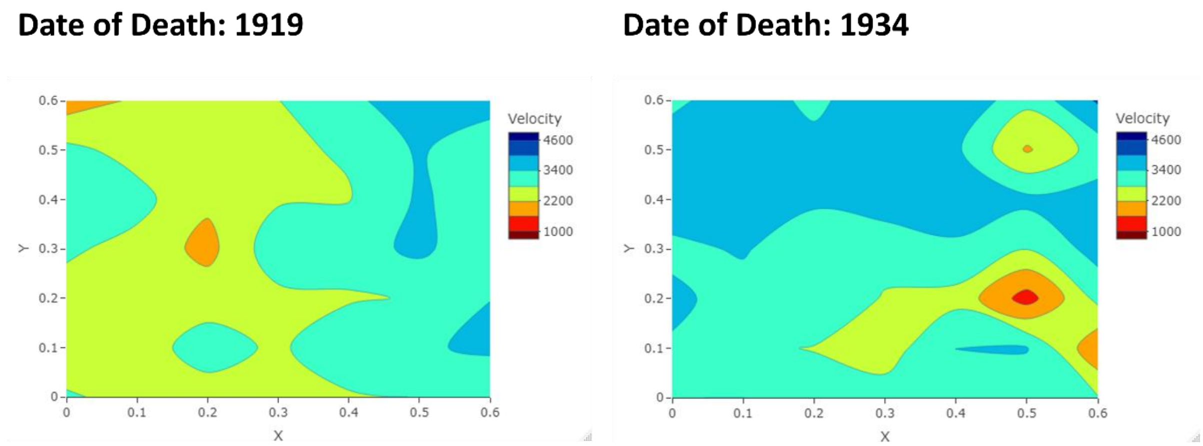


Figure 83. Ultrasonic pulse velocities of two tombstones placed in 1919 and 1934, Stellawood Cemetery

The semivariograms for these stones both show a strong monotonically increasing relationship (Model B), which indicates a heterogenous distribution of UPV values across each of these tombstones.

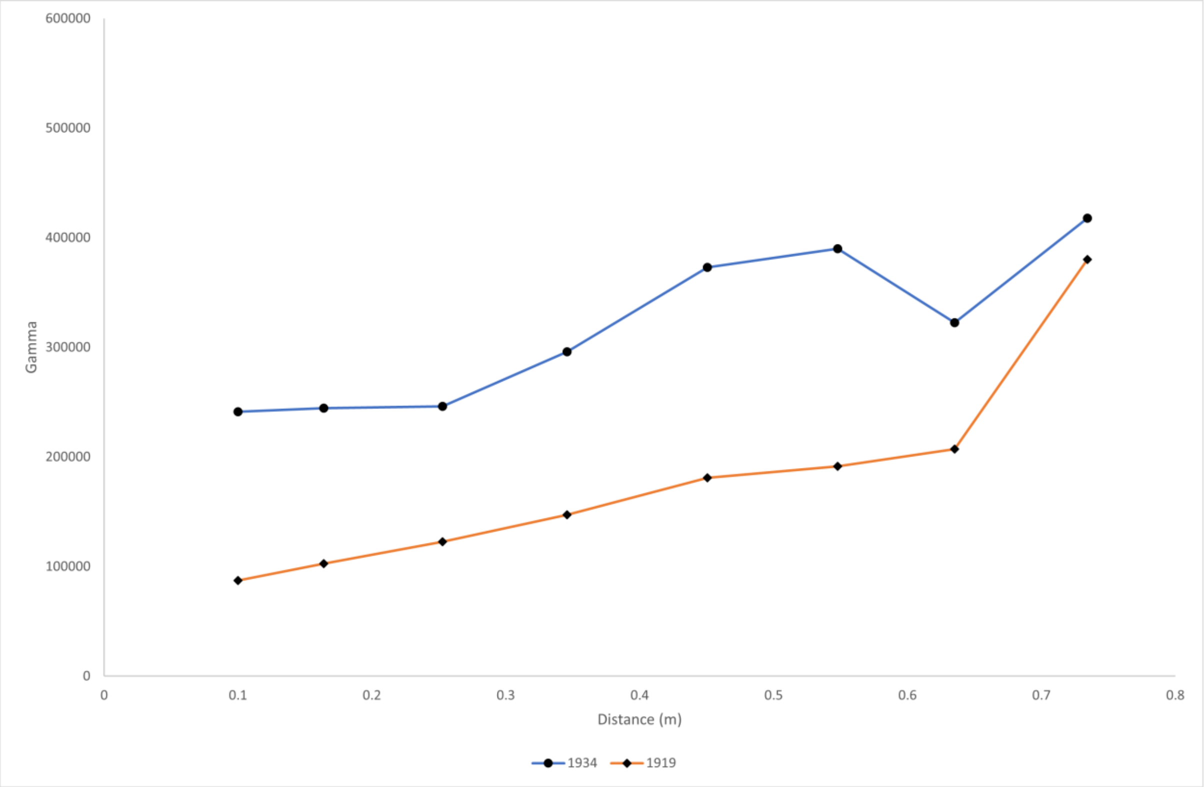


Figure 84. Semivariogram representing the relationship between gamma and distance values for two tombstones (age 1919 and 1934)

6.3.3.2. Stellawood Wargraves

As indicated above, Stellawood Cemetery has a special section dedicated to the fallen soldiers. At Stellawood, this section is filled almost exclusively with soldiers and sailors that fell in World War 2, or just after. Since Durban is a port city, it is not surprising that many of these people served in the South African Navy. Twenty tombstones were assessed from this group. 19 of the 20 fell in combat in either 1943 or 1944, with one person passing away in 1947. This gives a narrow temporal band for this particular dataset. These tombstones are of very similar design and manufactured from gabbro. Any differences in weathering intensity or rock structure are, therefore, due to the pre-existing structure of the rock that comprises each tombstone. Most of the tombstones in this data set have patterns similar to those represented in Figure 85. However, six of the twenty tombstones have displayed a different pattern, a selection of which are shown in Figure 86. The entire dataset is displayed in Appendix 7.

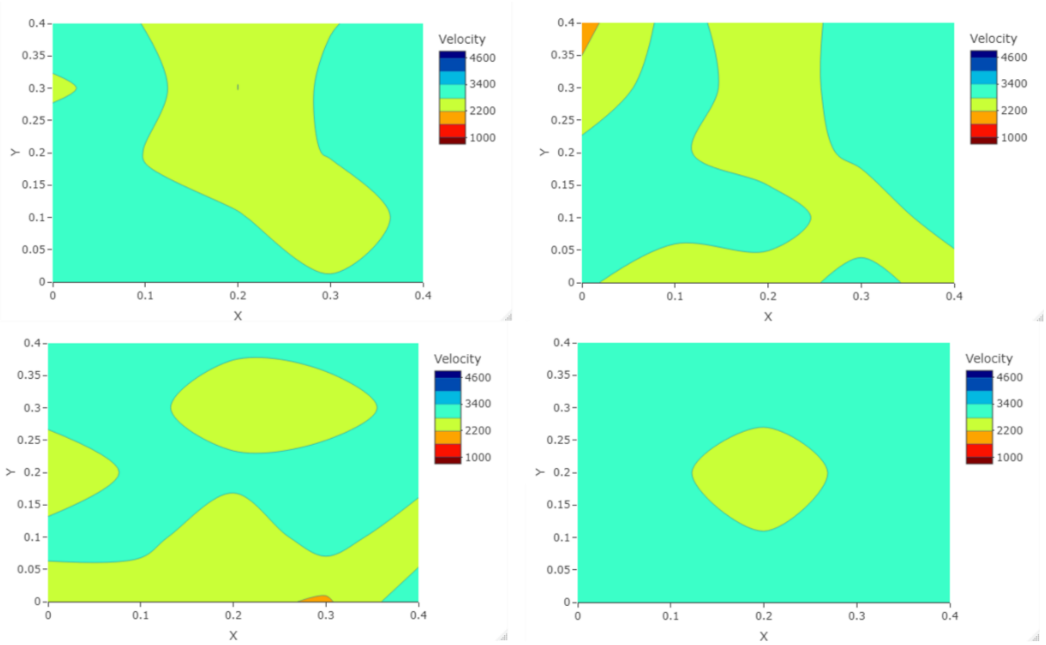


Figure 85. UPV values for four typical wargraves in Stellawood Cemetery

These tombstones show larger UPV ranges than the other tombstones. In particular, they have similar maximum UPV values to the rest of the set, but exhibit lower than average UPV values for between 1 and 3 measurements out of the total 25. This means that these tombstones contain small regions that are more highly degraded than other parts of the sample.

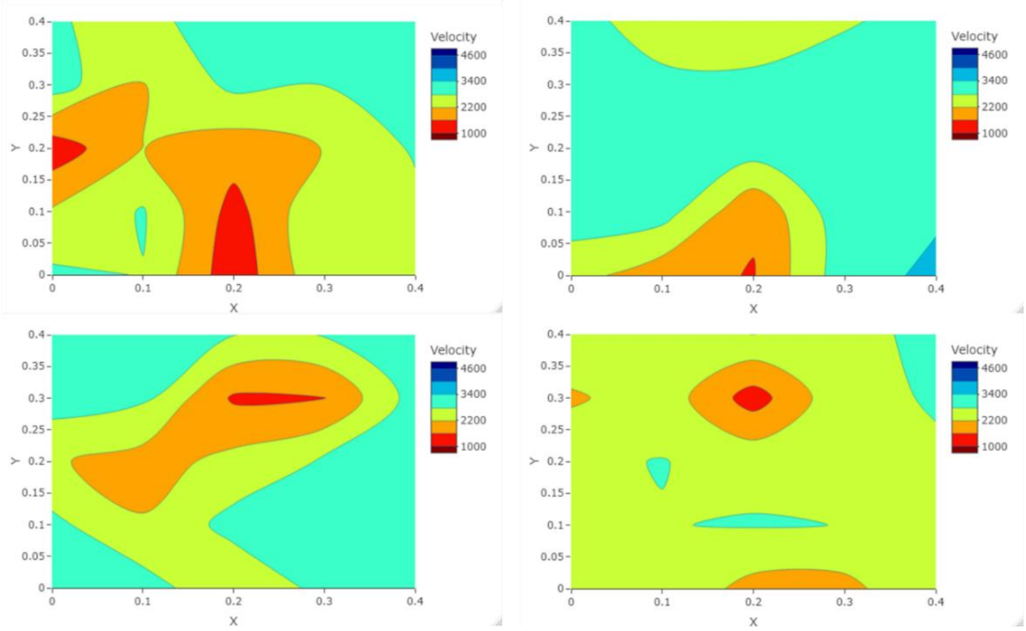


Figure 86. UPV values for four atypical wargraves in Stellawood Cemetery

6.3.3.3. Stellawood time series analysis

The time series analysis graphics do not display the same levels of significance as do the tombstones in Maitland. The Spearman Rank correlations for the average values are statistically significant for $p < 0.05$ (Figure 87), and the minimum values are statistically significant for $p < 0.01$ (Figure 88). However, this represents a much weaker relationship than that observed in Maitland.

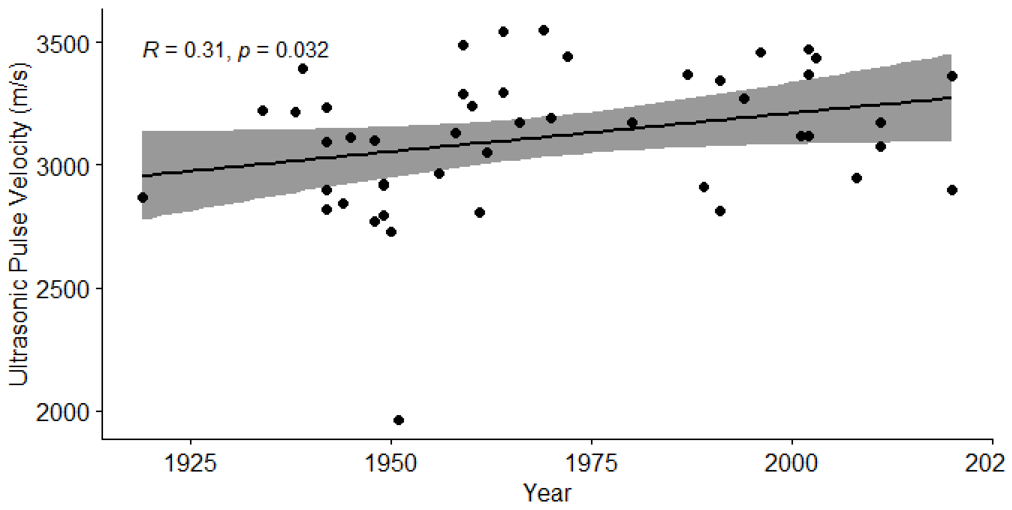


Figure 87. Linear regression relationship between Age (Year) and average UPV, with Spearman Rank correlation, for Stellawood Cemetery, Durban (n = 48)

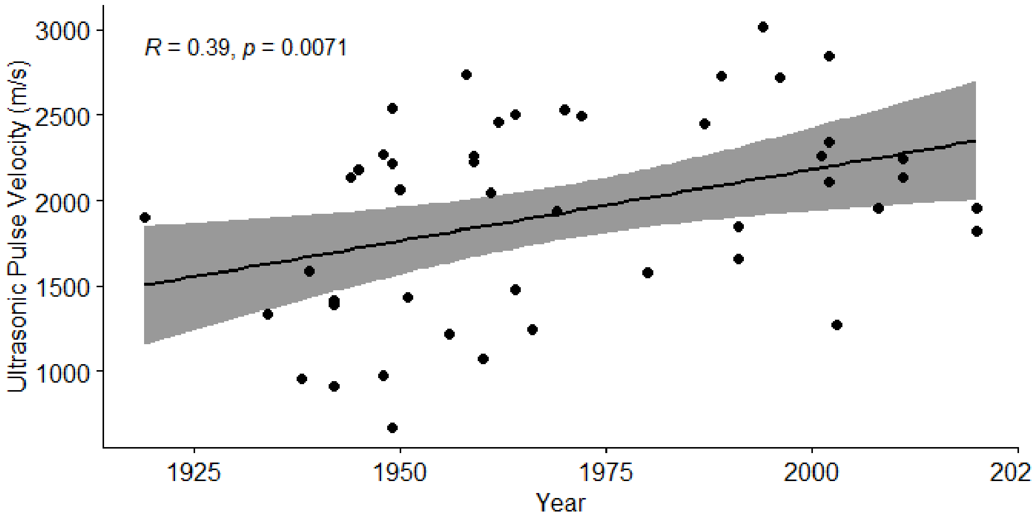


Figure 88. Linear regression relationship between Age (Year) and minimum UPV, with Spearman Rank correlation, for Stellawood Cemetery, Durban (n = 48)

The stones in Stellawood Cemetery are thus not degrading according to the same pattern as those in Maitland, but rather degrade in a more random fashion.

6.3.3.4. Variation of ultrasonic pulse velocities for old and new tombstones

The spatial distribution of UPV values is different to those of Maitland, but exhibit some similarities (Figure 89). Specifically, for the majority of stones, most of the returned

UPV measurements lie between 2667 m/s and 3500 m/s. Two notable differences are the greater number of high UPV values for the older stones as compared to the new ones, and the reduced number of measurements that lie below 2667 m/s for the older stones. This shows that, from a spatial perspective, there is a wider range of UPV values for the older stones than for the newer ones, but this signal is weaker than that observed for Maitland Cemetery.

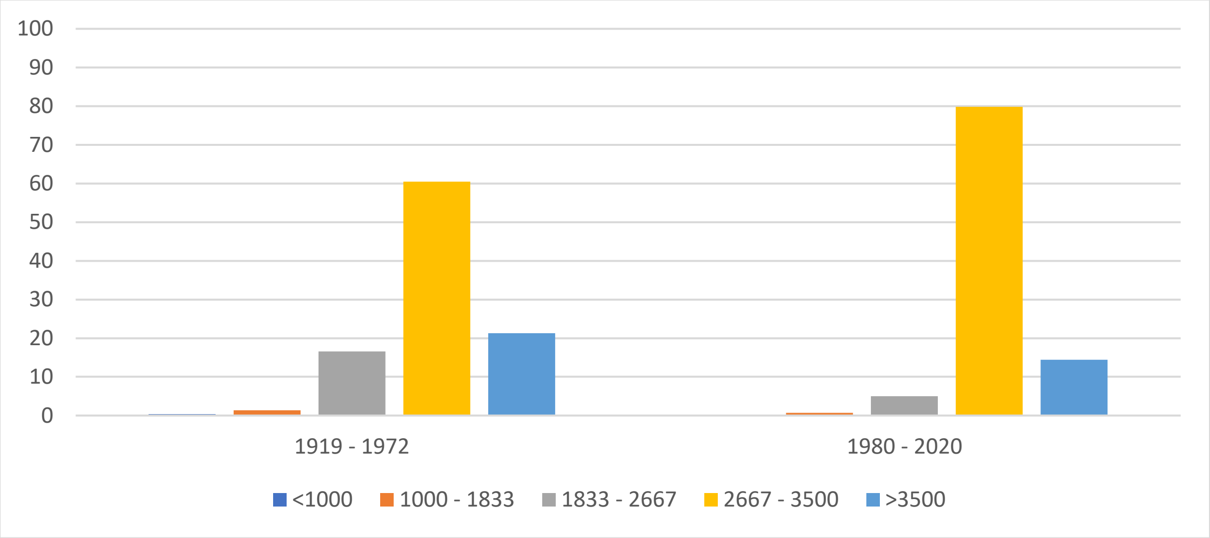


Figure 89. Ultrasonic pulse velocity coverage of tombstones as a function of age, divided into 50 year increments in Stellawood Cemetery

6.3.4. Howick Cemetery results

Howick Cemetery is very small, so only ten samples were collected. The average UPV was compared to tombstone age (Figure 90), but no statistically significant relationship was observed.

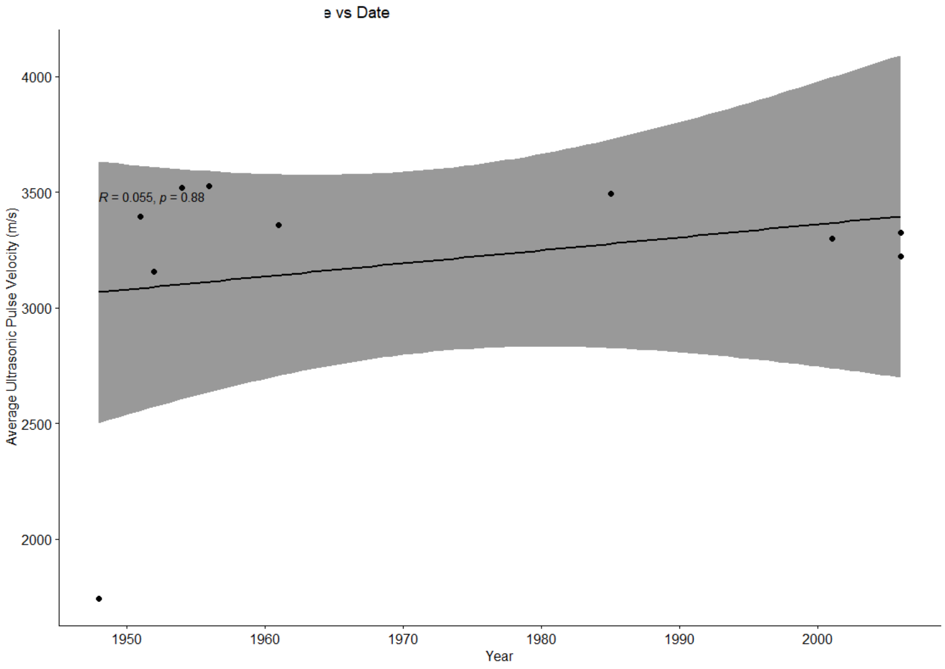


Figure 90. Linear regression relationship between Age (Year) and average UPV, with Spearman Rank correlation, for Howick Cemetery, Howick (n = 10)

The relationship between Minimum UPV and tombstone age also yields no statistically significant results (Figure 91).

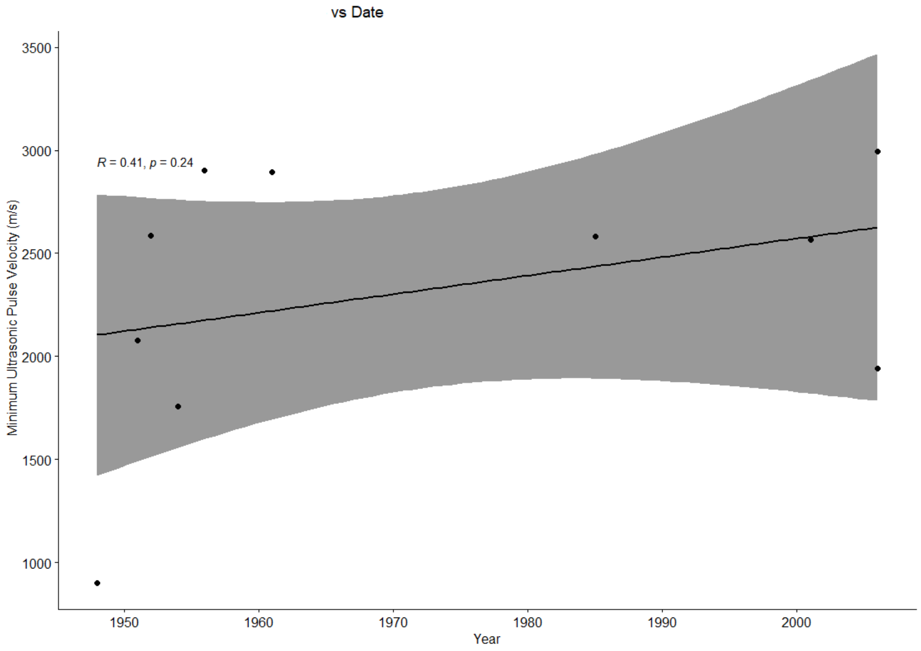


Figure 91. Linear regression relationship between Age (Year) and minimum UPV, with Spearman Rank correlation, for Howick Cemetery, Howick (n = 10)

The lack of statistically significant relationships in these datasets has most likely resulted from the very small sample size, although the minimum value does have a stronger correlation with tombstone than does the average value, although neither are significant.

6.4 Discussion

The data from the various study sites show a vast number of potential outcomes and that the individual cemeteries each produce their own unique patterns. The data from each region will be discussed individually in the following paragraphs and will be addressed in relationship to one another at the conclusion of this chapter.

Maitland Cemetery produced the dataset with the most consistent results across the entire study. The application of a Spearman rank correlation test showed a statistically significant relationship between the average UPV values and tombstone age ($p < 0.05$). This aligns with what was found for the initial Cullinan Main Cemetery study discussed in Chapter 5 of this thesis. There was an even stronger statistical relationship between minimum value and tombstone age ($p < 0.001$). This strongly suggests that weathering is not homogenous across the surface of any given tombstone, but rather occurs at different rates across each tombstone’s surface. This assertion is supported by an analysis of the tombstones which show that all tombstones, regardless of age, have between 10% and 20% of their surface display high UPV values (above 3500 m/s), which is indicative of low levels of weathering. However, for stones that have been in the cemetery for longer periods of time, a larger portion of their collective surfaces begin to show lower UPV values. Therefore, the most likely explanation is that certain, highly resistant segments of each tombstone display very little weathering, even over a time period of up to 100 years. However, there are areas on each tombstone that are more susceptible to weathering and most of the weathering is concentrated in these locations. These weathering ‘hot spots’ would have targeted these locations because of pre-existing weaknesses within the sample stone, such as dislocations or micro-fractures already present in the material. Weathering rates in these areas would consequently be more rapid, manifesting as a lower measured UPV value. However, once weathering had begun at a given location, the surrounding areas would also become susceptible. The result is a greater percentage of UPV readings registering in the lower UPV categories. These pre-existing weaknesses could have any number of sources; either natural or as a function of the tombstone manufacturing process. Regardless of the cause though, their presence in each tombstone will affect their ultimate weathering patterns.

Dido Valley Cemetery is very small, with a consequently small number of data points. As such, any conclusions drawn from this dataset must be treated carefully, but there is a stronger correlation between average UPV and age than the minimum UPV. The lack of protective vegetation and the fact that the tombstones face directly onto the sea may cause these stones to weather more consistently over their face than tombstones at cemeteries that are not as exposed.

Stellawood Cemetery had the largest number of samples, with 48 tombstones measured. However, it demonstrateed generally weaker correlations between Average UPV, Minimum UPV and tombstone age than does Maitland Cemetery, although both variables still show a statistically significant relationship. This means that there is greater variation between individual tombstones at Stellawood Cemetery than at Maitland, from which it follows that weathering rates vary from one tombstone to another more at Stellawood Cemetery than at Maitland.

Howick Cemetery shows essentially no trend for the small number of tombstones sampled, which shows that either ten samples is not enough to generate a meaningful pattern, or there is no pattern at all. The same effect was present at Dido Valley, although at that cemetery the correlations were stronger because of the greater degree to which the tombstones were exposed to salt-laden air.

Rock decay at the various cemeteries is highly complex and the exact rates of decay depend on an array of different elements. These decay rates are not exclusively determined by either climatic drivers or rock property controls, but rather by a complex interplay between the two. It is perhaps not correct to say that one or the other is dominant in any particular environment, but instead that climatic drivers and rock property controls exist in tension with one another and that the interplay between these two elements is what will ultimately create the specific weathering regime of a given sample. Since even tombstones that are spatially very close to one another can show different weathering patterns, the weathering system of each specific location is likely to be dynamically unstable, with samples within it exhibiting very different weathering outcomes, even with similar initial conditions. The above arguments agree with Phillips (2005), who suggested that weathering systems at a regolith scale are likely to be initially unstable. Phillips (2014) asserted that geomorphic systems would initially be unstable but gradually stabilise as they approached equilibrium. This equilibrium point has likely not been reached in the stones assessed in this study and can be expected to continue to deteriorate in future.

The data also appear to indicate that different factors may drive weathering at different scales. The fact that both Maitland and Stellawood Cemeteries showed statistically significant relationships between average and minimum UPV and tombstone ages indicates that there is a general weathering signal that can be detected within the data, and the fact that these relationships were different for the two cemeteries suggests that weathering regimes are not the same for the two locations. This suggests that effects of climatic drivers as espoused by classical texts such as Yatsu (1988) and Bland and Rolls (1998) are correct, and that different climates do generate different weathering regimes. Weathering may also be influenced by broader environmental factors, such as exposure to salt-laden air in Dido Valley, or lichen cover at Stellawood. However, alternate theories appear to hold weight as well. The observed weathering behaviour of tombstones within this thesis can be explained within the context of the model suggested by Pope et al. (1995), who stated that weathering products observed at a mesoscale are to be regarded as a product of an array of interacting microscopic elements, which in turn were a combination of rock properties, microclimatic and environmental variables. In this model, changes to any variables should ultimately lead to differences in observed weathering. It is important to note that ‘weathering’ in this discussion is considered purely within the context of the measured UPV values for the tombstones at each site. In agreement with several other texts (Hall et al., 2012; Hall & Thorn, 2014; Vasile & Vespremeanu-Stroe, 2017), it is not easy (or even potentially possible) to determine the precise spectrum of weathering processes operating in each area. However, the tombstones do at least appear to weather differently in different regions, even if the exact environmental parameters causing the changes are difficult to identify. The UPV values correlate roughly to tombstone age in a linear fashion, which agrees with the results gathered by Inkpen and Jackson (2000), who showed a linear relationship between tombstone age and degree of wear around the inscriptions on marble tombstones in the United Kingdom. It should be noted, that UPV and tombstone wear do not necessarily relate directly to one another. UPV, as a proxy measurement, perhaps compares better conceptually to that of Wilhelm et al. (2016b), who used rock hardness measurements as a proxy for rock weathering, which were correlated against the exposure time of limestone tombstones in the UK. They found, unexpectedly, that longer exposure time did not necessarily correlate with decreased rock hardness measurements. This odd result was not attributed to differences in climate, since the tombstones in question were all spatially quite near to one another. Rather, they ascribed the observed differences to a complex relationship between artificial stone maintenance routines, variations in microclimate and the presence of biological coverings on some of the tombstones. This last idea may offer an explanation as to why the Stellawood tombstones appeared to weather less that the tombstones at Maitland (the Stellawood tombstones typically showed a lower percentage of low UPV values than Maitland tombstones did across similar temporal ranges). The Stellawood tombstones were frequently covered in lichen or moss, which may have acted as a protective agent and consequently limited weathering (Frings & Buss, 2019). While biological components are generally expected to act as catalytic elements and thus increase weathering rates, it is possible that the reverse might also be true, with biological components creating an inhibitive effect on total weathering.

On a more local scale, each tombstone appears to weather according to its own unique combination of physical rock properties and micro-climate. Stellawood Cemetery has greater topographical and shading variety than Maitland Cemetery, in which most of the tombstones are placed on flat ground, facing in the same direction, and are covered by dappled shade for at least part of most days. A more variable microclimate at Stellawood may explain the generally more varied average UPV values from one tombstone to the next. Different thermal regimes have been observed on different aspects of the same rock (Hall & André, 2001), and weathering forms have been shown to also differ with respect to aspect (Vasile & Vespremeanu-Stroe, 2017).

Each cemetery, therefore, has a general weathering regime, most likely driven by the regional climate, but each tombstone within each cemetery will have its own specific regime, driven by rock properties and individual micro-climatic elements and micro-topography, which may or may not conform to the generalised whole. This can be demonstrated by observing two or more tombstones of similar ages, of the same rock type and in the same cemetery. In the ideal case in which they are both identical, they should weather in the same way, since all other variables in the system (climate, biological activity, exposure time) are equal. If they do not, that means that the starting conditions of the two tombstones are different in some way. Since the initial external variables are the same, any differences in weathering pattern, therefore, come about as a result of the initial rock properties. Elements specific to a given tombstone, such as micro-crack distribution, can, therefore, have a large influence on how the rock will ultimately weather. This finding aligns well with Phillips (2007), who suggested that, in geomorphological systems, the local variances of a specific area may override the global geomorphological laws that would be expected to be operating. Thus, although a cemetery may be mathematically describable in terms of a generalised weathering system, it is in reality made up of a series of individual, interlocking weathering patterns, some of which will align with the generalised description, and some of which will oppose it.

If weathering systems on a tombstone scale are as sensitive to changes in micro-climate as this study suggests that they are, then each tombstone will experience a unique spectrum of weathering processes, as derived from the climatic forcings present at that particular location. For example, a tombstone that is exposed to sunlight without shade should theoretically be affected more aggressively by thermal processes such as thermal fatigue and thermal shock, but less so by moisture-driven processes. In contrast, a tombstone that is shaded may experience a less extreme thermal regime, but greater moisture fluctuations. However, it is important to realise that, in a single cemetery, all processes that are possible for that particular climate are likely functioning at varying intensities at all times, and it is only the relative contribution of weathering processes that changes for each tombstone. However, it would be impossible to ascribe a dominant weathering process that is active in any one cemetery. This outcome thus agrees with Hall et al (2012), who suggested that weathering processes are ubiquitous across most environments, with rock properties playing a critical role in defining the ultimate local weathering system.

Analysis of the data from the various cemeteries allows for the drawing of the following conclusions:

- Each cemetery displayed its own UPV regime and, therefore, it follows that the stones at each site are weathering differently.
- The individual tombstones within each cemetery also show a high degree of variation between one another, but the degree of variation is not ubiquitous across all cemeteries, but rather unique to each site.
- In order to compensate for the large levels of variation present at each site, it is necessary to assess as many tombstones as possible, at a recommended minimum of 30 tombstones, each of which should contain between 25 and 50 measurements each, depending on the tombstones' individual size. This is because results only became reliably statistically significant for datasets with more than 30 tombstones.
- An assessment of wargraves present at Stellawood Cemetery show that the degree of weathering can also be driven by the pre-existing physical structure of individual tombstones, and not exclusively by ambient climatic conditions.

Chapter 7: Conclusion

The primary aim of this thesis was to develop and assess an experimental method that would allow for weathering regimes to be assessed across different locations, with differing environmental conditions. The final outcome could be described as a partial success, although the vast complexity of most weathering systems makes application, deployment and subsequent data analysis equally complex. In summation, the outcomes of each specific objective will be discussed, and then placed within the context of the greater aim.

7.1. Experimental Repeatability in the Earth Sciences: key findings from Objective 1

Experimentation with the PUNDIT PL-200 in various configurations showed the importance of using consistent transducer and experimental configurations. Different transducer pairs generate data on different scales and as such cannot be integrated into a common dataset. The incomparable nature of apparently similar transducers shows that even small changes in experimental configuration or equipment can have a marked effect on generated data. Wilhelm et al. (2016) found a similar result when comparing rock hardness measurements taken with two different Equotip probes. A more profound difference was noted in a study that compared rock hardness measurements taken via Schmidt Hammer and Equotip and showed that the data from the two did not compare well (Viles et al., 2011). Viles et al. (2011) also noted that the Equotip Piccolo, which is a special low impact device, was more prone to operator bias that other hardness measurement devices because it was more easily affected by small micro topographical variances on the sample surfaces. In this thesis, a similar effect with a different instrument was observed for the rough surface ultrasonic transducer, whose small contact area also appears to introduce a larger degree of operator error than the standard broad headed transducers. The use of multiple operators can, therefore, introduce errors into a dataset, since even minor differences in measurement technique can create discrepancies in generated data, particularly with sensitive equipment. However, the degree of error introduced by multiple operators can be limited by ensuring that the operators are well-trained and experienced in using the equipment, and by keeping the number of operators as small as possible. The above limitation is likely to be present in other Earth Science experiments, especially in studies that involve multiple experimenters at different locations. The results obtained in this study correlate broadly with those of Church et al. (2020), who observed that experiments conducted at two different laboratories did not achieve the directly comparable results, even with extremely similar experimental setups.

The effects of the laboratory and field experiments carried out in this thesis have highlighted some concerns that have ramifications outside of this study's scope. The exploration of the effects of equipment setup and operator bias has shown that consideration of these factors is paramount in the Earth Sciences, especially in the case of studies involving mechanisms such as rock weathering, where the expected decay signal is likely to be very small. These studies would require only a small degree of experimental error to potentially occlude the signal that is under investigation. The exact nature and extent of this problem is unknown, but it may affect geomorphological studies more widely than is currently understood. An example of a possible line of investigation would be that of rock temperature studies. Nearly all of the studies reviewed in the literature review of this thesis have used unique equipment setups and measurement strategies, which makes each of the studies only generally comparable to one another.

The wide array of different experimental setups and methodological approaches also opens up a larger question about the nature of weathering research in general. Each study seems to primarily exist in isolation, with no intention of fitting into a larger research framework. The effects of operator and equipment bias are understood within the Earth Sciences, but their effects have not been extensively quantified.

This issue of reproducibility would seem to be a matter that most scientists at least intuitively are aware of, a point which is demonstrated by Baker (2016), whose survey of researchers in an array of different fields showed that 90% of them believed that reproducibility of data was a concern for them. The results obtained in this thesis confirm this intuition, showing that repeatable results are not guaranteed under controlled laboratory conditions, and even less so in uncontrolled field environments. The implications were directly relevant to this thesis and informed how field measurements were carried out, but these results also suggest that repeatability and reproducibility studies may be under represented in Earth Studies.

7.2. Assessment of UPV measurements as a viable proxy for rock weathering: key findings from Objective 2

An experimental method was developed to allow for the assessment of relationship between Ultrasonic Pulse Velocity measurements and tombstone age, as derived from the date of death stated on the tombstone. This method was tested at Cullinan Main Cemetery in Gauteng and the results published in the South African Geographical Journal (Loubser, 2022).

This initial experiment showed a statistically significant relationship between tombstone weathering and length of exposure, similar to that of Inkpen and Jackson (2000), although they measured tombstone downwearing. Wilhelm et al. (2016) showed a decrease in rock hardness as the exposure age of limestone tombstones increased, which is comparable to the relationship determined between UPV and gabbro tombstone age determined in this thesis. The similarity in results as measured by these weathering indicators supports the assertion that UPV is a viable indicator of rock weathering in gabbro stone.

Differences in measurements obtained for the standard transducers are not directly comparable to those of the rough surface transducers, and as such do not conform to criteria for data *replication*, as laid out by Church et al. (2020), in which results must be directly comparable with a reasonable margin of error. They possibly conform to the criteria for data *reproduction*, in which the data could be reconcilable under the same conceptual theoretical model. However, the nature of the results obtained by the standard transducer may lead a researcher to assume a more aggressive weathering spectrum than those obtained for the rough surface transducers, because analysis by linear regression showed a greater degree of UPV change when measured against exposure time than did the rough surface transducers. There is also a risk of confirmation bias playing a role in the use of the standard transducers, since they show a more robust statistical relationship between tombstone exposure age and UPV than do the rough surface transducers, and are, therefore, intuitively appealing to treat as more “correct”. Also, because the rough surface transducers have a higher degree of dependency on operator skill than the standard transducers. The standard transducers produce data that are more comparable between operators, which makes them more appealing to use in general.

To assess this effect under field conditions, and to test the repeatability of the experiment in general, the initial dataset measured at Cullinan Main Cemetery was carried out twice more, but with two different operators. The results were comparable across the three operators for standard transducers, but less so for the rough surface transducers. When assessed with linear regression, all operators could show the same general trends, but with different degrees of statistical significance.

Use of the exponential transducers showed that a statistically significant correlation existed between the average UPV value for each tombstone and the age of the tombstone. The effects of different transducer types and multiple operators were tested, but under field conditions, with the field experiment repeated multiple times with varying transducer configurations and operators. These data showed that the preferred transducer was the rough surface setup, even though the standard transducer produced generally more statistically agreeable results. The results obtained for multiple operators in the field showed broadly similar results, but differed enough from one another that a single operator is advisable for this particular study technique. In general, multiple operators can be considered viable, but not necessarily desirable for an experiment like this, since it will definitely introduce a degree of experimental error that could be challenging to quantify.

The field measurement technique was expanded to multiple cemeteries across South Africa to determine if the UPV signal observed at Cullinan Main Cemetery could be replicated. Measurements were taken at Stellawood Cemetery in Durban, Howick Cemetery in Howick, Dido Valley Cemetery in Simon’s Town, and Maitland and Plumstead Cemeteries in Cape Town. Surprisingly, the trends observed in Cullinan Main Cemetery were not observed at other cemeteries throughout South Africa, with most of them not revealing any statistically significant measurements. While intra-site differences were expected, having been demonstrated in studies in the United Kingdom (Cooke et al., 1995; Inkpen, 2013; Mooers et al., 2017), the lack of statistically significant relationships was not. The reason for this was determined to have resulted from heterogenous weathering of the tombstones, which was demonstrated in Chapter 5 and Loubser (2022), but was also observed on tombstones in the United States (Akoglu et al., 2020).

These data show that weathering can vary profoundly over a very a distance of centimeters, and since microclimate over such a small space is assumed to be constant, the difference must be a result of small-scale differences in rock properties, as proposed by Pope et al. (1995) and Hall et al. (2012).

7.3. Assessment of tombstones at high resolution in different regions: key findings from Objective 3

The adjusted experimental method was deployed at two primary sites (Maitland Cemetery in Cape Town and Stellawood Cemetery in Durban) and two secondary sites (Howick Cemetery in Howick and Dido Valley Cemetery in Simon’s Town). There was a statistically significant relationship between average and minimum ultrasonic pulse velocity values and tombstone age, aligning with the original findings from the Cullinan Main Cemetery that was assessed in Objective 2.

An assessment of UPV changes as a function of time and space showed that weathering could be highly heterogenous across a single tombstone’s surface, with some sections showing very little evidence of weathering and sections only centimetres away weathering much more. Older tombstones demonstrate a larger degree of UPV heterogeneity than newer ones, which implies the presence of a weathering front, as described by Phillips et al. (2019), which is an interface within a system between weathered and unweathered rock. In the case of these tombstones, weathering will operate more intensively at points of preexisting weakness in the rock, propagating outwards from the weak point as microcracks grow, increasing the available surface area upon which weathering can function. There is also a possibility that weaknesses may have developed after being placed in the cemetery due to dilatation effects (Vidal Romani & Twidale, 1999). There is a likelihood that, in areas on a tombstone that have few dislocations, weathering may be extremely limited, even over a long period of time. This is explained by the fact that almost all the tombstones measured in this study retained portions of their surfaces that returned high UPV values, indicating that little weathering had occurred. This finding concurs with other weathering studies showing changes (or potential changes) in weathering over a small area on the same rock (Hall, 2003; Vasile & Vespremeanu-Stroe, 2017; Akoglu et al., 2020). This high degree of variance over a small spatial scale also suggests that these weathering systems are dynamically unstable, as many Earth Science systems appear to be (Phillips, 2005, 2007, 2014).

The tombstones measured in Maitland Cemetery showed a different pattern overall to those of Stellawood, which shows that elements other than rock properties play a role in the weathering spectrum observed at each site. This would be an amalgamation of different external elements, including biological cover of the stones (Frings & Buss, 2019), climate (Jenkins & Smith, 1990; Viles, 2002; Vasile & Vespremeanu-Stroe, 2017) and pollution levels (Feddema & Meierding, 1987; McNeill, 1999; Inkpen, 2013), although it would be challenging to assign weightings to the relative contributions of each of these factors. However, it is clear that rock properties alone are not solely responsible for the weathering in any given place.

It is also apparent that looking purely at climate and rock properties as relevant controls for rock weathering is overly simplistic, and other factors (notably biotic elements) are also contributors. For example, the tombstones seen in the Stellawood Cemetery appear to have weathered less overall than the Maitland tombstones (as determined by the average percentage surface area of lower UPV values for older stones), and Stellawood tombstones also typically have more biological cover on them. Therefore, different climates may, in addition to any direct weathering effects, also have indirect effects by altering the biological components present in each region, which can change the weathering pattern (Frings &

Buss, 2019; Hall et al., 2012). Since the exact contribution of the effects of any of these factors cannot be readily determined under field conditions, it is perhaps more appropriate to say that a combination of rock properties and external environmental variables will determine the nature of the weathering spectrum in an area. This conclusion aligns well with the concept laid out by Pope et al. (1995), whose model considered not only climate and rock properties, but an array of environmental variables as well. Of the various conceptual models on offer, this one appears to explain the observed data well.

7.4. Concluding remarks

In conclusion, rock weathering is affected by climatic driving forces, but it is also affected by the specific nature of the rock being weathered, as well as local external variables such as shade-induced micro-climate, tombstone aspect and biological cover. The interplay between these factors (rock, climate and local variance) is highly unpredictable and differ between tombstones in the same cemetery, even if they are close to one another. Despite the variance, there is still a weathering signal that can be discerned in many of the cemeteries that becomes observable if enough tombstones have been sampled at a high enough resolution. This weathering signal is unique to each site and is produced by a combination of the local climatic conditions and any other local variances that may be unique to a specific site. Climate, therefore, does affect the specific weathering spectrum for a particular site, making each site unique. However, rock properties also play a significant role in the degree of weathering, with the starting condition of each tombstone being the most likely determinant for the observed weathering type. Climate will thus induce a weathering effect, the magnitude of which will be determined by the specific properties of a given tombstone.

While it may be possible to study the differences between tombstones on a regional scale, it is unlikely to be viable globally. This is due to the types of stone used in various locations. For example, limestone and marble tombstones found in the United Kingdom are likely to have been quarried in close proximity to one another, even for different cemeteries. However, the marble tombstones of the United Kingdom will not be comparable to the gabbro tombstones of South Africa. The relationship between climatic forcings and rock properties will thus lead to completely unique weathering spectrums for each site, and there will be no easy way to determine the exact combination of weathering processes that will lead to the observed outcome. This calls into question the validity of the traditional conceptual weathering model, particularly as a means for determining the weathering type at any given location.

The classical conceptual weathering model, upon which many contemporary studies are still built, is climate-focused at its core. This can be seen by examining its internal structure, and observing the nature of the research studies that stem from it. Within the structure of the model, weathering processes are, with the exception of dilatation, all categorised according to the climatic forcings that are believed to be necessary to drive them. Symptomatically, weathering studies typically have a specific regional focus, with researchers pairing different weathering processes with climatic regions that are believed to favour them. Alternatively, a small group of research studies have championed the role of rock properties as the dominant element that will determine the functionality of any one weathering process.

This study has shown that neither one of these elements exerts dominating control over the other. Rather, the weathering regime that exists at any given location exists as a function of the tension between these two aspects of weathering, with each exerting a dominating influence at a different spatial scale. This tension can be broken down in the following manner:

- Climatic forcings exert a general effect over a given region, putting in place the building blocks necessary to drive forward a specific weathering regime. The specific weathering process combination and intensity weightings may ultimately be unknowable, but each region will ultimately be identifiable by a detectable weathering signal, even if its precise quantification is imprecise with currently available technology.
- The specific properties of any individual rock or stone will dictate a unique local response to the generalised climatic forcings generated by local weather conditions. Simply put, even stones that are mineralogically equivalent may respond differently to local climatic elements due to differences in their individual structural composition.
- The tension between the above two aspects of weathering can be expressed thus: the climatic forcings of a given area will generate a unique weathering equilibrium state that all stones within that area will attempt to reach. However, the ability of each individual stone to conform to that state is a function of that stone's specific rock properties.
- Neither climate nor rock properties are sufficient individual consideration for defining the nature of weathering in any given area. Rather, both elements will have a role to play in determining the nature of rock degradation that will ultimately occur. Climatic

forcings and rock property controls will paradoxically war against each other and work together to create the weathering regime that is eventually observed.

In future, it is recommended that the study be extended beyond the South African region, if possible into continental Europe and the United Kingdom. The advantages to this are two-fold. First, many tombstones in these locations are constructed from limestone and sandstone, which are both more susceptible to weathering than gabbro. Second, many of the tombstones in these locations are much older than in South Africa, giving a temporal range in the order of centuries rather than decades. This would also allow for additional proxy measurement techniques like rock hardness, which, from trials run in the early phases of this study, yield very little useful information from stone that is as innately hard as gabbro.

More generally, an in-depth assessment of field and laboratory techniques should be scrutinised to quantify their susceptibility to operator and equipment bias. In geomorphology, quantitative study in fields such as weathering require the detection and measurement of small signals, which could be obscured by errors in experimental design or execution. The degree to which this effects geomorphological studies must be interrogated in more detail.

Finally, the current weathering model should be rigorously reviewed, particularly for assumptions that researchers may be making with respect to the relative effects of climate and rock properties in terms of weathering processes and effects. Conceptually, current weathering theory seems appropriate as an instructive tool, but appears to be difficult to use effectively when designing field experiments. In particular, more studies about the relative effects of climate and rock properties must be carried out to ensure that our current assumptions about their relative roles are valid.

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Appendix 1: Table listing selected published articles that used rock temperature as a proxy for rock decay

Author	Year	Title	Journal	Rock type	Field / Lab	Direct measurement? (Y/N)	High precision (Sample destroyed/ altered in test)	Location	Number of sites	Climate type	Link between climate and process (fundamental assumption in project design)	Cultural stone / Building stone / Natural Stone
Alomari, A., Beck, K., Brunetaud, X., Al-mukhtar, M.	2012	Climatic conditions and limestone decay in Al-Namrud monuments, Iraq: Review and discussion	The First National Conference for Engineering Sciences FNCES'12	Porous limestone	Both	Yes, mercury porosimetry	Yes	Al-Namrud-Iraq	1	Arid	Yes	Cultural
Al-Omari, A., Brunetaud, X., Beck, K., Al-Mukhtar, M.	2013	Effects of thermal stress, condensation and freezing-thawing action on the degradation of stones on the Castle of Chambord, France	Environmental Earth Sciences	Limestone	Field	Yes, mercury porosimetry	No	Castle of Chambord, France	1	Temperate oceanic	Yes	Cultural
Coutard, J-P., Francou, B.	1989	Rock temperature measurements in two Alpine Environments: Implications for frost shattering	Arctic and Alpine Research	Dolomitic limestone	Field	Yes, porosity and fracture spacing	No	Briançonnais region, French Alps	1	Temperate oceanic / Alpine	Yes	Natural

Eppes, M.C., Griffing, D.	2010	Granular disintegration of marble in nature: A thermal-mechanical origin for a grus and corestone landscape	Geomorphology	Marble	Field	Yes, leachate assessment/ Environmental Scanning Electron Microscope (ESEM)	Both	San Bernadino Mountains, California	1	Semi-arid	Yes	Natural
Eppes, M.C., Magi, B., Hallet, B., Delmelle, E., Mackenzie-Helnwein, P., Warren, K., Swami, S.	2016	Deciphering the role of solar-induced thermal stresses in rock weathering	Bulletin of the Geological Society of America	Granite	Field	Yes, strain gauge	No	Charlotte, North Carolina	1	Humid Sub-tropical	Yes	Natural
Gómez-Heras, M., Smith, B.J., Fort, R.	2008	Influence of surface heterogeneities of building granite on its thermal response and its potential for the generation of thermoclasty	Environmental Geology	Granite	Field	Yes, Optical petrography	No	Madrid, Spain	1	Mediterranean	No (But aspect was considered)	Building
Gruber, S., Hoelzle, M., Haeberli, W.	2004	Rock-wall Temperatures in the Alps: Modelling their Topographic Distribution and Regional Differences	Permafrost and Periglacial Processes	Limestone	Field	No	No	Swiss Alps	1	Marine West Coast Climate	No	Natural

Gruber, S., Peter, M., Hoelzle, M., Woodhatch, I., Haeberli, W.	2003	Surface temperatures in steep alpine rock faces - A strategy for regional scale measurement and modelling	Proceedings of the 8th International Conference on Permafrost	Limestone	Field	No	No	Swiss Alps	1	Marine West Coast Climate	No	Natural
Gunzburger, Y., Merrien-Soukatchoff, V.	2011	Near-surface temperatures and heat balance of bare outcrops exposed to solar radiation	Earth Surface Processes and Landforms	Gneiss	Field	No	No	Rochers de Valabres, French Alps	1	Marine West Coast Climate	No	Natural
Hall, K.	1997	Rock temperatures and Implications for Cold Region Weathering. I: New Data from Viking Valley, Alexander Island, Antarctica	Permafrost and Periglacial Processes	Arkose sandstone	Field	No	No	Alexander Island, Antarctica	1	Polar hyper-arid	Yes	Natural
Hall, K.	2003	Micro-transducers and high-frequency rock temperature data: changing our perspectives on rock weathering in cold regions	Proceedings of the 8th International Conference on Permafrost		Field	No	No	Antarctica	1	Polar	Under interrogation	Natural
Hall, K., André, M-F.	2001	New insights into rock weathering from high-frequency rock temperature data: an Antarctic study of weathering by thermal stress	Geomorphology	Medium grain grandodiorite	Field	No	No	Rothera Base, Antartica	1	Polar	Under interrogation	Natural

Hall, K., André, M-F.	2003	Rock thermal data at the grain scale: applicability to granular disintegration in cold environments	Earth Surface Processes and Landforms	Medium grain grandodiorite	Field	No	No	Rothera Base, Antartica	1	Polar	Under interrogation	Natural
Inigo, A.C., Vicente-Tavera, S.	2002	Surface-inside (10 cm) thermal gradients in granitic rocks: effect of environmental conditions	Building and Environment	Granite	Field	No	No	Avila, Spain	1	Mediterranean	Yes	Building (Quarry)
Jenkins, K.A., Smith, B.J.	1990	Daytime rock surface temperature variability and its implications for mechanical rock weathering: Tenerife, Canary Islands	Catena	Carboniferous quartz sandstone fom England (transported to Tenerife)	Field	No	No	Tenerife, Canary Islands	1	Tropical	Yes	Natural
Kelly, W.C., Zumberge, J.H.	1960	Weathering of a quartz diorite at Marble Point, McMurdo Sound, Antarctica	Journal of Geology	Fine-grained quartz diorite	Both	Yes, chemical mineralogical analyses	Yes	Marble Point, McMurdo Sound, Antarctica	1	Polar	Yes	Natural
Kerr, A., Smith, B.J., Whalley, W.B.	1984	Rock temperature from southeast Morocco and their significance for experimental rock-weathering studies	Geology	Chalk, granite, sandstone	Field	No	No	Southeast Morocco	1	Arid (Hot desert)	Yes	Natural
Lewkowicz, A.G.	2001	Temperature Regime of a Small Sandstone Tor, Latitude 80°N, Ellesmere Island, Nunavut, Canada	Permafrost and Periglacial Processes	Sandstone	Field	Yes, rock surface change	No	Ellesmere Island, Nunavut, Canada	1	Polar	Yes	Natural

Logan, J.M.	2004	Laboratory and case studies of thermal cycling and stored strain on the stability of selected marbles	Environmental Geology	Marble	Lab	Yes, Optical petrography	No	Laboratory	1	N/A	No	Building
Matsuoka, N., Sakai, H.	1999	Rockfall activity from an alpine cliff during thawing periods	Geomorphology	Granite	Field	Yes, rock joint spacing	No	Japanese Alps	1	Peri-glacial/Glacial	Yes	Natural
McAllister, D., Warke, P., McCabe, S.	2017	Stone temperature and moisture variability under temperate environmental conditions: Implications for sandstone weathering	Geomorphology	Sandstone	Field	No	No	Belfast, Northern Ireland	1	Temperate Oceanic	Yes	Natural
McFadden, L.D., Eppes, M.C., Gillespie, A.R., Hallet, B.	2005	Physical weathering in arid landscapes due to diurnal variation in the direction of solar heating	GSA Bulletin	Granite, limestone, sandstone, basalt, gneiss	Field	Yes, crack orientation	No	Mojave, Sonoran, Chihuahuan and central New Mexican Deserts	4	Arid	Yes	Natural
McKay, C.P, Molaro, J.L., Margarita, M.M.	2009	High-frequency rock temperature data from hyper-arid desert environments in the Atacama and the Antarctica Dry Valleys and the implications for rock weathering	Geomorphology	Dolerite	Field	No	No	Acatacama Desert and Antarctica	2	Hyper-Arid	Yes	Natural

Molaro, J.L., McKay, C.P.	2010	Processes controlling rapid temperature variations on rock surfaces	Earth Surface Processes and Landforms	Dolerite, Sandstone	Field	No	No	Death Valley and Mountain View, California	2	Sub-tropical, hot desert (DV) and Cold Summer Mediterranean (MV)	Yes	Natural
Smith, B.J.	1977	Rock temperature measurements from the Northwest Sahara and their implications for rock weathering	Catena	Limestone	Field	No	No	Hamada de Meski, Morocco and Remada, Tunisia	2	Arid	Yes	Natural
Sumner, P.D., Hedding, D.W., Meiklejohn, K.I.	2007	Rock surface temperatures in southern Namibia and implications for thermally-driven physical weathering	Zeitschrift für Geomorphologie, Supplementary Issues	Granite-gneiss	Field	No	No	Aus, Namibia	1	Arid/Hyper-Arid	Yes	Natural

Sumner, P.D., Meiklejohn, K.I., Nel, W., Hedding, D.W.	2004	Thermal attributes of rock weathering: Zonal or Azonal? A comparison of rock temperatures in difference environments	Polar Geography	Granite-gneiss, Basalt, Basalt, Sandstone	Field	No	No	Aus, Namibia / Drakensberg Mountains, South Africa / Subantarctica Marion Island / Alexander Island, Antarctica	4	Hyper-arid, Mid-latitude alpine, Periglacial, Polar	Yes	Natural
Vasile, M., Vespremeaunu-Stroe, A.	2017	Thermal weathering of granite spheroidal boulders in a dry-temperate climate, Northern Dobrogea, Romania	Earth Surface Processes and Landforms	Granite	Field	No	No	Northern Dobrogea, Romania	1	Dry-temperate climate	Yes	Natural
Viles	2005	Microclimate and weathering in the central Namib Desert, Namibia	Geomorphology	Granite, Marble	Field	Yes, SEM and visual assessment	No	Kleinberg / Vogelfederberg / Gobabeb / Ganab	4	Mid-latitude Steppe and Desert Climate	Yes	Natural

Warke, P.A., Smith, B.J.	1998	Effects of direct and indirect heating on the validity of rock weathering simulation studies and durability tests	Geomorphology	Sandstone, basalt, granite	Lab	No	No	Laboratory	1	Simulated Arid	Yes	Natural (Cut)
Warren, K., Eppes, M-C., Swami, S., Garbini, J., Putkonen, J.	2013	Automated field detection of rock fracturing, microclimate, and diurnal rock temperature and strain fields	Geoscientific Instrumentation Methods and Data Systems	Granite	Field	Yes, strain gauge	No	Gaston County, North Carolina	1	Humid Sub-tropical	Yes	Natural

Appendix 2: Table listing selected published articles that used rock hardness as a proxy for rock decay

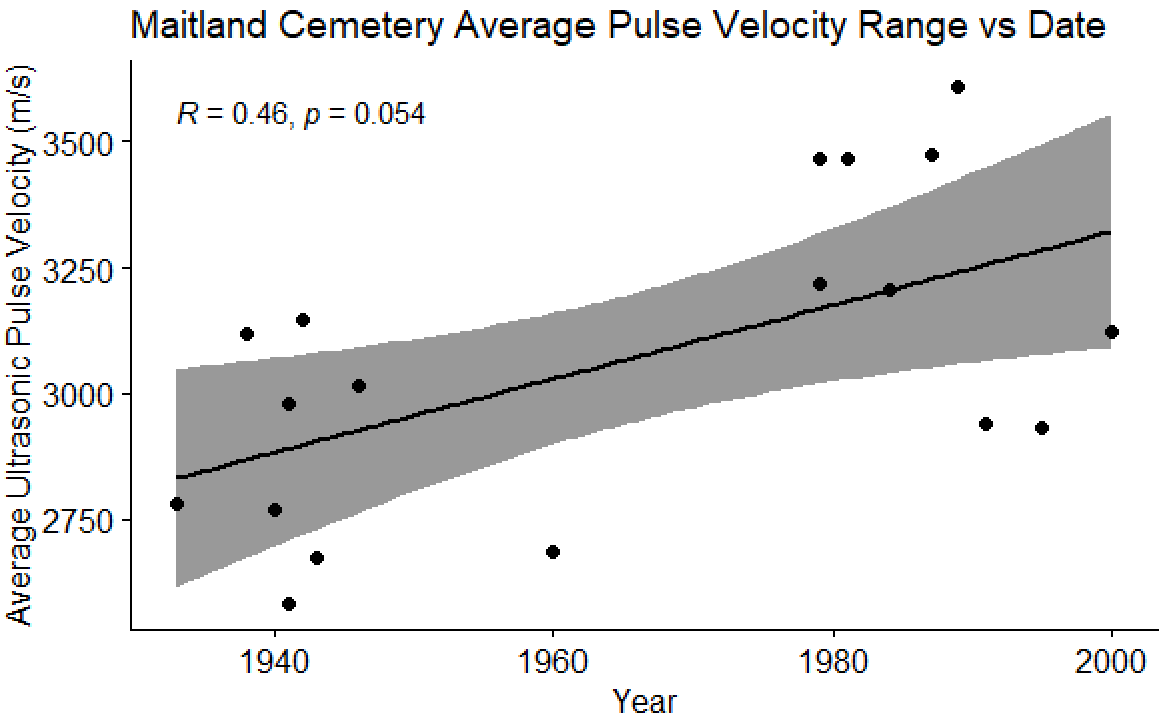
Author	Year	Title	Journal	Rock type	Field / Lab	Direct measurement? (Y/N)	High precision (Sample destroyed/ altered in test)	Location	Number of sites	Climate type	Link between climate and process (fundamental assumption in project design)	Cultural stone / Building stone / Natural Stone
Aoki, H., Matsukura, Y.	2007	A new technique for non-destructive field measurement of rock-surface strength: an application of the Eqotip hardness tester to weathering studies	Earth Surface Processes and Landforms	Sandstone	Field	No	No	Aoshima Island, Japan	1	Maritime	No	Natural
Aydin, A., Basu, A.	2005	The Schmidt hammer in rock material characterization	Engineering Geology	Various	N/A	Review article	N/A	N/A	N/A	N/A	N/A	Various
Gomez-Heras, M., Benavente, D., Pla, C., Martinez-Martinez, J., Fort, R., Brotons, V.	2020	Ultrasonic pulse velocity as a way of improving uniaxial compressive strength estimations from Leeb hardness measurements	Construction and Building Materials	Various rock types common to buildings in Spain	Lab	Yes, porosity	No	Laboratory	1	Laboratory	No	Building stone
Greco, R., Sorriso-Valvo, M.	2005	Relationships between joint apparent separation, Schmidt hammer rebound value, and distance to faults, in rock outcrops, Calabria, Southern Italy	Engineering Geology	Paragneiss, micaschists, augen gneiss, phyllite, metarenite	Field	Yes, joint apparent separation, distance to faults	No	Calabria, Southern Italy	1	Hot-Summer Mediterranean	No	Natural

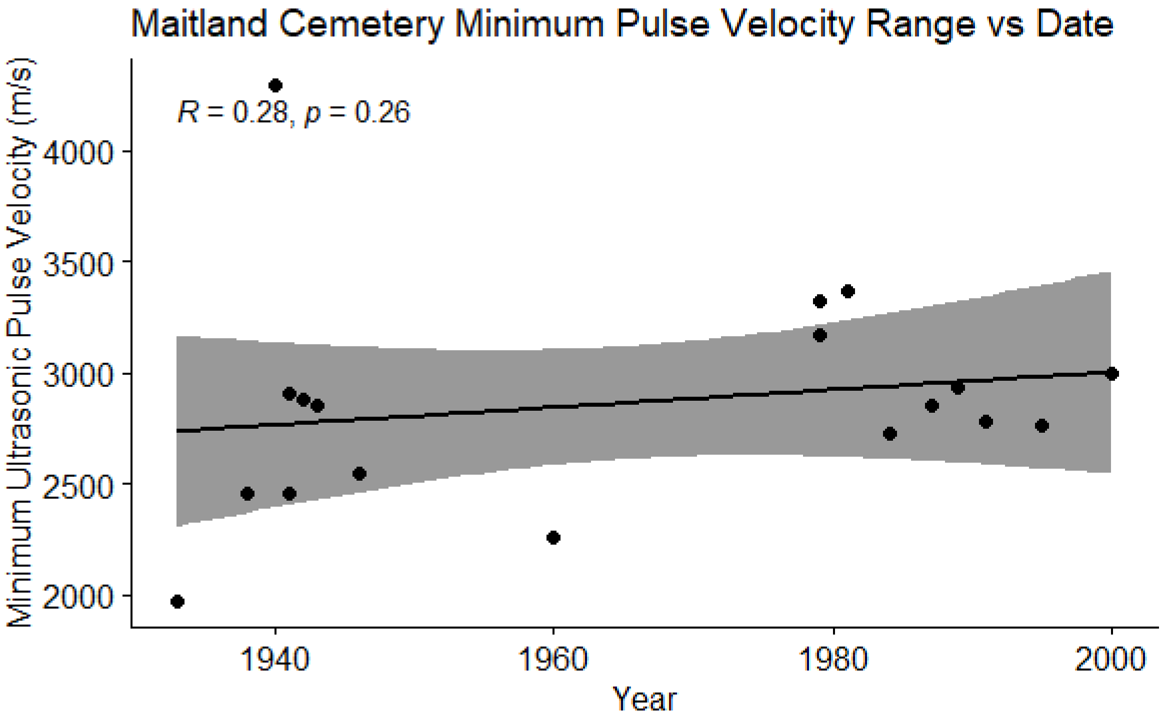
Guglielmin, M., Worland, M.R., Convey, P., Cannone, N.	2012	Schmidt hammer studies in the maritime Antarctic: Application to dating Holocene deglaciation and estimating the effects of macrolichens on rock weathering	Geomorphology	Diorite, granodiorite	Field	No	No	Marguerite Bay, Maritime Antarctic	1	Polar	No	Natural
Matsukura, Y., Tanaka, Y.	2000	Effect of rock hardness and moisture content on tafoni weathering in the granite of Mount Doe-Sung, Korea	Geografiska Annaler. Series A: Physical Geography	Biotite granite	Field	No	No	Mount Doeg-sung, Korea	1	Moist continental climate	Yes	Natural
Matthews, J.A., Owen, G., Winkler, S., Vater, A.E., Wilson, P., Mourne, R.W., Hill, J.L.	2016	A rock-surface microweathering index from Schmidt hammer R-values and its preliminary application to some common rock types in southern Norway	Catena	Various igneous and metamorphics	Field	No	No	Southern Norway	1	Tundra, Subarctic	Yes	Natural
Matthews, J.A., Shakesby, R.A., Owen, G., Vater, A.E.	2011	Pronival rampart formation in relation to snow-avalanche activity and Schmidt-hammer exposure-age dating (SHD): Three case studies from southern Norway	Geomorphology	Migmatitic gneiss	Field	No	No	Southern Norway	3	Tundra, Subarctic	Yes	Natural
Matthews, J.A., Wilson, P.	2015	Improved Schmidt-hammer exposure ages for active and relict pronival ramparts in southern Norway, and their palaeoenvironment implications	Geomorphology	Migmatitic gneiss	Field	No	No	Southern Norway	3	Tundra, Subarctic	Yes	Natural
Meulenkamp, F., 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	Various	Model	Yes, Unconfined Compressive strength	N/A	Computer Model	N/A	N/A	No	Model

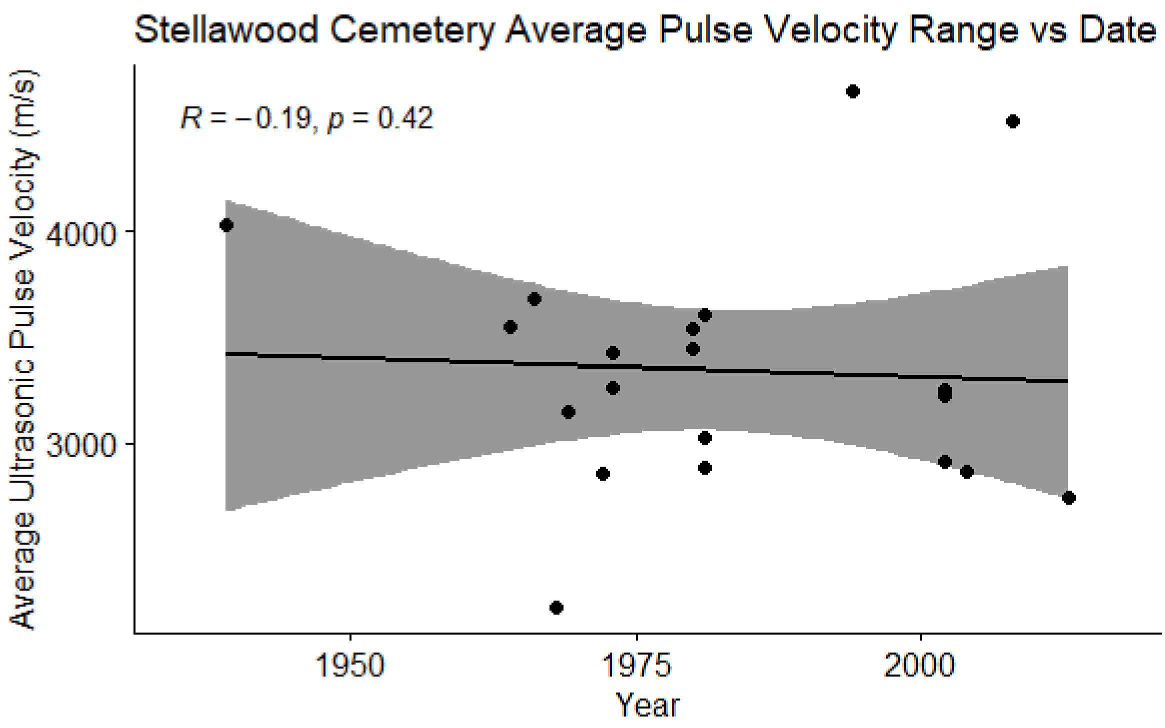
Shakesby, R.A., Matthews, J.A., Karlén, W., Sietse, O.L.	2006	The Schmidt hammer as a Holocene calibrated-age dating technique: Testing the form of the R-value-age relationship and defining the predicted age errors	The Holocene	Migmatitic gneiss	Lab	No	No	Southern Norway	3	Tundra, Subarctic	Yes	Natural
Strzelecki, M.C.	2011	Schmidt hammer tests across a recently deglacierized rock coastal zone in Spitsbergen - is there a "coastal amplification" of rock weathering in polar climates	Polish Polar Research	Plagiogneiss	Lab	No	No	Spitsbergen Islands	4	Polar	Yes	Natural
Sumner, P.D., 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	Basalt, Sandstone, Dolerite	Lab	No	No	Laboratory	1	N/A	No	Natural
Viles, H., Goudie, A., Grab, S., Lalley, J.	2011	The use of the Schmidt Hammer and Equotip for rock hardness assessment in geomorphology and heritage science: a comparative analysis	Earth Surface Processes and Landforms	Sandstone, limestone, basalt, dolerite	Field	No	No	Golden Gate, South Africa / Dorset coast, southern England	1	N/A	No	Natural
Wang, M., Wan, W.	2019	A new empirical formula for evaluating uniaxial compressive strength using the Schmidt hammer test	International Journal of Rock Mechanics and Mining Sciences	N/A	Model	No	N/A	Model	N/A	N/A	N/A	N/A
Wilhelm, K., Viles, H., Burke, O., Mayaud, J.	2016	Surface hardness as a proxy for weathering behaviour of limestone heritage: a case study on dated headstones on the Isle of Portland, UK	Environmental Earth Sciences	Limestone	Field	No	No	Isle of Portland, United Kingdom	1	Temperate maritime climate	Yes	Cultural stone

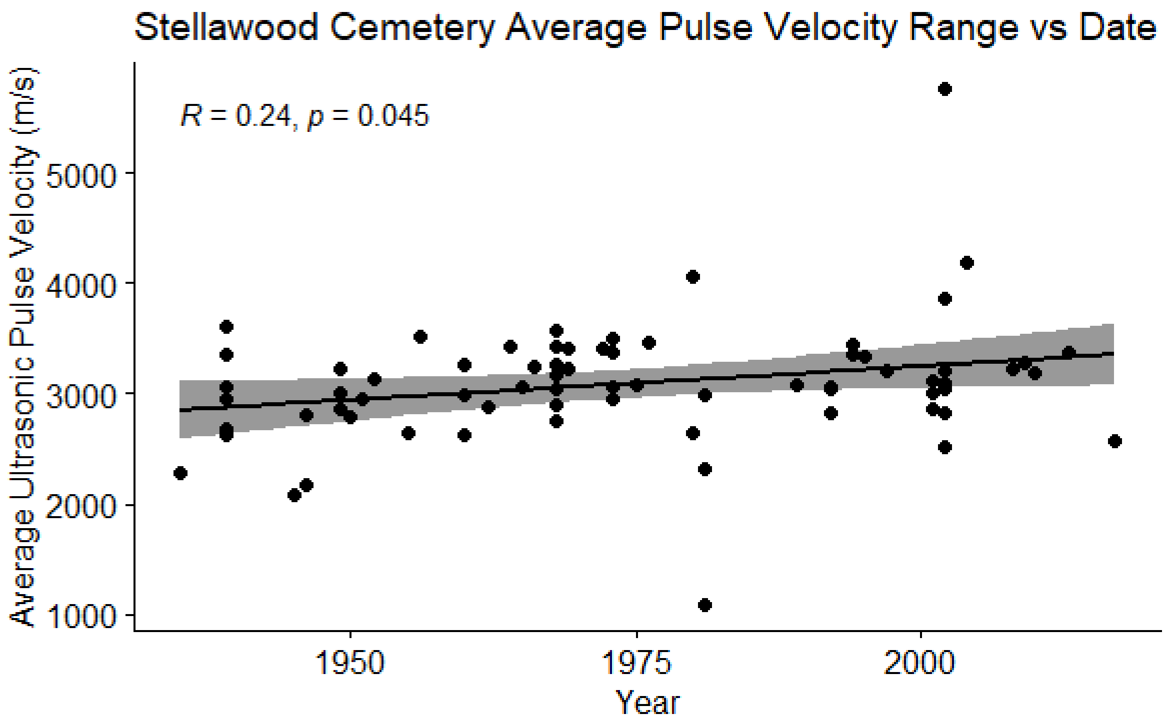
Wilson, P., Matthews, J.A.	2016	Age assessment and implications of late Quarternary periglacial and paraglacial landforms on Muckish Mountain, northwest Ireland, based on Schmidt-hammer exposure-age dating (SHD)	Geomorphology	Quartzite	Field	No	No	Muckish Mountain, northwest Ireland	1	Temperate oceanic climate	Yes	Natural
Winkler, S., Matthews, J.A., Haselberger, S., Hill, J.L., Mourne, R.W., Owen, G., Wilson, P.	2020	Schmidt hammer exposure-age dating (SHD) of sorted stripes on Juvflye, Jotunheimen (central South Norway): Morphodynamic and palaeoclimatic implications	Geomorphology	Migmatitic gneiss	Field	No	No	Southern Norway	1	Tundra, Subarctic	Yes	Natural

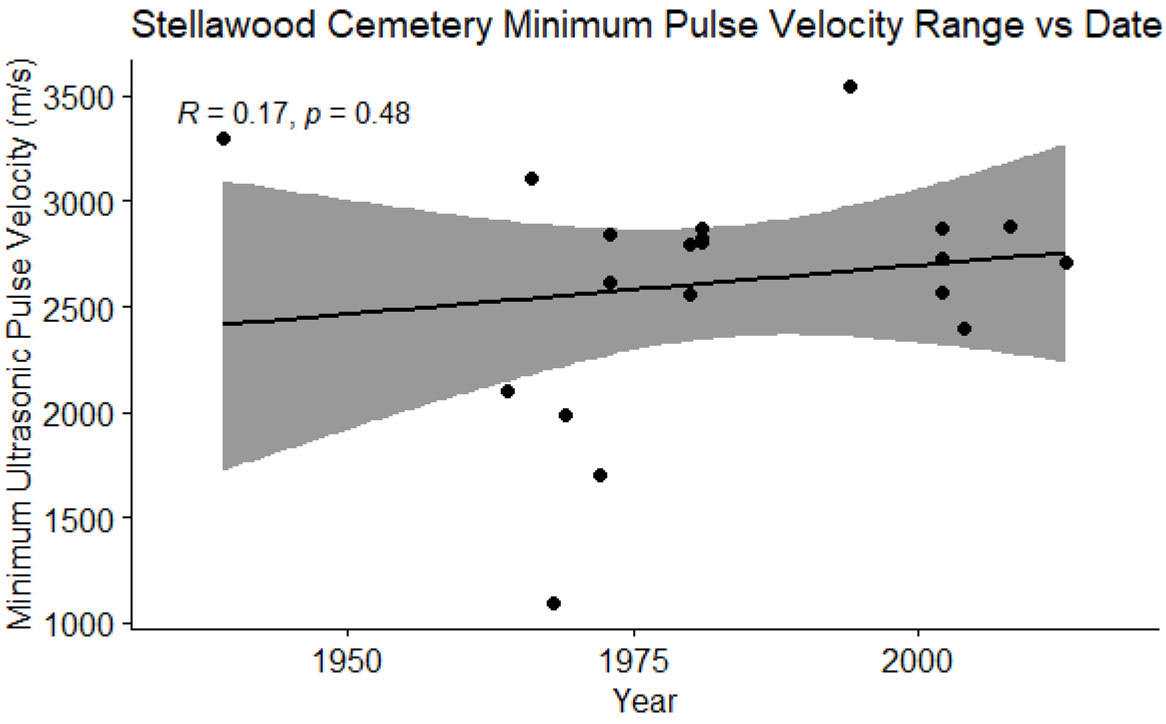
Appendix 3: Initial field experiments at additional cemeteries

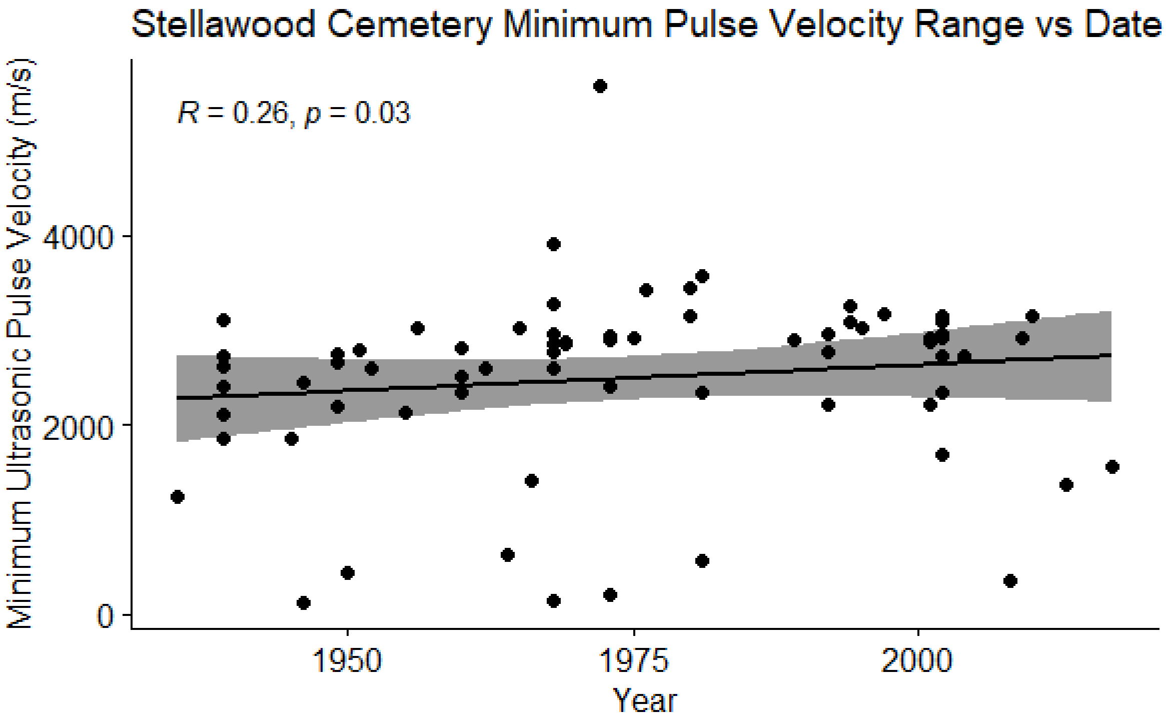


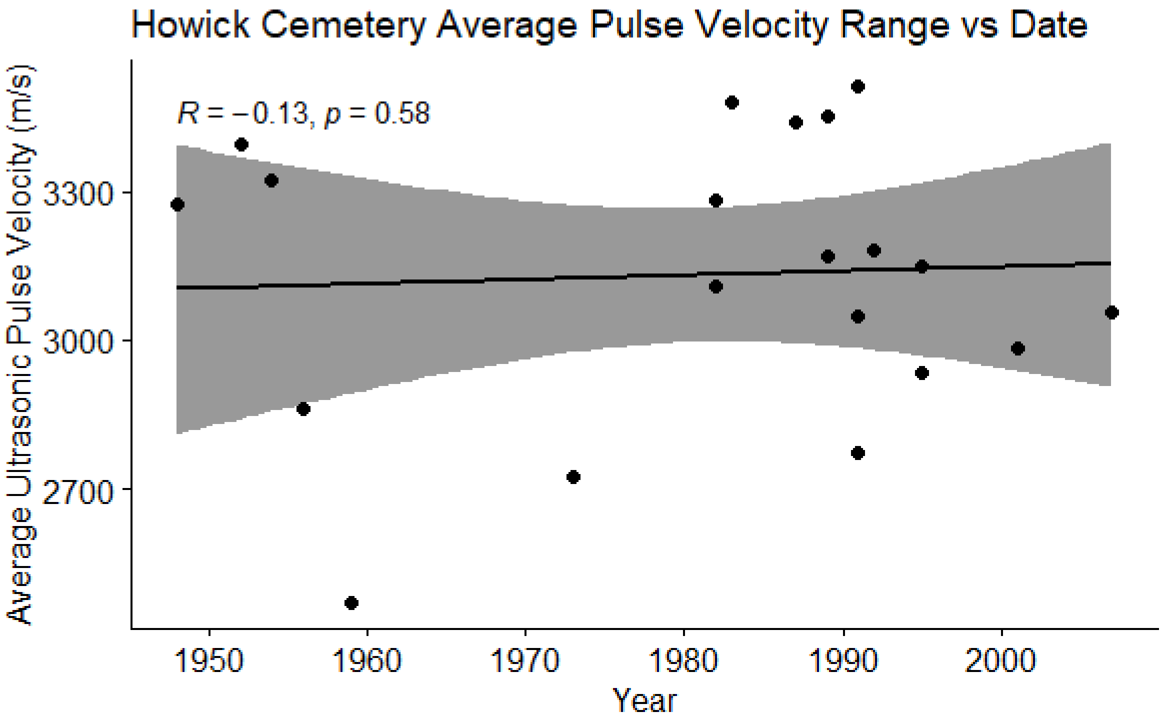


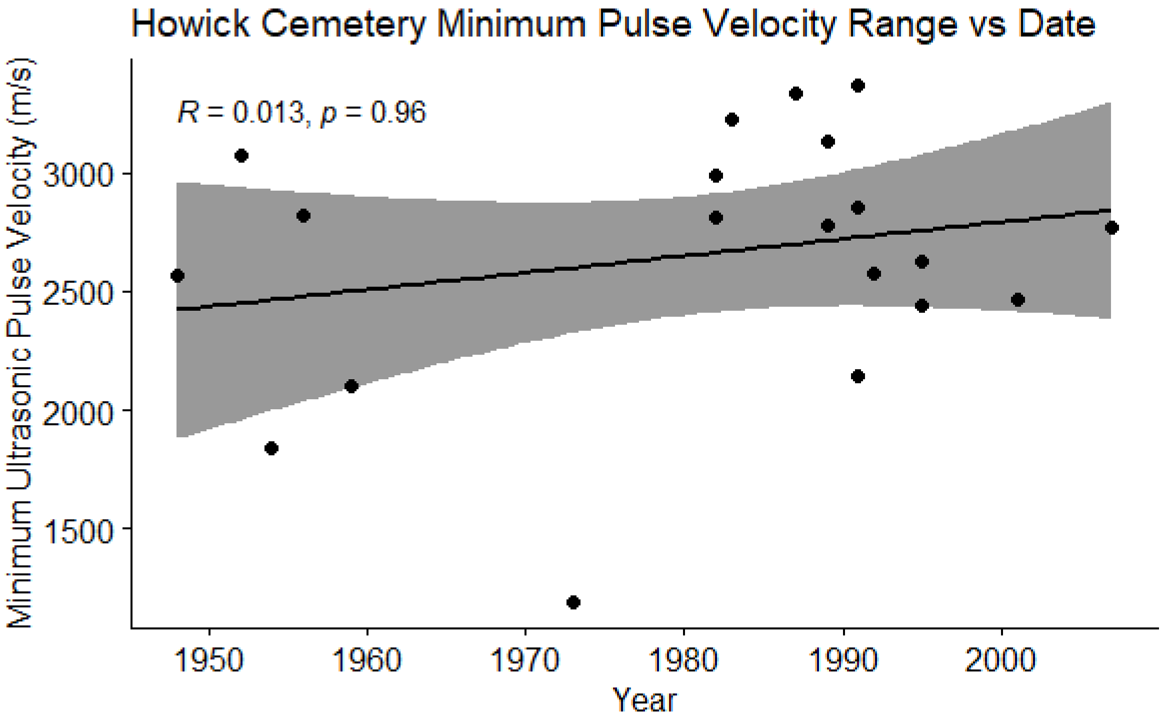

Stellawood Cemetery Average Pulse Velocity Range vs Date
R = −0.19, p = 0.42
Average Ultrasonic Pulse Velocity (m/s)
4000
3000
1950
1975
2000
Year

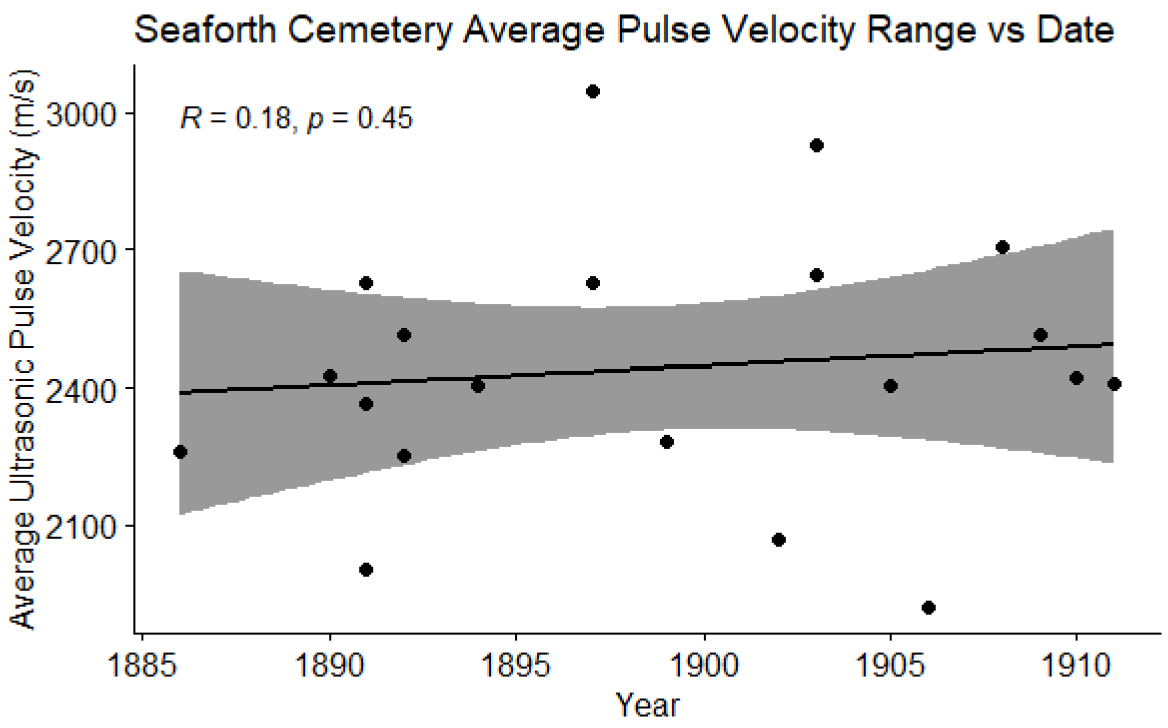

Stellawood Cemetery Average Pulse Velocity Range vs Date
R = 0.24, p = 0.045
Average Ultrasonic Pulse Velocity (m/s)
5000
4000
3000
2000
1000
1950
1975
2000
Year

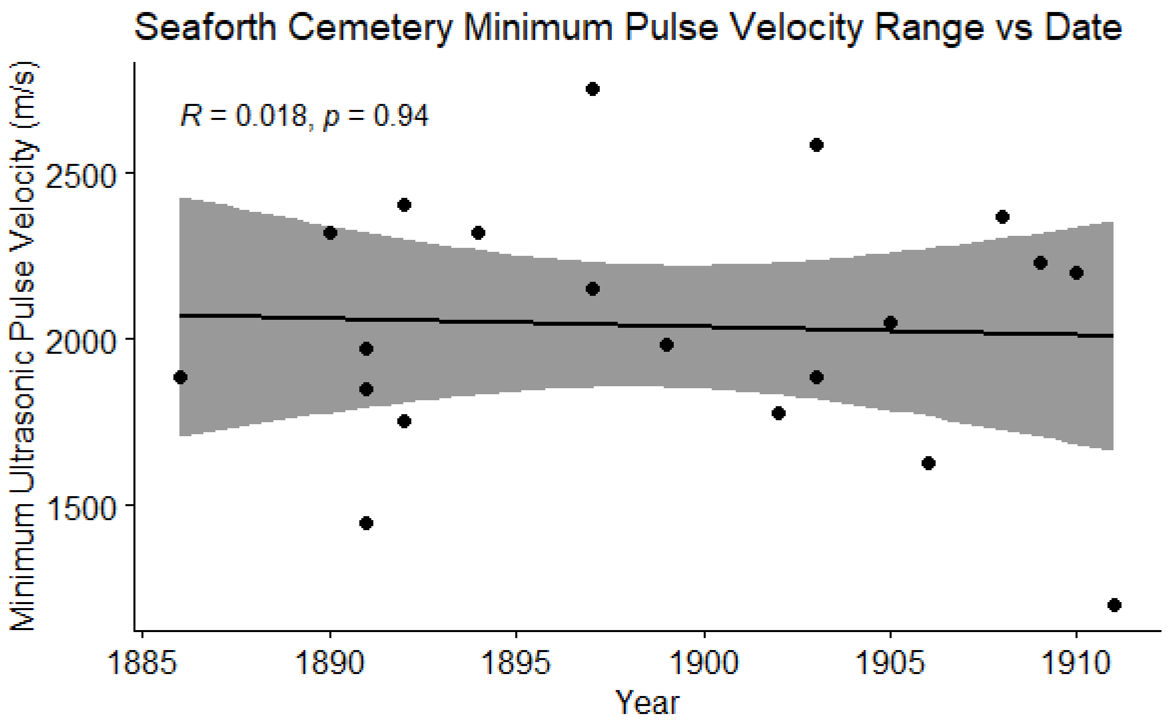

Stellawood Cemetery Minimum Pulse Velocity Range vs Date
R = 0.17, p = 0.48
Minimum Ultrasonic Pulse Velocity (m/s)
3500
3000
2500
2000
1500
1000
1950
1975
2000
Year

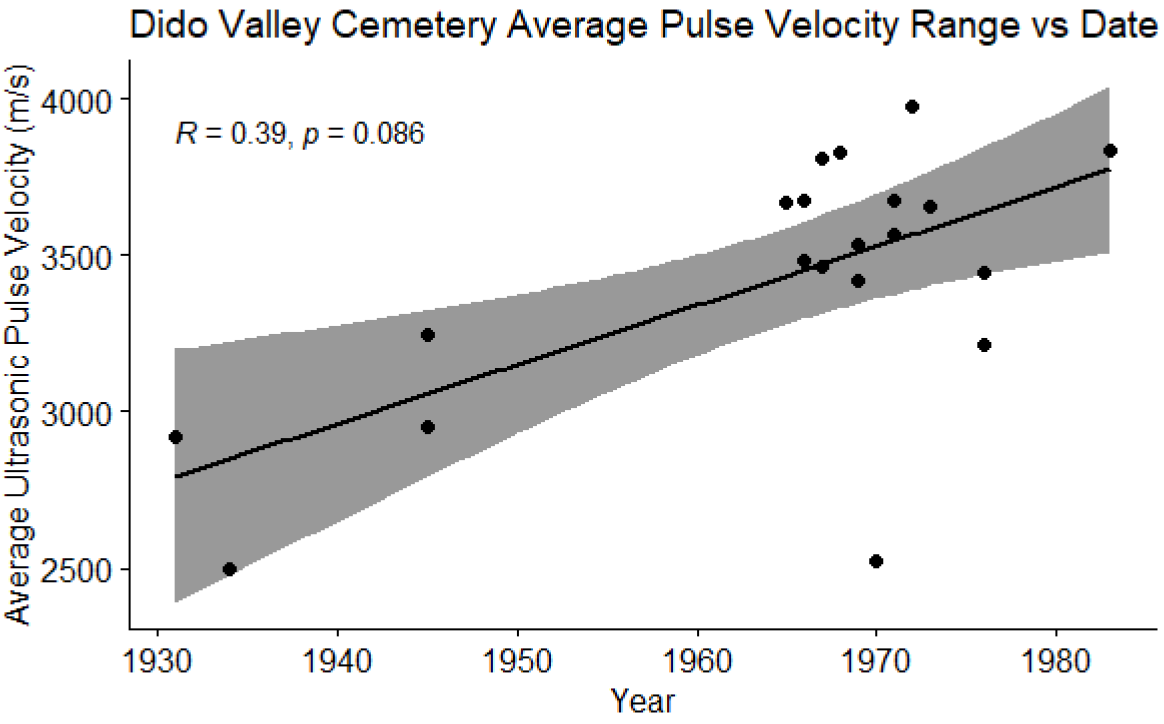

Stellawood Cemetery Minimum Pulse Velocity Range vs Date
R = 0.26, p = 0.03
Minimum Ultrasonic Pulse Velocity (m/s)
4000
2000
0
1950
1975
2000
Year

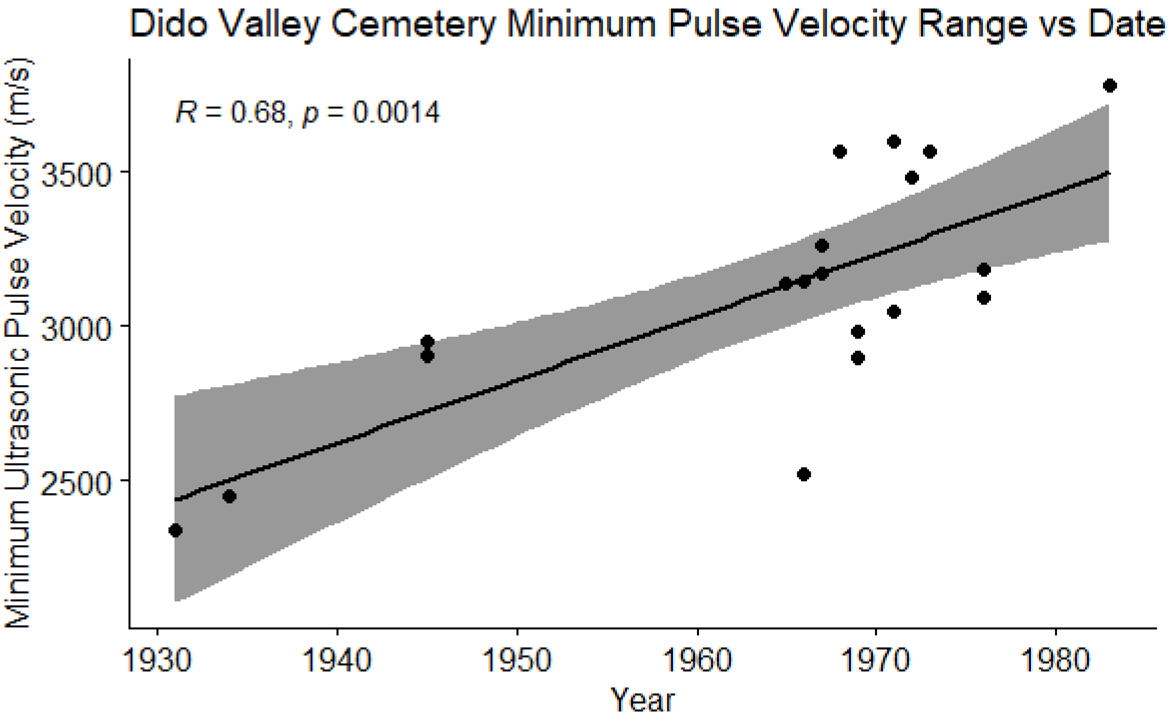

Howick Cemetery Average Pulse Velocity Range vs Date
R = −0.13, p = 0.58
Average Ultrasonic Pulse Velocity (m/s)
3300
3000
2700
1950
1960
1970
1980
1990
2000
Year


Howick Cemetery Minimum Pulse Velocity Range vs Date
R = 0.013, p = 0.96
Minimum Ultrasonic Pulse Velocity (m/s)
3000
2500
2000
1500
1950
1960
1970
1980
1990
2000
Year


Seaforth Cemetery Average Pulse Velocity Range vs Date
R = 0.18, p = 0.45
Average Ultrasonic Pulse Velocity (m/s)
3000
2700
2400
2100
1885
1890
1895
1900
1905
1910
Year

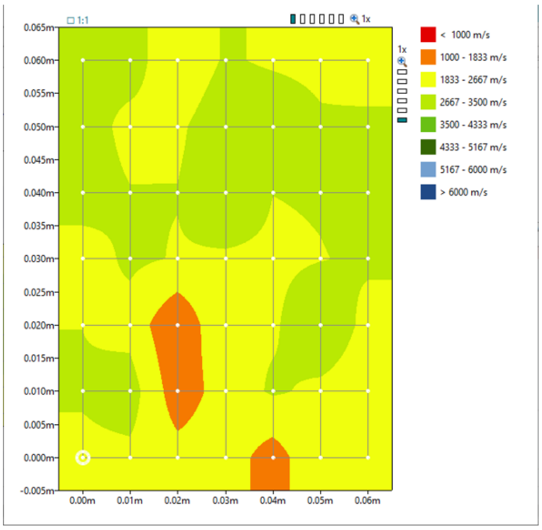

Seaforth Cemetery Minimum Pulse Velocity Range vs Date
R = 0.018, p = 0.94
Minimum Ultrasonic Pulse Velocity (m/s)
2500
2000
1500
1885
1890
1895
1900
1905
1910
Year


Dido Valley Cemetery Average Pulse Velocity Range vs Date
R = 0.39, p = 0.086
Average Ultrasonic Pulse Velocity (m/s)
4000
3500
3000
2500
1930
1940
1950
1960
1970
1980
Year

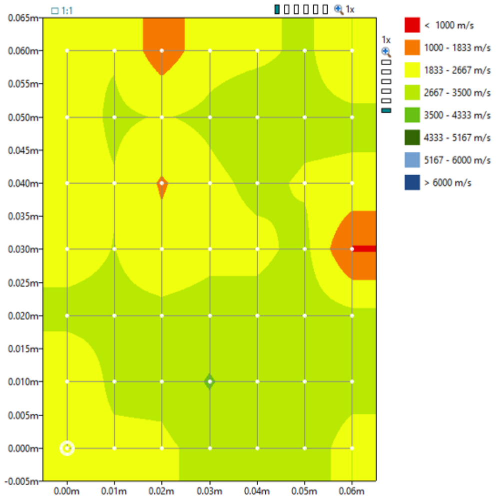

Dido Valley Cemetery Minimum Pulse Velocity Range vs Date
R = 0.68, p = 0.0014
Minimum Ultrasonic Pulse Velocity (m/s)
3500
3000
2500
1930
1940
1950
1960
1970
1980
Year

Appendix 4: Tombstone area scans (Maitland Cemetery, Cape Town)

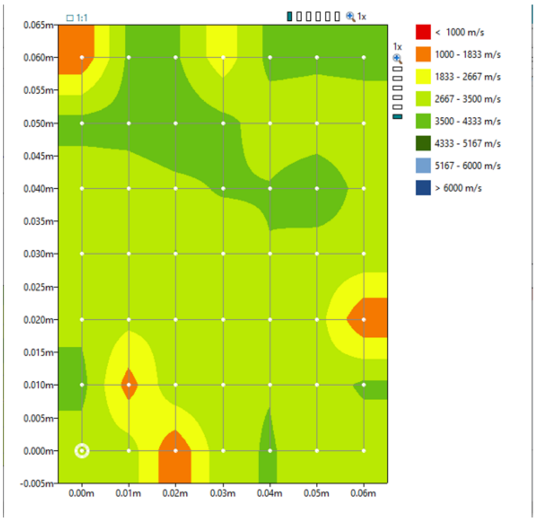
Date of Death: 1919



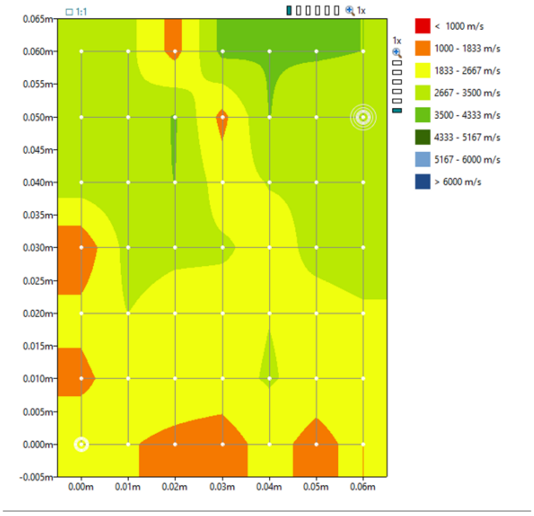
Date of Death: 1924



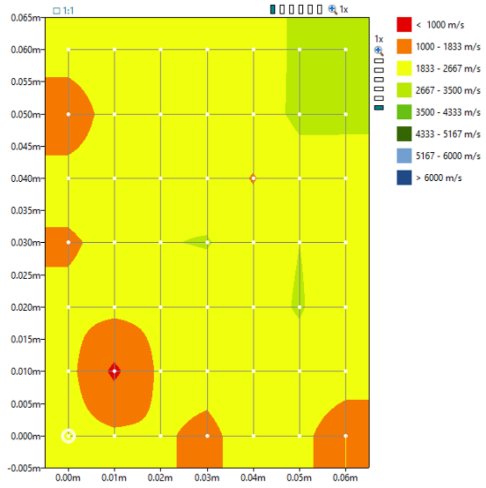
Date of Death: 1935



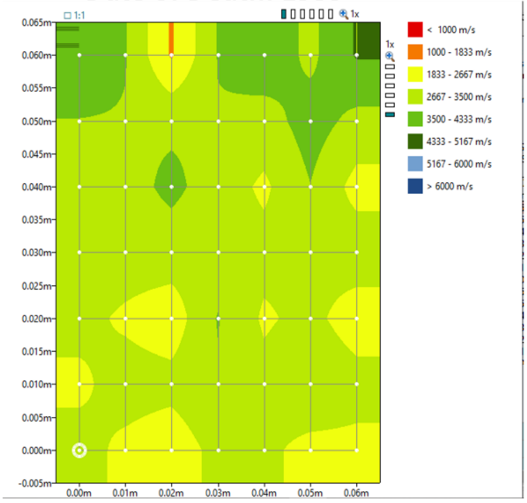
Date of Death: 1935



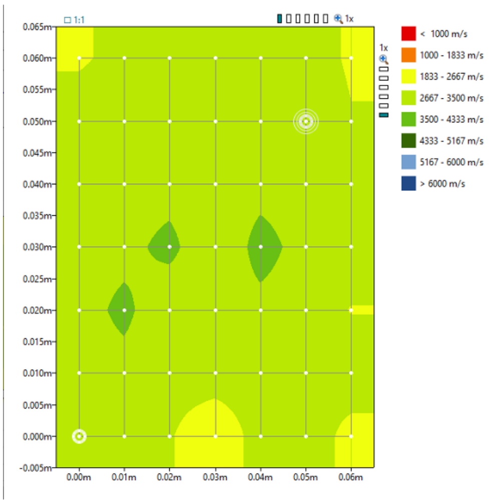
Date of Death: 1936



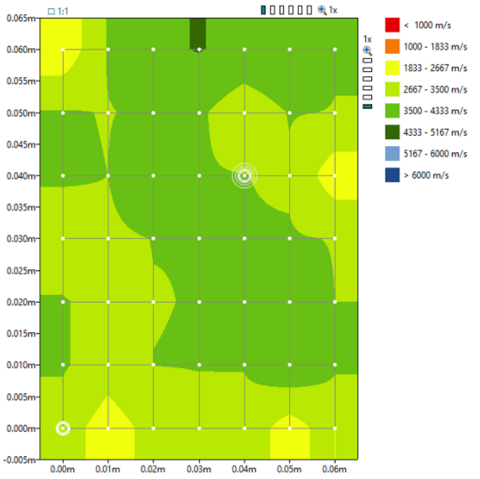
Date of Death: 1939



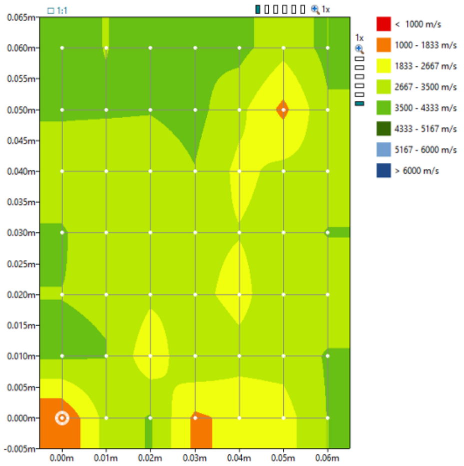
Date of Death: 1950



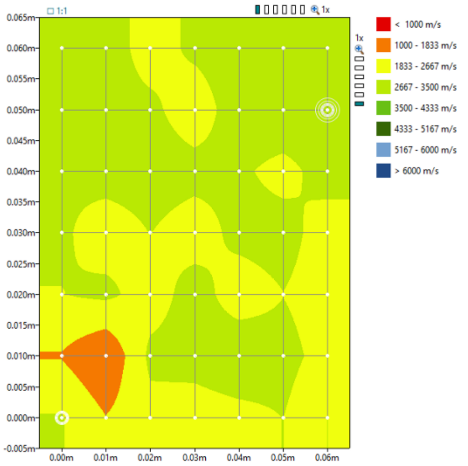
Date of Death: 1957



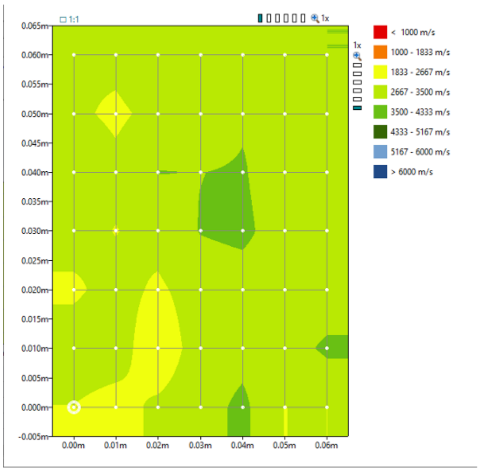
Date of Death: 1957



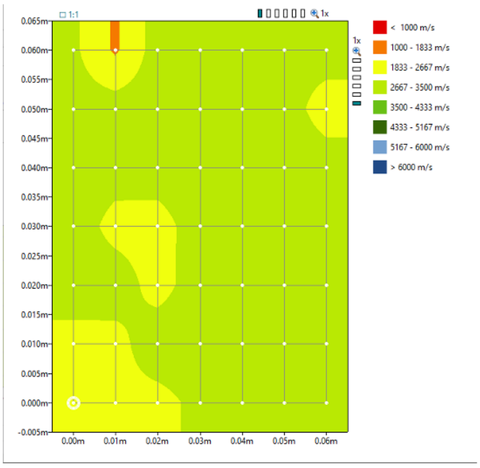
Date of Death: 1958



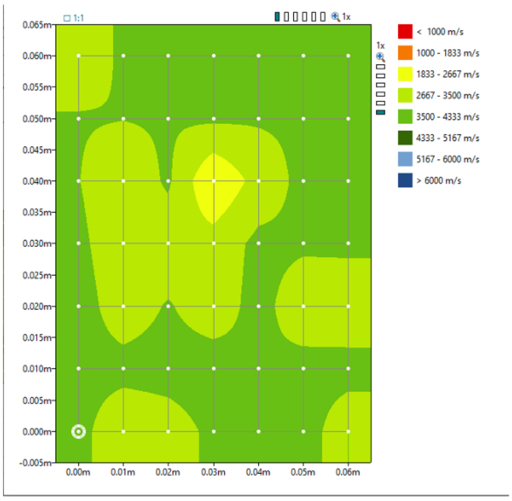
Date of Death: 1962



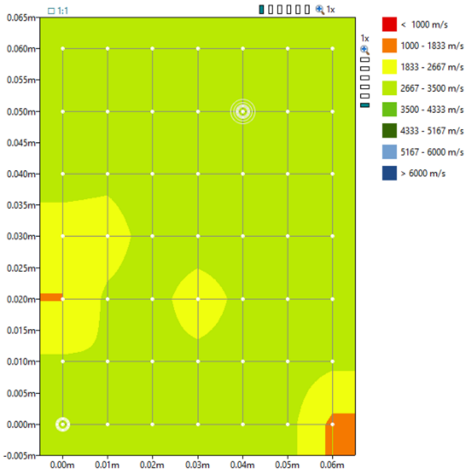
Date of Death: 1979



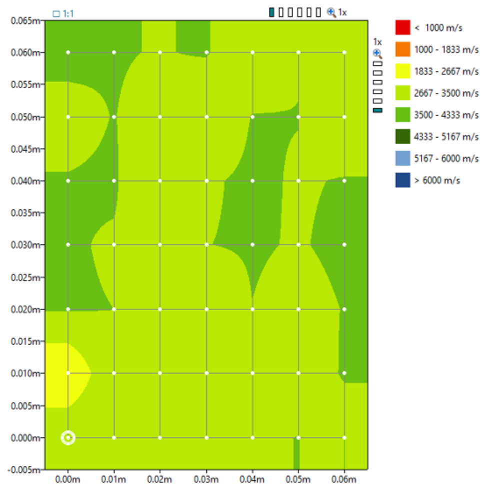
Date of Death: 1981



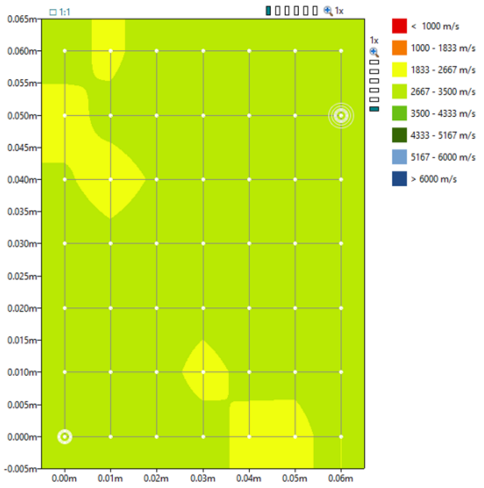
Date of Death: 1981



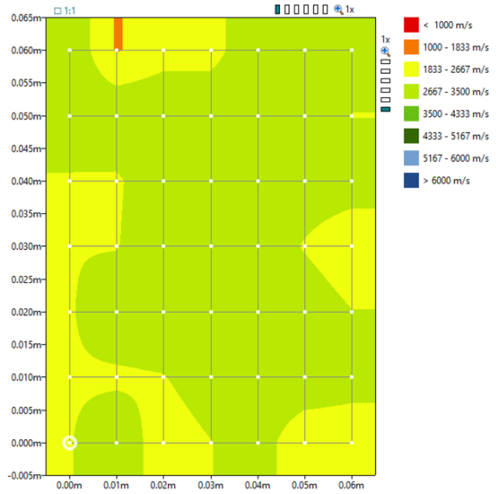
Date of Death: 1983



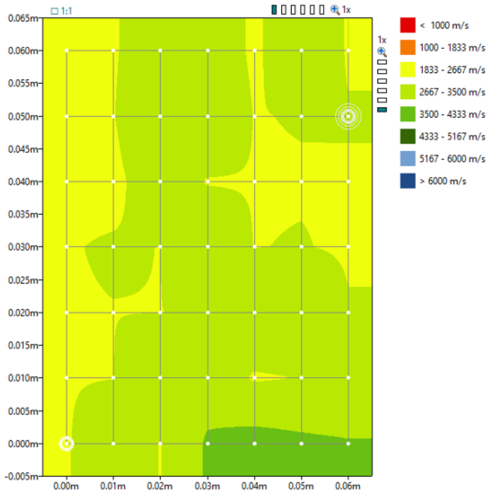
Date of Death: 1988



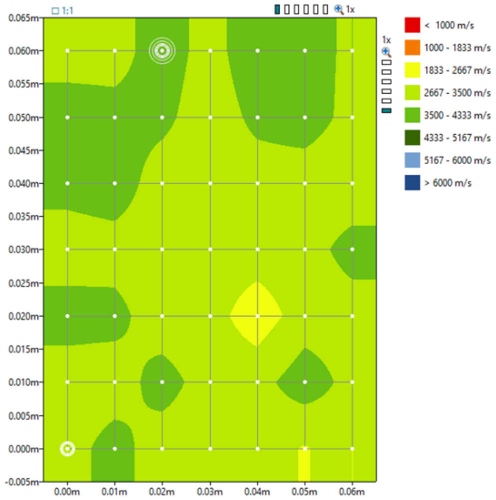
Date of Death: 2001



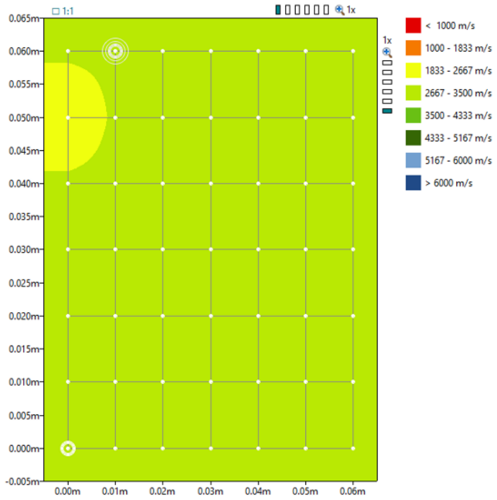
Date of Death: 2003



Date of Death: 2009

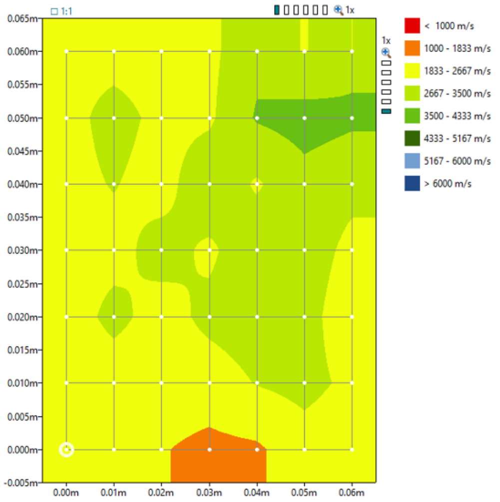


Date of Death: 2008

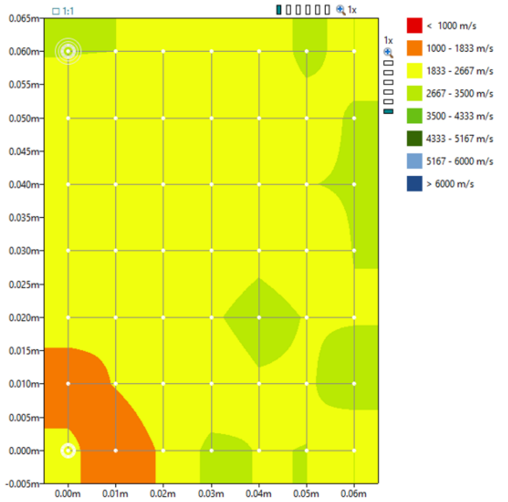


Appendix 5: Tombstone area scans (Dido Valley Cemetery)

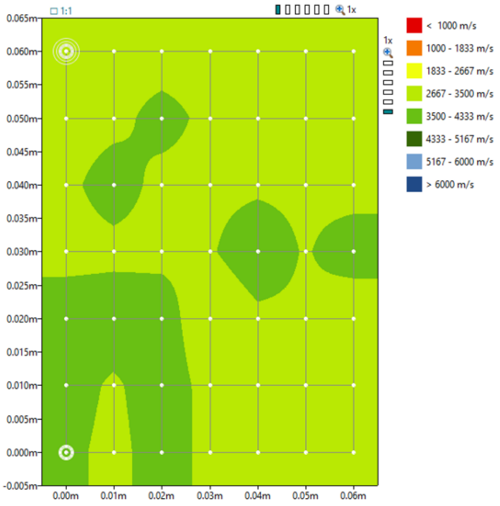
Date of Death: 1931



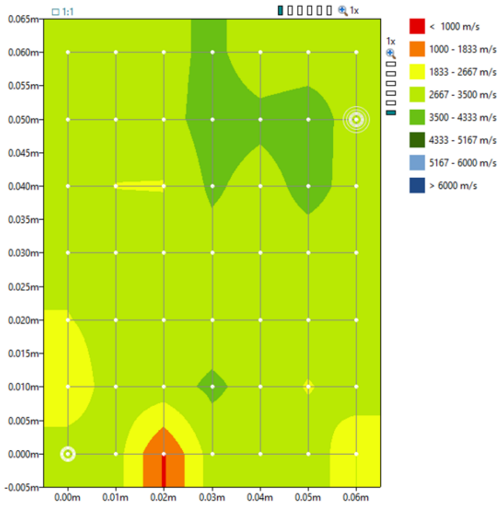
Date of Death: 1935



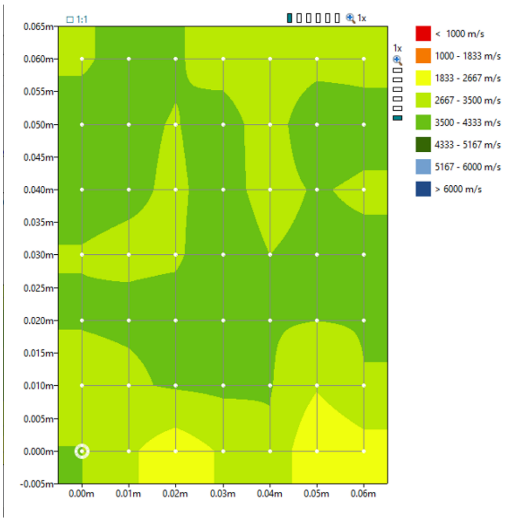
Date of Death: 1963



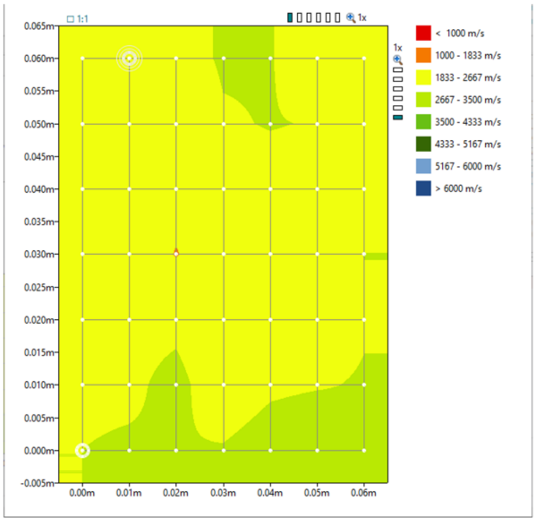
Date of Death: 1966



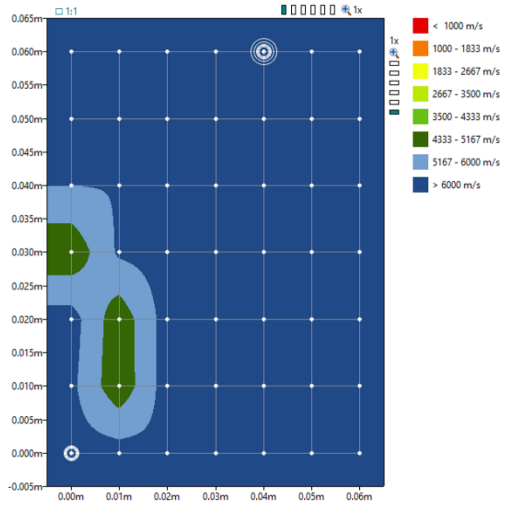
Date of Death: 1968



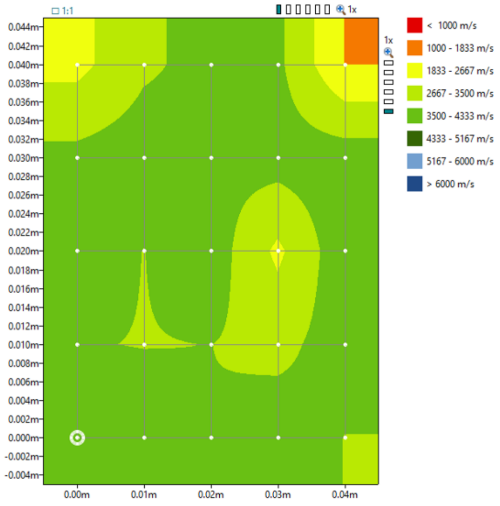
Date of Death: 1981



Date of Death: 2015

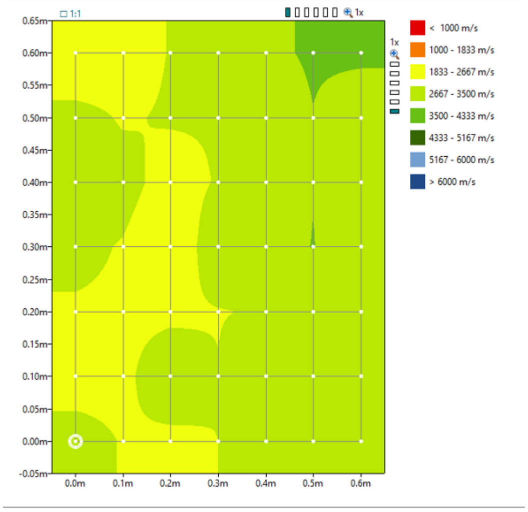


Date of Death: 2020

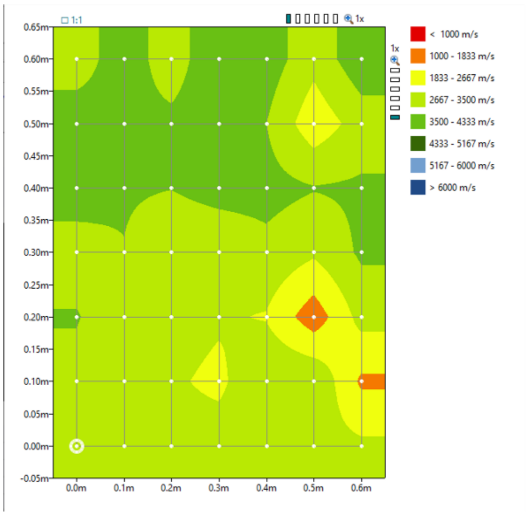


Appendix 6: Tombstone area scans (Stellawood Cemetery)

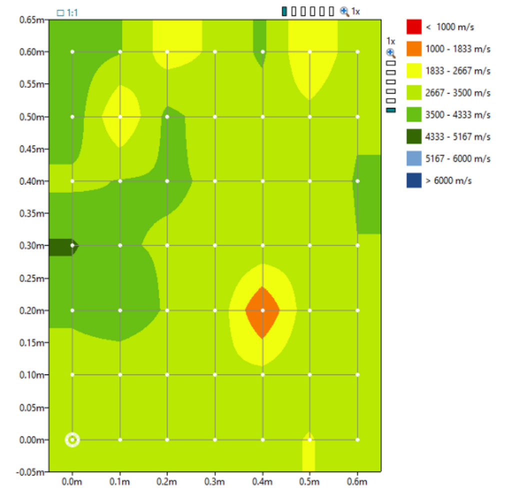
Date of Death: 1919



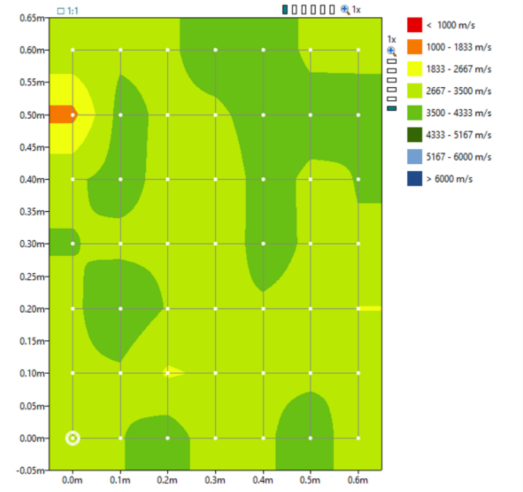
Date of Death: 1934



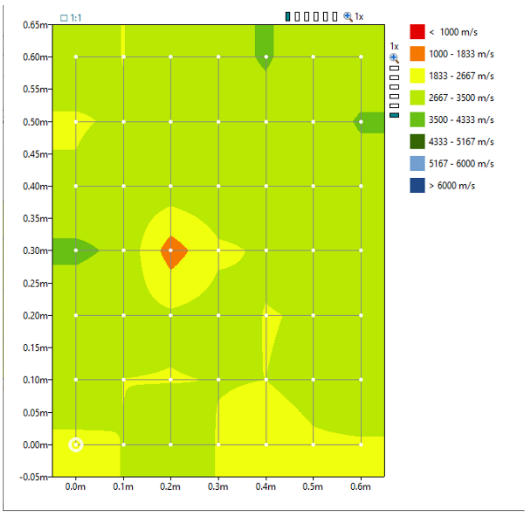
Date of Death: 1938



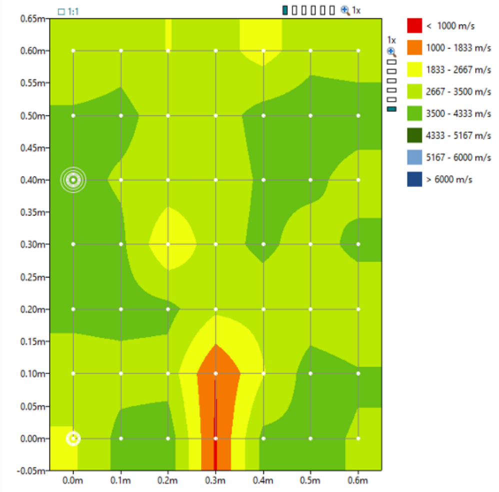
Date of Death: 1939



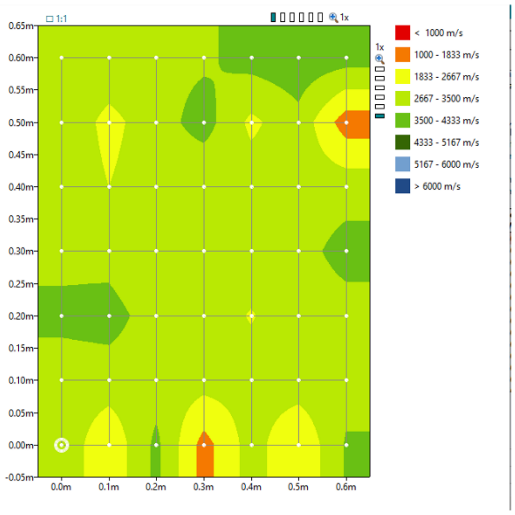
Date of Death: 1942



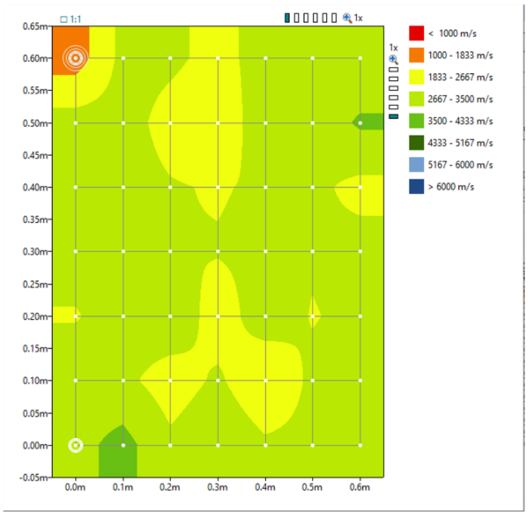
Date of Death: 1942



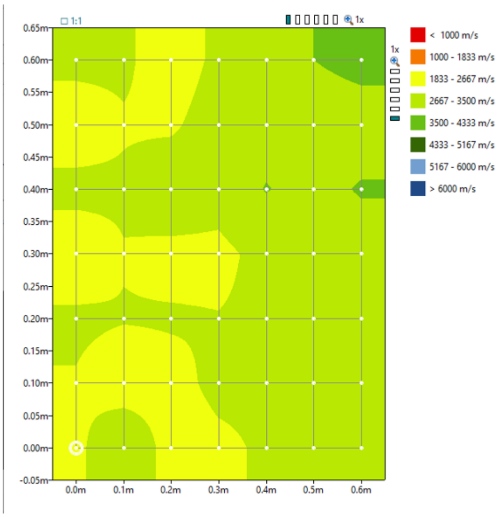
Date of Death: 1942



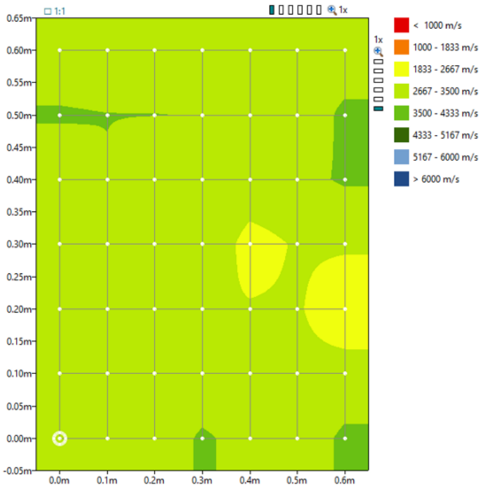
Date of Death: 1942



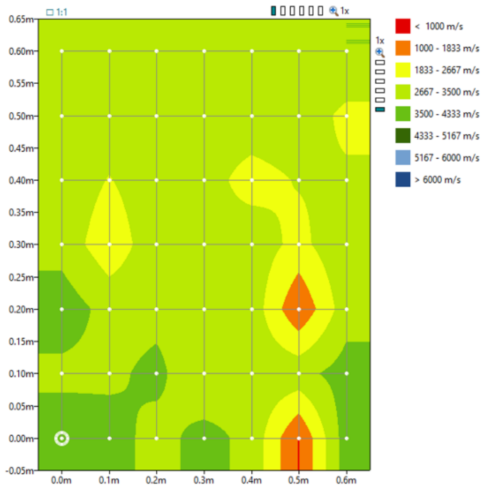
Date of Death: 1944



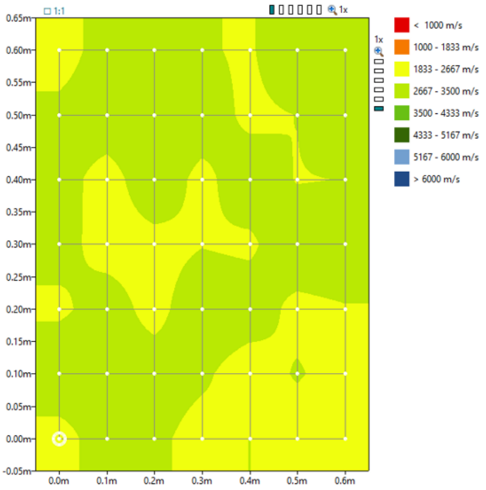
Date of Death: 1945



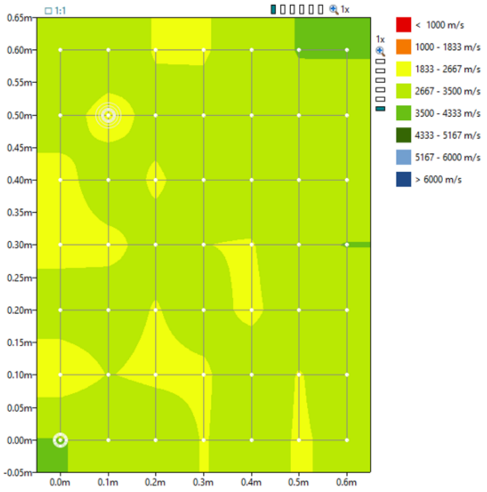
Date of Death: 1948



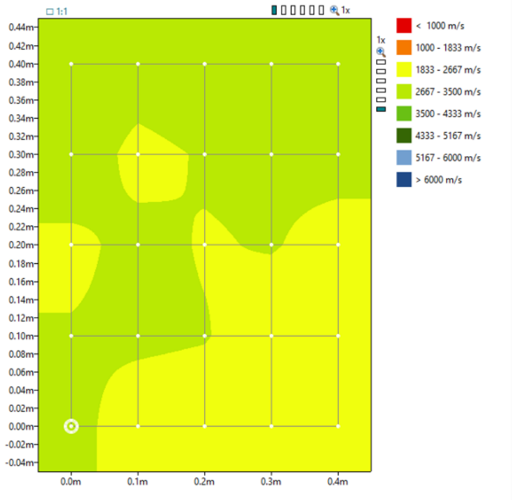
Date of Death: 1948



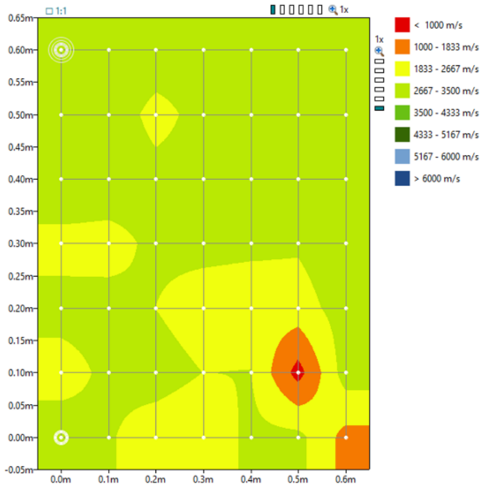
Date of Death: 1949



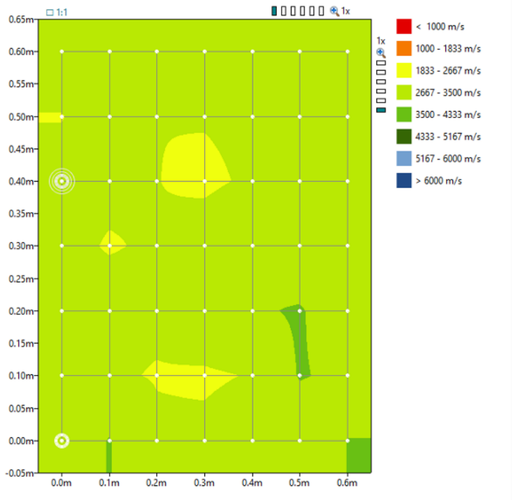
Date of Death: 1950



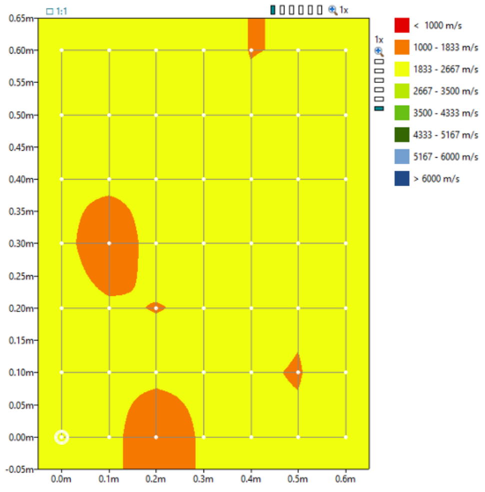
Date of Death: 1949



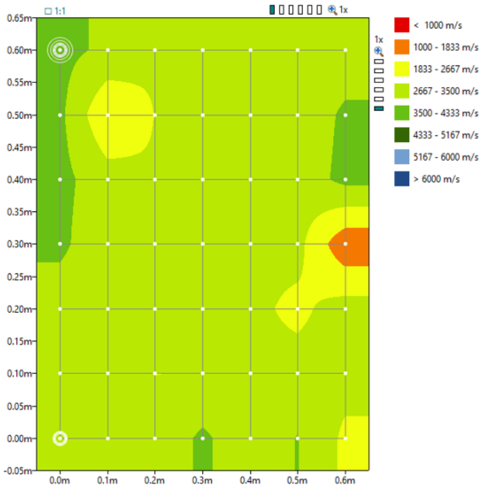
Date of Death: 1949



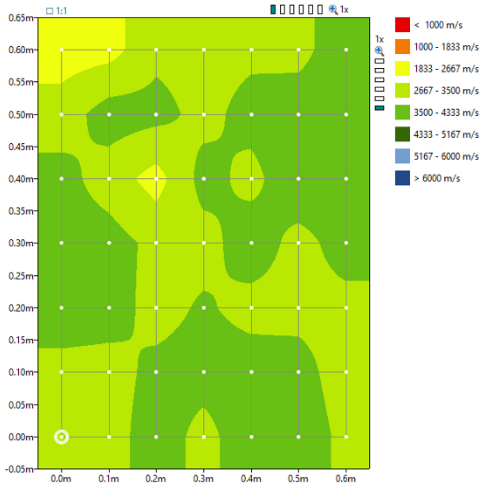
Date of Death: 1951



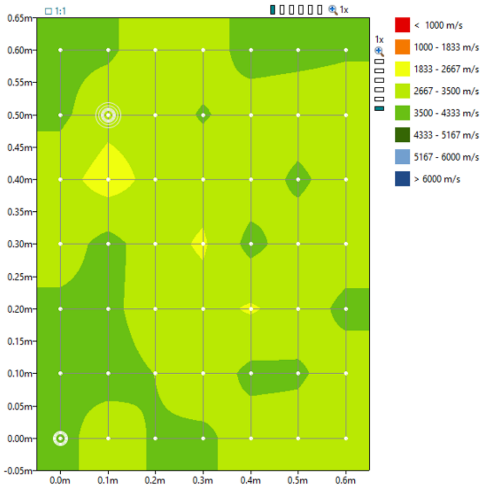
Date of Death: 1956



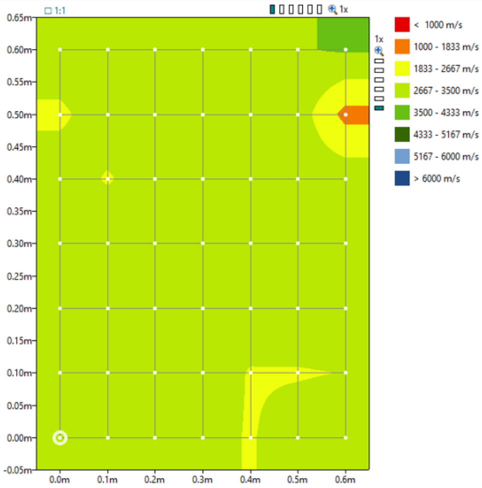
Date of Death: 1959



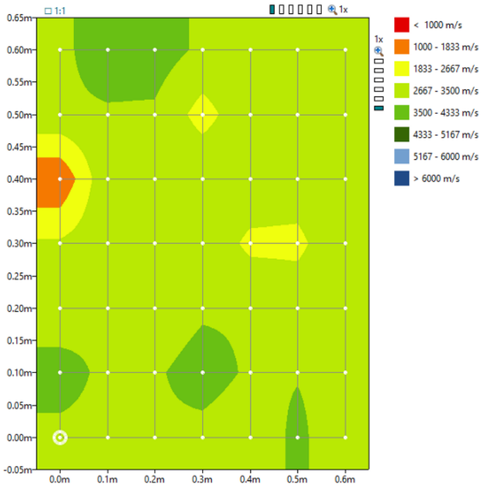
Date of Death: 1959



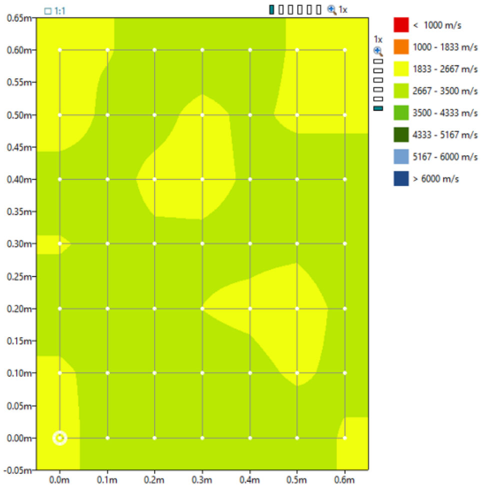
Date of Death: 1960



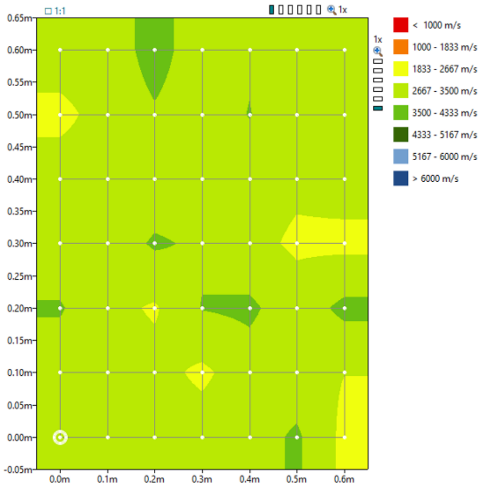
Date of Death: 1960



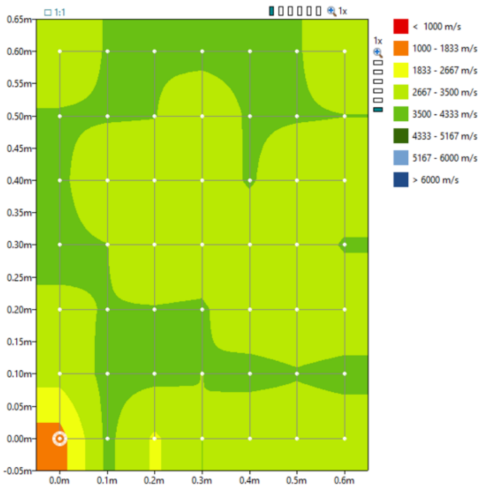
Date of Death: 1961



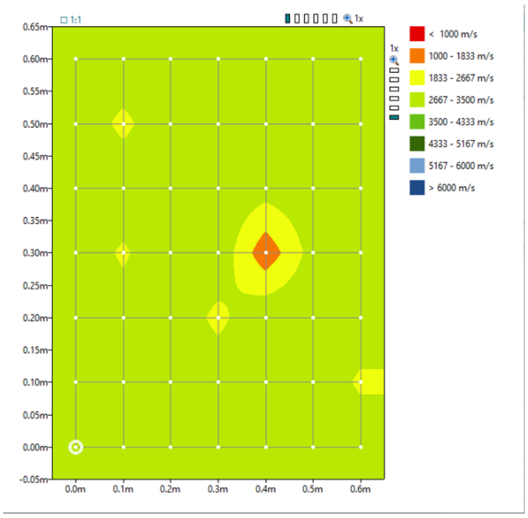
Date of Death: 1962



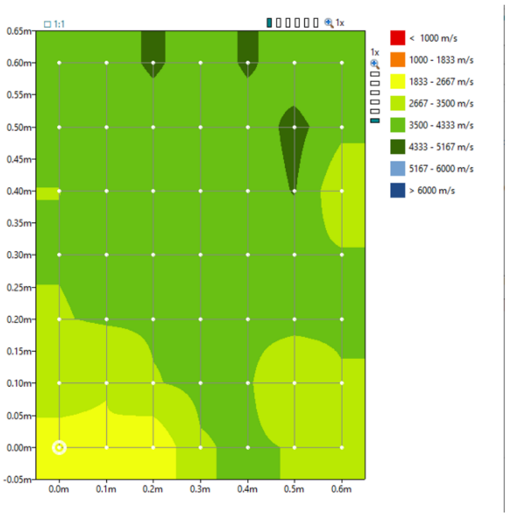
Date of Death: 1964



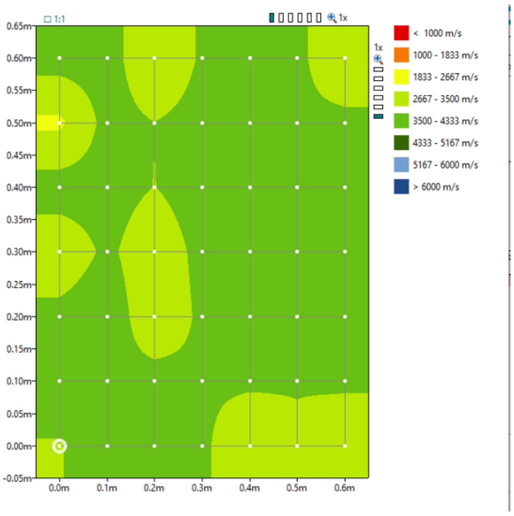
Date of Death: 1966



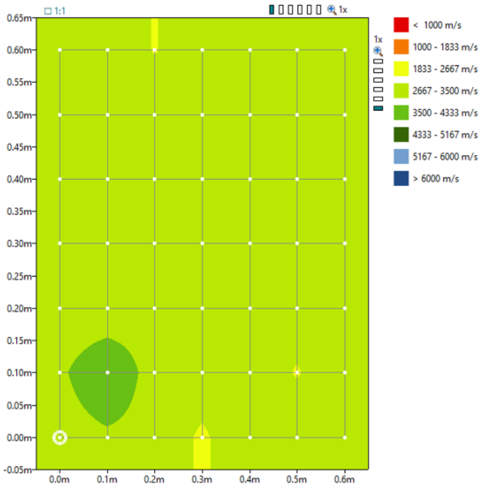
Date of Death: 1964



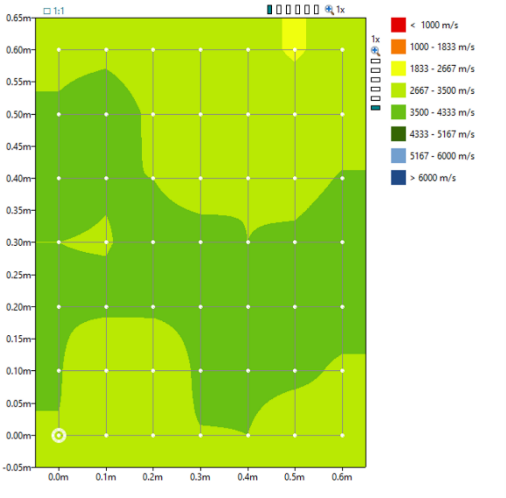
Date of Death: 1964



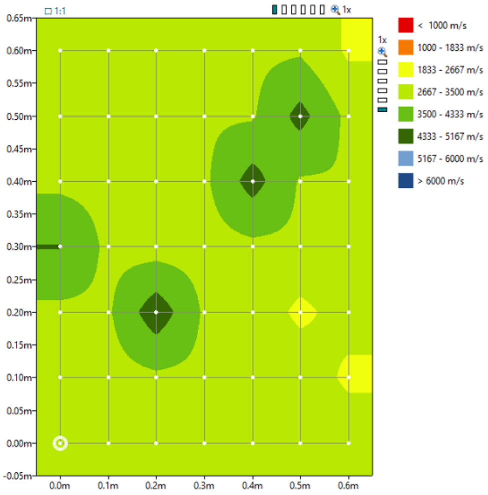
Date of Death: 1970



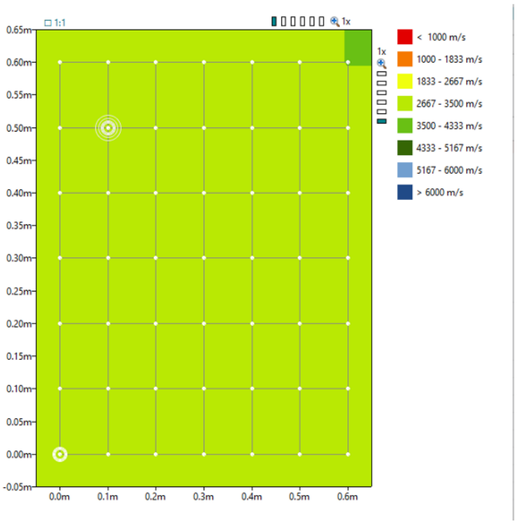
Date of Death: 1972



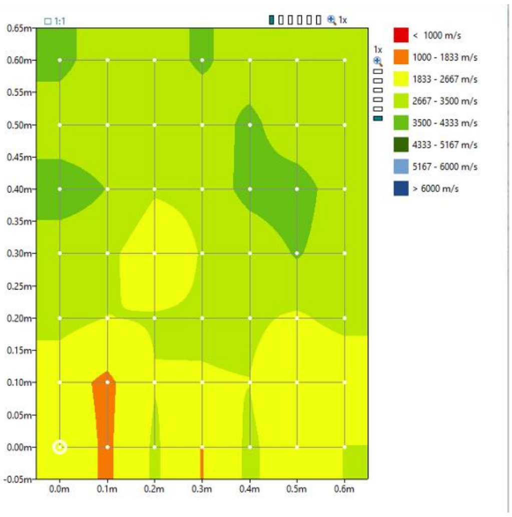
Date of Death: 1987



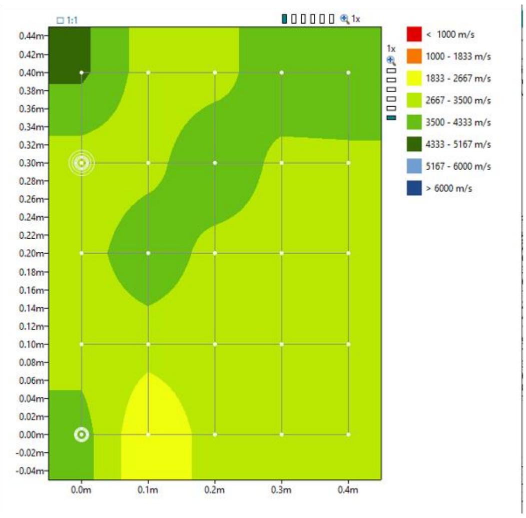
Date of Death: 1989



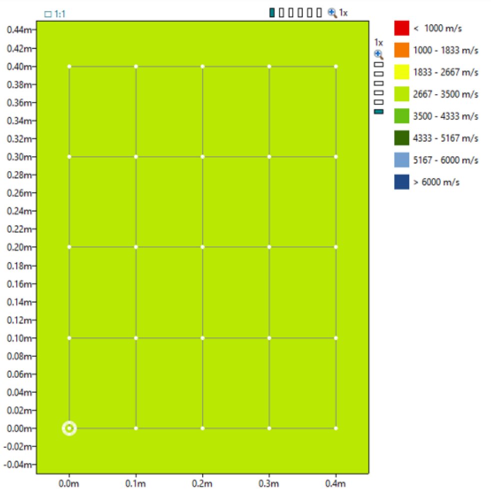
Date of Death: 1991



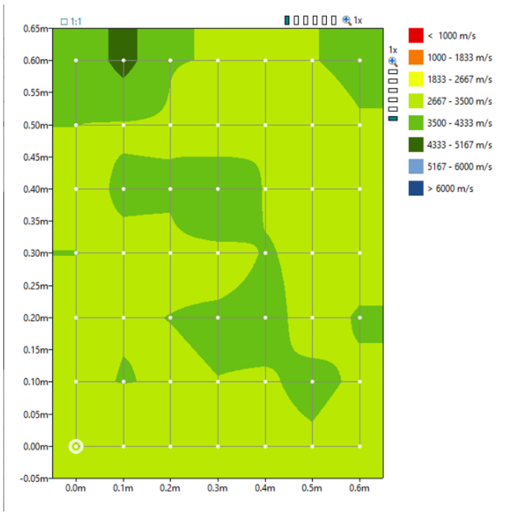
Date of Death: 1991



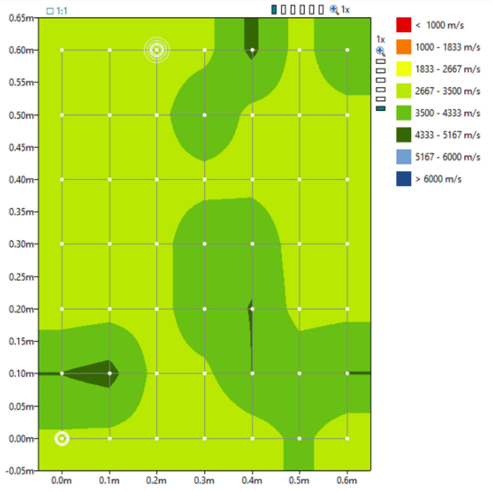
Date of Death: 1994



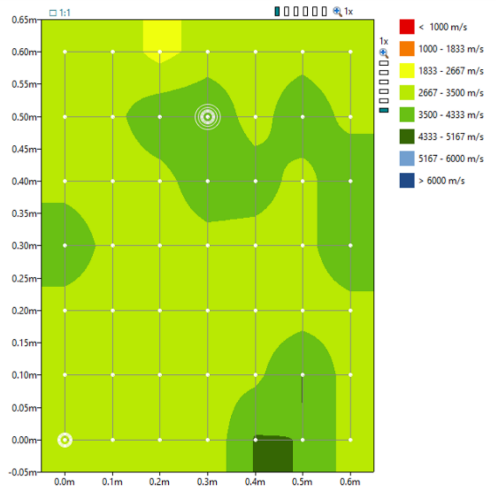
Date of Death: 1996



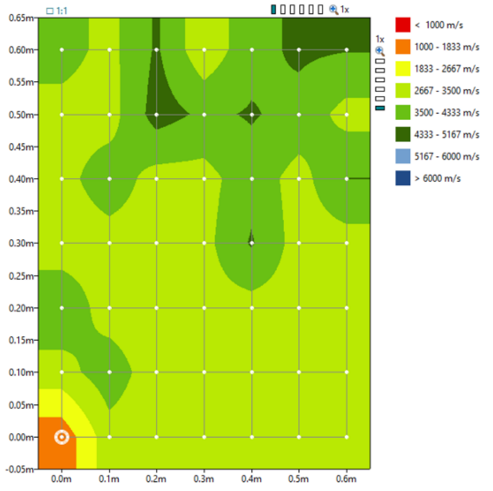
Date of Death: 2002



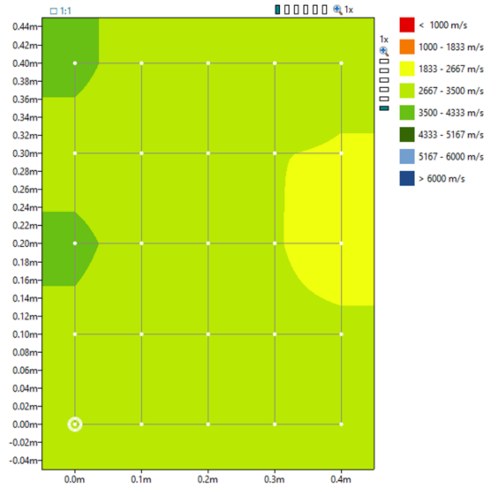
Date of Death: 2002



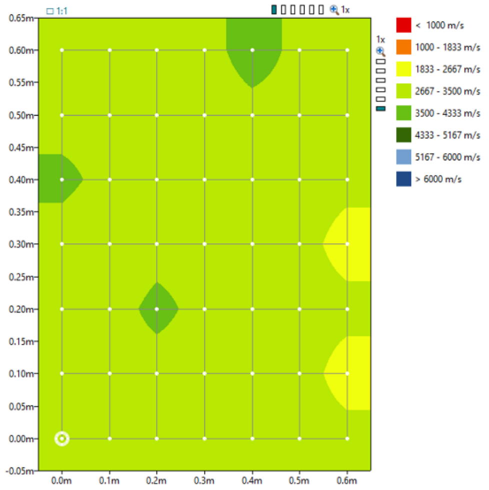
Date of Death: 2003



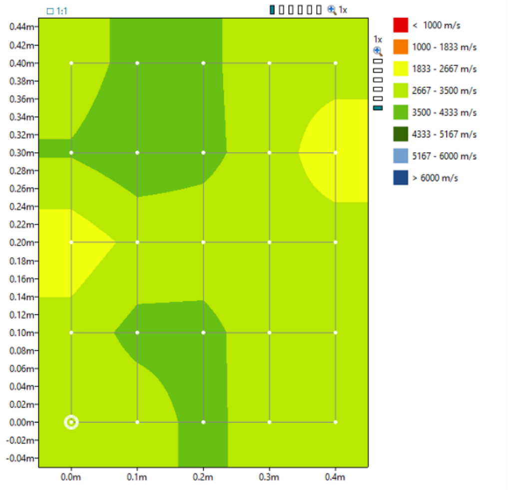
Date of Death: 2008



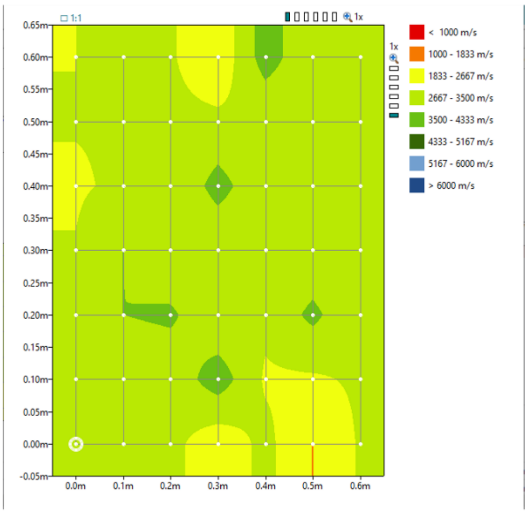
Date of Death: 2011



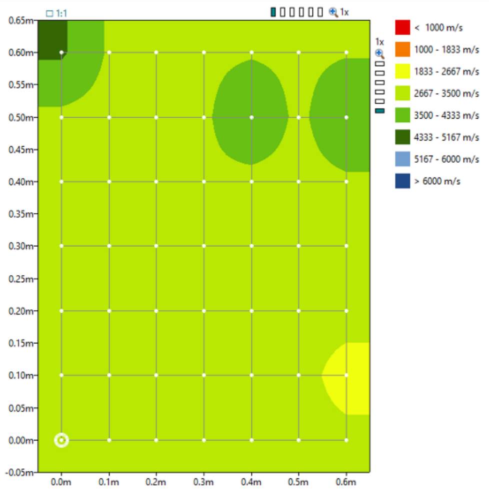
Date of Death: 2011



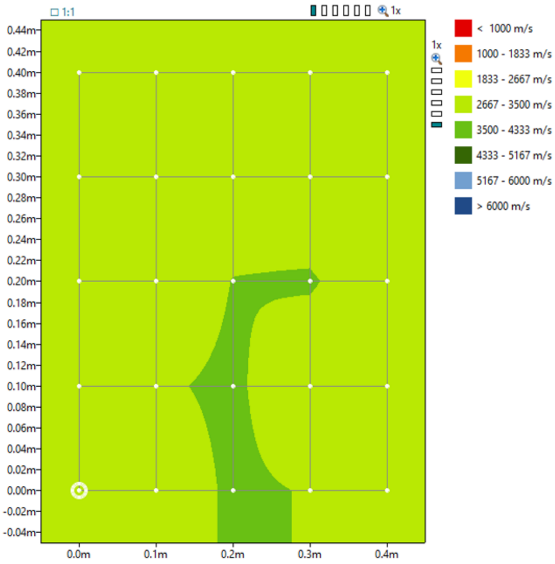
Date of Death: 2020

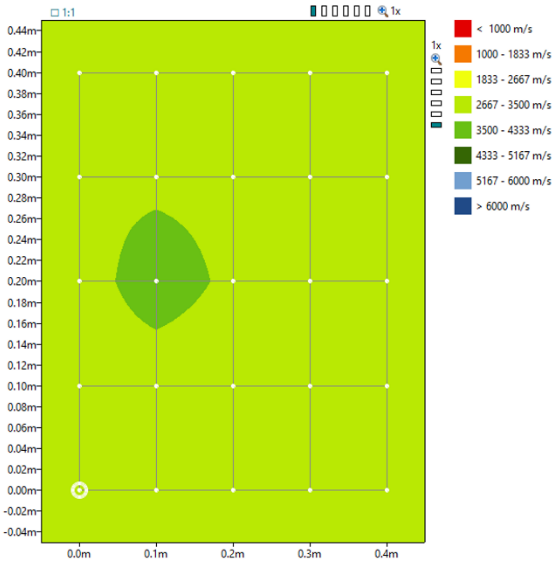


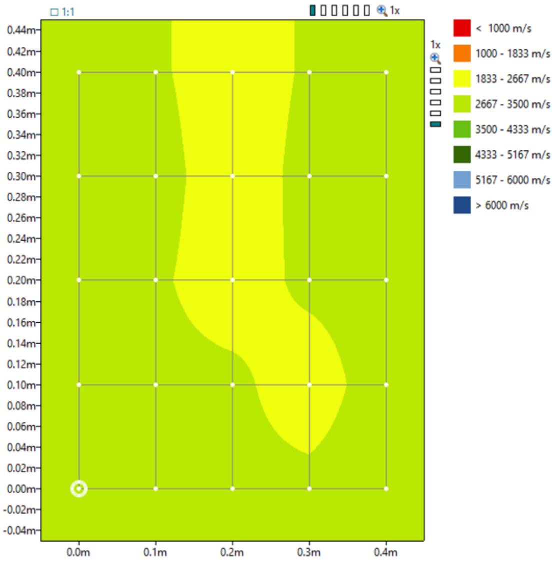
Date of Death: 2020

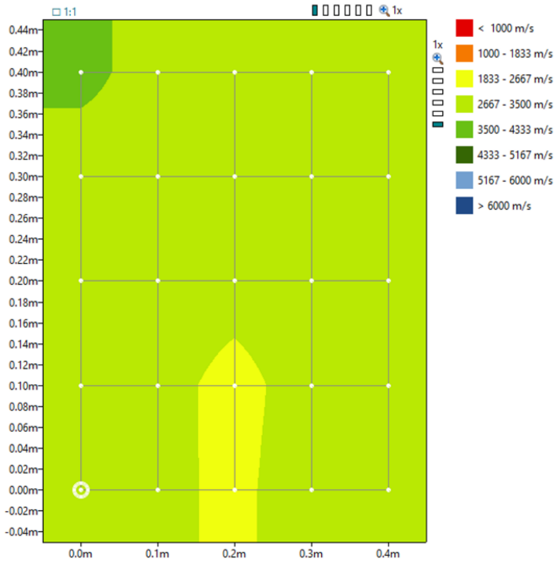


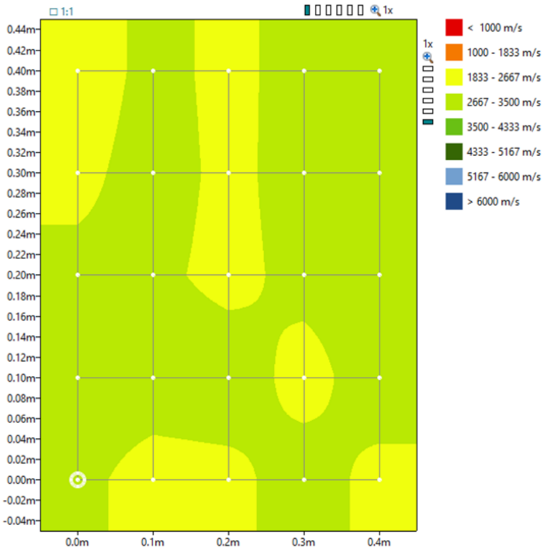
Appendix 7: Stellawood Wargraves (circa 1940 – 1947)







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0.42m
0.40m
0.38m
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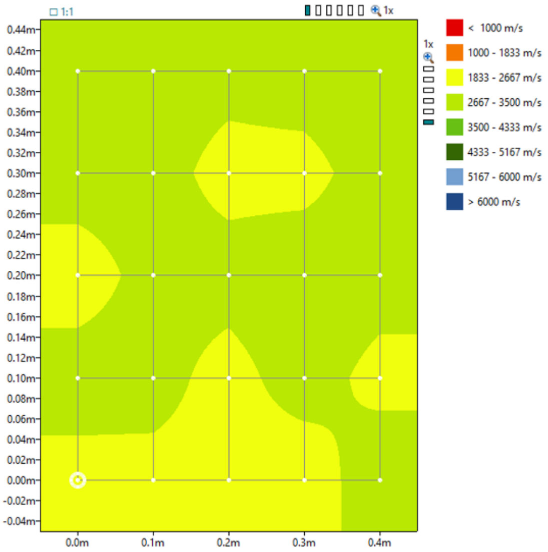
0.32m
0.30m
0.28m
0.26m
0.24m
0.22m
0.20m
0.18m
0.16m
0.14m
0.12m
0.10m
0.08m
0.06m
0.04m
0.02m
0.00m
-0.02m
-0.04m
0.0m
0.1m
0.2m
0.3m
0.4m
< 1000 m/s
1000 - 1833 m/s
1833 - 2667 m/s
2667 - 3500 m/s
3500 - 4333 m/s
4333 - 5167 m/s
5167 - 6000 m/s
> 6000 m/s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0.3m
0.4m
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1000 - 1833 m/s
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3500 - 4333 m/s
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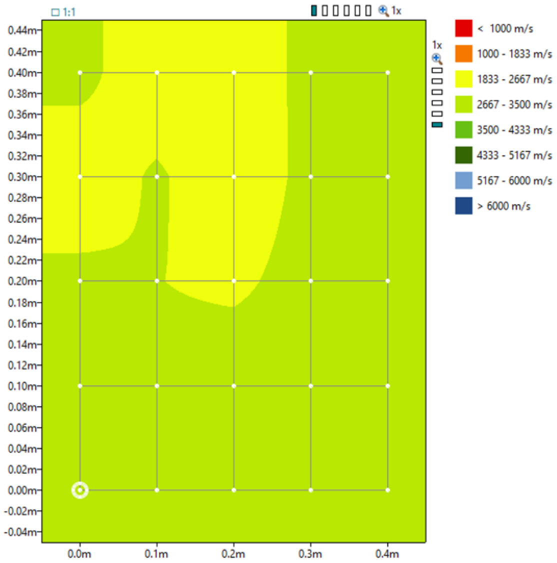
> 6000 m/s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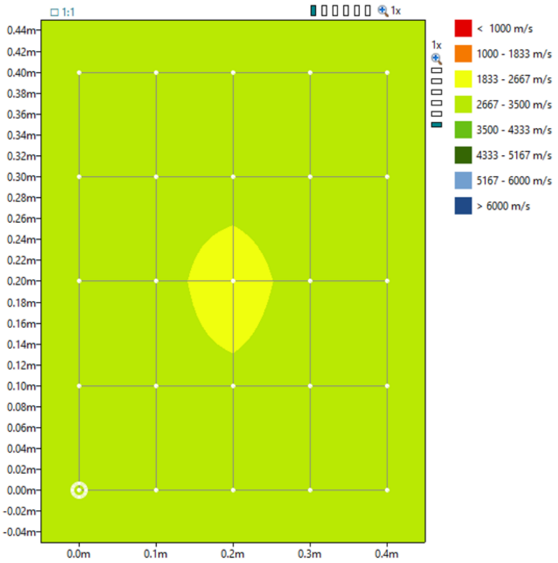
< 1000 m/s
1000 - 1833 m/s
1833 - 2667 m/s
2667 - 3500 m/s
3500 - 4333 m/s
4333 - 5167 m/s
5167 - 6000 m/s
> 6000 m/s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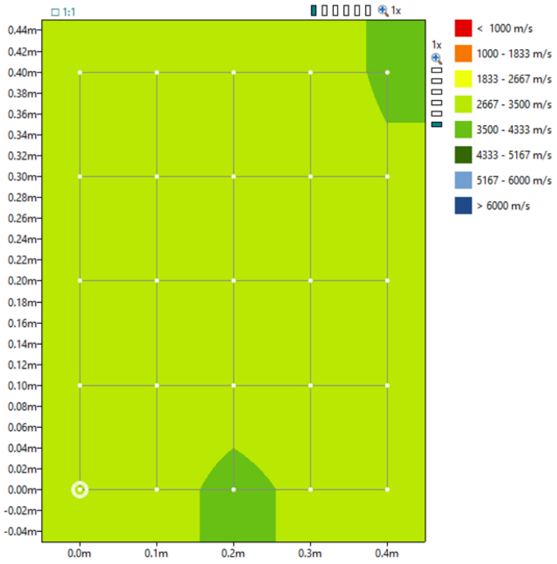
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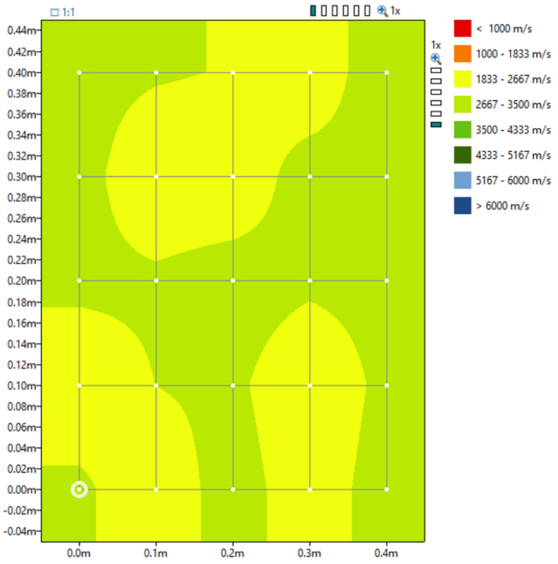
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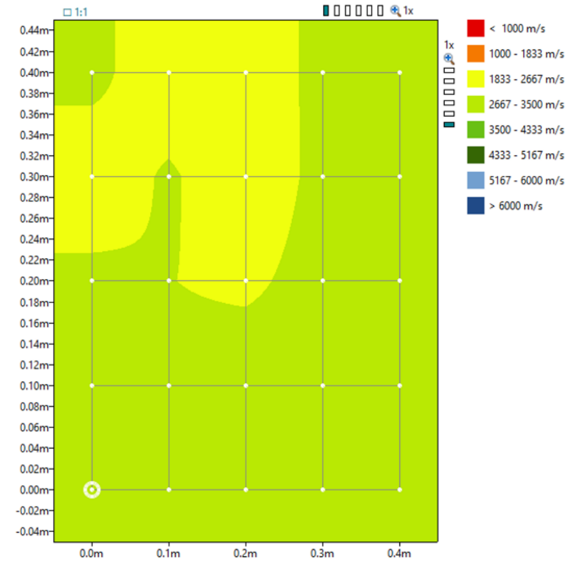
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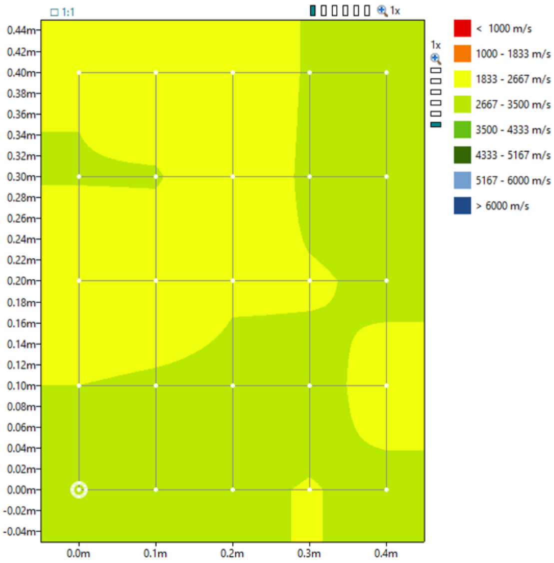
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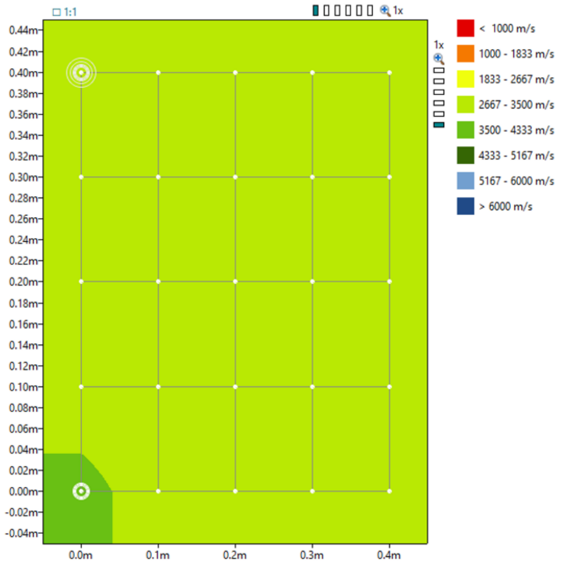
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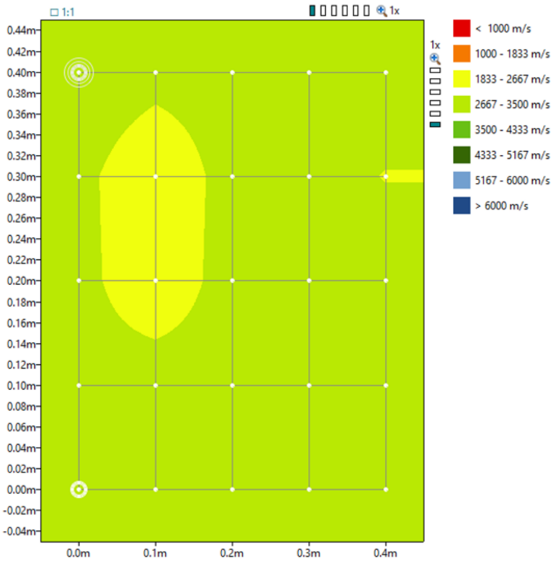
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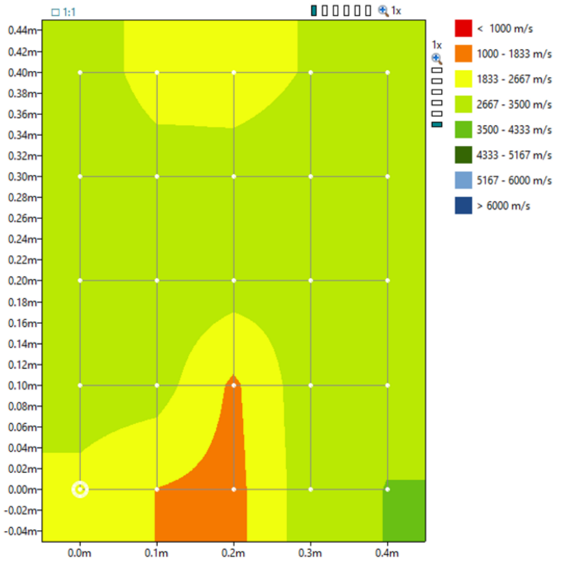
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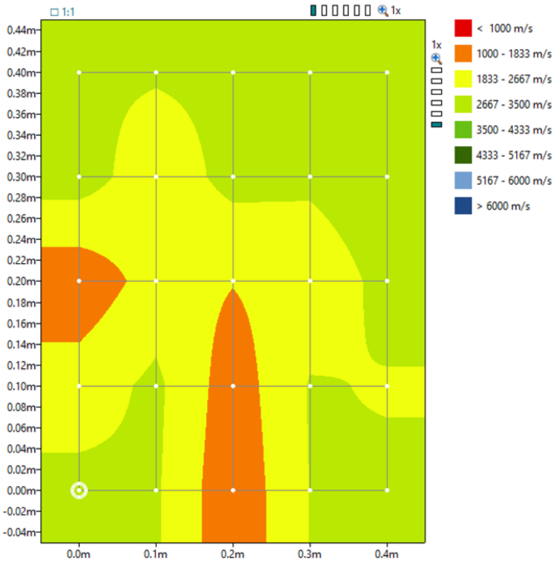
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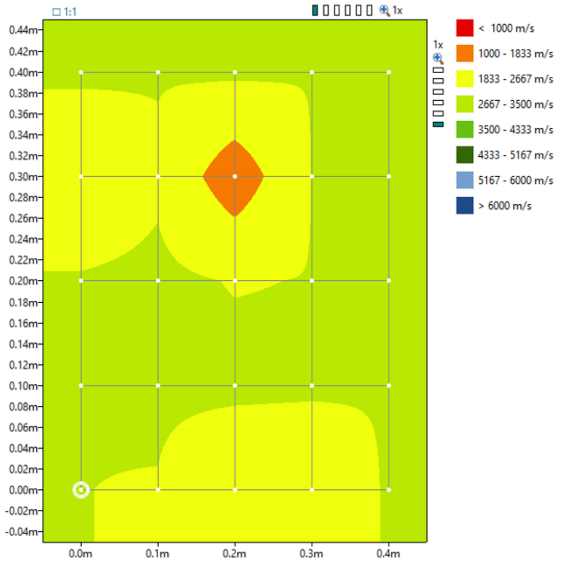
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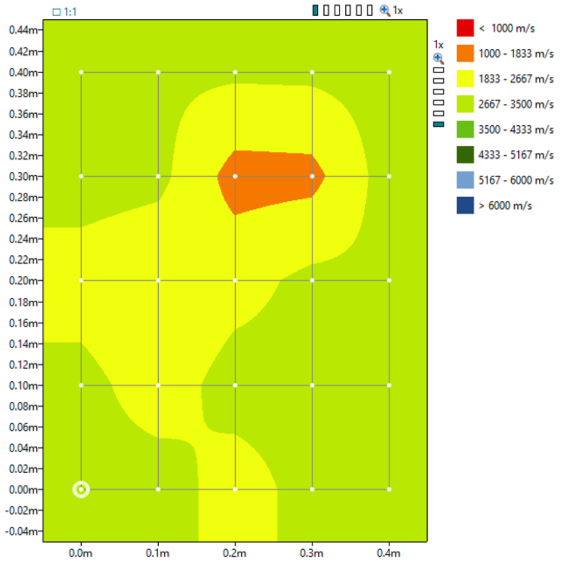
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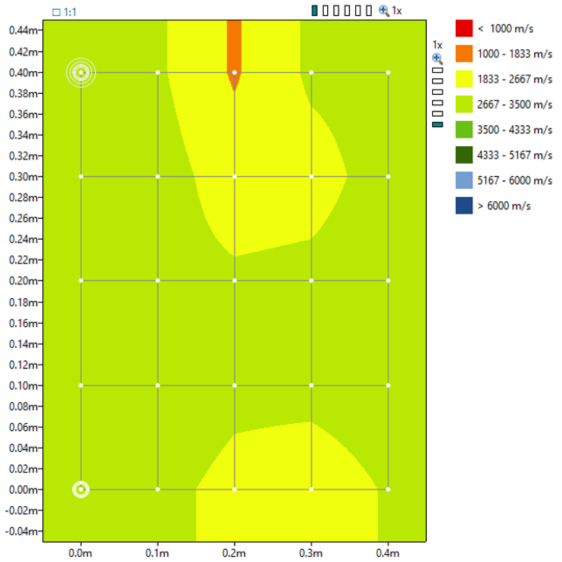
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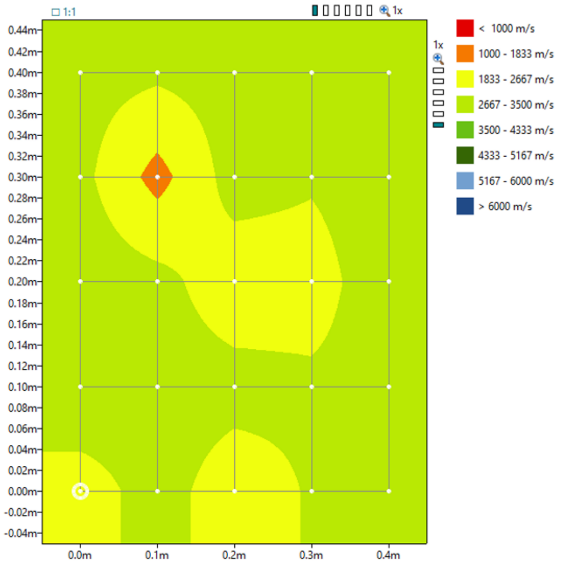
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