Conserving history in changing arid environments: a geomorphological approach

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"*A thing of beauty is a joy forever*" – John Keats

Introduction

One brief glance at the UNESCO World Heritage List (August 2010) shows that currently 18 cultural sites are 'under severe threat'. Of these, 14 are situated in arid environments. The harsh nature of these climates in combination with the often inaccessible and instable nature of their geographical location means that cultural heritage is often difficult to monitor, manage and conserve. Of the number of threats described in the 'Case studies on Climate Change and World Heritage' report (UNESCO, 2007), many apply specifically to arid regions such as increased erosion and weathering through desertification and salt weathering, ground water fluctuations, changes in wetting and drying cycles and extreme temperature fluctuations.

Whilst our knowledge of the causes of decay and how to control it is continually progressing, monuments are deteriorating at an alarming rate. Many stone monuments which are a testimony to and record of our history and cultural development are now at risk of fading away into the past rather than standing tall for future generations to see. Even when deterioration does not appear to be catastrophic, weathering processes are slowly chipping away at statues, fountains, doorways and foundations. This is a problem for stone-built heritage in any environment; Durham Cathedral (UK) for example recently had to be completely surveyed and substantial parts of its structure had to be replaced due to honeycombing and flaking of the stone work (Attewell and Taylor, 1990). Similarly, pollution has created problems for the future of the Cathedral of Cadiz, Spain (Torfs and Van Grieken, 1997) while sandstone weathering is damaging monuments such as Giza, Egypt (Fitzner et al, 2003). In addition, numerous reports are available discussing rapid deterioration of well-known heritage such as Petra, Jordan (Heinrichs, 2008) and Angkor Wat, Cambodia (Uchida *et* al, 2000). What makes weathering in arid environments different from weathering in temperate climates is the astonishing process rate. Research has shown, for example, that test blocks of stone left in the Namib desert virtually dissolved over the span of a few years (Goudie *et al*, 1997; Viles and Goudie, 2007). Furthermore, there are many examples of structures such as newly built housing as well as pipelines decaying badly in a matter of years (Goudie and Viles, 1997).

Arid environments are home to a vast range of different heritage sites; these vary from the stunning remains of Babylon (Iraq), where wholly intact temples, murals and houses can still be seen, to the fantastic rock art sites of the Tradat Acacus (Libya) to the extensive ruins of the trade city Paquimé Casas Grandes (USA). The entire area just north of the Tropic of Cancer is home to a vast number of UNESCO Cultural Heritage Sites, showing not only the density but also the importance of the historical and archaeological sites found in this region.

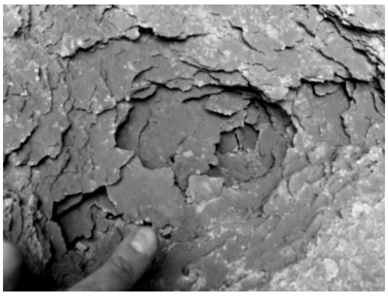
The questions that beg to be answered are 'How bad is stone weathering in arid environments, what can we about it and what implications does it have for the future enjoyment of stone heritage?' Placing heritage in the larger picture of war, food and water shortages and lack of education opportunities, how important is it to focus our efforts on understanding the decay of heritage? Keats' statement could actually go a long way towards explaining the importance of preserving cultural heritage. Many of these structures are 'things of beauty', positive additions to our cities and landscapes and reminders of cultural achievements. The ones that are not obviously beautiful but bear historical significance such as the barracks at Auschwitz also provide an important reminder of our past. Not only can joy be found in the aesthetically pleasing structures, structures such as Auschwitz also often remind us of the ugly parts of history as well, events that should never be repeated. They may not be able to solve world-wide problems, but they can act as a reminder to prevent future events that should never take place.

Stone weathering, a realistic threat?

As mentioned previously, stone weathering is a widely researched topic in which there has been significant progress over the past decade or so. Several international research projects have been set up for the further understanding of heritage deterioration and conservation. National and international organizations such as English Heritage, the Getty Conservation Institute and UNESCO focus on managing heritage sites while research projects such as the

EU-funded NOAH’s Ark Project have been set up to further collaboration and interdisciplinarity within stone weathering research.

So what are the primary processes that affect stone heritage in arid environments? Goudie and Viles (1997) have shown that salt weathering is prevalent in a wide geographical variety of arid areas. The destructive nature of soluble salts in combination with high evaporation rates causes high levels of salt to be mobilized within the rock surface and subsurface, creating a hostile environment in which rock weathering is rapid and often catastrophic. However, salt weathering is only one of a larger set of weathering processes. Table 1 shows an overview of the most common weathering processes and key research published on each process.

Weathering Process	**Sub-type**	**Research examples (further reading)**
Physical / Mechanical 	Thermal expansion Contraction and expansion of rock masses by temperature fluctuations	Siegesmund *et al* (2002 Hall and Hall (1991)
	Frost weathering Shattering of minerals by continual fluctuations of temperatures around zero ºC	McGreevy and Whalley (1985) Matsuoka (2001)
	Salt weathering (haloclasty) Disintegration of rocks by saline solution seep into cracks and joints	Goudie and Viles (1997) Robinson and Williams (2000)
	Insolation weathering Solar energy induced stress on rock surface	Singh (1988) McCabe *et al* (2006)
	Hydration weathering Wetting and drying of rock leading to expansion and contraction	Day (1994) Hall and Hall (1996)
Chemical	Solution (chemical	Welch and Ullman (1996)

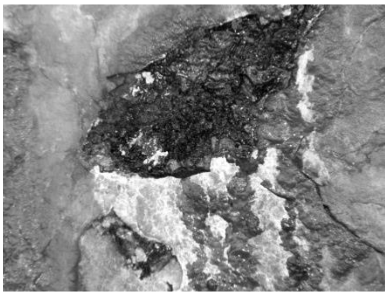
	denudation) Decomposition of minerals by solution in water Hydrolysis Replacement of metal cations (most commonly K^+, Na^+, Ca^+ and Mg^+) in a mineral lattice by H^+ ions and the combining of these released cations with hydroxyl OH- ions, causing disintegration of the mineral structure of the rock	Sherlock *et al* (1995) Pope *et al* (1995) Matsuoka (1995)
Biological 	Lichen and mosses These perform a dual role by creating a protective cover but also a damaging micro-environment through altered chemistry, temperature and intrusion in the actual rock face Bacteria, algae and fungi Geochemical agents in the upper lithosphere, mobilizing mineral constituents with inorganic or organic acids or ligands they excrete, as well as promote rock wethering by reodx attack of mineral constituents such as Fe or Mn	Winchester (2004) Carter and Viles (2005) Ehrlich (1998) Hoffland *et al* (2004)

Table 1: Overview of rock weathering processes and examples of research

The range of weathering processes that are presented here show the large number of deteriorating circumstances built heritage is subjected to on a day-to-day basis. These processes will be present in virtually every geographical location, however the intensity of each individual process will vary according to environmental circumstances. This includes factors such as exposure to sun, rain and degree of temperature fluctuations as well as exposure to pollution. However, a secondary category of threats does need to be briefly discussed. Physical contact with humans such as chemical deposited by sweat, bike handles and even shrapnel can do huge damage in armed warfare zones.

Rather shocking examples of the impact human interference and usage of weapons in arid environments are the Buddhas of Bamiyan in Afghanistan in March 2001. These 1,700 year old statues were destroyed because of what has been described as fanatic religious iconoclasm (Francioni and Lenzerini, 2006) using a large array of weapons such anti-tank missiles and dynamite. However, the problems do not cease with the total destruction of these irreplaceable objects. The high impact blasting has left the entire cliff face instable and has made the preservation of the remnants of the Buddhas and possible restoration of the sites very difficult (Margottini, 2004). The resulting rock face scars are vulnerable to weathering processes as well as catastrophic collapse due to the wider slope instabilities.

Thankfully incidents such as this are rare and heritage is acknowledged to be an important part of the recording of human development. The far larger challenge is to understand the processes which are deteriorating our heritage, developing techniques which will monitor *in situ* effectively and reliably and collecting an array of conservation and restoration techniques which will preserve our heritage for future generations.

Research and methods: how much do we know and what can be done?

Weathering studies used to be primarily the domain of soil scientists, geomorphologists and geochemists. However, in recent decades a large number of disciplines have taken an interest in understanding these processes. These include archaeologists, architects, engineers and conservationists (Pope, 2000a). A large number of laboratory as well as field studies have been undertaken to further our understanding of stone weathering in arid environments. This work builds on pioneering fieldwork such as Blackwelder’s observations of exfoliation (1925) and Goldich’s analysis of chemical changes during weathering of rocks (1938).

Winkler (1966) identified a number of important agents of weathering in stone, effectively linking chemical decay and the role of biological activity in weathering rates, followed by his 1987 work on weathering rates which identified the complex interaction of different weathering processes. In recent years the techniques and equipment available to researchers have consistently become more sophisticated. Research, both in the laboratory and in the field, has greatly improved our understanding of weathering processes. Methods for investigating, for example, rock fracturing (Liu *et al*, 2007), spalling (Sharmeen and Willgoose, 2006), flaking (Dragovich, 1967; Benito *et al*, 1993) and salt weathering (Viles and Goudie, 2007), have increased tremendously in availability and accuracy in the past two decades.

In particular, sandstone weathering has become an often-researched field (Turkington and Paradise, 2005). This soft stone is particularly susceptible to rapid weathering processes such as flaking and crumbling. Fitzner *et al*'s work (2003) in Luxor, Egypt, showed a wide range of weathering features within a relatively small area. Similarly, Sancho *et al* (2003) show that sandstone, in this case in the Ebro basin (Spain), exhibits particularly rapid weathering rates. Previous work by Mol and Viles (2010) has shown that not only external factors such as temperature fluctuations and precipitation but also internal factors such as internal moisture behaviour play an important role in the surface weathering rates of sandstone. Internal moisture is commonly found in both natural rock and building stone and is maintained by capillary rise of groundwater as well as sources within rock outcrops such as infiltrated precipitation travelling along bedding planes.

Research has shown that especially salt weathering is a destructive force, causing accelerated flaking and exfoliation of the surface (Goudie and Viles, 1997; Kuchitsu *et al,* 2000; Mottershead *et* al, 2003; Smith *et al,* 2005; Hosono *et al,* 2006). Figure 1 shows the impact of salt weathering on at the granite inselberg of Mirabib, central Namib desert. These inselbergs within Namibia are home to important archaeological sites such as extensive rock art sites and other evidence of early-human populations.

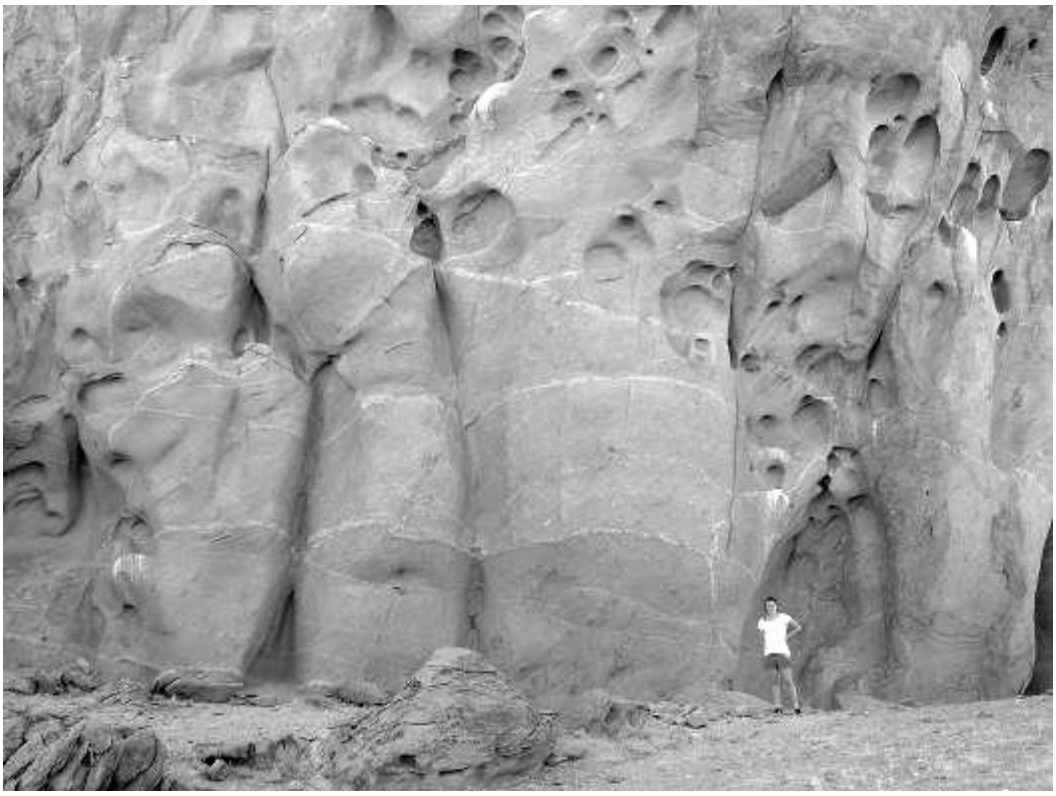


Figure 1: Salt weathering of a granitic inselberg, Namibia. Photo: Heather Viles

A large number of tools are now available to measure weathering of rock surfaces. We will briefly discuss a small selection to give an overview of the wide range of methods.

The *Schmidt Hammer* is a well known method which has been employed in measuring rock surface hardness for many decades now. It measures rock surface hardness by measuring the rebound of a metal piece off the rock wall, a low rebound measurement indicating low rock hardness and a high measurement indicating a hard surface. A wide range of studies have successfully employed this method (Goudie, 2006), both in the field (Viles and Goudie, 2004; Greco and Sorriso-Valvo, 2005) and laboratory (Aydin and Basu, 2005; Demirdag *et al*, 2009) situations. To follow up this method a new set of devices has been created which work along the same rebound principle but use far smaller impacts and can therefore be used on more fragile surfaces. The *Equotip* and its little brother the *Piccolo* are handheld devices that measure rock surface hardness in the field, giving the researcher a method for quantifying rock surface hardness and by implication the degree and spatial variability of weathering of the surface (Aoki and Matsukura, 2007; Aoki and Matsukura, 2008; Viles *et al*, 2010).

To survey small scale changes in surface weathering, a range of methods are available. The most common of these are *laser scanning* and *photography*. Yilmaz *et al* (2007) for example, surveyed a 18th C heritage building in Konya (Turkey), both before and after two devastating fires and used the photographs to model the damage. Similarly, Thornbush and Viles (2004) surveyed the discolouration and associated weathering of soiled limestone surfaces in Oxford, England. Using this technique, the researcher can build up a database of images which can be overlain to identify particularly active weathering areas (Lim *et al*, 2010). This data can be taken further with *photogrammetry*. This is a technique which builds up 3D models of objects by determining the 3D coordinates of an object, in this case a heritage structure, by combining photos taken at different angles (Fujii *et al*, 2009; Sturzenegger and Stead, 2009). Laser scanning works on much the same principle, but uses reflection of a laser beam to build up a 3D image of a surveyed site. By overlaying time lapse images the researcher can calculate which areas have deteriorated (Birginie and Rivas, 2005; McCabe *et al*, 2010). In addition *infrared thermometry* is often used in combination with these methods, as differences in temperature often indicate changes in weathering crust or moisture content, as well as surface response to changing environmental conditions (Hall *et al*, 2007).

Additional in situ measurements which are often employed include humidity and saturation measurements. Saturation of the near-surface can be measured using handheld moisture meters such as the *Protimeter* (Galdieri and Alva, 1981; Akiner *et al*, 1992; Lai and Tsang, 2008) or an *FMW* (Forsén and Tarvainen, 2000). Both of these use resistivity measurements to determine near-surface relative moisture content (*FMW*) and saturation (*Protimeter*). Humidity can be monitored using for example probes to monitor in-sample humidity levels (Basheer and Nolan, 2001; Gómez-Heras *et al*, 2006) or external monitoring devices such as hygrochrons (Cheng *et al*, 2010). All of these methods are then compared against data collected by *weather stations* (where these have been installed) to determine the importance of the measurements in relation to environmental conditions (see for example Viles, 2005).

Once field work is completed, there are a large range of laboratory methods that can be employed to analyse samples, inspect sample surface and test material properties. For example, *microscopy* is often used to take initial images of the weathered surface, as a first step towards understanding the weathering processes that have affected that particular piece of material. Further imaging can be carried out, using for example *scanning electron microscopy* (*SEM-imaging)*. This method uses a higher resolution and depth of field that the conventional optical microscope. It can be used to find characteristic signals that provide information on material type, weathering and colonization of the surface (Herrera and Videla, 2009). Chemical analysis is also readily available, as a wide range of methods varying from highly complex technology (such as *Dionex instruments,* Ryu *et al,* 2008 and *X-ray diffraction (XRD),* Török, 2003) to simpler methods such as determining biological content through peroxide reactions.

Electrical Resistivity Tomography: a case study in South Africa

There is, however, one particular method we want to discuss in greater detail as it is a good example of the technological advances geomorphology, and weathering studies in particular, have made. It also illustrates the complex interplay between internal and external processes.

Electrical Resistivity Tomography (ERT) applies electrical currents to a rock face, and measures the resulting voltage determine the resistivity. A transect can be set up on the rock face using medical ECG electrodes to provide contact with the rock face. Currents applied between progressively wider space electrode pairs allows the operator to build up a 2D profile resistivity distribution, from which a most-likely distribution of resistivity is derived using the inversion programme RES2DInv (for more information on this method see Mol and Preston, 2010). Resistivity of a porous body is highly affected by its moisture content and thus this resistivity distribution is used to assess which areas in the rock face harbour relatively large amounts of water, where the flow paths are and how these change over time. However, additional factors such as temperature and salt content changes, which are known to affect resistivity measurements (Cassiani *et al,* 2006; de Franco *et al,* 2009; Kemna *et al,* 2002) need to be considered when interpreting ERT measurements. Using additional methods, such as an Equotip, these changes can be correlated to surface weathering, creating a clearer picture of the influence of internal moisture on surface weathering.

This method was used to assess the internal moisture distribution of Clarens sandstone in the Golden Gate Highlands National Park, KwaZulu-Natal (South Africa). The Park is situated in the foothills of the Drakensbergen and consists of rolling hills with areas of exposed sandstone. The area is famous for its mushroom formations, created by the differential weathering of the soft Clarens sandstone and the much more resilient basalt capping. The subsequent shelter formation has been used by the San for shelter and as a canvas for rock art.

Unfortunately the rock face in these shelters is prone to crumbling, flaking and crack formation, threatening the canvas of the rock art (see figure 2). Because their rock faces are generally sheltered from direct exposure to rain and sunshine, they make ideal study sites for internal processes.

Clarens sandstone is grainy, friable and generally prone to high weathering rates. Its porous nature allows for continuous flow of moisture through the rock face. These flows are concentrated in outlets on the rock surface, where the moisture leaves the rock through small honeycomb-type outlets. This creates an environment in which cyanobacteria thrive, colonizing the pockets underneath semi-detached flakes and building substantial colonies. These are joined by algal colonies which are predominantly situated directly by the moisture outlets. This dynamic environment creates a problem for the rock art situated in this area, as detachment of the rock surface means an immediate and irrevocable loss of the rock art.

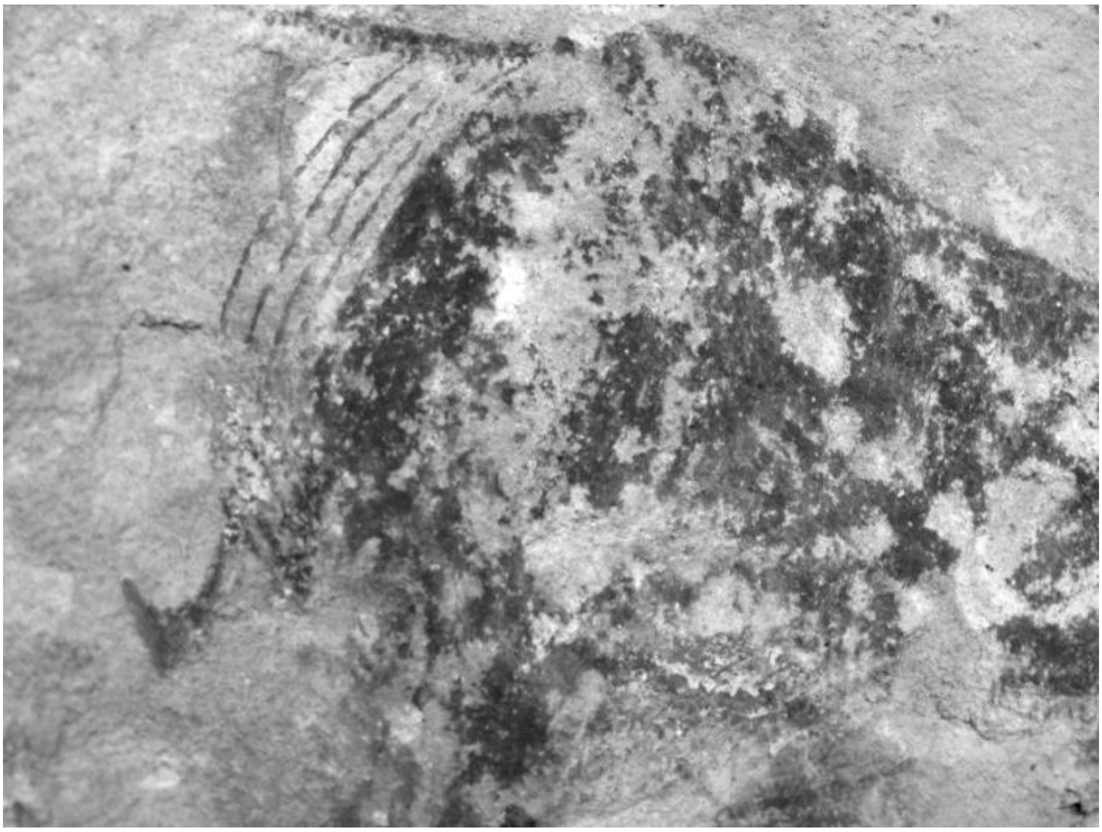


Figure 2: Damaged rock painting in the GGHNP showing the neck and part of the back of an eland

Our measurements showed that there is a direct correlation between internal moisture accumulation and surface weathering (Mol and Viles, 2010). Where there is an accumulation of moisture the surface shows significantly lowered rock surface hardness values (as measured with the *Equotip*, see figure 3), indicating flaking, crumbling and general deterioration of the rock surface mineral structure. The moisture accumulation is further shown using near-surface saturation as measured with a *Protimeter* (figure 3 b). These are then correlated to the ERT measurements (figure 3 c) and field observations (figure 3 d). This research was carried out to further our understanding of the extremely complex interaction between moisture and weathering. A number of factors can influence the interaction between moisture and surface such as temperature, exposure although preliminary research suggests that internal moisture is relatively unaffected by outside temperatures, and that the nature of the internal moisture regime is a key-element in rock surface deterioration.

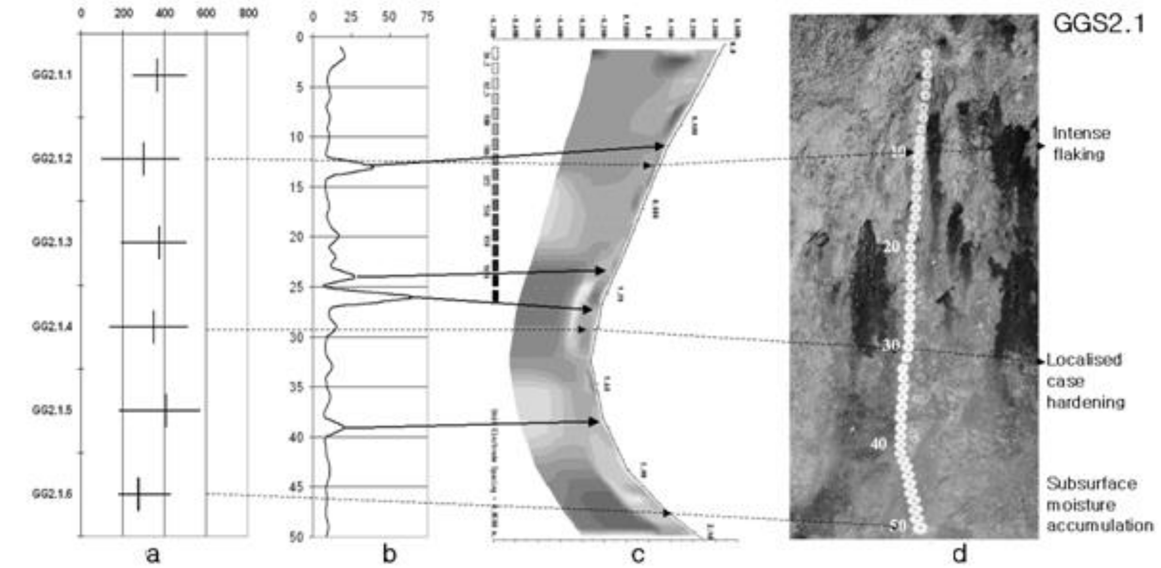


Figure 3: Example of field data correlation of site 2 in the GGHNP showing the relationship between lower surface moisture accumulation and surface weathering

Source: Modified from Mol and Viles (2010)

This research also shows the many scales on which weathering processes function. On a micro-scale weathering deteriorates grains and causes crumbling of the surface, accelerating flaking and pitting of the surface. On a meso-scale it causes rock surface retreat, creating shelters and caves. On a macro-scale it contributes to large scale rock falls and rock surface retreat, forming valleys, gorges and large cave systems, changing the dynamics of the landscape. This multitude of scales in combination with the complex interaction of internal and external weathering processes creates a difficult situation for researchers.

Scale problems in weathering research

So where does this interplay of a vast array of both internal and external weathering processes leave us? Despite the advances in weathering studies and techniques we are still stuck somewhere between a rock and a hard place really. As in most scientific disciplines, the need to see the small detail often conflicts with the necessity to understand the larger picture. It is possible to study and understand every minute weathering process that could take place on a particular rock face in a small part of a remote valley. It is also possible to study the general weathering effects of precipitation on sandstone globally. Both types of studies are helpful but neither achieves the ultimate goal of understanding weathering processes in any stone type in any environment. In addition to this, the difficulty of upscaling or downscaling conclusions drawn from specific studies is sometimes an obstacle that simply cannot be overcome (see for example Viles, 2001, for a comprehensive discussion on scale issues) The continuous interplay of factors increases the complexity of the situation even further. Figure 4 shows an example of the complexity of scale within research. In this case it is an investigation into rock weathering in southern Africa.

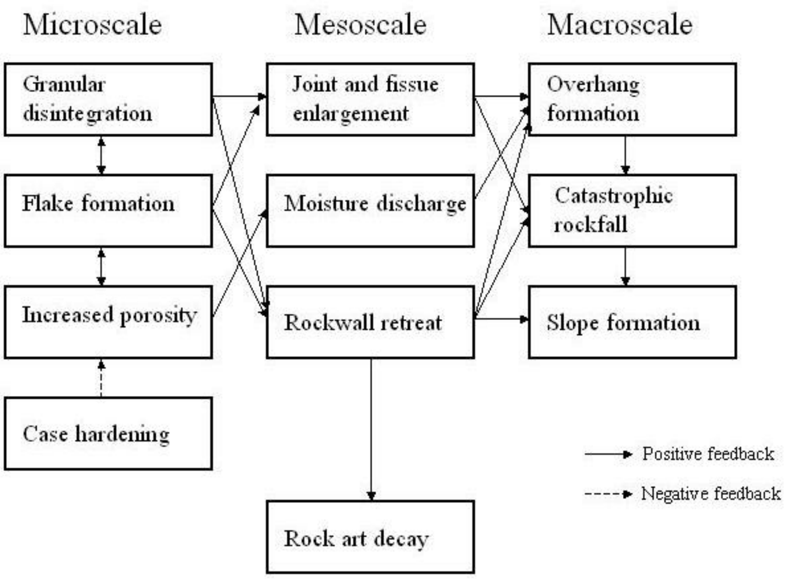


Figure 4: Flow diagram of the complexity of scale within a single research study

This figure illustrates the many connections on micro-, meso- and macro scales and the difficulty in 'disentangling' these.

Winkler (1987) accurately points out that while physical- and chemical weathering were studied as separate processes, they are in fact physicochemical processes that should be studied as connected factors. This has left the door open for a case-study approach, where weathering is now studied through individual sites or small-scale laboratory studies, giving us a large database of weathering studies through which we can start piecing together the larger picture. We will look at a few case studies, specifically arid environment heritage, to illustrate the progress made in weathering studies and the challenges still faced.

Petra, Jordan

The world famous heritage site of Petra in Jordan continues to attract many thousands of visitors each year. This is not surprising, as the awe-inspiring buildings of the Treasury and the Amphitheatre are more than reason enough to brave the heat and the long trek through the gorge. This continued interest not only provides the local economy with a boost, it also ensures that Petra continues to enjoy a prominent place on the World Heritage List.

However, this continued attention also brings with it a large number of problems. Unfortunately as well as a World Heritage Listing, it also regularly features amongst the most endangered sites (World Monument Fund 2009) because of increased magnitudes of weathering (Akasheh, 2002; Paradise, 2005; Waltham, 1991). The continued stream of tourists brings with it sweat and laboured breath, increasing humidity and salt content in the air which precipitates onto the rock. Add to this touching of the walls with sweaty, sun block covered fingers and a toxic mix of chemicals is added to the natural deterioration processes which are already attacking the stone surfaces. Smith (1986) studied the problems of humidity and erosion and found that in particular tafoni formation has intensified, but that weathering rates on the stone surface of Petra are high in general and pose a substantial risk to the future of these structures (see figure 5). Paradise (2005) showed that in a relatively short time span, the walls had retreated significantly due to the chemical deterioration of the surface and the increased humidity, both of which can be directly linked to the increased stream of tourists.

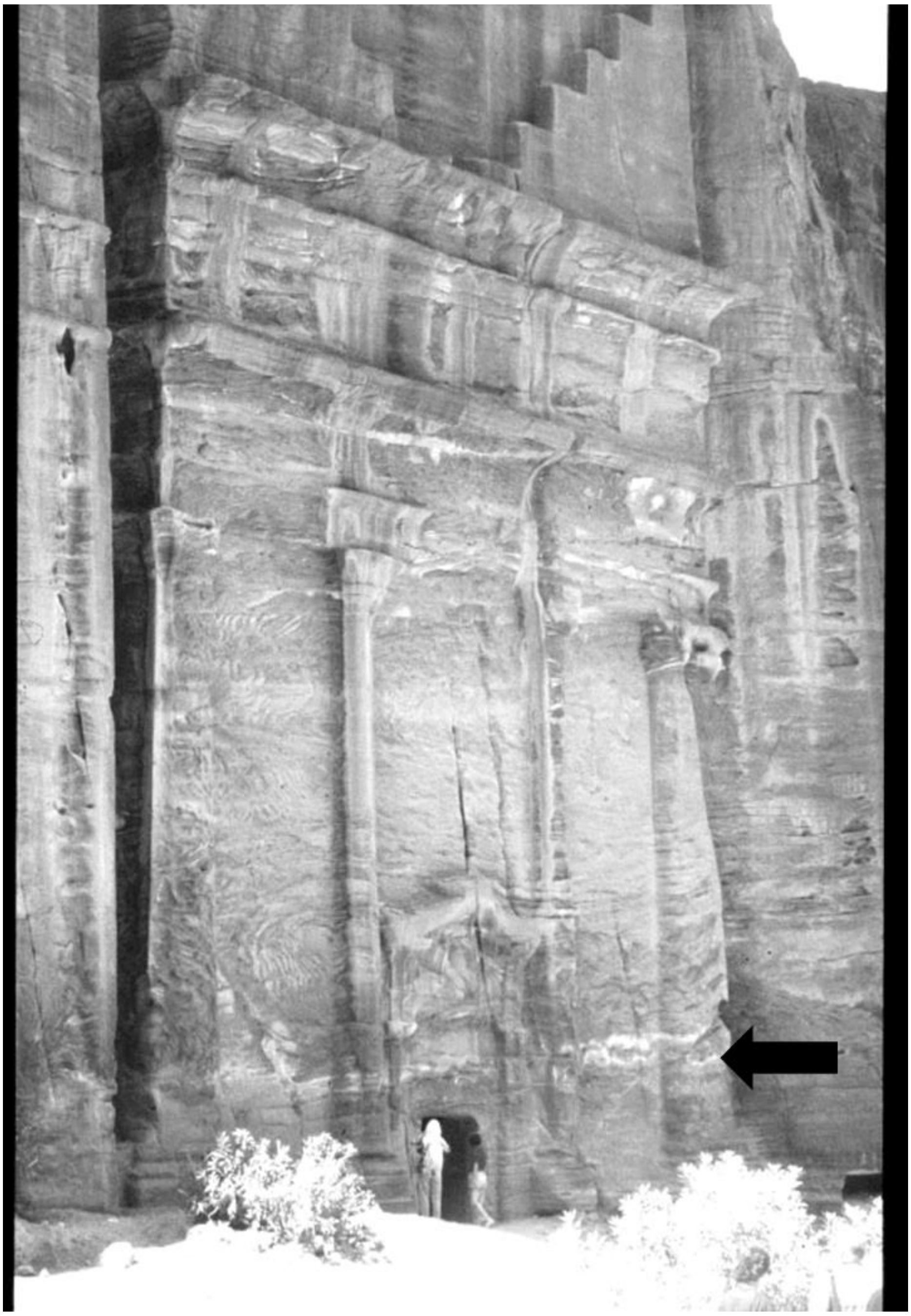


Figure 5: Weathering damage on the facade of the temples of Petra; the arrow indicates the capillary rise to above human height, illustrating the possibility of deterioration from soluble salts.

Identifying the problem is only half of the work though. Once weathering processes have commenced it is very difficult to halt or reverse them. This makes conservation of these sites very difficult, as the complex interaction of processes demands a complex approach.

Rock Art deterioration: a widely spread problem

Rock art is a particularly vulnerable type of heritage. It is often painted or carved onto friable rock, such as sandstone, and the sheer number of rock art sites makes monitoring and protecting all of them an almost impossible task. There are a few famous examples of rock art from around the world, such as the Game Pass Shelter in KwaZulu-Natal, South Africa (Meiklejohn *et al*, 2009), the caves of Lascaux, France (Malaurent *et al*, 2007; Bastian and Alabouvette, 2009), and the aboriginal rock paintings in the Jenolan Caves, Australia (Dragovich and Grose, 1990) which are well-documented and preserved but none the less still at risk of rapid deterioration. These, however, represent only the tip of the ice berg as in 1997 15,000 rock art sites in southern Africa were recorded but it is estimated there could be well in excess of 50,000 sites (Deacon, 2002).

Many of these sites are under threat from a number of factors. Exposure to precipitation and thermal fluctuations has caused fading of the pigments, leaving sometimes only faint outlines of the original painting. In the Albarracín Cultural Park in Spain, for example, some paintings have deteriorated to such an extent that they are barely identifiable (Benito *et al*, 1993). Similarly, abrasion of rock surfaces has caused wide-spread deterioration of rock carvings, especially ones carved into friable rock such as sandstone (Pope, 2000b). In arid environments the problems are exacerbated by the extreme thermal fluctuations, abrasion by sand picked up by air currents effectively sanding down the rock surface and, where applicable, intense rainstorms during limited annual periods.

The rock art of the Tuareq, Libya, for example is under constant threat of weathering damage. The friable sandstone is prone to deterioration through crumbling, flaking and cracking of the surface. Figure 6 shows an engraving of presumably a bull which is surrounded by a flaking and cracking rock surface.

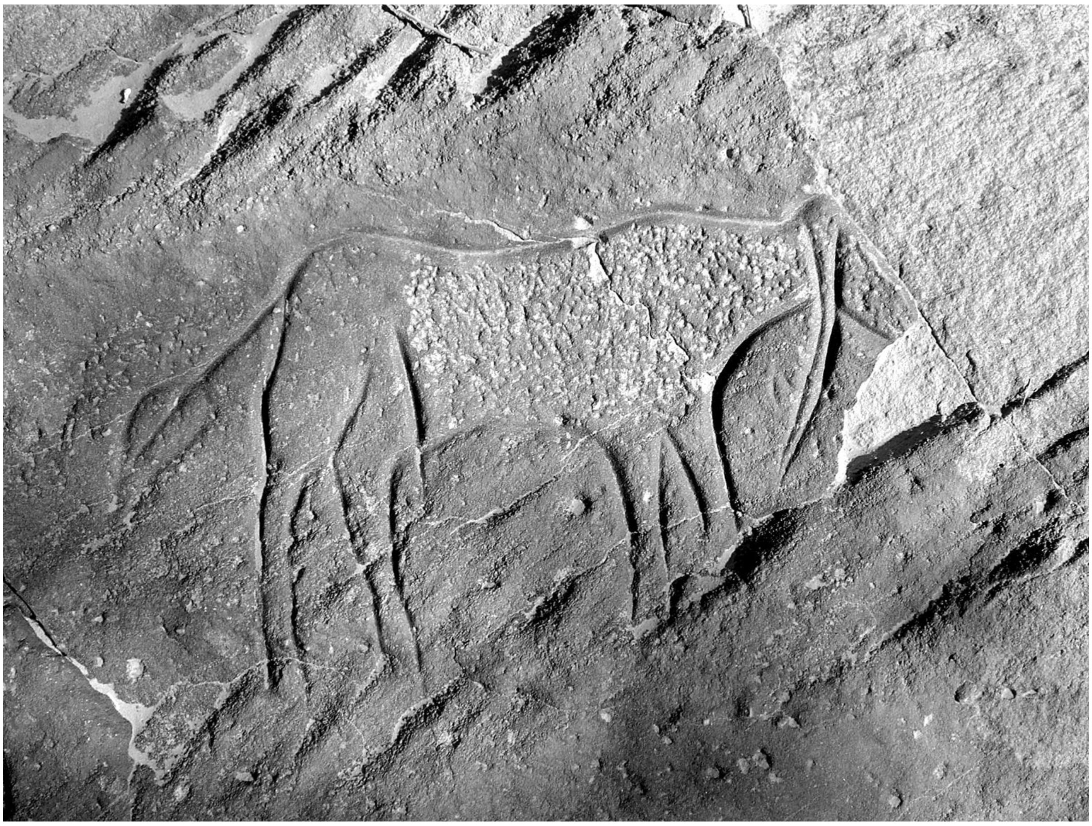


Figure 6: Engraving of a bull, MEssak Settafet plateau, Libya. Photo: Heather Viles

The Messak Settafet in SW Libya is a sandstone plateau within the Sahara Desert with plentiful and important engraved rock art. The climate today is hyperarid, but much evidence points to wetter conditions in the past, such as around the early to mid Holocene. The rock art probably dates back to about 3000 to 6000 years ago, when conditions started to dry out in the area. Much of the rock art is carved into sandstone surfaces which exhibit a dark brown patination, thought to be a desert varnish rich in iron and manganese oxides. Salt efflorescences are commonly found on the rocks within which the engravings are found, especially within cracks and shaded overhangs. Whilst the conditions today are generally too dry for much activation of the salts to occur, if future climate change caused any increase in precipitation the rock art could become seriously threatened. Already it is apparent that the rock surfaces flake easily around cracks and within sheltered areas where more moisture can accumulate.

Climate Change and heritage preservation

As mentioned previously, a large number of cultural heritage sites in arid environments are currently under threat. However, as bad as the situation may seem at the moment, it is only set to get worse in many cases. Climate change is undeniably happening, even though the reports may be controversial and the predictions vague, and our attitude towards preservation of heritage will have to adapt to changes in the physical environment. However general the IPCC projections may be at the moment, there are overall trends which can be extrapolated to estimate how conditions will change.

As an example, let's look at northern Africa. Climate change projections for Mediterranean Africa show an increase in extreme events, with higher temperatures but lower precipitation. According to the latest IPCC report, Tunisia is one of the countries where climate change will be most acutely felt, with approximately 1.5 times the global average temperature increase (Solomon et al, 2007) and a decrease in overall precipitation. These changes in climate regimes could have a disastrous effect on the conservation of heritage in this region which abounds in Roman monuments that document its rich and turbulent history (Ennabli, 2000). Salinization of arable land, caused by over-irrigation in low-precipitation areas, is known to be a large problem in northern Tunisia (Hachicha et al, 2000) but this increased level of salt may also pose a serious threat to the conservation of its built Roman heritage. Increased temperatures lead to increased evaporation of moisture from stone surfaces, leading to an accumulation of soluble salts on the surface. The salts, in combination with the increased thermal stressing of the stone surface, can speed up the already rapid deterioration process.

El Jem is a UNESCO World Heritage site, described as 'impressive ruins of the largest colosseum in North Africa, a huge amphitheatre which could hold up to 35,000 spectators (…). This 3rd-century monument illustrates the grandeur and extent of Imperial Rome" (UNESCO World Heritage List). Due to its location in an arid environment with close proximity to the Mediterranean Sea, and it's high salt levels, as well as high levels tourism interest, this site could be at risk of rapid decay within a relatively short time span. It faces the same problems which Petra is currently dealing with, increased chemical weathering of the surface due to the proximity of large crowds of people, but in addition now faces increased thermal stress due to higher temperatures as well as potential salinization problems due to over-irrigation in the region. Figure 7 shows the deteriorating walls of El Jem which have deteriorated heavily over the centuries. Rates of deterioration have been slowed down or accelerated by a number restoration projects over the past century.

Figure 7 A and B: Walls of El Jem, Tunisia. which show much evidence of past restoration and deterioration and may be further affected by future climatic changes in the area

This is just one example of a cultural heritage site under threat. As the uncertainties persist, or even grow, of the impact of climate change worldwide, the future of cultural heritage is also at risk. Increased intensity of temperature fluctuations, rainstorms, wind speeds and droughts are all possibilities raised by the IPCC reports (Soloman *et al* (Eds.) IPCC Climate Change 2007 I, section 11.2.3.1). Similarly, a large number of investigations are available discussing the movement of for example moisture through stonework (see for example Hall and Hoff, 2002; McKinley and McCabe, 2010; Sass and Viles, 2010). However, only recently has the impact of climate change on moisture regimes become one of the primary focuses of weathering research (Hall *et al*, In Press). Based on the knowledge we have of current processes and weathering rates, we can estimate how climate change will affect a variety of heritage sites using a multitude to models. But the difficulty lies in the exact prediction of climate change in a particular geographical location and it may not be possible to pinpoint the consequences until it's too late.

Pessimistic as this may sound, there is also good news. Our increasing understanding of geomorphological processes, and weathering in particular, can make identification and monitoring of deterioration processes more accurate. Environmental simulation tests have given us an understanding of the behaviour of stonework in a range of environments (Warke and Smith, 1998; Goudie *et al*, 2002; Smith *et al*, 2005) and the consequences of environmental change (Gislason *et al*, 2009). As discussed previously, we now have an ever increasing array of field- and laboratory tests at our disposal. This means that while we may not, currently, be able to predict the exact effect of future climate change on particular heritage sites, we may be able to gain a good understanding of changes in geomorphological processes at a variety of geographical locations far more accurately and swiftly than before.

Restoration and conservation, can a geomorphological approach help?

There is one last question that should be briefly touched upon. Once deterioration has set in, to what extend should we be allowed to interfere? In previous decades some rather disastrous restoration and conservation work has been carried out, often leading to far greater damage to the structure or object than deterioration processes could have done. This is largely due to a lack of understanding of deterioration processes in previous decades and also insufficient knowledge of conservation material behaviour. However, research is carried out which focuses on both the treatment of deteriorated stone surfaces and limiting the deterioration processes such as pollution control, traffic control, control of groundwater, visitor managed and disaster planning (Baer, 1991). Recent research has focussed on improving conservation techniques to prevent damage and instead stabilize the material without interfering with its structure too much (see for example Pinto and Rodrigues, 2008). This varies from large scale conservation projects such as adding supporting braces to structures to small scale interventions such as injecting wood and stonework with solidifiers to prevent further disintegration of materials (Favaro *et al*, 2006; Son *et al*, 2009). Geomorphological research can play a vital role in the selection of conservation method as it can identify deterioration processes, especially in stonework, map affected areas and pinpoint areas at future risk if the deterioration continues. Especially when an object, whether a building, a statue or a rock carving, is *in situ* geomorphology has a range of measurements techniques to offer that can determine the influence of exogenic processes on surface deterioration.

Concluding remarks

What future research needs to be undertaken to be better prepared for preserving our heritage in changing environments? As argued in this chapter, geomorphological research is making rapid progress. We are gaining a greater understanding of weathering processes and are now able to identify deterioration more accurately and swiftly than in previous decades. The wide range of techniques available to researcher has led not only to a wide knowledge base but also a considerable variety of research approaches. However, in addition to the existing natural processes we now also have to factor in the potential consequences of climate change. This is of even greater importance for fragile heritage sites. The disproportionate number of heritage sites 'under severe threat' on the World Heritage List that are located in arid areas indicates the harsh environmental circumstances to which these sites are subjected, which is estimated to worsen over time as climate change becomes even more noticeable. A geomorphological approach within conservation science could therefore be valuable, as recent advances in weathering research can greatly increase our understanding of heritage at risk, the challenges faced and the techniques required, and prepare us for future events which could prove to be the a considerable challenge for conservation science.

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