Rock weathering on the eastern mountains of southern Africa: Review and insights from case studies

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ABSTRACT

The mountains in the eastern region of southern Africa are of significant regional importance, providing for a diverse range of land use including conservation, tourism and subsistence agriculture. The higher regions are comprised of flood basalts and are immediately underlain by predominantly aeolian-origin sandstones. Our understanding of the weathering of these basalts and sandstones is reviewed here, with particular focus on the insights gained from the Lesotho Highlands Water Project and an ongoing study into the deterioration of rock art. While the chemical weathering attributes of the basalts have been substantially investigated, it is evident that the environmental surface conditions of rock moisture and temperature, as affecting weathering processes, remain largely unknown. Within the sandstones, studies pertaining to rock art deterioration present insights into the potential surface weathering processes and highlight the need for detailed field monitoring. Outside of these site-specific studies, however, little is understood of how weathering impacts on landscape development; notably absent, are detail on weathering rates, and potential effects of biological weathering. Some palaeoenvironmental inferences have also been made from weathering products, both within the basalts and the sandstones, but aspects of these remain controversial and further detailed research can still be undertaken.

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1. Introduction

The eastern escarpment region of southern Africa is the highest mountain range south of the central African Kilimanjaro massif. Called the Maloti mountains or Lesotho highlands in the west, and Ukhahlamba–Drakensberg in South Africa in the east, the highest summit Thabana Ntlenyana reaches 3482 m a.s.l. (Fig. 1). The landlocked Kingdom of Lesotho is bordered entirely by South Africa, and Lesotho’s eastern international boundary is delineated by the watershed which approximates the position of the mountain range escarpment. Late Triassic to early Cretaceous flood basalts comprise the area above approximately 1900 a.s.l. underlain by Karoo sediments the uppermost sequence of which is known as the Clarens Formation (Fig. 2). Above 3000 m the climate supports marginal periglacial conditions with a mean annual air temperature in the region of 5 °C and precipitation less than 1000 mm p.a. (Nel and Sumner, 2008). Temperatures are warmer in the foothills in the east where fluvially incised valleys expose the sandstones and precipitation increases to around 1200 mm p.a. (Sumner and Nel, 2006). Much of the mountain area bordering on the South African province of KwaZulu–Natal has recently been declared a Transfrontier National Park and is thus of considerable environmental and cultural importance. While the significance of the mountains from a climatological, hydrological and ecological perspective is generally appreciated, comparatively little is known of the area from a geomorphological viewpoint and few studies describe weathering processes within the region. Two focus areas, the study of rock art deterioration and the engineering feats of the Lesotho Highlands Water Project, have provided insights into weathering processes, while other studies draw palaeoenvironmental conclusions from weathering products.

San rock art, painted onto sandstone, is a major tourism and cultural heritage attraction. Interpretation of rock art has drawn much attention from archaeologists and anthropologists but geomorphological studies have also contributed through an ongoing analysis of rock art deterioration by weathering (Hall et al., 2007a). Recent studies utilize new techniques and have improved our understanding of, and asked new questions pertaining to, the weathering of sandstone. At higher altitudes the hydrological importance of the mountains is best illustrated by the Lesotho Highlands Water Project (LHWP). The LHWP transfers water from the highlands across catchments to the central industrial region of South Africa and was considered one of the largest civil engineering projects then undertaken in the world (Waites, 2000).

Water transfer tunnels drilled through basalt, as well as the requirements for construction aggregate, prompted studies into basalt weathering and durability and much was learned from problems encountered with the project. Both the rock art study and the water transfer project have thus contributed significantly to a relatively small but important body of literature on rock weathering processes in the region. This paper reviews our current understanding of basalt and sandstone weathering in the mountains and elaborates on the insights gained from the above two case studies. Comments are also made on the palaeoenvironmental inferences derived from weathering products.

2. Weathering of the basalts

2.1. Composition and alteration of the basalts

Volcanic eruptions heralded the splitting up of the supercontinent Gondwana and created a lava pile with an original...
thickness of approximately 1400 m (Duncan and Marsh, 2006). Individual lava flows vary from less than 1 m thick to more than 50 m, with an average flow thickness of 6 m in the northern parts of Lesotho. Flow contacts are generally welded and tight, indicating a relatively quick succession of lava outpourings that lack weathered flow contacts. The lower occurrences in the lava pile contain some volcanic clastics and tuffs with volcanic breccias. These rock types are an indication of early explosive volcanic activity although the extent of the lava flows suggests that the lava poured out from fissures as low viscosity flood basalts.

Typical of the basalts are the abundance of amygdales filled with various secondary minerals. Thin flows are amygdaloidal throughout the flow thickness while thicker flows exhibit a distinct zoning (from top to bottom) within the flow. The top layer is fine-grained, highly amygdaloidal and glassy as a result of the sudden temperature drop and pressure decrease. Due to the rapid outpouring of one flow on top of the other the upper parts of some flows also exhibit autobrecciation. The central part of the thick flows is massive with only scattered amygdales while the basal part is again fine-grained and contains numerous amygdales, some of which are typical pipe amygdales orientated perpendicular to the flow contacts. On both sides of the flow contacts, thin zones occur where the basalt is usually very fine-grained, highly amygdaloidal and glassy as a result of the sudden dramatic drop in containing pressure, release huge chemical breakdown due to cool temperatures.

Mineralogical composition is important when considering chemical weathering of the basalts. Primary minerals crystallized directly from the molten lava due to lowering in temperature and pressure either in the upper levels of a feeder channel or fissure, or on extrusion at the surface. A distinct order of crystallization occurred, with olivine, where present, crystallizing first, followed by plagioclase feldspar, then clinopyroxene. Solidification took place in most of the lavas after the crystallization of the pyroxene, presumably as a result of extrusion. Residual liquid trapped in the interstices between crystalline phases underwent rapid supercooling and solidified as glass, trapping within it incipient crystals of opaque iron oxide magnetite or the iron–titanium oxide ilmenite (van Rooy, 1992). Augite is the dominant pyroxene with plagioclase the most abundant mineral of the rocks. Glass is relatively abundant in most rocks and may reach 25% by volume and much of the glass is altered to a variety of radiating micaceous mineraloids. Zeolites are widespread in amygdales in areas of hydrothermal alteration and may exhibit a well-defined zonation (Hay, 1978). Clinoptilolite or mordenite characterizes the shallowest and coolest zones, and progressively deeper zones commonly contain analcime or heulandite, laumontite, and wairakite. The typical gas vug infill in Lesotho can be summarised as quartz (agate) and calcite in the basal 170 m of the lava pile and zeolite in the upper 1230 m. The zeolite zone is further defined by a lower (250 m) laumontite zone and an upper mesolite zone.

The early-formed olivine crystals are small and almost always completely replaced by minerals produced by deuteric action. Deuteric alteration is characteristic of volcanic rocks which, as a result of the sudden dramatic drop in containing pressure, release huge volumes of gases previously held in solution in the melt when extrusion at the surface takes place. Gases trapped within the rock constitute a potent agency for the transformation of the host rock while solidifying. At least part of the deuteric alteration observed in the Lesotho basalts took place virtually at the time of solidification or immediately thereafter. This includes changes to the primary minerals such as pseudomorphous replacement of olivines, the localised but intensive attack on the plagioclase feldspars, and partial or complete replacement of the original glass. Davidson (1972) postulated on three types of deuteric alteration: clay mineral alteration, carbonate alteration and zeolite alteration. A
A further type of deuteric action is where mineralizing fluids percolate through the solid rock and deuteronically alter the lava. The products of such deuteric action are visible in veins, in the round vesicular cavities formed by bubbles of gas evolved under high pressure in the still-fluid lava, and in angular interstitial voids that probably represent gas-filled cavities in parts of the flow in which solidification was complete at the time of the release and migration of the gas. This deposition of the secondary minerals was likely a slow process starting at some indefinite time after solidification was complete at the time of the release and migration of the gas. This deposition of the secondary minerals was likely a slow process starting at some indefinite time after solidification was complete at the time of the release and migration of the gas.

Where gas cavities are prominent, alteration of the basalt may be pronounced. These cavities are usually filled with quartz, agate, chalcedony, and calcite, or with zeolites such as heulandite, stilbite, thomsonite, and scolcrite (Walker and Poldervaart, 1949).

Chalcedony, and calcite, or with zeolites such as heulandite, stilbite, and scolcrite (Walker and Poldervaart, 1949) are signs of alteration in most mineral grains. This is seen as a penetration of the mineral, along cleavage planes and irregular fractures, by thin films of a clear to slightly greenish clay mineral. The main mineral produced in this type of replacement appears to be montmorillonite (Deer et al., 1963) but the changes generally exert little influence on the durability of the rock. A more serious form of deuteric alteration is the zeolitization of the feldspars. Early-formed euhedral crystals of olivine occur in almost all the basalts, and their complete replacement by deuteric minerals is almost universal. The dominant replacing mineral is again montmorillonite, which can be positively identified optically because of its occurrence as unusually large crystals in some of the pseudomorph crystals. Chlorite and hematite are closely associated with montmorillonite in the olivines. The latter forms rims around the original crystals and preserve their characteristic original fracture system, thereby facilitating distinction of olivine crystals from other concentrations of deuteric montmorillonite.

The rocks studied during the Lesotho Highlands Water Project feasibility investigations showed negligible weathering, but practically all would have been subjected to deuteric alteration during the late stages of solidification or shortly thereafter. This alteration manifests itself in the form of the transformation of original (devitrified) glass and early-formed olivine crystals wholly or partially to swelling clays of the smectite group. The feldspars in the rock may, to a lesser extent, be replaced by zeolites and clay minerals such as montmorillonite. Montmorillonite was identified as the major mineral present through thin section staining, XRD analysis, although minor amounts of nontronite also occurs (Van Rooy, 1992). The main cause for degradation or rapid weathering in these rocks is the presence of swelling clay minerals as demonstrated in the case study below.

While chemical alteration typifies basalt on exposure, relatively little is known of physical weathering aspects. Mechanical fracturing, flaking and spalling (Grab, 2007a) and extensive block production (e.g. Boelhouwers et al., 2002; see below), are reported for the basalts. Although, with the exception of dilatation (or unloading), mechanical weathering is based primarily on rock temperature and rock moisture conditions little is known of these environmental conditions. Grab (2007a) reports on short-term rock temperature oscillations that appear conducive to thermal stress at 3060 m near Sani Pass. Longer duration monitoring at 3300 m highlights the thermal potential for frost activity, with minimum temperatures at the rock surface of –13.6°C (Grab, 2007b). At a lower altitude, corresponding with the sandstone-basalt contact (1920 m), Sumner and Nel (2006) measured basalt temperatures and recorded a minimum of –6.7°C and a maximum of 56°C. Both studies note a poor correlation between air and rock surface temperature, and on potential for thermal stress. Notably absent are data on rock moisture and moisture chemistry conditions. Thus the efficacy of processes such as wetting and drying, salt weathering and freeze-thaw is speculative, particularly in winter when conditions are generally dry, while the role of biological activity and its potential integration with other weathering processes (Etiene, 2002) remains unknown.

### 2.2. Case study: the Lesotho Highlands Water Project (LHWP)

The LHWP transfers water from storage dams in the mountains of central Lesotho to South Africa (Fig. 1) through a system of tunnels. Katse and Muela Dams were constructed first and linked by a 45 km long Transfer Tunnel, bored with a 5 m diameter through basalt. From the Muela Dam, the 36 km long Delivery Tunnel exits in a tributary of the Vaal River in South Africa. The tunnel passes through the underlying sandstones and mudstones of the Karoo Supergroup and was lined segmentally during boring with precast concrete units. Mohale Dam supplies Katse Dam via a 31 km interconnecting tunnel, also drilled through basalt. While initial plans were that the tunnels through basalt would not need to be lined as required in the sedimentary sequences, during a visual inspection of the Transfer Tunnel in 1994 it was found that large sections of the tunnel length showed severe weathering. The quality and durability of the exposed rock and imminent sidewall disintegration eventually led to the decision to line the tunnel. The tunnel lining consisted of precast concrete segments with sound dolerite as coarse aggregate (LHC, 1994). This had a significant influence on the construction period as well as the final cost of the project, and the weathering processes involved thus warranted further investigation.

In early exposed rock core samples and from literature it was noted that fracturing of certain basalts, referred to as “crazing”, occurs. This was initially attributed to the action of swelling clays. Petrographic study showed, however, that the “crazing” is not genetically related to swelling clays although the fractures exploit patches of these clays as weak spots. “Crazing” was also confined to the coarsely amygdaloidal parts of basalt flows, generally in their upper zones. The fracture systems were found to originate in amygdales filled mainly by zeolites (OSC, 1986). The conclusion of the Lahmeyer MacDonald Olivier Shand Consortiums was that the presence of shrinkage cracks in montmorillonite-rich patches indicates that the basalts are in a dehydrated condition (OSC, 1986). The zeolites are noted for their capacity of holding water molecules loosely and of giving up this water easily (LHC, 1994). At high temperatures all the water is driven off irreversibly and there is evidence that structural changes take place. For some zeolites, the decrease in volume can be as much as 22% that will produce shrinkage forces in the closed system such as an amygdale. This may initiate the “crazing” and the failure of the rock in which the zeolites occur. Rapid deterioration encountered in some basalt rock types was later ascribed to a combination of the mineralogy of the different rock types that respond to changes in moisture content on exposure, the changes in stress regime on excavation, and the intrinsic geotechnical characteristics of each rock type (LHC, 1994).

It is now accepted that the main cause of basalt deterioration is the expansion of swelling clay minerals (e.g. montmorillonite) and active zeolites (e.g. laumontite) occurring within the rock mass (LHC, 1994). Volume changes in these minerals occur as soon as they are exposed to moisture changes. Microfissuring, jointing, fissuring or crazing will cause an incremental increase in rock

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porosity and this together with the strength of the rock material and the quantity and distribution of active minerals will determine the rate of disintegration (LHC, 1994). Smectite clay minerals, derived from the deuteritic alteration of olivine, glass and plagioclase, and active zeolites, laumontite–leonardite and scolecite are present in amygdales and as interstitial secondary minerals in all the basalts. Vertical zeolite zoning and dominant zeolites present were determined through exhaustive XRD analysis and research by Dunleavy et al. (1993). The influence of the active minerals is also dependent on the texture of the parent rock. If the texture results in low permeability rock material, the mineralogy may then not be sufficient on its own to cause deterioration of the rock within the design life of civil engineering structures.

3. Weathering of the sandstones

3.1. Chemistry, weathering and durability of the sandstones

The Clarens Formation is the uppermost of sedimentary rocks that comprise the Karoo Sequence; a large basin of sediments laid down between 200 and 160 million years ago. Overlain by the younger basalts, the Clarens is in turn underlain by the older Elliot and Molteno Formations and shows a depositional palaeoenvironment that increases in aridity from the Molteno through the Elliot to the Clarens Formation (Eriksson, 1983). The sequences, including the basalt layers, conformably overlie one another but, except for the basalt transition, boundaries are often indistinct. In the central Drakensberg region the Clarens Formation reaches a thickness of 300 m and is primarily of aeolian origin with predominantly fine-grained sandstone, subordinate siltstones, and medium grained sandstone and occasional mudstone horizons towards the base of the Formation. Eriksson (1983) identified four lithofacies, the dominant of which are massive cross-bedded structures that form the scenic cliffs commonly called the Little Berg. Based on petrographic work by Beukes (1970) and Eriksson (1981), the sandstones consist of 35–90% quartz, up to 20% feldspar with a matrix of 10–60% (van Rooy and van Schalkwyk, 1993). Silica and calcite are present as cementing agents, but will weather at different rates. Accessory minerals include zircon, hornblende, sphene, garnet and clay minerals kaolinite, illite, montmorillonite, chlorite, smectite with traces of mica (Beukes, 1970; Eriksson, 1981, 1983; Meiklejohn, 1994). Weathering and erosion of the structurally weaker, closely jointed alluvial-origin sediments in the lower sections of the Formation create overhanging shelters or “caves” within which numerous examples of San rock art are found.

Sandstone is more durable than the siltstones and mudstones, is less prone to slaking, and in the case of the Clarens sandstones, is more so if in association with moisture (e.g. Batchelor, 1990). Weathering and the rock (e.g. Loubser, 1991; Rudner, 1989; van Rijssen, 1987), the air humidity, may cause salt crystallization, hydration and dehydration of minerals, precipitates and clays, and solution processes (Meiklejohn, 1994). Chemical analysis shows that favourable moisture and temperature conditions alter the feldspars and break down calcite cement while chemical weathering products provide precipitates at or near the surface that can cause mechanical action. Meiklejohn (1994) does, however, note that much of the evidence for chemical weathering points towards a wetter period in the past.

While the detailed study by Meiklejohn (1994) provided insight into the rock properties and environmental conditions within shelters, recent observations and access to new equipment has seen a resurgence in interest in weathering and rock art (see Hall et al., 2007a). Several advances have been made that provide further insight into weathering of the Clarens Formation and are presented below in the context of understanding rock art deterioration.

3.2. Case study: sandstone weathering and rock art deterioration

Historically, weathering of the Drakensberg sandstone has been highly subjective and poorly understood. In the context of rock art, available information has suggested radiation-induced thermal stresses may play a role where paintings are exposed to direct sunlight (e.g. Loubser, 1991; Rudner, 1989; van Rijssen, 1987), the more so if in association with moisture (e.g. Batchelor, 1990). Moisture can also play a significant role (e.g. Avery, 1974) while salts, and their expansion/contraction resulting from hydration/dehydration cycles (e.g. Batchelor, 1990), may be a significant factor at some sites especially if the salts occur between the pigment and the rock (e.g. Loubser, 1991). Overall, although possibly sound in theory, most assessments of weathering lack appropriate data. To exacerbate this situation, some recent studies have added a further layer of obfuscation by misconstruing macro-cave climatic information for rock-surface micro-climatic data (e.g. Hoerlé and Salomon, 2004) by (wrongly) equating non rock-surface, air conditions within a shelter for those that occur at the (sub-)millimetre scale on the rock surface. Conversely, a well suited approach to evaluating the degree of weathering (but clearly not the cause of weathering) over recent (decadal) time spans is that of comparing photographs of the same paintings at different times and evaluating percentage loss (Hoerlé, 2005). As weathering rates are unlikely to be linear (e.g. Egli et al., 2003; Viles, 2001) and environmental conditions have probably changed, so this photographic approach still has limitations. Thus, the weathering of San rock art is still little understood, and assumptions are often somewhat simplistic in nature. It is therefore appropriate to review former comments and studies before outlining the state of current research.

The loss of San rock art, as with other sandstone cultural heritage, is a result of “natural and anthropogenic factors, involving physical, chemical and biological phenomena. Deterioration
processes often occur by means of phase transitions, most of which require months, years or centuries to take place" (Benedetti et al., 2008, p. 155). Considering the possible age of some of the art (>2000Y BP: Mazel and Watchman, 2003), it is perhaps more surprising it has survived so well. In some ways, the recognition of art durability is something not often identified (a ‘taphonomic’ attribute? – Bednarik, 1994) and yet it is a significant factor. Indeed, Bednarik (1994, p. 69) points out that survival of rock art can be dependent upon (p. 70) “...certain techniques, pigment or paint types, locations, media, climates etc.” Some paintings having been here for a few thousand years (Mazel and Watchman, 2003) identifies that they have experienced substantial climatic change. Thus, the present climatic variability is not unusual within the context of changes having taken place during the Holocene (Alley et al., 1997) and the apparent present degradation of the art requires that consideration also be given to other impacting factors.

Although used in a different context, Bradley et al. (2002) state that it may be just as important to study the rock as it is to investigate the art for (p. 109) in respect of the majority of (San) rock art studies, “the... paintings have come to dominate the discussion – the rock itself appearing to be of secondary importance.” Bakkevig (2004) points out that while such as an ancient ruin can produce differences in microclimate and can change the (local) environment markedly, this is in stark contrast to rock art which has little to no impact on the environment itself. Bakkevig (2004) also notes that the vegetation of a site may not be the same as that which was present when the art was created. This is because at a number of sites vegetation has been changed in recent times with the goal of improving access and visibility; as argued by Hall et al. (2007a,b) and Arocena et al. (2008) in respect to such changes affecting the microenvironment. Thus, there is a need to clearly understand the potentially complex nature of sandstone weathering if we are to preserve these cultural relics for future generations (Pope et al., 2002). Equally, we need to understand the properties of the paintings themselves (Odlyha et al., 1997), and how these directly impact their own weathering, as well as their interaction with the rock on which they are painted.

Antipathetical to the comment by Bradley et al. (2002) and Chalmin et al. (2003) note that while archaeologists have attempted to interpret rock art, they have often disregarded the technical aspects of the paints; a sentiment echoed by Zoppi et al. (2002). The physicochemical attributes of the paint can offer information on how the paints were created as well as on their properties and hence how they may react to the environment. Indeed, Casellato et al. (2000, p. 217) argue that conservation intervention can be more appropriate when “…quantitative physico-chemical properties of the object are sufficiently known” as this helps elucidate the modification the object has undergone as a result of “…the action of time, weather and human beings.” Once we better understand the chemical composition so we may better understand the performance properties of the pigments (Hao and Iqbal, 1997). Further, our knowledge of paint composition, and its interaction with the (light-transmissive) sandstone on which it is placed, may be significant to an understanding of possible bacterial colonization; given the nature of the rock and presence of the organic paints, the absence of any bacterial colonization may be scientifically significant. Bacterial activity is a factor not widely investigated with respect to the San rock art, but colonization of iron oxide art in a sandstone rock shelter has been reported from Spain (Gonzalez et al. 1999). Ultimately this may prove an important attribute, for Gonzalez et al. (1999) found a potential for microbial growth with hematite that could be significant from...
the perspective of conservation; the bacteria can also change the colour of paintings.

In broad terms, the San rock art appears to be on one of three types of surface: (1) (seemingly) directly on the natural rock surface, (2) on anthropogenically-smoothed rock surfaces, and (3) on a clay ground placed on top of a smoothed surface (Fig. 3). Where rock has been anthropogenically smoothed to create a surface for the painting, this action has theoretically “zeroed” the weathering clock (Pope et al., 2002, p. 213). However, the surface may not be truly “fresh”, as it can possess a ‘memory effect’ insofar as “...weathering often penetrates into the rock...” (Pope et al., 2002, p. 213) and future weathering-related changes to that rock may well reflect non-visible attributes created under the previous weathering regime. However, where a ground is applied to the smoothed rock (Hall et al., 2007a) and the paint put on top of that then the situation is somewhat different, but some of the memory attributes can still play a role at some point in the weathering process. Pope et al. (2002, p. 220) note, cultural stone may not be that representative of the natural world in that “The acts of preparing cultural stone create structural stresses that are different from those found in nature.” Further, the changes to atmospheric chemistry due to economic development, a notable factor in the past 100 years of southern Africa, have a significant impact because present weathering activity may differ significantly from that of pre-human-impact weathering (Pope et al., 2002, p. 221). Thus the age of paintings (and possibly the impact of previous vegetative cover) may well be critical to our full understanding of the current weathering. In addition, the art age may be a useful tool for evaluating the rates of rock weathering, as proposed by King (1945), but the scarcity of accurate dates (see Mazel and Watchman, 2003), as well as the potential degrading effects of pre-weathered surfaces, militates against further detail in this regard.

Findings to date in the ongoing rock art weathering study were recently detailed in Hall et al. (2007a) and so it would not serve to repeat them in detail here. The key points germane to weathering of the sandstone are, first, that the paint acts as surface modifier (Bullet and Prosser, 1983), significantly changing albedo, light transmissivity, thermal, and moisture properties of the rock, and second, where the paints are applied on top of a clay ground so both the ground and the paint change surface properties. Thermal infra-red data have shown that white and red pigments, as well as the rock, all have quite different responses to solar radiation that can lead to pigment-to-pigment as well as pigment-to-rock stresses (Hall et al., 2007a,b). Thermal and moisture fluctuations can lead to fracturing of the clay ground allowing the entrance of microbial activity (Arocena et al., 2008). In many instances it is the detachment of the clay ground rather than the weathering of the rock that is the destructive factor. It has also been suggested (Hall et al., 2007a,b; Arocena et al., 2008) that recent changes to surrounding vegetation may have increased exposure to solar and moisture impacts leading to accelerated deterioration.

At the local scale, the sandstone is reasonably uniform, with regard to colour, thermal properties, albedo, moisture transmission, and light transmissivity, such that the nature of weathering is fairly constant in character. However, with paints and/or ground, so the properties change significantly within the area of application. Deflorian et al. (2007, p. 244) note that, in order to evaluate the art weathering there is a need to measure “…a few different environmental parameters affecting the organic coating properties: total amount of energy coming from UV radiation, time with relative humidity higher than a defined threshold (causing surface water condensation), environmental temperature higher than the polymer Tg, temperature range, etc.” The key is the paints themselves may vary in respect to their responses to these parameters, and in regard to the responses of the subsurface and surrounding rock (e.g. Hradil et al., 2003). Of possible importance to longevity of some art, Deflorian et al. (2007) note that coating thickness has a strong influence on weathering and that loss of adhesion of the paint to the medium can also accelerate degradation. Loss of adhesion is dealt with in detail by Perera (1996) where he found most organic coatings under stress due to variation in temperature and relative humidity. The result of these stresses (internal, thermal, hygroscopic) acts against adhesion and provokes delamination (Perera, 1996, p. 23); a high tensile stress is induced under dry, cold conditions and a compressive stress under humid, warm conditions – conditions applicable to the Drakensberg. Thus, at the scale of the art weathering there is a need to evaluate both the art/rock physico-chemical properties and the environmental conditions (and how these have changed with time).

In the ongoing study, research directions are: (1) further determination of the paint composition, coupled with (2) evaluation of paint pigment properties, (3) on-going monitoring of environmental determinants at scales appropriate to determining pigment-to-pigment, pigment-to-ground, ground-to-rock, and rock-to-pigment stresses, (4) investigating environmental changes at art sites, (5) studies of anthropogenic preparation of rock surface impacts on weathering, (6) measurement of pigment thickness as a determinant in painting/pigment longevity, and (7) using all of the forgoing to model the stress fields associated with the three identified methods of paint applications. Indirectly, this will also help better understand the weathering of the sandstone per se, and thus have applicability to the preservation of the many buildings composed of this material found throughout southern Africa.

4. Weathering and palaeoenvironmental inferences

Within the Clarens Formation, many rock surfaces are covered by a gypsum precipitate, originating from chemical alteration of the sandstone. Given that rock art is painted on the surface of the gypsum (an excellent example is the Battle Scene at Battle Cave), it is clear that some of these precipitates formed during previous wetter climates (Meiklejohn, 1997). Accurate dating of the art, which has thus far remained largely elusive, may thus provide a useful tool for estimating minimum ages for the wetter periods of the late Holocene. Within slope deposits, clast angularity, or the absence thereof, has been central to interpreting Late Pleistocene palaeo-weathering processes. Sandstone, however, appears to be predisposed to angularity. In contrast under wet conditions chemical weathering of the basalts produces rounded products, although angular blocks have also been observed (see below). Several studies interpret angular sandstone clastic deposits as evidence for former frost action, notably conditions expected around the Late Pleistocene Last Glacial (max. 18,000 B.P.) but the presumptions have been strongly criticized (see Hall, 1992). With specific reference to southern African conditions, Hall (1991, 1992) notes that angularity can be produced through several processes, including thermal stress fatigue, dilatation and wetting and drying. The presumption of oscillations around 0 °C as a critical value for frost action in rock is also questioned and thus the palaeoenvironmental interpretation for the deposits, namely a cold and relatively moist, frost active environment, is problematic (Hall, 1992, 2007). Clastic form is thus considered as a poor indicator of palaeo-weathering process; a problem typically associated with interpreting landforms or weathering features from processes (Turkington and Paradise, 2005). Within the basalts, however, more recently proposed palaeoenvironmental interpretations are drawn mainly from the depositional (or slope) environment rather than the block attributes alone.

Several studies have focused on the nature of relict block accumulations at altitudes above 3000 m in Lesotho. Boellhouwers (1994, 1999a), Boellhouwers et al. (2002), Boellhouwers and Sumner (2003) and Sumner (2004) report on basalt openwork block accum-
mulations and extensive blocky deposits that often converge into blockfields and blockstreams similar to those found elsewhere, such as in Tasmania (Caine, 1983) and Norway (Rea et al., 1996). Block accumulations in Lesotho are superimposed over, and thus older than, slope colluvium and such deposits predominate on south-facing slopes (Boelhouwers et al., 2002; Sumner, 2004). The origin of these block deposits is attributed to former colder periods, notably within the Late Pleistocene, when mechanical weathering is considered to have predominated. Such an argument concurs with evidence within the Highlands (see Boelhouwers and Meiklejohn, 2002, for a review on the glacial vs non-glacial debate), supporting rather a former periglacial-type environment with little permanent snow cover. In contrast to a cold-climate origin, similar block accumulations can also be associated with warmer environments (see Boelhouwers and Sumner, 2003; André et al., 2008). Several problems thus remain in the interpretation of such landforms as entirely cold-climate dominated (Boelhouwers, 1999a; Sumner and Meiklejohn, 2004) and the highland areas of Lesotho, where weathering horizons may date back to the Tertiary (Boelhouwers, 1999a), still provides a largely unexplored avenue for further research.

5. Conclusions

A small but significant body of literature has provided insights into the weathering processes associated with the basalts and sandstones of the eastern escarpment region of southern Africa. While the case studies into rock art and for the Lesotho Highlands Water Project provide detail on current state of weathering, and potential processes, it is evident that a substantial amount of research remains to be undertaken. Although some field data are available, the environmental conditions controlling weathering processes and rates remain largely unknown given the diversity of the landscape including aspect and altitudinal conditions. Investigations using high resolution instrumentation and novel approaches, such as with moisture and light penetration (see Hall et al., 2007a) are ongoing and illustrate the intricacies required for field studies on weathering. Direct measurement of weathering rate is notably absent, however, although some inferences could be made, and how this impacts on landscape development is a key question for the future. Any form of biological weathering has also not been reported on in detail. Lastly, interpreting palaeo-weathering processes and climatic reconstructions from weathering products remains problematic, but the highlands area may provide new insights into cross-climate linkages given long geological history associated with weathering of the basalts.

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References


