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Geomorphology's role in the study of weathering of cultural stone ☆

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Abstract

Great monumental places—Petra, Giza, Angkor, Stonehenge, Tikal, Macchu Picchu, Rapa Nui, to name a few—are links to our cultural past. They evoke a sense of wonderment for their aesthetic fascination if not for their seeming permanence over both cultural and physical landscapes. However, as with natural landforms, human constructs are subject to weathering and erosion. Indeed, many of our cultural resources suffer from serious deterioration, some natural, some enhanced by human impact. Groups from the United Nations to local civic and tourism assemblies are deeply interested in maintaining and preserving such cultural resources, from simple rock art to great temples. Geomorphologists trained in interacting systems, process and response to thresholds, rates of change over time, and spatial variation of weathering processes and effects are able to offer insight into how deterioration occurs and what can be done to ameliorate the impact. Review of recent literature and case studies presented here demonstrate methodological and theoretical advances that have resulted from the study of cultural stone weathering. Because the stone was carved at a known date to a “baseline” or zero-datum level, some of the simplest methods (e.g., assessing surface weathering features or measuring surface recession in the field) provide useful data on weathering rates and processes. Such data are difficult or impossible to obtain in “natural” settings. Cultural stone weathering studies demonstrate the importance of biotic and saline weathering agents and the significance of weathering factors such as exposure (microclimate) and human impact. More sophisticated methods confirm these observations, but also reveal discrepancies between field and laboratory studies. This brings up two important caveats for conservators and geomorphologists. For the conservator, are laboratory and natural setting studies really analogous and useful for assessing stone damage? For the geomorphologist, does cultural stone data have any real relevance to the natural environment? These are questions for future research and debate. In any event, cultural stone weathering studies have been productive for both geomorphologists and conservators. Continued collaboration and communication between the geomorphic, historic preservation, archaeological, and engineering research communities are encouraged.

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1. Introduction

Humans hold a nostalgia, respect, even a need for things ancient. As Urbani (1996, p. 449) remarked:

...at a time when man begins to feel the ominous historical novelty of the destruction of his own environment, certain values, like ancient art, demonstrate how the potential of human activity can integrate rather than destroy the beauty of the world.

Accepting only the essence of that statement, one has to admit that antiquities link us to our heritage. As a society ready to leap into the next millennium, we spend a lot of time looking to the past. Places such as Petra, Chaco Canyon, Giza, and Machu Picchu thrive on the economic potential of “heritage tourism.” Cities and sites strive for UNESCO “World Heritage” status. Substantial funds from both governments and private foundations help support preservation. On philosophical, historical, and economic grounds, there is a need to protect antiquities.

Yet, our cultural heritage is at risk. This is especially true for paper, paint, and other organic materials; but even stone objects face deterioration due to exposure to pollution, to tourists (and scholars), and even to the natural climatic environment. In a widely read commentary, Burns (1991) urgently called for a holistic understanding of basic stone deterioration processes. A variety of experts—museum curators, architectural engineers, material scientists, chemists, to name a few—are at work on these problems. In the realm of stone conservation (in architecture and sculpture), geomorphologists have also made notable and publicized contributions.

The best approach to stone conservation is an interdisciplinary one combining art conservation, engineering, and geomorphology. That said, one can still draw a distinction among the geomorphic, engineering, and art conservation approaches to stone conservation. Each discipline brings its own scientific and methodological culture (Fig. 1). Such a division is admittedly oversimplified, but it illustrates the challenge of integrating very disparate types of knowledge. Art conservators bring an expertise formed in a tradition of the humanities and aesthetic appreciation, and many are well trained in chemistry. They also

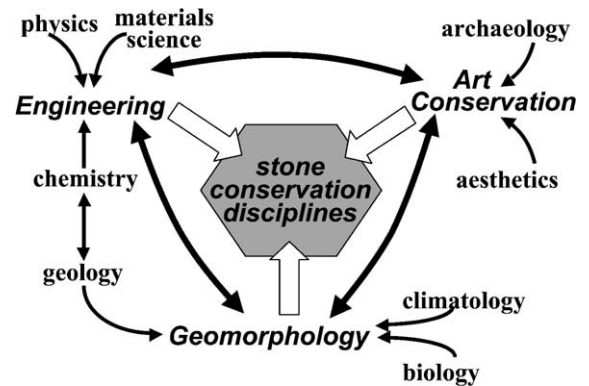


Fig. 1. The disciplinary relationships of research regarding cultural stone weathering. Each approach comes with a background of expertise, although individuals from any specific discipline tend to borrow from other fields.

bring the inviolable rule of nondestructive testing of cultural objects, which is not the norm in field geomorphology. Engineers apply tested methods based on structural, physical, and chemical properties of materials. Geomorphologists are well acquainted with looking into the past and understand processes and rates. Thus, geomorphologists contribute an understanding of slow physical and biogeochemical processes that occur to rocks in the natural environment, and most are knowledgeable about climatic processes at scales ranging from global to micropore levels (Smith et al., 1992). Undoubtedly, geomorphologists can contribute to the holistic, interdisciplinary approach required for the study and conservation of cultural stone (Torraca, 1996). In order to be practical at stone conservation, each disciplinary approach borrows from the other two.

Smith et al. (1992) outlined a “geomorphic approach” for stone weathering assessment, essentially providing a short primer in geomorphology to the practice of stone conservation. We also promote this perspective, but we also expand on the feedback to the study of geomorphology. This paper does not intend to extol the virtues of a discipline we already know to be effective. What is interesting and bears reviewing are the methodological and theoretical advances that have come from the marriage of geomorphology and cultural resource management. As we intend to show through this literature review, geomorphologists working in cultural resource management have made obser-

vations that contribute toward the study of landforms and the study of human structures. Sometimes, these discoveries are at odds with what has been accepted by other geomorphologists or conservators. The artifacts of human heritage provide a laboratory for the study of environmental processes. Few scientists have the opportunity, and challenge, to work with material so important and so exposed to “the public eye”.

2. Definitions

We use the term “cultural stone” for stone that has been physically altered by humans—abraded, engraved, quarried, chipped or chiseled, or dressed. This includes architectural stone and sculpture that make up the bulk of weathering studies in stone conservation literature. But, we also open the discussion to rock art and other rock engravings, megalithic monuments, rock-cut excavations and quarries, lithic tools, and carved stone ornaments. All involve anthropogenic removal of rock to expose a new surface, theoretically “zeroing” the weathering clock.

Dressing or otherwise removing rock surface does not necessarily expose unaltered rock. “Fresh” exposures may be new, but may also be partially weathered, because weathering often penetrates into the rock. Thus, our use of “fresh,” and the use of the term throughout the body of literature on the subject, should be viewed with this caveat.

“Weathering” is a term familiar to geomorphologists, but other terms also appear in the stone conservation literature. Thus, depending on the audience, terms such as surface diagenesis, deterioration, degradation, decay, and stone pathology are used to convey the same meaning. All involve changes to the rock (and its constituent minerals) as it adjusts toward an equilibrium state in the surface environment. Discoloration, structural alteration, precipitation of weathering products (mass transfer), and surface recession (mass loss) are all products of weathering processes.

What falls under the guise of geomorphology is harder to define. If geomorphology is the study of the origins, evolution, processes, form, and spatial distribution of landforms (Christopherson, 2000), the study of cultural stone by geomorphologists is only a means to an understanding of the natural landscape. Yet, many geomorphologists, trained in earth sciences,

apply their skills to stone conservation. Geomorphologists look for geographic variation, interacting systems, and rates of change over time in terms of weathering features and processes. This is not to say that other scientists do not make similar inquiries, and this review includes works from archaeology, art conservation, civil and materials engineering, and geochemistry. Geomorphologists working with cultural stone have, in turn, applied techniques and philosophies used by these other disciplines (Fig. 1).

3. The heritage of geomorphic studies of cultural stone

Camuffo (1992) reviewed very early observations (Greek, Roman, and 17th and 18th Centuries) regarding deterioration of monuments under atmospheric pollution. Both Strabo and Herodotus recognized the formation of tafoni on building stone and recommended preventive action. However, quantitative studies of stone weathering would not appear until the late nineteenth and early twentieth century where Geikie (1880), Goodchild (1890), Brigham (1903), Loughlin (1931), and Emery (1941) were among the first to equate observations about cultural stone with weathering and erosion in the natural landscape.

Weathering studies have not been the dominant focus of geomorphic research through most of the twentieth century (Klein, 1984). Yet, over the past 40 years, numerous geomorphologists employed research in cultural stone to help answer geomorphological questions, and in turn, address issues of stone conservation. A number of early researchers took advantage of tombstones and similar monuments to assess weathering rates (Matthias, 1967; Rahn, 1971; Cann, 1974; Kupper and Pissart, 1974; Kupper, 1975). Going one step further, some researchers made their own stone tablets to place in various environments with more rigorous experimental control (Trudgill, 1975; Day et al., 1980). These tablets, while technically “cultural stone” by our definition, are not particularly cultural (i.e., worthy of interest as a heritage resource). But they provided a means to study weathering processes for stone conservation and geomorphology and are widely used today (for instance, see Butlin et al., 1992; McGee and Mossotti, 1992; Gorbushina et al., 1993; Yerrapragada et al., 1996).

Around the same time, other researchers concentrated on larger structures. More numerous works within the engineering geology literature overshadowed works by geomorphologists such as Emery (1960) and Goudie (1977). Winkler is most prominent among these engineering geologists (Winkler, 1965, 1966, 1978), and his works culminate with his oft-cited text (Winkler, 1973, since revised, Winkler, 1994). Winkler's studies (Winkler, 1965, 1978) of Cleopatra's Needle in New York City have given that particular landmark a sort of sacred status among those who study weathering. More recently, Gauri et al. (e.g., Gauri and Holdren, 1981) and Amoroso and Fassina have taken a lead in stone conservation, the

latter also publishing a widely read text (Amoroso and Fassina, 1983). The cross-pollination within the field of stone conservation (Fig. 1) is evident in the frequent citation of these authors by geomorphologists active in stone conservation.

Following these notable steps, a wave of weathering rate studies beginning in the late 1970s took advantage of the "natural laboratory" afforded by building stones and tombstones. These emanated out of several "schools" of cultural stone weathering research (Table 1). The "UK School" is perhaps strongest and most prolific in the geomorphic literature, hosting numerous conferences and sponsoring several special editions of peer-reviewed journals. Cultural

Table 1

Selected studies of weathering of cultural stone, covering a variety of contexts and methods, arranged by region of study; weathering assessment methods developed specifically for cultural stone are described in detail in the text

Study	Location	Context	Method(s)	Lithology
Sharp et al., 1982	London, England	18th C. cathedral	surface recession	limestone
Jaynes and Cooke, 1987	SE England	architecture, various ages	morphology, mass loss	limestone
Mottershead, 1998	Salcombe, England	16th–19th C. architecture	petrography, surface recession	greenschist
Inkpen, 1999	various UK	tombstones	surface recession	marble
Sjöberg, 1994	Sweden	petroglyphs	Schmidt hammer	gneiss
Storemyr, 1997	Nidaros, Norway	13th C. cathedral	morphology, petrography	various
Sellier, 1997	Carnac, France	megaliths	morphology, surface recession	granitic
Delgado Rodriguez, 1994	W. Europe (esp., Portugal, Spain)	megaliths; Medieval and Renaissance architecture	various	granitic
Romão and Rattazzi, 1996	Portugal	megaliths	visual, microscopy	granitic
Pope, 2002	Portugal	prehistoric to modern cultural stone	Schmidt hammer	granite
Emery, 1960	Giza, Egypt	Great Pyramid	debris accumulation	limestone
Gauri et al., 1990	Giza, Egypt	Sphinx	petrography	limestone
Paradise, 1995	Petra, Jordan	Roman theater	surface recession	sandstone
Topal and Doyuran, 1997	Cappadocia, Turkey	Carved bedrock, petroglyphs	structural integrity	tuff
Gauri and Holdren, 1981	Agra, India	Taj Mahal	microscopy, chemical conservation methods	marble
Van Tilberg, 1990	Easter Island	large statues		basalt
Winkler, 1965	New York, USA	Egyptian obelisk	visual	granitic
Brown and Clifton, 1978	Southwest USA	adobe architecture	visual, structural properties	clay
Petuskey et al., 1995	Southwest USA	Prehistoric (12th C.) ruins	surface recession, microscopy, chemistry	sandstone
Meierding, 1981	various USA	tombstones	inscription legibility	marble
Vogt, 1999	Arizona, USA	tombstones	confocal laser microscope	sandstone
Dragovich, 1981, 1986	Sydney, Australia	tombstones	surface recession	marble
Gorbushina et al., 1993	various	statuary and architecture, lab	microscopy	marble
McGee and Mossotti, 1992	experimental	stone samples	mass loss, gypsum accumulation	marble, limestone
Yerrapragada et al., 1996	experimental	lab and outdoor tests	chemical mass loss and gain, surface recession	marble

stone weathering research frequently appears from Germany, France, Poland, and the Czech Republic as well, where acid pollution damage is a major concern. A “Mediterranean School” exists among stone conservators in Greece, Italy, Spain, and Portugal, driven by the cultural wealth of Classical as well as Medieval and Renaissance sculpture and architecture. Ancient monuments throughout the Middle East and India provide a focus for a body of weathering studies as well. Pre-Columbian art and architecture and notable examples of historic architecture have been the subject of stone conservation work in the Americas. A healthy but scattered “American School” of geologists and geomorphologists are active globally, and the Getty Conservation Institute in Los Angeles is one of the premier centers for stone conservation research. Finally, the world’s most weathered continent, Australia, is short on ancient architecture but has produced groundbreaking research in cultural stone weathering via tombstones. Other parts of the world—Africa, China, Southeast and East Asia—provide sporadic focus for weathering studies but remain relatively untouched. In the content of this paper, enumerating a fair sample of all the examples given above would be impossible. [Table 1](#) provides a brief snapshot of current and recent work on cultural stone weathering from a variety of contexts.

Although weathering studies still lag behind other subdisciplines of geomorphology in number, a large and growing body of work now exists, aided to a large part by studies in cultural stone weathering. SWAPNet, the Stone Weathering and Air Pollution Network, and ASMOSIA, the Association for the Study of Marble and Other Stones in Antiquity, promote studies in stone conservation; and geomorphologists actively contribute in both organizations. The Association of American Geographers has hosted special Weathering Geomorphology sessions at their annual meetings since 1994 where cultural stone has been a frequent subject of study. The Getty Conservation Institute in Los Angeles sponsors (among its other art conservation efforts) considerable research into cultural stone conservation, while the European Union and UNESCO are active in supporting studies of heritage sites. Journals such as *Quarterly Journal of Engineering Geology*, *Earth Surface Processes and Landforms*, *Physical Geography*, *Zeitschrift für Geomorphologie*, *Studies in Conservation*, and *Atmospheric Environ-*

ment are most likely to feature studies in geomorphic stone weathering, along with the periodical proceedings of different specialty groups (e.g., [Webster, 1992](#); [Jones and Wakefield, 1999](#)). Interestingly, because cultural stone weathering studies translate so well to educational applications, the *Journal of Geological Education* also contains a fair share of studies on this topic. Nevertheless, based on our unscientific survey of the literature, we feel that cross-pollination of ideas is often weak among the disciplines and even between geomorphologists from different parts of the world. What, then, are the contributions from the geomorphic perspective? And how can geomorphologists work to communicate these further?

4. State of the art: advances in methods

Application of geomorphic knowledge translates readily to cultural stone ([Smith et al., 1992](#)). Conversely, cultural stone weathering studies contribute substantially to what we know about weathering rates. The crux of weathering studies of cultural stone is that the surface of the stone has been made fresh by human alteration. Assuming that human alteration totally removes previous weathering (not a valid assumption in some cases), weathering begins anew on the fresh rock surface. One assesses, by a variety of methods ([Table 1](#)), the degree of weathering (or proxy indicator) that has occurred since this baseline of alteration. If the age of the resurfacing is known (date of construction, inscription date, etc.), then an average weathering rate can be determined. Researchers working in cultural stone have developed several innovative (and usually inexpensive) methods more or less unique to cultural stone, and these are described in more detail below. How representative these are to the natural environment and what they say about actual episodic processes is debatable. These questions will be addressed later in this paper.

4.1. Surface recession and weathering rates

Surface recession occurs when weathered material is removed from the rock. If one can establish where the original surface lay, then a rate of recession can be calculated. This answers a key problem in geomorphology: namely, how fast does weathering and ero-

sion occur and, extrapolating to landscapes, how long does it take for landscapes to recede or lower? In natural landscapes, determining recession rates is difficult and rare because little evidence exists of the original surface. On cultural stone, it is sometimes possible to know an original surface from an assumed previous geometry, for instance:

- (i) precisely carved stones, such as tabular tombstones (Meierding, 1981; Baer and Berman, 1983; Dragovich, 1981) and building stones (Dragovich, 1980; Paradise, 1998);
- (ii) remnants of quarry or dressing marks (Danin, 1983; Paradise, 1995; Fig. 2);
- (iii) remnants of polish (Meierding, 1981);
- (iv) protrusions of less weathered minerals or metal (Winkler, 1966; Cann, 1974; Kupper, 1975; Neil, 1989; Inkpen, 1999).

Surface recession measurements can be confounded if there has been subsequent alteration to the stone (such as sandblasting or other cleaning) or if the stone has been displaced into a different weathering environment. Still, through measurement of surface recession in various contexts, a very large database is available now for weathering rates, produced very cheaply and with reproducible results. These data have been translated to geomorphic studies in natural environments (e.g., Pope et al., 1995).

4.2. Inscription legibility and corner rounding

Inscriptions carved into stone soften over time as the sharp corners weather and recede. Similarly, carved corners become more rounded. Cernohouz and Šolc (1966) presented a corner recession measurement to estimate the exposure age on statues and natural sand-

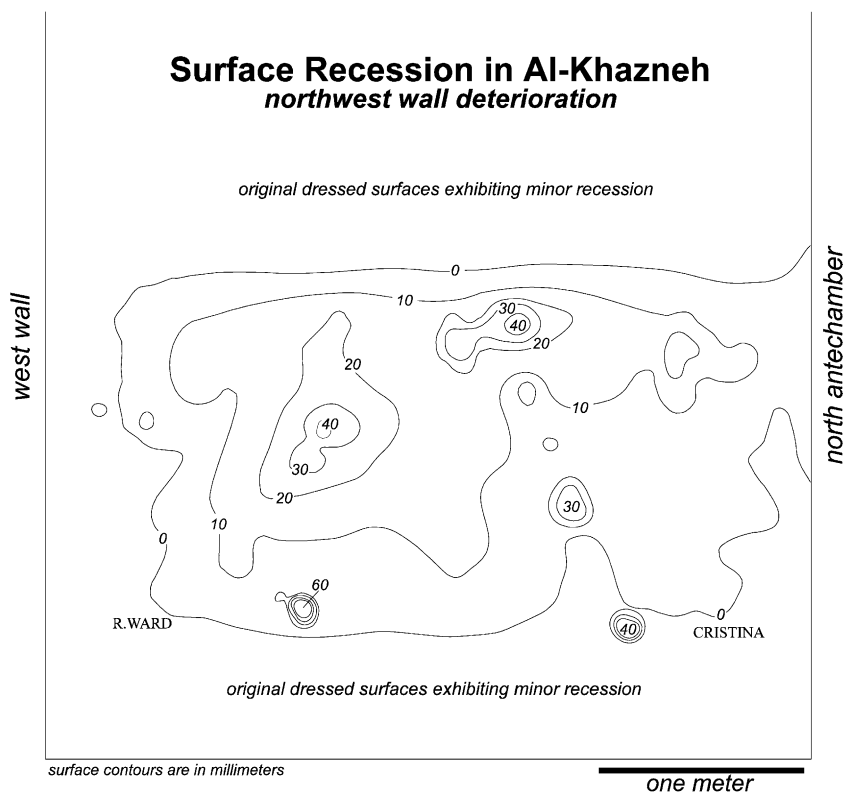


Fig. 2. Surface recession rates, Al-Khazneh, Petra, Jordan. The sandstone wall is over 2000 years old, but most recession is assumed to be due to human contact within the last 100 years. Greatest recession (upward of 30 cm) occurs in the 1.5–2.0 m height above floor level (within reach of hands).

stone talus blocks (ca. 0.2–40 ka). [Bednarik \(1993\)](#) modified the method on a microscopic scale to date petroglyphs (> 1 ka). As geomorphic and archaeometric dating methods, these types of measurements may not be accurate because there is no way of knowing whether new corners formed subsequent to the original corner cutting ([Pope, 2000a](#)). Such secondary alteration is usually verifiable on more recent cultural stone, so corner recession can be a quantifiable weathering phenomenon in these cases. Following [Rahn's \(1971\)](#) lead, another approach was adopted by [Meierding \(1993a\)](#), who established a categorical ranking of inscription legibility for engravings on tombstones and landmarks. This method is usually not translatable to the natural environment (as datable inscriptions are seldom found outside of tombstones) and does not calculate a recession rate directly unless it is calibrated to a measured surface recession rate. It does provide a quantification of the degree of weathering in cultural stone where no other method is possible.

4.3. Surface roughness and morphology

Stone decay tends to produce uneven surfaces out of differential weathering of various minerals and inclusions. Thus, smooth or polished surfaces become pitted and etched over time. Surface roughness can be assessed qualitatively or categorically. Total relief can be measured more easily at the visual scale than at the microscopic scale. Scanning electron microscopy is frequently applied in the latter case ([Doehne and Stulik, 1990](#); [Rao et al., 1996](#); [Viles and Moses, 1998](#)). A new method developed by [Rautureau et al. \(1993\)](#) and [Vogt \(1999\)](#) uses the confocal laser microscope to quantify surface roughness as a measurement of weathering on carved stone.

4.4. Rock integrity: hardness, structure

Rock integrity is a value often measured by civil and structural engineers. As weathering can alter the hardness and structure of the rock, measurements of either can be seen as a proxy for the amount of weathering. The Schmidt hammer, developed to test concrete, is useful for geomorphic weathering assessments ([Day, 1980](#)). Weathering softens rock (by granular disintegration) or hardens it (by case hardening). [Sjöberg \(1994\)](#) tested rock hardness on petro-

glyphs and stone stair steps; and [Pope \(2000a\)](#) used rock hardness to assess weathering rates on cultural stone ranging from Neolithic megaliths to Roman, Medieval, and Renaissance architecture ([Fig. 3](#)).

Weathering phenomena in the rock interior include core softening and altered zones surrounding joints and fracture networks. Internal impacts on cultural stone have been impossible to detect without cutting into the stone and destroying it, until the advent of new remote sensing techniques. It is now possible to assess the internal structure of stone with tomography ([Delgado Rodriguez, 1994](#)) and perhaps ground penetrating radar.

4.5. Chemical changes and secondary deposits

Chemical changes are routinely assessed in establishing the degree and type of weathering. Several chemical phenomena are unique to cultural stone, primarily due to impacts of atmospheric pollution in urban settings. Aerosol deposits of black carbon discolor stones but are not particularly damaging in a weathering sense (unless they can be said to affect the microclimatic surface temperature of the rock, see [McGreevy, 1985](#)). Dry deposition associated with aerosols may include sulfur and nitrogen compounds that promote acid dissolution with the addition of water. Sulfurous crusts appear on calcareous stone

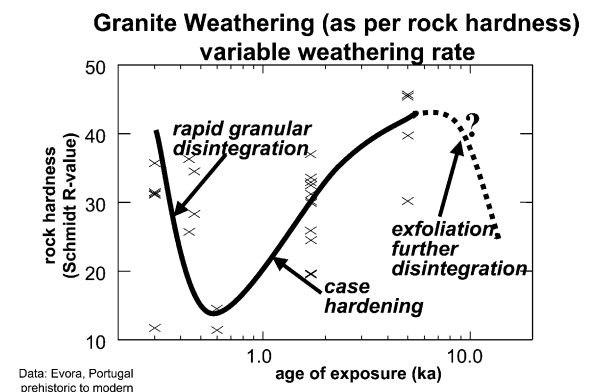


Fig. 3. Variable weathering rates, based on Schmidt hammer test of rock hardness, on Portuguese granite. All samples are of cultural stone, ranging from Neolithic megaliths (~ 6000 ka) to Roman ruins and Medieval- and Renaissance-era architecture near the city of Évora (SE Portugal). The “fitted” curve is diagrammatic only (not based on a nonlinear regression model) drawn to emphasize changes in rock hardness according to different stages of weathering.

when it reacts with the SO₂ in the atmosphere (Atlas et al., 1987; McGee and Mossotti, 1992). Salt, now regarded as a common weathering agent (Goudie and Viles, 1997), is particularly notable in cultural stone. Salt weathering occurs in marine and desert situations (Goudie, 1977; Mottershead, 1994; Goudie and Viles, 1997), but it also appears with the application of saline irrigation water (Billard and Burns, 1980; Meierding, 1981) and salting of streets for ice removal (Winkler, 1973). Biological weathering agents, also common outside of cultural stone, are particularly noticeable on building stones (Wakefield and Jones, 1998). Chemical analysis of stone may be accomplished with any of the standard techniques used in petrography, but a newer method combining the chemical and textural/morphological view of mineral weathering afforded by backscatter electron microscopy (Dorn, 1995) can be applied when it is possible to acquire samples.

5. Theoretical advances

5.1. Weathering rates

Stone recession measurements provide solid evidence of average weathering rates in a variety of environmental settings and with different lithologies (Livingston and Baer, 1984). Such information is useful not only in establishing the time scale for cultural stone deterioration but also the rates of geomorphic processes. Geomorphologists are key contributors to this aspect of stone conservation, having experience in solving these problems in the natural environment (Smith et al., 1992).

For the most part, studies of cultural stone weathering rates assume a linear weathering rate, although a few prescribe nonlinear (exponential or episodic) rates. There is no agreement in the geomorphic literature as to whether weathering rates decrease over time, reaching a state of equilibrium (Colman and Pierce, 1981; Taylor and Blum, 1995; Yaalon, 1996), or increase with time, with weathering accelerating as more surface area is exposed to weathering agents (Stonestrom et al., 1998). Tombstone studies by Klein (1984) and Neil (1989) seem to support the rate acceleration theory. In contrast, Yerrapragada et al.'s (1996) test of marble samples and Inkpen et al.'s (1994) tombstone survey concur with a weathering rate decrease.

Cooke (1989) surmised that further studies are necessary to single out different weathering agents and factors, delayed response intervals, and lack of resolution over the long term. Over a decade later, we can echo the same recommendations.

Average weathering rates may pertain to a particular weathering process (for instance, dissolution or cryostatic pressure) or, more often, a suite of weathering processes working together producing some observable end result. Notably, *average* rates sometimes mask the variability of rates and processes over time. What is more likely, and consistent with other geomorphic processes (Phillips, 1999), is that weathering is episodic, perhaps even chaotic. Weathering rates respond to thresholds based on different intrinsic and extrinsic variables (Inkpen et al., 1994; Smith et al., 1994; Paradise, 1995, 1998, 2000). These may relate to individual processes or several processes working together. The significance of microscale weathering factors becomes very important to these rates and thresholds (see below). Examples are numerous of abrupt weathering rate changes over short time spans. Smith et al. (1994) suggested that accumulated weathering effects could account for sudden rapid deterioration in Belfast sandstones. Paradise (2000) pointed out rapid weathering of sandstone walls in Petra that were recently exposed to tourists, illustrated in Fig. 2. Finally, Pope (2002) observed variable weathering rates of granitic cultural stone from Portugal (Fig. 3), demonstrating that rapid granular disintegration is replaced by case hardening. Eventually, case-hardened crusts would exfoliate, exposing the core-softened interior to rapid weathering again. Weathering processes in all environments will likely exhibit similar variability.

5.2. Weathering factors, agents, and geography

Studies of cultural stone reveal the importance of specific weathering agents and weathering factors. Again, the crossover from geomorphic observations to stone conservation is obvious, as most weathering agents and factors active in the geomorphic environment are likewise prevalent on cultural stone.

Biotic agents, ranging from bacteria (Danin, 1983) and algae (Young and Urquhart, 1998) to fungi (Gorbushina et al., 1993) and lichens (Romão and Rattazzi, 1996), are common if not ubiquitous in most weath-

ering environments. Biotic weathering agents are among the most aggressive, contributing to acid dissolution, oxidation, chelation (complexing), and physical fracturing induced by root hyphae. Microbes are involved in fixing atmospheric SO_2 to create gypsum crusts on carbonate stones (Atlas et al., 1987) and in the formation of rock varnishes and oxalate coatings (Dorn, 1998). Dorn (1998) and Viles (1995) summarized organic coatings and organic weathering agents, respectively, and Wakefield and Jones (1998) reviewed various organic agents particular to building stone.

Salts contribute to weathering in a variety of ways. Salts exert physical pressure by thermal expansion, hydration, and crystallization (Goudie and Viles, 1997; Rodrigues-Navarro and Doehne, 1999). Salts also catalyze dissolution reactions, causing accelerated chemical weathering (Xie and Walther, 1993). The impacts of salt weathering on cultural stone are well known (Goudie and Viles, 1997). Salts (marine, aerosol, or from ground water) create tafoni and alveolar weathering forms (Mottershead, 1994; Williams and Robinson, 1998). Granular disintegration in granitic monuments in Portugal (Alves et al., 1996) is attributed to salts, although salts are observed to induce surface hardening in sandstones and marble in simulation tests (Rossi-Manaresi and Tucci, 1991; Williams and Robinson, 1998). Salts are not restricted to marine or arid environments, as demonstrated by Smith et al. (1994) and Williams and Robinson (1998), who showed that salt weathering occurs in temperate European cities.

Human weathering factors have been a key subject of cultural stone studies. Cultural stone is, by definition, physically weathered by human agency (mechanically broken down by processes of carving, abrasion, quarrying, etc.; Dixon, 1993). Human impacts are not limited to mechanical forces, however, Paradise (2000 and this paper, Fig. 2) mentions the impacts of casual human contact (touching, walking, additions to humidity in rooms—combinations of mechanical and chemical weathering processes) on deterioration of stone. Pope and Rubenstein (1999) identified enhanced chemical weathering under prehistoric dwellings due to inputs of organic wastes. These examples are typical of local and microscale influences.

The most obvious example of human-impact weathering, dominating the stone conservation literature, is the weathering caused by atmospheric pollution, evident at local to regional scales. Cooke (1989)

pointed out that geomorphic research in cultural stone weathering was critical toward understanding the geography and temporal variability of acid rain. One of the key findings Meierding (1981, 1993a,b) made was that atmospheric pollution completely overrides large-scale climatic factors (namely precipitation and air temperature) in the weathering of marble tombstones across the United States. In “pristine air” areas such as Nevada and even Hawaii (in a tropical environment), marble weathering rates are very low.

Feddema and Meierding (1987) and Meierding (1993b) demonstrated that dry deposition of SO_2 gas was the chief agent of weathering on vertical marble tombstone faces. This is a two-step, chemical/mechanical process whereby added water creates sulfuric acid that promotes gypsum crystal growth, which then mechanically weathers the marble by granular disintegration. Recent studies (Meierding, 2000) now show that horizontal stone tablets at ground-level record actual acid precipitation and calcite dissolution, although with lower recession rates than those due to SO_2 (Fig. 4). Acid precipitation varies over a broader gradient, while the greatest SO_2 -gypsum weathering is confined to local areas. Although regional patterns in weathering are apparent (e.g., in the “acid deposition” region of the upper Ohio Valley; Meierding, 1993a,b), SO_2 weathering can vary in a complex local geographic pattern, depending on the influence of local

Dry SO_2 vs acid precipitation weathering: transect across Philadelphia

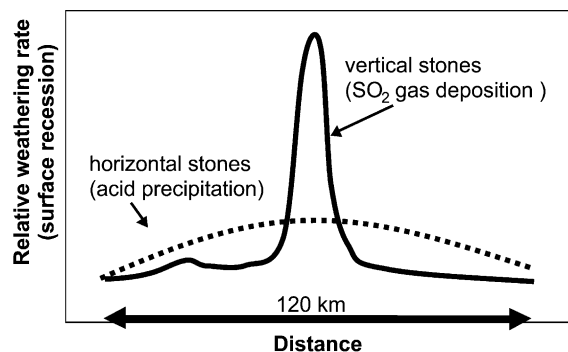


Fig. 4. Generalized Pennsylvania marble surface recession rates (calibrated from inscription legibility) in a transect across Philadelphia, PA (USA). Vertical tombstones weather by SO_2 gas-influenced gypsum crystal growth (most pronounced near the city center), while horizontal tablets record acid-rain-induced dissolution (dispersed over a more regional gradient).

polluters such as short stack industries and even home coal furnaces (Schreiber and Meierding, 1999).

Studies in cultural stone demonstrate the importance of microscale factors in weathering (Pope et al., 1995). The “microscale” ranges from a few tens of meters (for instance, one side of a building to another) down to submillimeter scale (in the pores and mineral boundaries of the rock). One factor that has received considerable attention is the importance of exposure orientation, to solar insolation in particular. The impact of solar insolation on weathering has been debated for over a century. It has been argued variously that thermal expansion may or may not cause enough stress to affect the rock and cause mechanical weathering (Bland and Rolls, 1998). Interestingly, there is comparatively little information on the possible effect of insolation on temperature-controlled chemical reaction rates. Nevertheless, studies in cultural stone demonstrate preferences for sun-facing and sun-shaded weathering. Pope (2000b) illustrated both with bipolar weathering maxima to the SW and NE on individual granite monuments, suggesting a combination of solar- and moisture-influenced weathering. Observations by McGreevy (1985), Paradise (1995, 1998), Warke et al. (1996), Halsey et al. (1998), and Robinson and Williams (1999) supported enhanced weathering of cultural stone due to thermal stress in sun-facing exposures. In contrast, shaded exposures are subject to different extremes. More moisture efficiency on exposures protected from evaporation could account for enhanced weathering (through increased dissolution or solution or through more prevalent organics such as lichen or algae). This indirect effect of solar exposure is supported by observations from Meierding (1993a). Keeble (1987) pointed out that shaded temperatures contribute to extreme temperature ranges that may cause deterioration on stone. Petuskey et al. (1995) anticipated both moisture efficiency and temperature extremes as weathering factors for sandstone ruins in Mesa Verde, although only temperature proved to be significant in this case.

6. Feedback to geomorphology and the cause for cultural preservation

Many geomorphologists involved in weathering studies turned to tombstones and building stones as

the best approach to assess the geography and rates of weathering. This was supposed to be an ideal compromise between the streamlined yet environmentally unrealistic laboratory experiments and the sometimes hopelessly complex environmental system responsible for weathering in the natural world. Cultural stone was attractive for several reasons. (i) It had no inherited weathering history because it was quarried. (ii) Cultural stones often had a precisely known weathering history because they were dated. (iii) It was possible to survey a large number of stones with a consistent lithology. Sometimes, cultural stone could be compared with the fresh rocks exposed in quarries. (iv) Finally, it was possible to attain some environmental control through orientation, location with respect to vegetation, moisture sources, types of weathering agents, etc. With better understanding of field conditions, geomorphologists working with cultural stone have recently arrived at more realistic laboratory approaches that compare favorably with field measurements (Yerrapragada et al., 1996; Trudgill and Viles, 1998).

One question is seldom addressed by geomorphologists: how representative is cultural stone of the natural world? In fact, cultural stone, like the laboratory samples undergoing stress tests, is not particularly representative of natural weathering either. Several conditions work against the usefulness of cultural stone as a proxy for real-world conditions.

(i) Cultural stones are almost always fresh (except for where field stones have been incorporated into walls, for instance). Fresh exposed rock can be found in the natural world in glacially scoured areas or on rapidly retreating sea cliffs and canyon walls. But the rest of the landscape is composed of already weathered rock approaching equilibrium with the environment. Erosion in the natural world does not always remove inherited weathering, for instance, on weathering rinds, saprolite profiles, or weathered joints (see articles in Lidmar-Bergström, 1995).

(ii) The acts of preparing cultural stone create structural stresses that are different from those found in nature. Many cultural stones are dressed, even polished; a condition not common in nature except perhaps under glacial ice or in bedrock streams. Polishing (as on tombstones, some architectural stone, and perhaps engraving) imparts an impermeable glassy seal (Bielby, 1921) that is resistant until the

weakest areas finally succumb to weathering agents. Even without polishing, abrasion and engraving may compact the rock surface, making it somewhat more resistant to weathering (Pope, 2000a).

(iii) Most cultural stone (particularly in urban areas) weathers in an atmosphere that has been severely altered by humans. Exceptions to this would include cultural stone found in remote regions (for example, Moai statues of Easter Island, petroglyphs in the Sahara, or tombstones in rural cemeteries of the western United States). Natural rock exposures, even those within polluted urban areas, differ in that they have a considerable pre-human-impact weathering history. Human atmospheric weathering impact is not limited to the modern industrial age: Camuffo (1992) explored the possibility of acidic atmospheres existing in early- and pre-industrial cities.

(iv) There are few opportunities to apply methods such as surface recession, inscription legibility, and corner modification to the natural environment. (However, methods such as tomography and confocal laser microscopy, developed for stone conservation applications, do have potential in the natural environment.)

Working with cultural stone has stimulated many of our thoughts concerning weathering processes in both the human and natural contexts. Yet, in terms of weathering rates, cultural stone has only a minimal connection to geomorphology in natural settings, although geomorphologists (present authors included) go about citing works in cultural stone to support their data in the natural environment. Cultural stone provides some of the best data on weathering geography, processes, and rates. These data show that weathering is dominated by microscale factors and that weathering rates are probably episodic and nonlinear, responding to thresholds. However, like any laboratory-derived information, data from the realm of cultural stones should be taken with appropriate caution.

On the other hand, our studies are certainly applicable to stone conservation. As demonstrated in this paper, a number of geomorphologists are doing valuable work in stone conservation. Yet each of us can recount instances where the traditional experts in stone conservation—art historians, architectural engineers, archaeologists—are surprised to find that geomorphologists like ourselves are also active. A case in point is the poor representation of geomorphic work on cultural stone (outside the standard stone conser-

vation literature) in Price (1996). Ironically, The Getty Conservation Institute, which publishes this and other texts in stone conservation, employs several researchers active in geomorphic research. Geomorphologists need to communicate their work to these venues outside our discipline, and the traditional stone conservation community needs to become more aware of the geomorphic literature. The interdisciplinary network (Fig. 1) is not fully realized and should be better connected.

What can geomorphologists recommend for stone conservators? First, everything weathers and erodes and will eventually disappear. Geomorphologists more than anyone should know this. To some geomorphologists, the act of “conserving” may seem to be an ill-advised attempt at arresting nature. It is as if we wish to arbitrarily freeze a snapshot of the building or monument in question at a point in its ruination. This notion was recognized in nineteenth century European landscape architecture when “ruins”—real or created—were incorporated into the designs of gardens and courtyards. Urbani (1996) conveys that there is aesthetic and historic value in being “ruined.” Geomorphic processes are integral in the creation of the “ruined” aesthetic. Geomorphologist Emery’s (1960) last statement on the weathering of the Great Pyramid of Giza was that the ancient structure should “remain as the last of the seven ancient wonders of the world for 100,000 years to come.” He did not remark, although we can speculate, on whether it would be recognized as a pyramid during this protracted time!

Second, weathering is not necessarily an act of destruction (at least in some stages). Weathering crusts, case hardening, and even biotic colonies act to bind and indurate surfaces. Cleaning and resurfacing can destroy this natural protection. Still, this recommendation comes with a significant caveat—indurated crusts eventually spall off. This may not occur, however, in the anticipated lifetime of the stone as a cultural object.

Third, applications to the stone (binders, sealants, biocides, repellants, etc.) have unknown long-term effects on weathering processes. We have witnessed the disastrous consequences of inappropriate conservation efforts from the past. Cleopatra’s Needle, the Egyptian obelisk in New York City, was once treated with wax to seal it from the elements, but this also sealed in saline moisture. This treatment exacerbated

an already deleterious action of moving the monument from an arid to a humid environment (Winkler, 1978). Binders derived from mortars or cements may exert new pressure on masonry when they solidify or crystallize, such that the substances used to repair the stone end up actually causing greater destruction. Modern application methods are much improved from the experimental steps of the past, but little accumulated evidence is available on how these newer conservation efforts will withstand time and how they will impact natural weathering and erosion processes. Price (1996) points out that we know little about the microscale structure and interactive effects of sealants and binders on rock. Geomorphologists can lend their expertise in this research (Young and Urquhart, 1998; Young et al., 2000).

Fourth, there is a growing trend in the application of “artificial weathering” substances to mask fresh, cleaned, or repaired surfaces (Elvidge and Moore, 1980; Griswold, 1999). Artificial weathering applications may simply color the stone or may actually accelerate the growth of microbial rock varnish. Some may also act to bind or protect the stone to some extent. Artificial weathering applications go beyond the “antiquing” of architectural stone. Artificial varnishes have been used on road cuts to dampen the harsh appearance of excavated rock and on rock art panels to repair vandalism. Geomorphologists are well acquainted with what makes rock surfaces appear weathered. Geomorphologists today play a role in developing and applying these substances (Dorn, 1998) and should continue to do so in this evolving field.

Fifth, the best recommendation for slowing the rates of deterioration is to limit human contact. This goes for tourists—touching, vibrating, evapotranspiring, breathing—as well as scholars, doing the same but also prodding, measuring, and conserving. All of our research points to human impact as the greatest cause of stone deterioration. Appreciation of our cultural treasures, scientifically and aesthetically, unfortunately contributes to the human impact on stone. Geomorphologists can lend their comprehension of interacting physical, biological, and human processes toward the study of cultural stone while adopting the “don’t touch” attitude of the art conservators.

These views may tend toward the extreme and are brought forth mainly as food for thought. In any case, weathering geomorphologists have an incredible

opportunity to participate in a most public venture, that of cultural resource management. Not only contributing to the applied and the theoretical, we also have a forum to educate conservators and the cultural heritage-craving public. This must be one of the most satisfying applications of geomorphology in the public eye.

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