Suggested citation format:

Taylor, Paul Michael, and Trevor Merrion

2012. A Survey of the Rock Substrates of Petroglyphs at Gobustan, Azerbaijan. (Online report:“Gobustan Rock Survey.” Presented in partial fulfillment of Smithsonian-BP Grant Agreement for: Provision of the Cultural Heritage Public Outreach and Capacity Building Programme in the AGT Pipeline Corridor Regions.) Published within "Online Resources," in: Taylor, Paul Michael, Christopher R. Polglase, Najaf Museyibli, Jared M. Koller, and Troy A. Johnson. *AGT - Ancient Heritage in the BTC-SCP Pipelines Corridor: Azerbaijan – Georgia – Turkey*. Washington, D.C: Smithsonian Institution.

http://www.agt.si.edu/uncover_more/GobustanPetroglyphSurveyOnlineD1.pdf

Online report:

“Gobustan Rock Survey”

Presented in partial fulfillment of

Smithsonian-BP Grant Agreement for: Provision of the Cultural Heritage Public Outreach and Capacity Building Programme in the AGT Pipeline Corridor Regions.

(Grant number: G-08-BPCS-151448)

“A Survey of the Rock Substrates of Petroglyphs at Gobustan, Azerbaijan”

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February, 2012

ABSTRACT

The Gobustan Rock Art Reserve is a significant cultural heritage landmark for both Azerbaijan and the world. It is one of the largest repositories of petroglyphs on Earth. Consequently, the preservation of rock art is a primary objective for government institutions and scholarly organizations affiliated with Gobustan. Considering the reserve's location in a coastal, semi-arid desert, the effects of wind erosion, salt-decay, biodeterioration, and tourism will be addressed as the most significant challenges to sustainable preservation of the rock art. Strategies available to mitigate the various erosive processes will be discussed, particularly innovations in biocide and biomineralization techniques. Finally, three-dimensional image cataloguing and archaeological survey mapping are recommended for both the enhancement of scholarship in the region and as a preventive measure against the consequences of further deterioration.

INTRODUCTION TO THE RESERVE

History & Cultural Significance

The Gobustan Rock Art Reserve was discovered during a mining expedition in 1939-1940 and recognized as a UNESCO World Heritage site in 2007. Beginning with I.M. Djafarsade's excavations in the 1940s, archaeologists have presently discovered over 6,000 carvings dating from the Paleolithic Era to the Middle Ages. For archaeologists tracing the history of cultural development, this record is of vital importance to understanding the cultures that existed in prehistoric Europe and Asia. Emmanuel Anati, Italian archaeologist and founder of the Centro Camuno di Studi Preistorici, also worked at Gobustan, and his view of the importance of rock art to anthropological studies:

> Consciously or unconsciously, directly or indirectly, rock art illustrates the human effort to survive: it reveals work patterns, economic activities, social practices, aesthetic tendencies, philosophies, and relations with the natural and 'supernatural' environments. In all these regards, it is much like every other art form since art is, collectively, humanity's means of articulating the world and or response to it. (Anati 1983, 30)

Archaeologists today are undertaking the task of interpreting the ancient knowledge stored in the petroglyphs our ancestors left behind, though their important efforts are compromised if petroglyph records like those of Gobustan become significantly deteriorated. Therefore, the primary value of Gobustan as a cultural landmark is only sustained if measures are taken to ensure that the petroglyphs in the reserve remain intact and legible for years to come. As a contribution to that on-going effort, this report surveys some of the relevant literature on Gobustan and on the rock substrates of the petroglyph sites there, and reports on summary chemical analyses of selected samples of the rock substrate.

Geography and Geology

The Gobustan Reserve is located approximately fifty-four kilometers south-west of Azerbaijan's capital city, Baku. This semi-arid desert region is hemmed in between the Caspian Sea and the southern Caucasus Mountains. Petroglyphs in this region are primarily located on the Beyukdash, Kichikdash, and Jingirdag and Yazly-Tepe mountains. Within these mountains are several natural and man-made caves which at one time provided refuge to the region's inhabitants and which now house an array of petroglyphs.

Gobustan has experienced several climate shifts over the millennia and now has a semi-arid desert climate. The BP report on Gobustan mentions no specific relative humidity level for the area, though it speculates the RH level to be around 70%. It is clear that this region was once more hospitable to vegetation due to the palynological analysis of fossilized pollen, which shows amongst other vegetation the existence of oak and pine trees (Farajova 2009, 111). However today, Gobustan is undergoing the effects of desertification and has been identified by the United Nations Convention to Combat Desertification (UNCCD) as a region requiring the implementation of protective measures to ensure the preservation of plant species ("Rare vegetation monitoring in the Azerbaijan Republic," www.unccd.int). With little cover from vegetation, rock surfaces are more susceptible to erosion from wind particles. While at the same time, there is adequate moisture in the air and ground for processes such as salt decay and biodeterioration, significantly dependent upon water transport onto and throughout stone surfaces, to occur.

Throughout the Quaternary Period, seismic and volcanic activity made drastic changes to the landscape of Gobustan. During the Pleistocene era, orogenesis, the geological process primarily responsible for the development of mountains, was occurring in conjunction with the rising and falling of ocean levels, causing the present-day Beyukdash, Kichikdash, and Jingirdag Mountains to be inundated with diatomic marine organisms from the Khalvin Sea (Farajova 2009, 109). It may be speculated that the diatomaceous and calcareous rocks in the region of Gobustan are the result of this period of inundation due to the derivation of these rock types from marine sediment. Diatomaceous earth is primarily composed of deposits of fossilized diatoms, one-celled marine organisms with hard shells, while calcareous rocks are primarily formed from marine shells and the carbonate that is precipitated from marine organisms. Centuries after the water has receded from Gobustan, the composition of rock substrates in the region remains as evidence of these periods of inundation. Measuring the stratification of diatomaceous and calcareous sediments allows scientists to trace the sea transgressions during the Holocene and Pleistocene epochs and may enhance rock art dating (Farajova 2009, 109-111).

After centuries of glaciations and weathering, the geological features at Gobustan have transformed into what may be described as “wave cut limestone terraces” (Gallagher 2007, 2). Environmental and geological processes have also left the plateaus of Gobustan littered with karsts and open-air caves. Emmanuel Anati describes the formation of these caves,

> "The sites are located on flat hills, like mesa, the slopes of which are covered by large calcareous blocks which were detached from the upper levels when the lower softer levels eroded. This process formed chaotic heaps, caves and shelters, mostly reached by sun light, where the numerous remains of material culture reveal that clans found refuge here." (Anati 2001, 21)

The Ana Zaga Cave in Beyukdash is a prime example of this feature at the reserve. While landslides commonly occur from the erosion of soft, primarily-clay rock foundations (Birot 1968), it is also reasonable to assume that seismic activity expedited this process.

The high density of mud volcanoes within the fields of Gobustan is evidence of the tectonic activity that is present in the region to this day. Due to its position along a fault line, the monuments at Gobustan will always be vulnerable to destruction from volcanic or seismic activity. Though these natural phenomenons cannot be protected against, there are several processes that cause a more subtle destruction of stone monuments which can be mitigated. These processes and potential protective measures will be addressed in the following sections.

POTENTIAL THREATS TO PRESERVATION

There are several processes, mechanical, biological, human and natural, which present challenges to preservation efforts at the Gobustan Reserve. The rock faces upon which the carvings are preserved are especially susceptible to mechanical and microbial deterioration due to the calcareous and diatomaceous composition of the stone. Due to its high altitude and proximity to the sea, the open-air monuments at Gobustan are exposed to high winds and will gradually deteriorate through abrasion and deflation. Gobustan's proximity to a marine environment also suggests deterioration is occurring through salt-crystallization, a common erosive process affecting stone substrates in areas where marine aerosols are present. Additionally, the likelihood of deterioration resulting from microbiological growth is increased by the calcareous composition of rocks at Gobustan, the presence of marine aerosols, and the potential for photosynthesis on the hypogeal surfaces of open-air caves. Beyond these natural erosive processes, human activity and insufficient management of the rock art sites is liable to compromise any preservation efforts at Gobustan.

Rock Composition

Due to its soft composition and highly porous substrate, diatomaceous earth and calcareous stone are particularly susceptible to erosion caused by wind, salt decay and human activity. Calcareous rocks are also vulnerable due to a considerably high bioreceptivity, which increases the likelihood that the substrate will host deteriorative microbiological growth (May et al. 2003, Tretiach 2007). Furthermore, calcium carbonate, which is the primary component in calcareous rock, readily dissolves in the presence of acidic substances (Tretiach 2007, 45). As the metabolic processes of most bacteria produce acidic precipitates, calcareous rock surfaces and substrates are especially prone to the effects of biodeterioration. The BP report on Climate and Soil in the Absheron Peninsula and Gobustan describes a high alkaline content in the calcareous rock of the region (BP Report on Climate and Soil 2002). This may facilitate the catalysis of certain metabolic processes and exacerbate biodeteriorative effects.

Wind

Wind erosion poses a significant natural, mechanical threat to preservation efforts in Gobustan. This form of erosion, also referred to as Aeolian processes, is most common in arid to semi-arid climates where there is little to no vegetative growth (Dott 2003). Wind currents cause erosion primarily through deflation and abrasion, leaving grooves, etchings, potholes, and staining upon the rocks. In the case of deflation, dust particles are gradually transported from a rock surface and deposited in another location. Sand dunes serve as an indicator of when deflation is occurring (USGS Publications Warehouse 1997). The dunes are formed by the accumulation of sand that is eroded from nearby bedrock. Abrasion occurs when dust particles suspended in a wind current grind into a rock formation, gradually grooving etches and polishing layers of the rock surface. Desert varnish and ventifacts are both evidence of the effects of wind abrasion (Powers 1936).

Located at high altitudes along the coast, the Gobustan Reserve is in a geographic location prone to enduring high winds. Warm fronts from the Caspian Sea and Kur Steppes often collide with cold fronts from the northeast and northwest, causing intense air currents (Farajova 2009, 108). The BP report on the BTC Pipeline from December 2002 states that the region where Gobustan is located experiences over 100 days a year in which the wind blows faster than 15 meters per second (BP Report on Climate and Meteorology 2002).

Due to the semi-arid climate, the landscape has limited vegetation and is comprised mostly of loose dust particles. The sand dunes that line the Caspian Sea just east of Gobustan are evidence of the deflation that is occurring in the region. As Farajova describes the influence of wind on the geological features of the area,

> “Folded mountainous structure of the surface is very well seen in the western part of the peninsula, in the eastern part mountains are cut off with abrasion and blocked with its deposits. Here, plain relief was formed. This whole area is covered with ancient Caspian and contemporary deposits. To the extreme eastern zone of this lowland directly adjoining the shore of the Caspian Sea sand dunes are characteristic, which run almost continuously along the shore of the Caspian Sea up to Absheron peninsula.” (Farajova 2009, 108-109)

The location and shape of sand dunes in the region serve as an indication that particles are being transported primarily by westerly winds. Therefore, petroglyphs facing the east which are shielded from this westerly flow of deflation will sustain less erosion than petroglyphs on surfaces exposed to the west.

The result of centuries of wind abrasion, erosion caused by the persistent impact of loose particles suspended in wind currents, is the deformation of rock surfaces and a discoloration known as rock varnish, or desert varnish. This dark brown to black coating, which is usually 10-200 microns thick, is due primarily to the presence of iron and manganese oxides and other clay minerals (Dietzel et al. 2008). Abrasion over thousands of years leads to the accretion of loose mineral particles on the rock surface and a varnish is formed (Elvidge & Moore 1980). While desert varnish threatens to damage petroglyphs through discoloration, it is important to note that varnish was the medium for many petroglyphs in the first place (Allen 1978, 744). An image could be rendered by exposing the lighter colored substrate in contrast to the darker surficial varnish. Today, petroglyphs can be dated by measuring the number of varnish layers present on a carving relative to the surrounding rock surface (Dietzel et al. 2008). Also, though desert varnish has typically been associated with wind abrasion, a recent study by Dietzel et al. suggests this phenomenon is more attributable to microbial growth on the rock surface (Ibid).

Salt Weathering

Salt weathering is another mechanical process commonly recognized by scientists as a cause of erosion in desert and coastal regions (Chapman 1980, Goudie et al. 1997, Fahey 1986, Young 1987, Rodriguez-Navarro & Doehne 1999). Due to its semi-arid climate and location approximately 7-8 kilometers from the Caspian Sea, salt weathering is undoubtedly affecting the geological features of Gobustan. The effect is most evident in the dramatic honeycomb weathering, also referred to as tafoni, present at the reserve. There are several mechanisms by which various salts contribute to the decay of rock surfaces and substrates, as well as several indicators that these processes are occurring. Factors relevant to salt decay such as supersaturation, salt type, and stone porosity will be discussed.

The presence of salts at Gobustan is the result of several environmental processes including transport within fog and mist, redistribution by wind deflation from coastal sabkhas, and seepage from underground stream flows, which enter the substrate through a process known as the “wick effect” (Goudie 1986; Goudie et al. 1997, 588). The salt present in all of these processes is ultimately derived from the Caspian Sea. Due to the significant influence proximity to a marine body of water has on the distribution of salt in an environment, the presence of salt decreases rapidly as distance from the coast increases (Young 1987, 964). Chapman believes the effects of salt weathering in deserts have not been adequately recognized because they are often incorrectly attributed to other mechanical processes such as wind erosion (Chapman 1980, 127). He outlines the indicators of salt weathering as follows:

> (1) soft, spongy surfaces covered with fine granules and thin exfoliation scales; (2) a zone of very intense weathering at the base of many cliffs and pedestal rocks; (3) readily detectable salt crystals in pores and in small veins on the rock surface; (4) fine-grained weathering detritus (rock meal) at the foot of steep cliffs; and (5) within rock hollows and caves, weathering characteristics similar to those but less intense. (Chapman 1980, 116)

However, it is important to note that some of these indicators may result from wind erosion as well. Due to the fact that salts may be transported onto rock surfaces by wind currents, and that the erosive effects of Aeolian processes and salt weathering are occurring often simultaneously, it is difficult to determine the extent to which deterioration may be attributed to one process or the other.

The most common mechanisms by which salt weathering is believed to occur includes salt crystallization, salt hydration, and thermal expansion, though many scientists consider salt crystallization the only mechanism that causes significant deterioration (Goudie et al. 1997, Fahey 1986, McGreevy & Smith 1982). Therefore, salt crystallization will be the primary focus regarding the impact of salt weathering at Gobustan.

The processes by which salts crystallize are different for each salt compound; however, it is always the result of a saline solution reaching a level of supersaturation (Rodriguez-Navarro & Doehne 1999). As evaporation reduces the amount of water in a saline solution, the excess salt in the solution crystallizes. This partially explains why salt weathering is more typical in desert climates, where lower relative humidity levels translate to faster evaporation rates (Ibid).

While the deleterious effects of salt crystallization are acknowledged by experts in the field, there is debate concerning why exactly this deterioration occurs. The traditional opinion is that salt crystallization causes ruptures within a stone, leading to flaking of the rock surface (Fahey 1986, 110; McGreevy & Smith 1982, 167). According to this model, salt penetrates the pores of a stone while in an aqueous state. As the stone dries, the salt crystallizes, expands, and ruptures the stone. However, Young argues that deterioration is not directly caused by the presence of soluble salts that cause physical ruptures as they crystallize. Rather, salt crystallization merely increases a stone's porosity and therefore facilitates the normal processes of granular disintegration, whereby substrates with greater porosity erode at a faster rate (Young 1987, 966).

According to Rodriguez-Navarro and Doehne's study, "Salt Weathering: Influence of Evaporation Rate, Supersaturation, and Crystallization Pattern," which compared the crystallization mechanisms of sodium chloride and sodium sulphate, the means by which salt-crystallization causes erosion is largely determined by salt type (Rodriguez-Navarro & Doehne 1999). The crystallized form of sodium chloride, halite, appeared at lower supersaturation levels then mirabilite or thenardite, crystallized forms of sodium sulphate. The differential in crystallization pattern and growth kinetics between the two salts creates a situation where "mirabilite and thenardite tend to precipitate inside the solution creating subflorescence within the pores of the stone, while halite tends to precipitate at the air-solution interface, preferentially creating harmless efflorescence growing on the stone surface." (Ibid, 203). Efflorescence refers to crystallization that occurs on the surface of a stone while the more deleterious subflorescence refers to crystallization that occurs within the substrate. Assessing the degree of salt decay at Gobustan will require determining to what extent each of these crystallization processes are occurring. Rodriguez-Navarro & Doehne's study suggests that this assessment would be facilitated by analysis of the salts present and the manner in which they react with the specific climate and geology at Gobustan.

The most dramatic evidence of salt weathering in Gobustan is the presence of tafoni, or "honeycomb weathering," at several cave sites. Several geologists attribute the deep rock pitting recognized as tafoni to pressure exerted on rock pores through the mechanical processes of salt crystallization (McGreevy & Smith 1982; Rodriguez-Navarro & Doehne 1999). McGreevy & Smith reference several studies that suggest this phenomenon is the result of increased relative humidity at ground level (McGreevy & Smith 1982, 164). This would complement an explanation of why tafoni are usually present within and near caves, where microclimates have approximately 100% relative humidity except near openings (Cigna 2004). Caves in Gobustan, which are often described as "open-air," nonetheless have evidence of tafoni development. Young challenges the notion that pressure exerted from salt-crystalization causes that pitting that characterizes tafoni, claiming that scanning electron microscopy shows no evidence that "salt crystals infill pore spaces and exert pressure on the surrounding grains," including photomicrographs from a study conducted by McGreevy in 1985 (Young 1987, 963). In their defense, McGreevy & Smith do acknowledge the importance of chemical weathering in conjunction with the mechanical processes of salt-crystallization. Recognizing the importance of biological desert varnish to tafoni development he states, "it is recognized that incipient hollows can develop behind indurated surface veneers. Once the surface is breached the chemically weakened subsurface material is fairly rapidly exploited by weathering processes including salt crystallization. (McGreevy & Smith 1982, 167).

The diversity of explanations for the mechanics and effects of salt-crystallization indicates that this is a complex weathering process. While the process can be conveniently isolated in the laboratory, any explanation is complicated by the reality that several weathering processes are in effect at any given time. To understand how geological features *in situ* develop it is important to assess all of these processes from a holistic perspective. Studies concerning the mechanisms of wind erosion and salt decay have been enhanced in collaboration with recent geological research concerning microbial growth and an erosive process known as biodeterioration.

Microbes

While most are familiar with the mechanical processes of erosion from the natural elements, such as wind erosion and salt crystallization, scientists are just beginning to grasp the effect of biodeterioration on monuments and archaeological structures (Warscheid 2003). Though many more studies are necessary to fully understand the causes and effects of biodeterioration, scientific research suggests that microbial communities are having a significant impact on stone structures around the world and are likely contributing to the destruction of petroglyphs in Gobustan. Ehrlich enumerates the pathways by which microbes may exploit the process of mineral dissolution and formation for their survival,

> "Some microbes are able to dissolve a mineral by using it: (1) as a source of energy, (2) as a terminal electron acceptor in respiration, (3) as a trace element requirement, or (4) to enhance competiveness in a microbial community. Some others form minerals: (1) in the oxidation or reduction of a dissolved inorganic species in energy metabolism; (2) in the detoxification of poisonous inorganic species; (3) in active or passive uptake of one or more dissolved inorganic species followed by conversion into a cellular support or protective structure; and (4) in enhancing their competitiveness in a microbial community." (Ehrlich 1996, 5)

These different pathways refer to various metabolic processes that typically result in the secretion of acid on the rock surface and within the substrate. Furthermore, this acid is often contained on and within the surface by the biofilm created from the growth of microbial communities. The residual acid and biofilm may cause erosion through exfoliation, whereby the rock surface begins to flake or crack (Ortega-Morales et al. 2005).

Relatively little is certain about this bio-geological process and the severity of biodeterioration varies from case to case. In assessing what is known, archaeologists recognize that each microbial community impacts stone differently based on parameters related to the variability of environment, rock surface, degree of penetration into the rock substrate and microbe type (McNamara et al. 2003, Warscheid 2003). Blázquez et al. distinguish five zones between the external surface of a stone and the unaltered substrata that can be referred to when measuring penetration. These zones include the lichen thallus, the microcorrosion surface, the altered zone, the transition zone and the unaltered substratum (Blázquez et al. 1995). Biological mechanisms determine how aggressively microbes penetrate a stone and ultimately the extent of biodeteriorative effects. Strongly aggressive deterioration is caused by biogenic mineral or organic acids. Mildly aggressive deterioration results from the ability of hydrophilic slimes such as heteropolysaccharides or biofilms to accumulate water and salts. However, exoenzymes are strictly surficial and contribute insignificantly to biodeterioration (Sand & Bock 1991).

Though many studies have been conducted, it must be reiterated that scientists are just beginning to understand the extent in which microbes are destructive to monuments and historical structures. It is necessary to evaluate the variables influencing biodeterioration, particularly environment, surface composition, and microbial presence, before assessing the extent of biodeterioration at Gobustan. It may only be speculated at this time that aspects of biodeterioration addressed in recent studies may be relevant to the Gobustan Reserve. Some of these aspects include the extensive presence of calcareous stone, the effluence of marine aerosols due to Gobustan's proximity to the Caspian Sea and the potential for photosynthesis on the hypogeal surfaces found in open-air caves, where many of the petroglyphs are carved.

C. McNamara, who conducted field studies on the presence of microbial communities in southern Mexico, found evidence of biodeterioration on ancient Mayan archaeological buildings. Microbial communities had caused surface discoloration and deterioration on the monuments and made them more susceptible to the effects of mechanical erosion. While the climate of southern Mexico is significantly more humid than the climate of the Absheron Peninsula in Azerbaijan, McNamara notes, "a diverse microbial community is normally found on historic limestone, and may contribute significantly to deterioration of the stone" (McNamara 2003, 249). As previously mentioned, due to the high bioreceptivity of calcareous stone and the tendency for calcium carbonate to dissolve in the presence of acidic compounds, it is likely that the geological features at Gobustan are vulnerable to biodeterioration.

Due to the presence of marine aerosols at Gobustan, it is worth considering the interaction between salt-crystallization and microbial growth. In their report, "Consequences of Microbe-Biofilm-Salt Interactions for Stone Integrity in Monuments," E. May et al. detail the deteriorative effects of salt and the ways these effects are enhanced by biofilm growth. The study discovered a correlation between material loss and an increase in microbial growth when experimenting with the mechanics of salt-decay (May et al. 2003, 467). Furthermore, salt seemed to foster the development of biofilms, which imposed their own mechanical stress upon the rock surface by shrinking and swelling within the stone's pores (Ibid. 467). It remains undetermined whether biofilms directly exacerbate the erosive effects of salt-crystallization or if they deteriorate the stone through an individual process that functions synergistically with salt-crystallization. Either way, the study concluded that deterioration was greater when microbial populations were present.

The climate of Gobustan is defined as semi-arid with low relative humidity, suggesting rock surfaces in the reserve should not be ideal for microbial growth. However, many petroglyph sites are located within open-air caves which may support a more hospitable microclimate. The hypogeal environment of the cave provides the moisture to allow for bacterial growth, as exposure to the sun provides the means for the photosynthesis that facilitates this growth. While it is purely speculative at the moment that the climates in the caves of Gobustan are hypogeal in nature and optimal for microbial life, the likelihood warrants recognition of the positive correalation between hypogeal environments, microbial growth, and biodeterioration.

The caves of Gobustan are particularly sensitive for preservation purposes because they were once the refuge for inhabitants of the region, therefore they contain a majority of the petroglyphs in the reserve.

Initial microbial growth in the open-air caves of Gobustan was likely the development of autotrophic populations that could acquire energy through photosynthesis. To understand the ecological process by which microbial growth then progressed, it is important to understand the role of the pioneer microorganism. These autotrophic microbes develop within a niche environment and make the habitat more hospitable for other forms of life. As J. Karbowska-Berent describes, “The pioneer species effect these changes through their development, i.e., the secretion of metabolites, slimes, the decomposition of particular components, and hindering water evaporation” (Karbowska-Berent 2003, 268) The pioneer microorganisms are the initial producer in a micro food cycle and provide energy for heterotrophic bacteria to thrive on. Autotrophic and heterotrophic bacteria, as well as algae and fungi, develop according to tendency to coexist symbiotically. Decomposing autotrophs provide the organic matter for the metabolic processes of heterotrophs, an ecological chain that is started by the appearance of pioneer microorganisms. P. Albertano describes this cyclical process and its implications for biodeterioration, “the photosynthetic activity that sustains the production of new biomass in to the ecosystem support the development of numerous populations of heterotrophic bacteria and fungi that graze on cyanobacterial and algal exopolysaccharides, metabolites, and cell debris, thereby increasing the deterioration of stone by synergistic action” (Albertano 2009, 309). The availability of light in the caves of Gobustan and the ability for cyanobacteria to survive in even the most extreme environments encourages the development of autotrophic microbial populations (Wynn-Williams 2002). Subsequently, the presence of these decomposing autotrophs in the moisture-rich microclimate of a cave creates ideal conditions for extensive microbial growth.

Scientists have recognized certain cyanobacteria strains that are particularly detrimental to calcareous surfaces. P. Albertano has studied various cyanobacteria biofilms on hypogeal surfaces and determined that the metabolic functioning of the cyanobacteria *Syctonema julianum* and *Loriella osteophila* makes these strains especially damaging to calcareous surfaces. This process utilizes "their ability to precipitate carbonate crystals on their polysaccharide sheath and, therefore, to mobilize calcium from calcareous surfaces" (Albertano 2009, 312). These bacterial strains, in essence, deteriorate the calcareous surface by disrupting its molecular structure. Other bacteria types have also proven deleterious to stone through different mechanics. Actinomycetes' mycelial growth pattern effectively penetrates the stone surface upon which it grows, leading to fissures in the stone. This is especially critical if the stone is friable, such as diatomaceous rock. This process of erosion is markedly different from that caused by *Syctonema julianum* and *Loriella osteophila* and is due to the actinomycetes "ability to excrete a wide range of enzymes." (May et al. 2003; citing McCarthy and Williams 1992, and Williams 1985.)

At this time, it is not possible to speculate which strains of bacteria grow on the surfaces of the Gobustan monuments. Many strains have little to no effect on the constitution of the rock, while others can be quite damaging. Therefore, it is necessary that further testing be conducted to determine which bacterial strains are present and how they interact with the stone. Simply identifying bacterial strains is insufficient due to microorganisms' ability to morph and adapt in different environmental situations. For example, in a study on microbial growth in the Mayan pyramid Ek Balam in southern Mexico, bacteria strains on the walls of the ruins were isolated and tested for their ability to dissolve calcium carbonate. Over 5% of isolates cultured proved capable of calcareous dissolution including *Salmonella bongori, Staphyloccocus sciuri, Intrasporangium calvum,* and an organism from the *Acinetobacter baumanii* subgroup of the γ-proteobacteria. However, the authors of the study noted that "because the phenotype of microorganisms may change in response to environmental conditions, simple identification of the organisms may supply minimal information about detrimental effects on the stone" (McNamara et al. 2003, 261). Understanding the mechanics by which a microorganism operates in relation to a rock substrate is as essential as identification of the microorganism. The details of tests suitable for this research objective will be discussed in the "Testing and Analysis" section of this report.

Tourism

As long as the Gobustan Reserve remains a cultural destination for Azerbaijanis and foreign tourists, human activity will pose a threat to the preservation of the petroglyphs. Damage from activities can range from the insignificant, such as the increased presence of dust particles from pedestrian traffic, to the more invasive, such as visitors climbing on rock faces, contamination from skin oils and deliberate vandalism. Any human presence will introduce unnatural stress upon monuments and historical structures; however, awareness of a heritage site can also cultivate interest in a site and stimulate fundraising for its protection. The declaration of the Gobustan Reserve as a UNESCO World Heritage Site in 2007 will ensure greater efforts are taken to preserve the site. However, global recognition of the value of Gobustan also means there is a likelihood of increased tourism to the area that will require more substantial conservation efforts to be established. This section will speculate on inadequacies in the current management plan for the Gobustan Reserve. A subsequent section in "Methods of Preservation" will offer guidelines for enhancing management strategies at the site.

The most egregious damage caused by tourists at Gobustan results from the practice of filling the petroglyphs with toothpaste to enhance their visibility for pictures (Arnold 2001). Numerous travel sites and blogs make reference to this phenomenon. Some sites even recommend the practice, such as a site sponsored by the Australian Centre for International Agricultural Research (ACIAR) titled "Plants Genetic Resources in Central Asia and Caucasus." On their section concerning Gobustan they advise, "Should you want to get the perfect photos as seen on the postcards, the trick is simple: fill the carvings with toothpaste" (PGR 2003). Travel writer Nicholas Griffin even claims Thor Heyerdahl, the Scandinavian archaeologist who famously studied the petroglyphs of Gobustan, was responsible for some of the toothpaste applications (Griffin 2001, 17), though the verity of this fact is difficult to determine. Toothpaste introduces chemicals to the rock surface and substrate that will lead to rapid corrosion of the petroglyphs.

Though a heritage site's appeal to tourists may be compromised by excessive restrictions limiting the public's ability to enjoy the petroglyphs, reactions to the informality of operations at Gobustan suggest the need for more stringent maintenance. A contributor to *The Independent* reacts to her visit to Gobustan,

> "Any more visitors and the place will soon be destroyed. Compared to the cave in Lascaux where visitors have to wear masks to protect the carvings from their

breath, the Gobustan petroglyths are pitifully neglected; our taxi, disgorging black fumes from its exhaust, parked right next to a boulder bearing a depiction of 10,000 year-old warriors brandishing spears" (Arnold 2001).

Furthermore, erosion of petroglyphs can be accelerated if guests are able to touch or walk upon the rock faces. Oils from human skin make rock faces more habitable for microbes while the pressure and wear from guests walking along petroglyphs can lead to premature exfoliation.

Both the Azerbaijani government and UNESCO have recognized Gobustan's importance as a heritage site and have taken measures to ensure its protection. According to the International Council on Monuments and Sites report following the 2007 induction to UNESCO's World Heritage Site list, "the legal protective measures for the property are adequate. There is a need to complete the documentation, put in place active conservation measures and improve the technical competence of staff to carry out necessary urgent conservation work" (ICOMOS 2008). Methods by which the management staff of the Gobustan Reserve may better implement preservation strategies will be addressed later in this report.

SAMPLING AND CHEMICAL ANALYSIS OF PETROGLYPH SUBSTRATES

For this report, after an initial survey of literature on the topic had been completed, the staff of Gobustan Reserve obtained permission from Azerbaijan's Ministry of Culture to take six samples from selected sites throughout Gobustan, for chemical analysis.

5 samples (9 items) were collected by staff of the Gobustan Reserve in the vicinity of petroglyphs, from five different locations, in October 2010, and were sent to the Smithsonian. The samples, numbered T-1 through T-5, are from the following localities:

T-1 Kaniza Mountain, height 395m, shell.

T-2 Boyukdash Mountain, The Bull's Den, 2 rocks

T-3 Boyukdash Mountain, The Hunters Den, 2 rocks

T-4 Kaniza Mountain, height 391m, 2 rocks

T-5 Kichikdash Mountain' foot, depth 2m 75 cm, 2 shells

As seen from the above list, the rocks were from three localities. The purpose of the samples was to identify the rock type and basic chemical composition.

A photo of the five samples, as they were originally received, appears below:

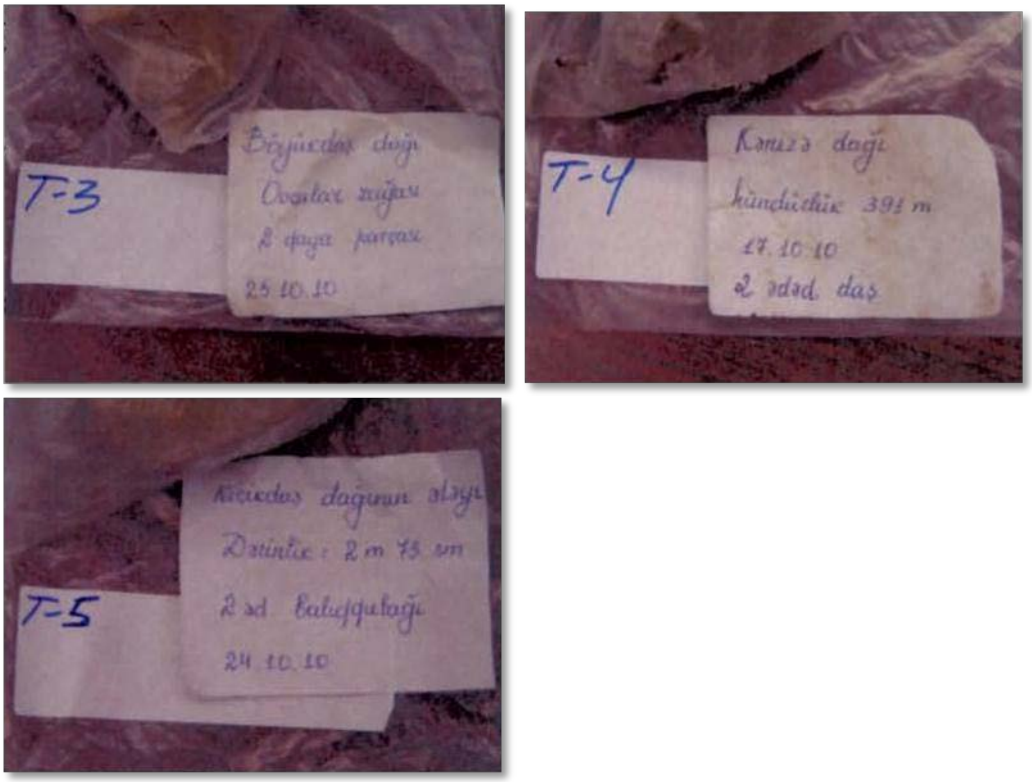

Figure 1. Five samples of Gobustan rock for chemical analysis, as received.

A summary of observations and testing of the rock samples received follows.

Dilute hydrochloric acid (10%) was used to evaluate the carbonate content of the materials from Gobustan National Park in Azerbaijan. The presence of CO2 bubbles indicate the presence of Calcium Carbonate as it reacts with the acid. The chemical reaction is the following:

2HCL (liquid) + $CaCO_3$ (solid) -> CO_2 (gas) + $CaCl_2$ + H_2O

T -4 Kaniza Mountain, height 39 1 m, 2 rocks, 17.10.10.

The acid was applied to the cleaned surface with no result. The stone appears to be a high grade metamorphic rock, possibly an amphibole.

Figure 2. T-4 sample after light rinsing with de-ionized water. The HCL drop produced no bubbles.

T -1 Kaniza Mountain, height 395m, shell, 17. 10. 10.

T -2 Boyukdash Mountain, The Bulls Den, 2 rocks, 25.10. 10.

T-3 Boyukdash Mountain, The Hunters Den, 2 rocks, 25.10.10.

T -5 Kichikdash Mountain foot, depth 2m 75m, 2 shells, 24,1 0.1 0.

The other samples—T-1, T-2, T-3, T-5--bubbled vigorously with the application of HCL. The stones had a patina of lichens, though this did not hinder the chemical reaction. These stones are most likely highly carbonaceous rocks such as a high calcium limestone. They also display mili-scale porosity with a course texture. The texture may have been created as the stone formed and water evaporated from its internal structure.

Figure 3. T-3 sample bubbling vigorously.

Figure 4. T-1 sample of a shell bubbling vigorously.

POTENTIAL FOR ADVANCED ANALYTICAL TESTING & ANALYSIS

It is intended that, in the future, more advanced analytical techniques may be applied to the samples collected so far, and hopefully also in the future to an even broader range of samples.

With regard to characteristics of the stone itself, surface hardness and porosity serve as useful indicators of a stone's ability to endure natural and man-made causes of erosion. For instance, the susceptibility of calcareous stone to salt decay and biodeterioration has been attributed to dense porosity that facilitates permeability (Rodriguez-Navarro & Doehne 1999, Chapman 1980). Another factor worth investigating is the effect of salt-crystallization and microbes on rock surfaces and within rock substrates at Gobustan. With the use of scanning electron microscopy and x-ray diffractometry, scientists are able to create extremely-detailed pictographs of crystallization within a stone. The presence of salt alone is not enough to ensure deterioration, but through detailed imaging preservationists may determine if there is evidence of decay and the phases by which decay may have transpired. Advancements in our understanding of biodeterioration and the technology to test for microbial populations allows for investigations previously unexplored by preservationists. It is important that preservationists are able to identify not simply the presence of microbes, but also the type of microbe present and how it interacts with stone, as the deteriorative effect of a microbial population is determined more by the strain of microbe and its mechanics than by the quantity of bacteria, fungi, or algae present.

Micro-computed x-ray tomography (μCT), used extensively by medical doctors for over two decades, is becoming more prevalent in archaeological analysis. The test produces a 3D image of a sample by compiling a series of two-dimensional x-rays in a process known as digital geometry processing. Micro-computed x-ray tomography is ideal for archaeologists because it creates a detailed, 3D image without damaging the sample. Archaeologists studying biodeterioration have used the method to document microbial growth on both the stone surface and substrata, allowing for a thorough analysis of stone composition and deterioration (McNamara et al. 2003). As has been noted above, understanding how microorganisms interact with stone is just as important as identifying which microorganisms are present. Micro-computed x-ray tomography is an especially useful method of analysis because of its ability to produce imaging of both the surface and substrata of a rock.

Acoustic wave velocity tests are also useful for assessing the surface and substrata of a rock. The test captures data for measurements from the transmission velocity of sound that passes through the sample. Material loss, reduced surface hardness, and increased porosity are all factors that can cause a reduction in the transmission velocity (May et al. 2003, 467). Essentially, the more susceptible a stone is to erosion, the more it will impede the transmission of sound. While this test measures many qualities of a sample, including subsurface discontinuities, its results are generally only useful when correlated with other measurements, such as change in stone mass (McNamara et al. 2003).

Nuclear magnetic resonance spectroscopy (NMR) and scanning electron microscopy (SEM) are other tests used to measure the condition of stone on microscopic levels. Better known in medical circles as magnetic resonance imaging, or MRIs, technology that utilizes nuclear magnetic resonance measures the energy that is radiated from an object after it has absorbed energy from an applied magnetic field or electromagnetic pulse. Scanners measure this radiation and in the case of stones, archaeologists are able to measures the changes in pore size distribution within a stone. Scanning electron microscopy is a type of electron microscope which measures a sample's surface using a high energy electron beam. The transmitted beam reacts with atoms on the sample's surface to produce signals that can be used to measure the topography, composition, porosity and other properties of the surface.

The electron beam used in SEM is able to recognize more than just physical characteristics of a rock surface. It is a testing procedure for scientists studying salt-crystallization as it provides detailed imaging of crystal growth (Goudie et al. 1997, Lubelli & von Hees 2007, Rodriguez-Navarro & Doehne 1999, Young 1987). With micro-detailed pictographs scientists are able to determine how salt is interacting with the properties of stone. This process is also capable of measuring the presence and growth of bacteria and biofilm on substrates. In a study conducted by E. May on the effect of interactions between salt crystallization and biofilms, SEM was able to detect the hyphal penetration of the actinomycetes studied (E. May 2009, 468). Due to its ability to determine the positioning and movement of microbial populations, SEM may be useful in analysis of the mechanics of biodeterioration so that the severity of decay may be properly assessed.

X-ray diffraction has proven an effective method of analysis for the study of salt-crystallization on rock surfaces (Goudie et al. 1997). This method was developed for scientific study of crystals and utilizes diffraction to generate a three-dimensional image of the electron density of a crystal. With this information the distribution of atoms and chemical bonds present in a crystal can be determined. This allows for in-depth mineralogical analysis of the interaction between salt-crystals and stone.

Several testing methods exist to measure the qualitative and quantitative characteristics of microbial growth. Single-strand conformation polymorphism provides the "fingerprint" of a microbe population. After extraction of total genomic DNA from a biofilm sample, amplification of the extracted DNA is possible by means of PCR for more in-depth analysis. (Urzí et al. 2003). Culture-based testing, or biomass analysis, is another, more retrograde, method for identifying a microbial community. Results from these tests are unreliable, as it has been recognized that they detect only 1-5% of microbes present, however, this sample may still be sufficient for measuring biodeterioration (McNamara 2003).

Considering the number of samples collected so far and the variety of research tasks for the enhancement of preservation at Gobustan, SEM and X-ray diffraction are the most useful testing methods due to their versatility and quality of analysis, so it is hoped that the Smithsonian will be able in the future to add SEM and X-ray diffraction results for the samples collected from Gobustan.

STRATEGIES FOR PRESERVATION

Due to the variety of erosive processes that threaten the petroglyphs at the Gobustan reserve, including wind erosion, salt-decay, biodeterioration, tectonic activity, and tourism, a comprehensive management strategy will employ several preservation methods. While damage caused by wind erosion is difficult to mitigate, vegetative growth and the use of wind screens are two preservation methods that have proven relatively effective. Remedies to the effects of salt-decay have applied various techniques, but to date nothing has proven reliable. As scientists are learning more about the deteriorative effects of microorganisms on archaeological material, they are concurrently developing more effective preservative techniques against biodeterioration. Biocidal and biomineralisation treatments are both in the experimental stages of use, though studies have shown that each can provide safe and effective means to enhance current preservation measures. The erosive effects caused by human activity are the easiest to control. While the cultural and spiritual significance of Gobustan would make it unreasonable to deny access to the reserve outright, supervision is necessary to ensure that both intentional and unintentional tampering with the petroglyphs does not occur.

The preservationist's main objective should be to limit all deteriorative effects upon a monument; however, ultimately a degree of decay is unavoidable. Even if the damage caused by gradual processes could be nullified, there is still always the possibility that tectonic activity could completely destroy the monuments protected at the Gobustan Reserve. Therefore, as much effort and funding should be directed toward the documentation of known petroglyphs in the area. The technology of 3D imaging today can provide incredibly detailed graphic representations of petroglyphs and other relevant archaeological features. The secondary benefit to preservation through documentation is that a wealth of information would become more accessible to scholars wishing to database and analyze the petroglyphs in Gobustan.

Strategies to Limit Wind Erosion

Due to high winds and frequent dust storms in the Gobustan region, wind erosion contributes significantly to the deterioration of geological features. Aeolian processes of erosion occur through deflation and abrasion. Deflation is typically mitigated through the growth of vegetation (Hofman & Franzen 1997). As the roots of plants take hold, the soil becomes firm and shielded from the wind. Therefore, fewer dust particles are exposed to and transported by wind currents. Though the petroglyphs are not directly affected by deflation, as this process of erosion relates more to soils and sand, they are indirectly affected as an increase in deflation signals an increase in abrasion as loose particles from deflation become suspended in the wind. These suspended particles cause abrasion to occur on the rock surfaces the wind encounters. Hence, improved vegetative growth would not only help reduce deflation, it would also minimize abrasion and its effects.

The only means to effectively stop the effects of abrasion on stone is to shield the stone with wind shields or an ecosphere. Wind shields are intended to keep any wind currents from passing along a rock feature. According to the "Climate and Meteorology Baseline Report" conducted by BP on the BTC pipeline in 2002, the wind on the Absheron Peninsula where Gobustan is located typically blows north, north-westerly, or north-easterly. There is even a word, "Hazri," which refers to this strong northerly wind (BP Report 2002, Climate and Meteorology 13). Therefore, if preservationists were to consider wind shields for the petroglyphs in Gobustan, it would be in their best interest to install the shields to the south of the reserve. However, it must be recognized that wind shields present a considerable visual obstruction which significantly detracts from their value as a preservation strategy.

While erosion through Aeolian processes is certainly occurring at Gobustan, it is important to keep the time scale of its deteriorative effects in perspective. Top-heavy rock formations known as ventifacts, that are the best evidence for the effects and mechanics of wind erosion, take thousands of years to form (Powers 1936). Due to the prolonged nature of erosion from wind and abrasion, there is less urgency to take active preservative measures at this time.

Furthermore, the open-air caves must provide some natural protection from the wind as they have managed to preserve the petroglyphs already for several thousand years.

Strategies to Limit Salt Decay

In reaction to the significant deterioration from salt decay observed at various heritage sites around the world, scientists have been experimenting with methods to mitigate salt growth on rock monuments for several decades. Effective treatment would require limiting the presence of salts and the moisture that facilitates the transportation of salts (Lubelli & Hees 2007, 223). Scientists have experimented with desalination techniques and crystallization inhibitors since consolidants were investigated as early as the 1970s (Berry 1994). Available literature suggests that while these approaches may be sound in theory, they have yet to be proven adequately effective either in the laboratory or *in situ* (Berry 1994, Lubelli & Hees 2007).

Berry tested the ability of several marketed consolidants to limit the absorption of water by various salts. Ideally, consolidants would restrict further transportation of salts within a rock substrate, limiting the ability of salt to develop harmful subfloresence. The results of the experiment indicated that none of the consolidants tested were effective in restricting water absorption and transport (Berry 1994).

Desalination through water treatments is an ineffective strategy as well due to the likelihood of solution-decay. Rodriguez-Navarro & Doehne cite several studies that demonstrate an increase in cracking as a result of the presence of liquid in rock pores. In some cases this pressure was even greater than the pressure created by salt-crystallization (Rodriguez-Navarro & Doehne 1999, 193). Adding moisture to a rock in order to dilute the salts present would only facilitate transportation of the salts deeper into the rock substrate and effect more significant damage. Berry, citing Bradley and Thicket, mentions a compromise wherein a poulticing technique was employed, though acknowledges this practice only desalinized the outer 20 mm of the rock surface and therefore would require continual reapplication (Berry 1994, 30).

Crystallization inhibitors are a recent innovation in the science of building conservation. In theory, crystallization inhibitors would delay nucleation and the growth of crystals so that salt solutions would be more likely to crystallize in the form of efflorescence than the more damaging subflorescence. In Lubelli & Hees study, sodium-ferrocyanide (NaFeC) and diethylene-triaminepentakis methlyphosphonic acid (DTPMP) were tested because they demonstrated effectiveness in recent experiments, including an EU study on salt control (Lubelli & Hees 2007, 225). While NaFeC demonstrated effectiveness in mobilizing sodium chloride to the surface and creating efflorescence in limestone tests, trials for sodium sulphate and sodium chloride on sandstone and brick demonstrated no significant change. The study also determined that crystallization-inhibitors were less effective, and occasionally facilitated decay, when applied after the salt solutions had already absorbed into the rock substrate (Ibid., 233). This is due to the effects of solution-decay referenced in the previous paragraph.

Strategies to Limit Biodeterioration

There are many microorganisms that disintegrate minerals through their metabolic processes. In recent years, scientists have given greater credence to the effect certain bacterial, fungal, and algal growth has on rock substrates and surfaces (Koestler et al., 1985). Determining what microbes grow on and within a monument and how they interact with the mineral substance is an important step heritage site managers can take to prepare an effective preservation strategy. As these interactions are infinitely diverse, no action should be taken until biodeteriorative processes are analyzed and understood. Scientists studying the effects of biodeterioration have also begun experimenting with treatments to stymie these effects. Such techniques include biocide and biomineralisation treatments. The former preserves by deterring microbial growth while the latter preserves by actively regenerating mineral substance to restore the condition of the rock surface and substrate.

Biocides contribute to the preservation of monuments by inhibiting the growth of destructive microbial populations while contributing relatively little corrosive damage to the stone surface. At the stairway structure in the Copán archaeological site in Honduras, archaeologists have employed biocides with tremendous effect. As the archaeologists state,

> Different biocide treatments were applied in the late 1970s, and consolidation and stabilization works were carried out in the 1980s and 90s; a tarp was installed in 1985 over the Stairway for protection from rain. The present investigation shows an almost total death of lichens and a heavy reduction of the biodeterioration phenomena on the stone surfaces of this monument. (Caneva et. al 2005)

There are many biocides available, natural and chemical, water-soluble and water-insoluble, as well as several methods for their application. Biocides may be applied by brushing, paper poultice application, addition to absorbent clays, or application within solvent gels (Nugari and Salvadori 2003, 525) Frequently used organic biocides include organometallic compounds, phenolic compounds and derivatives, quaternary ammonium compounds, nitrogen-containing compounds, and urea derivatives (Ibid, 521). The six most common ingredients in chemical biocides are alkyl amine salts, quaternary ammonium salts, inorganic borate/zinc salts, sodium salt, and sodium hypochlorite (Wakefield 1997). Currently, biocides utilizing either ethanol or metabolites are most common (McNamara et al. 2003). Due to the contemporary nature of their use, any preservation effort will require experimentation to determine an effective treatment strategy.

McNamara et al. experimented with both ethanol and metabolite biocide treatments on Mayan ruins in southern Mexico (Ibid). An ethanol solution (50%) was administered on the limestone surfaces to test the efficacy of ethanol to clean the ruins and inhibit further microbial growth. Ethanol solution was perceived as optimal for treatment because, "it is inexpensive and easy to obtain. It evaporates and presents minimal danger to the stone, conservators, or local environment" (Ibid, 258). To test this, the scientists applied the ethanol solution to walls in one room of the Ek Balam pyramid while the walls of another room served as a control (these walls had been washed approximately a year before). Fifteen days later samples were taken for microbiological analysis. The results of this analysis showed no significant difference in bacterial presence, measured by the number of colony forming units (CFU) detected. While the study did not prove the ethanol treatment to be effective in the remediation of in microbial growth, for years it has proven a useful solvent for washing the monument surfaces at the archaeological site without contributing to biodeterioration.

Testing the efficacy of metabolite treatments produced more distinguishing results. Stone samples of limestone comparable to the rock used at the monument were treated with solution of citric acid and oxalic acid, two acids commonly produced by microbial metabolic processes. While micro-computed tomography showed significant dissolution of the limestone sample when treated with citric acid, the effect from oxalic acid was not significant. This is because when oxalic acid interacts with available calcium it forms calcium oxalate, a salt more insoluble than calcium carbonate. Due to this greater insolubility, it has been hypothesized that metabolic treatments which generate oxalic acid, and subsequently calcium oxalate, may effectively fortify rock surfaces and limit further deterioration (Di Bonaventura et al. 1999).

Until recently, the majority of biocides produced was engineered for agricultural purposes and did not adequately address the highly sensitive needs of historical restoration projects. Due to this need for specialization, a great deal of testing is necessary to determine whether or not utilization of a particular biocide would produce undesired effects in reactions with the rock substrate. Koretrel© is a biocide designed to eradicate microorganisms such as cyanobacteria, algae, mosses, and lichens from rock surfaces in open-air conditions and is perhaps the ideal biocide for restorative efforts in Gobustan. A study that tested the biocide's ability to remove lichen populations from sandstone and limestone determined that "at the end of the sixth month, all the species could be easily removed from the substratum with the aid of soft brushes and lancets: the two endoliths could be easily removed from the substratum by rubbing their thalli and the uppermost layer of calcite crystals with the fingertips." (Tretiach et al. 2007, 46). This rate of extraction was significantly faster than other biocides, such as those used on the

Stairway in the Copán archaeological site mentioned above, which can take from years to decades to achieve the same result.

Despite this success, there were some consequences that resulted from the use of Koretrel©. White marks persisted in places where hyphae from species, such as *A. intermutans* and *Lecidea fuscoatra*, had penetrated the substratum. The limestone sample also underwent significant color change, taking on a glossy veneer which lingered for about a month, until heavy rainfall washed the surface and returned the rock to its original appearance (Tretiach et al. 2007, 47-49). However, it is reasonable to assume that most biocides, having successfully exterminated all undesired microbial populations, would need to be rinsed from the rock surface to avoid any permanent corrosion resulting from prolonged exposure. It is also reasonable to assume that the benefits of using powerful biocides such as Koretrel© would come with some consequences.

Common drawbacks amongst heavy-duty biocides include discoloration and a decrease in capillary water absorption. The biocide Metatin N58-10/101 has been known to decrease capillary water absorption, resulting in the "formation of an amorphous, hydrophobic layer on large areas of the substratum (Ibid, 52; citing Altieri et al. 1997) which may be detrimental to the physical and chemical aspects of the stone. Washing biocides from stone surfaces after the growth of microbial communities has been contained may reduce the likelihood of unintended consequences regarding properties of the stone, but also the biocides ability to prevent future microbial growth. This is not a feature unique to Koretrel© as most biocides should be washed shortly after they have been applied (Nugari and Salvadori 2003, 524).

Biocides do not address all problems related to preservation and the maintenance of historical sites. They are limited in their ability to eradicate endolithic microbial communities that have penetrated into the rock substrate. These more persistent communities continue to deteriorate the stone and provide more favorable conditions for a microbe population to return to the rock surface. Furthermore, due to their caustic nature and the chemicals they utilize, biocides present health risks both for preservationists and the visitors of historical sites. The ideal biocide would prevent further bacterial, fungal and algal growth even after microbial populations had been eradicated, effectively preserving the stone without changing its chemical or physical properties, however, such treatment solutions are not yet available. Preservationists must test the efficacy of a biocide before administering the solution and weigh the benefits with the consequences. To test a biocide effectively requires both laboratory and field testing as controlled laboratory experiments are not always predictive of how a biocide will react with a stone surface *in situ*. Microorganisms isolated for tests in laboratories are often more sensitive than the microorganisms found on actual rock surfaces and substrates and do not demonstrate precisely how a biocide will function when applied in a complex ecosystem (Koestler and Salvadori 1996). Caution is always an imperative when dealing with substances that may have permanent ramifications and any approach to preservation that utilizes biocides should executed deliberately and sparingly.

Restoration as Preservation: Biomineralization Techniques

Beyond merely cleaning rock surfaces in defense against biodeterioration, scientists have recently developed ways to proactively combat the corrosion of stone.

Biomineralization is a naturally occurring process that preservationists have begun to replicate in order to consolidate and protect rock surfaces and substrates. Using biological mortars, or biocalcin sheets, scientists are able to synthesize stone powder and carbonatogeneous bacteria to produce carbonate that fuses with a host substrate. Though requiring human intervention, preservationists view this approach as having minimal interference with the physical and chemical parameters of the stone due to its use of natural, biological processes (Orial et. al 2003). This treatment solution is considered significantly safer and less invasive than the former approach that utilized synthetic resins. Resin treatments utilized chemical products that polluted the environment, presented health risks, and were ultimately ineffective due to peeling of the polymer coating (Le Métayer-Levrel 1999, Rodriguez-Navarro et al. 2003). While biomineralization promises to advance preservation techniques, there are still drawbacks that need to be considered before any strategy utilizing biological mortars is implemented.

The molecular mechanics by which bacteria cultivate calcium carbonate precipitation are not known. Nevertheless, the phenomenon has been observed amongst many microorganisms in a variety of environments (Barabesi et al. 2003). Strains recognized for their ability to produce calcium carbonate include *Bacillus cereus*, *Bacillus megaterium*, and *Pseudomona flourescens*, all which have demonstrated that, "whatever the process used by the bacteria, bacterial carbonatogenesis appears as the displacement of the hydrogenocarbonate balance: $Ca\ (HCO_3)_2 \rightarrow CaCO_3 + CO_2 + H_2O$ (Orial et al. 2003, 500; citing Castanier 1987). Industrial studies determined *Bacillus* *cereus* to be the most efficient precipitator of calcium carbonate (Orial et al. 2003, 501). When the carbonate is first precipitated it is hydrated and amorphous, and over time it solidifies into a crystalline structure, eventually hardening to the point that it is indistinguishable from the limestone substrate.

The method by which preservationists replicate the process of biomineralization has multiple phases. First, either the entire rock surface or the locations requiring solidification are coated in a bacterial suspension culture. The carbonatogeneous bacteria are introduced at this time. Afterward, at regular intervals a nutritional medium is applied to foster the metabolic process. As the bacterial population grows, a biofilm is produced which ultimately develops into a calcium carbonate precipitate (Le Métayer-Levrel et al. 1999). The suitable strain of carbonatogeneous bacteria and the duration and rate of intervals for the nutritional medium must be determined through preliminary testing in both the laboratory and *in situ*.

Biological mortars are a promising advancement in the preservation of stone because they prevent granular disintegration at both the surface and substrate level. Protection at the surface level requires waterproofing of the stone so that water and weathering agents may be prevented from entering into the stone's core. Consolidation refers to the hardening of a stone's substrate in order to prevent erosion resulting from increased porosity (Rodriguez-Navarro et al. 2003, 2182). To date, the efficacy of biocidal, epoxy-resin, and lime-water treatments have been limited by their inability to fortify the sub-surficial layers of a stone. While these methods are able to protect and consolidate the stone to a degree through calcite layers, they lack the ability to develop coatings that bond with the substrate (Tiano et al. 2003, 488). Though it is acknowledged that there is not accurate information yet on how deep the biocalcin sheet bonds with the substrate (Rodriquez-Navarro et al. 2003, 2191), based on the nature of the biological process by which a biocalcin sheet becomes indistinguishable from the host stone (Orial et al. 2003, 501), it is believed that biomineralization has the potential to be much more effective than former treatment methods.

The testing of biological mortars prior to implementation is necessary not only to determine which application method is most efficient but also to address potential consequences that may arise. Discoloration, glossy appearance, crust formation and substrate exfoliation are all undesirable effects that may potentially result from intervening biomineralization. Beyond problems directly affecting the stone, the environmental repercussions from biological mortars are not well known (Tiano et al. 2003, 487). Testing must also consider a stone's capacity for capillary water absorption, as "it has been demonstrated that plugging accelerates decay…[therefore] stone treatments should leave the stone surface free to "breathe," i.e., to allow vapor transfer" (Rodriguez-Navarro et al. 2003, 2183). Plugging of the substrate causes decay much in the same way salt-crystallization does. When a substance is first introduced to a rock surface it may penetrate into the fissures of the stone. If that substance than expands it will apply pressure within the pore walls of the stone and weaken its constitution.

Another factor requiring sensitive attention is the growth of bacteria in the biomineralization process. In order to produce a calcium carbonate precipitation, certain bacteria must be allowed to thrive. Preservationists may apply culture mediums and manipulate the environment to encourage this growth. However, if undesirable bacteria begin to metabolize and grow in significant population, biofilms may soon develop that cause the biodeterioration preservationists were trying to remediate in the first place (Rodriguez-Navarro et al. 2003, 2183). In order to avoid this cycle of consolidation and deterioration, preservationists must maintain strict control over the bacterial populations present. This requires employing careful sanitation measures, both with the stone and the equipment used to apply a biological mortar. To accomplish this, preservationists may be tempted to use biocides to kill any microbial populations present on the stone. However, the efficacy of a treatment solution may be compromised when incorporated with other solutions. As with every stage in the process of formulating a preservation method, experimentation of how solutions interact with one another is imperative.

In the case of the preservation of the Thouars Church in central France, mortars were formed from the strain *Bacillus cereus*. The optimal feeding solution for this bacteria incorporated a fungicide, "the role of which is to block the parallel and disruptive development of molds present in a latent state on every support, even mineral ones (Orial 2003, 501). This approach seems to have been effective, as the carbonate precipitate was "perfectly integrated" to the original stone without further detrimental microbial growth (Ibid., p. 515). Another study tested the collaborative effects of biocides and water repellents; while the effectiveness of the water-repellents was diminished when applied after the biocide, there was little to no effect when the biocide was applied after the protective polymer. The products selected for both consolidant and biocide also contributed to the variance in effect (Malagodi et al. 2000). As Nugari and Salvadori explain, immobilization of the biocide is necessary otherwise it may interact with the consolidant and substrate in undesirable ways. They reference a case in which bright orange discoloration resulted from the interaction between an organo-iodide bacteria and silane consolidant on a marble surface (Nugari & Salvadori 2003, 528; citing Tudor et al. 1990).

It is likely both biocidal and biomineralization treatments will be useful if not essential to preservation efforts at Gobustan. The calcareous composition of the stone in the reserve is particularly vulnerable to both biodeterioration and natural granular disintegration. Biocides and biological mortars have both been proven effective in mitigating these erosive processes. However, due to variances in environment, stone composition, and active microbial populations, it is necessary to do extensive testing on the range of options available for biocide and biomineralization treatments before implementing a preservation strategy. While some options have been addressed, they do not fully represent the scope of all products available. For comprehensive testing, preservationists should experiment with how available products interact both in isolation and in collaboration.

Tourist Management

The viability of a rock art site is improved if the expense of preservation measures can be balanced by revenue from tourism. Resources to fund research, preservation strategies, and preservationists' salaries are necessary and may be provided through tourism. Therefore, preservationists should address both cultural and economic interests when assessing a management plan. Sustainability is the ideal relationship between these factors, whereby the economic potential of the site increases the protection and consideration invested into a site. The longer a site remains in good condition, the longer it will remain a destination for tourists seeking world heritage sites. Though the proper management plan will be different at every site, there are some standard operations that have been proven to limit the destruction caused by tourism (Deacon 2006). These standard operations include educational programs, limitation of access to sites, cooperation with local populations, and continual documentation and reevaluation of the effectiveness of strategies employed.

Considering the difficulty of controlling people's behavior, educational programs are perhaps the most effective way to ensure visitors are considerate of fragile and sensitive monuments. As Deacon explains,

> "Across the spectrum of human behavior, there are probably as many people who are concerned about rock art conservation as there are rock art vandals, but the vast majority of people between the two extremes do not have a particular commitment. Conservation is learned behavior and conservators and site managers committed to the protection of rock art are tasked with winning over the people in the middle." (Deacon 2006, 396).

Once people have become interested in a heritage site, it is more likely they will be actively invested in its preservation. However, educational programs not only encourage preservation by cultivating interest in a site, they also can be a means by which people are informed of how monuments deteriorate. Educating the public on the natural and human-induced processes of erosion will likely encourage more considerate and deliberate behavior amongst visitors at the site.

Another solution to control damage from tourism are area restrictions to limit the wear from pedestrian and automobile traffic. Focusing the areas available for observation increases the damage inflicted in one location while significantly improving protection of the other areas. For instance, as the local museum is currently located at Beyukdash, this location could become the sole tourist location while the Kichikdash and Jingirdag Mountains could be shut off and reserved only for academic research. A recommendation for this approach is implied in the ICOMOS 2008 report, which states, “the most remote and undisturbed landscapes are the Jinghirdag Moutain-Yazylytepe hill and Kichikdash Mountain. These areas need to be fully protected in order to ensure they keep their authenticity. The most visited site, Boyukdash, has more disturbances in the form of installations such as a prison and stone quarry, which should be managed as part of the Management Plan.” (ICOMOS 2008). While Beyukdash would be marginally at greater risk, the other two sites of petroglyphs would remain isolated from the deteriorative effects of tourism. Furthermore, with less space to manage, on-site staff could more effectively control visitor behavior. Mandates requiring visitors to remain on marked paths could be more adequately enforced.

For a management plan to be effectively implemented it is important that on-site staff are properly trained and employed in permanent positions. The staff should understand the archaeological significance of a site and be knowledgeable of the risks of deterioration present so they may form long-term preservation objectives that may be frequently evaluated for efficacy (Deacon 2006, 381). Currently, there are charters such as ICOMOS International Cultural Tourism Charter that may assist staff in developing their management strategy. Furthermore, staff should strive to establish good rapport with both locals and visitors as this will increase the popularity of the site and improve its economic viability. With more effective management and capital for preservation, Gobustan may be a frequented world heritage site for years to come.

Preservation through Documentation: 3D Imaging Technology

After addressing the ways preservationists can mitigate the effects of erosion and biodeterioration at the Gobustan Reserve, it is important to consider which secondary strategies may be implemented if initial preservation strategies are not adequately effective. Furthermore, considering the constant threat of seismic and volcanic activity in the region, it is impossible to predict how long the petroglyphs at Gobustan may remain undisturbed. By documenting and archiving the petroglyphs, the history of inhabitants in the Gobustan Reserve may be preserved permanently. While archaeologists in the 20th century studying the petroglyphs have already begun this process of documentation, improved 3D imaging technology offers preservationists a means to generate replications of the petroglyphs more efficiently and in significantly greater detail and quality.

Documenting the petroglyphs at Gobustan is not a new idea. After rock art was discovered in Gobustan by miners in the 1930s, Azeri archaeologist I.M. Djafarsade devoted three decades to sketching and describing nearly 3,500 petroglyphs of varying figures. These sketches brought awareness to the rich cultural heritage preserved at Gobustan and inspired the Azeri national government to declare the area a historical landmark in 1966. While these tracings were schematic and show only the most evident figures, they nonetheless provided a useful overview for analysis of the themes and styles present at Gobustan (Anati 2001, 21). From the 1970s to the 1990s, archaeologist R. Djafargulu expanded upon Djafarsade's efforts and today over 6,000 petroglyphs have been discovered and documented at Gobustan. While tracings and photographs have been sufficient for the purposes of archaeological analysis to date, future studies may benefit from the availability of a more accurate catalogue of petroglyph image renderings. Along with enhanced image replication of the petroglyphs, computer generated imaging technology may also be capable of generating retrospective images of the rock carvings prior to several centuries of erosion. Beyond innovating archaeologists' approach to the study of rock art at Gobustan, 3D imaging would permanently "preserve" the petroglyphs in their current state.

Computer generated 3D imaging technology has developed rapidly over the last few decades. Initially technology designed for medical testing, 3D imaging is now employed in several fields, including the inspection and documentation of cultural sites and artifacts (Bernardini & Rushmeier 2002; Boulanger et al. 1998). There are a variety of options available for generating a 3D image based on how an object is scanned and analyzed. These options utilize methods referred to as triangulation, time-of-flight scanning, conoscopic holography, and computed tomography.

Triangulation, time-of-flight scanning, and conoscopic holography technology function similarly to sonar technology by capturing reflections of radiation or light rays off of scanned objects. Active scanners, usually charge-coupled devices, emit either radiation or light that is detected upon reflection from the object being scanned. Digital processing then allows the series of collected data points to be collated into a 3D image (Bernardini & Rushmeier 2002). Devices utilizing time-of-flight scanning technology have significantly greater range than triangulation devices, but are less accurate. The advantage to conoscopic holography is that it utilizes only a single ray-path for measuring, thus is more suited for objects that cannot be scanned from all angles, like petroglyphs carved into rock faces at Gobustan.

The most detailed three-dimensional images are generated by computed tomography and nuclear magnetic resonance spectroscopy, or magnetic resonance imaging. This technology, which creates a 3D image by collating a series of 2D X-ray scans, was discussed above in the section concerning testing methods for analysis of rock surfaces and substrates. Unfortunately, due to the need for a full axial orientation around a scanned object, CT and MRI scans will not be applicable to documentation of large petroglyphs *in situ*. Nonetheless, preservationists at Gobustan should invest in this technology for its value to rock analysis.

The use of 3D imaging has become increasingly more common in studies at heritage sites, where minimal tampering with the archaeological material is an objective. Generating digital reconstructions from scans is considered significantly less invasive than former methods, such as foil impressions (Simpson 1993). The National Research Council of Canada (NRC) has been developing 3D technology for research and documentation purposes for over two decades. To facilitate work in the field, they have developed portable scanners that are capable of scanning large objects from distances up to ten meters. These devices, referred to as the Biris 3D Laser Camera and the Large Field of View Laser Scanner, have scanned a variety of objects from oil paintings and museum artifacts to large tombs. The NRC was able to use the images generated from this technology to develop interactive virtual reality museum exhibits, reconstruct deteriorated artifacts and produce imaging to facillitate archaeological studies (Boulanger et al. 1998).

Over the last two decades, 3D imaging has enhanced several professional fields, such as medical and industrial testing, museum studies, microbiological analysis, astronomical observation and cultural heritage restoration. Today, there are a variety of 3D cameras and scanners developed for retail. For example, the Biris 3-D Laser Camera developed by NRC is now available for purchase as the ShapeGrabber™ from the Vitana Corporation (Boulanger et al. 1998, 2). However, considering the rate at which this technology is progressing and the specific requirements facing any documentation project at Gobustan, it may be worthwhile to develop unique equipment solely for the scanning of petroglyphs at this site. Every year there are conferences, such as the International Conference on 3D Digital Imaging and Modeling and the International Conference on Virtual Systems and Multimedia, where the most recent innovations in the field of 3D imaging are presented. The brightest minds in the field of 3D imaging will be present for discussion at these conferences. Collaborations may even be possible with companies looking to demonstrate their engineering capacities and improve their stake in the field of heritage site management. There are limitations in scanning options due to the fact that any scanner used in Gobustan must be portable and capable of scanning large objects, however many options are still available that meet these specific requirements. Ultimately, the benefit to be incurred from the availability of 3D representations of Gobustan's petroglyphs must be balanced with the expense of implementing a project of this costly nature.

CONCLUSION & TASKS AT HAND

The deterioration of geological features is a natural and relentless process. Weathering from wind currents, salt-decay, and biodeterioration continue to shape the landscape as they have for countless millennia. Although erosion is inevitable, scientists are rapidly developing technology to stymie the effects of these natural processes and preserve the geological features that host the petroglyphs at Gobustan. Several applicable methods concerning the preservation of the rock surfaces and substrates at Gobustan have been addressed in this survey. Vegetative growth and the installation of wind shields may potentially mitigate the effects of wind erosion. Salt-consolidants and crystallization-inhibitors, though not yet proven effective, have the potential to someday limit the devastating effects of salt exposure to rocks. Several studies have shown biocide treatments to be effective in eliminating destructive microbial populations and biomineralization treatments are an increasingly reliable method to proactively restore the surface and substrate of a stone.

Though mitigating natural processes of erosion is complicated and difficult, tourism management is an aspect of the preservation strategy that site managers can immediately improve upon. Effective tourism management plans require full implementation of policies as well as periodic reevaluations of a plan's efficacy. Finally, documentation should be considered as an indirect means to "preserve" the petroglyphs at Gobustan. Traditionally documented through sketches and photographs, 3D imaging technology presents an efficient and innovative way to generate significantly more detailed representations of the petroglyphs. Several scholars who have studied Gobustan in the past have recommended similar catalogue and databasing efforts to enhance archaeological studies in the area. Farajova calls for "a review map-scheme of the location of all ensembles of rock art" in order to enhance an understanding of how the petroglyphs fit into the natural landscape (Farajova 2009, 109). As well, several scholars suggest thorough excavation surveys to determine if any petroglyphs have yet to be discovered (Gallagher & Islamov 2003, Anati 2001, ICOMOS 2008). As Azerbaijan enters the global stage in the 21st century, it is important that concerted efforts and sufficient finances are invested in the country's cultural capital. Funding for the reserve should provide for extensive testing and analysis of the geological features, further archaeological surveying with the most advanced imaging technology, resources to implement the most effective preservation strategies, and training for staff relating to the philosophy and management of low-impact tourist sites. If the necessary steps are taken, the Gobustan Rock Art Reserve will surely remain a prized cultural heritage site in Azerbaijan and the world for centuries to come.

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