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The effects of repeated wet-dry cycles as a component of bone weathering

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ABSTRACT

Subaerial weathering is a taphonomic process that affects many archaeological and paleontological bone assemblages and is characterized by surface bleaching, loss of organic component, and progressive cracking and splintering of the bones. Although the mechanisms of such changes are not well understood, previous research has indicated that multiple processes contribute to weathering, including ultraviolet exposure, mineral leaching, mineral recrystallization, thermal expansion/contraction, freezing/thawing, and wetting/drying. In order to examine specifically how wetting/drying cycles can contribute to weathering, a laboratory sample ($n = 100$) of ribs, phalanges, vertebrae, and distal tibiae from white-tailed deer (*Odocoileus virginianus*) were subjected to 150 cycles of complete wetting and drying. The bone surfaces developed the characteristic surface cracking of subaerial weathering, with weathering stage 1 (WS 1) reached by 50 cycles on three bones. By 150 cycles, 27 bones had reached WS 1, with all but 15 bones exhibiting some kind of new cracking damage. One bone reached WS 2 by 125 cycles, with additional bones exhibiting beginning surface delamination. Wet-dry cycles in some environments are a potentially important component of the overall osseous subaerial weathering process and can on their own weather bone.

1. Introduction

Subaerial weathering is a taphonomic process whereby bones exposed on the surface undergo gradual breakdown, including bleaching, loss of organic content, and cracking and flaking, leading to eventual splintering apart into fragments (Behrensmeyer, 1978; Miller, 1975). These changes generally take years, and their timing has been demonstrated to vary greatly by environment (Andrews and Armour-Chelu, 1998; Andrews and Cook, 1985; Andrews and Whybrow, 2005; Junod and Pokines, 2014; Miller, 2009, 2011, 2012; Pokines and Ames, 2015; Tappen, 1992, 1994, 1995), indicating that variables including moisture regime may play a large role. The weathering processes include the overall breakdown of the organic content/grease, leaving bone more brittle and thus more prone to fracturing (Collins et al., 2002; Symes et al., 2014). The loss of grease content also will affect the ability of transient water content to bring about weathering or related changes, including recrystallization (Prassack, 2011; Trueman et al., 2004), demineralization through acidic dissolution, and expansion and contraction caused by wet-dry cycles. Loss of organic content and the incidence of UV light cause bone bleaching (Beary, 2005). Crack propagation often parallels the osteon structure (Tappen and Peske, 1970), following the weaker planes in the bone, and cracking may be enhanced by thermal expansion-contraction from daily sun exposure (Conard et al., 2008). Cracking also is caused in part by freeze-thaw cycles, where expanding ice crystals force the bone apart and form cracks (Guadelli, 2008, 2015; Guadelli and Ozouf, 1994; Mallye et al., 2009; Pokines et al., 2016; Texier et al., 1998; Todisco and Monchot, 2008). With the exception of freeze-thaw cycles, the physical and chemical mechanisms of bone weathering have undergone relatively little research in settings that isolated the effects of these different processes. The present research examines one environmental process, wet-dry cycles, and their cumulative effect upon bone macroscopic characteristics (surface cracking) as a component of the overall weathering process.

The six-stage system of Behrensmeyer (1978) is standard in osteology/taphonomy to describe weathering changes in megafaunal (average adult body mass > 5 kg) bones. These stages start at weathering stage 0 (WS 0), where the bone is unweathered and displays no fine surface cracking. At WS 1, the bone has begun to display fine surface cracking, and the surface starts to delaminate and flake away in

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WS 2. At WS 3, a roughened surface texture is exposed, and the bone starts to splinter and has weathering penetrating into the interior in WS 4. In WS 5, the bone is fragmenting apart. These changes need only affect a minimum of 1 cm^2 of bone and not the entire surface, so small areas advancing to the next weathering stage cause the bone to be scored at that more advanced stage. In addition, drying cracks can form on bones due to shrinkage (Evans, 2014), and this type of taphonomic alteration can form even on bones in protected storage environments.

Weathering stages can be used to estimate the duration of surface exposure that bone assemblages have undergone and also as a more general indicator that they may have undergone surface exposure at all prior to burial. The duration of surface exposure for bones can be used as a proxy for the postmortem interval (PMI) in forensic cases (Cunningham et al., 2011; Junod, 2013; Junod and Pokines, 2014), although some time of soft tissue decomposition will occur prior to the bones being exposed (Megyesi et al., 2005). Bones may reach WS 1 in under a year in many environments (Behrensmeyer, 1978; for a summary, see Junod and Pokines, 2014), and the maximum duration of bone survival also varies. For example, Miller (2009) noted some bones surviving in recognizable but degraded state (WS 4) even after 200 years of exposure in Yellowstone National Park, U.S.A. Bones would not have endured for so long exposed in many other environments, fragmenting completely and getting incorporated back into the soil matrix. In addition, weathering changes can indicate time of exposure prior to burial in archaeological or paleontological cases and relative timing of deposition of different portions of the same osseous assemblage (Cutler et al., 1999; Fernández-Jalvo et al., 2010; Tappen, 1992, 1994, 1995). Some assemblages have varied depositional histories, where skeletal elements are added over multiple episodes and have different durations and/or microenvironments of exposure. These include faunal traps, which can have multiple sources of introduced bone (Pokines et al., 2011). They also include carnivore dens where multiple species inhabited in succession or overlapping (Brain, 1981; Pokines and Kerbis Peterhans, 2007). Weathering data in these settings are useful in helping to determine which species introduced a subset of the bones into the deposits based upon their habits of collecting fresh or weathered bone (Pokines and Kerbis Peterhans, 2007). Weathering data often help contextualize taphonomically zooarchaeological and paleontological deposits in terms of the sources of bones introduced into a site and therefore the biases in species and element representation (Lyman, 1994; Lyman and Fox, 1989, 1997) upon which interpretations of hominin behavior are based.

Bones lying on the ground surface that are protected in some manner may not undergo visible bone weathering for years. Shielding by desiccated soft tissue may hinder the onset of weathering, even in an environment where overall weathering is rapid such as in the desert of eastern Jordan (Pokines and Ames, 2015; Potmesil, 2005). The accumulation of leaf litter or shelter by artificial objects including aircraft debris can inhibit weathering (Pokines, 2009). Multiple intrinsic and extrinsic variables affect the rate at which bones weather (Lyman and Fox, 1989, 1997), and the present research addresses one of these potential mechanisms for bone weathering by isolating the effects of repeated wet-dry cycles.

1.1. Weathering of other materials from wet-dry cycles

Other materials undergo weathering effects due to wet-dry cycles, indicating that this process also may affect exposed bones. The effects of wet-dry cycles upon rock has been examined in isolation and in combination with other weathering factors such as freeze/thaw or warming/cooling cycles (Aires-Barros et al., 1975; Arnold et al., 1996; Coombes, 2011; Elliot, 2004; Hall and Hall, 1996; Ito et al., 2015; Kanyaya and Trenhaile, 2005; Loubser, 2013; Swantesson, 1985; Wells et al., 2005; Yavuz, 2011). Swantesson (1985) found that greater weathering effects were produced by freeze/thaw cycles on Swedish rock samples, but Ito et al. (2015) tested sedimentary and volcanic rocks and noted that wet-dry cycling was equally and in some cases more destructive than freeze/thaw cycles.

A variety of factors commonly encompassed by wet/dry cycles also have been shown to affect rock weathering. The degree to which water is applied to the rock affects weathering processes, with differences noted between partial submersion, full submersion, and spraying (Hall and Hall, 1996). Different types of rock, due to their varied internal crystalline structures (Wells et al., 2005), often dictate weathering responses, including cracking/fracturing (Loubser, 2013; Matsuoka and Murton, 2008). Hall and Hall (1996) suggest that changes to internal structure of rock, such as a gradual increase to the size/amount of pores and microfissures, could explain the weathering response to wetting/drying cycles. Kanyaya and Trenhaile (2005) reported granular disintegration of sandstone. Wells et al. (2005), however, found that earlier stages in the wetting/drying cycles of schist produced larger fragments with little to no granular material.

Wet-dry cycles also have been found to contribute to the weathering of artificial objects, including metal, glass, ceramics, and stone monuments and buildings (Huisman et al., 2008; Gentaz et al., 2011; Purdy and Clark, 1987). Chabas et al. (2010) experimentally examined the effects of wet and dry pollution deposits on modern, "self-cleaning" glass and found that the most harmful process was the accumulation of pollutants and salt crystallization. Skibo and Schiffer (1987) attributed water as the mechanism for multiple forms of weathering to ceramics including transporting chemicals into porous material, facilitating the crystallization of minerals, and transporting minerals out of the material through leaching.

Wet-dry cycles also affect recrystallization of component minerals, which can contribute to weathering. Studies of ivory and stone artifacts and stone monuments and buildings have found that if the surface of the material is less porous than its underlying structure, salts can crystallize just below the surface, creating pressure and causing spalling or flaking (Doehne, 2002; Johnson, 1998; Kuchitsu et al., 2000; Pardini, 2003). Cann (2012) found that wet-dry cycles were the main causes of physical weathering of slate gravestones in an area of Australia and that salt recrystallization contributed to the widening and deepening of the drying cracks. In a study of sandstones, Hale and Shakoor (2003) found that larger and more numerous pores make material more susceptible to weathering, and that the cycles produced a cumulative loss of compressive strength in the material. The deeper the water penetrates, the deeper below the surface that recrystallized salts can damage the stone (Coombes, 2011; Heinrichs, 2008; Karatasios et al., 2009; McCabe et al., 2012; Ruedrich et al., 2011; Sass and Viles, 2010). Waragai (2016) surveyed sandstone temples in Cambodia and found that the main contribution to their physical weathering was the wet-dry cycles that they were subjected to as result of the extreme seasonality. Weathering also increased the susceptibility of the stone material to deeper penetration of water and, therefore, further weathering.

1.2. Weathering of bone from wet-dry cycles

The effects of wet-dry cycles on bones have been studied in isolated laboratory settings (Miller, 1975; Murphy et al., 1981) and within natural weathering environments (Andrews, 1995; Conard et al., 2008; Tappen, 1992, 1994). Miller (1975) investigated wetting-drying and freezing-thawing of cattle (*Bos taurus*) tibias and metapodials to determine the effects on the overall weathering rate. Bones were either soaked in distilled water ranging from 18 to 24 °C for three weeks or placed in a freezer for three weeks. The bones were then removed and dried for 24 h. Deep, longitudinal cracks penetrating the marrow cavity and superficial surface cracks were observed. Audible "pops" heard by observers during the drying process suggested that new cracks formed with "explosive" force, a phenomenon also noted by Evans (2014).

The effects of wet-dry cycles in human bone, ceramics, and shells in an archaeological setting were observed by Murphy et al. (1981). Standard osteological measurements were taken prior to the experiment