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The effects of experimental freeze-thaw cycles to bone as a component of subaerial weathering

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ABSTRACT

Subaerial weathering of bone is a taphonomic process that affects many archaeological and paleontological assemblages and is characterized by surface bleaching, loss of organic component, and progressive cracking and fragmentation of the bone surfaces. The mechanisms by which these changes occur, however, are poorly understood but are hypothesized to include ultraviolet exposure, degreasing, leaching, remineralization, wetting/drying, thermal expansion/contraction, and freezing/thawing. In order to examine the potential contribution of the latter process to weathering, a sample ($n = 93$) of naturally decomposed and degreased metapodials of white-tailed deer (*Odocoileus virginianus*) were subjected to up to 75 cycles of complete freezing and thawing under laboratory conditions, with samples withdrawn each 25 cycles for histological examination of the taphonomic alterations to the bone microstructure. Macroscopic and microscopic changes included progressive cracking that parallels part of the progressive degradation of weathered bone, but no elements unequivocally reached weathering stage 1 over this interval.

1. Introduction

Subaerial weathering is the chemical and physical breakdown that bones undergo when exposed on the surface (Behrensmeyer, 1978; Nielsen-Marsh and Hedges, 2000; Miller, 1975). These changes include surface bleaching, breakdown of the organic component, and progressive cracking and fragmentation of the bone surfaces leading to eventual bone destruction and reincorporation into the sediment matrix. The system of Behrensmeyer (1978) has come into standard use to describe the stages of breakdown, ranging from weathering stage (WS) 0 (bone displaying no surface cracking) through WS 5 (bone is fragmenting apart). Intermediate stages plot the deepening of cracking, roughening of the surface, and splintering of the bone. The mechanisms by which weathering occurs and how these vary in their effects in different depositional environments, however, have undergone relatively little research. The present research examines one environmental condition, freeze-thaw cycles, and their cumulative effects upon bone macroscopic characteristics (surface cracking) and microscopic characteristics (microfracturing of osteon structure) as one potential component of weathering.

Weathering has the potential to affect most osseous assemblages where burial was not rapid and complete. These include kill sites and natural die-offs (Andrews and Whybrow, 2005; Behrensmeyer, 1978; Coe, 1978; Miller, 2009; Pokines and Ames, in press; Potmesil, 2005; Tappen, 1994, 1995), occupational middens (Brain, 1981; Madgwick and Mulville, 2012), and open faunal traps (Pokines et al., 2011). Weathering as a taphonomic agent creates a potential analytical bias to osseous assemblages, since this process can more rapidly break down weaker elements and/or those from smaller taxa (Lyman and Fox, 1989). Highly weathered assemblages therefore tend to be composed of a greater frequency of more robust bones and/or bones from larger species (Behrensmeyer, 1978).

Weathering can be used to reconstruct variable depositional histories where all skeletal elements were not introduced at the same time or have undergone varying amounts of exposure prior to burial. The relative timing of introduction of remains therefore may help determine which taphonomic agencies contributed to assemblage formation. This includes, for example, porcupine dens, as some taxa (e.g., *Hystrix* spp.) gather bones in various weathered states from the surrounding landscape and concentrate them in dens for gnawing (Brain, 1981; Pokines and Kerbis Peterhans, 2007). Relative timing of deposition is also relevant to landscape studies in reconstructing the contemporaneity of death events and changes to exposed skeletal remains over time (Cutler et al., 1999; Fernández-Jalvo et al., 2010; Miller, 2009, 2011, 2012; Tappen, 1992, 1995).

Weathering also can be used to estimate absolute durations of exposure time over forensic intervals (Bell et al., 1996; Calce and Rogers, 2007; Cunningham et al., 2011; Junod, 2013), typically no more than multiple decades, or the amount of time which has elapsed from

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death until the time of discovery (i.e., the postmortem interval). Other available methods for estimation in forensic situations generally cluster toward the early postmortem interval, spanning hours to months (Megyesi et al., 2005), or rely upon artifactual associations (Junod and Pokines, 2014). As weathering changes take years to decades, the rate of these processes in most environments makes them suitable to give broad estimates of the postmortem interval in forensic cases and indicate time of accumulation prior to burial in archaeological or paleontological cases.

1.1. Effects of environment

Depositional environment greatly influences the rate of osseous weathering (Behrensmeyer and Miller, 2012). Environments that have been examined include temperate deciduous forest and grassland (Andrews and Cook, 1985; Janjua and Rogers, 2008; Junod, 2013); boreal forest (Miller, 2009, 2011, 2012); arctic tundra (Miller et al., 2013); high alpine (Bertran et al., 2015; Guadelli, 2008, 2015; Guadelli and Ozouf, 1994; Mallye et al., 2009; Texier et al., 1998); semi-arid equatorial savanna (Behrensmeyer, 1978; Cutler et al., 1999; Hill, 1976; Western and Behrensmeyer, 2009); true deserts (Andrews and Whybrow, 2005; Pokines and Ames, in press); and tropical rain forests (Pokines, 2009; Ross and Cunningham, 2011; Tappen, 1992, 1994, 1995). The rate of weathering likely varies across these environments due to broad differences in temperature regimes, precipitation, snow cover, and vegetation cover (Junod and Pokines, 2014). Skeletal remains deposited in cooler climate areas can progress more slowly through weathering stages (Andrews and Armour-Chelu, 1998; Andrews and Cook, 1985; Fiorillo, 1995; Miller, 2009, 2011, 2012) than skeletal remains deposited in warmer climate areas (Behrensmeyer, 1978; Western and Behrensmeyer, 2009). Colder temperatures will also depress microbial activity and its degrading effects upon bone (Bell et al., 1996). Miller (2009) found that surface-exposed bones could survive in a degraded but recognizable state (WS 4) for over 200 years in Yellowstone National Park, U.S.A. Snow covering the bones for a substantial portion of each year may factor heavily into their relatively slow weathering. Fiorillo (1995) also noted a relatively slow weathering rate for large ungulate osseous remains deposited in a subalpine, open grassland in southwest Colorado, U.S.A. In contrast to these cooler climates, Behrensmeyer (1978) found that bones reached WS 1 or WS 2 within one year and WS 5 within fifteen years of surface deposition in the Amboseli Basin, southern Kenya. Tappen (1992, 1994) found that the rate of bone weathering in the savanna environment at Parc National des Virunga, Zaire, is comparable to the rates noted by Behrensmeyer (1978). Coe (1978) found that elephant (*Loxodonta africana*) bones deposited in the savanna environment of Tsavo (East) National Park, Kenya, exhibited similar rates of weathering. Rainforest environments also have been noted to slow the rate of weathering, likely due to constant moisture, lack of freeze-thaw cycles, and dense vegetation protecting bones from solar radiation (Pokines, 2009; Tappen, 1992, 1994, 1995). Studies in desert environments, however, have indicated variable rates of bone weathering (Andrews and Whybrow, 2005; Pokines and Ames, in press).

1.2. Mechanisms of weathering

Bleaching occurs as part of the weathering process and may be the first visible change. Beary (2005) examined the effects UV radiation on the surface color of bone under experimental conditions. He noted progressive bleaching of natural beige bone color that strongly positively correlated to the amount of UV radiation absorbed. Along with bleaching, progressive drying of the bone including loss of lipid content will make it more susceptible to other weathering processes. The lipid content can be lost via consumption, decomposition, or slow leaching to the surface. Progressive drying also includes desiccation of protective adhering soft tissue, the presence of which generally halts or greatly slows the weathering process (Pokines and Ames, in press). Continued exposure causes the bone to lose its internal moisture content, which can get replenished from precipitation or ground water. Weathering in general appears to be slower where bones are kept moist and protected by vegetation or other cover (Behrensmeyer, 1978; Miller, 2009; Pokines, 2009; Tappen, 1992, 1994, 1995), although moisture has long been recognized as an important factor in the breakdown of the organic component of bone (Hare, 1974). In addition, as bone is repeatedly wet and dried, shrinking and swelling of the material may cause additional crack formation.

The formation of crystals within bone can also cause cracking, as these minerals expand and force apart the existing bone structure (Trueman et al., 2004). This phenomenon has been noted directly affecting bone. Behrensmeyer (1978), Cutler et al. (1999), and Trueman et al. (2004) noted the frequent presence of alkaline soils in Amboseli Park, Kenya, where they observed long term large mammal bone weathering. In some cases, weathering was more advanced on the bone surfaces in contact with the ground than on the opposite surface exposed to more direct solar radiation. They attribute this reverse pattern to the formation of crystals on the undersides of bone which forced apart cracks and increased the overall degree of fragmentation. Key to this taphonomic (diagenetic) process is the infiltration of groundwater with soluble/exchangeable minerals from the soil (Pate and Hutton, 1988; Pate et al., 1989; Sillen, 1989). As this solution reaches the surface of bone and other porous materials, the water evaporates, leaving behind the minerals to crystallize (Rodriguez-Navarro and Doehne, 1999). Other factors in their weathering include the dissolution of more-soluble minerals, weakening the overall structure (Walderhaug, 1998), similar to the breakdown of the organic component through digestion by microbes and chemical breakdown (Fernández-Jalvo et al., 2010; Nielsen-Marsh et al., 2000; Smith et al., 2005; Turner-Walker, 2008) weakening its overall resistance to weathering.

Thermal expansion-contraction is a factor the weathering of bedrock (Hall, 1999). Material fatigue accumulates, which may cause microfracturing (i.e., thermal stress fatigue) or sudden failure (i.e., thermal shock). This model should apply to bone, where expansion-contraction damage may accrue slowly over many diurnal cycles, and sudden changes in temperature may induce localized failure of the bone structure (Conard et al., 2008), especially in parallel to the heterogeneous structures of osteons (Skedros et al., 2005; Tappen, 1969; Tappen and Peske, 1970). In the temperature range of $-20°$ to 20 °C the coefficient of thermal expansion of human bone ranges from 23 to 32×10^{-6}/°C; from 30° to 60 °C (or temperatures likely reached by objects lying in direct sunlight in warm environments), the coefficient reaches 37.1×10^{-6}/°C (Pal and Saha, 1989). In some depositional environments, temperature swings of tens of °C per day are possible for bone lying in direct sunlight. This expansion and contraction, although small, may contribute to the microfracturing and breakdown of the bone structure.

Freezing water within pore spaces and cracks already formed within a bone has a high potential to contribute to overall weathering cracking (Guadelli, 2008, 2015; Matsuoka, 1996). Approximately 12% of fresh cortical bone volume consists of pore space (Nielsen-Marsh et al., 2000), so even the denser portions of a bone can absorb water. Since freezing water exerts up to 30,000 lb-force/in^2 (207 MPa) as it expands approximately 9% in volume while freezing (Matsuoka and Murton, 2008), this force may contribute greatly to the widespread cracking of weathering bone. The maximum tensile strength of bone is greatly exceeded by this force (Pietruszczak et al., 2007; Turner et al., 2001; Weiner and Wagner, 1998). Subsequent thawing would then allow water to penetrate deeper into the expanded cracks, followed by refreezing and more expansion (Matsuoka and Murton, 2008).

Freeze-thaw cycles also have been observed in geological contexts to cause fractures in mineral formations, where, like in bone, the tensile stresses induced by expansion of ice overcame the tensile strength of the mineral (Hall, 2007; Hall and Thorn, 2011; Thorn, 1979; Yavuz,