BONE WEATHERING IN THE MEDITERRANEAN CLIMATE OF THE NORTHERN CALIFORNIA FOOTHILLS: A TAPHONOMY STUDY

A Thesis

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in

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by

Peter J. Morris

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by

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Department of Anthropology
Abstract

of

BONE WEATHERING IN THE MEDITERRANEAN CLIMATE OF THE
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Statement of Problem

Six arbitrary stages of bone weathering were identified in 1978 (Behrensmeyer 1978), using data gathered from animal bones located in surface depositional contexts in the Amboseli Basin of Africa. Since 1978, these six bone weathering stages have been used as a guideline for determining the age of bones according to their weathering stage. Although the weathering stages have been broadly applied across the globe, they have not been verified in all possible geographic locations, i.e., the Sierra Nevada foothills of Northern California. This thesis research studied the effects and rate of bone weathering on domestic pig bones over a period of 133 days to determine the speed of bone weathering in the cool Mediterranean climate of Auburn, California in the Sierra Nevada foothills, and whether or not the rate fit into Behrensmeyer's (1978) six weathering stages. One set of domestic pig bones was placed in an enclosure exposed to full sunlight, and an identical set of bones was placed into an enclosure shaded by an oak tree. The exposure period was from the summer month of July to the winter month of December 2012.

Sources of Data

Twenty-two sets of domestic pig (Sus scrofa) bones were used for this study. Two identical sets of bones were placed within two reinforced chicken wire enclosures: one shade enclosure, and
one sun enclosure. Each enclosure had eleven stations, each station with a set of domestic pig bones consisting of a femur, a rib, and a vertebra. Data was collected over a period of 133 days. Data collected throughout the study period included the ongoing condition of the bones and daily weather patterns, including ambient temperature, UV index, rain, cloud cover, and wind.

**Conclusions Reached**

After 133 days, the bones in this study were still in the condition of Weathering Stage 0, as defined by Behrensmeyer (1978). The bones were in a state of dryness, but no cracks were present on the bone surfaces. This result is consistent with the timeframe of the original weathering stages. The conclusion is that in the cool Mediterranean climate of the Northern California foothills, the early bone weathering stages defined by Behrensmeyer (1978) are valid. To achieve Weathering Stage 1 it may be necessary for a longer study period, possibly up to or at least one year.

_______________________, Committee Chair
Samantha Hens

_______________________
Date
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CHAPTER I

INTRODUCTION

Taphonomy was originally described and defined by Efremov in 1940. Efremov (1940) considered the field of taphonomy to be a combination of sciences into one field that studies the "science of embedding," the process of fossilization as a living organism passes from the biosphere into the lithosphere after death. Actualistic taphonomy, or neotaphonomy, studies taphonomy in real time to examine what occurs during the process.

The process of bone weathering has been linked to two factors:

1. Bone structure and chemistry.
2. Climate and environment.

Many studies have linked bone structure (Gifford 1980; Guy, et al. 1997; Hare 1980) to the susceptibility of weathering. Other studies have focused on the effects of the environment on bone weathering, i.e., freezing (Texier, et al. 1998) to hot temperatures (Galloway 1997), and sunlight (Fernandez-Jalvo, et al. 2002) versus shade (Andrews and Cook 1985).

Behrensmeyer's (1978) work in the Amboseli Basin in Kenya was the pioneering study in the field of bone weathering. During the course of examining the skeletal remains of animals that had died of natural causes in various environments, Behrensmeyer (1978) discovered that bones weather in progressive patterns over time, after which she defined and described 6 arbitrary stages of bone weathering (see Methods, pages 53-54). Several studies have since tested Behrensmeyer's stages in
various environments, e.g., desert (Shipman 1977), tropical (Tappen 1994), periglacial and permafrost (Janjua and Rogers 2008; Sutcliffe 1990), and temperate (Andrews and Armour-Chelu 1998) locations. Results from these studies are suggestive of regional, environmental, and/or climatic variations in bone weathering patterns. From the preceding information, information suggests that bones in shade environments weather at slower rates than those in full sun, and bones in cool conditions can weather slower than bones in hot conditions.

Statement of Problem

Taphonomic studies and their applications, including forensic anthropology, archaeology, climatology, paleontology, etc., are only as good as their regional applicability. Behrensmeyer's (1978) study about bone weathering in a tropical climate of Africa, and the resultant bone weathering stages, has been referred to time and again by researchers studying bone accumulations in other regions of Africa, in temperate climates, and in cold environments, to name a few. However, several climate zones have not been represented by taphonomic studies, including the Mediterranean climate zone of the Sierra Foothills of Placer County, California (Figure 1).
Figure 1. Climate Zone Map, showing the Mediterranean Zone of the research site.

(http://tornado.sfsu.edu/geosciences/classes/m356/RainfallVariability/TempVar.html)

Project Summary

This thesis proposes to test Behrensmeyer's six stages of bone weathering in the Sierra Foothills of Northern California. This area represents a Mediterranean climate with geography and vegetation similar to that of the Jordan Valley in Israel (Lotan 2000).

The research completed for this thesis will be a positive addition to the growing literary catalogue of taphonomy. The goal of this thesis research is to identify whether or not bones will weather in the Northern California environment following Behrensmeyer's Weathering Stages. The results of this study will be relevant and applicable to various disciplines, including archaeology and anthropology, as well as sub-fields within these disciplines.
CHAPTER 2

LITERATURE REVIEW

History of Taphonomic Studies

During the third decade of the 20th century Weigelt (1927) produced a study written in a narrative format, about the decomposition of animal remains in the southern United States and their possible transition into the fossil record. Weigelt (1927) studied how animals died naturally, the circumstances and environmental conditions leading to their death, and the decomposition process of the remains. Weigelt discussed what occurs to non-human and human remains while they remain in surface contexts, and his main focuses were soft tissue decomposition and the effects of gravity and scavenger disarticulation on skeletons. There also is a brief mention of the lack of research into decomposition for the purpose of forensic medicine (Weigelt 1927). Although the book does not refer in depth to the process of bone decomposition or weathering, Weigelt's (1927) study is considered the first definitive volume delving into the details of the decomposition of animal remains. In 1940, not long after Weigelt's publication, the field of taphonomy was formally defined by Efremov (1940). Taphonomy, according to Efremov (1940), was a sub-discipline to the field of paleontology, as the study of how animal remains transitioned from living organisms to fossils in the very long term. The term "taphonomy" has come into use with many other modern fields of study, including forensics and archaeology, with the underlying definition as meant by Efremov: what happens to animal, or vegetal, remains after death and before rediscovery. Bone weathering research began in earnest in the 1970's, starting with Shipman's (1977) bone
weathering study at Fort Ternan, Kenya, the product of which was her own list of nine bone weathering "stages". Shipman was concerned primarily with two bone weathering aspects: the contributing factor of microenvironments and the results, i.e., bone coloration. Regarding the coloration of bones, Shipman (1977) believed it reflects several factors that affect the preservation of bone, including depositional sedimentary environment and depositional microenvironment.

The study that may have had the most impact on the subject of bone weathering has been the 1978 paper by Behrensmeyer. Behrensmeyer's (1978) paper outlined very specifically how to identify six stages of bone weathering using macroscopic changes of the bone material, from Stage 0 with no noticeable changes and the bone still having a greasiness to it, to Stage 3 with textural changes and deep cracks in the bone surface, to Stage 5 in which bones are essentially falling apart. Further studies into bone weathering have either been based on or have referred to Behrensmeyer's original 1978 publication, including but not limited to, Fernandez-Jalvo et al. (2002), Gifford (1980), and Janjua and Rogers (2008); these are discussed later. Behrensmeyer's weathering stages are sometimes used for direct identification of a bone's age, but recent research critically examines Behrensmeyer's six stages for their relevance to weathering in various environmental and geographical contexts.

Byers (2005) lists five reasons for bone weathering to occur at different rates in different regions. The first reason is the effect of climate on tissue loss, i.e., different geographic locations have different climates, which in turn allows for different rates of weathering. The second reason is variation in tissue decomposition rates, which causes an
uncertainty in the post-mortem interval. The third reason is the "continuous spectrum," (Behrensmeyer 1978) meaning that elements of a skeleton do not always fit one category of a weathering stage, but rather have characteristics of two or more stages on a single element. The fourth reason is the fact that bone weathering rates are generally identified from elements that have been weathering sub-aerially, making it unreasonable to use weathering stages to identify the age of a skeletal element that has been buried. The fifth, and final, reason provided by Byers (2005) is varied temperature fluctuations throughout the year in different geographic locations; because of temperature fluctuations decomposition and weathering rates will vary according to the time of year of deposition the skeleton. All of these reasons give cause for further research into bone weathering rates in various scenarios and environments.

In the paper A Critical Evaluation of Bone Weathering As An Indication of Bone Assemblage Formation, Lyman and Fox (1989) state that Behrensmeyer's stages of bone weathering have been applied "uncritically" to bone assemblages, and that the stages have generally gone untested. Lyman and Fox also criticize the assumption often made that bone weathering ceases as soon as a bone is buried. The criticisms of Lyman and Fox (1989) of the application of Behrensmeyer's Weathering Stages and continued weathering of bones in subsurface contexts are issues that lend strong support to the necessity for continued field research into bone weathering.

Many factors affect the process of bone weathering, including either exposure to sunlight or protection by shade, the precipitation rate, surface or sub-surface deposition, soil type, wind, and vegetation. Questions about bone weathering that require further
study include weathering rate in surface and sub-surface contexts, and bone coloration due to deposition factors, e.g., soil minerals, vegetation presence, and sunlight exposure. This thesis study concentrates on the weathering rate of bones in exposed and shaded subaerial (surface) conditions.

Structure and Chemistry of Bone

The speed at which bone weathers is a measurement of time (Lyman 1994); a certain length of time is necessary for bones to achieve each progressive stage of weathering. The rate of bone weathering is a result of many factors, including the composition of bone, the structure of bone, and the local environmental and weather conditions (Johnson 1985). Within the primary topic of bone technology and the usage of bones as tools, Johnson (1985) also discusses the biomechanics, structure, and composition of bone, which are relevant to the subject of bone weathering. Bone weathering has two overall causes: desiccation and chemical processes, both of which can occur whether a bone is in a sub-surface context or exposed on the surface. Surface exposure can cause a bone to desiccate, which leads to "micro-cracking", and eventually exfoliation of the cortical surface of the bone (Johnson 1985). Johnson (1985) believes that bone weathering is dependent on two main factors, the local environment and the length of exposure.

In a chapter from Forensic Taphonomy: The Postmortem Fate of Human Remains (Haglund and Sorg 1997) Schultz discusses bone structure and what happens to buried archaeological bone. According to Schultz (1997), bone that has been excavated from a sub-surface context will have lost a certain amount of elasticity depending on the length
of internment, and often is brittle due to decalcification from chemical changes. He comments that excavated archaeological bone has often been decalcified and is dry, and should not be sampled for slide mounting using a microtome because of its brittleness. On the other hand, soil mineral content, such as the presence of copper, can sometimes protect bone (Schultz 1997); Schultz does not provide an explanation for this phenomenon.

In a study about the degradation of DNA in bones by Misner et al. (2009), the authors used Behrensmeyer's (1978) bone weathering stages to identify the weathering stages of skeletal remains from the Voegtly Cemetery in Pittsburgh, Pennsylvania. Misner et al. (2009) classified the weathering stages of 36 skeletons from the Voegtly Cemetery, which itself was aged from between the years 1833 and 1861. Due to specific needs for their study the authors also developed a four-stage bone weathering classification system. Based on their finds, Misner et al. (2009) realized that DNA levels are not correlated with the weathered condition of bone, and regardless of a bones physical condition, the authors were still able to extract DNA. In addition they found that dense, compact bone such as that of the femur was usually less weathered than spongy bones like ribs and pelves. Lastly, Misner et al. (2009) state that microenvironment has the largest effect on the condition of bones over time, and local pH levels can affect bone and degrade its DNA.

Another factor of bone weathering that has not been studied extensively is bone coloration or color staining. The color of a bone can be changed for various reasons, such as bleaching from sun exposure or the addition of color due to the mineral content of
soils. Huculak and Rogers (2009) believe further research is necessary into the effects of bone weathering on bone coloration and make several suggestions, such as the required length of time for bone to become sun-bleached, and differentiations in bone color according to geographic location.

In their study about bone coloration from surface and sub-surface contexts, Huculak and Rogers (2009) used two scenarios, one in which 40 juvenile pig humeri bones were buried for four weeks before being exposed on the surface for four weeks, and an opposite scenario in which bones were exposed on the surface for four weeks before being buried for four weeks. The goal of Huculak and Rogers (2009) was to discover whether subaerial exposure or the burial of a body might cause bone staining during the weathering process. Comparing bone coloration to Munsell® Color Charts, the authors identified five color schemes and two conclusions from the two research scenarios. The five color schemes were as follows: light yellowish brown, resulting from soil staining; dark reddish brown from hemolysis; white due to sun bleaching; dark reddish grey was staining from decomposition fluids; and greenish grey and olive were colors due to various fungi, primarily *Aspergillus* and *Penicillium*. Bones that were buried first showed signs of bleaching with no fungal growth, whereas bones that were exposed then buried resulted in a green coloration from fungal growth, but no bleaching (Huculak and Rogers 2009).

Guy et al. (1997) studied the rate of weathering of human infant, juvenile, and elderly bones versus those of human adults in an attempt to explain why there is a difference. Bones of infants, juveniles, and the elderly weather at a faster rate than do
adult bones perhaps due to size and low mineralization. Bone begins losing mineral content at birth for the first couple of years of life, then the mineral content increases into adulthood, until later in life when bone mineral content begins to drop again to levels similar to that of infancy (Guy et al. 1997). The bones of human children, and presumably the juveniles of other mammals as well, are brittle, not very strong, and have low density. The low density and mineralization of infant bones can allow for: minerals to leach easier due to water movement, for crushing due to covering soil, and for further demineralization by acidic soils (Guy et al. 1997). Because infant bones have a relatively low density, they may be affected more easily than adult bones by weather elements such as sunlight and hot and cold temperatures.

Prior to Behrensmeyer's (1978) weathered bone study in Kenya, another researcher had studied weathered bone in order to understand the structure and strength of bone via weathering cracks. Beginning with a paper in 1969 and continuing in research papers thereafter (Tappen 1969, 1976; Tappen and Peske 1970), understanding that weathering cracks were informative in the study of the functional analysis of bones, Tappen (1969) discovered several factors that can contribute to the development of weathering cracks on bones while in subaerial contexts. First, weather elements such as sunlight, cold, and rain as well as local environmental chemical conditions can cause the racemization of protein, and affect the collagen fibers of bone. After bone collagen denatures, weathering cracks will occur in the same direction as collagen fibers, with cracks occurring along the length of long bones, for example (Tappen 1969). The second contributing factor of weathering cracks is bone shrinkage; Tappen (1969) discovered
that weathering cracks tend to occur in bones that have been shrunk. The third cause of bone cracks is decalcification (Tappen 1976); for example, in order to prepare bones for making split-line crack preparations, Tappen (1976) used a dilute acid solution to decalcify bones, which removed the bone mineral component and left behind a non-mineral "ghost" of the bone, making it easier for the methodology used to artificially start cracks in the bone cortex. The usage of acidic solutions to decalcify bones in order to make split-line cracks artificially seems to be more evidence pointing to how an acidic soil will interact with bones and cause weathering cracks to occur naturally.

In the informative volume *Vertebrate Taphonomy*, Lyman (1994) discusses many aspects of bone weathering, including rate and duration of subaerial exposure. Lyman (1994) believes three factors contribute the most to the weathering rate of bones, and refers to Behrensmeyer (1978) for all of them. The first factor is the size of a bone; according to Behrensmeyer (1978), small compact bones will weather at a slower rate than larger bones, even if they are from the same skeleton. The second factor is that bones from different taxa and body sizes will have varying weathering rates (Behrensmeyer 1978). The third factor is microenvironment: a harsh or unfavorable environment immediately surrounding a bone can cause a faster weathering rate (Behrensmeyer 1978). Bone porosity can make a difference in the speed of diagenetic change; bones that are more porous will "exchange" ions with the depositional sediment faster than bones with more density (Lyman 1994).
Bone Weathering: An Explanation

What is the cause of bone weathering? What factors cause a bone, or bones, to crack, and show signs of exposure to elements, and possibly eventually disintegrate? In general, there are several factors that seem to be the primary causes of bone weathering. These weathering-inducing factors include water flow, desiccation, soil chemistry, temperature, and ultra-violet (UV) exposure. Surface exposure of bone allows for exposure to UV rays, wind, and temperature fluctuations, all of which can cause the desiccation of a bone.

Bones exposed on the ground surface can become air-dried, and bones in an air-dried condition are less durable and less flexible than bones that still have moisture content (Johnson 1985). Dried bones are brittle, and when bones become dry micro-cracks and split-line cracks occur between collagen bundles. Micro-cracks are tiny cracks that create a mosaic pattern on the bone cortex, and split-line cracks are larger cracks that occur between collagen bundles. Micro-cracks and split-line cracks will eventually cause the cortex of a bone to exfoliate (Johnson 1985), which is one of the weathering characteristics defined by Behrensmeyer (1978). As desiccation and exfoliation of a bone progress, a bone will eventually disintegrate completely, unless it becomes buried and the fossilization process begins (Johnson 1985). Freezing and freeze-thaw cycles also cause moisture loss in bones (Johnson 1985), a process that has been studied by authors including Texier et al. (1998). A bone will also desiccate and develop micro-cracks after the loss of moisture from freeze drying, a process that changes the biomechanics of a bone similar to moisture loss from drying any other way (Johnson 1985).
What causes bones to crack? According to Tappen (1969) and Tappen and Peske (1970), any weather effect or process that causes shrinkage of a bone is the cause of cracks in a bone. Tappen and Peske (1970) discovered that bones that shrink due to decalcification from exposure to acidic solutions, weather, or salt, have a tendency to crack, whereas buried bones are less likely to develop cracks. It is possible that water loss due to weather or salting (producing a gradient which will cause water to flow out of a bone), causes a bone to shrink as it dries, and during this process split-line cracks will develop between collagen bundles.

Ultra-violet rays from sunlight are another source of bone weathering (Andrews 1995a; Fernandez-Jalvo et al. 2002; Koch et al. 2001; Texier et al. 1998), as well as chemistry, freeze-thaw cycles, water flow (hydrolysis), and hot temperatures. Fernandez-Jalvo et al. (2002), claim that UV rays are most responsible for bone weathering on subaerial surfaces, whereas soil chemistry is the cause of damage to buried bones. Ultra-violet rays, according to Fernandez-Jalvo et al. (2002), cause the physical breakdown of bone collagen. Fernandez-Jalvo et al. (2002) refer to a bone weathering scenario in which a single skeletal element in a desert context, partly buried and partly exposed to sunlight, exhibited bleaching on the exposed portion of bone after only several years, whereas the buried portion maintained a brownish color (Andrews 1995b). Regarding soil chemistry and bone weathering, Fernandez-Jalvo et al. (2002) posit that alkaline soil will affect organics, such as tooth dentine and roots, as well as causing the exfoliation of bone cortex by affecting bone collagen, and acidic soil will affect the mineral portion of a bone and cause corrosion. A study by Koch et al. (2001) is supportive of the findings by
Fernandez-Jalvo et al. (2002), that bone weathering can be caused by UV rays and soil alkalinity. Koch et al. (2001) examined the bones and results from the Amboseli Desert study by Behrensmeyer (1978), and found that over time apatite crystals in the bones had increased in size, and the solubility of protein increased while its’ concentrations decreased. The conclusion of Koch et al. (2001) as to what caused the change in the bone apatite crystals and protein solubility is that the combination of UV rays and soil alkalinity caused the hydrolysis of bone collagen polypeptides, and allowed them to be leached from bone through the movement of water. Over time, with little or no shade or protection, bones in the Amboseli Desert progressively weathered due to sun exposure and soil pH, and eventually would disintegrate completely (Koch et al. 2001).

Texier et al. (1998) present results that dispute the importance placed on UV rays in the process of bone weathering as given by Fernandez-Jalvo et al. (2002). Texier et al. (1998) believe that freeze-thaw cycles are more important to the modification of bones than UV rays, based on their study of the effects of a periglacial environment on archaeological assemblages including bone. A freeze-thaw cycle will cause cracks, peeling, and shattering of bones in a fairly rapid succession (Texier et al. 1998).

**Animal Bone and Weathering**

Bone weathering has been studied using the bones of many types of animals, including terrestrial and sea mammals, birds, and occasionally herpetofauna (reptiles). In regard to sea and land mammals, there are bone weathering studies of cow bones (Andrews and Cook 1985), pig (Janjua and Rogers 2008; Reeves 2009; Schoenly et al. 2006), oryx (Lotan 2000), and seal, walrus, caribou, and bear (Todisco and Monchot
Domestic pig (*Sus scrofa*) bones seem to be the most commonly used for bone weathering experiments. This may be for a couple of reasons, the first being that it may be easy to obtain through local butchers, the second reason being a pig's anatomical and physiological similarity to the human body (Schoenly et al. 2006).

As the primary subject of the Schoenly et al. (2006) paper is the usage of bone weathering in a forensic setting, i.e., the length of time it takes bones to get to different weathering stages and its applicability to human skeletal remains in legal cases, the paper suggests the usefulness of animal bones that will weather similarly to human bones. Aerssens et al. (1998) compared bones for this exact purpose, i.e., which animals bones act more precisely as analogs to human bones. Aerssens et al. (1998) analyzed and tested the biochemistry, strength, and density of femoral shaft and lumbar vertebral bone samples of the seven most common vertebrates that are used for bone tests. The seven vertebrates tested include human, dog, pig, cow, sheep, chicken, and rat. Biochemical analyses indicated that rat bones are the least similar to human bones, and dog bones are the most similar (Aerssens et al. 1998). According to strength and density tests in the Aerssens et al. (1998) study, both pig and dog bones are the most similar to those of humans. Aerssens et al. (1998) used female bones from all of the species, including human. The results of the strength and density analyses performed by Aerssens et al. (1998) are suggestive that domestic pig (*Sus scrofa*) and dog (*Canis familiaris*) bones may be the best analogs for human bones for bone weathering studies.

Regarding actualistic studies that have used animal bones for forensic, taphonomic, or archaeological research, there are two preferred animals: the first
preferred animal is canine (*Canis familiaris*) and the second preferred animal is the
domestic pig (*Sus scrofa*). Canine bone is preferred for forensic studies because it
resembles human bone more so than bone from other typical test animals (Aerssens et al.
1998). Pig bones are the other option, as domestic pigs (*Sus scrofa*) have been called the
"second best animal" for studies (Huculak and Rogers 2009).

Aerssens et al. (1998) conducted a series of tests on bones from various animals
that are commonly used as analogues to humans for FDA trial runs; their purpose was to
determine which animal bone is most analogous to human bone. The samples included in
the Aerssens et al. (1998) study were from dog, cow, sheep, pig, rat, and chicken, in
addition to adult human; all of the samples were from mature females of the various
species. Samples of bone were taken from femoral diaphyses (shaft) as well as lumbar
vertebra from the various test species. In stress tests, pig and dog bone most resembled
human bone (Aerssens et al. 1998); in bone composition tests, including bone mineral
content (BMC), and volumetric bone mineral density (vBMD), dog bone most resembled
human bone. Aerssens et al. (1998) conclude that animal bone with the most
resemblance to human bone in strength and composition is from dogs, and of all the
animals whose bones were compared to human bone in the tests, rats are the most
different.

Domestic pigs (*Sus scrofa*) have often been used for actualistic studies, including
bone coloration changes from the decomposition process (Huculak and Rogers 2009), the
speed of decomposition (Schoenly et al. 2006), the rate and patterns of bone weathering
Janjua and Rogers (2008), and the damage or alterations caused to bone by scavenging vultures (Reeves 2009).

In a study conducted to determine the cause of coloration differentiation of bones during the taphonomic process, Huculak and Rogers (2009) used 80 defleshed and 20 fleshed pig humeri for two scenarios. Pig humeri were chosen for the study because of the survivability rate of the humerus in forensic contexts (Huculak and Rogers 2009). In one scenario the pig humeri were buried for several weeks and then exposed to sunlight, and in the other scenario the opposite was done: bones were first exposed then buried. The goal of the research was to determine what effect exposure, burial, and tissue decomposition had on coloration or discoloration of bones. The color of the bones was determined using a Munsell Color Chart (Huculak and Rogers 2009).

Janjua and Rogers (2008) conducted an investigation into bone weathering and its relation to time since death; this field study also used pig (Sus scrofa) bones. The researchers (Janjua and Rogers 2008) used 24 pig femora, 1 pig humerus, and 25 pig metatarsals, obtained from either a butcher or a farm. The femora were already defleshed prior to the researchers obtaining them, but it was necessary to remove the flesh from the pig feet to expose the metatarsals. It was important for the pig bones to be exposed as the primary purpose of the study was to investigate bone weathering patterns, not soft tissue decomposition; although some pig hind sections with flesh were also used in part of the study to investigate decomposition rates (Janjua and Rogers 2008). There are several reasons to use pig bones for field research studies, including their ease of obtainment, their low cost, and they fulfill the minimum 5 kilogram requirement for mammal bone
weathering rates as established by Behrensmeyer (1978). Janjua and Rogers (2008) let the bones for their weathering study remain exposed to weathering elements for 291 days. Bone color changed by day 155, and the equivalent of Behrensmeyer's Stage 1 cracking occurred by day 181 (Janjua and Rogers 2008). Janjua and Rogers (2008) describe in detail their methodologies for studying bone weathering patterns and rates, including observation and recording methods, obtaining materials, and site and material set-up methods.

Two more studies, Reeves (2009) and Schoenly et al. (2006), also describe the usage of domestic pig carcasses in actualistic taphonomy studies. Reeves (2009) paper, *Taphonomic Effects of Vulture Scavenging*, describes the speed at which a pig (*Sus scrofa*) carcass is scavenged by vultures, as well as the damage and scattering that occur to the bones when carcasses are scavenged by vultures. Reeves (2009) used pig carcasses because of their general acceptance as analogues to human remains for the purpose of research. Schoenly et al. (2006) describe the usage of pig carcasses in college courses to teach students forensic science, such as decomposition rates, entomology, effects of weather, and observation and recording. As with other researchers, including Reeves (2009), Aerrsens et al. (1998), and Janjua and Rogers (2008), the reason Schoenly et al. (2006) recommend using pig carcasses for forensic research is their anatomical and physiological similarity to humans.

*Environmental Effects on Bones*

Stojanowski et al. (2002) discovered that burial depth, or the stratigraphic level of a burial, as well as water action can cause physical damage to bones. In examining the pH
levels in and around Windover Pond in Florida and the condition of the skeletons of upwards of 168 individuals from all age ranges that had been buried there, Stojanowski et al. (2002) made several discoveries. The pH levels were mostly neutral at Windover Pond; therefore chemistry was not to blame for any osteological deterioration. Stojanowski et al. (2002) also found that dense bone such as long bone diaphyses were more likely to have survived than less dense bone such as vertebra and pelves. The authors (Stojanowski et al. 2002) believe that water action at shallower burial depths (i.e., closer to the surface) was a likely cause for bone destruction, whereas deeper burial levels may have assisted in the improved preservation of bone.

Examining bison and cow bones from archaeological sites in South Dakota, White and Hannus (Dirkmaat, et al.) determined that acidic soils could definitely leach minerals from bones and cause "chemical" weathering. The authors (White and Hannus 1983) discovered that acidic soil can leach calcium (Ca) and phosphate (PO$_4$) ions from bones, causing a breakdown in the hydroxyapatite composition of bone. White and Hannus (1983) concluded that at higher pH levels hydroxyapatite is not very soluble, but as pH decreases, especially below 6, the solubility of hydroxyapatite increases.

In terms of what exactly causes the breakdown of bones during the weathering process, Koch et al. (2001) believe the most important factor is microhabitat. Other authors agree with this conclusion, including Tappen (1994), Behrensmeyer (1978), Sutcliffe (Sutcliffè), Texier (1998), and Shipman (1977b). The opinion of Koch et al. (2001) is that the factors of microhabitats, i.e., soil moisture, shade, and burial, can vary from location to location, and the overall effects of microhabitat differences are more
important than time when it comes to bone weathering. The two most important factors to bone weathering, according to Koch et al. (2001) are ultraviolet radiation from sunlight, and highly alkaline soils; these two factors cause the hydrolysis of protein peptide bonds within the bone, which causes leaching of bone constituents to occur at a faster pace.

Continuing with causes of bone weathering in both surface and sub-surface contexts, Fernandez-Jalvo et al. (2002) offer what they consider to be primary causes. Surface weathering is caused primarily by the UV rays from direct sunlight, according to the authors (Fernandez-Jalvo et al. 2002), which causes collagen protein to breakdown and leads to the cracking and exfoliation of the outer-most bone surfaces. This can be seen in cases where a bone in a sub-aerial context is either shaded by vegetation, or in situations where a direct comparison can be made on a single bone that is both exposed and buried. In cases where a bone is partially exposed to direct sunlight, and partially buried, the exposed portion of bone is often bleached and the buried portion of bone can appear unweathered (Fernandez-Jalvo et al. 2002). Sub-surface weathering, or "soil corrosion" as Fernandez-Jalvo et al. (2002) refer to it, is the decomposition of bone caused by the pH, or chemistry, of soil. The authors proclaim that highly alkaline soil, between pH 7 and 14, alters the organic portion of bone and teeth (i.e., collagen) and causes dryness, after which bones and teeth will crack, and then exfoliate. Highly acidic soil, on the other hand, affects the mineral portion of bones and teeth, and will cause them to appear corroded.

An acidic pH in water or soil can cause the loss of the mineral portion of a bone, via water action which causes minerals to leach from bone (i.e., diagenesis), and can also
be the catalytic reaction needed to leach protein from a bone (Hare 1980). As water reacts with bone protein, racemization and hydrolysis of protein can occur and occasionally a bone will develop a chalky texture. If a bone survives long enough in soil that has water flow and mineral content, the external mineral content will eventually replace a bone's minerals, and over time the bone may become fossilized (Hare 1980).

Environmental Studies on Bone Weathering

Bone weathering studies have been conducted in a variety of environments and climates, including arid North American and African deserts, tropical forests, permafrost and periglacial environments, mild Mediterranean environments, temperate locations, and other arid or semi-arid environments. The primary factors reviewed here include: environment type, precipitation, vegetation, sun exposure, temperature, soil chemistry, type of animal, skeletal element, and speed of weathering.

Behrensmeyer (1978) worked in the Amboseli Basin in Africa, studying bone weathering in multiple environments within a very specific location of one continent, and included the following environment types: swamp, dense and open woodlands, plains, bush, and lakebed. Behrensmeyer (1978) defined six arbitrary stages of weathering from the observation of animal bones located in the lakebed region of Amboseli Basin at the northwest base of Mount Kilimanjaro in Kenya. The Amboseli Basin National Park is centered on the equator on the eastern side of the African continent. The soils within the basin generally have an alkaline content, the temperatures fluctuate between hot middays and cool nights, and there is occasional heavy rain (Behrensmeyer 1978). Behrensmeyer's (1978) study is based on the progressive weathering condition of the skeletal remains of
35 mammals with known dates of death and with a body size greater than 5 kilograms, and included remains from zebra (*Equus burchelli*), cow, Grant's gazelle (*Gazella granti*), rhinoceros (*Diceros bicornis*), and wildebeest (*Connochaetes taurinus*). The study also included the weathering stages for the total mammal sample within the study area, a total of 1534 carcasses (Behrensmeyer 1978). Behrensmeyer (1978) concluded that bone weathering effects are caused by temperature and moisture fluctuations; bones of juveniles and small animals weather more rapidly than those of adults and large animals; and bones tend to weather slower in more "equable" environments, i.e., swamp and dense woodland versus desert. In a subsequent study, Behrensmeyer et al. (Behrensmeyer, et al.) commented that bones in tropical, temperate, or arctic environmental settings weather at slower rates than those in dry seasonal settings such as savannahs and hot, dry deserts.

**Desert Environment**

Andrews (1995a) refers to camel bones located in a desert context in the United Arab Emirates. The bones were located in a "sheltered valley" with scant vegetation (Andrews 1995a:149), and the weathering process began in 1984. Andrews (1995a) commented on the condition of a bone that had been partially exposed and partially buried for 6 years. The exposed portion was within Behrensmeyer's Stages 1-2, similar to the rates identified by Behrensmeyer (1978) in the Amboseli Basin, whereas the portion of bone buried in sand was still in Bone Weathering Stage 0, with little or no identifiable weathering (Andrews 1995a). The "sheltered valley" location as well as vegetation cover
within it could both have been contributing factors to the camel bone weathering patterns in the desert setting being consistent with Behrensmeyer's weathering stages.

In the arid Namib Desert of Africa at a research station approximately 70 miles inland east of Walvis Bay, Namibia, Brain (1967) studied the phenomenon of "pseudo-tools". "Pseudo-tool" bones were believed to have been bones made into tools by people of local tribes, but in fact had simply been naturally abraded and polished over time by the movement of the sand in which they have been deposited (Brain 1967). The bones examined by Brain (1967) had mostly been discarded by the Hottentot people around their camps. Many of these bones had been lying on the sandy desert surface, fully exposed to human and animal movement, sunlight, and rain. The geographic region of study receives only about a ½ inch of rain per year (Brain 1967), therefore it is typically very dry. Bones that have been left to weather on the surface in the Namib Desert become bleached from sun exposure, and they also develop a chalky surface from chemical alteration (Brain 1967). Brain (1967) claims that a chalky surface can develop on bones when they weather in an arid environment, but that this effect can also occur to bones lying in well-drained locations in moist climates.

At the Tsavo East National Park in the sub-Saharan Desert of Kenya, northeast of Walvis Bay and Namibia, Coe (1980) observed and recorded the decomposition rate of the remains of four elephants for which there was a known date of death. The elephant remains were located in various habitats, including open range, riverine, and scrub environments. Elephant remains located in open habitats endured temperatures between 35-40°C (95-104°F), and the bones began to crack and exfoliate within 5 weeks after
exposure. Some of the bones in open habitats were also deposited upon lateritic soils, which are high in iron and aluminum and may affect the rate or effect of bone weathering (Coe 1980). A microclimate effect slowed the bone-weathering rate of bones situated in thick scrub or riverine locations, even at only a minimum of 2 meters away from bones located in open situations. Shaded areas in Tsavo East National Park may only reach up to 20°C (68°F) versus 35-40°C (95-104°F) in open areas; bones in shaded areas therefore endure much lower temperatures, and the rate at which bones crack and exfoliate slows down. In addition, bones in vegetated areas with humic material nearby were more likely to be stained brown by decomposing vegetation, unlike bones that bleached when located in open spaces (Coe 1980).

Gifford (1980) studied the bones of medium to large ungulates at Lake Turkana, northwest of Tsavo East National Park, and reported that these bones tend to survive at least fifteen years on the surface of well-drained areas, and bones aged between 17 and 20 years old had not even reached Weathering Stage 5. According to Behrensmeyer (1978), bones in open situations in Amboseli Park began disintegrating (WS 5) in less than 15 years; Gifford (1980) reported 15-year old bones still in Stage 4 at Lake Turkana, and bones between 17 and 20 years old were "flaky and fragile", and appeared to only be in Weathering Stage 4.

In North America, Galloway et al. (1989) and Galloway (1997) studied the decomposition rate of human remains from 189 forensic cases from the arid Arizona-Sonoran Desert in Southern Arizona. Temperatures in the Arizona-Sonoran Desert range from the mid-60's Fahrenheit during the winter months of December and January to
above 100°F during the months of June and July (Galloway 1997). The desert also maintains low average humidity of 30%, and dips to lower humidity levels between 17 and 18 percent, with an average of 9 to 11 inches of rain per year. The high temperatures and low humidity of the Arizona-Sonoran Desert tend to cause remains that are exposed to the elements to decompose very quickly (Galloway 1997). In the Arizona-Sonoran Desert, remains begin to skeletonize after between two and nine months of exposure. During the skeletonization process, bones can begin to bleach, occurring between two and six months after skeletal exposure begins; bone exfoliation usually occurs between 12 and 18 months, but sometimes as soon as four months after exposure (Galloway 1997). The speed at which bodies and bones decompose in the Arizona-Sonoran Desert is primarily due to high ambient temperatures, but other factors, including humidity and soil pH, also contribute to the rate of decomposition (Galloway 1997).

Tropical Environment

Two separate bone weathering studies conducted in rain forest contexts agree that bone weathering does occur there, but at a slower rate than in open landscape contexts such as savannas. Kerbis-Peterhans et al. (1993) researched the fate of primate skeletal remains in rain forests, conducting the study by locating and examining chimpanzee remains in the Kibale Forest Reserve in western Uganda. Bones in the Kibale Forest are subject to a fair amount of rainfall and humidity, mild temperatures averaging between 61°F to 75°F, and more shade than if in a savannah setting (Kerbis-Peterhans et al. 1993). In addition to the relatively mild microenvironment in the Kibale Forest, the soil pH there is close to neutral, having been recorded at 5.92 (Kerbis-Peterhans et al. 1993). Kerbis-
Peterhans et al. (1993) refer to the condition of the remains of eight chimpanzees (*Pan troglodytes schweinfurthii*) that had been located in two different areas of the Kibale forest, namely Kanyawara and Ngogo. Ranging in element completion from only a skull to a complete skeleton, the bones of all eight chimpanzees were in Weathering Stage 0 (Behrensmeyer 1978; Kerbis-Peterhans et al. 1993). In addition to the chimpanzee case studies, which ranged in exposure length from an unknown amount of time to several months (Kerbis-Peterhans et al. 1993), the authors claim that results from bone caching experiments indicate bones may remain in Weathering Stage 0 in the Kibale Forest for at least several years due to the lack of full sunlight, vegetation cover, mild temperatures, humidity, and neutral soil chemistry.

Another tropical forest bone weathering study, Tappen's (1994) *Bone Weathering in the Tropical Rain Forest*, was conducted in the Ituri Rain Forest in Zaire, approximately 150 miles from the Kerbis-Peterhans et al. (1993) study in the Kibale Forest. Tappen compares bone weathering from two different environments: an equatorial savanna, and a tropical rain forest, which will be the main focus here. Tappen (1994) studied the remains of eight elephants (*Loxodonta africana*), the bones of which are much larger than those of the chimpanzees of the Kerbis-Peterhans et al. (1993) study. Similar to the Kibale Forest, the vegetation of the Ituri Rain Forest is thick, but rainfall is higher in the Kibale Forest compared to the Ituri Forest (1900 mm per year average in Kibale compared to about 1500 to 1700 in Ituri), and the soil pH is lower in the Ituri Forest, ranging between 4.0 and 4.25, compared to 5.92 in Kibale. The exposure length for three of the eight sets of elephant remains is unknown; the bones of one of the
three were judged to be in Weathering Stage 2 (Site I), and the bones at the other two elephants were in Weathering Stage 0 (Sites II and IV). It was determined that the bones at Sites III (over seven years old) and VI (16 years old) were in Weathering Stage 0; these were located in the forest. At Sites VII (10 years old) and VIII (over 15 years old), also located in the forest, the bones were either in Weathering Stage 1 (Site VII) or between Stages 1 to 3 (Site VIII). Bones at the only site with sun exposure (Site V) were believed to be between 1 and 25 years old; these bones were in Weathering Stage 1, and 13 of the 32 bones had cracks from weathering. According to Tappen (1994), bones in the Ituri Rain Forest weather slowly because the combination of shade, mild temperatures, and humidity do not allow wet/dry cycles or extreme dryness. Also, cracks are likely to occur equally on any surface of a bone when located in a rain forest context, unlike bones that are exposed to sunlight which tend to crack on the exposed surface or bones that crack on the underside after exposure to soil pH (Tappen 1994).

Permafrost and Periglacial Environments

In cold environments, weathering damage to bones primarily comes from freeze/thaw cycles, sunlight, and wind. The locations where the studies have been performed include the cold environment of southern Ontario (Janjua and Rogers 2008), periglacial environments north of Canada and in the French Alps (Texier et al. 1998; Todisco and Monchot 2008), and the permafrost environment of the Canadian High Arctic on Bathurst Island (Sutcliffe 1990).

Janjua and Rogers (2008) studied weathering effects on bones in the cold environment of southern Ontario, in an attempt to determine if bones weather there at a
rate similar to Behrensmeyer's (1978) weathering stages. The research by Janjua and Rogers (2008) used 25 domestic pig (*Sus scrofa*) femurs and metatarsals, what the authors comment on as being the second best analogues to human bones. The study lasted 291 days, starting in the fall of 2004 and lasting until the following fall in 2005. During the spring and summer seasons of the study period the bones began exhibiting weathering damage in the form of cracks on the diaphyses of three femurs. These cracks first appeared on the 181st day (Janjua and Rogers 2008), which, according to the authors, are Stage 1 cracks (Behrensmeyer 1978) that show up between 0 and 3 years. The reason for cracks appearing earlier than expected was due to a freeze-thaw effect, which increased the speed of the weathering process (Janjua and Rogers 2008).

There are two bone weathering studies performed in periglacial environments; one study was conducted in the French Alps (Texier et al. 1998), and the other study is on the survival of bones on Qikirtaq Island in Canada (Todisco and Monchot 2008). The primary factor affecting bones in periglacial environments is a freeze-thaw effect, which causes the shattering and fragmentation of bones.

The goal of Texier et al. (1998) was to evaluate the effects of a periglacial environment in the French Alps on archaeological artifacts, including bone. Texier et al. (1998) used fresh bones from cow, fox, and sheep, fossil bones from reindeer and horse, fresh teeth from sheep, and fossil teeth from Saiga antelope (*Saiga tatarica*), as their test material for the bone study. Several test plots were arranged on the southeast facing slope of the Massif of La Mortice, at an elevation of 3090 meters (10,137 feet); these plots were meant to mimic archaeological sites found in southern France (Texier et al. 1998).
The bones and teeth were left in surface exposure situations, allowing them to be affected by weathering elements such as freezing cold and sunlight during the study period. The results of the study led to a conclusion that freeze-thaw cycles increase the rate of bone weathering (Texier et al. 1998). Within the four year period, the study bones were affected in the following ways: long cracks developed on fresh mandibles; the development of platy or scaly disintegration patterns on long bones; "little stick" fragmentation, surficial peeling, and sometimes frost shattering; and the shattering of fossil teeth (Texier et al. 1998).

In northern Canada between Victoria Island and Nunavik lies the Palaeoeskimo site of Tahyara on Qikirtaq Island, where Todisco and Monchot (2008) conducted a bone weathering study based on a periglacial setting. Qikirtaq Island is located above Hudson Bay, within a geographic continuous permafrost zone that encourages the long-term preservation of bones (Sutcliffe 1990; Todisco and Monchot 2008). The 1667 bones studied by Todisco and Monchot (2008) were recovered during the excavation of archaeological sites. The recovered bones fit into four non-human mammalian categories: large sea mammals, including beluga whales and walrus; small sea mammals, i.e., seals; terrestrial mammals, particularly fox, caribou, and polar bear; and unidentifiable bone splinters (Todisco and Monchot 2008). Bones were recovered from different cultural levels from varying soil depths. The majority of bones examined were from Level II, which ranged in depth from 25 to 120 cm below surface (Todisco and Monchot 2008). It was determined that the age of Level II was between 1900 and 2100 years BP, and Level III was around 2500 years BP (Todisco and Monchot 2008). Only bones from the
excavated cultural levels were analyzed; no bones from the surface level with recent exposure to weather elements were included in the analysis. Todisco and Monchot (2008) used the weathering stage identification methodology suggested by Behrensmeyer (1978) to identify the weathering stages of the excavated bones. What Todisco and Monchot (2008) discovered was that bones from all taxa are subject to weathering in similar ways; the only difference in weathering was in element type. The most weathered bones overall were spongy types, including vertebrae and ribs (Todisco and Monchot 2008). Longitudinal and irregular cracks, but no perpendicular cracks, were associated with long bones, but all bones were subject to irregular cracks (Todisco and Monchot 2008). Bones affected the least by weathering were from walrus; of the walrus bones, only an axis and two vertebrae showed significant weathering, and were categorized in Weathering Stage 4. Although the bones collected from the excavations on Qikirtaq Island were of a substantial age, ranging from 1900 to 2500 years old, they were all well preserved (Todisco and Monchot 2008). Todisco and Monchot (2008) believe the bone preservation is due to rapid burial of the remains, either soon after death or skeletonization; regardless, the bones were not subject to the exposure of weather elements long enough to become significantly weathered. Bones with a thin covering of soil were typically weathered more than bones in deeper depositions, possibly because shallower soil depths were more likely to be subjected to freezing temperatures than bones in deeper soils (Todisco and Monchot 2008).

Sutcliffe (1990) studied the long-term preservation of bones in several locations in the Canadian Arctic Islands within the permafrost zone of the Canadian High Arctic
region, including Eskimobyen, Brooman Point on Bathurst Island, Cape Storm, and Mercy Bay on Banks Island. Several microenvironments were identified that have varied effects on the preservation of animal remains within the High Arctic zone. The microenvironments identified and discussed by Sutcliffe (1990) include the permafrost layer, the active layer, and several subaerial microenvironments, including dry scree and bare rock surfaces, damp ground, and the seashore.

Sutcliffe (1990) reports that mammal remains, including soft tissue, were able to survive upwards of 800 years within the permafrost layer at Brooman Point. The preserved mammal remains at Brooman Point include whale, walrus, seal, polar bear, fox, and caribou, all of which appear to be household refuse and were impregnated with seal oil, which, along with the fact that the remains were located within a frozen layer of soil, possibly assisted in their preservation (Sutcliffe 1990). Mammalian remains were also identified from the active layer, above the permafrost layer; these remains were all skeletonized, presumably because the soil was not frozen, allowing for the decomposition of soft tissue (Sutcliffe 1990). In the permafrost zone, skeletonized remains on the ground surface have the potential to survive a long time. Deposited on dry limestone scree at Brooman Point, a moss-covered dog skull has survived about 800 years, a moss-covered seal skull has survived about 1,000 years, and mixed remains including some seal bones have survived upwards of 3,000 years (Sutcliffe 1990). Some of the 3,000 year-old bones had been "planed down", as Sutcliffe described the remains, possibly by wind-blown sand that caused a sandblasting effect. Other than being planed down and not of their original thickness, these bones, located on high beach areas, were in good condition
In areas with damp ground, bones were affected by algae either on their underside or on points that were in contact with or buried in the ground (Sutcliffe 1990). Two sets of remains of differing ages located on two different islands were noted to be in similar condition. The first set of remains were those of a muskox that died in 1967 and was examined in 1979, located in Polar Bear Pass on Bathurst Island; the other set of remains were of a muskox that died between 1855 and 1890, located on Banks Island. Of both carcasses, the bones that were above ground and exposed were apparently intact and in good condition; whereas the portions of bone and horn that penetrated the ground were in a rotted state, having been affected by ground vegetation and roots (Sutcliffe 1990).

Two whale skulls, as well as smaller bones, were located near the sea shoreline in Eskimobyen, and were approximately the same age as the Thule house sites nearby, giving them an age of around 800 years old (Sutcliffe 1990). Although the bones near the shoreline were bleached and lacked lichen growth on the exposed upper surfaces possibly due to salt spray from the close-by sea, they were apparently in better condition than the bones at the nearby Thule sites. Still, with bleaching and a lack of lichen growth on exposed surfaces, bones that were located near the shoreline in Eskimobyen exhibited algae growth on the unexposed underside (Sutcliffe 1990).

Large bones and robust bones, including skulls and adult limb bones from animals such as whales and muskox, are more likely to survive weathering as well as foraging by animals (Sutcliffe 1990). Seasonal changes in the continuous permafrost zone, including short summers and long winters, improve the likelihood that bones on the ground surface will survive a long time. With very low year-round average temperatures, it would seem
unlikely that bones endure freeze-thaw cycles very often, but instead may stay either cold or frozen, both of which could lengthen bone weathering rates and bone survival rates considerably. With radiocarbon dates of whale bones between 8,770 and 9,600 years old from Cape Storm east of Bathurst Island, Sutcliffe concludes that bones could survive longer than 9,000 years in permafrost conditions, particularly that of the High Arctic (Sutcliffe 1990).

**Mediterranean Environment**

From the mid- to late-1990's Lotan (2000) studied the survival of animal remains in the Jordan Valley of Israel. The Jordan Valley has a Mediterranean climate, with seasonal rain occurring between September and May that averages approximately 384 mm (about 15 inches) per year, and temperatures ranging from a high average of 49°C (120°F) in the summer and a low average of 3°C (37°F) in the winter (Lotan 2000). The purpose of Lotan's (2000) research was to investigate implications of the survival of animal remains on the study of human paleodiet, and the research involved the observation of the scavenging, weathering, and scattering of 16 animal carcasses, including 15 calves/cows (*Bos taurus*) and one male oryx, or gazelle (*Oryx leucoryx*). The carcasses were divided into 3 sub-groups. Group A included all young calves aged between 1 and 21 days; these were placed in the field during a five and a half month period from September 1995 to February 1996, during which time the carcasses and bones completely disappeared due to scavenging (Lotan 2000). Group B included one mature calf aged 175 days, as well as the oryx, which was aged 1.5 years; this group had the only surviving bones for which analysis of scavenging and weathering could be
performed. The fresh calf carcass was placed in the field in early September of 1996, and was collected 759 days later in mid-July of 1998. The fresh oryx carcass was placed in the field in early September of 1995 and the remains were collected 1126 days later in early October of 1998 (Lotan 2000). Group C consisted of two mature calves; observation was not completed for either calf, due to the lack of scavenging or the likelihood of natural burial.

Lotan (2000) reports that skeletal exposure of the Group B calf bones required at least 96 days. Bone weathering did not occur until after the bones were devoid of flesh and exposed to the elements. Only 18 of the calf's bones were recovered at the end of the study. The color of the bones was considered "normal" on the side exposed to sunlight, whereas the underside closer to soil was a darker color; in addition, it was the exposed sides of the bones that were affected by cracks (Lotan 2000). A radius diaphysis and a lumbar vertebrae were each rated at Weathering Stage 2 (Behrensmeyer 1978), being described as scaly and cracking on the sides exposed to the sun, after a 26-month exposure period. Mandibular and maxillary molars and premolars also displayed weathering cracks on the sun-exposed side. Although the buccal sides of the teeth were also cracked, Lotan (2000) suggests these cracks might have resulted from ambient temperature changes between night and day.

The remains of the oryx had been placed on the bank of a "wadi", a type of dry riverbed or small valley, which exhibited enough vegetation that it apparently impeded the weathering process of the bones. Only 10 of the oryx bones remained after three years of exposure. After more than 1100 days, the most weathering displayed on the surviving
oryx bones was Weathering Stage One (Behrensmeyer 1978); Lotan (2000) believes this is likely due to shade protection from the sun provided by vegetation in the depositional location of the wadi. Lotan (2000) does not provide information as to which of the oryx bones had weathering damage. The weathering stages of the calf and oryx bones of Group B fall within the guidelines of Behrensmeyers' (1978) Weathering Stages. The calf falls within the range of Stage 2, which is given a time scale of 2 to 6 years, and the oryx falls within the range of Stage 1, which is given a time scale of zero to 3 years (Behrensmeyer 1978).

Temperate Environment

Three studies representing temperate environments come from various locations on the southwest side of the United Kingdom, and include Draycott, Somerset (Andrews and Cook 1985); Stratton, Dorset, also in Somerset, near the southern shore of the UK (Andrews 1990); and Rhulen, Powys (Andrews and Armour-Chelu 1998), which is at the southwest side of the UK, north of the Bristol Channel. Compared to the climate and weather in Amboseli National Park, the location of Behrensmeyer's (1978) study, the weather and climate in the southern part of the United Kingdom is relatively cool (Andrews and Armour-Chelu 1998; Andrews and Cook 1985; Canty et al. 2012), with average annual low temperatures of 45°F, and average high temperatures of 56°F (Canty et al. 2012). Precipitation between Rhulen in Wales and Stratton in Somerset (Andrews 1990; Andrews and Armour-Chelu 1998; Canty et al. 2012) averages 29 inches per year, and days per year below freezing temperatures ranges from 20 in Draycott, Somerset (Andrews and Cook 1985; Canty et al. 2012) to 38 days in Rhulen (Andrews and
Armour-Chelu 1998; Canty et al. 2012); Amboseli does not get below freezing any time of the year.

With average temperatures in the southern part of the UK much lower than those of Amboseli National Park, and with more rainy days, it seems plausible that the weathering rate of bones is a little slower in the UK than in Africa. Andrews (1995b:350) states "My work...on weathering in temperate climates covering a period of 15 years suggests a protraction of Behrensmeyer's (1978) surface weathering stages by two to three times."

Studying the taphonomy of cow (Bos taurus) bones in Draycott, Somerset near the southern part of the UK, Andrews and Cook (1985) conducted annual observations to examine the condition of the remains over a course of 7 to 8 years. The cow died naturally, having fallen 14 meters (about 46 feet) off a limestone cliff in 1977. The authors observed the dispersal and condition of the carcass and bones until 1984, when the remaining bones (the ones that could be rediscovered) were collected and examined (Andrews and Cook 1985). The authors identified modifications to the cow bones caused by animal trampling, but there were no signs of weathering, especially cracks or exfoliation (Andrews and Cook 1985). The microenvironment of the location of the cow remains included a woodland setting at the base of a slope, which may have provided some cover from weathering elements, such as sunlight. After more than seven years the cow bones were still at Weathering Stage 0 with no evident weathering, but they should have at least been in Weathering Stage 3 according to Behrensmeyer (1978).
Although not covered by Behrensmeyer in 1978, Andrews (1990) was able to categorize the weathering progress of small mammal bones (under 5 kg in body weight) within the framework of the Weathering Stages. It appears that in a temperate climate the bones of small mammals may weather at rates similar the weathering rates of the bones of larger mammals in Amboseli, which is quite different from the slow rate of weathering of the cow bones in Somerset, UK, described by Andrews and Cook (1985).

Andrews and Armour-Chelu (1998) reported on the results of a long-term study which began in 1978, comparing the taphonomy of animal remains and bones in a temperate setting to Behrensmeyer’s taphonomic study of bone weathering in a tropical setting (Behrensmeyer 1978). Andrews and Armour-Chelus’ (1998) research was conducted in Rhulen, Powys, a location in Wales on the southwest side of the United Kingdom. During the 18-year study (Andrews and Armour-Chelu 1998), the carcasses of 100 animals were monitored from time and place of death to the time of disappearance or burial. At the end of the study, what bones could be found were collected and examined for condition, including damage from carnivore scavenging and weathering. The carcasses of wild and domestic animals, including horse, sheep, and cow were monitored in their natural environments, mainly hilltop moors with areas of rocky scree and vegetation such as heather and bracken (Andrews and Armour-Chelu 1998). The climate in Rhulen consists of mild temperatures ranging between averages of 43°F and 57°F annually, with annual averages of 77 rainy days, 27 inches of rain, and 38 days below freezing (Canty et al. 2012). Andrews and Armour-Chelu (1998) state that in this
temperate environment, bones weather at a much slower rate than they do in the tropical environment of Behrensmeyer's (1978) study.

According to Andrews and Armour-Chelu (1998), of the bones recovered in Rhulen there is a positive correlation between bone density and bone survival. The reasons posited for bone survival include the nutrient value of bones to scavengers, the mineral density, size, and shape of bones, and the age of the animal. The majority of the bones recovered were skulls, scapulae, humeri, femurs, tibias, and ribs; other bones recovered included metatarsals and metacarpals, mandibles, pelves, and radii (Andrews and Armour-Chelu 1998). The 133 recovered bones varied in their stages of weathering, with the majority of bones in Weathering Stage 0 (62.5%), and dwindling in numbers for each consecutive stage to only 4 within Weathering Stage 4 and none in Stage 5 (Andrews and Armour-Chelu 1998). Andrews and Armour-Chelu (1998) make a direct comparison to Behrensmeyer (1978), claiming that unlike the rate of bone weathering in a tropical environment in Africa, bones weather much more slowly in a temperate climate such as that found in the UK, and they state that bones sometimes have not weathered beyond Stage 2 even after as long as 22 years.

Another type of bone weathering that can occur in temperate climates is described by Andrews and Armour-Chelu (1998) as "corrosive weathering", which happens to bones in a microenvironment with plenty of rain or humidity and an acidic substrate pH, such as soil or peat. This type of corrosive weathering is very similar to what occurs in the permafrost environment of the Canadian High Arctic on Bathurst Island as described by Sutcliffe (1990). Portions of bones will corrode if submerged in, or in direct contact
with, an "acidic" substrate, while portions of the same bone can remain in relatively good condition if openly exposed and not in contact with the substrate. Bone corrosion due to an acidic substrate can potentially cause their complete destruction before any surface weathering can occur (Andrews and Armour-Chelu 1998).

Statement and Elaboration of the Problem

This thesis project examined two primary factors in bone weathering research: location and rate. These factors are not specific to taphonomy and/or bone weathering, as they encompass environmental and forensic issues similarly. The crux of the question is this: Behrensmeyer's 1978 study was specific; it was based on how bones weathered in a surface context in various environments, but those environments were all located in East Africa, within one geographic location: Amboseli National Park. All of the environments where the bones were located have their own unique environmental characteristics, i.e., precipitation rate, humidity level, UV levels, wind, and soil type. In addition, weather patterns change in Amboseli Park between the various seasons. As evidenced by previous studies, Behrensmeyer's (1978) weathering stages do not necessarily apply to how bones will react in all environments of the world even if it is one similar to those in the original study, such as a desert, a swamp, or a tropical forest. Regionally and environmentally specific studies are necessary for various geographic locations as well as for various archaeological, forensic, and environmental topics including bone weathering and soft tissue decomposition in order to determine the compatibility between the issues of environmental variability and research results. Many authors point out the necessity for bone weathering studies in a variety of geographic locations and microenvironments,
including Behrensmeyer et al. (2000), Byers (2005), Lyman and Fox (1989), and Huculak and Rogers (2009).

Behrensmeyer et al. (2000) considered bone-weathering research a "key focal area" for future taphonomic research, including field and lab studies on sub-aerial and sub-surface bone weathering.

This study examined bone weathering in the Mediterranean foothill environment of Auburn, California. Pig (Sus scrofa) bones were used as the study specimens for this bone weathering research. Although dog bones may be preferable for archaeological or forensic actualistic studies, it is simpler and less expensive to use pig bones, making the study comparable to the myriad other research conducted previously. Pig (Sus scrofa) bones are often considered to be the second best animal bones to use as a model for research that might be applicable to humans.
CHAPTER 3
MATERIALS AND METHODS

Materials

Twenty-two sets of pig bones were placed within secure enclosures in an outdoor environment. To study weathering patterns between large and small, and compact bone versus cancellous bone, a variety of bone types made up the study sample sets. The research sample sets consisted of the following pig (*Sus scrofa*) bones: femurs (large, compact bone); ribs (long, cancellous bone); and vertebrae (irregular shaped, cancellous bone). The bone specimens were placed within two enclosures built with chicken wire fencing, t-stakes, and wire fasteners, and were similar to those used for the Reeves (2009) vulture study and the Schoenly et al. (2006) decomposition project. One enclosure was placed in a location where the bones would be exposed to full sunlight throughout daytime hours, and the other enclosure was placed in the shade of an oak tree, approximately 20 feet west of the sun enclosure.

The enclosures were rectangular and approximately 2 feet to 2.5 feet in height, and were intended to keep out large scavengers, such as raccoons, coyotes, and bear, thus maintaining the quantity and position of the bones throughout the study period. A cover of chicken wire with 2-inch squares was placed and connected over the enclosures, in order to allow the remains to be exposed to all weathering elements. The walls of both enclosures were constructed of 1-inch octagonal opening chicken wire. Four 3-foot tall t-posts were driven into the ground to act as the corner supports, and the chicken wire walls and "roof" were wired to the t-posts. During the second week of the field study, the
enclosures were infiltrated by an unidentified animal intruder, and for this reason it was necessary to modify the enclosures. The animal intruder/s gained access to the bones inside both enclosures by pulling the bottom of the enclosure wire walls up from the ground. The walls were initially fastened to the ground by 10”-12” tent stakes, which apparently were not secure enough.

To improve the security of the enclosures for the sample bones, some simple additions were made. A perimeter floor was placed and secured around the outside of the enclosures. This perimeter floor was approximately 22” wide, extending outward from the enclosure walls; the floor was made of the same 2-inch square chicken wire as the enclosure roofs. All four sides of the floor, North, South, East, and West, were tied to each other with wire ties, while the floor itself was secured to the base of the walls with twisted wire ties and secured to the ground with camping tent stakes. Fallen tree limbs and large rocks were placed on top of the wire perimeter floor. The purpose of the wire perimeter floor was such that an animal standing on it and attempting to pull up the enclosure walls would also in effect pull up the floor beneath it, causing the animal confusion, distress, and discouragement. Other improvements included additional tent stakes at the base of the enclosure walls, and placing additional wire ties every several inches at the top of the enclosure walls to securely connect the walls to the roof (Figures 2 and 3).
The test sample of bones consisted of 22 ribs, 22 vertebra, and 22 femurs, all from domestic pigs (*Sus scrofa*). The ribs and vertebra, composing the requirement of this research study for spongy bones, were obtained from a local butcher in Auburn, CA on July 13, 2012. The bones were kept frozen until the day of field placement on Sunday,
July 15, 2012. The bones were in the form of "half-racks", a layman's term meaning the thorax was cut at the center of the spine, leaving half of the thorax intact from the center of the vertebrae. The intact half spine and rib cages still had soft tissue connecting the vertebrae and ribs to each other. It was therefore necessary to remove the soft tissue as best possible from the bones prior to placing the bones into the experiment enclosures. The majority of the remaining soft tissue was butchered from the bones the same day as field placement, on Sunday, July 15, 2012. Holes were drilled into each vertebrae and rib in order to connect individual ribs to individual vertebra with wire, creating twenty-two rib/vertebra sets. Splitting the difference for the total number of bones, eleven rib/vertebra sets were positioned in the sun enclosure, and eleven sets in the shade enclosure. Pink marker flags were placed with each bone set to delineate the set number, i.e., Station 1, Station 2, etc., with eleven stations total per enclosure.

Five days after placing the costals (ribs) and vertebra, on Friday, July 20th, domestic pig femurs were added to the field study sample. The reason the femurs were added a week later than the ribs and vertebrae was a matter of finding a supplier. Twenty-two femurs were added, matching the number of rib/vertebra sets, and allowing for comparison of weathering patterns between large compact bone (femur) and small spongy/soft bone (ribs and vertebrae). The pig femurs were obtained from a different butcher (Longhorn Meats, Auburn CA) than where the ribs and vertebra were obtained. The femurs had been de-boned from hams, but still retained minimal soft tissue. The remaining minimal soft tissue was left intact on the bones with the hope that during the summer heat insects would be attracted and remove the tissue naturally, and with the
intention of placing in the field bones that were in a natural state with little or no modifications.

On Friday, July 20, when conducting an on-site examination of the experiment, it was discovered that during the first week the Station 1 rib/vertebrae set in the sun enclosure had been removed and was missing, leaving 10 sets; the shade enclosure still had its' original eleven sets of bones. Additional bones – the 22 pig femurs - were added to all stations of both enclosures during the second site visit. When visiting the site on Saturday, July 28, it was discovered that sometime during the experiment's second week an unknown animal had infiltrated both enclosures, gaining access by pulling the bottom of all eight walls up from the ground. The bones from all stations in both enclosures had been removed and scattered. The enclosures were examined in order to assess the damage, followed immediately by a visual search of the nearby field surrounding the research site to identify and recover as many bones as possible. The majority of the bones from both enclosures were found within feet east of the sun enclosure and west of the shade enclosure. The bones that were found were returned to the enclosures, and replaced immediately at numbered stations. Bones that were recovered and replaced in the enclosures are in the list below:

1. 19 femurs (9 in sun enclosure, 10 in shade enclosure)
2. 15 ribs (5 in sun enclosure, 10 in shade enclosure)
3. 15 vertebrae (6 in sun enclosure, 9 in shade enclosure)

Redistribution of the individual bones was arbitrary; the bones were repositioned at the individual enclosure stations according to their proximity to each enclosure, i.e.,
bones closest to the sun enclosure were replaced there, and bones closest to the shade enclosure were placed in the shade enclosure (Figures 4 and 5).

**Figure 4.** Sun enclosure with final set of *Sus Scrofa* (pig) bones. Includes femurs, ribs, vertebra.

**Figure 5.** Shade enclosure with final set of *Sus scrofa* (pig) bones. Includes femurs, ribs, vertebra.
Methods

All of the factors that were monitored were recorded in a logbook. The factors monitored include the following:

A. Site visit dates and times.
B. Bone weathering condition/stages.
C. Bone color.
D. Weather.

Photographs of the bones were taken at the start, during the course of, and at the end of the experiment using a digital camera. Tracking and recording the bone weathering progress (physical changes), weather patterns, and ecology of the experiment sites will constitute a bone weathering "baseline study" for this region and environment, according to Schoenly et al. (2006). Regarding site visit frequency for an actualistic weathering study such as this, Schoenly et al. (2006) and Reeves (2009) visited their sites and recorded the progress of decomposition on a daily basis. As an example of site visit frequency for a bone weathering study, as their study progressed over time, Janjua and Rogers (2008) visited the bone weathering sites of their experiment in varying frequencies, changing from daily, to every other day, to weekly, and finally biweekly for the last 100 days. It was not until 150 to 180 days into the study that Janjua and Rogers (2008) noted color changes and weathering cracks on the bones. Prior to starting the field research, it was believed that with the preceding examples of site visit frequency that for this actualistic bone weathering study a frequency of one site visit per week or every other week for a period of 16 to 20 weeks would be sufficient to observe and record any
weathering changes that occurred to the bones. The actual site visit frequency and length of the study period differed from the examples and the initial planned visit frequency, as seen in Table 1.

**Table 1. Bar graph: On-site visits per month for experiment duration.**

<table>
<thead>
<tr>
<th>Days On Site</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Starting on July 15, 2012, with the initial deposition of the sample bones in their field position for the weathering experiment, the bones were left in place for 133 days. On-site visits to the experiment location were conducted approximately once per week for the first two months, followed by approximately every other week for the remainder of the experiment period. A total of 14 on-site visits were made over the 19-week span of the study, with the final site visit and the end of the experiment period on Saturday, November 24, 2012.

As this thesis research is about bone weathering rates and how they compare to the Bone Weathering Stages identified by Behrensmeyer (1978), the primary methodology for identifying weathering on the study bones followed those described by
Behrensmeyer, i.e., the highest bone weathering stage identified on an area of 1 cm$^2$ per bone according to the stages already defined, and the usage of bones from mammals greater than 5 kg in size, e.g., domestic pigs (*Sus scrofa*). Stages 0 and 1 are of primary concern for this study, as they have the highest potential for occurring within a short time-span. In Stage 0, there are no cracks or flaking of the bone, and the bone still retains some soft tissue and greasiness; this stage occurs during the first year. Stage 1 bone weathering presents with some cracks on long bones as well as articular surfaces, and some greasiness or soft tissue may still be present (Behrensmeyer 1978). Stage 1 can occur within the first 3 years. Remains were scored for Behrensmeyer's (1978) six Bone Weathering Stages:

Stage 0 – No weathering, i.e., cracking or flaking. Bone is still greasy and may retain some soft tissue.

Stage 1 – Bone will show cracking in direction of collagen fibers, i.e., longitudinally on long bones. Possible mosaic cracking on articular surface tissues as well as the bone itself. Some soft tissue may still be present.

Stage 2 – Bone flaking and peeling associated with cracks on outermost bone layers. In cross section, edges of the cracks are angular. Thin, attached flakes of bone are likely present.

Stage 3 – The external bone layers have been removed. The bone surface has a rough, fibrous texture. Edges of weathering cracks are rounded. No soft tissue remains.
Stage 4 – Bone surface has a texture that is coarse and fibrous, rough. Presence of large and small bone splinters that are easily separated from the bone. Weathering is throughout the entire bone. Cracks have opened, and have edges that are splintering or rounding.

Stage 5 – Bone is disintegrating and may be difficult to identify by shape. Cancellous bone may be present and exposed, more so than external compact bone.

According to Behrensmeyer, during Weathering Stage 0 a bone can retain soft tissue and greasiness for the first year. For this thesis experiment, bones were examined for the amount of soft tissue remaining as well as for greasiness, both of which are relevant to bone dryness and the weathering process. During on-site visits the amount of soft tissue remaining on the bones was determined by visual observation, and greasiness was determined using a touch test. An example of the results of a touch test is seen in Figure 6.
As can be seen in Figure 6, the greasiness of a bone can be arbitrarily determined from oils left on the latex gloves. The photo in Figure 6 is from day 28 of the experiment on August 11, 2012.

Similar to the Janjua and Rogers' (2008) bone weathering study, bone coloration was recorded near the beginning of the study after bones were deposited, and again at the end of the study period. Although color identification is subjective, the standard Munsell® Color Chart was used to identify coloration. The primary color change that was expected by the end of the study period was bleaching from sun exposure, although color changes can occur due to contact with soil or vegetation (Huculak and Rogers 2009). Huculak and Rogers (2009) studied color changes occurring to bones over an 8-week period using two different scenarios, and during the course of the study period the bones did go through color changes, including bleaching, soil staining, and hemolytic staining.
Climate and local weather are important factors in the bone weathering process. For this field experiment the daily local weather for the experiment sites was tracked initially using The Weather Channel software application, but the primary weather application for the study duration was the Fahrenheit software application for Apple iPad© and iPhone© (allowing weather tracking and recording while offsite). After the conclusion of the field study, averages were compiled from daily weather reports for the various weather factors that were monitored during months of the experiment. Weather factors that were monitored include the UV index (Tappen 1994), cloudiness, high and low temperatures, humidity, precipitation/rain, and wind. Ambient temperatures, ground temperatures, and humidity were also recorded at the immediate site locations during site observation visits. The temperature and humidity at the sites was monitored using outdoor thermometers and a humidity gauge.

To summarize, in order to identify potential bone-weathering patterns in the Mediterranean climate of Auburn, California, bone coloration, local weather, and bone weathering stage using Behrensmeyer's (1978) 6-stage bone-weathering scoring system, were all recorded and photographs were taken on a weekly, bi-weekly, or once monthly basis for a period of 19 weeks, or 133 days.
CHAPTER 4

RESULTS

The costal/vertebrae bone samples were exposed to elements for 133 days, and the femur bone samples were exposed for 128 days. During this period, the condition of the bones was recorded during on-site visits, and the daily weather conditions were recorded both on- and off-site, using on-site instruments and weather software applications for local regional weather when off-site.

Bone condition

The bone conditions that were observed and recorded were fresh, greasiness/dryness and coloration. For the purpose of this experiment, arbitrary bone condition stages were used to graph the progression of the weathering process within the given exposure period, as seen in Table 2. During the 133-day exposure period the bones went through three arbitrary stages, all of which are within Behrensmeyer's Stage 0. All of the bones from both enclosures reached similar pre-weathering stages in similar timeframes, the information for which is presented in the following information. The bar graph in Table 2 details the arbitrary bone condition stages as they progressed through the experiment. Below is a list of the stages in shown in Table 2:

Arbitrary Stage 0: Fresh

Arbitrary Stage 1: Greasy

Arbitrary Stage 2: Dry
Table 2. Bar Graph: Arbitrary Bone Condition Stages per Month.

Arbitrary Stage 0, "fresh", represents the condition of the bones when they were first placed in the experiment enclosures. The fresh bones, *Sus scrofa* (pig) costals (ribs) and vertebrae, were placed in the field July 15, followed by the fresh pig femurs on July 20. At the time of the second site visit on July 20, the costals and vertebrae were already in Arbitrary Stage 1, greasy with minimal soft tissue. Following the placement of the femurs, all of the bones remained in a state of decreasing greasiness through the on-site visit of Saturday, November 3, 2012, which was the 112^{th} day of exposure. The bones did not begin to present a state of "dryness" until the final on-site visit on Saturday, November 24, 2012, which was the 133^{rd} day of exposure (19 weeks). The primary difference in weather conditions before and after November 3^{rd} was the occurrence of several days with measurable precipitation, starting prior to November 3^{rd}. The following two figures, Figure 7 and Figure 8, are examples of bone greasiness in Arbitrary Stage 1,
and the dryness of Arbitrary Stage 2, both "stages" still within Behrensmeyer's (1978) Weathering Stage 0 (WS-0). The "dry condition" of the bones means they were dry to the touch, with very desiccated soft tissue as well as the periosteum appearing dry, cracked, or flaking away from the bone, as seen in Figure 8.

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**Figure 7.** Photo: Sun Station 2: femur greasiness, Day 22. Arbitrary stage 1.
Bone Color

To identify possible color bleaching effects of climate or sun exposure on bones, the color was recorded from femurs in each enclosure near the experiment beginning, and at the end of the experiment. Comparing them to color tiles in the Munsell® Soil Color Charts book identified the color of the bones. This method of color identification is subjective and can lead to inter-observer error, as color is usually viewed differently per person. In the case of this thesis research, only the researcher identified the color of the bones. Four different color schemes were identified and recorded on two femurs, one in the sun enclosure, and one in the shade enclosure. Only the color of the bone tissue itself was recorded, other colors, including hemolysis stains from blood and fungal stains were not recorded. The recorded colors were as follows: light yellowish brown, very pale brown, yellowish brown, yellow.
Examples of the bone colors that were recorded for the pig femurs in each enclosure are shown in Figures 9 through 12:

1. Bone color for Sun Enclosure, Station 2: Femur.

**Figure 9.** Photo: Sun station 2 – Femur: Munsell color: 10 YR 6/4: Light yellowish brown. Day 14.

**Figure 10.** Photo: Sun station 2 – Femur: Munsell color: 10 YR 8/3: Very pale brown. Day 133.
2. Bone Color for Shade Enclosure, Station 4: Femur.

![Image of femur]

**Figure 11.** Photo: Shade Station 4 – Femur: Munsell color: 10 YR 5/4 Yellowish brown. Day 14.

![Image of femur]

**Figure 12.** Photo: Shade station 4 – Femur: Munsell color: 10 YR 8/8 Yellow. Day 133.

**Weather**

The primary weather factors that were tracked during the course of this bone-weathering experiment were rain, wind, temperature, UV index (Andrews 1995b), and
humidity. Tables and values for rain totals and sky conditions can be found in the appendix.

Rain

The first measurable rainfall during the field experiment occurred on September 5, 2012, and according to the weather app measured at .06 inches. There were three days of rainfall during October, at a total of approximately 1.87 inches, and during November, the final month of the field experiment, 4.53 inches of rain fell. Prior to the next-to-the-last on-site field check, which was November 3, there had been four days of measurable rain. Between the dates of November 3 and the last field check on November 24, there were nine days of measurable rain, for an approximate total of 4.38 inches. Table 3 is a bar graph representing the average rainfall per month during the field experiment.

Table 3. Bar graph: Rain totals per month, July-November 2012.

Table 3 shows the increase of measurable precipitation (rainfall) as the experiment progressed from start to end. The months of July and August had no
measurable rainfall, and from there the rainfall increased per month from September through November. A table for the days with measurable rainfall can be found in the Appendix, Table A1.

Wind

The wind was recorded regularly with the other weather factors using the weather app, and also on-site during several site visits. In Table 4, the bar graph displays the average monthly wind speeds according to the weather app.


![Wind Speed Graph]

Wind speeds varied during the study period, with occasional outliers above and below the averages, down to three miles per hour, and up to thirteen and fourteen miles per hour. The wind was recorded during eight of the site visits, once in July, three times in August, once in each September and October, and during both visits in November. The information within Table 5 details the wind recordings during several of the on-site visits.
Table 5. On-site wind speed recordings, miles per hour (mph).

<table>
<thead>
<tr>
<th>Date</th>
<th>Wind Speed, On-site</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/20/2012</td>
<td>0-3 mph</td>
</tr>
<tr>
<td>8/11/2012</td>
<td>2 mph</td>
</tr>
<tr>
<td>8/18/2012</td>
<td>2.5 mph - SW</td>
</tr>
<tr>
<td>8/25/2012</td>
<td>4.5-7 mph - NE</td>
</tr>
<tr>
<td>9/1/2012</td>
<td>2.2 mph - N</td>
</tr>
<tr>
<td>10/20/2012</td>
<td>2 mph - NW</td>
</tr>
<tr>
<td>11/3/2012</td>
<td>0-2 mph</td>
</tr>
<tr>
<td>11/24/2012</td>
<td>2-3 mph - N</td>
</tr>
</tbody>
</table>

Temperature

The temperature for this experiment was recorded several ways – macroclimate temperature recordings for the Auburn area using the weather app, and microclimate temperatures at the experiment location. Microclimate temperature readings consisted of ambient sun and shade temperatures and ground sun and shade temperatures.

The macroclimate temperatures have been divided into two categories: one for monthly high and low temperature averages, and one for monthly highest and lowest temperatures. Tables 6 and 7 are bar graphs with accompanying tables, showing the macroclimatic temperature information during the study period.

Table 6 details the average macroclimate high and low temperatures for July through November in the Auburn area, as recorded from the Fahrenheit weather app. Average temperatures never went higher than 100°F or lower than the mid-40's. The highest average temperatures were in July and August, and the lowest average temperatures were in October and November.
Table 7. *Bar graph: Highest and lowest temperatures per month, July-November, 2012.*

Table 7 details the highest and lowest temperatures recorded for the macroclimate area of Auburn from the Fahrenheit weather app. Values are for the months of the experiment, July through November. The highest temperatures are for daytime hours, and the lowest temperatures are for nighttime hours. In August the temperature did reach over 100°F at least once, but in November, the coldest month of the experiment, temperatures did not reach or go below freezing.

During conducting on-site experiment checks the ambient temperatures for the sun and shade enclosures were recorded from outdoor thermometers mounted on each enclosure. Information within Table 8 are details for on-site ambient temperature recordings.
Table 8. On-site sun and shade enclosure temperatures.

<table>
<thead>
<tr>
<th>Weather</th>
<th>On-site Sun Temperature</th>
<th>On-site Shade Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>July</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/20/2012</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>August</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8/11/2012</td>
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<td>100</td>
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<td>93</td>
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<tr>
<td>8/25/2012</td>
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<td>87</td>
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<td></td>
</tr>
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<td>80</td>
<td>76</td>
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<tr>
<td>9/5/2012</td>
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</tr>
<tr>
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</tr>
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<td>88</td>
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<td>9/29/2012</td>
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<td></td>
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<tr>
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<td>80</td>
<td></td>
</tr>
<tr>
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<tr>
<td>10/25/2012</td>
<td>68</td>
<td></td>
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<td></td>
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<td>11/3/2012</td>
<td>76</td>
<td>74</td>
</tr>
<tr>
<td>11/11/2012</td>
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</tr>
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<td>11/24/2012</td>
<td>70</td>
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</table>

The on-site sun and shade temperatures were typically recorded midday at the time of arrival to the experiment location. Temperatures therefore represent the warmest time of the day. On-site temperatures show that there were temperature differences between the two enclosures. The sun enclosure temperatures were sometimes as high as six to seven degrees above the shade enclosure temperatures. During August there were two days for which the enclosures had a difference of six to seven degrees, in September
one day with a difference of seven degrees, and one day in October with a six degree
difference between the enclosures.

Ground temperature for the sun and shade enclosures were also recorded using a
ground thermometer during on-site checks of the experiment. Data regarding the recorded
ground temperatures is found within Table 9.

**Table 9. On-site ground temperatures for sun and shade enclosures.**

<table>
<thead>
<tr>
<th>Date</th>
<th>Ground Temperature: Sun</th>
<th>Ground Temperature: Shade</th>
</tr>
</thead>
<tbody>
<tr>
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<td>8/5/2012</td>
<td>102</td>
<td>84</td>
</tr>
<tr>
<td>8/11/2012</td>
<td>120</td>
<td>98</td>
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<td>8/25/2012</td>
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<td>September</td>
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<td>82</td>
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<tr>
<td>November</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11/3/2012</td>
<td>72</td>
<td>72</td>
</tr>
<tr>
<td>11/24/2012</td>
<td>67</td>
<td>68</td>
</tr>
</tbody>
</table>

The information enclosed within Table 9 shows that there were much larger
disparities between ground temperatures for the enclosures compared to the ambient
temperatures between enclosures. As an example, for ground temperatures at the sun and
shade enclosures there was a difference of 26 degrees on July 20 and a 12 degree
difference on October 20, with the shade enclosure temperatures cooler than the sun
enclosure temperatures, compared to a 6 degree difference ambient temperatures, as seen
in Table 8. As seasons changed from Summer to Fall, and then Winter, ground temperatures decreased and temperatures between enclosures equalized to no difference as recorded during the last two site checks on November 3 and November 24.

UV Index

Because a UV recorder was not set up at the site of the experiment, the Fahrenheit weather app was relied upon instead. Even though the weather app is more of a macroclimate tool, the usage of it for recording the UV index is reasonable as the index is a reflection of sun exposure, or the lack thereof. The UV index changes dependent upon the cloud cover as well as the position of the sun, therefore as seasons changed from summer to winter during the experiment, the UV index decreased. Table 10 is a bar graph for the average UV indices as they were recorded from the Fahrenheit weather application from July through November 2012.

The bar graph in Table 10 shows that as the months and seasons advanced through the course of the bone weathering study, the UV index decreased steadily. The UV index for the Fahrenheit weather application is a measure out of 16, i.e., 4 of 16, or 10 of 16, with 0 being the lowest and 16 the highest. As the graph shows, the UV index did not climb above 10 during July, and there were only five days that the index was below 2. There was one day in October and there were three days in November for which the UV index was only 1, as well as one day in November with a UV index of 0. The days with very low UV indices had high cloud coverage. As the seasons turned from summer to Fall, there was a steady decrease of the average UV index due to increased cloud coverage in the cooler months and the position of the sun. Figure A2 in the Appendix graphs the number of days with either cloudy or clear skies during the course of the experiment.

Humidity

The final primary climate factor that was recorded throughout the course of the experiment was humidity. Two methods were incorporated for recording humidity – an on-site humidity gauge, and the Fahrenheit weather application for daily macroclimate humidity information. Table 11 details the macroclimate humidity information for the study site in Auburn, CA.
As Table 11 shows, the average humidity is low during the summer months for the macroclimate region of Auburn. The average humidity level was in the low- to mid-30 percentile range for July through September. After seasons turned from Summer to Fall in 2012, the average macroclimate humidity almost doubled to 63 percent in October and more than doubled from the summer months to an average of 77 percent in November. The increased humidity in the fall months is antithetical to decreases for both temperatures and the UV index.
CHAPTER 5

DISCUSSION

Bone weathering

After the bones in this experiment, including pig femurs, ribs, and vertebrae, were exposed for 133 days in full sunlight and shaded conditions, they reached a state of dryness, but did not yet show signs of weathering. The condition of the bones fell within Behrensmeyer's (1978) Weathering Stage 0, a stage in which bones do not present with cracking or flaking of the bone, some soft tissue is still present, and there is peeling and flaking of the periosteum (bone covering tissue). The photograph in Figure 13 is a detail photo of the dry condition of a femur at Sun Station 2 of the sun enclosure, with the periosteum flaking at the proximal end.

Figure 13. Photo: Detail of dry condition of pig femur, Sun Station 2, Day 133.

Weathering Stage 0 can last for at least one year, according to Behrensmeyer (1978). Although the bones had become dry on the exposed surfaces, there was no sign of
cracking or flaking on Day 133. For the most part, the bones in the sun enclosure had less soft tissue still adhering than did the bones in the shade enclosure. Less soft tissue on the sun bones may have been due to higher insect activity, including dermestid beetles. Insects, including flies and instars, ants, and dermestid beetles, had been identified on bones within either enclosure on several occasions, including the last site visit. But as insects were not of primary concern for this study, they were only recorded as conspicuously present or not. Some of the sun bones also had numerous small spots of fungal growth on the exposed surface, more so than did the shade bones, as well as fungal growth on the soft tissue of the unexposed surface. The shade bones tended to have a drier unexposed surface with less fungal growth than those in the sun, and no fungal growth on the exposed surfaces. The disparity between the fungal growth on the exposed surfaces, as well as the dryness on unexposed surfaces, may be related to vegetation covering. By Day 133, all of the bones in the sun enclosure were covered by tall grass, and most of the shade bones except for the femur at Shade Station Three were covered by grass as well.

Other neotaphonomic studies had achieved similar non-bone weathering results, such as Janjua and Rogers (2008). In their study, which was located in the cold environment of southern Ontario, Janjua and Rogers (2008) did not identify cracking of the bones according to Behrensmeyer's (1978) Weathering Stage 1 until up to the 181st day.

Alternatively, Coe (1980) found that large robust elephant bones in an open desert habitat in Kenya with high temperatures between 95°F and 105°F show signs of
weathering very quickly. Coe (1980) stated that the elephant bones located in the hot, dry African desert were cracking and exfoliating within five weeks after becoming exposed to the elements.

In the Mediterranean environment of Jordan Valley in Israel, Lotan (2000) identified bone weathering characteristics that fit within Behrensmeyer's (1978) established Weathering Stages. During a 26-month period, the bones of a calf reached Weathering Stage 2 on the sides of the bones that were exposed to sunlight. And oryx bones located in a dry riverbed with protective covering vegetation only reached Behrensmeyer's Weathering Stage 1 during 1126 days of exposure (Lotan 2000).

**Bone Color**

The bones in the sun enclosure seemed to be lighter in coloration on Day 133, having changed from light yellowish brown on Day 28 to very pale brown by the last study day. The bones in the shade enclosure also changed in color from the beginning of the study to the end. At the beginning of the study, the color of bones in the shade enclosure was yellowish brown, whereas at the end of the study the bone coloration was yellow. By appearance, it could be said some bleaching may have occurred with the bones in the sun enclosure, as they were lighter in coloration at the end of the study than at the beginning. There was no bleaching of the bones in the shade enclosure, as they were more yellow at the end of the study than at the beginning, which may have been caused by staining from the animal fats. Another coloration present on the bones was spots of hemolytic staining. Because hemolytic stains were showing signs of presence on the bones at the beginning of the study when the Munsell© colors were recorded, the
stains were avoided when identifying the bone color. As such, the Munsell® colors that were recorded for the bones were of the bone tissue itself; soft tissue and hemolytic stains were avoided when identifying the color. Whether bleaching of the sun bones in this study was from sun exposure or the removal of fats via rainfall/water action, bleaching is possible within the study period of 19 weeks, as seen from Huculak and Rogers (2009). The Huculak and Rogers (2009) bone coloration study, spanning an eight week timeframe involving the burial of bones for four weeks which was either preceded or followed by exposure for four weeks, identified bone bleaching within their study period. The results of the Huculak and Rogers study combined with the results of this thesis study predict that sun exposure does cause bone bleaching, and potentially only requires between two to five months.

Weather

Rain

Prior to the next-to-the-last on-site field check of the bones, which was the 112th day of November 3, 2012, there had been five days of measurable rain (see Appendix, Figure A1). At the time of the field check on November 3, the bones were still greasy to the touch. By the last day of field checks and recordings, November 24, 2012, there had been an additional nine days of measurable rain, according to the weather application, totaling 14 rain days and approximately 6.5 inches of precipitation. At the final field check, November 24, the exposed surface of most of the bones in both enclosures were dry to the touch. Both of the bones at Shade Station 3, a left pig femur and a left rib, were still slightly greasy to the touch.
If not for the rainfall, the bones may have remained greasy for some time longer, which would extend the length of time for which the bones remained unweathered. According to several authors, water action is a necessary component of the bone weathering process. Rain is listed as a required element for bone weathering by Tappen (1969), as one of the weather elements that causes protein racemization and denaturation, leading to weathering cracks parallel to collagen fibers. Water action is considered by Stojanowski et al. (2002) to be the cause of destruction for bones in shallow burials. Hare (1980) also states that water action will cause minerals and proteins to leach from bones, but the process can cause a bone to appear chalky.

In the case of this thesis experiment, it seems that the rain (water action) was a necessary element for the removal of fats (greasiness) from the bones. If not for the movement of the fats out of the bones by way of the water action, the grease would not have had any way to be removed and the bones may have remained in a state "greasiness" for an undetermined length of time.

Wind

As seen in the Results section, wind speeds within the macroenvironment area of this study were never extreme. The highest average wind speeds were during the month of July, at 8 miles per hour. Sutcliffe (1990) stated that 3,000 year old bones in a shoreline setting in the Canadian High Arctic region had a planed-down appearance, likely from wind-blown sand. Wind can also be a contributing factor to bone desiccation, which is important in the weathering process (Tappen 1969). As the wind speeds in the macro- and micro-climate location of this experiment were not high during the study
period, it would appear that wind was not a factor in the weathering process in this instance.

Temperature

The ambient temperature of a bones’ depositional location does appears to be a contributing factor to the speed at which a bone will weather and survive. Comparing several environments, including permafrost, desert, periglacial, and mediterranean, bones in these settings can survive for varied lengths of time. At Brooman Point in the Canadian High Arctic, Sutcliffe (1990) identified bones from 800 to 3,000 years old in surface settings. In the permafrost zone, where temperatures do not fluctuate much, soil and the bones situated on or in it remain frozen year round, which has a preservation effect in which bones can survive for hundreds to thousands of years (Sutcliffe 1990). At Tsavo East National Park, a sub-Saharan Desert location in Kenya, bones in open settings with no shade can weather much faster than bones in shaded conditions (Coe 1980). Coe (1980) noticed that in open locations with temperatures between 95°F and 104°F, bones could dry and present with cracks within 5 weeks, whereas bones in shaded conditions with temperatures around 30 degrees cooler than those in direct sun would have much slower weathering rates. In periglacial settings, such as the French Alps, bones can go through freeze-thaw cycles, affecting their survival rate greatly (Texier et al. 1998). Bones exposed to sunlight in open settings would freeze at night and thaw during the day, causing frost shattering and disintegration patterns within four years. According to Texier et al. (1998), freeze-thaw cycles increase the rate at which bone weathering occurs. Bones in the warm Mediterranean climate of Jordan Valley in Israel reached states of
weathering from between two to four years (Lotan 2000). A radius and a lumbar vertebrae, from a mature calf, reached Weathering Stage 2 after 26 months of exposure in Jordan Valley, whereas the bones from an oryx that had been in a location with some shade protection required approximately three years (1126 days) to reach Weathering Stage 1. Temperatures in Jordan Valley reach a summer high average of 120°F and a winter low average of 37°F (Lotan 2000).

In comparison to Lotan's (2000) Mediterranean bone weathering study, the Mediterranean climate for this thesis research was somewhat milder at both ends of the thermometer. Compared to the temperatures in Israel's Jordan Valley, the highest average temperature for the macro-climate area of Auburn during the study period was 94°F in August, and the lowest average temperature was 46°F during November. It may be possible for heat to dry bones out, but it seems likely that bone dryness from heat would be associated more from the evaporation of the water content in bones than from the oil and fat content. In this case, water content, oil/fat content, and bone dryness seem to go hand in hand. For ambient temperatures to the affect bones by drying them, the oils/fats had to first be removed from the bones, which did not happen until water action from rainfall may have washed the oils from the bones and allowed the bones to begin drying.

UV Index

Some researchers feel that ultraviolet radiation (UV) is of main importance when it comes to bone weathering, including Koch et al. (2001) and Fernandez-Jalvo et al. (2002), whereas Behrensmeyer (1978) felt that the primary causes of bone weathering are moisture and temperature fluctuations, and Texier et al. (1998) lean toward freeze-thaw...
cycles having more of an impact on bones than UV. In this thesis experiment, two enclosures with bones were set up to test the effects of sun exposure versus shade protection, one enclosure was in full sunlight, the other mostly in the shade of an oak tree. Other factors affecting sun exposure and UV radiation are the seasonal angle of the sun and cloud cover (Appendix Figure A2).

The Fall season of 2012 began in late September, at which time the angle of the sun was coming from more of a southern direction, and the amount of sunlight in the daytime hours was also decreasing. During July, the average UV index for the Auburn region was a level 10 out of 16, with the average UV index decreasing per month to a level 2 out of 16 in November at the end of the experiment duration. According to Koch et al. (2001) and Fernandez-Jalvo et al. (2002), UV radiation is a primary cause of the breakdown of protein polypeptide bonds, which leads to cracking along the fiber direction of bone collagen. By the end of this thesis study cracks were not observed on any of the bones in either enclosure, making a determination on the importance of UV radiation in the process of bone weathering not possible at the time.

Humidity

Humidity is one of two primary factors required for bones to weather, according to Behrensmeyer (1978), the other factor is temperature. The question is, why is humidity a factor when it comes to bone weathering? According to Tappen (1969), weathering cracks occur in bones due to shrinkage and decalcification. A bone will shrink due to desiccation, which can happen in low humidity situations. Galloway (1997) recorded bone exfoliation and cracks in as little as four months in the Arizona-Sonoran Desert,
where humidity levels range from as low as 17 percent to an average of 30 percent. As the bone shrinks from becoming dry, and collagen and calcium are removed via UV, heat, and water action, cracks will occur in the direction of the bone's collagen bundles; for example, along the length of a long bone (Tappen 1969). The humidity at the Auburn location for this thesis study was mild, compared to Galloway's (1997) desert conditions, with lows in the mid-30 percentile range in the summer months to as high as 77 percent in the Fall month of November. Presumably, because the air in Auburn was somewhat humid for the duration of the study period in comparison to locations such as the Arizona-Sonoran Desert (Galloway 1997), the humidity levels were a contributing factor to the study bones not advancing in weathering stages within the brief study period.
CHAPTER 6

CONCLUSION

A bone weathering study such as this can provide insight to and have implications for a broad number of topics, including paleontology, bioarchaeology, and forensic anthropology. Behrensmeyer's 1978 study, which first outlined 6 stages of bone weathering, was important for the fact that it set a research standard for a defined timeline for the survival of bones in open environmental contexts.

Temperature, UV exposure, and soil pH can all play roles in the breakdown of bone proteins; temperature, rain, humidity, and wind have roles in the removal of bone proteins, fats, minerals, and water. All of the factors mentioned in the preceding sentence are climatic and environmental contributors to the weathering rate of bones in sub-aerial and sub-surface contexts.

Although the Sus scrofa (pig) bones of this thesis field study did not reach Behrensmeyer's (1978) Weathering Stage 1, the study was still informational. In comparison to desert or savannah locations, the Auburn study site has mild climatic conditions, and according to Behrensmeyer (1978) it would be an equable environment contributing to slower bone weathering rates. Even in the equable cool Mediterranean Auburn climate, the bones reached a state of dryness within one-third of a year, and were potentially on the verge of Stage 1 weathering within a one-year timeline. According to Behrensmeyer (1978) bones can either remain at Weathering Stage 0 or can attain Stage 1 during the first year of exposure.
Future research opportunities for bone weathering should include studies in additional climatic or environmental locations, adding to the database of existing information for bone weathering rates. Additionally, oils from bone marrow or intramuscular fats may cause slower weathering rates. Removal of soft tissues and fats could be accomplished either manually or by allowing animals, including birds, access to the bones. Further, at the end of this study field grasses were growing higher than the bones and covering them, which will in effect interfere with the weathering rate because the bones will not be exposed. To explore long term weathering, it might be best to locate bones either on bare ground, a rock surface, or on a surface such as a sheet of plywood that would not allow vegetation growth. Lastly, the field study for this thesis lasted 133 days, yet Behrensmeyer (1978) concluded that bone weathering, i.e., Stage 1, could be attained in the first year. It may behoove future research to maintain a bone weathering field study for at least one year, checking the samples regularly within that timeframe, in order to observe whether Stage 1 does occur during at least a year-long exposure period.

<table>
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<td><strong>August</strong></td>
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<td>Monthly Total</td>
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<tr>
<td><strong>September</strong></td>
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</tr>
<tr>
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Table A2: Bar graph: Number of days/month for various weather conditions, July-November, 2012.
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Figure 1. Climate Zone Map. Adapted from: Measures of Temporal Variability. http://tornado.sfsu.edu/geosciences/classes/m356/RainfallVariability/TempVar.html. Accessed on August 2012. *Climate Zone Map, showing the Mediterranean Zone of the research site.*