USING SOLAR RADIATION AS A MEANS FOR UNDERSTANDING SKELETAL DECOMPOSITION THROUGH PHYSICAL CHANGES CAUSED BY BONE WEATHERING

by

Justin A. Pyle, B.S.

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Committee Members:

M. Kate Spradley, Chair

Daniel Wescott

Michelle D. Hamilton

Christina Conlee

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LIST OF ABBREVIATIONS

Abbreviation	Description
ADD	Accumulated Degree Days
EPA	Environmental Protection Agency
FACTS	Forensic Anthropology Center at Texas State
FARF	Forensic Anthropology Research Facility
PMI	Postmortem Interval
UV	Ultraviolet
TBS	Total Body Score
TSUDSC	Texas State University Donated Skeletal Collection

ABSTRACT

Bone weathering has often been used in forensic, archaeological, and paleoanthropological sites to better understand the context in which remains are found. In forensic settings bone weathering is used to estimate the postmortem interval of deceased individuals. The application of bone weathering as a tool for estimating time since death stems from Behrensmeyer's 1978 study on bone bed assemblages in Africa. Previous research has looked at weathering in varying climates using animal remains, but none have used human skeletal remains nor have they attempted to quantify the underlying variables that are associated with weathering. The present research represents a quantitative analysis of solar radiation as a variable of weathering using human skeletal remains. Donations (n=19) from the Willed Body Donation Program at the Forensic Anthropology Center at Texas State were separated into two groups. The groups consisted of individuals exposed to solar radiation (n=9) and individuals unexposed to solar radiation (n=10).

Upon initial skeletonization of the remains, weekly observations for signs of weathering were conducted. Once weathering characteristics were marked as present; solar radiation, ADD and calendar day required for the onset of weathering were calculated. Data were analyzed using Mann-Whitney U, Kruskal-Wallis, and Pearson's Correlation. The median values were reported due to the non-normal distribution of the data. The median value for the appearance of bleaching was 51366.4 W/m^2 for total solar radiation, 997 ADD, and 47 calendar days. Weathering rates were not significantly different between long bones and flat/irregular bones (p=0.158) and among different groups of bone (p=0.985). The Pearson's Correlation indicates that solar radiation is significantly correlated with ADD (p=0.000) and the number of calendar days (p=0.000) observed when bleaching appeared. It also became apparent while conducting observations that new definitions for weathering characteristics were needed to clarify and standardize descriptions of features associated with weathering. Results from this research in conjunction with similar studies on the different weathering variables will impact not only forensic settings but will aid in better understanding the circumstances and conditions affecting human remains in the archaeological and paleoanthropological record.

I. INTRODUCTION

Forensic anthropologists often use bone weathering, or skeletal decomposition, as a general indicator of the postmortem interval (PMI). The use of skeletal decomposition stems from work in paleoanthropology and zooarchaeology and provides a system for estimating the amount of time that skeletal elements have been exposed to the surrounding environment (Behrensmeyer 1978). Bone weathering stages were developed and published by Behrensmeyer (1978) as a means to quantify skeletal decomposition. Despite the original intent of the study for use in zooarchaeological and palaeoanthropological applications, Behrensmeyer's stages (1978) are included in *Standards for Data Collection from Human Skeletal Remains* (Buikstra and Ubelaker, 1994). The stages are used as a means for recording bone taphonomy in human remains found in archaeological and forensic contexts. Behrensmeyer’s published stages are from animal bone assemblages in Amboseli National Park in Kenya, Africa. During her study, Behrensmeyer documented the result of long periods of bone decomposition but did not provide any information on when particular characteristics like cracking and flaking first became observable. A better understanding of these characteristics (e.g. bleaching, cracking, and flaking) within the stages and when they become visible in human remains will benefit the field of forensic anthropology. Knowing when these characteristics, first described by Behrensmeyer, appear in human bone will provide practicing forensic anthropologists a starting point to better understand human skeletal decomposition and ultimately the ability to better estimate PMI.

Previous studies that developed methods for PMI estimation strictly focus on soft tissue decomposition (Megyesi *et al.* 2005 for sources). The most commonly used method is the Total Body Score (TBS) (Megyesi *et al.* 2005). This method uses a scoring system in conjunction with Accumulated Degree Days (ADD). Scoring consists of breaking down decomposition into four main stages including fresh, early decomposition, advanced decomposition, and skeletonization. The final stage uses scores based on the degree of skeletonization and whether or not the bone is "greasy" or "dry." Dry bone receives the largest score in this method; once the bone receives a score as dry, there are no further options for analysis, and therefore PMI estimation ends with dry bone.

Research surrounding soft tissue decomposition plays an important role in understanding taphonomy. It has been used for breaking down early decomposition into defined stages and understanding the varying factors that influence the rate and order that an individual will move through these stages. However, as previously stated this does not include the decomposition of skeletal remains. The skeleton is often the last physical manifestation of an individual to undergo the processes of decomposition. Studying the breakdown of skeletal material is the only way to have a comprehensive understanding of taphonomic processes acting upon skeletal remains in forensic, archaeological, or paleoanthropological settings.

Behrensmeyer's Weathering Study

Behrensmeyer's technique uses physical changes caused by weathering, to classify bones into one of six weathering stages, where each stage is thought to be indicative of a particular temporal period (Behrensmeyer 1978). These stages (Table 1) were established by studying animal remains as a way of understanding the taphonomy of fossil bone assemblages (Behrensmeyer 1978:150), which has applications in paleoanthropology and archaeology. Behrensmeyer's stages (1978) have been cited in numerous studies relating to bone weathering and the postmortem interval (PMI) (Andrews and Chelu-Armour 1998; Fisher 1995; Janjua and Rogers 2008; Littleton, 2000; Lyman and Fox 1989; Tappen 1994; Ross and Cunningham 2011; Andrews and Cook 1985). Further, Behrensmeyer's stages were developed in Amboseli National Park in Kenya; an area characterized as a savanna environment (Tappen 1994:671). Behrensmeyer (1978) noted that different climates produce different rates of weathering, and thus the general application of Behrensmeyer's stages to all climates may not result in consistently comparable results.

Table 1:Condensed version of Behrensmeyer's Weathering Stages

Stage	Definition of Weathering Stages	Years
0	No cracking or flaking; greasy; soft tissue present	0-1
1	Cracking parallel to fiber structure (longitudinal) in long bones	0-3
2	Flaking of outer surface, usually associated with cracks; flakes are long and thin with one edge attached to bone; crack edge angular; exfoliation started	2-6
3	Bone surface rough, fibrous texture, weathering only 1.0 to 1.5 mm deep; crack edges rounded	4-15+
4	Bone surface coarse, rough, and fibrous; large and small splinters loosely attached; weathering penetrates to inner cavities; cracks open	6-15+
5	Bone mechanically falling apart into pieces, very fragile	6-15+

Lack of studies on human remains in varying climates may result in biases when using Behrensmeyer's stages (1978) for assessing human skeletal remains. In Behrensmeyer's longitudinal study (Behrensmeyer *et al.* 1979), data collection occurred once over a 3-month period in 1975. The remains used in the study were animal carcasses naturally deposited on the surface for anywhere between less than 1 year to 15 years

(Personal Communication with Behrensmeyer and Dechant, 2015. Thus, Behrensmeyer was unable to note exactly when certain characteristics arose, rather she was only able to observe the end stage of a given period of time.

Previous Weathering Studies

All previous weathering studies have used non-human animal remains to follow the rates of weathering patterns on skeletal elements (Behrensmeyer *et al.* 1978; Janjua and Rogers 2008; Tappen, 1994; Carter *et al.* 2007; White and Hannus 1983; Huculak and Rogers 2009; Cutler *et al.* 1999; Grupe *et al.* 1993; Morton and Lord. 2006; Reeves 2009; Andrews and Chelu-Armour, 1998; Todisco and Monchot 2008; Beary 2005; Prassack 2011; Junod and Pokines 2013; Osterholtz *et al.* 2014; Frison and Todd 1987; Pokines *et al.* 2016; Cunningham *et al.* 2011). Many of these studies are also retrospective in nature, and either focuses on archaeological sites or naturally occurring bone assemblages.

Retrospective studies carried out on archaeological sites and naturally occurring bone beds, while useful, do not provide an accurate time frame for understanding when weathering characteristics occur on skeletal remains. Further, given the time scale associated with these studies, the degree to which weathering is observed often reflects the more extreme examples. These studies do not show the beginning stages of weathering characteristics, which may be useful in a forensic setting or for remains that were slightly weathered and then interred.

Janjua and Rogers (2008) is one of the first studies to observe active weathering on skeletal elements. The authors used defleshed porcine remains to determine differential weathering patterns between femora and metatarsals. While many of these studies look at varying factors affecting the different characteristics observed from weathering, none attempt to explain or understand the causal mechanisms such as solar radiation of weathering and other characteristics.

A study published by Pokines (2016) subjected animal bones to multiple freezing and thawing cycles in an attempt to understand how this process affects bone weathering. The results of this study indicate that freeze-thaw cycles can cause cracking and cortical flaking in bone, but notes that this is not the only process involved in weathering. Pokines (2016) states the need to look at other variables affecting weathering rates including solar radiation.

Dirkmaat *et al.* (2008), Spradley *et al.* (2011:57), and Shirley *et al*. (2011) state the need for more taphonomic research using human remains within forensic anthropology. Taphonomy is the "study of postmortem processes which affect (1) the preservation, observation, and recovery of dead organisms, (2) the reconstruction of their biology or ecology, or (3) the reconstruction of the circumstances of their death" (Haglund and Sorg 1996:13). Shirley *et al*. (2011) also argue that studies on animal remains are not sufficient for use when interpreting taphonomic events on human skeletal remains. Because Behrensmeyer's stages were developed using animal bones from Bovidae, Suidae, and various other animals, it is unknown if characteristics such as longitudinal or cortical flaking in long bones would occur within the same time frame in human remains due to differences in overall morphology and cortical thickness. Further, differences in solar radiation at different latitudes and different times of the year may result in variable weathering rates. Such knowledge of bone weathering characteristics in conjunction with high amounts of solar radiation would be beneficial in areas such as the United States/Mexico border where a humanitarian crisis exists resulting in a large number of deceased individuals with exposure of their skeletal remains to high levels of solar radiation (EPA 2015).

In the Southwest, forensic cases that remain on the surface for extended periods of time are subject to predation including vulture scavenging. The Southwest region of the United States has a high vulture population density (Buckley 1999; Kirk and Mossman 1998), and forensic anthropologists receive more human skeletal remains for identification there than any other single jurisdiction in the United States (Martinez and Anderson 2014; Reineke and Anderson 2014; Ross *et al.* 2014; Baker 2014; Soler *et al.*). Scavenging can considerably affect the soft tissue decomposition and the associated PMI due to rapid skeletonization (Trammell *et al.* 2014; Spradley *et al.* 2012), which increases the amount of UV exposure if remains are not recovered immediately. The majority of forensic anthropology cases at the Pima County Office of the Medical Examiner are found in the Sonoran Desert and are either mummified or skeletonized (Trammel *et al.* 2014). A similar situation has been unfolding in Texas along the Mexico border (Baker 2014), where an increase in migrant crossings has created more forensic cases involving mummified or skeletonized remains. These skeletal remains have taphonomic signatures of vulture scavenging including damaged lacrimal bones, broken sterna, and ribs (Personal communication with Spradley, 2015). The skeletons also display signs of weathering including sun bleaching, longitudinal cracking, cracking parallel to the fibrous structure, and cortical flaking (Personal communication with Spradley 2015; Goots 2016). It is currently unknown how long it takes for characteristics such as sun bleaching, longitudinal cracking, cracking parallel to the fibrous structure, and cortical flaking to occur. While some studies have discussed solar radiation in the context of weathering (Beary 2005; Pokines *et al.* 2016; Prassack 2011; Cunningham *et al.* 2011; Junod and Pokines 2013), there are no published studies on bone weathering that incorporate quantifying solar radiation as a unit of analysis, a factor that heavily influences bone weathering.

The ability to understand the continuum along which these skeletal decomposition characteristics initiate could provide valuable information to forensic anthropologists to assist with an estimation of PMI, helping to narrow down the search within missing persons reports based on the estimated last known alive date. Therefore, the purpose of this study is to 1) provide a baseline study of bone weathering and degradation in human skeletal remains and 2) determine the amount of solar radiation required to display initial weathering characteristics such as bleaching and longitudinal cracking on human skeletal remains. Donated human remains placed at the Forensic Anthropology Research Facility (FARF) for up to three years were used to ascertain the timing and appearance of bone weathering characteristics. This will be the first study to use human remains in an attempt to better understanding of taphonomic processes surrounding skeletal decomposition that will aid in the interpretation of forensic, paleoanthropological, and archaeological sites that contain human remains.

Specific Research Questions:

1. Is solar radiation the primary variable responsible for weathering?
2. When do weathering characteristics appear?

3. Do differences exist in the amount of solar radiation required for bleaching to occur in long bones vs. flat/irregular bones?

4. Are there differences in the amount of solar radiation required for bleaching to occur among different skeletal elements?

5. Is solar radiation correlated with ADD and can it be used to estimate PMI?

II. MATERIALS AND METHODS

Materials

Longitudinal skeletal decomposition data were collected on a total of 19 skeletal remains from the Texas State University Donated Skeletal Collection (TSUDSC), part of the Willed Body Donation Program at the Forensic Anthropology Center at Texas State (FACTS). The 19 remains were divided into two groups, 10 unexposed remains serving as a control and 9 exposed and vulture scavenged remains. Unexposed remains, which can be seen in Figure 1, were part of longitudinal decomposition study taking place at FARF and were not subjected to solar radiation exposure. The remains in this study were wrapped in tarps in an attempt to see if this would affect early decomposition rates. The unexposed remains were placed outside at FARF, for varying amounts of time and were used as controls representing non-solar radiation exposed bodies. This was done in an

Figure 1: Example showing unexposed skeletal remains in a tarp

attempt to control for solar radiation with the expectation that unexposed remains would show no signs of weathering.

The 9 exposed remains were placed without protective cages, which allowed for animal scavenging to occur. The exposed remains used in this study were actively observed at weekly intervals to determine the precise time that particular characteristics of weathering, such as bleaching, cracking, and flaking occured. A total of 6 of the 9 exposed donations were fully fleshed individuals exposed to solar radiation and subjected to scavenging (Figures 2 and 3), and the other 3 were freshly skeletonized remains not exposed to solar radiation utilized from the previous unexposed study (Figure 4).

Figure 2: Fully fleshed remains placed for exposure to solar radiation.

Figure 3: Vultures actively scavenging remains.

Figure 4: Remains from tarp study placed for weathering.

Only the long bones, the skull, scapulae, and ossa coxae were used in the present study (Table 2). These elements were chosen for two reasons: First is because these bones are larger and often preserve better than the smaller bones and are more commonly found at a forensic recovery site. Secondly, Behrensmeyer (1978:152) highlights in her study that these skeletal elements are easier to score and that smaller bones such as carpals and phalanges "weather more slowly and may not exhibit all of the characteristics associated with weathering."

Table 2: Sample size by group

Group	Crania	Mandibles	Scapulae	Humeri	Radii	Ulnae	Ossa Coxae	Femora	Tibiae	Total
Exposed	9	7.0	16	14	12	13	18	16	13	118
Unexposed	10	10	17	18	20	18	20	19	19	151
Total	19	17	33	32	32	31	38	35	32	269

While assessing skeletal decomposition, emphasis focused on physical alterations to the bone that occur from exposure to solar radiation and temperature. Observation of physical changes to skeletal elements include longitudinal cracking, cortical flaking, and cracking parallel to the fibrous structure (Behrensmeyer 1978:151). Bleaching was also included, as this is often one of the first effects of weathering to be displayed. It is important to note that Behrensmeyer’s stages did not contain bleaching as a characteristic associated with weathering. Bleaching was later included in an adaptation of the stages by Haglund and Sorg (1996). This research will attempt to identify the amount of time required for bleaching and other weathering characteristics, as described by Behrensmeyer, to appear on human skeletal remains exposed to the effects of environment and to sun exposure. To accurately score Behrensmeyer's characteristics, the presence and associated severity or absence of these physical alterations were recorded (Appendix A).

Methods

Data collection for the 9 exposed donations required motion sensor game cameras, photographs, weekly notes, solar radiation data, and temperature data in the form of Accumulated Degree Days (ADD). Game cameras were placed near the 6 donations that were intended for exposure and subjected to scavenging. This allowed for thorough photographic documentation of the remains from fully fleshed to skeletonization. Photos and notes of all six donations were taken once a week to record the onset of skeletonization and when the initial signs of weathering appear. For this study, skeletonization was defined as the initial exposure of any part of the bone to the environment. Solar radiation and temperature were measured to test for a correlation between solar radiation exposure, temperature, and the time it takes for the onset of previously mentioned weathering effects. Solar radiation was collected using the HOBO brand weather station at FARF. Observations were recorded from the end of July 2015 until the end of February 2016. Solar radiation is measured in W/m^2 every half hour for a total of 48 measurements in a 24-hour period. The amount of solar radiation required for any individual bone to display bleaching or any other weathering characteristic will be identified as total solar radiation. Total solar radiation was calculated by summing all measurements of solar radiation between sunrise and sunset for each day for 7 days, averaging the sums, and adding those averages from the date of initial bone exposure to the date of first observed signs of weathering.

Because this study is using variables that vary by region and climate, it is important to note the climate in Central Texas where the study will be taking place. Central Texas is classified as Cfa in the Köppen−Geiger Climate Classification system. This classification means Central Texas has a warm temperate, fully humid, hot summer climate. This environment is quite different compared to the equatorial dry winter where Behrensmeyer's weathering stages were analyzed. It is also important to note that solar radiation is made up of several different components including ultraviolet light. According to the Environmental Protection Agency (EPA) the level of exposure to solar radiation varies depending on several factors including time of year, latitude, and altitude. Central Texas begins experiencing high levels of UV exposure in February or March, and reaches very high to extreme levels of UV exposure from June to August and falls back down to high levels of UV exposure by October or November.

Temperature data and the number of calendar days were also analyzed to have a more holistic view of skeletal decomposition and to see if any correlations appeared between the variables. Temperature data was analyzed in the form of ADD. ADD is calculated by adding the maximum and minimum temperature in degrees Celsius for each day and then taking the average (max + min/2). This was done as a way to standardize temperature data across skeletal and soft tissue decomposition studies. ADD is the most commonly used type of temperature data in soft tissue decomposition.

As this study progressed, it became apparent that better definitions are needed to have an improved understanding of the different weathering characteristics and standardize descriptions for use in future research. Behrensmeyer's study only uses extreme examples of weathering when explaining things such as bleaching, cracking, longitudinal cracking, and cortical flaking. This is to be expected, given that Behrensmeyer's study was retroactive in nature with observations only being conducted once a year during the field season in Amboseli National Park. (Personal communication with Behrensmeyer and Dechant, 2015). New definitions and examples for each of the weathering characteristics are given in the results section in an attempt to improve and standardize the analysis of weathering characteristics on human bone.

Statistical Analysis

The data collected on solar radiation, ADD and number of days were first tested for normality using a Shapiro-Wilk's test. This was done to make sure the appropriate statistical tests were used in analysis. Testing for normality revealed that traditional descriptive statistical analytical methods are not suitable for this study. Rather, the median values will be reported, and statistical tests such as the Mann-Whitney test, Kruskal-Wallis test, and logistic regressions along with linear regressions will be utilized. The Mann-Whitney test will be used in place of the t-test to determine if there is a statistically significant difference between the median values of solar radiation, ADD, and the number of days required for weathering characteristics to occur.

The first research question of this project was if solar radiation is the primary variable responsible for weathering characteristics appearing on skeletal elements. Data for solar radiation, ADD, and the amount of days required for bleaching to occur was collected from both the unexposed and exposed remains. Median data for solar radiation, ADD, temperature, and the number of days were also compared to test for significant differences. A Mann-Whitney test was run against the median amount of solar radiation when bleaching occurred and the amount of solar radiation the unexposed remains received.

The second question in this project focuses on when weathering characteristics appear; This was addressed by running statistical analysis to quantify the amount of solar radiation, ADD, and the number of calendar days required for weathering characteristics to occur on skeletal remains. Once bleaching appeared, the date was recorded, then solar radiation data was averaged for each day from the beginning of skeletonization until bleaching appeared. This was done for all skeletal elements utilized in the study. The total solar radiation was then recorded for each skeletal element, then the median solar radiation for bleaching to occur was determined. This was done by adding together all total solar radiation data for each skeletal element (n= 118) in the study and dividing by the total number of skeletal elements used. Mann-Whitney and Kruskal-Wallis tests were run against the median amount of solar radiation, ADD, and the number of days required for bleaching to occur on skeletal elements. To be as thorough as possible, median values were also calculated for ADD and number of days.

The third question from this study addresses whether or not differences exist in the required amount of solar radiation needed for bleaching to occur in long bones versus flat/irregular bone. A Mann-Whitney test was also run to see if there is a statistically significant difference in the median amount of solar radiation, ADD, and the number of days required for bleaching to appear in long bones versus flat/irregular shaped bones. This test was done to determine if surface area is a factor in the rate of weathering.

The fourth research question examines whether or not there are differences in the amount of solar radiation required for bleaching to occur among different skeletal elements. This was done by testing for differences between groups required using the Kruskal-Wallis test in place of the ANOVA. Skeletal elements were grouped by type of bone, i.e. crania, mandibles, scapulae, humeri, radii, ulnae, ossa coxae, femora, and tibiae. The median amount of solar radiation, ADD, and the number of days for each group was then compared against each other to determine if there was a statistically significant difference between groups for the amount of solar radiation, ADD, and number of days required for bleaching to appear.

The fifth question addresses if there is a correlation between solar radiation, ADD, and the number of days, and to determine which variables contributed to weathering the most and if any variables correlated with each other. A Pearson's Correlation was performed to determine if solar radiation, ADD, and the number of days required for bleaching to occur are correlated. A binary logistic regression was also carried out to determine if solar radiation was the primary variable responsible for weathering on bone.

III. RESULTS

Data were first assessed for normality; this was done to make sure the proper statistical tests were being utilized. Results from the Shapiro-Wilk's Test indicate the data is not normally distributed (Table 3). Non-normally distributed data cannot be analyzed with traditional statistical tests. Nonparametric tests must be used to make accurate inferences.

Table 3: Results from Shapiro-Wilk's test for normality

	Statistics	df	p-value
Solar Radiation	5.683	15	0.000
ADD	6.559	15	0.000
Calendar Days	6.561	15	0.000

For the first question, is solar radiation the primary variable responsible for weathering characteristics appearing on skeletal elements? Visual analysis of the remains showed that the control group wrapped in tarps showed no signs of weathering characteristics. Remains that were exposed on the surface showed varying signs of weathering ranging from bleaching to longitudinal cracking. The only differing variables between the groups was exposure to solar radiation and scavenging. In the control group, the tarp prevented the skeletal remains from being exposed to solar radiation. However, the remains were still subject to similar temperature and humidity levels that the experimental group received for a significantly longer period of time than the exposed remains.

Running a Mann-Whitney test shows a statistically significant difference at the 0.001 level of confidence in the median amount of exposure to solar radiation, ADD, and the number of days between unexposed and exposed remains (Table 4). As expected, solar radiation was the primary variable responsible for the presence of weathering characteristics on skeletal remains; this is evident when looking at the ADD and number of days between the two groups. The unexposed remains were exposed to statistically higher amounts of ADD, number of days, and no solar radiation, but no weathering was observed on any skeletal elements.

Table 4: Mann-Whitney U test comparing median values of unexposed and exposed remains

	Solar Radiation	ADD	Calendar Days
Mann-Whitney U	0.000	1459.000	1718.500
Wilcoxon W	11476.000	8480.000	8739.500
Z	-15.514	-11.776	-11.369
p-value (2-tailed)	0.000	0.000	0.000

Addressing the second question “when do weathering characteristics appear?” required using descriptive statistical analysis to determine the median amount of solar radiation required for different weathering characteristics to appear on bone. The temporal aspect of this study has only allowed for the analysis of early weathering characteristics such as bleaching, fissures, and longitudinal cracking. Bleaching was the first variable analyzed as it is often the first component to appear on bone. In order to do this, solar radiation data was collected from the time each skeletal element was exposed through decomposition or scavenging until the first signs of bleaching appeared. Table 5 below shows the median amounts for solar radiation, ADD, and number of days. The median solar radiation required for bleaching to appear across all skeletal elements is 51366.4 W/m^2. The median amount of thermal energy required for bleaching to occur on skeletal elements is 997 ADD and the median amount of calendar days is 47.

Table 5: Median values for solar radiation, ADD, and calendar days

	Median	Min	Max
Solar Radiation	51366.4	11210.7	146890.4
ADD	997.1	156.6	2584.2
Calendar Days	47	8	127

The third question, “do differences exist in the required amount of solar radiation for bleaching to occur in long bones versus flat/irregular bone?” attempted to determine if the shape of bone or exposed surface area resulted in differential weathering rates. In order to do this, bones were separated into two categories. The crania, mandibles, scapulae, and ossa coxae were classified as flat/ irregular bones while the humeri, radii, ulnae, femora, and tibiae were classified as long bones. A Mann-Whitney test was utilized to determine if there was a statistically significant difference between the median amounts of solar radiation required for bleaching to occur between the two groups (Table 6). The nonparametric test shows that there is no significant difference ($p= 0.158$) between the median amounts of solar radiation required for bleaching to occur on long bones vs. irregular bone. Nonparametric tests were also run to see if there was a statistically significant difference between the amount ADD ($p= 0.172$) and number days ($p= 0.937$) required for bleaching to occur on long bones versus flat/irregular bones. The tests found there was no significant difference between the two groups. Median values for total solar radiation, ADD and calendar days for long and flat/ irregular bones can be seen in Figure 5.

Table 6: Results from Mann-Whitney U testing the difference between flat/irregular bone and long bone

	Total Solar Radiation	ADD	Calendar Days
Mann-Whitney U	1441.500	1540.000	1685.500
Wilcoxon W	2716.500	2725.000	4031.500
Z	-1.412	-1.365	-0.079
p-value (2-tailed)	0.158	0.172	0.937

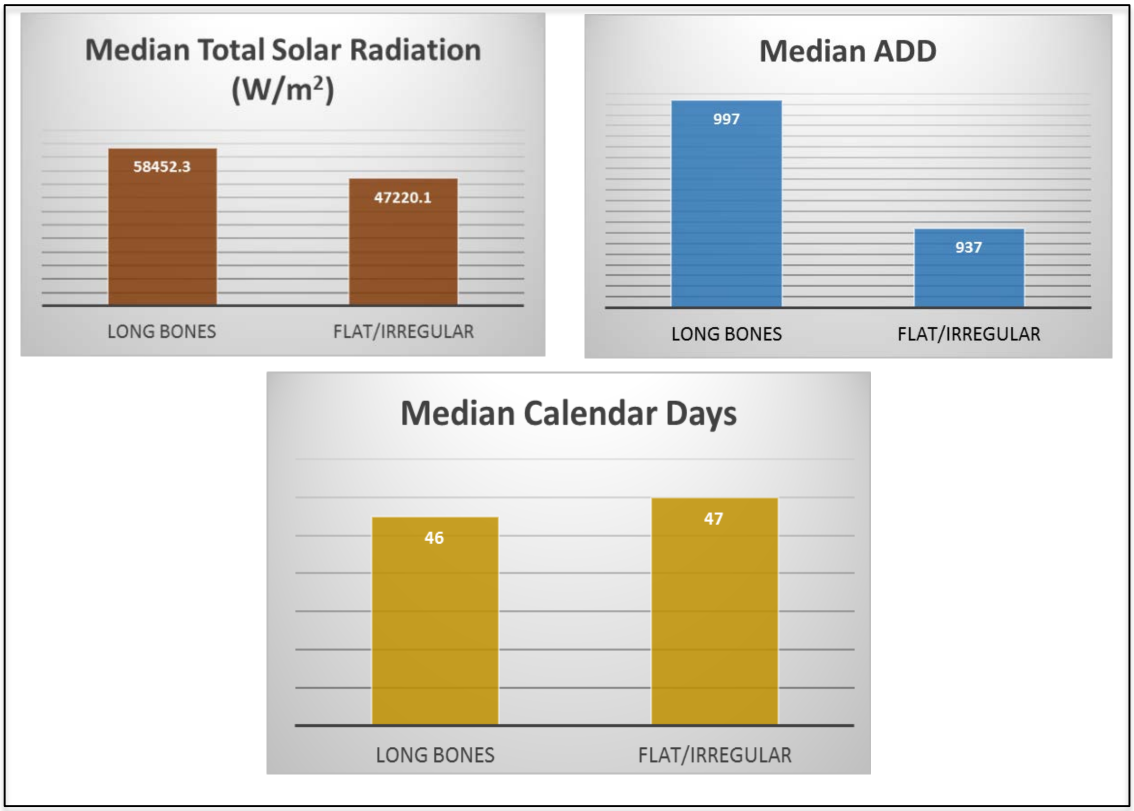

Figure 5: Graphs showing median values of total solar radiation, ADD, and calendar days for long and flat/irregular bones

For question four "are there differences in quantities of solar radiation required for bleaching to occur among different skeletal elements?", the Kruskal-Wallis test was run separating skeletal elements into groups based on the type of bone. These groups included crania, mandibles, scapulae, humeri, radii, ulnae, ossa coxae, femora, and tibiae. The Kruskal-Wallis test compared the medians of each group to see if there was a statistically significant difference. The results from the Kruskal-Wallis show that there is no statistically significant difference (p= 0.985) in the required amount of solar radiation for bleaching to occur between crania, mandibles, scapulae, humeri, radii, ulnae, ossa coxae, femora, and tibiae. A Kruskal-Wallis test was also run comparing the median amount of ADD (p= 0.969) and the number of days (p= 0.969) required for bleaching to occur among the different groups of skeletal elements. Results showed that there is no statistically significant difference. Results for the Kruskal-Wallis tests and median values can be seen below in Table 7 and Figure 6.

Table 7: Kruskal-Wallis test results

	Chi-Square	df	p-value
Solar Radiation	5.683	15	0.985
ADD	6.559	15	0.969
Calendar Days	6.561	15	0.969

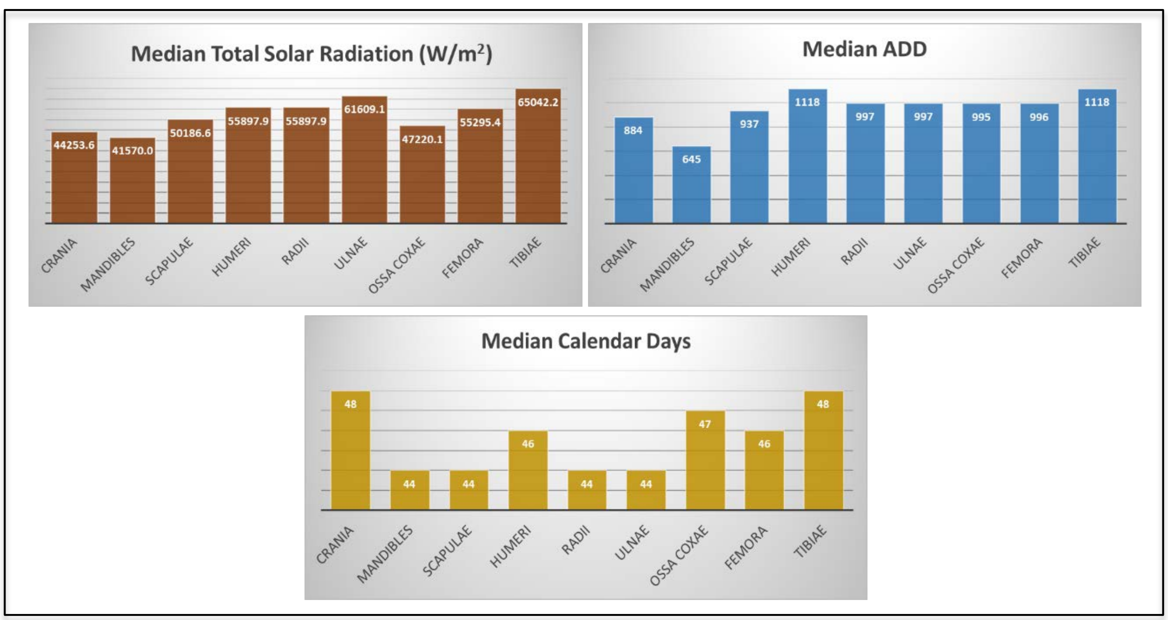

Figure 6: Graphs showing median values of total solar radiation, ADD, and calendar days for groups of skeletal elements

In order to address question five “is bleaching correlated with solar radiation, and are solar radiation, ADD and the number of days correlated?”, a Pearson’s Correlation was performed to determine if there is a correlation between bleaching, solar radiation, ADD, and the number of days (Table 8). Scatter plots (Figures 7 and 8) can be seen below showing the correlation between total solar radiation, ADD and calendar days. Both ADD and calendar days were included in the correlation with the expectation that ADD, or calendar days could be used in the absence of solar radiation data. A binary logistic regression was also run to determine if there is a correlation between bleaching and solar radiation (Table 9). The odds ratio (OR= 1.003) is greater than 1; this indicates that the group exposed to solar radiation has 1.003 times greater chance of bleaching for every 1-unit increase in solar radiation. This was expected, as solar radiation was thought to be the primary variable responsible for causing bleaching on bone.

Table 8: Pearson’s Correlation results

		Total Solar Radiation	ADD	Calendar Days
Solar Radiation	Pearson Correlation	1	0.848**	0.668**
	p-value		0.000	0.000
	N	118	118	118
ADD	Pearson Correlation	0.848**	1	0.810**
	p-value	0.000		0.000
	N	118	118	118
Calendar Days	Pearson Correlation	0.668**	0.810**	1
	p-value	0.000	0.000	
	N	118	118	118

** Indicates significance at the 0.001 level of confidence

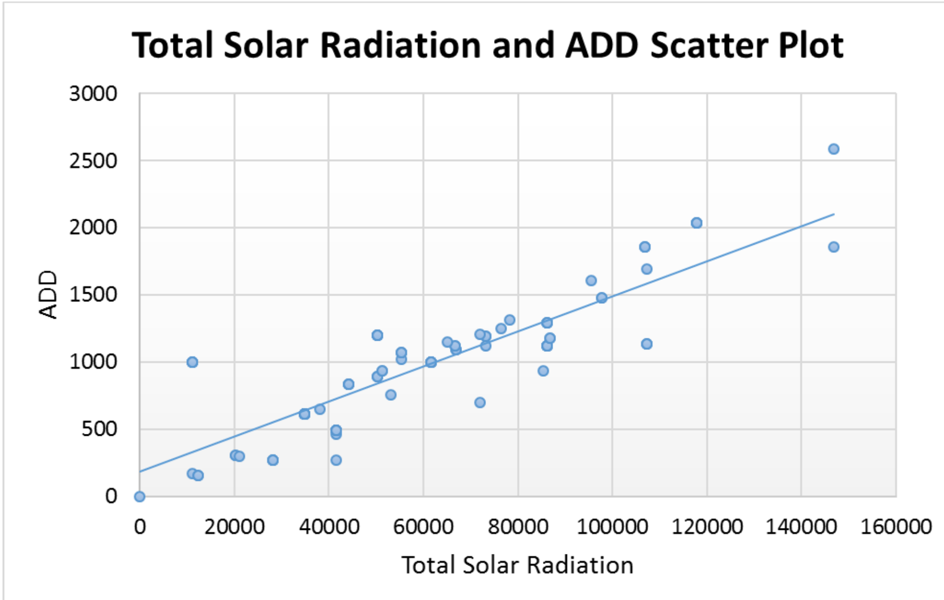

Figure 7: Scatter plot with trendline showing correlation between total solar radiation and ADD

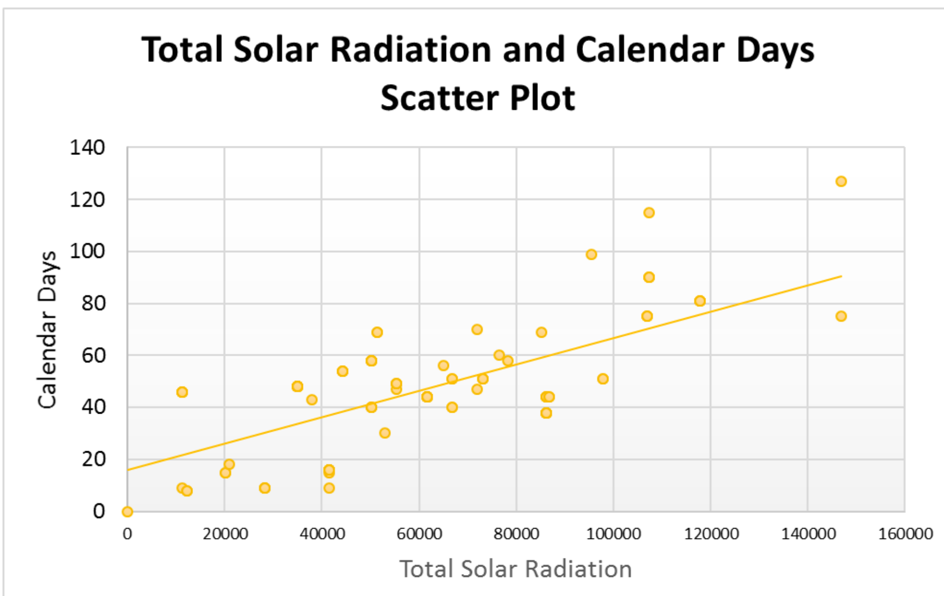

Figure 8: Scatter plot with trendline showing correlation between total solar radiation and calendar days

Table 9: Binary Logistic Regression results for bleaching and solar radiation.

	B	S.E.	Wald	df	Sig.	Exp (B)
Total Solar Radiaiton	0.003	0.104	0.001	1	0.977	1.003
Constant	-18.446	824.15	0.001	1	0.982	0.000

The results from the Pearson's Correlation indicate that solar radiation may be used as an indicator for ADD or number of days in PMI estimation surrounding bone weathering. This may allow for a possible formula to be created using a regression model. The Binary logistic regression confirms that solar radiation is the primary variable responsible for weathering, more specifically bleaching, on bone.

Defining Weathering Characteristics

Individual bones were analyzed for macroscopic signs of weathering. However, the focus was given to the most weathered area of the bone. Observations revealed that weathering will begin in a particular area or areas and then gradually spread throughout the bone. This can create problems when attempting to diagnose bleaching, cracking, and cortical flaking. This is because these features are not always as clear cut and easily identifiable as laid out in Behrensmeyer's study. Lack of clear definitions of what constitutes a particular weathering characteristic, or confusing and repetitive terminology surrounding these features can create discrepancies between different researchers when discussing bone weathering in research or case reports. It is important to remember that weathering and the characteristics associated with it are continuous processes. This means that physical manifestations associated with weathering are continually undergoing changes. The temporal range of these changes are highly influenced by the surrounding environment, which can significantly affect the degree of weathering displayed. In the example of bleaching, this means that a bone will start out its natural off-white color, then change to yellowish-brown, and then gradually change color from either staining due to soil and decompositional fluids, or bleach white from solar radiation. However, it is important to note that the bone does not bleach white all at once. This is a gradual process and often first appears as small patches of white staining or lightening of the bone and then progress into larger areas of bleached bone until the entire surface of the bone that is facing the sun is bleached.

Bleaching

Because bleaching occurs over an extended period of time, it is beneficial to break bleaching up into three categories. Mild bleaching is defined as small patches of lightened or white bone (Figures 9 and 10). These small patches may be associated with initial skeletal exposure to the environment when the soft tissue decays away and the bone is exposed to solar radiation.

Figure 9: Mild bleaching present on the shaft of a left humerus

Figure 10: Mild bleaching on the distal posterior portion of a femoral shaft.

Moderate bleaching can be defined as generalized whitening of the majority of a single skeletal element (Figure 11).

Figure 11: Moderate bleaching present on the shaft of a left humerus.

Heavy bleaching occurs when the entire bone is bleached a bright white, and the bleaching appears to permeate the outer layer of cortical bone into the underlying layers (Figure 12).

Figure 12: Example of heavy bleaching that has spread throughout an entire left tibia

Bleaching can be defined as the process of the outer cortical layer of the bone fading to lighter shades of the natural or stained color of the bone and eventually turning whiter than original color or surrounding bone.

Cracking and longitudinal cracking are also characteristics that do not have precise definitions and may present problems when trying to differentiate between the two. From this point forward, cracking will be referred to as fissures, in order to clarify and prevent confusion when discussing cracking and longitudinal cracking.

Fissures

Fissures are an extremely variable characteristic of weathering both in physical and temporal manifestation. Fissures can appear on both long bones and flat/ irregular shaped bones. Cracks often appear as small fissures in the surface of the bone less than 1cm long. They can appear singularly, or appear as multiple cracks running adjacent to each other or connecting. The depth of their permeation into the cortical bone varies from superficial to significant penetration of the cortical bone. An example of fissures on a cranium can be seen below in Figure 13.

Figure 13: Example of fissures on the right frontal, parietal, and temporal bones of a cranium.

Longitudinal Cracking

Longitudinal cracking will be defined as linear cracking that is greater than 1cm and clearly permeates the cortical layer of bone (Figure 14). These long cracks are most often associated along the vertical axis of the shaft of long bones; linear cracks can also be seen in the subscapular fossae, illium, and along the ramii of the ossa coxa and mandible.

Figure 14: Longitudinal cracking on the shaft of a tibia

Cortical Flaking

Like bleaching, cortical flaking appears to occur as a continuous process. This weathering characteristic begins as small patches of exfoliating cortical bone and according to Behrensmeyer (1978:151) expands into larger flakes often associated with "cracking" falling away from the bone, leaving the underlying fibrous structure. The TSUDSC did have examples of mild or light cortical flaking shown below in Figure 15.

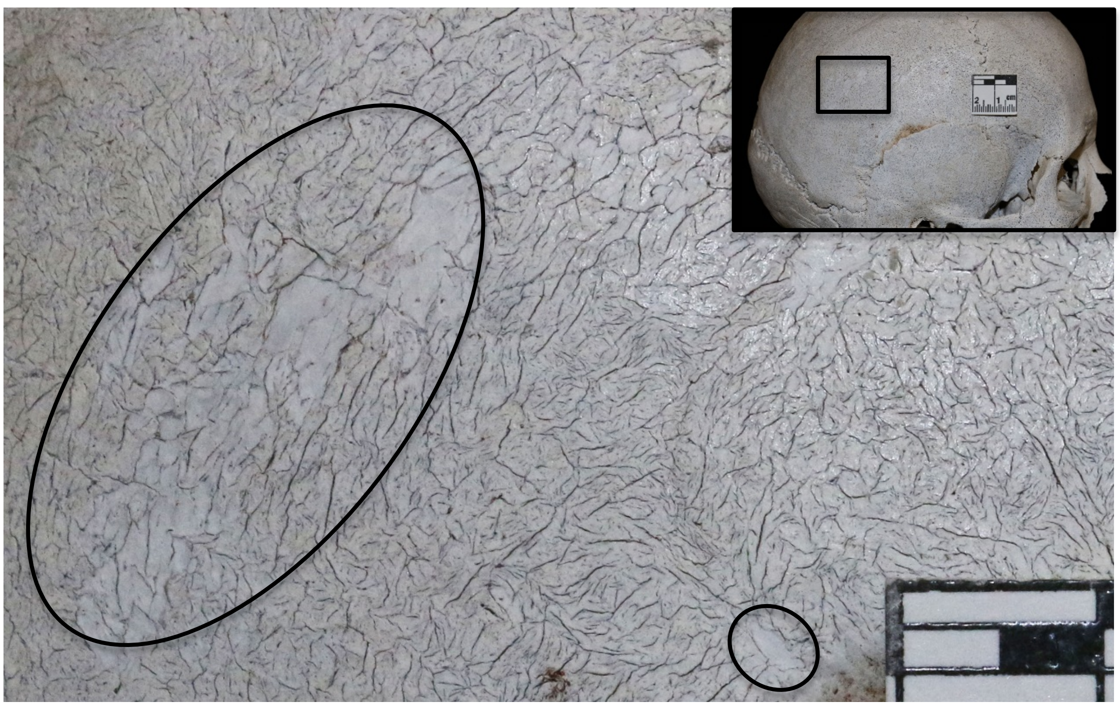

Figure 15: Mild cortical flaking (circled) on the right parietal of a cranium.

IV. DISCUSSION AND CONCLUSION

As expected, results from the study indicate that solar radiation is the primary variable tested responsible for weathering characteristics appearing on skeletal elements. Therefore, solar radiation may provide a standard unit of analysis and provides a quantitative method which helps better understand the process of weathering and how it affects human skeletal remains. Identifying the median amount of solar radiation required for bleaching to occur along with confidence intervals allows for future studies to have a standard unit of measurement to compare against. Studies in different climates will hopefully be able to compare results to this research and see if it is replicable in different environmental zones. It is expected that this research will lay the foundation to develop criteria for using solar radiation to estimate PMI for surface scattered skeletal remains found in forensic settings. Further, the median ADD and number of days required for bleaching to occur may provide additional units of PMI estimation in the absence of solar radiation data.

Surprisingly, bleaching rates did not significantly differ between flat/irregular bones and long bones. During the initial stages of data collection, it was thought that the surface area might determine the rate at which different bones weather. Given that the amount of surface area does not play a statistically significant role in weathering, the use of any long or flat bones should be sufficient when analyzing weathering in either a research or forensic setting. Similarly, it was assumed that there would be a difference in the rate of weathering among the different groups of bone. However, statistical analysis revealed that there is no significant difference. It was originally thought that the morphology, more specifically shape and size of the bone might affect the rate of weathering, with some types of bone weathering faster. The significance of these findings along with findings associated with surface area imply that weathering occurs in a relatively uniform process regardless of the bone or area of bone being affected. Running a binary logistic regression shows that skeletal elements exposed to solar radiation, for every 1-unit increase in solar radiation, there is 1.003 times greater chance for bleaching. The strong correlations between solar radiation, ADD, and number of days in conjunction with the binary logistic regression suggest these variables can be used to create a formula which will help PMI estimates for surface scatter skeletal remains that display signs of weathering characteristics.

This study lays the foundation for using solar radiation as a quantifiable unit to help estimate PMI based on the presence of bone weathering characteristics and supports statements made in previous research regarding solar radiations role in weathering rates (Beary 2005; Prassack 2011; Junod and Pokines 2013; Osterholtz *et al.* 2014; Frison and Todd 1987; Pokines *et al.* 2016; Cunningham *et al.* 2011). While all of the studies listed discuss the importance of solar radiation as a component of the weathering process, none of these studies attempt to understand the role of solar radiation. This study along with Pokines *et al.* (2016) illustrate that using Behrensmeyer's stages for estimating weathering rates may not be sufficient for several reasons. The first would be problems with definitions and how lack of clarity influences analysis and placement of bone into different stages. Secondly, Behrensmeyer's temporal ranges for each stage are very broad ranging from 1 year to 11 years or more. Thirdly, Behrensmeyer attributes the weathering characteristics observed in her study to temperature and moisture. She does not account for any other variables that may affect weathering rates and does not include bleaching.

The use of solar radiation in conjunction with the definitions developed in this study will help to standardize the analysis of weathering on human bone. This approach involves using data on solar radiation within the general region where the remains were discovered. Macroscopic observation for the presence or absence of weathering would then be performed guided by the definitions for bleaching, fissures, longitudinal cracking, and cortical flaking. Once it was determined which characteristics are present, it would simply be a matter of adding up the total solar radiation for each day starting on the day of recovery of the skeletal remains and working backward until the median amount of solar radiation required for that weathering characteristic, plus or minus the standard error. Doing this would give an estimate of the temporal range of exposure to solar radiation for the skeletal remains. This method, in conjunction with soft tissue decomposition methods and local scavenger activity would create a more holistic and accurate estimation of minimum time since death.

Limitations

It is important to note that this study has several limitations. The most important of which is that results found in this study are currently only applicable to areas that receive solar radiation levels similar to Central Texas and the Southwest United States. The sample size is also a point of concern, since this is the first study of its kind that uses human remains to look at weathering rates. The sample size is limited by the number of donations received, other projects, and the amount of time allotted for the research. Additionally, the time frame for this project does not allow for observation and analysis of more advanced weathering characteristics. While some characteristics like longitudinal cracking did appear on some of the skeletal elements, there was not enough data to confidently report the results in this study. Finally, it must be addressed that different seasons can have an effect on the amount of time required for bleaching to occur. As seasons change, solar radiation levels rise and fall. During the summer, solar radiation reaches higher levels, which means fewer days for weathering characteristics to appear. This correlation was illustrated with the logistic regression which showed that solar radiation and number of days are negatively correlated.

Longitudinal Cracking, Fissures, and Cortical Flaking

Data collection of longitudinal cracking, fissures, and cortical flaking did occur during this study. However, the presence of these features was so varied that statistical analysis was not assessed. Many skeletal elements did not show signs of these weathering characteristics. This absence is mostly likely due to the timescale allotted for this project. There are skeletal elements from different studies at FARF that have been outside for up to 3 years that do not display longitudinal cracking; they do however show varying degrees of fissures. The amount of solar radiation and the temporal range required for longitudinal cracking and fissures to appear is much more varied than bleaching. It is also important to note that Pokines (2016) showed freezing and thawing cycles can cause fissures and longitudinal cracking to appear on skeletal elements. Fissures and longitudinal cracking that occurred in subscapular fossa and the iliac fossa have been omitted from this study. This exclusion is because personal observation of skeletal remains has shown that these characteristics can appear in the scapulae and ossa coxae without exposure to solar radiation. Fissures and longitudinal cracking present in the subscapular fossa and the iliac fossa are most likely caused by a multitude of variables including the thinness of the bone in these areas. Observations will continue on the remains still undergoing weathering at FARF. There are plans to undertake future research projects which will attempt to more accurately estimate the amount of solar radiation needed for longitudinal cracking and fissures to occur on human skeletal remains.

Future Directions

The most important direction for this study is for weathering studies on human skeletal remains to be implemented in different regions of varying climate. These studies would provide information on whether or not solar radiation is a standard unit that can be used across all areas and determine if similar amounts of solar radiation are required for weathering characteristics to occur regardless of region. Having a good understanding of regional soft tissue decomposition will allow for better understanding of the timing of bone weathering. It would also be beneficial for a more long-term study to be done; this would permit the collection of more data involving weathering characteristics such as longitudinal cracking and cortical flaking. Long-term research focusing on the later stages of weathering on human bone would provide for more accurate upper ranges when estimating PMI for extremely weathered human skeletal remains.

Future research for this project will include data collection on fissures, longitudinal cracking, and cortical flaking. The time frame for this study did not allow for enough data to be collected on these latter weathering characteristics for confident statistical analysis to be performed. The next phase of this research will utilize skeletal remains that have been at FARF for up to 3 years. This will give a more holistic view of the more advanced stages of bone decomposition resulting from weathering.

This study allows for a more in-depth look at how decomposition of skeletal remains can be assessed. Using human remains for taphonomic studies and attempting to understand and analyze the underlying variables that cause specific taphonomic processes is the only way to produce reliable and quantifiable scientific research in the areas of forensic anthropology, bioarchaeology, and paleo anthropology. While Behrensmeyer's study in 1978 laid the foundations for future research, the manner in which it was implemented never addressed when characteristics of weathering appeared, how they progressed, and factors that influenced them. The use of qualitative methods such as scoring skeletal elements that place them in stages based on the presence or absence of weathering characteristics does not show the totality of the events surrounding weathering. While the present study does not address every issue surrounding bone weathering, it is an attempt to better understand the underlying factors of weathering and move away from strictly qualitative observations. Conclusions reached from this research will impact not only forensic settings, but will aid in better understanding the circumstances and conditions affecting human remains in the archaeological and paleoanthropological record.

APPENDIX SECTION

APPENDIX A: EXAMPLE OF DATA COLLECTION AND NOTES SHEET

ID:	Date:			
Bone	Bleaching	Longitudinal Cracking	Cortical Flaking	Fissures
Cranium				
Mandible				
R-Scapula				
L-Scapula				
R-Humerus				
L-Humerus				
R-Radius				
R-Ulna				
L-Radius				
L-Ulna				
R-Os Coxa				
L-Os Coxa				
R-Femur				
L-Femur				
R-Tibia				
L-Tibia				

Notes:

ID:	Date:			
Bone	Bleaching	Longitudinal Cracking	Cortical Flaking	Fissures
Cranium				
Mandible				
R-Scapula				
L-Scapula				
R-Humerus				
L-Humerus				
R-Radius				
R-Ulna				
L-Radius				
L-Ulna				
R-Os Coxa				
L-Os Coxa				
R-Femur				
L-Femur				
R-Tibia				
L-Tibia				

Notes:

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